АКАДЕМИЯ НАУК АВИАЦИИ И ВОЗДУХОПЛАВАНИЯ
ACADEMY OF AVIATION AND AERONAUTICS SCIENCES

РОССИЙСКАЯ АКАДЕМИЯ КОСМОНАВТИКИ ИМ. К.Э.ЦИОЛКОВСКОГО
RUSSIAN ASTRONAUTICS ACADEMY OF K.E.TSIOLKOVSKY'S NAME

РОССИЙСКО-АМЕРИКАНСКИЙ НАУЧНЫЙ ЖУРНАЛ ♦ RUSSIAN-AMERICAN SCIENTIFIC JOURNAL
ISSN 1727-6853

12.04.1961

АКТУАЛЬНЫЕ ПРОБЛЕМЫ
АВИАЦИОННЫХ И АЭРОКОСМИЧЕСКИХ СИСТЕМ
процессы, модели, эксперимент

2(39) 2014

ACTUAL PROBLEMS
OF AVIATION AND AEROSPACE SYSTEMS
processes, models, experiment

КАЗАНСКИЙ ГОСУДАРСТВЕННЫЙ ТЕХНИЧЕСКИЙ УНИВЕРСИТЕТ
Казань

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY
Daytona Beach

АКТУАЛЬНЫЕ ПРОБЛЕМЫ АВИАЦИОННЫХ И АЭРОКОСМИЧЕСКИХ СИСТЕМ
Казань, Дайтона Бич Вып. 2 (39), том 19, 1-206, 2014

СОДЕРЖАНИЕ / CONTENTS

ACTUAL PROBLEMS OF AVIATION AND AEROSPACE SYSTEMS
Kazan, Daytona Beach No.2 (39), volume 19, 1-206, 2014

ACTUAL PROBLEMS OF AVIATION AND AEROSPACE SYSTEMS
Kazan-Daytona Beach

Main goals of this Journal -

- to inform the specialists of appropriate fields about recent state in theory and applications; about global problems, and actual directions;
- to promote close working contacts between scientists of various Universities and Schools; between theorists and application oriented scientists;
- to mathematize the methods in solving of problems, generated by engineering practice;
- to unite the efforts, to synthesize the methods in different areas of science and education...

In Journal the articles and reviews; the discussions communications; engineering notices, the statements and solutions of problems in all areas of aviation and aerospace systems are published (including new results, methods, approaches, hypothesizes, experimental researches,...).
Authors of theoretical works have to show the possible areas of applications in engineering practice.
The languages of publications are RUSSIAN, ENGLISH.

Edition is carried out in the co-operation with MAI - Moscow Aviation Institute (National Research University), with Moscow State Technical University of N.E.Bauman's name, with Cosmonautics Federation of Russia

"…we value cooperation with Russia…
since **in Russia it is World Sharpest Engineers,**…",
Josef Byden, Vice President, USA, (2011).

If to be, it is necessary to be ***the First***
V.P.Chkalov

From International Editorial Board

New issue of the International scientific journal "Actual problems of aviation and aerospace systems", *No.2(39), Vol.19, 2014,* is another special issue devoted to the greatest events of the history of Mankind associated with Aviation and Cosmonautics, with the beginning of Space exploration Era.

This Era is associated with distinguishing achievements in space exploration, implemented on the basis of fundamental science and thought-out engineering practice: from the *first,* Soviet, Earth satellite (4 October 1957) – to the *first* Man on space orbit (Yu.A.Gagarin, 12 April 1961), to the satellite constellations and International space stations, to the space flights and lunar landing, to the interplanetary missions…

Great Russian scientist **Konstantin Eduardovich Tsiolkovsky** was the originator of the Epoch of Space exploration, with profound development of all the areas of basic and applied astronautics. Scientific theories and approaches that became a basis for the first space calculations, theoretical and applied research, including the problems of dynamics of celestial bodies and artificial satellites and engineering problems of space flights, are associated with the names of outstanding specialists in mechanics and mathematics, with *Russian* scientific and design Schools, which have been recognized all over the world. They are the Academicians: **Leonard Euler**; **Alexander Mikhailovich Lyapunov**, founder of the motion stability theory; **Nikolay Guryevich Chetaev**, who interpreted A.M.Lyapunov's concepts and theory to the whole scientific and engineering world, who founded Kazan Chetaev's School of stability and Kazan Aviation Institute (A.N.Tupolev KAI-KNRTU); **Sergey Pavlovich Korolev**, Chief Designer of rocketry; **Mstislav Vsevolodovich Keldysh**, scientific supervisor of the USSR Space Program, theorist in astronautics – a brilliant specialist in *mechanics and mathematics*…

This was an event of paramount importance for the history of Mankind that logically resulted from the efforts of the USSR people, who had managed to join the achievements of basic and applied science, engineering, socio-political system.

Contribution to that notable breakthrough, the projects and creativity of the outstanding scientists and designers of that time – M.K.Tikhonravov, V.P.Barmin, M.S.Ryazansky, G.Ye.Lozino-Lozinsky, V.P.Glushko, V.N.Chelomey, M.K.Yangel, V.F.Utkin, G.N.Babakin,V.P.Makeev,.…

… – are the subject of special scientific research.

It was the fundamental higher Engineering Education, powerful scientific Schools, lofty ideas, boundless loyalty and inexhaustible enthusiasm that provided the Soviet Union with the chance for such a brilliant breakthrough in science, technology and ideology.

These positive results were provided by professional heroism of the Soviet Representatives of science and engineering and by policy of the country's top Leadership who made the fantasy come true and ***the Soviet Union win the Victory*** **(*in the struggle for Peace…*)**

The city of Kazan and Kazan Aviation Institute is directly relevant to the development of aviation and astronautics; the world-famous names – Nikolay Guryevich Chetaev, Valentin Petrovich Glushko, Sergey Pavlovich Korolev, Andrey Nikolaevich Tupolev,..., as well as Andrey Vladimirovich Bolgarsky, Yuri Georgievich Odinokov, Vyacheslav Yevgenyevich Alemasov, Georgy Sergeevich Zhiritsky (one of the lunar craters was named after him), Vladimir Mefodyevich Matrosov (*minor planet – Object* 17354 – "**Matrosov**")… – all of them are associated with Kazan and Kazan Aviation Institute, alma mater of engineering personnel for aviation and rocket-and-space engineering.

It was in 1945 in Kazan where ***the first in the country Department of rocket propulsion engineering*** *was founded in Kazan Aviation Institute (Head of Department – V.P.Glushko, Professor of Department – G.C.Zhiritsky, Teachers – S.P.Korolev, D.D.Sevryk, ...).*
Among the famous designers of rocket-and-space hardware there were also the following graduates of KAI: B.I.Gubanov, Chief Designer of Energiya-Buran Space System; V.I.Lobachev, Head of Mission Control Center, ...

Close interdisciplinary link between the fundamental and applied domains of science, between its separate disciplines is of vital importance for successful development of the whole aviation and rocket-and-space engineering, for space exploration. This was established as a basis for the entire scientific, educational, engineering and design work aimed at the training of specialists in Kazan on N.G.Chetaev's initiative and according to the innovative ideas of the "*Fathers of Russian Aviation*" **N.E.Zhukovsky, S.A.Chaplygin**, aiming at extension of traditions of advanced scientific and educational Engineering School (**P.L.Chebyshev – A.M.Lyapunov – N.G.Chetaev - …**).

The special issues are devoted to the 120-th Anniversary of General Designer, Academician *S.V.Iljuschin*; 80-th Anniversary of First Cosmonaut of Earth planet *Yu.A.Gagarin*.

The papers published in this special issue describe the developments of the leading specialists in aerospace; they contain the historical analysis of the way that led to the positive results of the beginning of Space Era. Scientific research, analytical reviews on these events and relevant problems, analytical and information articles, polemical ideas and prospects of further development of Astronautics in Russia and in the World, scientific meditations about Mankind Evolution, reflections on the meaning of space scientific and engineering heritage for the whole world society and results in the sphere of aviation and aerospace systems are presented.

Our Partners on special issues:
Cosmonautics Federation of Russia Central Scientific Research Institute for Machine Building, Federal Space Agency, K.E.Tsiolkovsky Russian Academy of Cosmonautics, Academy of Aviation and Aeronautics Sciences, A.A.Maksimov Scientific and Research Institute of Space Systems, N.E.Bauman Moscow State Technical University, Moscow Aviation Institute (National Research University), International Academy of Astronautics, Institute of Control Sciences of RAS, Concern "TsNII "Electropribor", International Center of Computing Methods in Engineering (CIMNE).

Our authors are well-known specialists, researchers, representatives of the Academies of Sciences, design bureaus, scientific and research institutes, universities, space agencies, who work in the spheres theoretical and applied aviation and astronautics.

G.V.Novozhilov (Ilyushin Aviation Complex, Russia), Academician of RAS, General Designer, President of the Academy of Aeronautics and Aviation Sciences, leading specialist in area of aircraft engineering, represents a comprehensive review of life and career of S.V.Ilyushin , an outstanding aircraft designer. The review analyses Ilyushin's engineering, design and organizational methods of work, which always led him to success.

Alexander Bolonkin (International Space Agency, National Research Council, USA), specialist in domain of aviation and aerospace systems, represents an interesting research project on methods of utilization of high-altitude wind power.

Emilio Spedicato (University of Bergamo, Italy), specialist in operation research, represents a review on the problems and method of simulation of the problem of "large space body – Earth" interaction, including interdisciplinary processes of capturing of a body by the Earth, dynamics of the body and the Earth, geodynamics, dynamics of the Earth atmosphere, ocean

dynamics,… and subsequent evolution of human society on the Earth; mathematical models are discussed, author's opinion on some aspects of evolution theory are submitted.
M.V.Levskii (Khrunichev State Research and Production Center, Space Systems Research and Development Institute, Russia), specialist in area of control theory, design of instruments and systems of automatic control theory, represents his results on optimal control of motion of a spacecraft with inertial executive devices.

V.A.Afanasyev, A.S.Meshchanov, E.Yu.Samysheva (South Ural State University, KNRTU-KAI, Russia), specialists in area of design and control of complex engineering systems in respect to astronautics, represent their results in the development of a reusable aerospace system intended for cargo transportation from the near-Earth orbit.

A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, L.K.Kuzmina, S.V.Tarasov, A.A.Fokov (Institute of Technical Mechanics of NASU and SSAU, KNRTU-KAI; Ukraine, Russia), specialists in domain of dynamics and control of complex mechanical systems, in development of A.M.Lyapunov's methods in respect to aviation and astronautics problems, represent and discuss currently important developments and modifications of calculation schemes in the problems of simulation and control of large-scale space structures.

O.L.Starinova, I.L.Materova (Samara State Aerospace University, TsSKB Progress, Russia), specialists in area of control of dynamic systems in respect to astronautics, represent their results in optimization of trajectories of a spacecraft with low-thrust engine performing a lunar mission.

Scientific-Information Section

A.G.Milkovskiy, M.N.Kovbich (TsNIIMash, Russia), specialists in area of system research of information support in rocket and space related activities, represent scientific and information review of the contribution made by research and test Center of TsNIIMash into "Energia-Buran" system development.

A.A.Gafarov, E.Yu.Kuvshinova, I.E.Vlasov, L.P.Vershinina (M.V.Keldysh Research Center, Council of Veterans of Command and Measurement Center, TsNIIMash, Russia), specialists in domain of utilization of nuclear power engineering in space, history of rocket-and-space engineering and science, represent the review of the scientific works presented at the Session "History of rocket and space engineering – from the past to the future" that was organized in the framework of the 38th Academic Readings on astronautics.

В 2014г. В ЖУРНАЛЕ ОПУБЛИКОВАНО

№1(38), т.19, 2014

№2(39), т.19, 2014

PUBLISHED IN 2014

№1(38), v.19, 2014

№2(39), v.19, 2014

To the 120th Anniversary of Sergey Vladimirovich Ilyushin

G.V.Novozhilov
Ilyushin Aviation Complex
45g Leningradskiy Prospect, Moscow, 125190, Russia

The 120th Anniversary of **Sergey Vladimirovich Ilyushin**'s birth was celebrated in March 2014. He was a **worldwide famous aircraft designer**, Colonel General of engineering and technical service, full member of the USSR Academy of Sciences, thrice the Hero of Socialist Labor.
The decision to hold festive events in honor of S.V.Ilyushin's 120th Anniversary was endorsed by the President of the Russian Federation V.V.Putin.

S.V.Ilyushin (31.03.1894- 09.02.1977)

S.V.Ilyushin was an outstanding aircraft designer, engineer, scientist and production organizer. He was born in a multi-child family in the very depth of Russia – in Dilyalevo, a remote village of Vologodskaya region, on 31 March 1894. He attended school in his village, but at the age of fifteen he had to leave the village to work and earn money, as most of his fellow countrymen did.
1910 – a spademan at Kolomyazhskiy racecourse, which was converted into an airfield on the occasion of the first "Aviation Week" in Russia. This event made Ilyushin acquainted with aviation. Since 1914 – a soldier of hangar team, motor mechanic's assistant, and finally – aviation motor mechanic – these were the first steps made by S.V.Ilyushin in aviation. Motor

mechanic S.V.Ilyushin strived for attending pilot training courses, which was hard to attain at that time, but he passed the exam and became a pilot-aviator at All-Russian Aero Club school.
S.V.Ilyushin was drafted into the army in May 1919; he started his service as a mechanic of aircraft repair train, which travelled from one Civil War front to another; later he became a senior mechanic and a commissioner of aircraft fleet. This allowed S.V.Ilyushin to thoroughly examine the structure of almost all the airplanes of that time, their operation features and tactical employment.
In 1921-1926, S.V.Ilyushin attended N.E.Zhukovskiy Academy of Air Fleet. He stood out from the rest of the Academy students due to his organizing and design abilities. He supervised the enthusiasts in their attempts to build training gliders. S.V.Ilyushin headed Technical committees of glider convents in Koktebel and spent much time on glider pilots training. On 18 August 1933, his major role in the development of glider flying activities was awarded with the first government prize – Order of the Red Star.
After graduation from the Academy (1926-1927) S.V.Ilyushin was appointed the Chairman of the First (aircraft manufacturing) section of the Scientific-and-Technical Committee of the Air Force Administration of the Red Army (STC AFA). **It was the time when R&D bureaus and research institutes started their goal-oriented work, new aircraft manufacturing plants were built and engineers were trained. These activities were managed by the plans in the development of the Soviet Air Force, which were prepared with S.V.Ilyushin's direct participation.** S.V.Ilyushin's work at STC AFA and in Aviation Technical Committee not only broadened his horizons but also promoted the development of his own design style with the following features: ability to distinguish main trends in aviation and initiative in design studies and development of airplanes of different purposes that are simple to produce, efficient in operation and meet the requirements of time.
At the beginning of 1930s, it was decided to reinforce the management of aircraft industry. It was headed by a former head of AFA P.I.Baranov. In August 1931, S.V.Ilyushin was added to the Red Army Reserve and sent to work for aircraft industry.
In 1931-1932, he was a Deputy Chief of TsAGI, Chief of test construction section at TsAGI.
On 13 January 1933, P.I.Baranov appointed S.V.Ilyushin Head of Test Design Bureau of Plant No.39 named after V.R.Menzhinsky. He began to form a design team – team No.3. It was the beginning of R&D Bureau.
The first airplane built under the supervision of S.V.Ilyushin (test long-range bomber TsKB-26) brought to him fame: the first officially registered world records of the USSR in aviation were set by this plane. This aircraft developed into long-range bombers and torpedo bombers DB-3, DB-3T, DB-3F, Il-4. They formed the basis of Soviet long-range aviation and mine-and-torpedo aviation used during the Great Patriotic War. The crews of long-range bombers and torpedo bombers made bombing attacks on distant strategic targets; they destroyed enemy transportation by torpedoes and mining. In August 1941, these airplanes performed the first bombing of the capital of Nazi Reich – Berlin. The total amount of DB-3 and Il-4 and their modifications was 6784.
Examining and estimating the experience of local military conflicts in Spain and China, S.V.Ilyushin appealed to the government proposing to develop an armored attack aircraft intended for direct battlefield support of troops in conditions of intense enemy air defense. It was supposed that its combat efficiency would surpass the one of its counterparts developed at the same time.
"The task to create an armored attack aircraft is difficult and it is associated with high technology risk, but I am undertaking this project with enthusiasm and confidence of success", wrote Ilyushin addressing the government. Ilyushin's confidence was based on the possibility to implement his outstanding design idea. He made the armor not only defend but

also serve as a glider frame, which allowed significant weight reduction and equipment of the airplane with powerful small arms, artillery, missile and bomb armament. He set himself an extraordinarily difficult task. But it could be solved on the basis of advances of Soviet science and engineering of the time: powerful aircraft engine with liquid cooling (A.A.Mikulin), stamped heterogeneous aircraft armor with hard superficial layer (S.T.Kishkin, N.M.Sklyarov), transparent aircraft armor (B.V.Erofeev, M.M.Gudimov), quick-firing aircraft gun (B.G.Shpitalniy), aircraft jet projectile (JRI). S.V.Ilyushin managed to use all these achievements.

S.V.Ilyushin's foresight proved true. Armored attack aircrafts Il-2 played a notable role in the Patriotic War battles

"The Red Army needs Il-2 airplanes like it needs air and bread…" These words cited from I.V.Stalin's telegram became a slogan of those who produced attack aircrafts. Il-2 grouped together with artillery and tank attack forces cracked the enemy defence, preparing the way for the attacking troops. Air Force commander A.A.Novikov stressed "***Since 1943 Il-2 planes have become the main striking force of the Red Army Air Force***". A total of 36154 Il-2 planes were produced. High-speed and agile armored attack aircrafts Il-10 participated in the last stage of the Patriotic War. **4600 Il-10 and Il-10M planes were built till 1956.**

After the war S.V.Ilyushin supervised the development of the first jet frontline bomber Il-28, which was produced on a mass scale and lifted Soviet frontline aviation to a higher level. A total of 6316 Il-28 planes and its modifications were built. It was also mass-produced in People's Republic of China.

Carrying on the development of attack aircrafts, **S.V.Ilyushin's team created the first ever armored jet attack aircraft Il-40.**

Long before the victory, in 1943, when furious battles were on, S.V.Ilyushin started works on a passenger airplane. He realized that after the end of the war the country would need more high-speed, comfortable and fuel-efficient passenger plane as compared to the available Li-2. And in January 1946 a permanent test pilot of the design bureau V.K.Kokkinaki took the air in the first passenger plane Il-12. Intense operation of Il-12 planes highly praised by the test pilots started in 1947 by Aeroflot, Polar Aviation and Air Force (transport modification). A total of 663 Il-12 airplanes and its modifications were built.

Il-14, a workhorse of Aeroflot and Polar Aviation, was created on the basis of generalized huge experience of Il-12 operation in the variety of climatic and weather conditions. Il-14 gained a reputation of highly-reliable, safe, simple to operate and maintain, able to take off and land on small airfields with dirt runways, fuel-efficient airplane. Until the second half of 1950s, Il-14 was the main airplane of governmental division. Il-14 modifications were operated until the beginning of 1990s. A total of 839 Il-14 airplanes and modifications were built. Il-14 planes were built in Czechoslovakia and German Democratic Republic under a license. They were used in many countries.

At the beginning of 1956, S.V.Ilyushin proposed to create a highly efficient turboprop capable of carrying 75 passengers. It was supposed that this turboprop would reduce the airplane ticket cost down to the railway compartment ticket cost. Acknowledged authority of S.V.Ilyushin and the design team dictated the possibility of simultaneous development of test Il-18 plane and the start of its mass production. The first flight of the test Il-18 plane was performed on 4 July 1957. In April 1959, it began regular passenger transportation. Owing to operation of a large number of Il-18 planes, early 1960s for Aeroflot were characterized by steep increase of both domestic and international passenger traffic density. Il-18 version capable carrying 75…110 passengers was exported and operated in many countries. Some versions are still in use. A total of 564 Il-18 planes were built.

Il-18 served as a basis for outstanding special-purpose planes designed for Air Force, which are still in service: antisubmarine Il-38, scout plane Il-20, flying command post Il-22.
On 26 February 1960, S.V.Ilyushin submitted a proposal to the Government to create a long-range passenger airplane Il-62. **The proposal was approved. Much attention was paid to the lift-to-drag ratio of Il-62, its flight safety**, comfort for the passengers. The airplane was designed with four jet engines mounted on fuselage tail section, which allowed a “clean” wing with high lift-to-drag ratio. Particular emphasis was put to critical operation modes when the plane reached large angles of attack. New aerodynamic layout of Il-62 wing eliminated the risk of its deep stall.
Despite the originality of Il-62 layout and the necessity of much research work, all the required technical documentation was quickly developed, and the first test long-range intercontinental passenger plane Il-62 performed its first flight on 2 January 1963. State acceptance and in-service testing of Il-62 were carried out in August 1967, and Il-62 started its regular passenger transportation with an international flight Moscow-Montreal on 15 September 1967.
Il-62 and its modification Il-62M with new engines, increased range and enhanced efficiency provided transportation of 168…186 passengers over long-range domestic and international routes. They were used by airlines of different countries. Il-62M airplanes are still in service. A total of 290 Il-62 planes and its modifications were built.
Special versions of Il-18 and Il-62 were used for government transportation.
Successful work of DB headed by S.V.Ilyushin on the development of military and passenger planes to a large extent resulted from S.V.Ilyushin’s personal skills, his talent to foresee the trends in aviation, outstanding engineering and managerial skills, an ability to implement the newest scientific results in the developed airplane, his incredible personal performance efficiency and self-discipline. Such milestones of aviation as Il-2, Il-12, Il-28 and Il-18 airplanes had been developed upon S.V.Ilyushin’s initiative before the government task was obtained.
The services of Colonel-General S.V.Ilyushin in the development of Soviet aviation were awarded with many Government Prizes. He is thrice the Hero of Socialist Labor, laureate of Lenin Prize and eight National Prizes of the USSR. For his scientific and engineering work Ilyushin was elected a full-member of the USSR Academy of Sciences.
S.V.Ilyushin took an active part in public activities of the country. He was a deputy of the Supreme Soviet of USSR of seven convocations, a representative delegated to a number of Soviet Union Communist Party Congresses.
Note that Sergey Vladimirovich could not stand cigarette smoke. Smoking was prohibited in DB. When discussing movies and TV shows, Sergey Vladimirovich always criticized producers. He surprised at the purpose of showing the characters smoking in complicated situations.
He said that a cigarette did not help to find the right answer or the way out of trouble. It is remarkable that Ilyushin looked ahead in the long term concerning the issue of smoking: today smoking in public is prohibited in Russia and many other countries. S.V.Ilyushin was always neatly dressed wearing a shirt with a tie, a suit or sometimes a three-piece suit.
One cannot forget the meetings held at Sergey Vladimirovich’s, when he lived near Pokrovsko-Razumovskiy Proezd. His apartment was not luxurious.
Ilyushin visited health resorts rarely. He spent his vacations in Delyalevo village, where he was born. Kubinskoe Lake was near. His favorite hobbies were hunting and fishing. He usually hooked nelma fish, cooked it himself and invited all the DB chiefs (his old friends and colleagues) to taste it.

A New Year party was always held for the whole DB team. DB departments held the party each and every year. The working day before the New Year was shorter, all necessary food and drinks were purchased. The party was nice, with champagne and wishes of health and success.
Sergey Vladimirovich visited every department with a glass of champagne and wished Happy New Year to everyone. Such parties drew the whole team together.
When somebody asks me about Ilyushin's main trait, I answer without any doubt: *it was his ability to foresee, which airplane will be necessary for Air Force, civil aviation and national economy in the nearest future, how to make it promptly with minimal expenses, providing perfect flight characteristics, combat effectiveness, efficient performance, safeness and potential for further improvement, hence long-term operation.*
S.V.Ilyushin retired in 1970 for health reasons. He passed the management of DB to his disciple G.V.Novozhilov, who kept and developed the traditions, structure and work style of his Teacher. DB team hands on the lamp of its founder developing Il-76 planes and its numerous modifications Il-86, Il-96-300, Il-114, Il-114T, Il-144-100, Il-96MO, Il-96T.
Il-86 airplane was the first mass-produced Soviet wide-body aircraft. The airplane was required in the USSR in 1967, when Aeroflot formulated specification for an aircraft with 250-350 seats.

Famous IL-86

Turboprop IL-114
(developed by Ilyushin’s Design Bureau at the end of the 1980s for USSR regional airlines)

V.V.Livanov was appointed General Director - General Designer of Ilyushin Aviation Complex in December 2005. Modernization of Il-38, Il-96-400T airplanes, startup of mass production of improved Il-76MD-90A on the basis of “digital” technology (a novelty for Russian airplane industry), development of new promising aircrafts are conducted in complicated economic conditions.
The team of Ilyushin Aviation Complex keeps and develops the traditions established by its Founder.

Genrikh Vasilyevich Novozhilov, Academician of the Russian Academy of Sciences, President of the Academy of Aviation and Aeronautics Sciences, Honorary Professor of KNRTU-KAI; MAI graduate; General Designer. G.V.Novozhilov is a disciple and follower of S.V.Ilyushin; he has been working at Ilyushin Design Bureau (since 1991 Aviation Complex) since 1948. Since 1964 – Chief Designer, since 1970 – General Designer. He took part in the development of IL-18, IL-40, IL-54, IL-62, IL-72, IL-74 aircrafts, supervised the development of IL-76, IL-78, IL-86, IL-96-300, IL-96M, IL-112, IL-114 and other aircrafts. He has 130 inventor’s certificates and patents; twice the Hero of Socialist Labor, Lenin Prize Laureate (1970), awarded three Orders of Lenin and Order "For Merit to the Fatherland" II Class (2000).

Utilization of wind energy at high altitude

Alexander Bolonkin
V.P. of Consulting and Research Co.
1310 Avenue R, 6-F, Brooklyn, NY 11229, USA

Ground based, wind energy extraction systems have reached their maximum capability. The limitations of current designs are: wind instability, high cost of installations, and small power output of a single unit. The wind energy industry needs of revolutionary ideas to increase the capabilities of wind installations. This article suggests a revolutionary innovation which produces a dramatic increase in power per unit and is independent of prevailing weather and at a lower cost per unit of energy extracted. The main innovation consists of large free-flying air rotors positioned at high altitude for power and air stream stability, and an energy cable transmission system between the air rotor and a ground based electric generator. The air rotor system flies at high altitude up to 14 km. A stability and control is provided and systems enable the changing of altitude.
This article includes six examples having a high unit power output (up to 100 MW). The proposed examples provide the following main advantages: 1. Large power production capacity per unit – up to 5,000-10,000 times more than conventional ground-based rotor designs; 2. The rotor operates at high altitude of 1-14 km, where the wind flow is strong and steady; 3. Installation cost per unit energy is low. 4. The installation is environmentally friendly (no propeller noise).

Nomenclature (in metric system)

A – front area of rotor [m^2];
α – exponent of wind coefficient; α = 0.1 - 0.25; one depends from Earth's surface roughness;
A_a – wing area is served by aileron for balance of rotor (propeller) torque moment [m^2];
A_w – area of the support wing [m^2];
C – retail price of 1 kWh [$];
c – production cost of 1 kWh [$];
C_L – lift coefficient (maximum $C_L \approx 2.5$);
C_D – drag coefficient;
$\Delta C_{L,a}$ – difference of lift coefficient between left and right ailerons;
D – drag force [N];
D_r – drag of rotor [N];
E – annual energy produced by flow installation [J];
F – annual profit [$];
H_o – standard altitude of ground wind installation; H_o =10 m;
H – altitude [m];
I – cost of Installation [$];
K_1 – life time (years);
K_2 – rotor lift coefficient (5-12 [kg/kW]);
L – length of cable [m];
L_y – lift force of wing [N];
M – annual maintenance [$];
N – power [W, joule/sec];
N_o – power at H_o ;
r – distance from center of wing to center of aileron [m];
R – radius of rotor (turbine)[m];
S – cross-section area of energy transmission cable [m^2];
V – annual average wind speed [m/s];
V_o – wind speed at standard altitude 10 m [m/s] (V_o= 6 m/s);
W – weight of installation (rotor+cables) [kg];
W_y – weight of cable [kg];
γ – specific density of cable [kg/m^3];
η – efficiency coefficient;
θ – angle between main (transmission) cable and horizontal surface;
λ – ratio of blade tip speed to wind speed;
v – speed of transmission cable [m/s];
ρ – density of flow, ρ =1.225 kg/m^3 for air at sea level altitude H = 0; ρ =0.736 at altitude H=5 km; ρ = 0.413 at H =10 km;
σ – tensile stress of cable [N/m^2].

Introduction

Wind is a clean and inexhaustible source of energy that has been used for many centuries to grind grain, pump water, propel sailing ships, and perform other work.
Wind farm is the term used for a large number of wind machines clustered at a site with persistent favorable winds, generally near mountain passes. Wind farms have been erected in New Hampshire, in the Tehachapi Mountains at Altamont Pass in California, at various sites in Hawaii, and may other locations. Machine capacities range from 10 to 500 kilowatts. In 1984 the total energy output of all wind farms in the United States exceeded 150 million kilowatt-hours.

A program of the United States Department of Energy encouraged the development of new machines, the construction of wind farms, and an evaluation of the economic effect of large-scale use of wind power.
The utilization of renewable energy ('green' energy) is currently on the increase. For example, a lot of wind turbines are being installed along the British coast. In addition, the British government has plans to develop off-shore wind farms along their coast in an attempt to increase the use of renewable energy sources. A total of $2.4 billion was injected into renewable energy projects over the last three years in an attempt to meet the government's target of using renewable energy to generate 10% of the country's energy needs by 2010.
This British program saves the emission of almost a millions tons of carbon dioxide. Denmark plans to get about 30% of their energy from wind sources.
Unfortunately, current wind energy systems have deficiencies which limit their commercial applications:

1. Wind energy is unevenly distributed and has relatively low energy density. Huge turbines cannot be placed on the ground; many small turbines must be used instead. In California, there are thousands of small wind turbines. However, while small turbines are relatively inefficient, very huge turbines placed at ground are also inefficient due to the relatively low wind energy density and their high cost. The current cost of wind energy is higher then energy of thermal power stations.
2. Wind power is a function of the cube of wind velocity. At surface level, wind has low speed and it is non-steady. If wind velocity decreases in half, the wind power decreases by a factor of 8 times.
3. The productivity of a wind-power system depends heavily on the prevailing weather.
4. Wind turbines produce noise and visually detract from the landscape.

There are many research programs and proposals for the wind driven power generation systems, however, all of them are ground or tower based. System proposed in this article is located at high altitude (up to the stratosphere), where strong permanent and steady streams are located. The also proposes a solution to the main technologist challenge of this system; the transfer of energy to the ground via a mechanical transmission made from closed loop, modern composite fiber cable.
The reader can find the information about this idea in [1], the wind energy in references [2-3], a detailed description of the innovation in [4-5], and new material used in the proposed innovation in [6-9]. The application of this innovation and energy transfer concept to other fields can be found in [10-19].

Description of innovation

Main proposed high altitude wind system is presented in fig.1. That includes: rotor (turbine) 1, support wing 2, cable mechanical transmission and keep system 3, electro-generator 4, and stabilizer 5. The transmission system has three cables (fig.1e): main (central) cable, which keeps the rotor at a given altitude, and two transmission mobile cables, which transfer energy from the rotor to the ground electric generator. The device of fig.1f allows changing a cable length and a rotor altitude. In calm weather the rotor can be support at altitude by dirigible 9 (fig.1c) or that is turned in vertical position and support by rotation from the electric generator (fig.1d). If the wind is less of a minimum speed for support of rotor at altitude the rotor may be supported by autogiro mode in position of fig.1d. The probability of full wind calm at a high altitude is small and depends from an installation location.

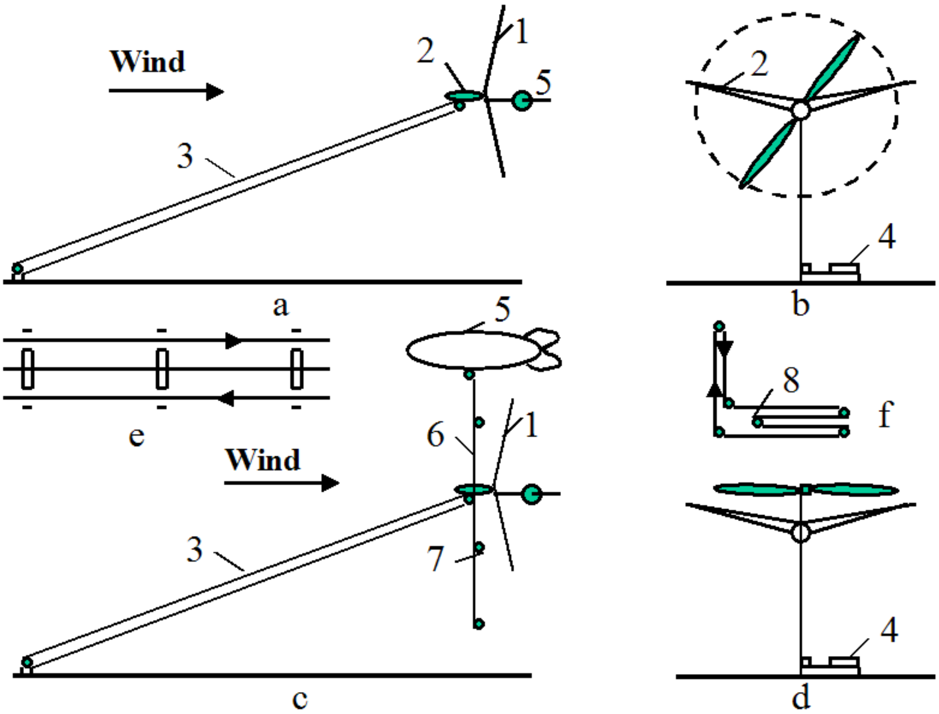


Fig.1. Propeller high altitude wind energy installation and cable energy transport system. Notation: a – side view; 1 – wind rotor; 2 – wing with ailerons; 3 – cable energy transport system; 4 – electric generator; 5 – stabilizer; b – front view; c – side view with a support dirigible 9, vertical cable 6, and wind speed sensors 7; d - keeping of the installation at a high altitude by rotate propeller; e – three lines of the transmission - keeper system. That includes: main (central) cable and two mobile transmission cables; f – energy transport system with variable altitude; 8 – mobile roller.

Fig.2 shows other design of the proposed high altitude wind installation. This rotor has blades, 10, connected to closed-loop cables. The forward blades have a positive angle and lift force. When they are in a back position the lift force equals zero. The rotor is supported at the high altitude by the blades and the wing 2 and stabilizer 5. That design also has energy transmission 3 connected to the ground electric generator 4.

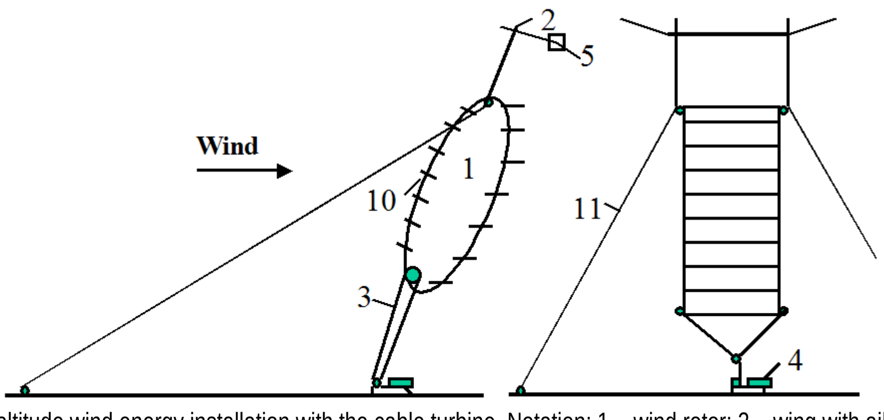


Fig.2. High altitude wind energy installation with the cable turbine. Notation: 1 – wind rotor; 2 – wing with ailerons; 3 – cable energy transport system; 4 – electric generator; 5 – stabilizer; 10 – blades; 11 – tensile elements (bracing) (option).

Fig.3. shows a parachute wind high altitude installation. Here the blades are changed by parachutes. The parachutes have a large air drag and rotate the cable rotor 1. The wind 2 supports the installation in high altitude. The cable transmission 3 passes the rotor rotation to the ground electric generator 4.
A system of fig.4 uses a large Darries air turbine located at high altitude. This turbine has four blades. The other components are same with previous projects. Wind turbine of fig.5 is a wind

ground installation. Its peculiarity is a gigantic cable-blade rotor. That has a large power for low ground wind speed. It has four columns with rollers and closed-loop cable rotor with blades 10. The wind moves the blades, the blades move the cable, and the cable rotates an electric generator 4.

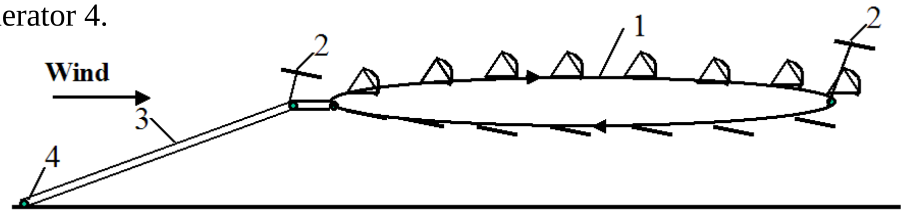


Fig.3. High altitude wind energy installation with the parachute turbine; 1 – wind rotor; 2 – wing with ailerons; 3 – cable energy transport system; 4 – electric generator;

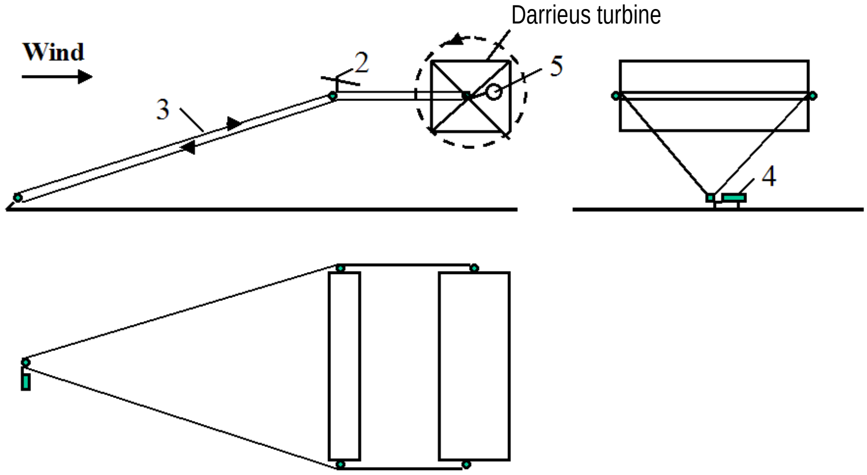


Fig.4. High altitude wind energy installation with Darrieus turbine; 2 – wing with ailerons; 3 – cable energy transport system; 4 – electric generator; 5 – stabilizer.

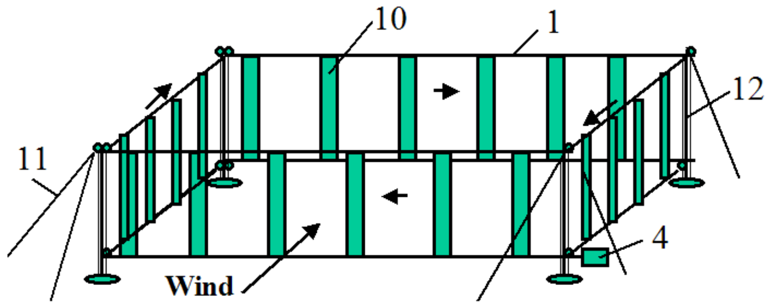


Fig.5. Ground wind cable rotor of a large power.

Problems of launch, start, guidance, control, stability, and others

Launching. It is not difficult to launch the installations having support wing or blades as described in figs.1 – 4. If the wind speed is more than the minimum required speed (>2-3m/s), the support wing lifts the installation to the desired altitude.

Starting. All low-speed rotors are self-starting. All high-speed rotors (include the ground rotor of fig.5) require an initial starting rotation from the ground motor-generator 4 (figs.1 – 5)**.**

Guidance and control. The control of power, revolutions per minute, and torque moment are operated by the turning of blades around the blade longitudinal axis. The control of altitude may be manual or automatic when the wind speed is normal and over admissible minimum. Control is effected by wing flaps and stabilizer (elevator), fin, and ailerons (figs. 1, 2, 4).

Stability. Stability of altitude is produced by the length of the cable. Stability around the blade longitudinal axis is made by stabilizer (see figs.1,2,4). Rotor directional stability in line with the flow can be provided by fins (figs. 1). When the installation has the support wing rigidly connected to the rotor, the stability is also attained by the correct location of the center of gravity of the installation (system rotor-wing) and the point of connection of the main cable and the tension elements. The center-of-gravity and connection point must be located within a relatively narrow range 0.2-0.4 of the average aerodynamic chord of the support wing (for example, see fig. 1). There is the same requirement for the additional support wings such as fig.2-4.

Torque moment is balanced by transmission and wing ailerons (figs.1-4).

The wing lift force, stress of main cable are all regulated automatic by the wing flap or blade stabilizer.

The location of the installation of fig.2 at a given point in the atmosphere may be provided by tension elements shown on fig.2. These tension elements provide a turning capability for the installation of approximately $\pm 45^0$ degrees in the direction of flow (fig.2).

Minimum wind speed. The required minimum wind-speed for most of the suggested installation designs is about 2 m/s. The probability of this low wing speed at high altitude is very small (less 0.001). This minimum may be decreased still further by using the turning propeller in an autogiro mode. If the wind speed is approximately zero, the rotor can be supported in the atmosphere by a balloon (dirigible) as is shown on fig.1c or a propeller rotated by the ground power station as is shown on fig.1d. The rotor system may also land on the ground and start again when the wind speed attains the minimum speed for flight.

A Gusty winds. Large pulsations of wind (aerodynamic energy) can be smoothed out by inertial fly-wheels.

The suggested Method and Installations for utilization of wind energy has following peculiarities from current conventional methods and installations:

1. Proposed installation allows the collection of energy from a large area – tens and even hundreds of times more than conventional wind turbines. This is possible because an expensive tower is not needed to fix our rotor in space. Our installation allows the use of a rotor with a very large diameter, for example 100-200 meters or more.
2. The proposed wind installations can be located at high altitude 100 m - 14 km. The wind speeds are 2-4 times faster and more stable at high altitude compared to ground surface winds used by the altitude of conventional windmills (10-70 meters of height). In certain geographic areas high altitude wind flows have a continuous or permanent nature. Since wind power increases at the cube of wind speed, wind rotor power increases by 27 times when wind speed increases by 3 times.
3. In proposed wind installation the electric generator is located at ground. There are proposals where electric generator located near a wind rotor and sends electric current to a ground by electric wares. However, our rotor and power are very large (see projects below). Proposed installations produce more power by thousands of times compared to the typical current wind ground installation (see point 1, 2 above). The electric generator of 20 MW weighs about 100 tons (specific weigh of the conventional electric generator is about 3-10 kg/kW). It is impossible to keep this weigh by wing at high altitude for wind speed lesser then 150 m/s.
4. One of the main innovations of the given invention is the **cable transfer** (transmission) of energy from the wind rotor located at high altitude to the electric generator located on ground. In proposed Installation it is used a new cable transmission made from artificial fibers. This transmission has less a weigh in thousands times then copper electric wires of equal power. The wire having diameter more 5 mm passes 1-2 ampere/sq.mm. If the electric generator produces 20 MW with voltage 1000 Volts, the wire cross-section area must be 20,000 mm^2, (wire diameter is160 mm). The cross-section area of the cable transmission of equal power is only 37 mm^2 (cable diameter 6.8 mm^2 for cable speed 300 m/s and admissible stress 200 kg/mm^2, see Project 1). The specific weight of copper is 8930 kg/m^3, the specific weight of artificial fibers is 1800 kg/m^3. If the cable length for altitude 10 km is 25 km the double copper wire weighs 8930 tons (!!), the fiber

transmission cable weighs only 3.33 tons. It means the offered cable transferor energy of equal length is easier in 2682 times, then copper wire. The copper wires is very expensive, the artificial fiber is cheap.

All previous attempts to place the generator near the rotor and connect it to ground by electric transmission wires were not successful because the generator and wires are heavy.

Some information about wind energy

The power of a wind engine strongly depends on the wind speed (to the third power). Low altitude wind (H = 10 m) has the standard average speed V = 6 m/s. High altitude wind is powerful and that has another important advantage, it is stable and constant. This is true practically everywhere.

Wind in the troposphere and stratosphere are powerful and permanent. For example, at an altitude of 5 km, the average wind speed is about 20 m/s, at an altitude 10-12 km the wind may reach 40 m/s (at latitude of about 20-35°N).

There are permanent jet streams at high altitude. For example, at H = 12-13 km and about 25°N latitude. The average wind speed at its core is about 148 km/h (41 m/s). The most intensive portion, with a maximum speed 185 km/h (51 m/s) latitude 22°, and 151 km/h (42 m/s) at latitude 35° in North America. On a given winter day, speeds in the jet core may exceed 370 km/h (103 m/s) for a distance of several hundred miles along the direction of the wind. Lateral wind shears in the direction normal to the jet stream may be 185 km/h per 556 km to right and 185 km/h per 185 km to the left.

The wind speed of V = 40 m/s at an altitude H = 13 km provides 64 times more energy than surface wind speeds of 6 m/s at an altitude of 10 m.

This is a gigantic renewable and free energy source. (See reference: *Science and Technolody,* v.2, p.265*)*.

Cable transmission energy problem

The primary innovations presented in this paper are locating the rotor at high altitude, and an energy transfer system using a cable to transfer mechanical energy from the rotor to a ground power station. The critical factor for this transfer system is the weight of the cable, and its air drag.

Twenty years ago, the mass and air drag of the required cable would not allow this proposal to be possible. However, artificial fibers are currently being manufactured, which have tensile strengths of 3-5 times more than steel and densities 4-5 times less then steel. There are also experimental fibers (whiskers) which have tensile strengths 30-100 times more than a steel and densities 2 to 5 times less than steel. For example, in the book [6] p.158 (1989), there is a fiber (whisker) C_D, which has a tensile strength of σ = 8000 kg/mm^2 and density (specific gravity) of γ = 3.5 g/cm^3. If we use an estimated strength of 3500 kg/mm^2 ($\sigma = 7\times10^{10}$ N/m^2, γ = 3500 kg/m^3), then the ratio is $\gamma/\sigma = 0.1\times10^{-6}$ or $\sigma/\gamma = 10\times10^{6}$. Although the described (1989) graphite fibers are strong ($\sigma/\gamma = 10\times10^{6}$), they are at least still ten times weaker than theory predicts. A steel fiber has a tensile strength of 5000 MPA (500 kg/mm^2), the theoretical limit is 22,000 MPA (2200 kg/mm^2) (1987); the polyethylene fiber has a tensile strength 20,000 MPA with a theoretical limit of 35,000 MPA (1987). The very high tensile strength is due to its nano-tubes structure.

Apart from unique electronic properties, the mechanical behavior of nanotubes also has provided interest because nanotubes are seen as the ultimate carbon fiber, which can be used as reinforcements in advanced composite technology. Early theoretical work and recent experiments on individual nanotubes (mostly MWNT's, Multi Wall Nano Tubes) have confirmed that nanotubes are one of the stiffest materials ever made. Whereas carbon-carbon covalent bonds are one of the strongest in nature, a structure based on a perfect arrangement of these bonds oriented along the axis of nanotubes would produce an exceedingly strong material. Traditional carbon fibers show high strength and stiffness, but fall far short of the theoretical, in-plane strength of graphite layers by an order of magnitude. Nanotubes come close to being the best fiber that can be made from graphite.

For example, whiskers of Carbon nanotube (CNT) material have a tensile strength of 200 Giga-Pascals and a Young's modulus over 1 Tera Pascals (1999). The theory predicts 1 Tera Pascals and a Young's modules of 1-5 Tera Pascals. The hollow structure of nanotubes makes them very light (the specific density varies from 0.8 g/cm^3 for SWNT's (Single Wall Nano Tubes) up to 1.8g/cm^3 for MWNT's, compared to 2.26 g/cm^3 for graphite or 7.8 g/cm^3 for steel).

Specific strength (strength/density) is important in the design of the systems presented in this paper; nanotubes have values at least 2 orders of magnitude greater than steel. Traditional carbon fibers have a specific strength 40 times that of steel. Since nanotubes are made of graphitic carbon, they have good resistance to chemical attack and have high thermal stability. Oxidation studies have shown that the onset of oxidation shifts by about 100^0 C or higher in nanotubes compared to high modulus graphite fibers. In a vacuum, or reducing atmosphere, nanotube structures will be stable to any practical service temperature.

The artificial fibers are cheap and widely used in tires and everywhere. The price of SiC whiskers produced by Carborundum Co. with σ=20,690 MPa and γ=3.22 g/cm^{3}was $440/kg in 1989. The market price of nanotubes is too high presently (~$200 per gram) (2000). In the last 2-3 years, there have been several companies that were organized in the US to produce and market nanotubes. It is anticipated that in the next few years, nanotubes will be available to consumers for less than $100/pound.

Below, the author provides a brief overview of some research information regarding the proposed experimental (tested) fibers (Table 1, [6-9]). In addition, the author also addresses additional examples, which appear in these projects and which can appear as difficult as the proposed technology itself. The author is prepared to discuss the problems with organizations which are interested in research and development related projects.

Table 1. Material properties.

Material "Whiskers"	Tensile strength, kg/mm^2	Density, g/cm^3	Fibers	Tensile strength, kg/mm^2	Density, g/cm^3
AlB_{12}	2650	2.6	QC-8805	620	1.95
B	2500	2.3	TM9	600	1.79
B_4C	2800	2.5	Thorael	565	1.81
TiB_2	3370	4.5	Allien 1	580	1.56
SiC	1380-4140	3.22	Allien 2	300	0.97

Industrial fibers with σ = 500-600 kg/mm^2, γ = 1800 kg/m^3, and $\sigma/\gamma = 2{,}78\times10^6$ are used in all our projects (admissible σ =200-250 kg/mm^2).

Brief theory of estimation of suggested installations

Rotor

Power of a wind energy N [Watt, Joule/sec]

$$N=0.5\eta\rho AV^3 \qquad (1)$$

The coefficient of efficiency, η, equals 0.15-0.35 for low speed rotors (ratio of blade tip speed to wind speed equals $\lambda \approx 1$); η = 0.35-0.5 for high speed rotors (λ = 5-7). The Darrieus rotor has η=0.35-0.4. The propeller rotor has η=0.45-0.50. The theoretical maximum equals η=0.67. The energy is produced in one year is (1 year $\approx 30.2\times10^6$ work sec) [J]

$$E=3600\times24\times350 \approx 30\times10^6 N \text{ [J]} \quad (1')$$

Wind speed increases with altitude as follows

$$V=(H/H_o)^{\alpha}V_o \quad (2)$$

where $\alpha = 0.1 - 0.25$ exponent coefficient depends from surface roughness. When the surface is water, $\alpha = 0.1$; when surface is shrubs and woodlands $\alpha=0.25$.
Power increases with altitude as the cube of wind speed

$$N=(H/H_o)^{3\alpha}N_o \quad (3)$$

where N_o is power at H_o.
The drag of the rotor equals $D_r=N/V$ (4)
The lift force of the wing, L_y, is

$$L_y=0.5C_L\rho V^2A_w, \quad L_y\approx W \quad (5)$$

where C_L is lift coefficient (maximum $C_L \approx 2.5$), A_w is area of the wing, W is weight of installation + 0.5 weight of all cables.
The drag of the wing is

$$D = 0.5C_D\rho V^2A_w \quad (6)$$

where C_D is the drag coefficient (maximum $C_D \approx 1.2$).
The optimal speed of the parachute rotor equals $V/3$ and the theoretical maximum of efficiency coefficient is 0.5. The annual energy produced by the wind energy extraction installation equals

$$E=8.33N \quad \text{[kWh]} \quad (7)$$

Cable energy transfer, wing area, and other parameters

Cross-section area of transmission cable, S, is

$$S=N/v\sigma \quad (8)$$

Cross-section area of main cable, S_m, is

$$S_m=(D_r+D)/\sigma \quad (8')$$

Weight of cable is

$$W_r=SL\gamma \quad (9)$$

The production cost, c, in kWh is

$$c = \frac{M + I / K_1}{E} \quad (10)$$

The annual profit

$$F= (C-c)E \quad (11)$$

The required area of the support wing is

$$A_w = \frac{\eta A \sin\theta}{C_L} \quad (12)$$

where θ is the angle between the support cable and horizontal surface.
The wing area is served by ailerons for balancing of the rotor (propeller) torque moment

$$A_a = \frac{\eta AR}{\lambda_i \Delta C_{L,a} r} \quad (13)$$

The minimum wind speed for installation support by the wing alone

$$V_{\min} = \sqrt{\frac{2W}{C_{L,\max}\rho A_w}} \qquad (14)$$

where W is the total weight of the airborne system including transmission. If a propeller rotor is used in a gyroplane mode, minimal speed will decrease by 2-2,5 times. If wind speed equals zero, the required power for driving the propeller in a propulsion (helicopter) mode is

$$N_s = W/K_2 \quad [\text{kW}] \qquad (15)$$

The specific weight of energy storage (flywheel) can be estimated by

$$E_s = \sigma/2\gamma \quad [\text{J/kg}] \qquad (16)$$

For example, if σ=200 kg/mm^2, γ=1800 kg/m^3, then E_s=0.56 MJ/*kg* or E_s=0.15 kWh/kg.
For comparison of the different ground wind installations their efficiency and parameters are computed for the standard wind conditions: the wind speed equals V=6 m/s at the altitude H=10m.

PROJECTS

The Project 1. High-speed air propeller rotor (fig.1)
For example, let us consider a rotor diameter of 100 m (A = 7850 m^2), at an altitude H = 10 km (ρ = 0.4135 kg/m^3), wind speed of V = 30 m/s, an efficiency coefficient of η = 0.5, and a cable tensile stress of σ = 200 kg/mm^2.
Then the power produced is N = 22 MW [Eq. (1)], which is sufficient for city with a population of 250,000. The rotor drag is D_r = 73 tons [Eq.(4)], the cross-section of the main cable area is $S = 1.4D_r/\sigma$ =l.35×73/0.2 ≈ 500 mm^2, the cable diameter equals d =25 mm; and the cable weight is W =22.5 tons [Eq.(9)] (for L=25 km). The cross-section of the transmission cable is S = 36.5 mm^2 [Eq.(8)], d = 6.8 mm, weight of two transmission cables is W = 3.33 tons for cable speed v =300 m/s [Eq.(9)].
The required wing size is 20×100 m (C_L=0.8) [Eq.(12)], wing area served by ailerons is 820m^2 [Eq.(13)]. If C_L=2, the minimum speed is 2 m/s [Eq.(14)].
The installation will produce an annual energy E =190 GWh [Eq.(7)]. If the installation cost is $200K, has a useful life of 10 years, and requires maintenance of $50K per year, the production cost is c = 0.37 cent per kWh [Eq(10)]. If retail price is $0.15 per kWh, profit $0.1 per kWh, the total annual profit is $19 millions per year [Eq.(11)].

The project 2. Large air propeller at altitude H = 1 km (fig.1)
Let us consider a propeller diameter of 300 m, with an area A = 7×10^4 m^2, at an altitude H = 1km, and a wind speed of 13 m/s. The average blade tip speed is 78 m/s. The full potential power of the wind streamer flow is 94.2 MW. If the coefficient of efficiency is 0.5 the useful power is N = 47.1 MW. For other wind speed the useful power is: V = 5 m/s, N = 23.3 MW; V = 6 m/s, N = 47.1 MW; V = 7 m/s, N = 74.9 MW; V = 8 m/s, N = 111.6MW; V = 9 m/s, N = 159 MW; V = 10 m/s, N =218 MW.

Estimation of economical efficiency
Let us assume that the cost of the Installation is $3 million, a useful life of 10 years, and request maintenance of $100,000/year. The energy produced in one year is E = 407 GWh [Eq.(7)]. The basic cost of energy is $0.01 /kWh.

The some technical parameters. Altitude H = 1 km. The drag is about 360 tons. Ground connection (main) cable has cross-section area of 1800mm^2 [Eq.(8')], d = 48 mm, and has a weight of 6480 kg. The need wing area is 60×300(m). The aileron area requested for turbine balance is 6740m^2. If the transmission cable speed is 300 m/s, the cross-section area of transmission cable is 76mm^2 and the cable weight is 684 kg (composite fiber).

Altitude H = 13 km. At an altitude of H =13 km. the air density is ρ=0.2666, and the wind speed is V = 40 m/s. The power for efficiency coefficient 0.5 is 301.4 MgW. The drag of the propeller is approximately 754 tons. The connection cable has a cross-sectional area of 3770mm^2, a diameter is d =70 mm and a weight of 176 tons. The transmission cable has a sectional area 5 cm^2 and a weight of 60 tons (vertical transmission only 12 tons). The installation will produce energy E=2604 GWh per year. If the installation costs \$5 million, maintenance is \$200,000/year, and the cost of 1 kWh will be \$0.0097/kWh.

<u>The project 3.</u> Air low speed wind engine with free flying cable flexible rotor (fig.2)
Let us consider the size of cable rotor of width 50 m, a rotor diameter of 1000 m, then the rotor area is A=50×1000=50,000m^2. The angle rope to a horizon is 70°. The angle of ratio lift/drag is about 2.5°. The average conventional wind speed at an altitude H = 10 m is V = 6 m/s. It means that the speed at the altitude 1000 m is 11.4 - 15 m/s. Let us take average wind speed V=13 m/s at an altitude H = 1 km. The power of flow is

$$N=0.5\cdot\rho V^3 A\cos 20°=0.5\times1.225\times13^3\times1000\times50\times0.94=63 \text{ MW}.$$

If the coefficient efficiency is η = 0.2 the power of installation is

$$\eta = 0.2\times63 = 12.5 \text{ MW}.$$

The energy 12.5 MW is enough for a city with a population at 150,000.
If we decrease our Installation to a 100×2000 m the power decreases approximately by 6 times (because the area decreases by 4 times, wind speed reaches more 15 m/s at this altitude. Power will be 75 MW. This is enough for a city with a population about 1 million of people.
If the average wind speed is different for given location the power for the basis installation will be: V =5 m/s, N =7.25 MW; V =6 m/s, N =12.5 MW; V=7 m/s, N = 19.9 MW; V = 8 m/s, N = 29,6 MW; V = 9 m/s, N = 42.2 MW; V = 10 m/s, N = 57.9 MW.

Economical efficiency
Let us assume that the cost of our installation is \$1 million. According to the book "Wind Power" by P.Gipe [2], the conventional wind installation with the rotor diameter 7 m costs \$20,000 and for average wind speeds of 6 m/s has power 2.28 kW, producing 20,000 kWh per year. To produce the same amount of power as our installation using by conventional methods, we would need 5482 (12500/2.28) conventional rotors, costing \$110 million. Let us assume that our installation has a useful life of 10 years and a maintenance cost is \$50,000/year. Our installation produces 109,500,000 kWh energy per year. Production costs of energy will be approximately 150,000/109,500,000 = 0.14 cent/kWh. The retail price of 1 kWh of energy in New York City is \$0.15 now. The revenue is 16 millions. If profit from 1 kWh is \$0.1, the total profit is more 10 millions per year.

Estimation some technical parameters
The cross-section of main cable for an admissible fiber tensile strange σ = 200kg/mm^2 is S=2000/0.2 = 10,000 mm^2. That is two cable of diameter d =80 mm. The weight of the cable for density 1800 kg/m^3 is $W = SL\gamma = 0.01\times2000\times1800$ = 36 tons.
Let us assume that the weight of 1m^2 of blade is 0.2 kg/m^2 and the weight of 1 m of bulk is 2 kg. The weight of the 1 blade will be 0.2×500 = 100 kg, and 200 blades are 20 tons. If the weight of one bulk is 0.1 ton, the weight of 200 bulks is 20 tons.
The total weight of main parts of the installation will be 94 tons. We assume 100 tons for purposes of our calculations.
The minimum wind speed when the flying rotor can supported in the air is (for C_y = 2)

$$V=(2W/C_y\rho S)^{0.5}=(2\times100\times10^4/2\times1.225\times200\times500)^{0.5} = 2.86 \text{ m/s}$$

The probability of the wind speed falling below 3 m/s when the average speed is 12 m/s, is zero, and for 10 m/s is 0.0003. This equals 2.5 hours in one year, or less than one time per year. The wind at high altitude has greater speed and stability than near ground surface. There is a strong wind at high altitude even when wind near the ground is absent. This can be seen when the clouds move in a sky on a calm day.

Project 4. Low speed air drag rotor (fig.3)
Let us consider a parachute with a diameter of 100 m, length of rope 1500 m, distance between the parachutes 300 m, number of parachute 3000/300 = 10, number of worked parachute 5, the area of one parachute is 7850m^2, the total work area is A = 5×7850 = 3925m^2. The full power of the flow is 5.3 MW for V=6 m/s. If coefficient of efficiency is 0.2 the useful power is N = 1 MW. For other wind speed the useful power is: V =5 m/s, N =0.58 MW; V =6 m/s, N = 1 MW; V =7 m/s, N =1.59 MW; V = 8 m/s, N=2.37 MW; V = 9 m/s, N =3.375 MW; V = 10 m/s, N = 4.63 MW.

Estimation of economical efficiency
Let us take the cost of the installation $0.5 million, a useful life of 10 years and maintenance of $20,000/year. The energy produced in one year (when the wind has standard speed 6 m/s) is E = 1000×24×360 = 8.64 million kWh. The basic cost of energy is 70,000/8640,000 = 0.81 cent/kWh.

The some technical parameters
If the thrust is 23 tons, the tensile stress is 200 kg/mm^2 (composed fiber), then the parachute cable diameter is 12 mm, The full weight of the installation is 4.5 tons. The support wing has size 25×4 m.

Project 5. High speed air Darreus rotor at an altitude 1 km (fig.4)
Let us consider a rotor having the diameter of 100 m, a length of 200 m (work area is 20,000m^2). When the wind speed at an altitude H=10 m is V =6 m/s, then at an altitude H = 1000 m it is 13 m/s. The full wind power is 13,46 MW. Let us take the efficiency coefficient 0.35, then the power of the Installation will be N = 4.7 MW. The change of power from wind speed is: V = 5 m/s, N = 2.73 MW; V = 6 m/s, N = 4.7 MW; V = 7 m/s, N = 7.5 MW; V = 8 m/s, N = 11.4 MW; V = 9m/s, N = 15.9 MW; V = 10 m/s, N = 21.8 MW.
At an altitude of H = 13 km with an air density 0.267 and wind speed V = 40 m/s, the given installation will produce power N = 300 MW.

Estimation of economical efficiency
Let us take the cost of the Installation at $1 million, a useful life of 10 years, and maintenance of $50,000 /year. Our installation will produce E = 41 millions kWh per year (when the wind speed equals 6 m/s at an altitude 10 m). The prime cost will be 150,000/41,000,000 = 0.37 cent/kWh. If the customer price is $0.15/kWh and profit from 1 kWh is $0.10 /kWh the profit will be $4.1 million per year.

Estimation of technical parameters
The blade speed is 78 m/s. Numbers of blade is 4. Number of revolution is 0.25 revolutions per second. The size of blade is 200×0.67 m. The weight of 1 blade is 1.34 tons. The total weight of the Installation is about 8 tons. The internal wing has size 200×2.3 m. The additional wing has size 200×14.5 m and weight 870 kg. The cross-section area of the cable transmission having an altitude of H = 1 km is 300 sq.mm, the weight is 1350 kg.

Project 6. Ground Wind High Speed Engine (fig.5)
Let us consider the ground wind installation (fig.5) with size 500×500×50 meters. The work area is 500×50×2= 50,000m^2. The tower is 60 meter tall, the flexible rotor located from 10 m to 60 m. If the wind speed at altitude 10 m is 6 m/s, that equals 7.3 m/s at altitude 40 m.
The theoretical power is

$$N_t = 0.5\rho V^3 A = 0.5\times1.225\times7.3^3\times5\times10^4 = 11.9 \text{ MgW}.$$

For coefficient of the efficiency equals 0.45 the useful power is

$$N = 0.45\times11.9 = 5.36 \text{ MW}.$$

For other wind speed at an altitude 6 m/s the useful power is: V = 5 m/s, N = 3.1 MW; V = 6 m/s, N = 5.36 MW; V = 7 m/s, N = 8.52 MW; V = 8 m/s, N = 12.7 MW; V = 9 m/s, N = 18.1 MW; V = 10 m/s, N = 24.8 MW.

Economic estimation

In this installation the rotor will be less expensive than previous installations because the high-speed rotor has a smaller number of blades and smaller blades (see technical data below). However this installation needs 4 high (60 m) columns. Take the cost of the installation at $1 million with a useful life of 10 years. The maintenance is projected at about $50,000 /year.
This installation will produce E = 5360 kW x 8760 hours = 46.95 MWh energy (for the annual average wind-speed V = 6 m/s at H = 10 m). The cost of 1 kWh is 150,000/46,950,000 = 0.4 cent/kWh. If the retail price is $0.15/kWh and delivery cost 30%, the profit is $0.10 per kWh, or $4.7 million per year.

Estimation of some technical parameters

The blade speed is 6×7.3 = 44 m/s. The distance between blades is 44 m. The number of blade is 4000/44 = 92.

Discussion and conclusion

Conventional windmills are approached their maximum energy extraction potential relative to their installation cost. No relatively progress has been made in windmill technology in the last 50 years. The wind energy is free, but its production more expensive then its production in heat electric stations. Current wind installations cannot essential decrease a cost of kWh, stability of energy production. They cannot increase of power of single energy unit. The renewable energy industry needs revolutionary ideas that improve performance parameters (installation cost and power per unit) and that significantly decreases (in 10-20 times) the cost of energy production. This paper offers ideas that can move the wind energy industry from stagnation to revolutionary potential.
The following is a list of benefits provided by the proposed system compared to current installations:

1. The produced energy at least in 10 times cheaper then energy received of all conventional electric stations includes current wind installation.
2. The proposed system is relatively inexpensive (no expensive tower), it can be made with a very large thus capturing wind energy from an enormous area (hundreds of times more than typical wind turbines).
3. The power per unit of proposed system in some hundreds times more of typical current wind installations.
4. The proposed installation not requires large ground space.
5. The installation may be located near customers and not require expensive high voltage equipment. It is not necessary to have long, expensive, high-voltage transmission lines and substations. Ocean going vessels can use this installation for its primary propulsion source.
6. No noise and bad views.
7. The energy production is more stability because the wind is steadier at high altitude. The wind may be zero near the surface but it is typically strong and steady at higher altitudes. This can be observed when it is calm on the ground, but clouds are moving in the sky. There are a strong permanent air streams at a high altitude at many regions of the USA.
8. The installation can be easy relocated in other place.

As with any new idea, the suggested concept is in need of research and development. The theoretical problems do not require fundamental breakthroughs. It is necessary to design small, free flying installations to study and get an experience in the design, launch, stability, and the cable energy transmission from a flying wind turbine to a ground electric generator. This paper has suggested some design solutions from patent application [4]. The author has many detailed analysis in addition to these presented projects. Organizations interested in these projects can address the author (http://Bolonkin.narod.ru aBolonkin@juno.com aBolonkin@gmail.com

References

see also http://Bolonkin.narod.ru/p65.htm

1. A.A.Bolonkin. Utilization of Wind Energy at High Altitude. AIAA-2004-5756, AIAA-2004-5705, International Energy Conversion Engineering Conference at Providence, RI, USA, Aug.16-19, 2004.
2. P.Gipe. Wind Power. Chelsea Green Publishing Co., Vermont, 1998.
3. R.W.Thresher and etc. Wind Technology Development: Large and Small Turbines. NRFL, 1999.
4. A.A.Bolonkin. Method of Utilization a Flow Energy and Power Installation for It. USA patent application 09/946,497 of 09/06/2001.
5. A.A.Bolonkin. Transmission Mechanical Energy to Long Distance. AIAA-2004-5660.
6. F.S.Galasso. Advanced Fibers and Composite. Gordon and Branch Scientific Publisher, 1989.
7. Carbon and High Performance Fibers Directory and Data Book. London-New York: Chapmen&Hall, 1995, 6th ed., 385 p.
8. Concise Encyclopedia of Polymer Science and Engineering. Ed. J.I.Kroschwitz, N. Y: Wiley, 1990, 1341 p.
9. M.S.Dresselhaus. Carbon Nanotubes; by Springer, 2000.
10. A.A.Bolonkin. Inexpensive Cable Space Launcher of High Capability. IAC-02-V.P.07, 53rd International Astronautical Congress, The World Space Congress – 2002, 10-19 Oct. 2002/Houston, Texas, USA.
11. JBIS. Vol.56, pp.394-404, 2003.
12. A.A.Bolonkin. Non-Rocket Missile Rope Launcher. IAC-02-IAA.S.P.14, 53rd International Astronautical Congress, The World Space Congress – 2002, 10-19 Oct 2002/Houston, Texas, USA.
13. JBIS. Vol.56, pp.394-404, 2003.
14. A.A.Bolonkin. Hypersonic Launch System of Capability up 500 tons per day and Delivery Cost $1 per Lb. IAC-02-S.P.15, 53rd International Astronautical Congress, The World Space Congress – 2002, 10-19 Oct 2002/Houston, Texas, USA; JBIS, Vol.57, pp.162-172. 2004.
15. A.A.Bolonkin. Employment Asteroids for Movement of Space Ship and Probes. IAC-02-S.6.04, 53rd International Astronautical Congress, The World Space Congress – 2002, 10-19 Oct. 2002/Houston, USA.
16. JBIS. Vol.56, pp.98-197, 2003.
17. A.A.Bolonkin. Non-Rocket Space Rope Launcher for People. IAC-02-V.P.06, 53rd International Astronautical Congress, The World Space Congress – 2002, 10-19 Oct 2002/Houston, Texas, USA.
18. JBIS. Vol.56, pp.231-249, 2003.
19. A.A.Bolonkin. Optimal Inflatable Space Towers of High Height. COSPAR-02 C1.1-0035-02, 34th Scientific Assembly of the Committee on Space Research (COSPAR), The World Space Congress – 2002, 10-19 Oct 2002/Houston, Texas, USA.

20. JBIS. Vol.56, pp.87-97, 2003.
21. A.A.Bolonkin. Non-Rocket Earth-Moon Transport System, COSPAR-02 B0.3-F3.3-0032-02, 34th Scientific Assembly of the Committee on Space Research (COSPAR), The World Space Congress – 2002, 10-19 Oct 2002/Houston, Texas, USA. Advanced Space Research, Vol.31, No. 11, pp. 2485-2490, 2003.
22. A.A.Bolonkin. Non-Rocket Earth-Mars Transport System. COSPAR-02B0.4-C3.4-0036-02, 34th Scientific Assembly of the Committee on Space Research (COSPAR), The World Space Congress – 2002, 10-19 Oct 2002/Houston, Texas, USA. Actual problems of aviation and space system. No.1(15), vol.8, pp.63-73, 2003.
23. A.A.Bolonkin. Transport System for delivery Tourists at Altitude 140 km. IAC-02-IAA.1.3.03, 53rd International Astronautical Congress, The World Space Congress – 2002, 10-19 Oct. 2002/Houston, Texas, USA. JBIS, Vol.56, pp.314-327, 2003.
24. A.A.Bolonkin.”Hypersonic Gas-Rocket Launch System.”, AIAA-2002-3927, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, 7-10 July, 2002, Indianapolis, IN, USA.
25. A.A.Bolonkin. Multi-Reflex Propulsion Systems for Space and Air Vehicles and Energy Transfer for Long Distance, JBIS, Vol, 57, pp.379-390, 2004.
26. A.A.Bolonkin. Electrostatic Solar Wind Propulsion System, AIAA-2005-3653. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
27. A.A.Bolonkin. Electrostatic Utilization of Asteroids for Space Flight, AIAA-2005-4032. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
28. A.A.Bolonkin. Kinetic Anti-Gravitator, AIAA-2005-4504. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
29. A.A.Bolonkin. Sling Rotary Space Launcher, AIAA-2005-4035. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
30. A.A.Bolonkin. Radioisotope Space Sail and Electric Generator, AIAA-2005-4225. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
31. A.A.Bolonkin. Guided Solar Sail and Electric Generator, AIAA-2005-3857. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
32. A.A.Bolonkin. Problems of Electrostatic Levitation and Artificial Gravity, AIAA-2005-4465. 41 Propulsion Conference, 10-12 July, 2005, Tucson, Arizona, USA.
33. A.A.Bolonkin. Space Propulsion using Solar Wing and Installation for It. Russian patent application 3635955/23 126453, 19 August, 1983 (in Russian). Russian PTO.
34. A.A.Bolonkin. Installation for Open Electrostatic Field. Russian patent application 3467270/21 116676, 9 July, 1982 (in Russian). Russian PTO.
35. A.A.Bolonkin. Getting of Electric Energy from Space and Installation for It. Russian patent application #3638699/25 126303, 19 August, 1983 (in Russian). Russian PTO.
36. A.A.Bolonkin. Protection from Charged Particles in Space and Installation for It. Russian patent application #3644168 136270 of 23 September 1983, (in Russian). Russian PTO.
37. A.A.Bolonkin. Method of Transformation of Plasma Energy in Electric Current and Installation for It. Russian patent application 3647344 136681 of 27 July 1983 (in Russian), Russian PTO.
38. A.A.Bolonkin. Method of Propulsion using Radioisotope Energy and Installation for It. of Plasma Energy in Electric Current and Installation for it. Russian patent application 3601164/25 086973 of 6 June, 1983 (in Russian), Russian PTO.

39. A.A.Bolonkin. Transformation of Energy of Rarefaction Plasma in Electric Current and Installation for it. Russian patent application #3663911/25 159775 of 23 November 1983 (in Russian). Russian PTO.
40. A.A.Bolonkin. Method of a Keeping of a Neutral Plasma and Installation for it. Russian patent application 3600272/25 086993 of 6 june 1983 (in Russian). Russian PTO.
41. A.A.Bolonkin. Radioisotope Propulsion. Russian patent application 3467762/25 116952 of 9 July 1982 (in Russian), Russian PTO.
42. A.A.Bolonkin. Radioisotope Electric Generator. Russian patent application 3469511/25 116927 of 9 July 1982 (in Russian). Russian PTO.
43. A.A.Bolonkin. Radioisotope Electric Generator. Russian patent application 3620051/25 108943 of 13 July 1983 (in Russian). Russian PTO.
44. A.A.Bolonkin. Method of Energy Transformation of Radioisotope Matter in Electricity and Installation for it. Russian patent application 3647343/25 136692 of 27 July 1983 (in Russian). Russian PTO.
45. A.A.Bolonkin. Method of stretching of thin film. Russian patent application 3646689/10 138085 of 28 September 1983 (in Russian). Russian PTO.
46. A.A.Bolonkin. Non-Rocket Space Launch and Flight, Elsevier, London, 2006, 488 ps.

AIAA-2004-5705, AIAA-2004-5756
T/F 718-339-4563. aBolonkin@juno.com http://Bolonkin.narod.ru
Article of Flow Energy after Glenn one space 5 15 04

Alexander Bolonkin, Dipl.Eng., Ph.D.; Senior Research Associate of the USA National Research Council at Eglin AFB, Former Senior Researcher of NASA; he graduated Kazan Aviation Institute (1958); he worked as engineering leader at Antonov Aircraft Construction Bureau (Kiev), chairman of reliability department at Glushko Rocket Engine Construction Bureau (Moscow), as a professor (teacher) in different Russian and American Universities.
Dr. Bolonkin is member of Director Board of International Space Agency; the area of scientific interests is the problems of aviation systems; nine of his reports on actual problems have been approved by the World Space Congress (2002, USA).

About modelling interaction of Earth with large space object: the script with explosion of Phaeton and the subsequent evolution of Mankind (part II)

Emilio Spedicato

Department of Mathematics, University of Bergamo
via Caniana, 2; 24127 Bergamo, Italy

This work is devoted to problems and methods of modelling in a problem of interaction of large space object with the Earth, including processes of capture of a body by the Earth, dynamics of a body and the Earth, geodynamics, dynamics of Earth atmosphere, dynamics of oceanic masses, … and the subsequent evolution of a human society on the Earth [1-89]. On the basis of careful studying an extensive historical material, with the description of the physical and social processes occurred on the Earth and in near Earth Space, the author builds model of interdisciplinary processes, considering corresponding natural-science and sociopolitical subsystems as parts of Unity in whole. Thus all technique is applied to the processes connected with catastrophic event of super-Tunguska class, namely the explosion over southern Denmark of the space object known in Greek mythology as Phaeton. The Deucalion Flood and the demise of the Minoan civilization are also explained within this context. The Phaeton explosion may be seen as the final event of the interaction of Earth with a captured external body, lasting possibly a few months, resulting in the disasters known as the Ten Plagues of Egypt and in worldwide migrations, particularly the Indo-Aryan migration from north-western Eurasia to India and Iran.

Also in this paper we consider the passage of the Red Sea by the Hebrew tribes during Exodus, as described in the Bible. Using additional information from the *Antiquities of the Jews* by Josephus Flavius, a crucial passage in *Historiae Adversus Paganos* of Orosius, and other classical sources, we claim that the passage of the Red Sea was made possible by local effects in the Gulf of Aqaba of a indicated catastrophic event in the super-Tunguska class. Also it is necessary to note that from mathematical point the developed model is requiring the additional investigations. In more detail the multidisciplinary problems (from areas of mechanics, physics, geodynamics, …) are presented in Appendix. It is important in nearest time to realize the computer modelling of elaborated scenario. This is feasible.

In this Journal issue it is presented the article part (part II) with Appendixes, with discussion of problems of mathematical modelling in considered processes. Part I of article was published in previous issue (No.1(38), v.19, 2014).

Appendix 1: the chronology of the event

Dating ancient events is a difficult problem, since not all people had written history with a chronology as we intend now. About the events considered in this paper we cite the following chronological information, partly from ancient texts and partly from modern analysis of ancient geological material:

1. Exodus can be dated from Biblical data on the Solomon temple in Jerusalem, whose construction is stated to have begun 480 years after Exodus. That year, from the biblical chronology of the kings up to the deportation first of the Ten Tribes by Sargon II the Assyrian in 722 BC and then the Judah and Benjamin tribes by Nebuchadnezzar in 587 BC, can be determined to be year 967 BC. A difficulty for some time was the apparent incompatibility of dates relating to the kingdoms of Israel and of Judah. However Thiele [52] has been able to remove such problems, stemming to a large extent from the fact that the two kingdoms followed different calendars, one Assyrian, the other Egyptian (the beginning of the year being different, either in autumn or in spring). Therefore we get the date 1447 BC for Exodus, accepted by Velikovsky and a number of other scholars.

2. Dating the Deucalion Flood is not immediate from the classical sources, since Plato states that Solon was going to date it by generation counting, whose number is not given. I

remember reading in some classic source that there were 20 generations till the first Olympics, but I am unable to retrieve the specific source (reading about three books per week and no more having the memory of younger years leads to such type of problem). I have by no way made a complete survey of the classical sources about Deucalion. It is however interesting that dating Deucalion at circa 1500 BC was commonly accepted about two hundred years ago, when classical literature was more studied than now, see for instance the *Classical Dictionary* of Lempriere [53]. About dating the end of the great Minoan civilization, and the several eruptions of Santorini, there has been much debate, see [54, 55]; a date around the mid 15th century seems to be acceptable.

3. There is also discussion about the date of the invasion of India by the powerful Hindi or Sindhi, who imposed their dominion in the northern part of India, where, in the valley of the Indus river, had developed the great civilization of Vallindia, see Mandel [65]. A date around the mid 15th century seems acceptable. It is quite possible that there had been invasions before, on a smaller scale, by the way of Kashgaria, Karakol and the passes leading into the Hunza valley (Mintaka and Khunjerab). Entering the low Indus valley by such a way is a hard task but not an impossible one. The most fertile part of the Indus valley lies at the foot of the mountains. It is called Punjab/Penjab, most probably this being the mysterious biblical *land of Punt*, i.e. *of the five rivers*, called in Sumerian documents *Meluhha*, this probably meaning the *land of the Meru*, the mount Meru being associated with the three pyramidal sacred great mountains Kailas, Hunza Kunji, Rakaposhi. The fact that the waters from these mountains all go to the Indus is probably the reason why in the 1439 map of Fra Mauro, now at the Marciana library in Venice, the Indus is called *Ameru*, i.e. *the water (river) from the Meru*…. The use of these passes in very ancient times has been shown by the discovery of over ten thousand rock inscriptions between Gilgit and Khunjerab during the construction of the Karakorum Highway, completed around 1980. The inscriptions are as old as the 4th millennium BC; a few dated at the second millennium BC had been found by Aurel Stein [56] at the end of his adventurous career. Remnants of Indo-Europeans who came by this way were possibly the Kafirs living in the Chitral area visited by Maraini [57] in 1959, whose anthropometric features, cultural and living habits were clearly of north-Eurasian origin. By this way India was briefly invaded by the Chinese in the first century BC and again by this way the great Kushana emperor Kanishka invaded Chinese controlled territory, occupying Kashgar for some time.

The Hindi/Sindhi after a while mixed with the culturally more advanced local population, leading to the present form of Hinduism, where pre-Indo-Aryan elements are present (Shivaism, Tantrism, Yoga….), see Daniélou [66]. They brought Vedaism, albeit the Rig Veda may be not only a religious text, but a description of even more dramatic events that affected Earth long before the Indo-Aryan migration to the south (even predating the Biblical Flood, i.e. the second catastrophe in Plato, datable at 3161 or 3172 BC, on the basis of arguments to be developed in a planned monograph). For an interpretation of the Rig Veda, and the very ancient astronomical book Surya Siddhanta, in astronomical terms, see Ackerman [27,28].

4. An event of more than continental effects as the one we have described (Phaeton exploding over Denmark after weeks of destructions due to fragmentation episodes) must have left geological evidence, even if it was certainly many orders weaker than the impact with a meteorite of about 10 km diameter that probably terminated the era of the dinosaurs, see Hsu

[58]. We thank geomorphologist Stuart Harris, who is preparing a monograph on such a critical period, for the following information:

A – *analysis of the California Bristlecone Pine tree database shows a pronounced minimum at 1445 BC. This year is part of a sequence of dust layers and minimum tree rings every 10, 12 or 18 years. But the dust layer of 1445 BC is quite different from the rest. From an archaeological viewpoint, then, 1445 BC is the date of the Plague of Darkness. This is derived by counting actual years – there is no recourse to radiocarbon estimates*, see [59]. Here we notice that not only darkness but also strong cooling would have produced a minimum growth, and that while dendrochronologists are very confident of the accuracy of their counting, errors can never be discounted (e.g. an axis reversal might result in *two* layers, or a strong cooling episode might result in no layer; also any local disturbance affecting the roots of the tree, that will survive but be impaired for a number of years, may affect the number of layers); anyway Harris noticed a glitch in the database that moved the year to 1446 BC, see [60]

B – *I revisited the GISP2 ice core data and found that it does contain a record of the dust associated with the plague of darkness…A group of scientists measured insoluble particle size from the present to 1800 BC. Their data shows that the largest particles ever recorded, by a factor of 3, occurred in a single sample covering the years 1444-1443 BC…*. see [61]. Again taking into account that dating of the layers may not be so precise as scientists claim, and that possibly more that one year might be needed for the dust to reach Greenland (it took four years for the Tunguska dust to reach Antarctica), the above information is a remarkable evidence that dust, whose origin might have been partly volcanic, partly from the disintegration of initial Phaeton, partly from fragments of Phaeton having impacted other parts of the world (there are reasons to include here the Carolina Bays and the clathrate rich Caribbean basin), affected the atmosphere, leading to darkness, that reduced vegetation growth, and cooling, hence causing large migrations from the middle and high latitudes to south.

C – the earthquake following the considered super Tunguska event, and possibly earlier smaller direct impacts, can result in a number of geological effects in addition to the awakening of volcanoes (we considered Santorini and the many volcanoes in the Danakil depression). One special effect, that will be amply discussed in the forthcoming monograph by Harris, is the sudden delivery of methane that is contained in sediments in the form of clathrate, an unstable compound of water and methane. Huge amounts of such clathrates are found in the Caribbean sea, especially in front of Texas and Louisiana. The sudden delivery of sizable quantities of methane from these structures probably takes place occasionally even now, and would be the natural explanation of the “mysterious” events described for the Bermudas triangles (disappearance of ships and airplanes). A very large emission of methane would lead inter alia to a great tsunami. Harris claims to have established, from analysis of satellite photographs, that such tsunamis affected the Mississippi basin and the US Atlantic coast around 1450 BC. It was this claim that led me to suggest him to look for a relation with the Exodus event. According to his latest estimate, see [62], there is evidence of tsunami in year 1445 BC. He has another evidence for year 1404 BC. Notice that 40 years after exit of Egypt, the military campaign against Canaan began, the Hebrew being led by Joshua. Among the events of such campaign the phenomena of the falling down of the walls of Jericho and the sun standing in the sky suggest another catastrophic event, related most probably to an axis reversal. See Spedicato and Del Popolo [63] for a mathematical analysis of this phenomenon, which would move Earth to a nearby orbit (with a change of the day length of about 10 minutes and of the distance to Sun of about 150.000 km, a too little change to affect the Earth climate; but the number of days in the year would change by two….).

Another possible effect of the methane explosion in the Caribbeans should be considered, namely that it carried in the upper atmosphere also amounts of oil. So hydrocarbons from the Caribbean might have contributed additional material in the stratosphere to produce manna. If the oil from the Caribbean was the main source for manna, then we have an explanation why it took several days for manna to appear.

The above considerations support the date 1447 BC as the year for Exodus and the other considered events. According to the standard Egyptian chronology, see e.g. Baines and Malek [67], this year would pertain to the New Kingdom 18th dynasty, dated at 1550 to1307 BC. The Hyksos, terminating the Middle Kingdom, would have arrived circa 1783 BC, to initiate the 13th dynasty, the following dynasties being in power either in the Delta or in the south. Particularly troublesome is the fact that no Egyptian references exist dealing with the departure of the Hebrew, the destruction of the Pharaoh army or even the Ten Plagues (unless, as suggested by Velikovsky [8], the Hermitage and the Ipuwer papyrus, describing catastrophic event, refer to this time; notice also the existence of a stele found near Gaza referring to a Pharaoh who died in a *whirlpool*). This problem has led scholars, who accept at least a core of truth in the book of Exodus, to propose several Pharaohs and theories about who left, all explicitly or implicitly meaning that the biblical tale grossly exaggerated the facts. The chronological change proposed by Velikovsky [18] completely removes this problem. The Hebrew leave just before the Amu/Amalekites come, which are the Hyksos of the Manetho story. Incidentally we have argued, see [68], that the name *Hyksos* means *people of the horses*, the name that also the Chinese gave to the invading Mongolians (horses of the best quality were bred in Turan; some two thousand years ago the horses of Ferghana were immensely prized, one horse worth more that one Chinese princess of imperial blood…). Part of the Egyptian army (not necessarily also the Pharaoh) perished in the Aqaba gulf when the waters returned; another part was probably drowned, with most of the civilians, when the Mediterranean waters pushed inside the Delta; the remaining troops either survived in the south or were destroyed by the advancing Amu people, who most probably were not significantly affected in their march by the catastrophes described. For the next 400 years Egypt was under control of the Hyksos. They destroyed most of what had been left by the natural disasters, and so they were the real villains, their invasion being immensely more grave in the eyes of the later Egyptian writers than the escape of some thousand of slaves.

Here we can give, with Velikovsky, the name of the Pharaoh who dealt with Moses, namely Dudimose, or, in Josephus *Contra Apionem* quoting Manetho, Tutimaios. About him almost nothing is known from Egyptian sources, his name having been preserved anyway in the badly damaged Turin papyrus that probably had a complete list of the Egyptian pharaohs.

We have not discussed the question of radiocarbon dating, for two reasons:

- radiocarbon dates that fall out of the date established on the basis of archaeological arguments are usually discarded, with the justification that the treated specimen has been contaminated
- it is known, see [57], that radioactive carbon C14 can be created in the atmosphere by an impacting body, thereby modifying the supposed fixed ratio of C12 and C14. Moreover the

events considered by Harris to have taken place in the Caribbean would lead to a huge increase of carbon in the atmosphere (not only methane but also CO2 would be liberated from the sediments), further complicating the ratio problem. Therefore radiocarbon dates are certainly less accurate than those provided by dendrochonology, ice cores, palynology (we are not aware now if pollen counts indicate a crisis around 1447 BC) or, best of all, precise year counting as is done in the Bible. Moreover it should be remarked that dates based upon the decay of radio-nuclides assume that the half-time decay constants are fixed. In 2001 the eminent Cambridge physicist John Barrow claimed the recent discovery that the *fine structure constant* increases with the expansion of the universe (if light speed and electron charge remain constant) as the *biggest discovery in 50 years*. Such result had been predicted in writing three years earlier by physicist Robert Bass, with the observation that an immediate consequence was that the so called half-time constants would increase with time, with enormous effects on all the dating so far performed for geological layers !!! See [69], and wait for a new dating of geological layers!

Finally we should discuss the numbers 805 and 810 given for the considered events in Orosius with reference to the foundation of Rome. If Rome was founded in 753 BC, the traditional date, then the events would have happened about 1550 BC, i.e. about a century before our date. It is likely that Orosius, or his sources Tacitus and Trogus, are not accurate, even letting apart the fact that there are doubts about the true date of the foundation of Rome. Unfortunately most of Tacitus and almost all Trogus are lost, so we cannot check how they obtained such numbers. Of course it is also possible that an error was made in copying the Orosius manuscript, or the number was changed by a copier who thought he knew better. This type of problem does not affect biblical codes, since absolute correctness in the new copy was a fundamental requirement, even so that errors could not be corrected but the whole scroll had to be written anew. The perfect concordance of the text of Isaiah found in Qumran with the Leningrad codex, the oldest extant code but about 1000 years later, is a confirmation of such accuracy over the centuries. No copier considered a grave sin to change the text of Orosius….

Appendix 2: the route of Moses to the point of the passage

It is not here the place of a full discussion of the route taken by Moses out of Egypt, up to the point of the passage of the Red Sea, then to the Mounts Horeb and Sinai where he received the Laws, finally to Canaan, whose conquest was reserved to Joshua, 40 years after the exit from Egypt. We leave to a future work a more extensive study of this problem via also the analysis of Arabic maps. Here we shall deal briefly only with the route from Egypt to the point of passage.

According to the Bible, the Hebrew entered in Egypt at the time of Joseph, 210 years before Exodus, increased in number faster than the Egyptian population, so that an unnamed Pharaoh, afraid that they would become too powerful, decided that all Hebrew males had to be eliminated. This law probably took place around the time Moses was born, i.e. about the year 1487 BC in our chronology. It is of course unlikely that the law was strictly enforced, but it was certainly applied to a significant degree, as indicated by the following two items of evidence, see Rohl [73]:

- analysis of the bones in a cemetery used by slaves indicates a number of infant bones higher than the usual
- names of slaves were found in the ruins of a private palace near Thebes; they are mainly Semitic names, typical of Hebrew people, but mostly names of females appear.

We may also provide a reason why the Hebrew increased faster than the Egyptians. There is no reason why their birthrate had to be higher than that of the Egyptians, both people having certainly a very high birthrate (of the order 7%, like in medieval Florence…); however we know from Diodorus, who describes conditions of his time that were probably also true at older times, that the Egyptian peasants cared of their children only until they stopped sucking. Then the children had to find the food by themselves. This resulted of course in a high death rate of children, letting the fittest to survive. Hebrew always had the greatest care for their children, hence their children likely had a lower death rate, implying a growth of the percentage of the total population that was of Hebrew blood.

We may also consider another consequence of the law establishing the elimination of the male infants. Only women would survive, not for a life of chastity of course, but to father children to Egyptians or other non Hebrew people. So in order to avoid the disappearance of their people, the seniors must have decided that being Hebrew depended only on the mother being herself Hebrew. A decision that is still fully valid.

The Hebrew in Egypt were apparently concentrated in the eastern part of the Delta, in a settlement called Goshen, where probably later (several centuries later in our chronology) Ramses II build his famous summer palace Pi-Ramses. Goshen has been excavated recently by the Austrian archaeologist Bietak, who has uncovered evidence of a settlement by Semitic people, and even an intriguing room under the soil with a defaced statue of a man covered by a special mantle. According to Rohl [73] this might have been the room containing the bones of Joseph, which were taken away by Moses, and the statue a representation of Joseph, with the special multi-colors mantel he was wearing when his brothers sold him to Madianite traders. In Goshen the Hebrew were involved in slave work, mainly to build bricks for construction of public structures. Here Moses killed an Egyptian officer who mistreated the Hebrew and had to flee from Egypt.

It is unlikely that all Hebrew were in Goshen, many or most of them were distributed around Egypt, down to the borders of Nubia; so it is virtually impossible that all Hebrew left the country with Moses, the time to collect them would have been very long and Moses had a special urgency to leave, if we are correct in our hypothesis that he knew of the arrival of the Amu.

The usual translations of the Bible, including the Septuaginta, state the Moses left with 600.000 men (not including children). This number would imply a total number of his followers of several millions, taking into account that women had to be the majority and that many slaves (probably non Hebrew husbands of most women…) were with them. This number is impossibly high, would generate tremendous management problems, not to say of the food and water problems in the desert. The number is certainly a wrong translation, possibly due to a desire to show the greatness of the Hebrew tribe, of the word *Eleph, Aleph* that, as suggested by several scholars including Ricciotti [4], means not only *thousands* but also *groups, clans, families.* Six hundred families, led by senior Hebrew who either were born before the law establishing the killing of the male babies or somewhat escaped death as was the case with Moses, represent a reasonable number. Each leader would have been accompanied by a group of persons, mainly women, numbering perhaps between 10 and 100. Assuming for default that such number was 50, this would give a total of 30.000 persons, a very reasonable number for the route that Moses had in mind. Not too many problems however even if the number was around 100.000. Notice also that the Pashtun of Afghanistan, who claim to be descendant of the Ten Tribes deported by Sargon II, are divided in about 400 clans all having clearly Hebrew names, see Kersten [43], names that may preserve the names of a large part of the 600 clans that left Egypt.

We are now going to propose a route that, as far as we are aware, has never been considered till now. Many investigators of the problem, e.g. Goedicke [7] and Anati [30], have considered a route along the Mediterranean, where the main road to Palestine, Phoenicia and Syria was found, called the *Royal Road* or the *way of Horus*, the road that was certainly usually followed by the Amu in their past incursions against Egypt, and that would be later followed by Cambises, Alexander, the Arabs, the Turks…. Under such a scenario the crossing of the Red Sea would correspond to the crossing of the shallow lakes that border the northern Sinai (now and probably also at Moses time), rich in reeds, and noting that the biblical name for the Red Sea, *Yam Suf*, also means *Sea of reeds*. We reject this scenario because from Josephus we know that the road was long and not the usual one, hence it could not be the Royal Road; along this road there are no impassable mountains moreover. This road would put Moses in the risk of meeting the Amu, too strong for him and probably also for the Egyptians. Finally the Hebrew would have been drowned in the tsunami that, following the Phaeton explosion, certainly flooded all northern Sinai peninsula for tens of km in the interior.

A second road proposed by several scholars, e.g. Barbiero [6], Phillips [31] and Manher [32], has the Hebrew passing near present Suez, location in ancient times of another shallow lake, Lacus Serbonis, and then moving towards Palestine by Central Sinai, a higher region with non difficult passes below 1000 meters (near the Mitla pass there was a famous tank battle during a recent conflict between Israel and Egypt). While the tsunami problem here would not arise, still this road would not be safe for Moses against the Amu danger and would not be unusual or particularly longer than the standard road.

Our proposal has the following features:

- it provides a longer road, by a factor at least two, over the Royal Road, but provided with water in many places; it agrees with a statement in Cosmas Indicopleustes [86], V, 14:*…they had the sea on their right, the desert on their left…*
- it would make Moses safe from the Amu, except possibly when he had to cross a stretch of the *desert of Shur* before reaching the safe mountains where he gets the Tablets of the Law (as proposed by Phillips [31] and other authors before him, with whom we tend to agree, these mountains are in present Jordan, in the region of Petra. They are called *Jebel Haroon (mountain of Haroon),* and there is a *Wadi Musa* and an *Ain Musa (source of Moses)*. They were inhabited by the Edomites, descendants of Esau, a people who probably had been contacted by Moses when he was in Madian. Esau being the first born of Isaac, it is virtually certain that he got from Isaac since a child knowledge on the past of the family of interest to Moses that had not been given to Jacob; here may lay the source of the material given in *Genesis*…)
- it provides an explanation of what was the mysterious Baal Sefon
- it may exactly pinpoint the place of the passage, albeit presently we are unable to do it with great precision, this requiring better maps than those available to us now and a local exploration, planned for a next future, hopefully with the sub water archaeologist Marco Chioffi…

- it provides a motivation why the Monastery of St Catherine was built in the southern part of Sinai, albeit we agree that this was not the place where the Tables were given
- it provides a new identification of *Elim* and *Migdol*.

We start by observing that Exodus (or Numbers) do not present the stages of Moses day per day. Only the important places are listed, either because the Hebrew spent there a longer time or because they were places with important natural or man made features. The time to the day of the passage should have been about 30 days, Moses reaching the Mountain of God in the third month after the exit from Goshen. The distance from Goshen to our point of passage is about 600 km, implying stages of about 20 km/day, an acceptable value. Note that Laurence of Arabia crossed from Aqaba to Suez, about 300 km, non stop in one day and a half, albeit using a camel. The standard time to reach Palestine from Egypt is given by Philon of Alexandria as only 3 days, see [79], section 163.

The first stopping place after leaving Goshen is named *Succot*, meaning *place of reeds*, that can be safely identified somewhere near present Suez, where brackish water in lagoons (now called the Great and the Little Bitter Lakes) allowed the growth of reeds. A wall, *shur* in Egyptian as noticed by Manher [32], had been built by Sesostris II, and may have given the name to the desert east of it. We disagree with Manher [32] that crossing the wall was a difficulty. The earthquakes taking place during the Ten Plagues had certainly badly damaged it and the thousand of men with Moses were anyway certainly able to open a passage.

After Succot Moses led his people SE, in the direction of the *Glory of God*, i.e. of Phaeton that was moving from the Indian Ocean towards northern Germany. He followed the rather flat and drab coast of the Sinai peninsula, then very sparsely populated by the Ichtyophagoi (living along most of the coasts of the Indian Ocean of seafood, speaking a very strange language, as described by several classic authors, especially in the *Peryplus Maris Erythraei*, see [82]). Ample water was probably available in places that even now bear names as *Springs of Moses*, *Hammam Pharaun*, *Hammam Mussa*, *Hammam* meaning *communal bath*, a term suggesting big pools of clean water. Many rivers descend as wadi from the Sinai massif, which reaches over 2500 meters; they might have had some water at the time of Exodus; even if dry, water can usually be obtained by pushing a reed in the sandy soil, to reach the water below the surface, as Bushmen have done for centuries in the Kalahari desert (from Herodotus we infer that Bushmen, called Troglodytes, lived in parts of the Egyptian desert, and possibly in Sinai, at his time; they were pushed to the south of Africa by the Bantus, who arrived there at the time of the first white immigrant Boers). A technique certainly of immense antiquity and well known to the Ichtyophagoi.

The next important stop is Baal Sefon, where the Hebrew take away gold, one third of the riches that Joseph had amassed by selling food during the great shortage, and where a statue existed and was not touched by them, that had survived the events of the Ten Plagues, contrary to what had happened to statues in Egypt proper, see the *Legends of the Jews* quoted in Section 2. This information indicates that the place had to be a kind of temple-fortress, Baal meaning Lord. The problem is Sefon.

For Sefon in the literature, see e.g. any Biblical Encyclopedia, we find the following "meanings":

- *Lord of the North*

- *Lord of the flies* (!!)

We now assume the following admissible phonetic changes in Sefon

SEFON = SEFO = SIFO = SIFA = SIVA = SHIVA

Therefore we propose that Bal Sefon was a temple dedicated to the Indian divinity Shiva or Siva, predating the Indo-Aryan invasion. The name *Baal Sefon* thus would mean *Lord Shiva.* Notice that according to the *Sifat Nama...* [78], Shiva was one of the three main gods of the Kafirs of Kabulistan in the 15th century, with the name *Sharvia*, another divinity being *Lambam*, identified with Lamech, the father of Noah, whose tomb was considered to exist in that region. Our identification is based upon the fact that contacts between Egypt and India were active during the Middle Kingdom. They were managed by the great Indian navigators called *Pani*, see Sahai [74] (who, being himself a Brahmin disregards the existence of such contacts before the Indo-Aryan invasion…), who were able to exploit the monsoons for long distance travel to Middle East, SW Asia, and possibly even around Africa to Europe and Americas. They had important bases on the western coast of India including certainly the now submerged town named Dwarka, see Gaur [75], located on a big island not far from the mouth of the Indus (now joined to main India as Peninsula of Kutch, a name probably indicating contacts with Kush…), probably the island referred to by Aethicus Ister [76] as being in front of the mouth of the river Euphrates/Indus. Another likely port was in the small island of Elephantina, in front of the present peninsula of Bombay/Mumbay, famous for containing an extremely ancient temple of Shiva, represented by a statue with three heads, see Maraini [77]. They would export to Egypt precious material as lapis lazuli from Badakshan, avoiding the overland passage prone to attacks by bandits, gold from the great Tibetan mines near the sources of the Indus on the north slope of the Kailas, ivory, emeralds, possibly asbestos from Bactriana (we are prone to think that asbestos is the mysterious *bdellium* quoted in Genesis as a product of the land of Havilah), slaves. We can even conjecture that Moses, during his years in Madian, was in touch with the Panis, imported precious items from an India he knew well, and was possibly even in contact by letters with his family in Kush. Maybe by this way he was informed of the planned move of the Amu towards Egypt. And by this way he returned to Kashmir…
We can retrieve the meanings of Sefon given above as follows:

A – Shiva had his throne on Mount Kailas, in present Tibet, hence north of India, and precisely north of the first ridge of the Himalayas
B – Indians believed in metempsychosis certainly before the arrival of the Indo-Aryans, hence they would never kill insects like flies, who might have been reincarnations of their ancestors. In India even now there are temples dedicated to snakes or rats. Indians would not care if there were plenty of flies around, attracted by the butter offered to the statues of the gods and melting for the heat; flies were actually needed to clean the temples! The association of Shiva with flies would have been noted by Egyptian or Middle East mariners voyaging to India and reported back home as something very peculiar.

Another possible association of Baal Sefon is with *Baal Zebub*, a Cananean and Phoenician divinity that has been considered in devilish terms, and considered in later Hebrew thought to be a devil, second only to Satan. By similar acceptable phonetic changes as above we can transform Sefon into Zebub. The association with a devil is possibly due to the fact that many

Indian gods were represented with statues having features easily considered in the west as monster-like or devilish, as the three heads quoted for Shiva's statue in Elephantine, or the statues of Shakti, the mystical wife of Shiva that reincarnated 10 times as Kali and other goddesses, all shown in frightening form, with colliers of skulls, or without head, this kept in one hand…..As we noticed above, Phoenicians are probably related to the Pani, and Cananaeans, in Salibi's scenario, were 2000 km closer to India than Egypt, with good ports available in the southern part of the Red Sea (they would export especially incense, myrrha, and their extraordinary honey, even now sold at 100 dollars a litre…), hence they had probably adopted some gods of Indian origin.

Our interpretation of Baal Sefon as Shiva suggests now its location. The Panis, on their way to the northern side of the Red Sea, would meet before reaching the ports near Suez and Eilat, the Sinai peninsula, jutting out in the sea as a triangle having on one side the Gulf of Suez, on the other the Gulf of Aqaba. The vertex of the triangle may be considered now as the small peninsula named *Ras Muhammad.* Now *ras* means *head* in Arabic, geographically hence "promontory". *Muhammad* probably refers to the Prophet of Islam, indicating that a place before named according to a divinity of a non monotheistic religion, was renamed after the prophet of strict monotheism. Now it has been a very common procedure for ancient navigators to build on well visible promontories temples with statues of gods, to protect them from the perils of navigation. Examples in the Mediterranean are the Temple of Poseidon at Cape Sounion in Attica and the Temple of Hera Lacyna in Calabria; several temples on the coasts of the Atlantic and the Channel were quoted by Pytheas, see [17]. So, it is likely that the Pani used to build such religious buildings. It is unlikely that Baal Sefon had an important role for trade, unless the Ichtyophagoi were interested in some trade, being probably able to provide pearls and grey amber. They were anyway in small number, would not constitute a danger, hence the temple could be used as storage of precious objects (as was the case for many temples in antiquity). Thus the fact that Moses took away a large amount of gold is a possibility to be considered. Very likely Moses knew of the gold since his time at the court of the king and as an Egyptian military officer, not to say of his contacts with the Panis when he was in Madian. He may have been in good relations with the people in charge of the temple. So taking the long detour along the whole coast of the Sinai peninsula added the bonus of the gold in Baal Sefon to the security against the expected Amu.
From Baal Sefon Moses now moved along the Sinai coast facing the Aqaba Gulf. The place where he was reached by the Egyptian army (possibly aiming to recover the stolen gold; the horses and the chariots were probably taken there by boat, from the port in Egypt at present Mersa Gawasis, in use since the third millennium BC) is called in Exodus *Pi-Hahiroth*, translated with *epaulis* in the Greek Septuaginta, with *Domaine* in our French translation of the Septuaginta. Pi-Hahiroth may be a translation into Hebrew of an Egyptian word meaning *place of marshes*, thereby possibly indicating a flat area near the sea where some wadi could overflow in the rainy season, so a place with availability of water. This place was set between Bal Sefon, in the south, and *Migdol* in the north. From the considerations that we already gave, it was likely close to present Abu Nuweiba, where the mountains of the Sinai massif reach the sea leaving only a narrow passage. Here the trail had to leave the steep coast over for an inland passage by the Wadi Watir, then reaching the *desert of Shur by* a low pass. Under this identification Pi-Hahiroth would be about 140 km from Baal Sefon as the crow flies, a distance that in the clear air of the desert allows perfect visibility. North of Pi-Hahirot was Migdol, a name indicating a tower, or a fortified place. We think that Migdol was located either in the short stretch of coast between present towns of Eilat and Aqaba, or on the *Island*

of the Pharaoh (Jezirat Faraun), where there was most probably the main port used by the Panis to trade with Egyptians, Arabs and other populations. The island is the most likely location, because at Solomon time, some 500 years after the considered event, it was transformed into the important port of *Ezion Geber*, wherefrom ships went to Punt (Punjab, India) and to Ophir (Africa). Here recently the remains have been recovered of a ship dated at Solomon's time. Within our scenario it is clear that the return sea wave after the wind stopped destroyed everything at the end of the Aqaba Gulf, hence it is extremely unlikely that any archaeological remain may be found of structures dated at Moses time. Distance from Pi-Hahiroth to Migdol in our identification would be less than 100 km as the crow flies, allowing again full visibility.
After the passage of the landslide blockading his way, Moses most probably took the way leading to the desert of Shur by the way of Wadi Watir. This road was the natural choice, since following the coast, where there is a road now, was probably too difficult, if there was a road at that time, and moreover the tsunami that had destroyed the Egyptians certainly had greatly damaged any trail, making a passage probably impossible. We are presently unable to pinpoint the place (possibly *Ain el Furtaga*?) called *Mara* where bitter water was found, changed by Moses into sweet water, a fact whose explanation we leave also aside. After Mara, the Hebrew stopped at a place with 12 sources and 70 palms called *Elim*. It is quite natural to identify this place with the area under *Jebel Ghlim*, that is reached by a short deviation to the south from the way to the desert of Shur. Moses needed to stop a number of days in order to ascertain whether the Amu had already arrived and to evaluate the effects of the tsunami on his itinerary. We think that his battle and victory with Amalek once he reached the desert of Shur involved only part of the Amu, possibly the last group. He may also have wanted to visit again the place where the voice from the Burning Bush had spoken to him, that we think was indeed near where St Catherine monastery was built, some 50 km as the crow flies from Elim. Here a church was built around 330 AD by Flavia Elena, mother of Constantine, in a place where local monks pointed out what they believed was the remain of the Burning Bush.
Here we stop, since a fuller analysis of the geography of Moses movements until he left for Kashmir before the Hebrew began the attack to Canaan will be made hopefully in another work.

Appendix 3: mathematical problems related to the proposed scenario
The scenario described above needs, in addition to the historical concordances that we have provided, geological and mathematical confirmations. Here we do not deal with the geological problems involved (determination of tsunami evidence in the Baltic, North Sea, Mediterranean, Red Sea…; finding of soot layers of the type associated with the Usselo horizon, see Kloosterman [70]; sediments datable to volcanic dust from the Afar volcanoes in the Red Sea and in front of the Nile Delta…). We only briefly consider how mathematical modeling and computation might validate or disprove the proposed model.

It is certainly impossible to model the whole episode of the capture of a cometary/asteroidal type object as Phaeton was, according to our scenario, and especially of the several fragmentation episodes that must have taken place, with debris and dust perturbing the atmosphere and several pieces impacting oceans and continents. Also we do not know at what elevation, with what energy, from which direction, the object exploded over the Eider. But modeling the effects on the atmosphere of a large body colliding with Earth is possible. This task has been performed with increasing degree of precision in the last thirty years, some of the best results being due to the physicist Elisabetta Pierazzo, working in Arizona; see also [84] where the authors considered the impact of a 10 km sized object with particular interest to atmospheric effects (they found that a part of the atmosphere in the hole punched by the object gets escape velocity, hence leaves our planet; but not so much as to dangerously deplete the atmosphere). As we wrote before, atmospheric effects at some distance from the explosion point are represented mainly by a hot wind with possible long duration. In our case we are especially concerned not with the general effects but, in order to validate the historical reconstruction, with some specific local effects, namely:

A: duration of the wind in the Aqaba gulf, its temperature, its speed

B: how much the sea level lowered in the Aqaba gulf and how much it increased at the Bab el Mandeb exit of the Red Sea

C: how long did it take to the waters to return to Nuweiba and how tall was the wave front of the returning waters

D: how much the sea surged in front of northern Crete

E: how much the sea surged inside the Patras-Corinth gulf, especially in the area of Amphissa and Corinth

F: how much the sea surged over the coasts of Abruzzo, Molise, Puglia

G: how much the sea surged over the northern Mediterranean coast

H: how much the sea surged over the Baltic and North Sea coasts.

Such problems must be solved using as parameters height and energy of the explosion, which can be set without loss of generality over the mid course of the Eider. The equations (parabolic-hyperbolic partial differential equations with free boundary) are basically known and good albeit expensive solutions methods are available. Present computers are quite fast and possess big memory. A precise calculation requires to input data on the topography of the area around the explosion point for a radius of at least 5000 km, both pertaining to the bottom of the seas and the surface of the continents. A huge task (more than one billion data to be input) but a feasible one, of the greatest interest for the reconstruction of a crucial past event, and useful also to evaluate the effects of another not impossible event happening in our time!

Appendix 4. Who was Phaeton?

According to Greek myth, Phaeton was the son of Helios, usually considered to be the sun. From our scenario it was an object captured by Earth in an unstable orbit, subject to fragmentation episodes (which indicate that it had no great strength, otherwise it would have survived entering the Roche limit) and whose core finally entered the atmosphere on an almost tangential orbit, to explode over the Eider river. Size was probably at most a few km, say 2 or 3.

Now it is very unlikely that the object was in orbit around the Sun. It is in our opinion more likely that it was a satellite of another very luminous body, considered by man for a long time as a second Sun. In the light of the work of Velikovsky [8], De Grazia and Milton [9], Ackerman [27, 28] and others that we do not quote here, it may have been a satellite of the object, initially extremely shining and called Agni in the Rig Veda, then losing its brilliancy and called Varuna, and finally ending up as our still very hot planet Venus. This suggestion agrees with the text of Hesiod given in section 2, where Phaeton is said to have been stolen by Aphrodites, a goddess to be associated, as a planetary divinity, with Venus. According to myth Athena-Venus was born from the *head of Jupiter.* Ackerman has interpreted this legend as Venus being born from the hot gases escaping from Jupiter in the location where is now the Red Spot. Here a planetary size body impacted in his scenario, delivering energy of the order ten to 40 erg (versus the ten to 30 of the asteroid that formed the Chicxulub crater and killed the dinosaurs), at a time to be set between the end of the Ice Age and the Noachian Flood, the event being described in the Rig Veda. We think that Ackerman's theory is the most important contribution to the understanding of the recent past of our planetary system, after Velikovsky's *Worlds in Collision.* We would date the birth of Agni/Varuna/Venus at circa 7500 BC, the time of the seven catastrophes documented by the geologist and paleontologist Alexander and Edith Tollmann [85] of the University of Vienna. Of course if Velikovsky and Ackerman are correct, so are ancient texts, read with intelligence, but no so are most people in the academia, a very good reason not to consider V & A.

Acknowledgements.
This author thanks for discussion, comments and providing important documentary material: John Ackerman, Antonio Agriesti, Emanuele Anati, Flavio Barbiero, Marco Chioffi, Luce Ciullo, Stuart Harris (particularly), Gabriele Mandel, Michele Manher, S. Schaible, Felice Vinci. But especially we must remember Immanuel Velikovsky and Kamal Salibi: only standing on the shoulders of these giants it was possible to see the forest beyond tree.

References

1. Gregorio di Nissa, Vita di Mosé, Fondazione Valla, Mondadori, 1984.
2. Israel Finkelstein and Neil Asher Silberman, The Bible unearthed, archaeology's new vision of ancient Israel and the origin of the sacred texts, The Free Press, NY. 2001.
3. Mario Liverani, Oltre la Bibbia. Storia antica d' Israele, Laterza, 2004.
4. Giuseppe Ricciotti, Storia d' Israele, SEI, 1934.
5. Philon d' Alexandrie, De vita Mosis, Editions du Cerf, 1967.
6. Flavio Barbiero, La Bibbia senza segreti, Rusconi, 1988.
7. H.Goedicke, Exodus: the Ancient Egyptian evidence, communication, Memphis Exodus Symposium, April 23-25, 1987.
8. Immanuel Velikovsky, Worlds in collision,, Mc Millan, 1950.
9. Alfred De Grazia and Earl Milton, Solaria Binaria, Origins and History of the Solar System, Metron, Princeton, 1984.
10. Roland de Vaux, Histoire ancienne d' Israel, des origines à l' installation à Canaan, Lecoffre, 1986.
11. Emilio Spedicato, Galactic encounters, Apollo objects and Atlantis. A catastrophical scenario for discontinuities in human history, Episteme, 5, 215-247, 2002.
12. Immanuel Velikovsky, The floods of Deucalion and Ogyges, Chronology Review I,7, 1977.

13. Louis Ginzberg, The legends of the Jews, The Jewish Public. Society of America, 1925.
14. Giuseppe Flavio, Antichità Giudaiche, UTET, 1998 (translated by Luigi Moraldi).
15. Louis Ginzberg, Le leggende degli ebrei, IV Mosè in Egitto, Mosè nel deserto, Adelphi, 2003) (translated by Elena Loewenthal).
16. Orosio, Le storie contro i pagani, Fondazione Valla – Mondadori, 1976 (translated by Aldo Bartalucci).
17. Barry Cunliffe, The extraordinary voyage of Pytheas the Greek, Penguin Books, 2001.
18. Immanuel Velikovsky, Ages in Chaos, Sidgwick and Jackson, 1953.
19. Plato, Timaeus and Critias, translated by Desmond Lee, Penguin Books, 1977.
20. Luciano di Samosata, Dialoghi, Newton Compton, 1995 (Greek text with Italian translation).
21. Felice Vinci, Omero nel Baltico, Palombi, 1998.
22. Giovanni Semeraro, L’ infinito, un equivoco millenario, Bruno Mondadori, 2001.
23. Kamal Salibi, Secrets of the Bible people, Saqi Books, London, 1988.
24. Kamal Salibi, The Bible came from Arabia, Naufal, Beirut, 1996.
25. Kai Helge Wirth, The emergence of the constellation signs, Migration&Diffusion 3, 12, 2002.
26. Emilio Spedicato, Numerics of Hebrew worldwide distribution around 1170 AD according to Binyamin of Tudela, Migration & Diffusion 1, 6, 2000.
27. John Ackerman, Firmament, in www.firmament_chaos.com
28. John Ackerman, Chaos, in www.firmament_chaos.com
29. George Whetherill, Apollo objects, Scientific American, 240, 38, 1979.
30. Emanuele Anati, Esodo tra mito e storia: archeologia, esegesi e geografia storica, Studi Camuni XVIII, Centro Camuno di Studi Preistorici, Capo di Ponte, 1997.
31. Graham Phillips, Mosé, i fondamenti del racconto biblico: un’ indagine tra storia e mito, Sperling & Kupfer, 2002.
32. Michele Manher, L’ esodo degli Ebrei dall’ Egitto, Archeomisteri, IV, 29 14-25, 2005.
33. Jürgen Spanuth, Atlantis of the North, Book Club Associates, London, 1979.
34. Pistis Sofia, Luigi Moraldi curator, Biblioteca Adelphi 380, 1999.
35. R.A.Strelitz, Meteorite impact in the ocean, Proceeding of the Lunar Planetary Conference, 1979.
36. Ovidio, Le Metamorfosi, BUR Classici Greci e Latini, 1994.
37. Tilak, La dimora artica nei Veda, ECIG, 1994.
38. Fosco Maraini, Paropamiso, Corbaccio, 2002.
39. Ferdowsi, The Epic of Kings (Sha-Nama), Routledge&Kegan Paul (translated by Reuben Levy), 1967.
40. Emilio Spedicato, Eden revisited: geography, numerics and other tales, Migration&Diffusion 4, 16, 2003.
41. Emilio Spedicato, Geography and numerics of Eden, Kharsag and Paradise: Sumerian and Enochian sources versus the Genesis tale, Migration & Diffusion 5, 18, 2004.
42. Franco Cimmino, Sesostri, Rusconi, 1996.
43. Holger Kersten, Jesus lived in India, Element Book, 1986.
44. Mario Pincherle, La civiltà minoica in Italia. Le città saturnie, Pacini Editore, 1990.
45. Hesiode, Théogonie, les Travaux et les Jours, le Bouclier, Société d’ Edition Les Belles Lettres, 1964.
46. Emilio Spedicato, Tunguska-type impacts over the Pacific basin around the year 1178 AD, Chronology and Catastrophism Review 1, 8-13, 1988.
47. a) Edward Bryant, Tsunami, The underrated hazard, Cambridge University Press, 2001.
b) Alberto Arecchi, Atlantide, un mondo scomparso, un’ ipotesi per ritrovarlo, Liutprand, 2001.

48. Emanuele Anati, La datazione dell' arte preistorica camuna, Studi Camuni 1, 1978.
49. Emanuele Anati, Valcamonica, 10.000 anni di storia, Studi Camuni 8, 1980.
50. Stuart Harris, On the geography of Troy-Toja, to appear.
51. Victor Clube and Bill Napier, The cosmic serpent, Faber & Faber,1982.
52. Edwin Thiele, The mysterious numbers of the Hebrew kings, Kregel Publications, 1983.
53. J.Lempriere, A classical dictionary, Cadell and Davies, London, 1815 (first edition 1788).
54. Hendrik Bruins and Johannes van der Plicht, The Exodus enigma, Nature 382, 212-213, 1996.
55. W.D. Downey and D.H. Tarling, Archeomagnetic dating of Santorini volcanic eruptions and fired destruction levels of late Minoan Civilization, Nature 309, 519-523, 1984.
56. Annabel Walzer, Aurel Stein, pioneer of the Silk Road, Murray, 1995.
57. C.Brown and D.W. Hughes, Tunguska's comet and nonthermal C14 production in he atmosphere, Nature 255, 512, 1977.
58. Kenneth J. Hsu, La grande moria dei dinosauri, Adelphi, 1993.
59. Stuart Harris, email communication, 31 Dec 2004, 03:48:05, cc to Felice Vinci.
60. Stuart Harris, email communication, 6 Jan 2005, 01:25:11.
61. Stuart Harris, email communication, 30 Dec 2004, 03:26:32, cc to Felice Vinci.
62. Stuart Harris, email communication, 25 Apr 2005, 12:22:25.
63. Emilio Spedicato and Antonino del Popolo, On the reversal of the rotation axis of Earth, a first order model, Report DMSIA 04/6, University of Bergamo, 2004.
64. Pomponio Mela, Del sito dell' orbe, Siena, Tipografia San Bernardini (trnslated by Domenico Pavone), 1893.
65. Gabriele Mandel, La civilta' della valle dell' India, Sugarco, 1976.
66. Alain Daniélou, Dei e miti dell' India, BUR, 2002.
67. John Baines and Jaromir Malek, Atlas of ancient Egypt, Phaidon, 1958.
68. Emilio Spedicato, Who were the Hyksos? Chronology and Catastrophism Review 1, 55, 1997.
69. Robert Bass, email communication, 3 May 2005, 11:35:14-0400.
70. Johan Kloosterman, The Usselo horizon, a worldwide charcoal-rich layer of Alleroed, in Proceedings of the Conference on New scenarios on the evolution of the solar system and consequences on history of Earth and man, Milano and Bergamo, June 7-9th 1999, University of Bergamo (Emilio Spedicato and Adalberto Notarpietro edts.), 2002.
71. Pausanias, Guide of Greece, Fondazione Valla – Mondadori, 1995.
72. The Exodus revealed, Search for the Red Sea crossing. Discovery Media Productions, Video, 2002.
73. David Rohl, A test of time: the Bible from myth to history, Century, 1995.
74. Baldeo Sahai, Aryan Panis migrate to West Asia, Migration & Diffusion 3, 12, 2002.
75. A.S.Gaur, Ancient Dwarka: study based on recent underwater archeological investigations, Migration & Diffusion 6, 21, 56-77.
76. Aethicus Ister, Cosmographia, Lugd. Batavorum, Apud Hieronymum de Vogel, 1645 (to appear in translation by Emilio Spedicato).
77. Fosco Maraini, Segreto Tibet, Corbaccio, 1989.
78. Gianroberto Scarcia, Sifat-Nama-Yi Darvis Muhammad Han-I Gazi, ISMEO, Serie Orientale Roma XXXII, 1976.
79. Exodus: myth or history, Proceedings of a Seminar held at the Institute of Archaeology, London, 19th October 1993, ISIS Occasional Publications Series II (Mike Rowland editor), 1994.

80. Joscelyn Godwin, Arktos, the polar myth in science, symbolism, and Nazi survival, Thames and Hudson, 1993.
81. John Bimson, A chronology for the Middle Kingdom and Israel's Egyptian Bondage I: The Time of Joseph, SIS Review III, 1978; John Bimson, A chronology for the Middle Kingdom and Israel's Egyptian Bondage II: Israel in Egypt, SIS Review IV, 1979.
82. The Periplus Maris Erythraei, Princeton University Press (translated by Lionel Casson), 1976.
83. S.Master, A possible Holocen impact structure in the Al'Amarah marshes, near the Tigris-Euphrates confluence, southern Irak, Communication, 64-th Annual Meteoritical Society Meeting, 2001.
84. William Newman, Eugene Symbalisty, Thomas Ahrens and Eric Jones, Impact erosion of planetary atmospheres: some surprising results, Icarus 138, 224-240, 1999.
85. Alexander and Edith Tollman, Unt die Sintflut gab es doch. Vom Mythos zur historisches Wahreit, Droener Knaur, 1993.
86. Cosmas Indiocopleustes, Topographie Chrétienne, Vol. 2, Les Editions du Cerf, 1970 (translated by Wanda Wolska-Conu-Conus).
87. Emilio Spedicato. To new evolution theory of Earth and Solar System (Ice Ago–Atlantis–Moon–Nibiru–…) Int. Journal, Problems of nonlinear Analysis in Engineering Systems, v.18, No.2(38), 2012, 1-18.
88. Emilio Spedicato. From Nibiru to Tiamat, an astronomic scenario for earliest Sumerian cosmology. Int. Journal, Actual problems of aviation and aerospace systems: processes, models, experiment, v.18, No.2(37), 2013, 25-47.
89. http://interval.louisiana.edu/conferences/2007_Stenger/Slides_of_talks/mose8-6.pdf; http://pdf.future4.org/a-super-tunguska-event-circa-1447-bc-a-scenario-for-the-w31041/

This work is dedicated:

– to **Paulus Orosius**, whose neglected Historian Adverse Pagans gave the key to the proposed scenario;
– to **Giovanni Barbareschi**, whose lectures inspired this work;
– to **Nieves Hayat de Madarriaga**, for her encouragement in these researches.

Emilio Spedicato is professor of Operations Research at Bergamo University, Italy, having a degree in physics and a PhD obtained China in computational mathematics, the first ever in the math field given to a non-Chinese. In mathematics his main contribution has been leading the development of ABS methods that provide unification of a larger part of mathematics via a simple class of formulas. In this framework in collaboration with Prof. Nezam Ahmadi-Amiri he has obtained the general solution of Hilbert tenth problem in the most important solvable case. Having a special knowledge in geography and languages, his interests have extended also to other fields, like astronomy and even operatic music, where a book of 600 pages devoted to the stars of opera is due to appear soon. He has devoted over thirty years to the study of discontinuities within human memory, looking at their causes and their chronology. He has used ideas from Velikovsky, a great Russian scholar, and other people who followed him, especially Alfred De Grazia, reaching an apparently coherent scenario for the evolution of Earth and Solar system since about 12,000 BC.
emilio@unibg.it

The time-optimal control of motion of a spacecraft with inertial executive devices

M.V. Levskii

Research Institute of Space Systems,
Khrunichev State Research and Production Space Center
Tikhonravov street, 27, Yubilejny, Moscow region, 141091, Russia

The aspects of time-optimal control of spacecraft motion are discussed. A concrete problem of spacecraft terminal reorientation is solved. The case when spacecraft angular position is changed with the use of inertial actuators (for example, control powered gyroscopes) is considered in this research. Therefore the magnitude of spacecraft angular momentum is limited by some value which cannot be exceeded. The conditions of optimality are written, and the properties of optimal spatial turn are studied. Key relations and equations for optimal motion which specify the variation of rotation parameters are given. Results of mathematical simulation of spacecraft motion dynamics under the designed control method are presented.

Introduction

The problem of transferring a spacecraft from an initial oriented position to a position with an assigned orientation in the optimal manner is solved. Efficiency of means and methods of control of spacecraft motion, also including rotary motion, directly influences the efficiency of performance of target programs – it influences the volume of the executed tasks, conducted observations and experiments, accuracy of received results, active orbital lifetime and target application, etc. Design of optimal control algorithms for an onboard attitude control system of a spacecraft also remains very important. For example, spacecrafts for Earth remote sensing, monitoring, and also astrophysical and other scientific satellites demand periodic change of orientation to direct scientific devices and the target equipment onto interesting sites of a terrestrial surface or area of celestial sphere. The less is the propellant consumption for one maneuver of orientation change, the more reorientations can be performed by the spacecraft with the same stock of onboard fuel, and the greater volume of measurements will be executed, and hence the end-user of space system will receive more helpful information. Minimization of turn duration will increase time of observation and will improve conditions of their execution. Optimization of a reorientation mode (in the sense of maximum speed or minimum of spent resources) raises efficiency of spacecraft operation, and in some cases, it increases resource of spacecraft functioning on the operational orbit.

In numerous cases orientation control is carried out by inertial executive devices (in particular, powered gyroscopes or gyrodynes). This paper is devoted to finding the optimal program for the spatial reorientation of a spacecraft in the minimum time taking into account the constraint imposed on the angular momentum. The solved problem is fairly important for practice.

1. Equations of spacecraft motion and statement of the problem

Spatial reorientation is understood to be a shift of *OXYZ* coordinate system associated with the spacecraft body from one known angular position to another known (usually assigned) angular position in finite time *T*. In this case the parameters of the turn (for example, the components of the quaternion of the turn) are known a priori, before the beginning of the maneuver; the initial angular misalignments can take any value (from a few degrees to 180°). The angular orientation of the *OXYZ* right-handed rectangular system of coordinates (as well as its initial position $OX_{st}Y_{st}Z_{st}$ and final position $OX_fY_fZ_f$) is determined relative to the chosen

system of coordinates (the reference basis ***I***). In this paper, it is considered that the inertial coordinate system (ICS) is a basic (or reference) coordinate system.
The equations of angular motion of a spacecraft as a solid body look like:

$$J_1\dot{\omega}_1 + (J_3 - J_2)\omega_2\omega_3 = M_1 \ ,$$
$$J_2\dot{\omega}_2 + (J_1 - J_3)\omega_1\omega_3 = M_2 \ ,$$
$$J_3\dot{\omega}_3 + (J_2 - J_1)\omega_1\omega_2 = M_3$$

where J_i are the principal central moments of inertia of a spacecraft (i = 1, 2, 3), M_i are the projections of the moment of external forces onto the principal central body axis, ω_i are the projections of the absolute angular velocity vector $\boldsymbol{\omega}$ onto the axes of the body-fixed basis ***E*** formed by principal central axes of spacecraft's ellipsoid of inertia (i = 1, 2, 3).
For the description of spatial motion of a spacecraft around its center of mass, the mathematical apparatus of quaternions is used [1]. We specify the motion of a body-fixed basis ***E*** with respect to a reference basis ***I*** by quaternion Λ. To be specific, we will assume that the basis ***I*** is inertial. In this case, the kinematics of spacecraft motion is described by the following kinematic equations:

$$2\dot{\lambda}_0 = -\lambda_1\omega_1 - \lambda_2\omega_2 - \lambda_3\omega_3 \ , \qquad 2\dot{\lambda}_1 = \lambda_0\omega_1 + \lambda_2\omega_3 - \lambda_3\omega_2 \ , \tag{1}$$
$$2\dot{\lambda}_2 = \lambda_0\omega_2 + \lambda_3\omega_1 - \lambda_1\omega_3 \ , \qquad 2\dot{\lambda}_3 = \lambda_0\omega_3 + \lambda_1\omega_2 - \lambda_2\omega_1$$

or in a quaternion form: $2\dot{\Lambda} = \Lambda \circ \boldsymbol{\omega}$, where λ_j are the components of quaternion Λ, determining orientation of body axes relative to the inertial coordinate system (j = 0, 1, 2, 3), and quaternion Λ is normalized, $\lambda_0^2 + \lambda_1^2 + \lambda_2^2 + \lambda_3^2 = 1$.
Angular position of initial and final orientations of the spacecraft concerning basic basis ***I*** is defined by quaternions Λ_{st} and Λ_f respectively (quaternions Λ_{st} and Λ_f are normalized quaternions). Boundary conditions of spacecraft position and its angular velocity we shall set as:

$$\Lambda(0) = \Lambda_{st} \tag{2}$$
$$\Lambda(T) = \Lambda_f \tag{3}$$

and $\boldsymbol{\omega}(0) = \boldsymbol{\omega}_0$, $\boldsymbol{\omega}(T) = \boldsymbol{\omega}_T$, where T is time of a turn.
The problems when boundary values $\boldsymbol{\omega}_0 = \boldsymbol{\omega}_T = 0$, and the quaternions Λ_H and Λ_K, specifying orientation of spacecraft axes at the initial and final moments of time have any arbitrary values is practically important.
In general case, the problem of reorientation consists in moving the body coordinate system *OXYZ* from its initial angular position $\Lambda_{st} = \Lambda(0)$ into the required final position $\Lambda_f = \Lambda(T)$ during given time T in accordance with the differential equations (1). The following formulations of optimization problem are possible: turn of a spacecraft with the minimal expense of fuel during limited (given) time, turn during minimal time with two forms of restrictions – fuel consumption and angular momentum. For the spacecraft with inertial control facilities of orientation, the problem of spacecraft turn during minimal time is the most important. In the latter case, the index of an optimality (optimized functional) becomes:

$$G = \int_0^T dt \tag{4}$$

At control of spacecraft orientation using inertial actuators (for example, the control powered gyroscopes), the vector of the angular momentum should be in the given limited domain, the exit from which results in loss of spacecraft controllability. The magnitude of the angular momentum defines controlling opportunities of a gyro-system. We shall assume that the module of the vector of a spacecraft angular momentum cannot exceed some value H_0, i.e. the condition should be satisfied:

$$J_1^2\,\omega_1^2 + J_2^2\,\omega_2^2 + J_3^2\,\omega_3^2 \le H_0^2 \qquad (5)$$

where $H_0 > 0$ is a specified positive value.

We shall formulate the problem of optimal control as follows: it is necessary to transfer a spacecraft from the state (2) into the state (3) according to the equations (1) under restriction (5) and with minimal value of functional (4). The formulated problem is original.

When a constraint of the form (5) is imposed on spacecraft motion, the control problem stated is fairly important. The outcomes of its solution can be useful for developers of orientation systems for spacecraft equipped with gyroscopic mechanisms, i.e., gyrodynes. In this case, control of a spacecraft turn is achieved by redistributing the angular momentum between the system of gyroscopes and the spacecraft body [2]; the total angular momentum of the spacecraft as a rigid body with rotating masses is equal to or close to zero. The control of a system of gyrodynes in order to produce the programmed motion of a spacecraft by creating the necessary moments M_1, M_2, M_3 is a separate, independent problem (these problems are not considered here). We merely note that for an assigned turning regime to be realized without having to use other actuators (beside the gyrodynes), for example, jet engines, the total angular momentum of the gyro system must lie within the closed region S (it depends on the design characteristics), which determines the control possibilities of the gyro system, over the entire control interval $[0, T]$. During the development, analysis, refinement, and simulation of algorithms for the attitude control of a spacecraft with control powered gyroscopes, it is assumed that the region S of admissible angular momentum values of the system of control powered gyroscopes is confined to a sphere. This assumption has been used by many researchers; it is valid for a large number (if not the majority) of spacecrafts (such as the *Mir* orbital station, the *Gamma* astrophysical laboratory, the *Alpha* international space station and others). Since the use of control powered gyroscopes in a turning regime presumes that the total angular momentum of the gyro system would not exceed the admissible value, a constraint, which is formalized for the angular velocity vector, is imposed on the motion of the spacecraft. If the condition $\mathbf{L} + \mathbf{H} \approx 0$, where $\mathbf{L}$ is the angular momentum of the spacecraft body, and $\mathbf{H}$ is the angular momentum of the system of control moment gyroscopes, is taken into account, satisfaction of constraint (5) means that the evolution of the vector $\mathbf{H}$ of the gyro system during the spacecraft motion will satisfy the condition that it lies within a region confined by a sphere; therefore, the turn is performed using only the control powered gyroscopes (the vector $\mathbf{H}$ does not extend beyond this sphere region S without additional input to the action of the control thrusters).

The general case of a spatial turn (three-dimensional rotation of the spacecraft when Euler's axis does not coincide with one of the axes of body-fixed coordinate system) represents interest. Let us consider this case in more detail.

2. Solution of the problem of optimal control of spacecraft spatial reorientation

The formulated problem and synthesis of the optimal program of control must be solved using Pontryagin's principle of maximum [3]. For this purpose, we will enter the conjugate variables ψ_j $(j = 0, 1, 2, 3)$, corresponding to quaternion components λ_j. For criterion of an optimality (4), Pontryagin's function of the problem (Hamiltonian) $\varGamma$ has the form:

$$\varGamma = -1 + \varGamma_k + \varGamma_d\,,$$

where $\varGamma_k$ is the kinematical part, $\varGamma_d$ does not depend on kinematic parameters λ_j.

$$\begin{aligned}\varGamma_k = &-0.5\psi_0(\lambda_1\omega_1 + \lambda_2\omega_2 + \lambda_3\omega_3) + 0.5\psi_1(\lambda_0\omega_1 + \lambda_2\omega_3 - \lambda_3\omega_2) + \\ &+ 0.5\psi_2(\lambda_0\omega_2 + \lambda_3\omega_1 - \lambda_1\omega_3) + 0.5\psi_3(\lambda_0\omega_3 + \lambda_1\omega_2 - \lambda_2\omega_1).\end{aligned}$$

The equations for conjugate functions ψ_j look like:

$$\dot{\psi}_i = -\frac{\partial \Gamma}{\partial \lambda_j} \quad \left(j=\overline{0,3}\right).$$

The conjugate system of the differential equations will be written down in the following form:

$$\dot{\psi}_0 = -0{,}5(\psi_1\omega_1 + \psi_2\omega_2 + \psi_3\omega_3)\ , \quad \dot{\psi}_1 = 0{,}5(\psi_0\omega_1 + \psi_2\omega_3 - \psi_3\omega_2)\ , \tag{6}$$
$$\dot{\psi}_2 = 0{,}5(\psi_0\omega_2 + \psi_3\omega_1 - \psi_1\omega_3)\ , \quad \dot{\psi}_3 = 0{,}5(\psi_0\omega_3 + \psi_1\omega_2 - \psi_2\omega_1)\ .$$

After simple transformations of function Γ_κ we will receive

$$\Gamma_k = 0.5\omega_1(\lambda_0\psi_1 + \lambda_3\psi_2 - \lambda_1\psi_3 - \lambda_2\psi_3) + 0.5\omega_2(\lambda_0\psi_2 + \lambda_1\psi_3 - \lambda_2\psi_0 - \lambda_3\psi_1) +$$
$$+ 0.5\omega_3(\lambda_0\psi_3 + \lambda_2\psi_1 - \lambda_3\psi_0 - \lambda_1\psi_2) = 0.5(\omega_1 p_1 + \omega_2 p_2 + \omega_3 p_3)\ ,$$

where

$$p_1 = \lambda_0\psi_1 + \lambda_3\psi_2 - \lambda_1\psi_0 - \lambda_2\psi_3;$$
$$p_2 = \lambda_0\psi_2 + \lambda_1\psi_3 - \lambda_2\psi_0 - \lambda_3\psi_1;$$
$$p_3 = \lambda_0\psi_3 + \lambda_2\psi_1 - \lambda_3\psi_0 - \lambda_1\psi_2.$$

In order to reduce the order of the system, it is sufficient to assume that expressions p_1 , p_2 , p_3 represent projections of a certain vector **p** onto the axes of body-fixed basis $\boldsymbol{E}$. From the equations (6) it follows that the set of variables $\psi_0, \psi_1, \psi_2, \psi_3$ can be accepted as components of a certain quaternion Ψ for which the expression is true: $2\dot{\Psi} = \Psi \circ \boldsymbol{\omega}$. Then the introduced vector **p** can be written down in the quaternion form: **p** = vect ($\tilde{\Lambda} \circ \Psi$), and the kinematical part of function Γ becomes: $\Gamma_k = 0.5\ \boldsymbol{\omega}\cdot\mathbf{p}$.

Differentiating expressions for p_i $(i=\overline{1,3})$ and substituting the equations for λ_j and ψ_j $(j=\overline{0,3})$ into them, we shall receive the necessary differential equations. Variation of the vector **p** is determined by solving the system of equations:

$$\dot{p}_1 = \omega_3 p_2 - \omega_2 p_3, \quad \dot{p}_2 = \omega_1 p_3 - \omega_3 p_1, \quad \dot{p}_3 = \omega_2 p_1 - \omega_1 p_2 \tag{7}$$

or, in vector form,

$$\dot{\mathbf{p}} = -\boldsymbol{\omega} \times \mathbf{p} \tag{8}$$

where p_i are the projections of vector **p** onto the axes of the body-fixed basis $\boldsymbol{E}$.

The received differential equation (8) for a vector **p** reflects its rotation with respect to body-fixed basis $\boldsymbol{E}$ with angular velocity $-\boldsymbol{\omega}$. In its turn, the body-fixed basis $\boldsymbol{E}$ makes angular motion relative to basic basis $\boldsymbol{I}$ with angular velocity $\boldsymbol{\omega}$, hence the vector **p** is motionless in basic system of coordinates. Hence $|\mathbf{p}|$ = const, we assume further that vector **p** is normalized: $|\mathbf{p}| = 1$.

Thus, the problem of definition of optimal control is reduced to the solution of the system of equations of spacecraft angular motion and the equations (7) provided that control is chosen from a condition of Hamiltonian maximization. Thus the conjugate system of equations (6) is replaced with the system of equations (7) which determines the behavior of vector **p** concerning spacecraft-connected axes. The family of solutions $\mathbf{p}(t)$ is defined by initial Λ_{st} and final Λ_f positions of the spacecraft. Equality holds true: $\mathbf{p} = \tilde{\Lambda} \circ \mathbf{c}_E \circ \Lambda$, where $\mathbf{c}_E = \Lambda_{st} \circ \mathbf{p}(0) \circ \tilde{\Lambda}_{st}$ = const [1]. Boundary conditions Λ_{st} , Λ_f and conditions of a maximum of function Γ specify the required solution $\boldsymbol{\omega}(t)$. The direction $\mathbf{c}_E$ depends on initial and final positions of a spacecraft. But not only on the latter. To make the spacecraft have the required orientation at right end $\Lambda(T) = \Lambda_f$, it is necessary to determine the vector $\mathbf{c}_E$ (or the value of the vector **p** at the initial moment of time) so that moving along the solutions of system (1) one comes to the position Λ_f at the final time $t = T$.

We consider the projections of angular velocity ω_i ($i=\overline{1,3}$) as controlling variables (controls). In result, from an original problem of control, the kinematical problem of spacecraft reorientation is naturally allocated. Solving this problem (finding characteristic trajectories of spacecraft motion), we remove restrictions for dynamic variables M_i, $\dot{\omega}_i$ (they are considered insignificant), and the problem of optimal control of spacecraft spatial turn is solved in impulse formulation. In this case, dimension of optimization problem is reduced from $n=7$ to $n=4$ (even down to three since $\|\Lambda\|=1$ and $\|\psi\|=\text{const}\neq 0$) and its solution becomes considerably simpler. Accepting that the problems of imparting the required angular rate and damping of actual angular rates have been solved, the original problem of optimal control is reduced to a presence of control function $\boldsymbol{\omega}(t)$ inside an interval of time between phases of acceleration and braking, which minimizes the functional (4) taking into account the inequality (5). Then Pontryagin's function Γ of a problem takes a form: $\Gamma = -1 + \Gamma_k = -1 + 0.5\,\boldsymbol{\omega}\cdot\mathbf{p}$.

The necessary condition of an optimality will be written down as: $\Gamma_k \to \max$. The equations (1) together with boundary conditions (2), (3), restriction (5) and the requirement of maximality of function Γ_k form a closed constrained extremum problem. To derive the equations describing the optimal decision, we shall enter new variables: $L_i = J_i\,\omega_i$ and $\mu_i = p_i / J_i$. Then we receive $\Gamma_k = (L_1\mu_1 + L_2\mu_2 + L_3\mu_3)/2$. Obviously, $\Gamma_k \to \max$ under the condition $L_1^2 + L_2^2 + L_3^2 \le H_0^2$, when vectors $\mathbf{L}=\{L_1, L_2, L_3\}$ and $\boldsymbol{\mu}=\{\mu_1, \mu_2, \mu_3\}$ have an identical direction. Thus equations hold true:

$$L_i = \frac{H_0 p_i}{J_i\sqrt{p_1^2/J_1^2 + p_2^2/J_2^2 + p_3^2/J_3^2}}\,,$$

whence $p_i = k\,J_i^2\,\omega_i$ ($i=\overline{1,3}$).

Optimal motion of the spacecraft is completely determined by the system of the differential equations:

$$\dot{\mathbf{p}} + \boldsymbol{\omega}\times\mathbf{p} = 0 \quad \text{and} \quad \omega_i = \frac{H_0 p_i}{J_i^2\sqrt{p_1^2/J_1^2 + p_2^2/J_2^2 + p_3^2/J_3^2}} \qquad (9)$$

with boundary conditions $\Lambda(0)=\Lambda_{st}$, $\Lambda(T)=\Lambda_f$ for solution $\Lambda(t)$ of the system (1).

The problem of constructing an optimal control consists in finding such value of vector $\mathbf{p}(0)$ that the equality $\Lambda(T)=\Lambda_f$ is executed as a result of spacecraft rotation according to the equations (1), (7), (9). It is almost impossible to find the common solution of the resulting system of equations. The difficulty consists in definition of boundary values $\mathbf{p}(0)$ and $\mathbf{p}(T)$ which are connected among themselves by the equality:

$$\mathbf{p}(T) = \tilde{\Lambda}_f \circ \Lambda_{st} \circ \mathbf{p}_o \circ \tilde{\Lambda}_{st} \circ \Lambda_f = \tilde{\Lambda}_t \circ \mathbf{p}(0) \circ \Lambda_t\,,$$

where $\Lambda_t = \tilde{\Lambda}_{st} \circ \Lambda_f$ is quaternion of turn.

Presence of restrictions on control moment $\mathbf{M}$ makes impossible the instant change of angular velocity $\boldsymbol{\omega}$ to the required value (imparting of calculated impulse at the beginning of a turn and damping of actual rate down to zero at the moment of arrival of spacecraft orientation into the given position), which leads to some increase of maneuver time T because of occurrence of acceleration stage and braking stage. Maneuver of a turn will consist of spacecraft acceleration till the necessary angular momentum, spacecraft rotation with a constant angular momentum and damping of angular rate. The required solution $\boldsymbol{\omega}(t)$ at the phase of nominal motion (between acceleration and braking) possesses the properties:

$$J_1^2\omega_1^2 + J_2^2\omega_2^2 + J_3^2\omega_3^2 = R = \text{const}\,,$$
$$J_1^4\omega_1^2 + J_2^4\omega_2^2 + J_3^4\omega_3^2 = D = \text{const}$$

Optimal turn of a spacecraft in minimal time occurs with the maximum possible angular momentum. An increase and damping of spacecraft angular rate are performed maximally quickly (using powerful enough engines of orientation system, time of reaching a steady-state regime $|\mathbf{L}| = H_0$ and braking time down to $\boldsymbol{\omega} = 0$ are negligible). Actual limitation of control opportunities $\dot{\omega}_i$ (or M_i) does not qualitatively change behavior of motion trajectory $\Lambda(t)$. The basic relation for the considered way of turn remains: $\omega_i = b(t) \cdot p_i / J_i^2$, and $b(t) \geq 0$, where $b(t)$ is scalar function of time (and between acceleration and braking phase $b = \text{const}$). Construction of optimal program of control $\boldsymbol{\omega}^*(t)$ is reduced to the choice of appropriate variation of value $b(t)$. Obviously, minimal time T is reached under minimal times of acceleration t_{ac} and braking t_{br} . For this purpose, at stages of acceleration and braking, the module of acceleration $\dot{b}$ should be maximal $|\dot{b}| \to \max$. Regime of acceleration to required angular rate and braking regime are determined basically by the type of used means of attitude control. In any case, at these phases the control moment **M** has the largest possible value and it also provides minimal time of achievement of the programmed value of spacecraft angular momentum (or damping of the real angular momentum down to zero), thus rotation of the spacecraft takes place with the maximal angular acceleration. At the stage of nominal motion (between acceleration and braking), the value $b(t)$ is the largest possible also, and it is determined by restriction (5), which is imposed on the control function $\boldsymbol{\omega}(t)$. The calculated values of the control moments can be determined from the condition of spacecraft motion along the given kinematic trajectory by the solution of an inverse problem of dynamics.

$\mathbf{M} = J^{-1} \cdot (\dot{b}\, \mathbf{p} - \boldsymbol{\omega} \times (J^2 \cdot \boldsymbol{\omega})) + \boldsymbol{\omega} \times (J \cdot \boldsymbol{\omega})$, where $J = \text{diag}(J_1, J_2, J_3)$ is the tensor of inertia.

Vectors $\mathbf{p}$ and $\boldsymbol{\omega}$ are the solution of the system of equations:

$$b \cdot \mathbf{p} = J^2 \cdot \boldsymbol{\omega} \quad \text{and} \quad \dot{\mathbf{p}} = -\boldsymbol{\omega} \times \mathbf{p}\,; \;\; b(t) \geq 0.$$

For a widespread case when boundary conditions $\boldsymbol{\omega}(0) = \boldsymbol{\omega}_0 = 0$, $\boldsymbol{\omega}(T) = \boldsymbol{\omega}_T = 0$, at the initial and final moments of time $b = 0$. The longest is the time during which $b(t) = b_{\max}$. The approximate form of the program of variation of function $b(t)$ is shown in Fig.1, where $b_{\max} = \max b(t)$. To find time-optimal control, $b_{\max}$ value is determined by restriction (5) for the vector of angular velocity $\boldsymbol{\omega}$.

$$b_{\max} = H_0 (p_1^2 / J_1^2 + p_2^2 / J_2^2 + p_3^2 / J_3^2)^{-0.5}.$$

At the phases of acceleration and braking, the spacecraft rotation takes place with the maximal acceleration: $|\dot{b}| \to \max$. Concrete value $\dot{b}$ is determined by control opportunities of the spacecraft, i.e. it follows from the requirement $\mathbf{M} \in \mathrm{U}$, where U is the acceptable region of the control moment. For the acceleration phase $\dot{b} > 0$, for the braking phase $\dot{b} < 0$. The value $\dot{b}$ is such that the vector **M** turns out to be at the border of area U.

Let us assume that the acceptable region of **M** is limited to the sphere $|\mathbf{M}| \leq m_0$. Then the value $\dot{b}$ is determined by solution of the equation:

$$|J^{-1} \cdot (\dot{b}\, \mathbf{p} - \boldsymbol{\omega} \times (J^2 \cdot \boldsymbol{\omega})) + \boldsymbol{\omega} \times (J \cdot \boldsymbol{\omega})| = m_0 \tag{10}$$

for known $\boldsymbol{\omega}$ (and $b(t)$). There exist two values $\dot{b}$ that satisfy the equation (10): one positive $\dot{b}_1 > 0$ (it corresponds to further acceleration), another is negative $\dot{b}_2 < 0$ (it corresponds to the subsequent braking). The analysis of the equation (10) demonstrates that value $|\dot{b}|$ decreases with growing $b(t)$. For $b = 0$, we have $|\dot{b}_1| = |\dot{b}_2|$ (i.e. $\dot{b}_2 = -\dot{b}_1$), value $|\dot{b}|$ is maximal; for $b = b_{\max}$ (at the borders of a segment of nominal rotation) value $|\dot{b}|$ is minimal. For the general case, $|\dot{b}_1| \neq |\dot{b}_2|$.

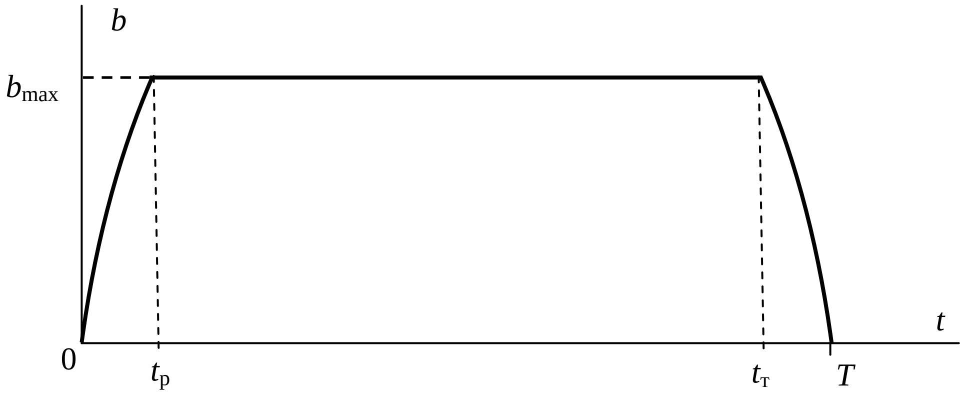


Fig. 1. The behavior of function $b(t)$

The required program of spacecraft turn from initial Λ_{st} into the given angular position Λ_f during time T is provided by maintaining the programmed angular velocity of spacecraft rotation with high accuracy. Application of the systems constructed according to a principle of acceleration management is the best to achieve this purpose [4]. They possess increasing dynamic properties, accuracy, adaptability and robust property which are especially necessary to tryout the calculated kinematics of spacecraft rotation.

For a spacecraft with axial symmetry ($J_2 = J_3$) the solution can be found in an analytical form. Optimal motion of a spacecraft is in a class of its simultaneous rotation as a solid body around a longitudinal axis OX and around some direction $\boldsymbol{\eta}$, which is motionless in inertial space and makes a certain angle ϑ with the longitudinal axis of a spacecraft. For the case of regular precession, relation $e^{\mathbf{p}_o \beta/2} \circ e^{\mathbf{e}_1 \alpha/2} = \tilde{\Lambda}_{st} \circ \Lambda_f$ is true, where $\mathbf{p}_0 = \mathbf{p}(0)$, and $\mathbf{e}_1$ is an ort of longitudinal axis of a spacecraft; α, β are turn angles of spacecraft around longitudinal axis and around vector $\mathbf{p}$, respectively. Let us find the solution of problem when $|\mathbf{L}| = \text{const}$. The solution $\mathbf{p}(t)$ necessary for synthesis of optimal control can be written down as:

$$p_1 = p_{10} = \cos\vartheta,\ p_2 = \sin\vartheta \sin(\dot{\alpha} t + \sigma),\ p_3 = \sin\vartheta \cos(\dot{\alpha} t + \sigma),$$

where $\sigma = \operatorname{arctg}(p_{20} / p_{30})$.

Programmed values of projections of angular velocity vector $\boldsymbol{\omega}^*$ onto the spacecraft axes will be the following:

$$\omega_1^* = \omega_{10} = \dot{\alpha} + \dot{\beta}\cos\vartheta,\ \omega_2^* = \dot{\beta} p_2 = \dot{\beta}\sin\vartheta \sin(\dot{\alpha} t + \sigma),\ \omega_3^* = \dot{\beta} p_3 = \dot{\beta}\sin\vartheta \cos(\dot{\alpha} t + \sigma).$$

Then $\Gamma_k = 0.5\,\omega_{10}\, p_{10} + 0.5\,\dot{\beta}\,(p_2^2 + p_3^2)$, and conditions of an optimality will become:

$$J_1^2(\dot{\alpha} + \dot{\beta}\cos\vartheta)^2 + J_2^2 \dot{\beta}^2 \sin^2\vartheta = H_0^2,\quad \dot{\alpha}\cos\vartheta + \dot{\beta} \to \max.$$

Here $\alpha = \dot{\alpha} T$, $\beta = \dot{\beta} T$.

Optimization consists in definition of such angles ϑ, α and β, under which the expression $(\alpha\cos\vartheta + \beta) / T$ has a maximum (and time of turn T is minimal) [5]. Angles ϑ, α and β are connected by equations:

$$\cos\frac{\beta}{2}\cos\frac{\alpha}{2} - \cos\vartheta\sin\frac{\beta}{2}\sin\frac{\alpha}{2} = \nu_o,\quad \cos\frac{\beta}{2}\sin\frac{\alpha}{2} + \cos\vartheta\sin\frac{\beta}{2}\cos\frac{\alpha}{2} = \nu_1$$

where ν_0, ν_1 are components of turn's quaternion $\Lambda_t = \tilde{\Lambda}_{st} \circ \Lambda_f$.

Thus, minimal time of a turn under the limited value of the angular momentum is achieved, if spacecraft makes precession around some axis $\boldsymbol{\eta}$, motionless in inertial space, and its longitudinal axis which is inclined relative to axis $\boldsymbol{\eta}$ with a calculated angle of nutation. For a special case when $J_1 = J_2 = J_3$, the solution $\boldsymbol{\omega}^*(t) = \{\alpha + \beta p_1,\ \beta p_2,\ \beta p_3\}$ comes to a particular solution $\boldsymbol{\omega} = \beta\,\mathbf{p}$ which corresponds to the spacecraft turn around the Euler axis ($\alpha = 0$).

To implement the described method of reorientation control, it is necessary to know the value of angle γ of a turn which should be made and also the current values of angular mismatch φ and angular velocity ω during the turn. Only having these data, the system of orientation can produce commands to stop acceleration and start braking at the necessary moments of time so that by the moment when turn through the angle γ is made, the spacecraft is stopped completely ($\boldsymbol{\omega} = 0$). The knowledge of current values of φ and ω is desirable also for improvement of quality of transition from rotary motion to the state $\boldsymbol{\omega} = 0$. Assuming that the restriction of controls is $| L | \leq m$, and considering the law of angular rate variation during the stage of angular velocity damping to be linear, we shall receive a condition for the beginning of braking:

$$\int_0^T (|\omega_1| + \sqrt{\omega_2^2 + \omega_3^2})dt + (|\omega_1| + \sqrt{\omega_2^2 + \omega_3^2})\tau / 2 = \theta$$

where $\theta = |\alpha + \beta\cos\vartheta| + \beta\sin\vartheta$, and $\tau = H_0 / m$ is the time of braking; $L = |\mathbf{L}|$ is a magnitude of spacecraft angular momentum. Similar criterion was applied in [6].

To define the start moment of braking more accurately, it is necessary to control the motion of the spacecraft not only over angular velocity $\boldsymbol{\omega}$, but also over the angle left before the final position is reached. The criterion for forming the signal for braking start is the following:

$$(|\omega_1| + \sqrt{\omega_2^2 + \omega_3^2})\,\tau = 2\theta\,\varphi / \gamma$$

where $\gamma = 2\arccos(\mathrm{sqal}\,(\tilde{\Lambda}_{st} \circ \Lambda_f))$, $\varphi = 2\arccos(\mathrm{sqal}\,(\Lambda \circ \tilde{\Lambda}_f))$.

The received control is almost-optimal (or suboptimal) due to linear character of variation of module of spacecraft angular momentum L at the stages of acceleration and braking. Such law of formation of spacecraft rotary motion is supported compulsorily by generation of the control moments. For such law of increase and decrease of angular momentum, the control moment is maximal only at borders of transitional sectors, and it does not allow to speak about an absolute optimality of the received solution.

3. Results of mathematical simulation

As an example, we give the numerical solution of an optimal control problem for a spacecraft programmed turn during minimal time T. The calculated value of vector $\mathbf{p}_0$ resulted from the solution of a kinematic problem of orientation of spacecraft moving from position $\Lambda(0) = \Lambda_{st}$ into position $\Lambda(T) = \Lambda_f$. Results of mathematical modeling of process of a turn under optimal control are submitted graphically. Time variation of angular velocities in a body-fixed coordinate system $\omega_1(t)$, $\omega_2(t)$, $\omega_3(t)$ is plotted in Fig.2. The figure clearly shows splitting of the whole turn into three characteristic stages: acceleration (increase of angular rate), rotation of a spacecraft with the maximal allowable angular momentum and braking of a spacecraft (decrease of angular velocities down to zero). Fig.3 illustrates the dynamics of time variation of the coordinates $p_1(t)$, $p_2(t)$, $p_3(t)$. A characteristic feature here is the insignificant variation of the projection p_1 (the component of angular velocity ω_1 also has almost constant value at the section between acceleration and brake). This testifies that OX is the longitudinal axis. And, finally, the plots of variation of the components $\lambda_0(t)$, $\lambda_1(t)$, $\lambda_2(t)$, $\lambda_3(t)$ of quaternion $\Lambda(t)$ which determines the current orientation of a spacecraft during executed rotary maneuver, are shown in Fig.4. The variables p_i and λ_i are smooth functions of time unlike the variables ω_i.

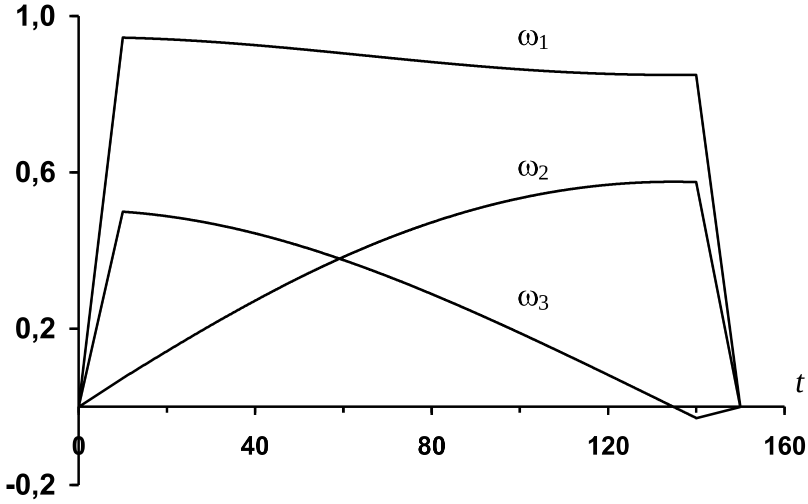


Fig. 2. Optimal variation of programmed angular velocities

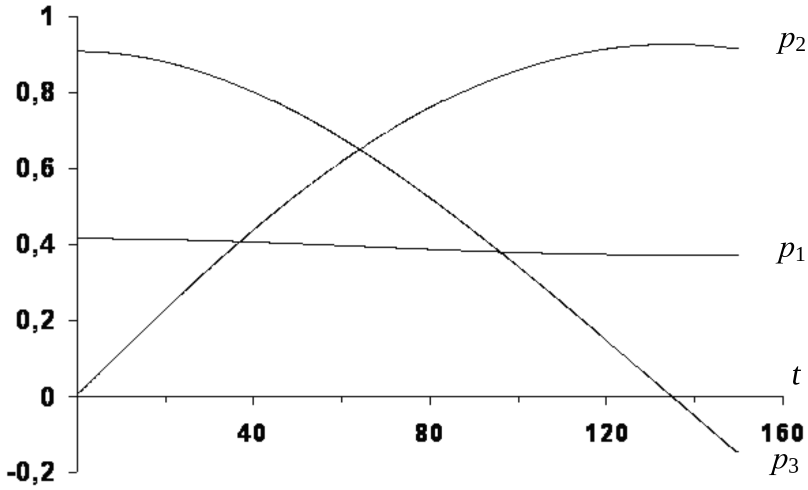


Fig. 3. The components of vector **p** as time functions

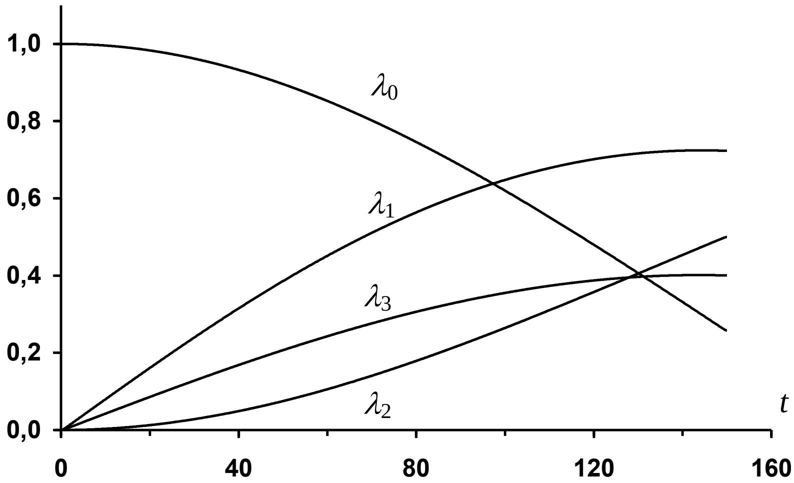


Fig. 4. Variation of the parameters of attitude during a turn

Conclusions

Here the problem of spacecraft motion from initial angular position to a given angular position is solved. The turn time is minimized. An interesting case is considered, when the value (module) of spacecraft angular momentum is limited. Properties of optimal motion during a spatial turn are investigated.

The control powered gyroscopes (CPGs) often act as actuators of a spacecraft orientation system. Their use in the turning regime requires that the total angular momentum **H** of the gyro system does not exceed the admissible value. Control by powered gyroscopes (by a system of gyrodynes) that create a moment **M** for producing the required programmed motion of the spacecraft about the centre of mass (in accordance with dynamical Euler equations) is an independent problem. These issues, as well as issues concerning the accuracy of the determination of the optimal moment **M**, allowing for the dynamics of the control gyroscopes, are not considered here. In most cases, the region S of admissible values of the angular momentum of a system of CPGs, intended for attitude control of a spacecraft, is confined to a sphere of radius H_{ad} with its centre at the origin of the attached system of coordinates $Oxyz$, where $H_{\text{ad}} > 0$ is the maximum admissible magnitude (absolute value) of the total angular momentum of the system of CPG actuators. “Saturation” of the system of CPGs, i.e. achievement of the boundary of the region S of admissible values by the angular momentum of the CPGs, starts from the time when the equality $|\mathbf{H}| = H_{\text{ad}}$ is satisfied. Further attitude control using only CPGs is impossible, and “unloading” of the CPG system is necessary. To make a spacecraft turn maneuver possible over the entire time interval $0 \le t \le T$ without the need for “unloading” the CPGs, satisfaction of the condition $|\mathbf{L}| \le H_0$ is required, where H_0 is an assigned constant, $0 < H_0 < H_{\text{ad}}$. Such spacecraft motions are considered to be admissible (for turns without “unloading” the CPGs). The difference $H_{\text{ad}} - H_0$ guarantees the absence of the angular momentum of the CPG system outside the region S of admissible values. It explains the presence of constraint (5) and the applied value of solution.

The necessary conditions of optimality for a spacecraft reorientation regime have been written in analytical form. It is shown that the optimal solution belongs to a class of regular motions that are close to the precession of a rigid body around a certain axis fixed in inertial space. In the general case (a turn from a state of rest to another state of rest), a spacecraft reorientation maneuver is divided into three characteristic phases: acceleration to the maximum admissible angular momentum, rotation with the maximum magnitude of the angular momentum, and decrease of the angular velocity to zero. During acceleration and stopping, the control moment has the maximum possible magnitude; at the phase between starting and stopping, spacecraft rotation takes place with a constant (maximum admissible) module of the angular momentum, and the control moment is determined by the solution of an inverse problem of dynamics (using calculated programmed velocity vector). The designed method can be easily implemented by spacecraft motion control systems. The offered algorithm of spacecraft reorientation control under the limited value of the angular momentum allows to considerably (from 20–30 percent and more) reduce a time of a turn. The greatest effect is reached when a turn is performed through large angles and the vector of final turn does not lie in the transversal plane of a spacecraft. The synthesized algorithm for controlling spatial spacecraft orientation enables us to apply this method in practice.

References

1. V.N. Branets, and I.P. Shmyglevskii. Use of quaternions in problems of orientation of solid body. Moscow: Nauka, 1973. (in Russian)
2. B.V. Raushenbakh, and E.N. Tokar'. Spacecraft attitude control. Moscow: Nauka, 1974. (in Russian)
3. L.S. Pontryagin, V.G. Boltyanskii, R.V. Gamkrelidze, and E.F. Mishchenko. Mathematical theory of optimal processes. Moscow: Nauka, 1983. (in Russian)
4. P.D. Krut'ko. Inverse problems of the dynamics of control systems. Nonlinear models. Moscow: Nauka, 1988. (in Russian)
5. M.V. Levskii. A system for determining the parameters of the regular precession of solid body. The patent for the invention of Russian Federation No. 2103736. // Bulletin of «Inventions. Applications and patents», 1998, No.3. (in Russian)
6. M.V. Levskii. A method of controlling the turn of a spacecraft. The patent for the invention of Russian Federation No. 2093433. // Bulletin of «Inventions. Applications and patents», 1997, No.29. (in Russian)

Mikhail Valer'evich Levskii, Candidate of engineering sciences, senior researcher; leading researcher of Khrunichev State Research and Production Space Center (Research Institute of Space Systems, Moscow region). Published more than 120 scientific papers, author of 25 inventions and patents, awarded by S.P.Korolev Prize, International Teacher of 2007; represented in Marquis Who's Who family (9th and 10th Anniversary Editions of **Who's Who in Science and Engineering**, 25th Silver Anniversary Edition of **Who's Who in the World**, and **Who's Who in the World** 2009). He is a specialist in the area of control theory and automatic control systems and devices. Area of scientific interests: mechanics of space flight, theory of systems of attitude control, navigation and stabilization of flying vehicles, motion around a center of mass of spacecrafts, booster units and orbital stations.

The reusable towing aerospace system for cargo transportation from near-Earth orbit

V.A.Afanasyev, A.S.Meshchanov, E.Yu.Samysheva
South Ural State University (affiliated societies in the city of Miass
Kazan National Research Technical University named after A.N. Tupolev – KAI
K.Marx 10, Kazan, 420111, Russia

This article presents results of research carried out by authors on a project concerning creation of a reusable towing aerospace system to quickly deliver cargoes from orbit to Earth. Two versions of the system have been considered: a version with three segments including a space towing vehicle, a reentry space vehicle and an air towing vehicle making soft vertical touchdown; the second version adds the first one by the forth segment that is a moving platform going along a runway for soft horizontal landing of the air towing vehicle. The effective algorithm has been obtained for stabilization of its longitudinal program motion under uncertain disturbances. Results are shown which significantly improve readings of a thermo-anemometric sensor measuring aerodynamic angles during their typical and no typical changes and taking into uncertain disturbances for the reentry space vehicle and air towing vehicle.

1. Introduction

Authors of this paper have presented research results of a project concerning creation of a towing aerospace system (TASS). It is a reusable transportation system for quickly returning cargos from international space station (ISS) to Earth. Mathematical description is developed for dynamics and control of a space towing vehicle (STV) with a solid propellant motor (SPM) equipped by removal powder charges. The STV produces deceleration impulse for deorbiting together with a reentry space vehicle (RSV) and then it returns to ISS orbit. Mathematical programming was carried out for angular motions, synthesis of control law was made by using feedback and an algorithm was suggested for identification of the SPM operational characteristics. Dynamics of angular motion and control were investigated for a RSV that during atmospheric descent has the unique rotation-precession properties in addition to its maximal aerodynamic drag. A flight problem was studied for a RSV that reduces its velocity to required values along ricochet trajectories. Mathematical programming of trajectories was carried out for rendezvous of an air towing vehicle (ATV) with RSV in the form of acceleration – deceleration by using some model systems. Algorithms of multi-step terminal control (MTC) were synthesized [1, 2].

In the first version of TASS the ATV after docking with RSV performs soft vertical touchdown by using the thrust forces of the same engines for deceleration values of which are regulated by algorithms developed on the base of the MTC method [3].

In the second version of TASS the ATV in the form of a two-body rocket with tail horizontal units performs the horizontal landing on a movable platform that with the ATV simultaneously moves along a runway. Some engineering decisions were found and kinematical parameters were determined for the landing. This TASS consisting already of four segments (STV, RSV, ATV, movable platform) improves performance specifications and reduces the cost per a kilogram of returned cargos still more. Effective algorithms were developed for stabilization of ATV program longitudinal motions.

On the base of digital simulation of flight for all segments of TASS with the developed control algorithms we have obtained the initial data for conceptual designing of all segments. Some characteristics were chosen for the propulsion systems as the main systems in the TASS. The presented numerical data are suggested to be used for subsequent designing and

more precise definition of mass and all-dimensional characteristics of the TASS segments. Methods and means were proposed for significant improvement readings of a thermo-anemometric sensor that measures aerodynamic angles of RSV and ATV at sliding modes during typical and no typical changes of angle of attack taking into account uncertain disturbances. Results have been obtained from simulation of measurement processes.
This topic was supported by Russia fund of fundamental research (09-01-97000).

2. Main part

Space is of great interest as before. Many countries increase their capital investment to settle it. The most outstanding achievement of the world association is the international space station (ISS) serviced by United State’s and Russian Federation’s fleets of space vehicles.
However a tragedy with American space shuttle Columbia happened February 1, 2005, has given us irrefutable evidence once more that it is necessary to develop a reliable space transportation system of the new generation.
That so, conceptual principles to develop a new and reusable towing aerospace system (TASS) for transportation of cargoes from ISS orbit to the Earth are suggested and researches are carried out on development of control algorithms used in designing and operations with TASS.
Originally the TASS consists of three segments which function independently and subsequently complement each other: a space segment (STV), a aerospace segment (RSV) and an air segment (ATV).
The space segment, or STV, constantly parks to ISS and waits a command to quickly descend with a cargo to the Earth. After this command STV generates a deceleration impulse after which the necessary reentry conditions are formed. After separation of a reentry space vehicle (RSV) the STV makes itself an acceleration impulse to return to ISS and wait the next RSV.
The main structural elements of the STV are shown in Figure 1, where corresponding numbers designate the following main elements of the STV structure: 1 is a swivel nozzle of a solid propellant motor (SPM), 2 is solid propellant motor (SPM), 3 is equipment of the control system (CS), 4 is reentry aerospace vehicle (RSV).
Two coordinate systems are introduced. The first coordinates $oxyz$ are connected with STV, its origin is in the STV center of mass (point o), axis ox is along the longitudinal axis to the its nose, axis oy is coincided with vertical axis of normal coordinate system in initial state, axis oz makes these three axes to be right coordinates. The second coordinates $o_p x_p y_p z_p$ are connected with the swivel nozzle, its origin o_p is in the nozzle swivel point The axis’s directions of coordinate systems $o_p x_p y_p z_p$ are coincided with axis’s directions of coordinate systems $oxyz$ in neutral position. So that, $oxyz$ and $o_p x_p y_p z_p$ are named as connected and swivel coordinates respectively.
A position of the swivel nozzle (or coordinates $o_p x_p y_p z_p$) relatively the connected with STV coordinates is determined by two independent angles: $\delta_\vartheta, \delta_\psi$. For the positive directions of read for angles $\delta_\vartheta, \delta_\psi$ are take appropriate directions of the nozzle swivel around axis’s $o_p z_p$ and $o_p y_p$ counterclockwise. A signs of vector projections P for control forces P_y and P_z, arising during deflection of the nozzle on angles $\delta_\vartheta, \delta_\psi$, are considered as positive if

forces act along directions of appropriate axis's of the connected coordinates. Kinematical connection between the connected and swivel coordinates is shown in Figure 2.

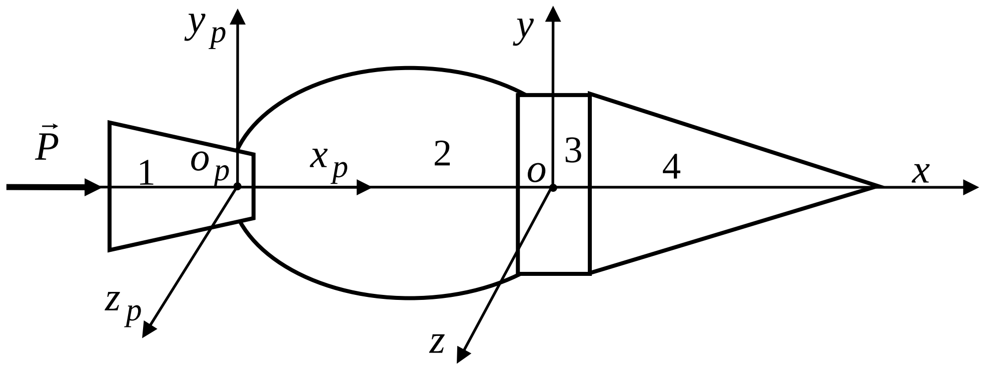


Figure 1. STV structural diagram

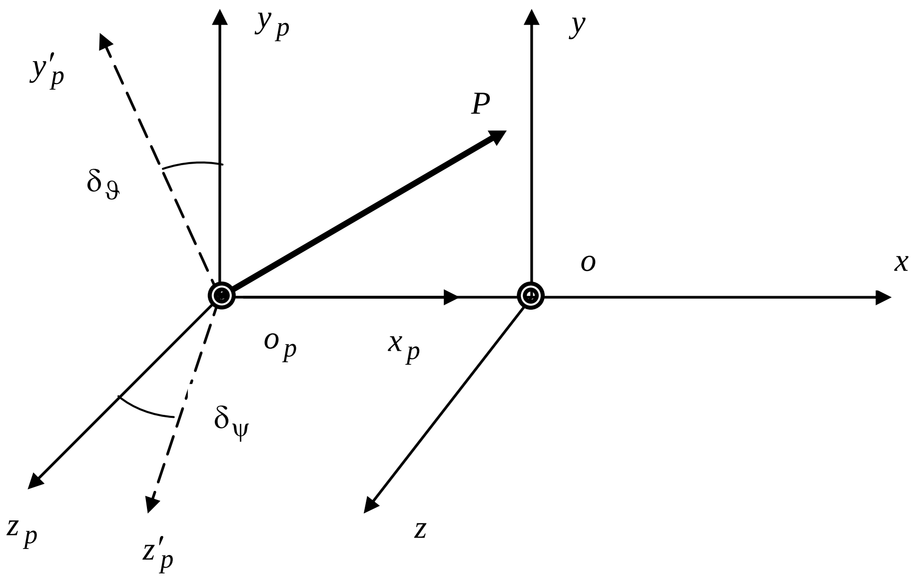


Figure 2. Kinematic connection between the connected and swivel coordinates

The RSV is the second aerospace segment of the TASS. The main purpose of this segment is to brake the giant reentry velocity. This problem is resolved by using atmospheric braking by means of high head resistance that a RSV special aerodynamic configuration has when it is formed by coupling two cone-shaped rotation bodies along their bottoms, which would be warhead cases of intercontinental ballistic or sea-launched missiles. After removal and utilization of the warheads the case has sufficient strength, heat protection and internal volume in order to be one half of the RSV. The distinctive feature of the RSV two-cone configuration is its ability to orient the direction of longitudinal axis perpendicular to the velocity during atmospheric descent, as result the RSV has the maximum possible aerodynamic resistance without any special additional devices as flaps, inflatable shields or parachutes (Figure 3).

Therefore appreciable negative acceleration influences to flight characteristics of RSV already at an altitude of more than 90 km, flight speed decreases smoothly and the maximum longitudinal acceleration g-load does not exceed value of 8.

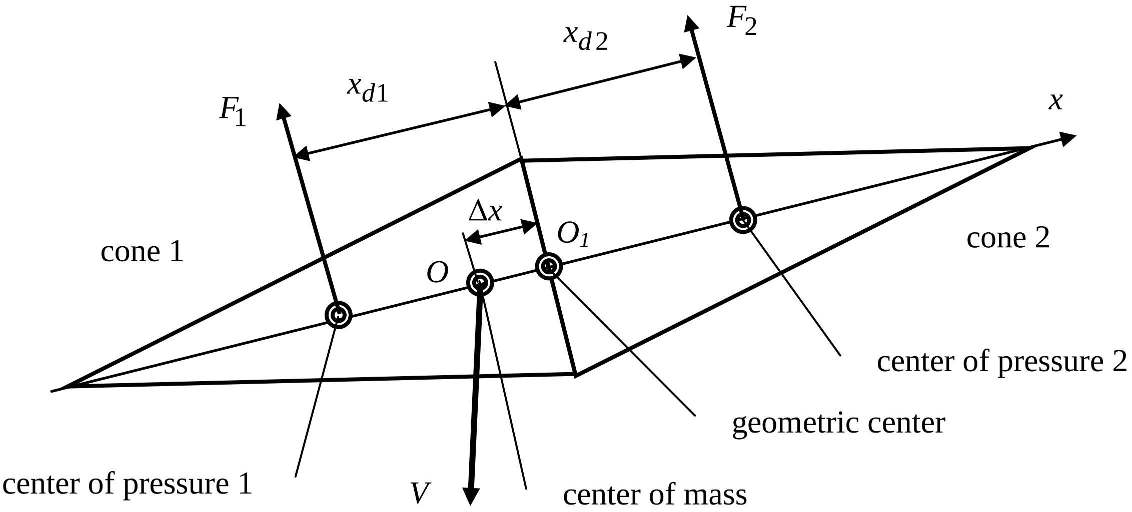


Figure 3. Kinematic diagram of two-cone configuration

A model problem has been also studied for the RSV flight into a terminal state point (on velocity and distance) during descent along ricochet trajectories. On base of analytical solutions for nonlinear differential equations describing atmospheric flight for altitude, distance of flight and velocity during the regime of descending and rising pitch-up the optimal reentry angle has been determined that provides the maximum distance of ballistic flight in dependence on reentry velocity and its fineness. A numerical example is considered.

The above cited results have been obtained for designing RSV and developing their onboard control algorithms. Here expressions for the RSV precession angular velocity $\dot{\psi}$, earlier found by the project authors' group, are considered relatively the vertical axis of normal coordinate system after longitudinal displacement Δx of the RSV center of mass relatively the geometric center of symmetry of its two-cone body (Figure 3). In particular during the RSV motion in the dense atmospheric layers at a constant determined in balance regime (balance angle) angle of attack $\alpha_0 = const$ the precession angular velocity is [4]:

$$\dot{\psi}_{1,2} = \frac{J_z \omega}{2 J_x \sin\alpha_0}\left(1 \pm \sqrt{1 + \frac{8 J_x m_0 q S l \sin^2\alpha_0}{J_z^2 \omega^2}}\right),$$

where $\omega = const$ is an angular rate of the RSV permanent rotation around the symmetry axis that is under angle near to 90 degrees with respect to the RSV velocity. The balance angle of attack α, $\alpha = \alpha_0$, is determined from relation:

$$F_1[x_{d_1}(\alpha) + \Delta x] - F_2[x_{d_2}(\alpha) - \Delta x] = 0, \quad \Delta x > 0,$$

where $F_1 = C_{n1}(\alpha) qs$, $F_2 = C_{n2}(\alpha) qs$ - aerodynamic forces of resistance on cone 1 and cone 2 respectively; $C_{n1}(\alpha)$, $C_{n2}(\alpha)$ are coefficients of the aerodynamic force normal components on cone 1 and cone 2 respectively; $x_{d_1}(\alpha)$, $x_{d_2}(\alpha)$ are distances to centers of pressure on the appropriate cones accounted along the longitudinal axis from the geometric center; Δx is displacement of the center of mass from the geometric center along axis $0z$; q is dynamic pressure; S is reference area of RSV. A given angle ψ for the RSV flight direction at balance angle of attack $\alpha = \alpha_0$ is ensured by regulating rotation angular rate ω.

The RSV and ATV motion is considered beginning with a moment when the first vehicle goes in regime state of vertical quasi-stationary fall that is achieved to an altitude of 10 – 15 km. The RSV velocity decreases gradually and in a definite time moment in its direction an air towing vehicle (ATV) starts that is the third segment of TASS. It would be any ordinary one-stage liquid propellant rocket with an acceleration speed not exceeding the acoustic speed, or two rockets in strap-on configuration with horizontal flap on each of external cylindrical surfaces near their bottoms (Figure 4). The ATV docks with RSV, captures it into the own body and makes soft landing by regulating a thrust force, according to an appropriate law, of the main engine by means of which the ATV at first accelerates and then brakes before rendezvous with RSV. Some effective algorithms are suggested on the base of MTC of ATV acceleration and deceleration for capture (docking) with RSV and for subsequent vertical soft touchdown. The results of analysis of numerical simulation for control process taking into account uncertain disturbances are completely coordinated with expected results.

Analytical research of dynamics and stabilization control are carried out for the regime of ATV program longitudinal motion under uncertain disturbances and the regime of ATV horizontal landing for the TASS second version, and also methods and means are suggested to significantly improve measurements of a sensor for angle of attack under no typical change of the measured angle of attack and actions uncertain disturbances. Let us consider this problems to be studied in more detail.

The reliability of the TASS is defined, as practice shows for designing of control systems, not only by the strength of the whole system but by the simplicity of algorithms by means of which flight is controlled for all three or four TASS segments. The earlier onboard control

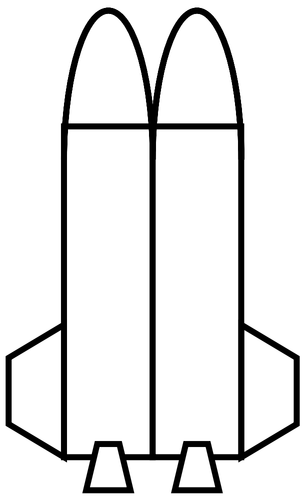


Figure 4. Rockets in strap-on configuration

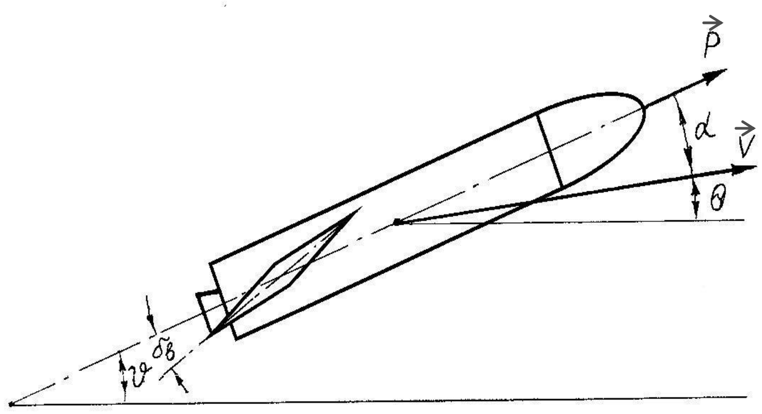


Figure 5. Control under disturbances

algorithms are used in TASS designing, applied then in operations with the ready system, the higher the quality of the TASS development. One of the most important trends in simplifica-

tion and, consequently, in improvement of the reliability for the whole system is to develop, in addition to algorithms of multistep terminal control (MTC) with the admirable quality of the terminal invariance to uncertain external and parametric disturbances, some new types of discontinuous controls in sliding modes which have a property to be invariant to the parametric and external disturbances into a sufficiently broad range of their possible changes and, consequently, to be used not only for development of the onboard algorithms but during designing stage as it is for the MTC [5-7]. Moreover, as it is known, during putting of a system in the sliding modes the system dimension decreases, as result controlled processes have more high qualities at restrictions on amplification coefficients in comparison with ordinary controls with fixed structure [8, 9]. In this connection a discontinues control algorithm was developed for stabilization of the ATV longitudinal program motion in atmosphere taking into consideration constant action of limited uncertain disturbances on the control system [10, 11]. High precise control under constant influence of uncertain external and parametric limited disturbances is performed in sliding modes by means of deflections of the main engines thrust vector P and rotation angle $\delta_в$ of the horizontal flaps from their program values, defined by means of pitch angle connected with trajectory angle and angle of attack as shows Figure 5.
The high frequency of structures' changeovers is not passed by any inertia elements of rocket engine and control actuators and could be also regulated, when it is necessary to go out it beyond any frequency bands dangerous in the resonance, by using various switching devices after tuning of values for their delay, in a sufficiently board range where switching frequencies change does not practically influence the quality of controll processes.
The landing is performed by using some new engineering decisions including the above cited strap-on configuration for ATV and arrangement of the tail horizontal units (Figure 4) which give the fineness sufficient to make the horizontal landing on a movable platform moving simultaneously with the ATV along a runway (Figures 6, 7). An undercarriage on the ATV is not used, as result quick cargo delivery from orbit to the Earth is cheaper. The series of the new engineering decisions suggested (in particular, air suspension of movable platform, suspension is made by electromagnetic forces created by current during transformation of kinetically energy to electrical one) would make the horizontal landing to be not only real but also profitable. Kinematical parameters were determined for a landing trajectory of the air space aircraft consisting of approach glide and flare. These data are used for conceptual designing and subsequent development of control algorithms for the ATV horizontal landing on the movable platform.

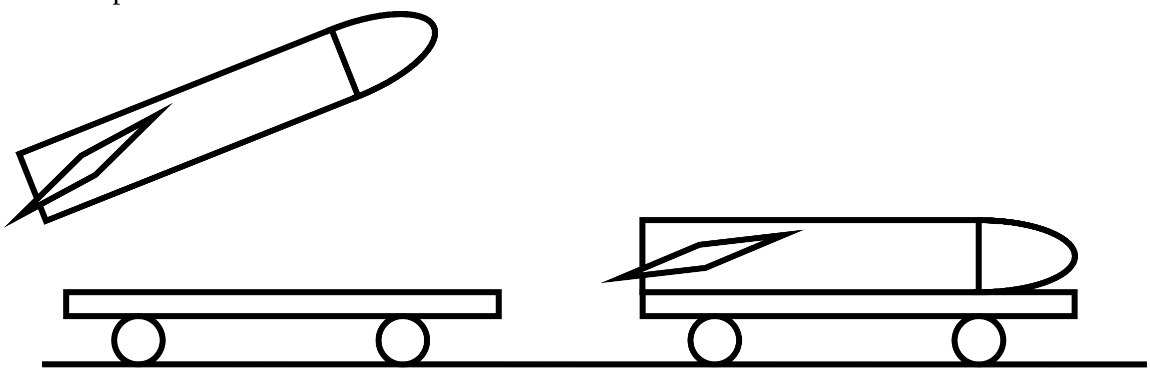


Figure 6. ATV landing on a movable platform

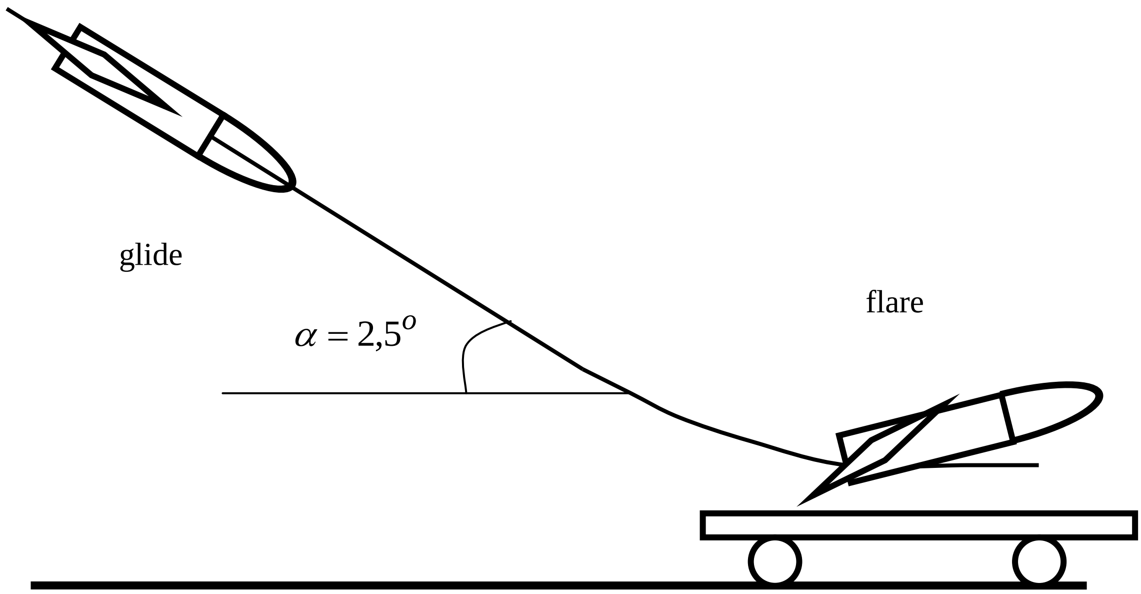


Figure 7. ATV horizontal landing trajectory

The main design parameters have been determined for three segments of the TASS in its first implementation version. The main parameters are defined for the STV, RSV and ATV before its rendezvous with RSV and during the vertical touchdown of ATV after its docking with RSV.

To measure angles of attacks during generation of the suggested new controls for a ATV, as well as for the two-cone RSV when it will be independently controlled in flight along a ricochet trajectory, two modified versions of thermo-anemometrical sensor are suggested to measure aerodynamic angles, an initial and suggested modified diagrams are shown in Figure 8 [12, p.146] and in Figures 9, 10. Because this servo system has only one integrator then for aerodynamic angels (AA), approximated by splines of higher first order, a steady-state error has unacceptable values. Increasing of the error causes also external $M_c(t)$ (moment of dry friction) and parametrical (parameters changing from product to product and degradation of elements) disturbances. In this connection to precise measure aerodynamic angels with its typical and no typical changes two versions are suggested to change the structural diagram of thermo-anemometrical sensor, then in both cases we suggest to apply anew developed discontinuous control in sliding modes, which are invariant to the above cited uncertain external and parametrical disturbances and to the measured aerodynamic angle [13, 14].

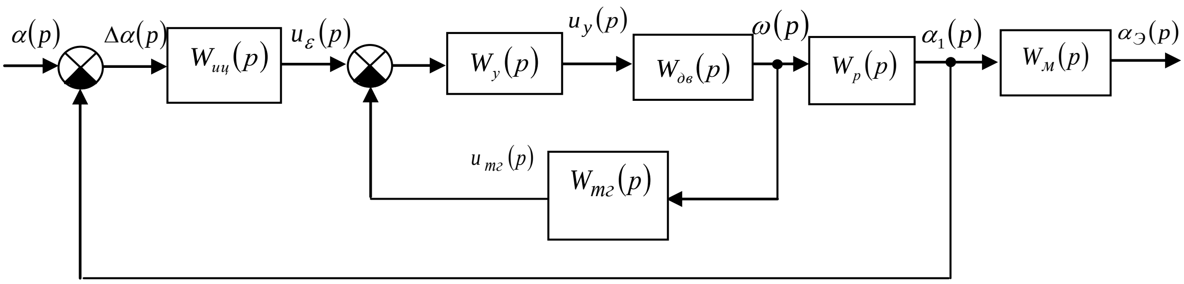


Figure 8. Structural diagram of thermo-anemometrical sensor

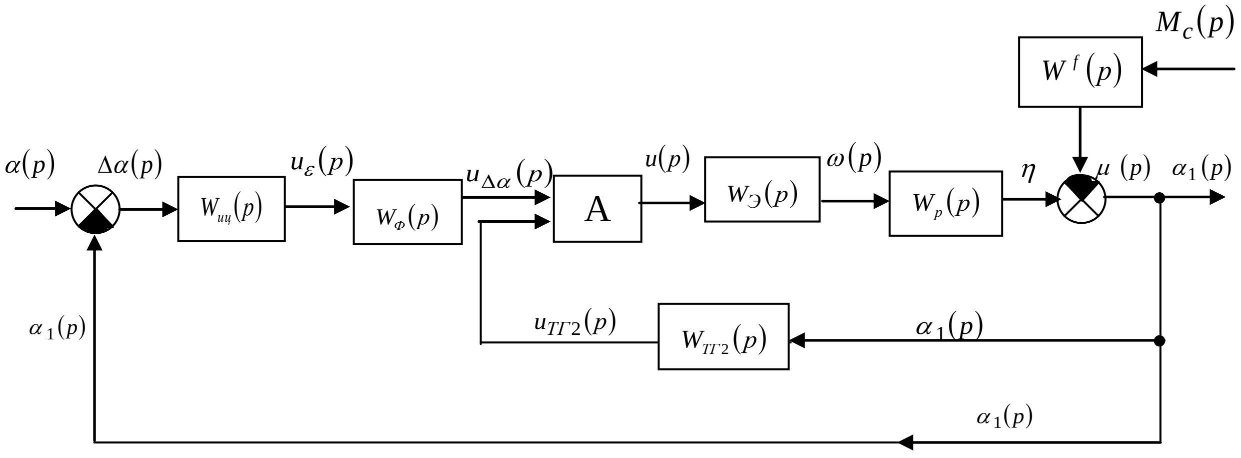


Figure 9. First modified version of structural diagram of thermo-anemometrical sensor

In both offered versions (Figures 9, 10) after the measurement link a forcing link is set that permits to have voltage proportional to a measurement error. In the first version (Figures 9) an additional tachogenerator is set to measure the derivative of the system output angle. Both signals are transmitted to an amplifier (A), that is before the internal loop with the equivalent transfer function $W_Э$:

$$W_э(p)=\omega(p)/u(p)=W_y(p)W_{дв}(p)/(1+W_y(p)W_{дв}(p)W_{тг})=k_э/(T_э p+1),$$

$$k_э=k_y k_{дв}/(1+k_y k_{дв}k_{тг}),\ T_э=T_д/(1+k_y k_{дв}k_{тг}).$$

In this version (Figure 9): $W_{иц}=Q_{иц}/(T_{иц}p+1)$ is the transfer function of the measurement circuit, $Q_{иц}=Q_{иц}(V,\rho,...)\Delta\alpha$ is a coefficient defining the sensitivity of the measurement circuit; α is aerodynamic angle to be measured;

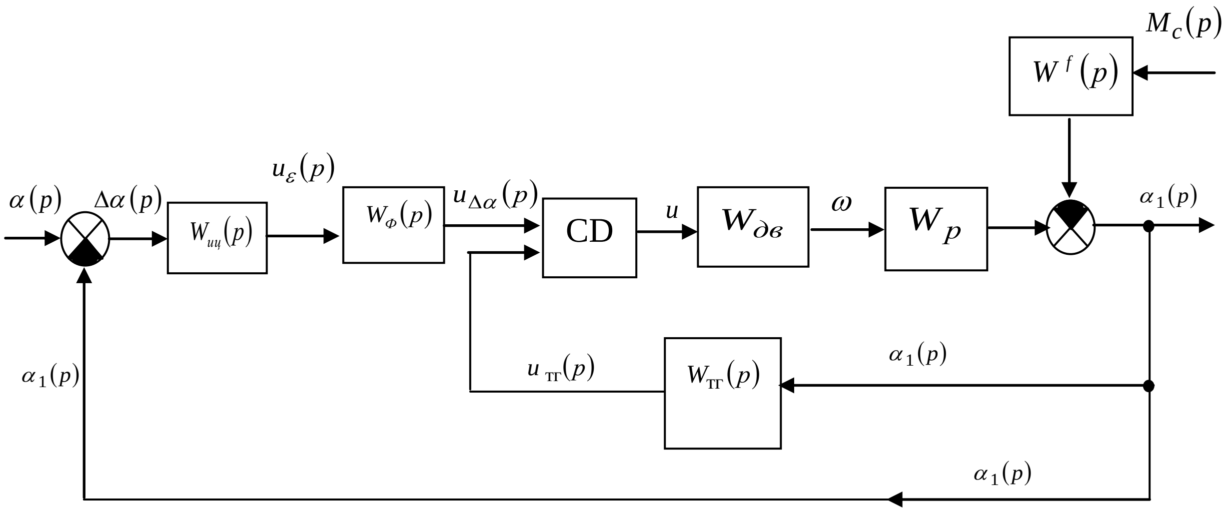


Figure 10. Second modified version of structural diagram of thermo-anemometrical sensor

$\Delta\alpha$ is a tracking error; V is speed of flight vehicle; ρ is atmosphere density; α_1 is a rotation angle of the aerodynamic converter (a device to pick up a signal is not shown); $W_y=k_y$ is a gain; $W_{дв}$, $W_{тг}$, W_p are the transfer functions of machine, tachogenerator, and a reductor, $W_{дв}=k_{дв}/(T_{дв}p+1)$; $W_{тг}=k_{тг}$; $W_p=k_p/p$, $k_p=1/i$, i is transfer ratio of the reductor; $W_ф(p)=k_ф(T_{иц}p+1)=u_{\Delta\alpha}(p)/\varepsilon(p)$, $W_{тг2}(p)=u_{тг2}(p)/\alpha_1(p)=k_{тг2}p$ are transfer functions of additional links (forcing link and second tachogenerator).

For the second version (Figure 10) any additional tachogenerator is not required, because the internal loop has no connection with tachogenerator that is switched to measure of a derivative of output angle the servo system (no angle of machine rotation) and control device (CD) is united with the amplifier. In the both versions CD leads the servo system into the sliding mode, that after addition, of the forcing device reduces the initial third order of the system to the second one and is described by a differential equation of the first order with a coefficient of the sliding straight line defined arbitrarily, and it does not depend on any both disturbances and the measured aerodynamic angle [15]. As a result we have the exponential damping of measurement errors to zero values with a required speed. Numerical simulation has been made for the initial and modified structural schemes with the previous and offered controls for some typical and untypical aerodynamic angels (in general case under their uncertain changing) the simulation results are completely in accordance with the presented data. For a sensor of the new type with structure scheme (Figure 11) are showed typical measurement processes according to error $\Delta\alpha$ and directly according to the angel attack α that is measured and α_1 that has been measured when it untypically changes as the cosine $\alpha=\alpha(t)=0.1\cos(\omega t)$, $\omega=5\pi=15.7\ rad/s$ (Figure 11, 12).

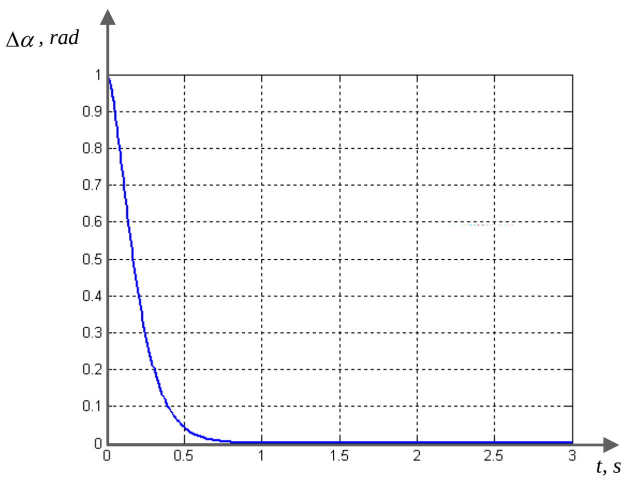


Figure 11. Measurement process according to error $\Delta\alpha$

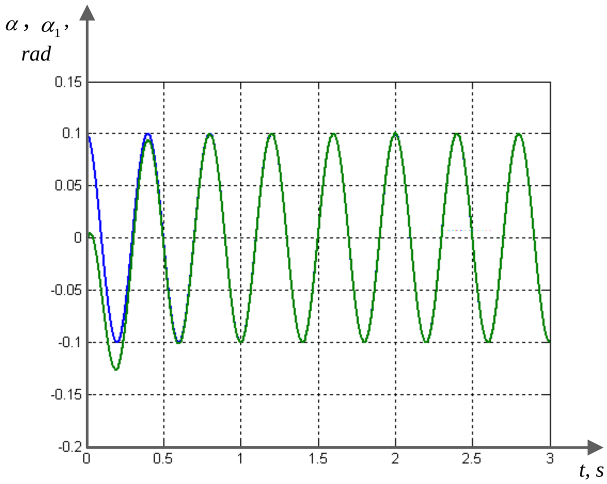


Figure 12. Measurement process according to the attack angle α and α_1

The initial modified sensor (Figure 8) is not designed for these non-typical changes of aerodynamic angles, as it is already noted here. It is completely in accordance with results of simulation for the initial sensor researched in the numerical example.

3. Conclusions

Thus the results obtained present initial data to further design the suggested towing aerospace system (TASS) and to improve the quality of the aerodynamic angels tracking for its reentry space vehicle (RSV) and air towing vehicle (ATV) segments. The simplicity of the offered transportation system together with a possibility that aerodynamic angels will be measured under typical and untypical changes is the base not only for its reliability but for the cost reduction per cargo kilogram delivered from orbit.

Abbreviation

A – amplifier;
AA – aerodynamic angle;
ATV –air towing vehicle;
CD – control device;
CS – control system;
ISS – international space station;
MTC – multi-step terminal control;
RSV – reenter space vehicle;
SPM – solid propellant motor;
STV – space towing vehicle;
TASS – towing aerospace system.

References

1. V.A. Afanasyev, T.K. Sirazetdinov. About problem of terminal control during gliding in atmosphere // News of HEE. Aviation engineering. № 4. 1983. p. 3-9. (in Russian)
2. A.S. Meshchanov. Justification for method of multiple terminal control by using simplified models in nonlinear nonstationary systems under uncertain disturbances. KSTU bulletin. 1999. № 4, P.65-70. (in Russian)
3. V.A. Afanasyev, A.S. Meshchanov, M.G. Meshcaryakov, T.K. Sirazetdinov. MTC of touchdown for descent flight vehicle // News of HEE. Aviation engineering, 1993, № 1, P.13-17. (in Russian)
4. V.A. Afanasyev, G.L. Degtyaryov, A.S. Meshchanov, T.K. Sirazetdinov. About mathematical description of motion of reusable descent flight vehicles with specific aerodynamic arrangements // News of HEE. Aviation engineering, 2001, № 3, p.10-14. (in Russian)
5. S.V. Emelyanov. Systems of automatically control with variable structure. M., Science, 1967, 336 p. (in Russian)
6. Theory of systems with variable structure. Edited by Emelyanov S.V. M., Science, 1970.-592 p. (in Russian)
7. Systems with variable structure and their application in problems of flight automation. Edited by Petrov B.N. M., Science, 1968.-324 p. (in Russian)
8. A.S. Meshchanov. About moving of multidimensional discontinues systems with a nonlinear nonstationary control object in the sliding mode. Book “Motion stability”, Novosibirsk: Science, 1985, p. 230 – 234. (in Russian)
9. V.A. Afanasyev, A.S. Meshchanov. Methods of construction of vector discontinues controls in systems with external and parametrical disturbances. – Kazan, 1985. – 7 p. (in Russian)
10. E.Yu. Samysheva, A.S. Meshchanov, V.A. Afanasyev. Research on dynamics of flight and control for an air space transformation plane in designing of the reusable space transportation system. Contest of science-innovation project “Flight into the Future”. Final

presentation of project. 19-21 july 2004, Moscow. Collection of annotation. p.12. (in Russian)
11. E.Yu. Samysheva. Discontinues controls of new types with their application for flight vehicle and sensors of aerodynamic angels. All-Russia university science-technical conference “Electro-mechanics processes in energetic plants, string acoustic and diagnostics, devices and methods of control of nature environment, substance, materials and goods” 17-19 may 2005, KHACU, Kazan, 2005. (in Russian)
12. V.M. Soldatkin. Methods and means for measuring of aerodynamics angels of flight vehicles. Kazan: KSTU. 2001. 448 p. (in Russian)
13. A.S. Meshchanov, E.Yu. Samysheva. About tracking aerodynamic angels of flight vehicles by means of temperature sensors and anemometers in sliding modes under uncertainties. Collected articles of V International conference “cybernetics and technologies XXI centure”, Voronezch t., 12-13 may 2004. – P.157-170. (in Russian)
14. E.Yu. Samysheva. Simulation of measurements and control of a sensor of aerodynamic angels under uncertainty. International science conference “Mathematical methods in engineering and technologies MMTT-18” 31 may-2 june 2005. KSTU, Kazan. 2005 p.13. (in Russian)
15. A.S. Meshchanov, E.Yu. Samysheva. Sliding with identification of uncertainties in stabilization of a flight vehicle along the heading. News of Tula state university. Serial: Problems of special mechanical engineering. Instalment 6 (part 1). Tula.-2003. P.342-346. (in Russian)

Victor Akimovich Afanasyev (South Ural State University, Miass city), professor at Department of applied information science and rocket dynamics, candidate of technical sciences. He graduated Kazan aviation institute (1969), his specialty is dynamics of flight and control. The specialist in control and designing of advanced flight vehicles and automatic control systems. Application fields of researches results: projecting and control of transformational retuned space vehicle of perspective configuration and other complex technical objects under uncertainty.
ava46@mail.ru.

Arsen Sergeyevich Meshchanov (Kazan National Research Technical University of A.N. Tupolev name – KAI), professor at Department of automatics and control, candidate of technical sciences, senior staff scientist. He graduated Kazan aviation institute (1969), his specialty is dynamics of flight and control. The specialist in control of complex dynamical systems under uncertainty, including aerospace systems. Application fields of researches results: determination of stability conditions and control synthesize of complex technical and industrial systems under uncertain limited disturbances.
mas41@mi.ru.

Ekaterina Yurevna Samysheva (Kazan National Research Technical University of A.N. Tupolev name – KAI), assistant professor at department of economic theory, candidate of technical sciences. She is graduate Kazan State Technical University (2003), her specialty is aviation devices and measuring and calculating complexes. She studies developments of methods for discontinuous controls taking into account uncertain disturbances. Application fields of researches results: aerospace systems and its devices.
eus@list.ru

Finite-dimensional design scheme of deformable elements of space structures

A.P.Alpatov[1], P.A.Belonozhko[1], P.P.Belonozhko[1], L.K.Kuzmina[2], S.V.Tarasov[1], A.A.Fokov[1]

1 – Institute for Engineering Mechanics of the National Academy of Sciences of Ukraine, 15 Leshko-Popel str., Dnepropetrovsk, 49005, Ukraine
2 – A.N.Tupolev Kazan National Research Technical University – KAI

This research is devoted to some methodical aspects in problems of modelling dynamics for large space vehicles. It is presented the development of methods and computational schemes for space structures, with consideration of non- absolutely rigid elements. The article is based on the paper that was presented at World Congress of International Federation of Nonlinear Analysts (IFNA, Greece, 2012) within Invited Session "Problems and methods of modelling and analysis in Complex multidisciplinary Systems Dynamics"(Co- Chairs : L.K.Kuzmina, Russia and I. Antoniou , Greece). This Session was devoted to
120-th Anniversary of "Stability theory of A.M. Lyapunov"
and to Memory of great, brilliant Scientists:
N.G.Chetayev (110 years); *I.R.Prigogine*, NOBEL LAUREATE (95 years); *V.M.Matrosov* (80 years).
Also this article is reflecting the following results.

Initial Statements

This part of research is presenting the actual developments and the modifications for computational schemes in problems of modelling dynamics of controlled motion for large space vehicles.

The term "Large space structures" (LSS) has been being widely used in the scientific and engineering literature since the beginning of the 1980s in respect to the class of space objects[1-32], which we will describe with a set of their inherent features (not aiming at strict definition) [1-3]:

- large if compared to traditional space vehicles (this follows from their functional purposes);
- significantly less rigid if compared to traditional space vehicles; this leads to compulsory allowance for deformability when solving the problems of dynamics and control;
- necessity for deployment of the structure when switching from transportation to operation after putting into orbit or necessity for in-orbit assembling.

Thus, LSS are unique engineering objects without any on-ground counterparts. Their design, production and operation are associated with some specific difficulties:

- they can not by tested on ground, hence space experiments and simulation modeling are important;
- mathematical models have high dimensions and are ill-defined, hence reduction problem together with parametric and structural identification are of vital importance;
- negligible in-orbit energy dissipation, hence compulsory allowance for lightly damped oscillations when synthesizing attitude, orientation and configuration control.

A widespread class of large space vehicles (SV), which can be more or less characterized with the listed features of LSS, consists of SV with extended peripheral elements, e.g. solar arrays. Fig.1 shows ISS solar arrays. Many authors [1, 3, 4, 6, 7, 12, 13], who study the effect of elastic oscillations of deformable elements on spatial motion of structure, consider a mechanical computational scheme of non-deformable solid body with attached extended peripheral elements like elastically deformable beams (beams with mass applied at their end). Growing size of a peripheral element is accompanied (allowing for the aforementioned transport restrictions on mass and size of payload) by reduction of structure rigidness and increased influence of elastic oscillations on "solid" motion (motion in inertial space somehow connected to the basis structure). The noted circumstance allows selection of a number of space objects, idealized by mechanical computational schemes of the mentioned type, as possessing qualitatively important features from the standpoint of control synthesis.

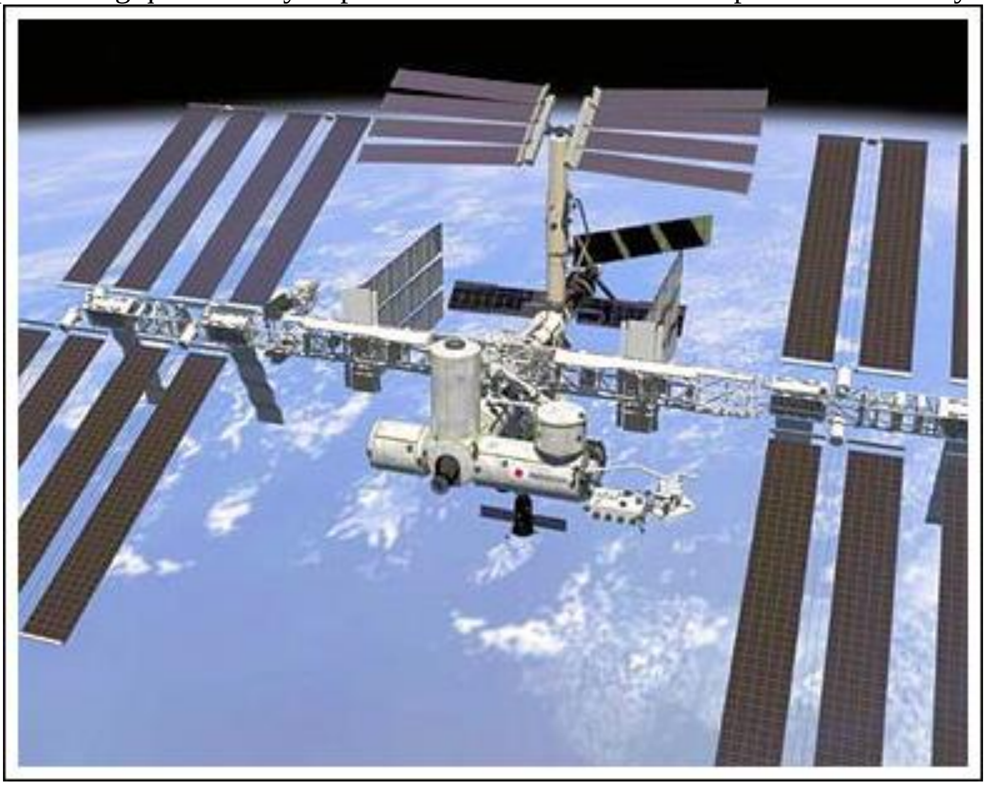


Figure 1.

The uniqueness of LSS as engineering objects defines significant difficulties in formalization of selection of efficient combination of orbit, on-ground and mathematical experiment during the design process. In general, while developing the mathematical model of dynamics, LSS are idealized by mechanical computational schemes of a group of solid and deformable bodies connected by elastic and dissipative couplings. In such case the ambiguities inherent to the correlation of a real object and mechanical computational scheme are escalated by the dimensions, variety of dynamic modes and a wide range of simulation tasks. Hence the approach to the simulation of dynamics of complex engineering systems based on hierarchical population of particular models describing computational schemes of different refining degree has gained special importance [2, 11, 32]. Simultaneously, it has been increasingly important to develop methods for efficient exploitation of computer resources. It should be noted that, despite the abilities of modern software, the experience of a researcher and availability of methodological experience are important [30, 31].

Basic Section (problems and methods of solving)

The following tasks should be highlighted in the framework of mathematical simulation of LSS:
- derivation, analysis and integration of LSS motion equations;
- refinement of parameters and structure of mathematical models using the parameters of real experiments;

- research of dynamic properties of LSS depending on combinations of structure parameters.
To solve the first group of tasks it could be useful, in addition to traditional methods of mechanics, to apply software which describes a mechanical object defined as a system of rigid bodies connected by kinematic and load-bearing elements only with given system's global structure, bodies' mass-inertia characteristics, types and parameters of links and load-bearing elements [14-16].
As authors [5] note, expedience of simultaneous development of the structure itself and the control system is a characteristic feature of LSS if compared e.g. to aviation objects. Here, flexible approach to the choice of factors allowed for by the model and efficiency of experimental (both full-scale and mathematical) task statement are important [2, 11].
We highlight the following tasks for LSS control:
- control of spatial motion of the structure allowing for its elastic deformations;
- control of the structure configuration.
Solution of the first group of tasks assumes the definition of LSS "solid" motion as motion in a certain way associated with the basic structure in respect to some basis, typically with the origin at the Earth center of mass, moving translationally in inertial space, the latter considered as inertial with acceptable accuracy. Here, it is natural to distinguish the motion of LSS center of mass along the Earth orbit and angular motion of basis associated with LSS, which defines LSS attitude.
The features of configuration control in each case are defined by functional purpose of structure (e.g. by requirements to the accuracy of reflecting surface) together with the construction and location of sensors and actuators and control tasks.
As it is mentioned in [5], the basis associated with deformed LSS characterizing its "solid" motion can be defined in different ways. Among the most convenient approaches is a "mean" coordinate system [5].
In some cases it is expedient to find a carrying body considered as non-deformable with acceptable accuracy. Then the attitude in the basis of sensors, actuators, etc. associated with this body as a solid body will be invariant, and the motion of this basis with respect to some inertial system of coordinates is considered as a controlled motion. Here, elastic deformations of LSS are allowed for from the standpoint of their effect on the motion of the carrying body. It allows confining to the description of dynamic processes of interest by ordinary differential equations. [3, 4, 7, 17] prove that to solve a wide variety of the problems of control of LSS spatial motion, it is expedient to use modal-physical models of LSS dynamics scalar description in the following form:

$$\ddot{\bar{x}}(t) = \gamma_0 F(t), \tag{1}$$
$$\ddot{\tilde{x}}_i(t) + \omega_i^2 \tilde{x}_i(t) = \gamma_i F(t),$$
$$x(t) = \bar{x}(t) + \sum_{i=1}^{n} \tilde{x}_i(t),$$

where $x(t)$ is a measured coordinate (displacement or rotation angle) associated with the carrying body and characterizing its single-axis motion in inertial basis; $\bar{x}(t)$ – "solid" component of the considered motion; $\tilde{x}_i(t)$ – i^{th} "elastic" component of the considered motion resulting from the influence of LSS elastic deformations on the carrying body; ω_i – natural frequency of i^{th} elastic mode; $\gamma_0, \gamma_1, ..., \gamma_n$ – model coefficients; $F(t)$ – control force applied to the carrying body (force or moment); n – number of oscillation forms considered.

The case of undamped oscillations is considered the most important from the standpoint of control (it should also be noted that enlargement of LSS is accompanied by reduction of internal damping [5]).

Owing to the aforementioned advantages of the software for simulation of dynamics of systems of bodies [14-16, 18, 19], at certain stage of research it is expedient to associate mathematical model of the form (1) with finite-dimensional computational scheme in the form of a set of solid bodies with link connection. The paper describes a criterion of dynamic equivalence that allows formalization of the procedure of comparison of continual and discrete mechanical computational schemes developed by the authors [20-30]. Let us illustrate the submitted approach with selection of parameters for a finite-dimensional computational scheme equivalent to an elastic beam free in inertial space and with mass attached to its end represented by a reduced model of the form (1).

Let the dynamics of controlled LSS motion be described by a set of models of the form (1) containing a finite number of summands. As it is mentioned among others in [7], the procedure of reduction of a finite-dimensional model of LSS dynamics to the form (1) assumes special research, and only in the simplest cases it can be fulfilled by dropping of summands corresponding to higher modes of oscillations. Further we assume models of the form (1) sufficiently substantiated according to e.g. [3, 4, 7, 17].

An important feature of models of the form (1) is selection of certain coordinates characterizing the displacement of the most important points of structure from the whole set (infinite in general case) of generalized coordinates characterizing LSS motion (e.g. as it was mentioned before, displacement of basis associated with non-deformable SV carrying elastically deformable elements). As it has been noted, mechanical computational scheme in the form of a solid body with elastically deformable beam attached is considered as a subject a) illustrative from the standpoint of studying main qualitative features of controlled motion and b) important from viewpoint of applications. Here the less is the relation of solid body mass to beam mass the stronger is the influence of elastic oscillations on solid motion. Thus, it is expedient to consider the limit case of planar motion of basis associated with the end of a beam free in inertial space, the basis being admittedly associated with the carrying body of zero mass.

Let us compare (fig.2) the computational schemes of the form of elastic beam and a chain of three solid bodies with link connection all of them performing weak movements in the figure plane around the initial positions marked with dotted line (without elastic deformations). Vertical displacement $y(t)$ and turn $\varphi(t)$ of bases associated with carrying body relative to the initial position of computational schemes of bases xy we consider as the compared separate coordinates. Similarity of $y(t)$ and $\varphi(t)$ for the compared computational schemes under similar impact of assumed carrying body – force $\overline{T}(t)$ and moment $M(t)$ – allows consideration of their dynamic equivalence.

Let us require that the length and mass-inertia characteristics of computational schemes “solidified” in non-deformed condition coincide, i.e. the following conditions are met:

$$\begin{aligned} m^{(sb)} &= m^{(mb)}, \\ J^{(sb)} &= J^{(mb)}, \\ L^{(sb)} &= L^{(mb)}, \end{aligned} \tag{2}$$

where $m^{(sb)}$, $m^{(mb)}$ are beam mass and chain-of-bodies mass, respectively; $J^{(sb)}$, $J^{(mb)}$ – moments of inertia of “solidified” beam and chain of bodies, respectively, about the axis

passing through the center of mass normally to the motion plane; $L^{(sb)}$, $L^{(mb)}$ – lengths of "solidified" beam and chain of bodies, respectively.
Fulfillment of conditions (2) obviously means similar motion of "solidified" computational schemes under external forces.

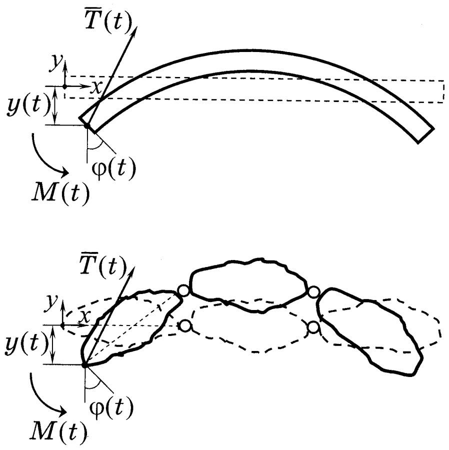


Figure 2

The issues of obtaining reduced models of the form (1) for infinite-dimensional computational scheme of the form of a rigid body (with zero mass in the limiting case) with an elastic beam attached were considered in detail e.g. in [1, 5, 6], and in respect to the solved problem they are discussed in [22, 28]. Further we will allow for two elastic modes (according to the number of oscillatory degrees of freedom of finite-dimensional computational scheme). The choice of a number of elastic modes is not critical from the standpoint of the submitted approach. It can be performed according to the specific engineering problem.
Let us introduce Laplace images:

$$y^{[L]}(s) = L[y(t)] = \int_0^\infty y(t)e^{-st}dt, \tag{3}$$

$$\varphi^{[L]}(s) = L[\varphi(t)] = \int_0^\infty \varphi(t)e^{-st}dt,$$

$$T_y^{[L]}(s) = L[T_y(t)] = \int_0^\infty T_y(t)e^{-st}dt,$$

$$M^{[L]}(s) = L[M(t)] = \int_0^\infty M(t)e^{-st}dt,$$

where $T_y(t)$ is a projection of the force $\overline{T}(t)$ to y axis; s − Laplace variable.
Since the assumed small-scale motion relative to the initial position (marked with dot line in fig.2) allows linearization, dynamics equations of both computational schemes under zero initial conditions can be reduced to the form:

$$y^{[L]}(s) = W_{Ty}^{(i)}(s)T_y^{[L]}(s) + W_{My}^{(i)}(s)M^{[L]}(s), \tag{4}$$

$$\varphi^{[L]}(s) = W_{T\varphi}^{(i)}(s)T_y^{[L]}(s) + W_{M\varphi}^{(i)}M^{[L]}(s),$$

$$i = sb, mb,$$

where i is the computational scheme index, taking values $i = sb$ for the beam and $i = mb$ for the chain of bodies; $W_{Ty}^{(i)}(s)$ – transfer functions "from vertical force to vertical displacement" (from T_y to y); $W_{My}^{(i)}(s)$ – transfer functions “from moment to vertical displacement” (from M to y); $W_{T\varphi}^{(i)}(s)$ – transfer functions “from vertical force to turn” (from T_y to φ); $W_{M\varphi}^{(i)}(s)$ – transfer functions “from moment to turn” (from M to φ).

As transfer functions are independent of the applied force and moment and depend only on the computational scheme parameters, conditions of dynamic equivalence can be stated as equality of corresponding transfer functions:

$$\begin{gathered} W_{Ty}^{(sb)}(s) = W_{Ty}^{(mb)}(s), \\ W_{My}^{(sb)}(s) = W_{My}^{(mb)}(s), \\ W_{T\varphi}^{(sb)}(s) = W_{T\varphi}^{(mb)}(s), \\ W_{M\varphi}^{(sb)}(s) = W_{M\varphi}^{(mb)}(s). \end{gathered} \tag{5}$$

Let us write transfer functions (5) as follows:

$$W_r^{(i)}(s) = \frac{k_{r0}^{(i)}}{s^2} + \frac{k_{r1}^{(i)}}{s^2 + (\omega_1^{(i)})^2} + \frac{k_{r2}^{(i)}}{s^2 + (\omega_2^{(i)})^2}, \tag{6}$$

$$i = sb, mb, \quad r = Ty, My, T\varphi, M\varphi,$$

where $\omega_1^{(i)}$, $\omega_2^{(i)}$ are natural frequencies; k_{r0}^{i}, k_{r1}^{i}, k_{r2}^{i} – coefficients of transfer functions. Then equivalence conditions (5) can be written as:

$$\begin{aligned} &k_{Ty0}^{(sb)} = k_{Ty0}^{(mb)}, && k_{Ty1}^{(sb)} = k_{Ty1}^{(mb)}, \\ &k_{My0}^{(sb)} = k_{My0}^{(mb)} \Leftrightarrow k_{T\varphi0}^{(sb)} = k_{T\varphi0}^{(mb)}, && k_{My1}^{(sb)} = k_{My1}^{(mb)} \Leftrightarrow k_{T\varphi1}^{(sb)} = k_{T\varphi1}^{(mb)}, \\ &k_{M\varphi0}^{(sb)} = k_{M\varphi0}^{(mb)}, && k_{M\varphi1}^{(sb)} = k_{M\varphi1}^{(mb)}, \\ &\omega_1^{(sb)} = \omega_1^{(mb)}, && k_{Ty2}^{(sb)} = k_{Ty2}^{(mb)}, \\ &\omega_2^{(sb)} = \omega_2^{(mb)}, && k_{My2}^{(sb)} = k_{My2}^{(mb)} \Leftrightarrow k_{T\varphi2}^{(sb)} = k_{T\varphi2}^{(mb)}, \\ & && k_{M\varphi2}^{(sb)} = k_{M\varphi2}^{(mb)}. \end{aligned} \tag{7}$$

Let us consider application of the submitted equivalence criterion to the case when parameters of continual computational scheme, and therefore parameters of transfer functions $W_{Ty}^{(sb)}(s)$, $W_{My}^{(sb)}(s)$, $W_{T\varphi}^{(sb)}(s)$, $W_{M\varphi}^{(sb)}(s)$, are given, and it is necessary to pick out corresponding geometric, mass-inertia and elastic parameters of the chain of bodies shown in fig.3 and providing the most accurate equalities (7).

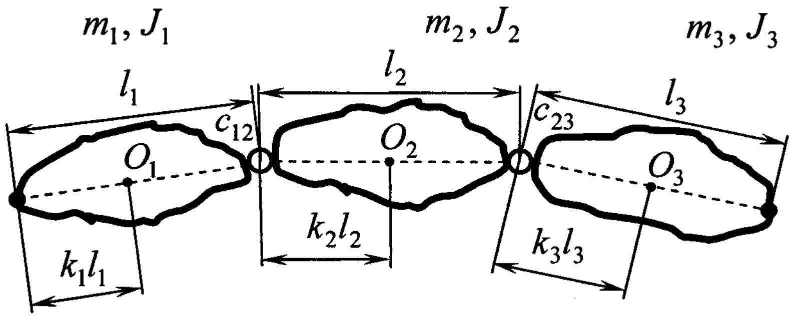


Fig. 3

In fig.3: m_1, m_2, m_3 are masses of bodies; J_1, J_2, J_3 – moments of inertia of bodies around axes passing through their centers of mass normally to the motion plane (figure plane); l_1, l_2, l_3 – distances between the end points of bodies (points of link connections of bodies or points of assumed attachment of external bodies – SV, the next body); c_{12}, c_{23} – angular stiffness of links; k_1, k_2, k_3 – dimensionless coefficients characterizing the positions of bodies' centers of mass. Bodies' centers of mass O_1, O_2 and O_3 are located at lines connecting end points.

The number of independent structural parameters can be reduced by introduction of simplifying assumptions. Let us assume that a cylindrical uniform rod with the mass $m^{(mb)} = m$ and length $L^{(mb)} = l$ is divided into three parts. The division points are symmetric with respect to the rod center; the middle part's length is *kl* ($0 < k < 1$). Elastic links with equal angular rigidness *c* are located at the division points. Allowing for the assumptions, one can characterize the chain of bodies with the following set of parameters:

$$m, l, c, k. \tag{8}$$

Parameters (8) are associated with the parameters shown in fig.3 as follows:

$$m_1 = \frac{(1-k)m}{2}, \quad m_2 = km, \quad m_3 = \frac{(1-k)m}{2}, \tag{9}$$

$$l_1 = \frac{(1-k)l}{2}, \quad l_2 = kl, \quad l_3 = \frac{(1-k)l}{2},$$

$$c_{12} = c, \quad c_{23} = c,$$

$$k_1 = \frac{1}{2}, \quad k_2 = \frac{1}{2}, \quad k_3 = \frac{1}{2},$$

$$J_1 = \frac{(1-k)m\left(\frac{(1-k)l}{2}\right)^2}{24}, \quad J_2 = \frac{km(kl)^2}{12}, \quad J_3 = \frac{(1-k)m\left(\frac{(1-k)l}{2}\right)^2}{24}.$$

Natural frequencies of the chain of bodies as functions of parameters (8) can be written in the form:

$$\omega_1^{(mb)} = \frac{\sqrt{c}}{l\sqrt{m}} \frac{4\sqrt{6}}{(k-1)\sqrt{-3k^2+2k+1}}, \tag{10}$$

$$\omega_2^{(mb)} = \frac{\sqrt{c}}{l\sqrt{m}} \frac{4\sqrt{6}}{k(k-1)\sqrt{-k^2-2k+3}}.$$

Thus, given the values *m* and *l* defined by conditions (3), one can provide equality of natural frequencies of the compared computational schemes by the proper choice of *c* and *k*.

Let us consider a cylindrical beam with parameters:

$$L^{(sb)} = 10\,\text{m}, \qquad d^{(sb)} = 0.01\,\text{m}, \tag{11}$$

$$\rho^{(sb)} = 7800\,\frac{\text{kg}}{\text{m}^3}, \qquad E^{(sb)} = 2.06 \cdot 10^{11}\,\frac{\text{N}}{\text{m}^2},$$

where $\rho^{(sb)}$ is volume-constant beam density; $E^{(sb)}$ - volume-constant Young's modulus.

Corresponding parameters of transfer functions $W_r^{(sb)}(s)$:

$$k_{Ty0}^{(sb)} = 0.6529\ \mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, \tag{12}$$
$$k_{T\varphi 0}^{(sb)} = k_{My0}^{(sb)} = -0.0979\ \mathrm{N}^{-1}\cdot\mathrm{s}^{-2},$$
$$k_{M\varphi 0}^{(sb)} = 0.0196\ \mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},$$
$$\omega_1^{(sb)} = 2.8744\ \mathrm{s}^{-1}, \tag{13}$$
$$\omega_2^{(sb)} = 7.9231\ \mathrm{s}^{-1},$$
$$k_{Ty1}^{(sb)} = 0.6529\ \mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, \tag{14}$$
$$k_{T\varphi 1}^{(sb)} = k_{My1}^{(sb)} = -0.3034\ \mathrm{N}^{-1}\cdot\mathrm{s}^{-2},$$
$$k_{M\varphi 1}^{(sb)} = 0.1410\ \mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},$$
$$k_{Ty2}^{(sb)} = 0.6529\ \mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, \tag{15}$$
$$k_{T\varphi 2}^{(sb)} = k_{My2}^{(sb)} = -0.5132\ \mathrm{N}^{-1}\cdot\mathrm{s}^{-2},$$
$$k_{M\varphi 2}^{(sb)} = 0.4033\ \mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}.$$

Let us assume for the chain of bodies according to (2):

$$l = L^{(sb)} = 10\ \mathrm{m}, \tag{16}$$
$$m = \frac{\pi (d^{(sb)})^2}{4} L^{(sb)} \rho^{(sb)} = 6.1261\ \mathrm{kg}.$$

Let us analyze a computational scheme with the parameters selected according to a static criterion from the standpoint of the submitted criterion of dynamic equivalence. We adopt the following values of angular rigidness and relative length of middle rod:

$$k = 0.5, \tag{17}$$
$$c = \frac{2E^{(sb)} J}{L^{(sb)}} = 20.22\ \mathrm{N}\cdot\mathrm{m/rad},$$

where $J = \frac{\pi (d^{(sb)})^4}{64}$ is a moment of inertia of beam's cross section with respect to the central axis. Parameters (17) correspond to division of the beam into two parts (according to the number of considered modes) and replacement of each part with a set of two rigid rods of equal length ($\frac{L^{(sb)}}{4}$) connected with links with angular rigidness c. Angular rigidness (17) provides equal angle of mutual turn of beam's ends and a set of three link-connected rods for the case of pure in-plane bending. Similar computational scheme was used in [18] to determine eigen modes and frequencies of a rigid disk's elastic cable, however, the number of parts (links) significantly exceeded the number of considered modes.

Parameters of transfer functions $W_r^{(mb)}(s)$ corresponding to the computational scheme characterized by parameters (8) (with values (16), (17)), from henceforth – computational scheme 1:

$$k_{Ty0}^{(mb)} = 0.6529\ \mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (0\%), \tag{18}$$
$$k_{T\varphi 0}^{(mb)} = k_{My0}^{(mb)} = -0.0979\ \mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (0\%),$$
$$k_{M\varphi 0}^{(mb)} = 0.0196\ \mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (0\%),$$

$$\omega_1^{(mb)} = 3.1843\ \mathrm{s}^{-1},\ (11\%), \tag{19}$$

$$\omega_2^{(mb)} = 5.3824\ \mathrm{s}^{-1},\ (32\%),$$

$$k_{Ty1}^{(mb)} = 0.8815\ \mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (35\%) \tag{20}$$

$$k_{T\varphi1}^{(mb)} = k_{My1}^{(mb)} = -0.4701\ \mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (55\%),$$

$$k_{M\varphi1}^{(mb)} = 0.2507\ \mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (78\%),$$

$$k_{Ty2}^{(mb)} = 0.6296\ \mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (3{,}6\%) \tag{21}$$

$$k_{T\varphi2}^{(mb)} = k_{My2}^{(mb)} = -0.4617\ \mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (10\%),$$

$$k_{M\varphi2}^{(mb)} = 0.3386\ \mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2},\ (16\%).$$

The difference (in %) between the values (18)-(21) and the corresponding values (12)-(15) is given in brackets.

Let us introduce frequency response functions obtained from transfer functions (6) by replacement of $s = j\omega$:

$$W_{Ty}(j\omega) = A_{Ty}(\omega)e^{j\psi_{Ty}(\omega)}, \tag{22}$$

$$W_{My}(j\omega) = A_{My}(\omega)e^{j\psi_{My}(\omega)},$$

$$W_{T\varphi}(j\omega) = A_{T\varphi}(\omega)e^{j\psi_{T\varphi}(\omega)},$$

$$W_{M\varphi}(j\omega) = A_{M\varphi}(\omega)e^{j\psi_{M\varphi}(\omega)},$$

where $A_{Ty}(\omega)$, $A_{My}(\omega)$, $A_{T\varphi}(\omega)$, $A_{M\varphi}(\omega)$ are amplitude-frequency characteristics (AFC); $\psi_{Ty}(\omega)$, $\psi_{My}(\omega)$, $\psi_{T\varphi}(\omega)$, $\psi_{M\varphi}(\omega)$ phase-frequency characteristics. In (22) the index of computational scheme is omitted for simplicity.

Fig.4-6 give AFC of transfer functions (6) for the beam (with parameters (12)-(15)) and the chain of bodies (computational scheme 1 with parameters (18)-(21)).

Damping is introduced into the system when plotting AFC curves. Transfer functions are written in the form:

$$W_r^{(i)}(s) = \frac{k_{r0}^{(i)}}{s^2} + \frac{k_{r1}^{(i)}}{s^2 + 2\zeta_1 s + (\omega_1^{(i)})^2} + \frac{k_{r2}^{(i)}}{s^2 + 2\zeta_2 s + (\omega_2^{(i)})^2}, \tag{23}$$

$$i = sb, mb, \quad r = Ty, My, T\varphi, M\varphi,$$

At $\zeta_1 << \omega_1$, $\zeta_2 << \omega_2$ transfer functions' (23) AFC curves are close to the transfer functions' (6) AFC curves.

It is clear from (18)-(21) and fig.4-6 that the choice of equal *c* and *k* (17) does not provide satisfaction of the rest of equalities (7). Thus, computational scheme (1), whose parameters are chosen according to static criterion, does not satisfy the dynamic criterion.

Let us further consider a computational scheme with parameters *c* and *k* chosen according to the submitted criterion of dynamic equivalence. As it has been already mentioned, the proper choice of *c* and *k* can provide equality of eigenfrequencies of the compared computational schemes. For the computational scheme (in what follows – computational scheme 2) with *m* and *l* equal to the values (16), and *c* and *k* equal to:

$$k = 0.26989, \tag{24}$$

$$c = 37.134\ \mathrm{N}\cdot\mathrm{m/rad}.$$

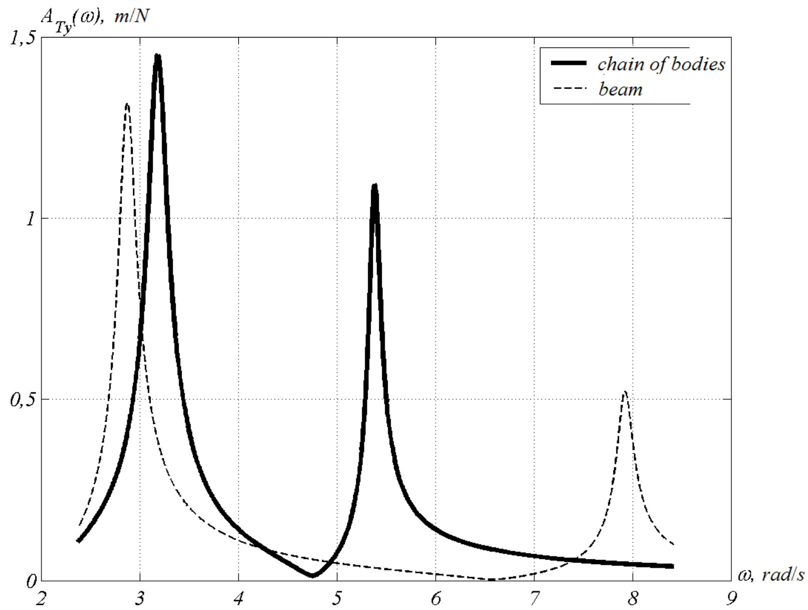

$A_{Ty}(\omega)$, m/N
1,5
1
0,5
0
2
3
4
5
6
7
8
9
ω, rad/s
chain of bodies
beam

Fig.4

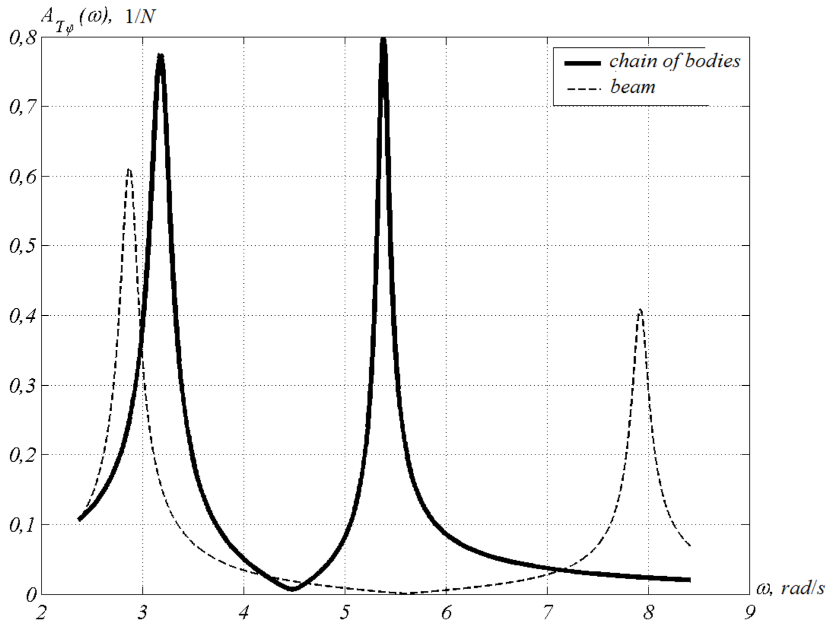

$A_{T\varphi}(\omega)$, 1/N
0,8
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
2
3
4
5
6
7
8
9
ω, rad/s
chain of bodies
beam

Fig.5

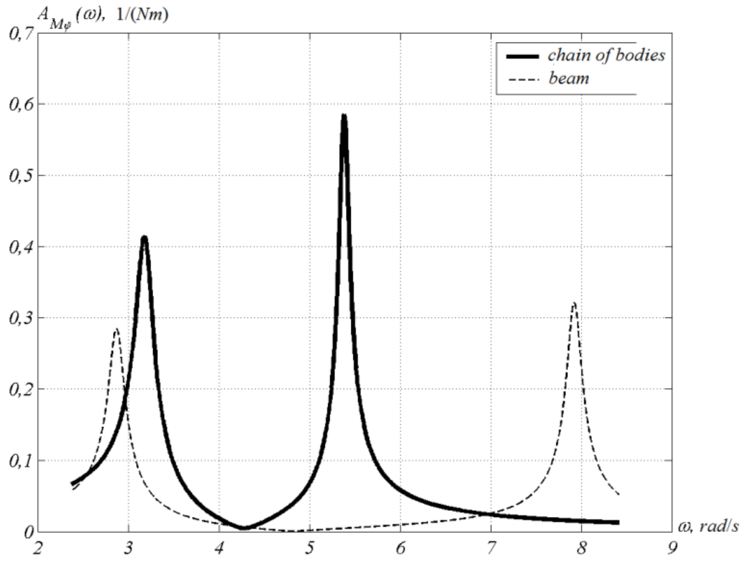


Fig.6

Parameters of transfer functions (6):

$$k_{Ty0}^{(mb)} = 0.6529\,\mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (0\%), \quad (25)$$

$$k_{T\varphi 0}^{(mb)} = k_{My0}^{(mb)} = -0.0979\,\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (0\%),$$

$$k_{M\varphi 0}^{(mb)} = 0.0196\,\mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (0\%),$$

$$\omega_1^{(mb)} = 2.8744\,\mathrm{s}^{-1}, (0\%), \quad (26)$$

$$\omega_2^{(mb)} = 7.9231\,\mathrm{s}^{-1}, (0\%),$$

$$k_{Ty1}^{(mb)} = 0.5977\,\mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (8.5\%) \quad (27)$$

$$k_{T\varphi 1}^{(mb)} = k_{My1}^{(mb)} = -0.2579\,\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (15\%),$$

$$k_{M\varphi 1}^{(mb)} = 0.1112\,\mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (21\%),$$

$$k_{Ty2}^{(mb)} = 0.3308\,\mathrm{m}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (49\%) \quad (28)$$

$$k_{T\varphi 2}^{(mb)} = k_{My2}^{(mb)} = -0.2089\,\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (59\%),$$

$$k_{M\varphi 2}^{(mb)} = 0.1319\,\mathrm{m}^{-1}\cdot\mathrm{N}^{-1}\cdot\mathrm{s}^{-2}, (67\%).$$

The difference (in %) between the values (25)-(28) and the corresponding values (12)-(15) is given in brackets. AFC of transfer functions (6) for the beam with parameters (12)-(15) and computational scheme 2 (chain of bodies with parameters (25)-(28)) are given in fig.7-9.

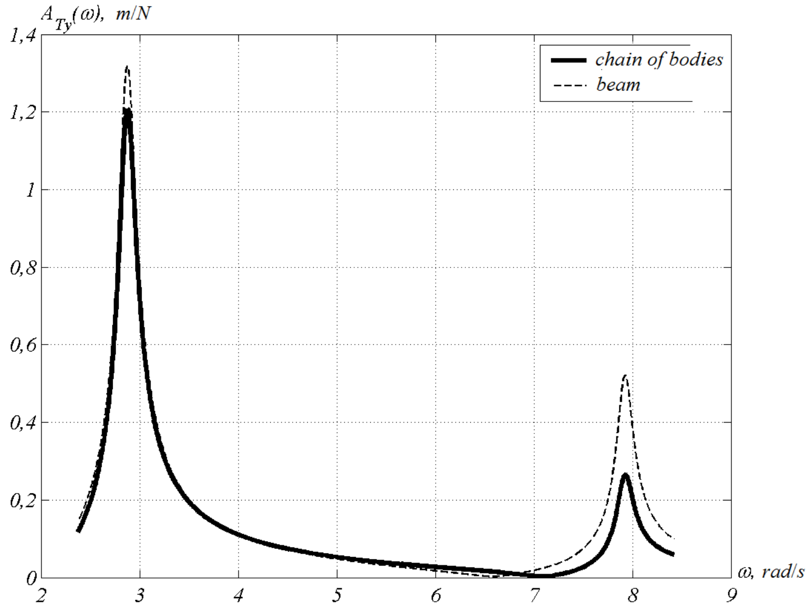

$A_{Ty}(\omega)$, m/N
1,4
1,2
1
0,8
0,6
0,4
0,2
0
2
3
4
5
6
7
8
9
ω, rad/s
chain of bodies
beam

Fig.7

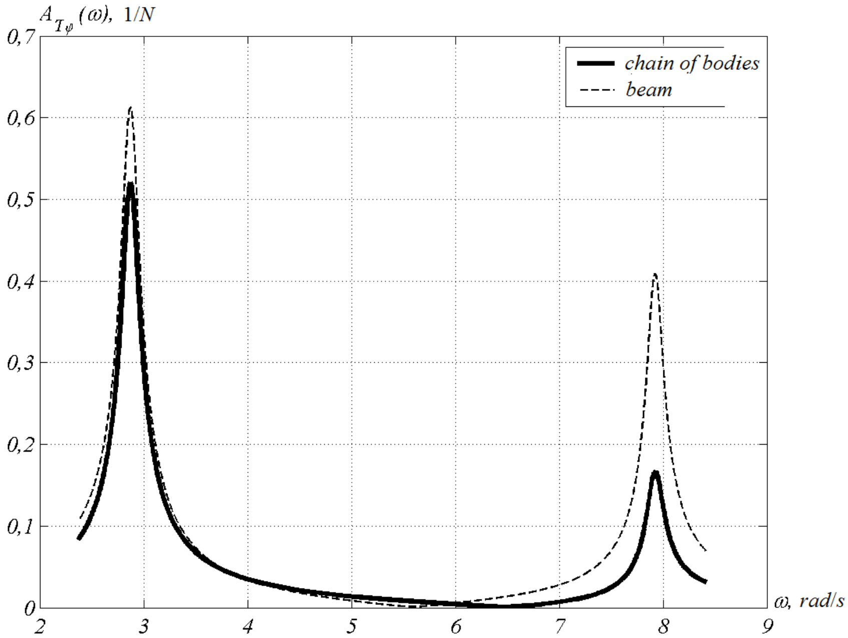

$A_{T\varphi}(\omega)$, 1/N
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
2
3
4
5
6
7
8
9
ω, rad/s
chain of bodies
beam

Fig.8

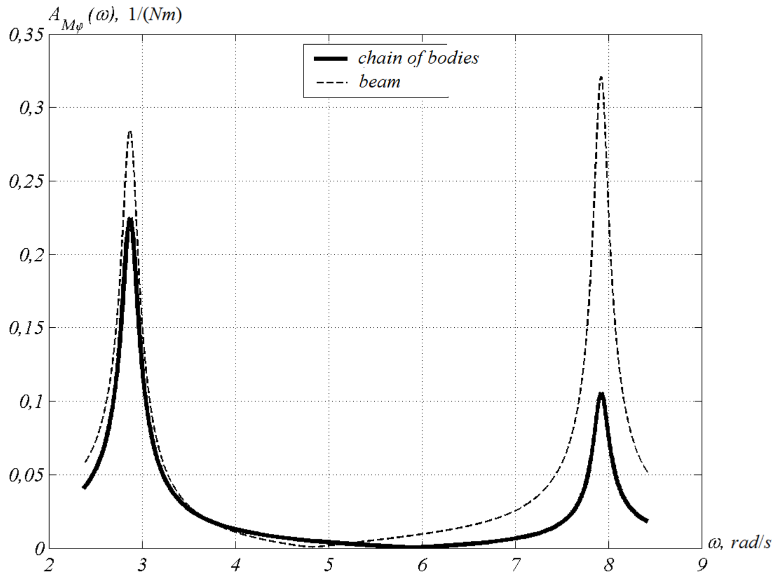


Fig.9

Comparison of schemes 1 and 2 shows that the choice of parameters of a computational scheme according to the assumed equivalence criterion provides equal eigenfrequencies, i.e. more accurate coincidence of dynamic properties. However, gain coefficients of conservative elements (27) and (28) are not equal to corresponding values (14) and (15), i.e. only partial equivalence is observed. The coefficients become closer to each other when a computational scheme is modified.

Let us introduce a chain of bodies characterized by a set of parameters:

$$m\,,\; l\,,\; c\,,\; k\,,\; k_{mass}\,,\; k_{centr}\,,\; k_{iner}\,. \tag{29}$$

The difference between the modified computational scheme characterized by parameters (29) and computational schemes 1 and 2 characterized by parameters (8) is in non-uniform distribution of mass over the volume of initial rod.

The mass is distributed so that:

- rods' masses are not proportional to lengths, and masses of utmost rods are equal to each other;
- utmost rods' centers of mass do not coincide with the centers of mass of uniform rods of the same form;
- utmost rods' moments of inertia around axes passing through the centers of mass normally to the motion plane do not coincide with the moments of inertia of uniform rods of the same form;
- center of mass of a "solidified" computational scheme does not change its position; and moment of inertia around the axis passing through the center of mass normally to the motion plane does not change its value compared to the rod with uniform mass distribution. Parameters (29) are associated with parameters shown in fig.3 by the relations:

$$m_1 = \frac{(1-k)m}{2}(1+k_{mass}), \quad m_3 = \frac{(1-k)m}{2}(1+k_{mass}), \quad m_2 = m-(m_1+m_3), \tag{30}$$
$$l_1 = \frac{(1-k)l}{2}, \quad l_2 = kl, \quad l_3 = \frac{(1-k)l}{2},$$
$$c_{12} = c, \quad c_{23} = c,$$
$$k_1 = \frac{1}{2}(1-k_{centr}), \quad k_2 = \frac{1}{2}, \quad k_3 = \frac{1}{2}(1+k_{centr}),$$
$$J_1 = \frac{(1-k)m\left(\frac{(1-k)l}{2}\right)^2}{24}(1+k_{iner}), \quad J_3 = \frac{(1-k)m\left(\frac{(1-k)l}{2}\right)^2}{24}(1+k_{iner}),$$
$$J_2 = \frac{ml^2}{12}-(J_1+J_3)-\frac{m_1 l^2}{2}[1-(1-k)k_1]^2.$$

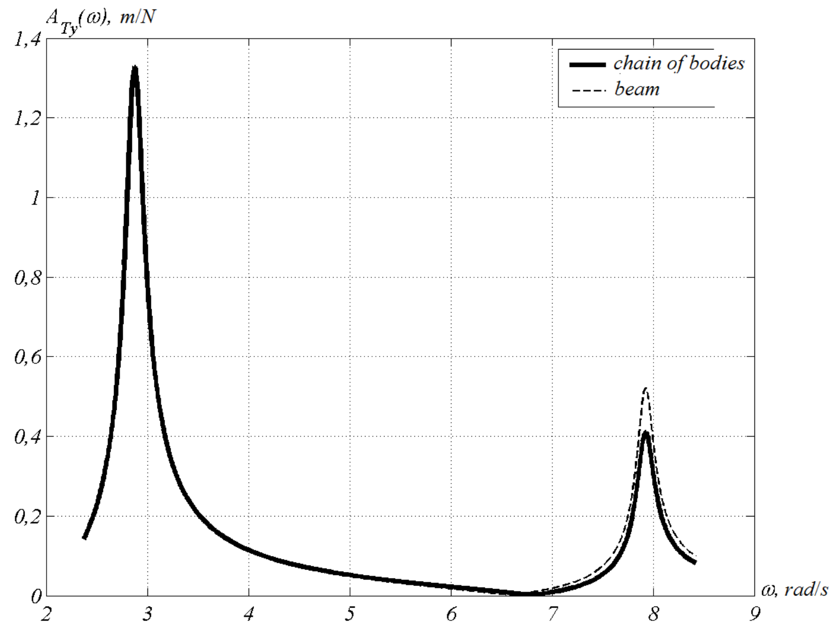
We give the computational results without going into details about the procedure for selection of modified computational scheme parameters (the procedure is based on minimization of specially introduced residuals).
For the modified computational scheme (computational scheme 3) with parameters:

$$l = 10 \text{ m}, \tag{31}$$
$$m = 6.1261 \text{ kg},$$
$$k = 0.34152, \tag{32}$$
$$c = 29.454 \text{ N}\cdot\text{m/rad},$$
$$k_{mass} = 0.01, \; k_{centr} = 0.03, \; k_{iner} = -0.12. \tag{33}$$

Parameters of transfer functions:

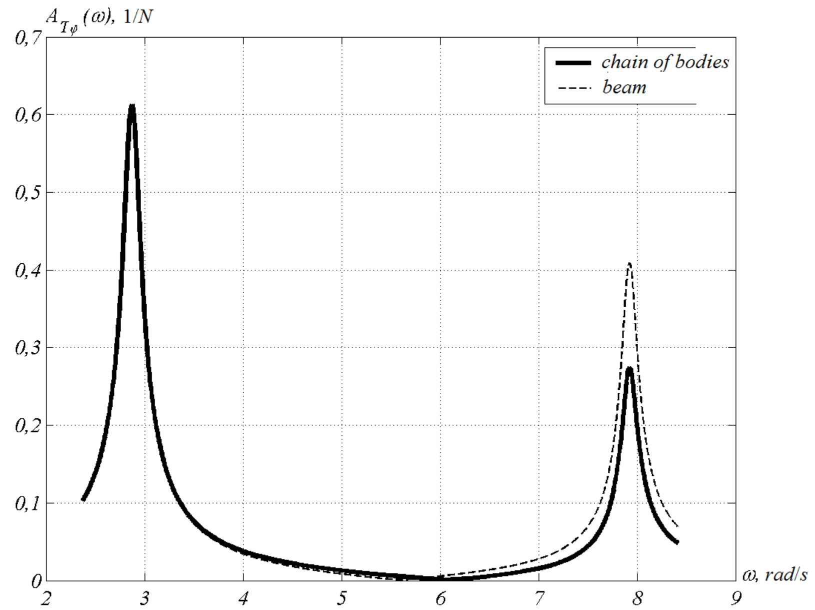
$$k_{Ty0}^{(mb)} = 0.6529 \text{ m}\cdot\text{N}^{-1}\cdot\text{s}^{-2}, (0\%), \tag{34}$$
$$k_{T\varphi 0}^{(mb)} = k_{My0}^{(mb)} = -0.0979 \text{ N}^{-1}\cdot\text{s}^{-2}, (0\%),$$
$$k_{M\varphi 0}^{(mb)} = 0.0196 \text{ m}^{-1}\cdot\text{N}^{-1}\cdot\text{s}^{-2}, (0\%),$$
$$\omega_1^{(mb)} = 2.8744 \text{ s}^{-1}, (0\%), \tag{35}$$
$$\omega_2^{(mb)} = 7.9231 \text{ s}^{-1}, (0\%),$$
$$k_{Ty1}^{(mb)} = 0.6572 \text{ m}\cdot\text{N}^{-1}\cdot\text{s}^{-2}, (0{,}7\%) \tag{36}$$
$$k_{T\varphi 1}^{(mb)} = k_{My1}^{(mb)} = -0.3036 \text{ N}^{-1}\cdot\text{s}^{-2}, (0{,}07\%),$$
$$k_{M\varphi 1}^{(mb)} = 0.1403 \text{ m}^{-1}\cdot\text{N}^{-1}\cdot\text{s}^{-2}, (0{,}5\%),$$
$$k_{Ty2}^{(mb)} = 0.5106 \text{ m}\cdot\text{N}^{-1}\cdot\text{s}^{-2}, (22\%) \tag{37}$$
$$k_{T\varphi 2}^{(mb)} = k_{My2}^{(mb)} = -0.3432 \, N^{-1}\cdot\text{s}^{-2}, (33\%),$$
$$k_{M\varphi 2}^{(mb)} = 0.2421 \text{ m}^{-1}\cdot\text{N}^{-1}\cdot\text{s}^{-2}, (40\%).$$

AFC of transfer functions for the beam with parameters (12)-(15) and computational scheme 3 are given in fig.10-12.



$A_{Ty}(\omega)$, m/N
1,4
1,2
1
0,8
0,6
0,4
0,2
0
2
3
4
5
6
7
8
9
ω, rad/s
chain of bodies
beam

Fig.10



$A_{T\varphi}(\omega)$, 1/N
0,7
0,6
0,5
0,4
0,3
0,2
0,1
0
2
3
4
5
6
7
8
9
ω, rad/s
chain of bodies
beam

Fig.11

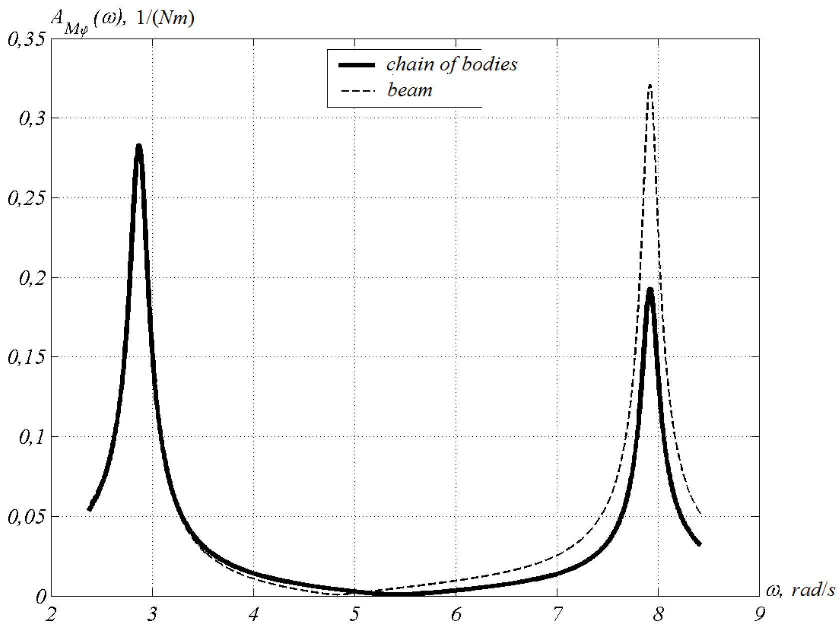


Fig.12

Thus, three computational schemes have been considered. Parameters *m* and *l* for all the considered computational schemes are chosen to be equal to the corresponding beam's parameters, i.e. they provide identical mass-inertia characteristics of the "solidified" beam and chain of bodies.

Computational scheme 1 – computational scheme characterized by parameters *m*, *l*, *c* and *k*. Parameters *c* and *k* are chosen according to the static equivalence criterion. Eigenfrequencies of the beam and chain of bodies do not coincide.

Computational scheme 2 – computational scheme characterized by parameters *m*, *l*, *c* and *k*. Parameters *c* and *k* are chosen according to the submitted dynamic equivalence criterion. Coincidence of eigenfrequencies of the beam and chain of bodies is provided.

Computational scheme 3 – modified computational scheme characterized by parameters *m*, *l*, *c*, *k*, k_{mass}, k_{centr} and k_{iner}. Parameters *c*, *k*, k_{mass}, k_{centr} and k_{iner} are chosen according to the submitted dynamic equivalence criterion. Coincidence of eigenfrequencies of the beam and chain of bodies is provided together with convergence of the conservative links' coefficients in the first harmonics.

Versions of modified computational scheme have been also considered that provide coincidence of eigenfrequencies of the beam and chain of bodies and convergence of the conservative links' coefficients in the second harmonics and in both of harmonics (this paper does not contain the values of coefficients and AFC curves for these computational schemes).

Numerical integration of dynamics equations of the compared computational schemes confirmed the correctness of the assumptions laid in foundation of the derived criterion of dynamic equivalence: the compared displacements are close if the forces are equal [25, 26, 29, 30- 32]. The differences result from inexact satisfaction of equivalence conditions (8).

Conclusion

Thus, analytic dependence of transfer functions' parameters on computational scheme parameters have been obtained for the computational scheme characterized by parameters *m*,

l, *c* and *k*. The case of displacement of basis associated with one of the beam's ends under the forces applied to the opposite end has been considered.
Numerical and analytic approaches have been used to explore the modified computational scheme. Parameters of the modified computational scheme have been chosen according to the condition of minimization of the submitted criterion, which gives numerical integral estimate of inaccuracy in equivalence condition (8) satisfaction.
The case of non-zero mass of the carrying body when obtaining the equations (4) describing the continual computational scheme has been studied.
Comparison of the submitted approach to representation of elastically deformable elements of complex engineering systems with the ones described in literature confirmed the expedience of its application to simulation of dynamics of LSS controlled motion. Also the strong mathematical methods of decomposition [30 -32], based on A. M. Lyapunov theory, are very effective.

References

1. G.L.Degtyarev, T.K.Sirazetdinov. Teoreticheskie osnovy optimalnogo upralvleniyz uprugimi kosmicheskimi apparatami. – M.: Mashinostroenie, 1986. – 216 s. (in Russian)
2. A.P.Alpatov, P.A.Belonozhko, V.V.Gorbuntsov, O.G.Ivlev, S.S.Chernyavskaya, V.N.Shichanin. Dinamika prostranstvenno razvityh mekhanicheskih system izmenyaemoy konfiguratsii. – K.: Naukova dumka, 1990. – 256 s. (in Russian)
3. V.Yu.Rutkovskiy, V.M.Sukhanov. Bolshie kosmicheskie konstruktsii: modeli, metody issledovaniya I printsipy upravleniya. I. // Avtomatika I telemekhanika. – 1996. – No. 7. – S. 52 – 65. (in Russian)
4. V.Yu.Rutkovskiy, V.M.Sukhanov. Bolshie kosmicheskie konstruktsii: modeli, metody issledovaniya I printsipy upravleniya. II. // Avtomatika I telemekhanika. – 1996. – No. 8. – S. 55 – 66. (in Russian)
5. N.V.Banichuk, I.I.Karpov, D.M.Klimov, A.P.Markeev, B.N.Sokolov, A.V.Sharanyuk. Mekhanika bolshikh kosmicheskikh konstruktsiy. – M.: Faktorial, 1997. – 302 s. (in Russian)
6. M.Z.Zgurovskiy, P.I.Bidyuk. Analiz i upravlenie bolshimi kosmicheskimi konstruktsiyami. / Natsionalniy tekhnicheskiy un-t Ukrainy "Kievskiy politekhnicheskiy in-t". – K.: Naukova dumka, 1997. – 451 s. (in Russian)
7. S.D.Zemlyakov, V.Yu.Rutkovskiy, V.M.Sukhanov. Nekotoriye problemy uprableniya pri robotizirovannoy sborke bolshikh kosmicheskikh konstruktsiy na orbite. // Avtomatika i telemekhanika. – 2006. – No. 8. – S. 36 – 50. (in Russian)
8. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, S.V.Grigoryev, A.A.Fokov. Aktualnie zadachi dinamiki kosmicheskikh apparatov s prostranstvenno razvitymi periferiynymi elementami. // Tekhnicheskaya mekhanika – 2007. – No. 2. – S. 32 – 38. (in Russian)
9. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, A.A.Vitushkin, A.A.Fokov. Bolshiye otrazhayushiye poverkhnosti v kosmose. Antenny sputnikovoy svyazi. // Systemniye tekhnologii – 2007. – No. 3(50). – S. 73 – 87. (in Russian)
10. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, A.A.Vitushkin, A.A.Fokov. Bolshiye otrazhayushiye poverkhnosti v kosmose. Radioteleskopy, solnechniye kontsentratory, ploskiye otrazhateli. // Systemniye tekhnologii – 2007. – No. 3(50). – P. 88 – 101. (in Russian)
11. A.L.Alpatov, V.V.Beletskiy, V.I.Dranovskiy, A.E.Zakrzhevskiy, A.V.Pirozhenko, G.Troger, V.S.Khoroshilov. Dinamika kosmicheskikh sistem s trosovymi i charnirnymi

soedineniyami. / – Moskva-Izhevsk: NITs «Regulyarnaya i khaoticheskaya dinamika», Institut kompyuternikh issledovaniy, 2007. – 506 s. (in Russian)

12. A.E.Zakrzhevskiy. Ob optimalnom ugle razvorota uprugogo kosmicheskogo apparata. // Prikladnaya mekhanika – 2003. – t. 39. – No. 1. – S. 106 – 113. (in Russian)
13. V.I.Gulyaev, I.S.Efremov, A.G.Chernyavskiy, V.L.Koshkin, V.K.Bondar, Yu.A.Shinkar. Dinamika orbitalnoy stantsii s protyazhennoy Fermoy. // Kosmicheskiye issledovaniya – 1994. – T.32, vyp.2 – S. 61 – 70. (in Russian)
14. A.A.Alyamovskiy, A.A.Sobachkin, E.V.Odintsov, A.I.Kharitonovich, N.B.Ponomarev. SolidWorks. Kompyuternoye modelirovanie v inzhenernoy praktike. / – SPb.: BHV-Peterburg, 2005. – 800 p. (in Russian)
15. http://real.uwaterloo.ca/~mbody
16. http://www.umlab.ru
17. V.M.Glumov, S.D.Zemlyakov, V.Yu.Rutkovskiy, V.M.Sukhanov. Modalno-physichexkaya model prostranstvennogo uglovogo dvizheniya deformiruemogo kosmicheskogo apparata i ee svoistva. // Avtomatika i telemekhanika. – 1998. – No. 12. – S. 38 – 50. (in Russian)
18. O.N.Dmitrochenko, N.N.Mikhailov, D.Yu.Pogorelov. / Modelirovanie geometrichesky nelineynykh uprugikh sterzhnevikh system tverdotelnymi konechnymi elementami. // Dinamika I prochnost transportnykh mashin // Sb. nauchn. trudov pod red. V.I.Sakalo. – Bryansk : Izd-vo BGTU, 1998. – S. 33–39. (in Russian)
19. D.P.Molenaar. Cost effective design and operation of variable speed wind turbines / D. P. Molenaar. – DUP Science, Delft, The Netherlands, 2003. – http://repository.tudelft.nl/file/80647/007206.
20. P.A.Belonozhko, P.P.Belonozhko, A.A.Fokov. Sopostavlenie mekhanizheskikh raschetnykh skhem prostranstvenno razvitykh kosmicheskikh obyektov metodom sravneniya peredatochnykh funktsiy. // Sbornik dokladov i tezisov mezhdunarodnoy nauchno-prakticheskoy konferentsii «Informatsionnye tekhnologii v upravlenii slozhnymi sistemami» (22-23 May 2008, Dnepropetrovsk). – Dnepropetrovsk: 2008. – S. 81–82. (in Russian)
21. P.A.Belonozhko, P.P.Belonozhko, A.A.Fokov. Ispolzovaniye apparata peredatochnykh funktsiy dlya opredeleniya parametrov mekhanicheskogo ekvivalenta periferiynogo protyazhennogo uprugogo elementa v sostave KA. // Sbornik dokladov i tezisov mezhdunarodnoy nauchno-prakticheskoy konferentsii «Informatsionnye tekhnologii v upravlenii slozhnymi sistemami» (22-23 May 2008, Dnepropetrovsk). – Dnepropetrovsk: 2008. – S. 83. (in Russian)
22. A.A.Fokov. Peredatochnie funktsii raspredelennogo uprugogo periferiynogo elementa v sostave KA v zadache opredeleniya parametrov ego mekhanicheskogo ekvivalenta. // Sistemnie tekhnologii. Regionalniy mezhvuzovskiy sbornik nauchnykh trudov. – 2008. – No.5. – S.27-36 (in Russian)
23. P.P.Belonozhko. Predstavleniye deformiruemykh uprugikh elementov kosmicheskikh apparatov sistemami tverdykh tel. // Sistemnyie tekhnologii. Regionalniy mezhvuzovskiy sbornik nauchnykh trudov. – 2008 – No.5(58). – S.3-16 (in Russian)
24. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, A.A.Fokov. Predstavlenie deformiruemykh prostranstvenno razvitykh periferiynykh elementov kosmicheskikh apparatov sovokupnostyami tverdykh tel. // Vtoraya Mezhdunarodnaya konferentsiya «Peredovie kosmicheskie tekhnologii na blago chelovechestva», Dnepropetrovsk, Ukraine, 15-17 April 2009. – Dnepropetrovsk: 2009. – S. 17. (in Russian)
25. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, A.A.Fokov. Ispolzovanie konechnomernykh raschetnykh skhem dlya issledovaniya dinamiki kosmicheskikh

apparatov s protyazhennymi uprugimi elementami konstruktsii. // Shestoy mezhdunarodniy aerokosmicheskiy kongress IAC'09, 23-27 August 2009. Tezisy dokladiv. – Moskva, Rossiya : 2009. – S. 20 (in Russian)

26. P.A.Belonozhko, P.P.Belonozhko, A.A.Fokov. Ob ekvivalentnosti mekhanicheskikh raschetnikh skhem s raspredelennymi i sosredotochennymi parametrami dlya prostranstvenno razvitykh periferiynykh elementov kosmicheskikh apparatov. // Tekhnicheskaya mekhanika. – 2009. – No. 3. – S. 77–86. (in Russian)
27. P.P.Belonozhko. Ob optimalnom vybore parametrov raschetnoy skhemy periferiynogo elementa kosmicheskogo apparata. // Tekhnicheskaya mekhanika. – 2009. – No.4. – S.77–86. (in Russian)
28. A.A.Fokov. Osobennosti vybora peredatochnykh funktsiy v zadache opredeleniya parametrov mekhanicheskogo ekvivalenta raspredelennogo uprugogo periferiynogo elementa KA. // Tekhnicheskaya mekhanika 2009. – No.4. – S.87-93 (in Russian)
29. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, A.A.Fokov. Ob ekvivalentnosti raschetnukh skhem uprugo deformiruemykh elementov kosmicheskikh konstruktsiy. // Trudy XXXIV akademicheskikh chteniy po kosmonavtike, 26-29 January 2010. – Moskva, Rossiya: 2010. – S. 371-372. (in Russian)
30. A.P.Alpatov, P.A.Belonozhko, P.P.Belonozhko, S.V.Tarasov, A.A.Fokov, L.K.Kuzmina. Modelirovanie dinamiki prostranstvenno razvitykh mekhanicheskikh system kosmicheskogo naznacheniya s ispolzovaniem sovremennykh kompyuternykh instrumentov. // Trudy XXXVII akademicheskikh chteniy po kosmonavtike, 29 January – 1 February 2013. – Moskva, Rossiya: 2013. – S. 547 (in Russian)
31. Lyudmila K.Kuzmina. A.M.Lyapunov methodology in modelling and dynamics analysis of stabilization and orientation systems. Proc. e-book version of 23-rd ISSFD Symposium. JPL-NASA, USA, 2012, 1-13. https://issfd.jpl.nasa.gov/home/assets/papers/ISSFD23.zip
32. Lyudmila K.Kuzmina. To reduction principle in dynamics of complex nonlinear systems. Proc. PhysCon2013, e-Book version, IPACS, 1-4.

Alpatov Anatoliy Petrovich, Graduated from Aircraft Department of Kazan Aviation Institute. Doctor of engineering sciences, Professor. Head of Department of system analysis and control problems of the Institute for Engineering Mechanics of the National Academy of Sciences of Ukraine and National Space Agency of Ukraine. Scientific interests: system analysis, dynamics of controlled motion of complex space systems, dynamics of space vehicles with magnetic control systems, mobile control of mechanical systems.

Belonozhko Petr Alexeevich, Graduated from Department of Physics and Engineering of Dnepropetrovsk State University. Candidate of engineering sciences. Senior Researcher at Department of system analysis and control problems of the Institute for Engineering Mechanics of the National Academy of Sciences of Ukraine and National Space Agency of Ukraine. Scientific interests: dynamics of spatially complex mechanical systems of variable configuration, control of complex space systems.

Belonozhko Pavel Petrovich, Graduated from Department of Physics and Engineering of Dnepropetrovsk State University. Candidate of engineering sciences. Senior Researcher at Department of system analysis and control problems of the Institute for Engineering Mechanics of the National Academy of Sciences of Ukraine and National Space Agency of Ukraine. Scientific interests: dynamics of spatially complex mechanical systems of variable configuration, control of complex space systems.

Lyudmila K. Kuzmina, principal Scientist, Dr.,Prof., Head of Russian Centre of International Federation of Nonlinear Analysts. Scientific research area : the development of A. M. Lyapunov theory methods for dynamics problems of complex multidisciplinary systems of singularly perturbed class.

Tarasov Sergey Vasileyvich, Graduated from Department of Physics and Engineering of Dnepropetrovsk State University. Candidate of engineering sciences. Leading Researcher at the Institute of Transport Systems and Technology of the National Academy of Sciences of Ukraine. Scientific interests: dynamics of spatially complex mechanical systems of variable configuration, control of complex space systems.

Fokov Alexander Anatolyevich, Graduated from Department of Physics and Engineering of Dnepropetrovsk State University. Candidate of engineering sciences. Senior Researcher at Department of system analysis and control problems of the Institute for Engineering Mechanics of the National Academy of Sciences of Ukraine and National Space Agency of Ukraine. Scientific interests: dynamics of spatially complex mechanical systems of variable configuration, control of complex space systems.

Optimization of lunar mission of a space vehicle with electrojet engine

O. Starinova, I. Materova
Samara State Aerospace University, "TSKB-Progress"
Russia, Samara

The paper deals with optimal fuel consumption during the flight of a spacecraft with a low-thrust engine to a near-circular selenocentric orbit of given radius. Examples of optimal trajectories for a spacecraft with one or two electric thrusters intended for the flyby at angular distance of 6 and 50 degrees to the Moon were considered. Control laws were optimized and the corresponding trajectories of the spacecraft with a low-thrust engine intended for transportation within the Earth-Moon system were obtained in the framework of the restricted three-body problem. Influence of the Earth and the Moon on the spacecraft is accounted for during the whole flight by introduction of additional acceleration into the motion equations. These accelerations are gained by the spacecraft owing to these planets' gravity fields.

Background and problem statement

The subject of research is the problem of minimal flow rate of the working substance in conditions of spacecraft flight from geocentric injection orbit to closed selenocentric orbit (Fig.1) and the problem of formation of operational orbit around the Moon. Formalism on the basis of Pontryagin's maximum principle seems to be an efficient solution method. It allows obtaining the necessary conditions of optimality of control laws for the Earth-Moon flight section. Transversality conditions can be discussed and corresponding boundary problems can be stated for different boundary conditions. Deceleration segment calculation and operational orbit computation can be performed on the basis of an interactive algorithm based upon three simple control laws introduced by V.N.Lebedev to reduce the orbit eccentricity and radius.

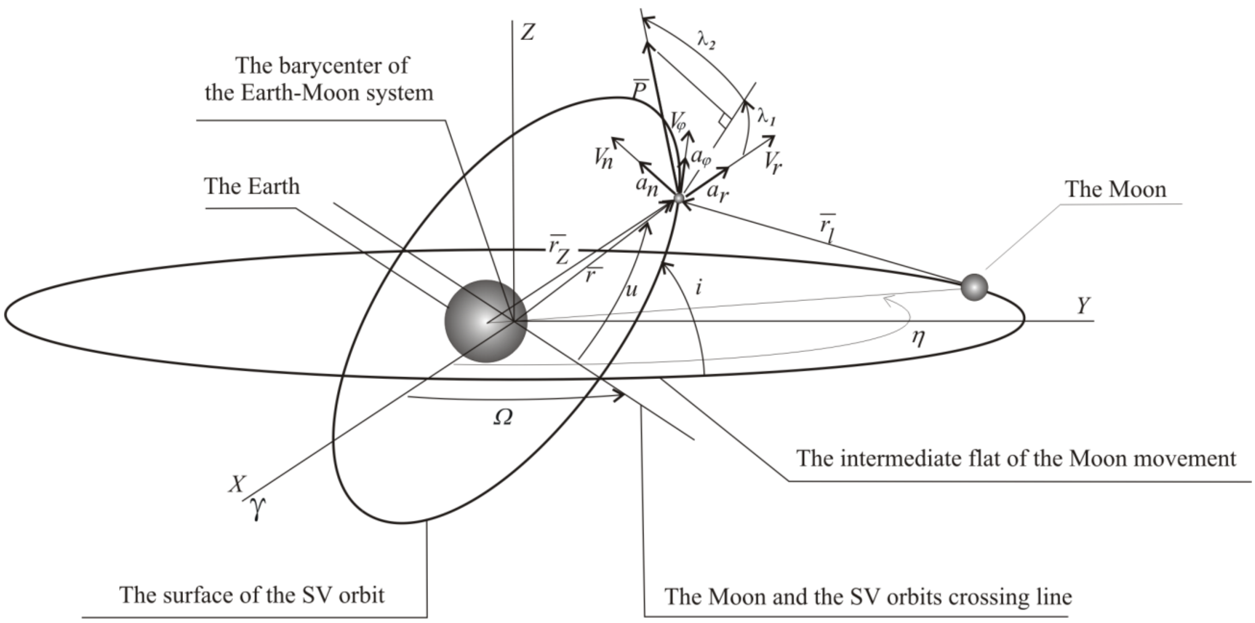


Fig. 1. The inertial polar barycenter system of coordinates

The present paper supposes that the space vehicle (SV) is delivered to the circle the Earth orbit by rocket.
But the orbit surface doesn't coincide with intermediate flat of the Moon's orbiting (Fig. 1). Flight trajectory is divided into two parts:

- the section in which SV travels under the Earth and the Moon gravity;
- the section of the Moon-orbiting mission.

1. The Optimization of SV movement under the Earth and the Moon Gravity

The spatial equations within the framework of restricted three-body problem are:

$$
\begin{aligned}
&\frac{dr}{dt} = V_r, \qquad (1)\\
&\frac{du}{dt} = \frac{V_\varphi}{r} - \frac{\cos i \ \sin u \ \sin\lambda_2 \ a}{\sin i \ V_\varphi} + \left(f_{n\,l} + f_{n\,z}\right)\frac{\cos i \ \sin u}{\sin i \ V_\varphi},\\
&\frac{dV_r}{dt} = \frac{V_\varphi^2}{r} + f_{rz} + f_{rl} + \cos\lambda_2 \ \cos\lambda_1 \ a,\\
&\frac{dV_\varphi}{dt} = -\frac{V_r V_\varphi}{r} + f_{\tau\,z} + f_{\tau\,l} + \cos\lambda_2 \ \sin\lambda_1 \ a,\\
&\frac{d\Omega}{dt} = \frac{\sin u \ \sin\lambda_2 \ a}{\sin i \ V_\varphi} + \left(f_{n\,z} + f_{n\,l}\right)\frac{\sin u}{\sin i \ V_\varphi},\\
&\frac{di}{dt} = \frac{\cos u \ \sin\lambda_2 \ a}{V_\varphi} + \left(f_{n\,z} + f_{n\,l}\right)\frac{\cos u}{V_\varphi},\\
&\frac{d\overline{m}}{dt} = \frac{a_0\delta}{c}, \qquad a = \frac{a_0\delta}{\left(1-\overline{m}\right)}.
\end{aligned}
$$

Here u is an argument of latitude;
r - vector which defines the position of SV relative to barycenter of the Earth-Moon system;
V_r, V_φ - constituents of velocity vector relative to the barycenter of the Earth-Moon system;
i - SV orbit inclination concerning intermediate Moon orbiting;
Ω - longitude of SV orbit node relative to intermediate Moon orbiting;
λ_1, λ_2 - control angles for space vehicle thrust vector;
$\mu_l \approx 0.0123$ – ratio of lunar mass to the total mass of the Earth-Moon system;
a_0 - nominal dimensionless engine acceleration;
c – dimensionless speed of fuel discharge;
δ - thrust on-off function;

$\overline{m} = \frac{m_{PT}}{m_0}$ - relative fuel consumption.

In the system (1) $\bar{f}_z = \begin{pmatrix} f_{r\,z} \\ f_{\tau\,z} \\ f_{n\,z} \end{pmatrix}$ is the acceleration vector, which SV gets as a result of Earth gravity action,

$\bar{f}_l = \begin{pmatrix} f_{r\,l} \\ f_{\tau\,l} \\ f_{n\,l} \end{pmatrix}$ - acceleration vector, which SV gets as a result of lunar gravity action, in the form of projections on coordinate system axes OXYZ (Figure 1), they are written as:

$$\bar{f}_z = \begin{pmatrix} f_{x\,z} \\ f_{y\,z} \\ f_{z\,z} \end{pmatrix} = -(1-\mu_l)\cdot \begin{pmatrix} \dfrac{r\cdot(\cos\Omega\cdot\cos u - \sin\Omega\cdot\cos i\cdot\sin u) + R_z\cdot\cos\eta}{|r_z|^3} \\ \dfrac{r\cdot(\sin\Omega\cdot\cos u - \cos\Omega\cdot\cos i\cdot\sin u) + R_z\cdot\sin\eta}{|r_z|^3} \\ \dfrac{r\cdot\sin i\cdot\sin u}{|r_z|^3} \end{pmatrix} \qquad (2)$$

$$\bar{f}_l = \begin{pmatrix} f_{x\,l} \\ f_{y\,l} \\ f_{z\,l} \end{pmatrix} = -\mu_l\cdot \begin{pmatrix} \dfrac{r\cdot(\cos\Omega\cdot\cos u - \sin\Omega\cdot\cos i\cdot\sin u) - R_l\cdot\cos\eta}{|r_l|^3} \\ \dfrac{r\cdot(\sin\Omega\cdot\cos u - \cos\Omega\cdot\cos i\cdot\sin u) - R_l\cdot\sin\eta}{|r_l|^3} \\ \dfrac{r\cdot\sin i\cdot\sin u}{|r_l|^3} \end{pmatrix}$$

here R_z - vector, which defines the Earth state relative to the barycenter of the Earth-Moon system;

R_l - vector which defines the Moon state relative to the barycenter of the Earth-Moon system;

η - the Moon position in its orbit relative to axis X;

r_l - vector, which defines SV state relative to the Moon;

r_z - vector, which defines the SV state relative to the Earth;

$\bar{r}_z = \begin{pmatrix} r\cdot(\cos\Omega\cdot\cos u - \sin\Omega\cdot\cos i\cdot\sin u) - R_z\cdot\cos\eta \\ r\cdot(\sin\Omega\cdot\cos u - \cos\Omega\cdot\cos i\cdot\sin u) - R_z\cdot\sin\eta \\ r\cdot\sin i\cdot\sin u \end{pmatrix}$ - vector, which defines the position of the SV relative to the Earth;

$\bar{r}_l = \begin{pmatrix} r\cdot(\cos\Omega\cdot\cos u - \sin\Omega\cdot\cos i\cdot\sin u) - R_l\cdot\cos\eta \\ r\cdot(\sin\Omega\cdot\cos u - \cos\Omega\cdot\cos i\cdot\sin u) - R_l\cdot\sin\eta \\ r\cdot\sin i\cdot\sin u \end{pmatrix}$ - vector, which defines the position of the SV relative to the Moon.

Projections of accelerations $\bar{f}_z$ and $\bar{f}_l$ on natural coordinate system axes are the following:

$$\bar{f}_z = \begin{pmatrix} f_{r\,z} \\ f_{\tau\,z} \\ f_{n\,z} \end{pmatrix} = -\frac{1-\mu_l}{|r_z|^3} \cdot \begin{pmatrix} r + R_z \cdot (\cos(\eta-\Omega)\cos u + \sin(\eta-\Omega)\sin u \cos i) \\ R_z \cdot (-\cos(\eta-\Omega)\sin u + \sin(\eta-\Omega)\cos u \cos i) \\ -R_z \cdot \sin(\eta-\Omega)\sin i \end{pmatrix} \tag{3}$$

$$\bar{f}_l = \begin{pmatrix} f_{r\,l} \\ f_{\tau\,l} \\ f_{n\,l} \end{pmatrix} = -\frac{\mu_l}{|r_l|^3} \cdot \begin{pmatrix} r - R_l \cdot (\cos(\eta-\Omega)\cos u + \sin(\eta-\Omega)\sin u \cos i) \\ R_l (-\cos(\eta-\Omega)\cdot \sin u + \sin(\eta-\Omega)\cos u \cos i) \\ R_l \sin(\eta-\Omega)\sin i \end{pmatrix}$$

To explore the problem of three bodies (the Earth, the Moon, SV), the minimum fuel consumption is used as an optimal criterion:

$$M_{PT} = \int_0^T \delta\beta dt \to \min , \tag{4}$$

here M_{PT} - fuel mass; β - fuel consumption per second.

The vector of SV phase coordinates $\overline{X} = (r, \;\; u \;\; V_r, \;\; V_\varphi, \; \Omega, \;\; \text{i}, \;\; \overline{m})^T$ is introduced. Formally the optimization problem is determined so: it is necessary to find the control function $\overline{\varepsilon}(t) = (\lambda_1(t), \lambda_2(t), \delta(t))^T$ from possible E set satisfying boundary conditions $\overline{X}(t_0) = \overline{X_0}$, $\overline{X}(T) = \overline{X_K}$ and supplying minimum of optimal criterion (4) at the fixed vector of designed parameters $\overline{p} = \{a_0, \;\; c\}^T$:

$$\overline{\varepsilon}_{opt}(t) = \arg\min_{\overline{\varepsilon}(t)} M_{PT}\left(\overline{\varepsilon} \middle| \overline{p} = fixe, \overline{X}_0 = fixe, \overline{X}_K = fixe\right). \tag{5}$$

In accordance with Pontryagin's principle of maximum, the vector of conjugate variables is $\overline{P} = \begin{pmatrix} P_r, & P_u, & P_{V_r}, & P_{V_\varphi}, & P_\Omega, & P_i, \, P_{\overline{m}} \end{pmatrix}^T$ and Hamiltonian is as follows:

$$H = P_r \cdot \{V_r\} + P_u \cdot \left\{ \frac{V_\varphi}{r} - \frac{\cos i \cdot \sin u \cdot \sin \lambda_2 \cdot a}{\sin i \cdot V_\varphi} + (f_{nl} + f_{nz}) \cdot \frac{\cos i \cdot \sin u}{\sin i \cdot V_\varphi} \right\} + \tag{6}$$

$$+ P_{V_r} \cdot \left\{ \frac{V_\varphi^2}{r} + f_{rz} + f_{rl} + \cos\lambda_2 \cdot \cos\lambda_1 \cdot a \right\} + P_{V_\varphi} \cdot \left\{ -\frac{V_r \cdot V_\varphi}{r} + f_{\tau z} + f_{\tau l} + \cos\lambda_2 \cdot \sin\lambda_1 \cdot a \right\} +$$

$$+ P_\Omega \cdot \left\{ \frac{\sin u \cdot \sin\lambda_2 \cdot a}{\sin i \cdot V_\varphi} + (f_{nl} + f_{nz}) \cdot \frac{\sin u}{\sin i \cdot V_\varphi} \right\} + P_i \cdot \left\{ \frac{\cos u \cdot \sin\lambda_2 \cdot a}{V_\varphi} + (f_{nl} + f_{nz}) \cdot \frac{\cos u}{V_\varphi} \right\} +$$

$$+ P_{\overline{m}} \cdot \left\{ \frac{a_0 \cdot \delta}{c} \right\}$$

The optimal direction of SV acceleration vector $\lambda_{1opt}(t)$, $\lambda_{2opt}(t)$ and SV thrust on-off function δ are obtained from Hamiltonian's maximum conditions:

$$\sin\lambda_{1opt} = \frac{P_{V_\varphi}}{\sqrt{{P_{V_r}}^2 + {P_{V_\varphi}}^2}} \tag{7}$$

$$\cos\lambda_{1opt} = \frac{P_{V_r}}{\sqrt{{P_{V_r}}^2 + {P_{V_\varphi}}^2}}$$

$$\sin\lambda_{2opt} = \frac{P_u \cdot \frac{\cos i \cdot \sin u}{\sin i \cdot V_\varphi} + P_\Omega \cdot \frac{\sin u}{\sin i \cdot V_\varphi} + P_i \cdot \frac{\cos u}{V_\varphi}}{\sqrt{\left\{P_{V_r} \cdot \cos\lambda_{1opt} + P_{V_\varphi} \cdot \sin\lambda_{1opt}\right\}^2 + \left\{P_u \cdot \frac{\cos i \cdot \sin u}{\sin i \cdot V_\varphi} + P_\Omega \cdot \frac{\sin u}{\sin i \cdot V_\varphi} + P_i \cdot \frac{\cos u}{V_\varphi}\right\}^2}}$$

$$\cos\lambda_{2opt} = \frac{P_{V_r} \cdot \cos\lambda_{1opt} + P_{V_\varphi} \cdot \sin\lambda_{1opt}}{\sqrt{\left\{P_{V_r} \cdot \cos\lambda_{1opt} + P_{V_\varphi} \cdot \sin\lambda_{1opt}\right\}^2 + \left\{P_u \cdot \frac{\cos i \cdot \sin u}{\sin i \cdot V_\varphi} + P_\Omega \cdot \frac{\sin u}{\sin i \cdot V_\varphi} + P_i \cdot \frac{\cos u}{V_\varphi}\right\}^2}}$$

here

$$\delta = \begin{cases} 0, & \Delta < 0 \\ 1, & \Delta > 0 \end{cases}, \tag{8}$$

$$\Delta = -P_u \cdot \frac{\cos i \cdot \sin u \cdot \sin\lambda_2}{\sin i \cdot V_\phi} + P_{V_r} \cdot \cos\lambda_2 \cdot \cos\lambda_1 + P_{V\phi} \cdot \cos\lambda_2 \cdot \sin\lambda_1 +$$

$$+ P_\Omega \cdot \frac{\sin u \cdot \sin\lambda_2}{\sin i \cdot V_\phi} + P_i \cdot \frac{\cos u \cdot \sin\lambda_2}{V_\phi} + P_{\overline{m}} \frac{a_0 \cdot (1 - \overline{m})}{c}$$

So the problem of optimization of optimal consumption during the spatial SV movement in the Earth-Moon system comes to a two-point twelve-parameter boundary problem with conjugate variables defined in vector form:

$$\frac{dP_i}{dt} = -\frac{\partial H}{\partial x_i}, \quad x_i \in \overline{X}, \quad P_i \in \overline{P}.$$

It is necessary to find such initial values of conjugate variables P_r, P_{V_r} P_{V_φ}, P_Ω, P_i, $P_{\overline{m}}$, P_u whose starting and ending conditions are complied at the optimal trajectory edges $\overline{X}(t_0) = \overline{X}_0$, $\overline{X}(T) = \overline{X}_T$.

Let the starting orbit is a circle and SV location relative to the Moon at the first moment is φ_0, in this case the initial vector of phase variable is assigned with values:

$$\overline{X}_0 = \left(\frac{r_0}{R_l}, \quad \varphi_0, \quad V_{r0} = 0, \quad V_{\varphi 0} = \sqrt{\frac{R_l}{r_0}}, \quad i_0, \quad \Omega_0\right)^T.$$

Final vector of SV phase variables for the Moon flyby at fixed angular distance $\Delta\varphi_k = \varphi_\kappa - \eta$

at unfixed velocity vector $\overline{V}_T = \left(V_{rT}, \quad V_{\varphi T}\right)^T$ with transversal conditions for the velocity vector is:

$$\overline{X}_T = \left(1, \quad \varphi_k, \quad P_{V_r} = 0, \quad P_{V_\varphi} = 0, \quad P_{\overline{m}} = -1, \quad i_l, \quad \Omega_l\right)^T.$$

After SV gets into the Moon action area, it starts inhibiting and forming the near-circle Moon-center orbit. In this case the model (1) – (3) is simplified and reduced to the system described in the paper [1].

2. The section of the Moon-Centre trajectory of SV

The problem of formation of near-circle Moon-centre orbit is solved by three simple laws proposed by Lebedev for inhibition, decrease of orbit eccentricity and radius.
At the initial inhibition stage directly after SV comes into the planet action area (up to the moment of parabolic speed achievement), the tangential control law decreasing SV velocity is used [2]:

$$\lambda = -\frac{\pi}{2} \tag{9}$$

depending on eccentricity value, the velocity decrease (tangential thrust) or the eccentricity reduction takes place according to the law [2]:

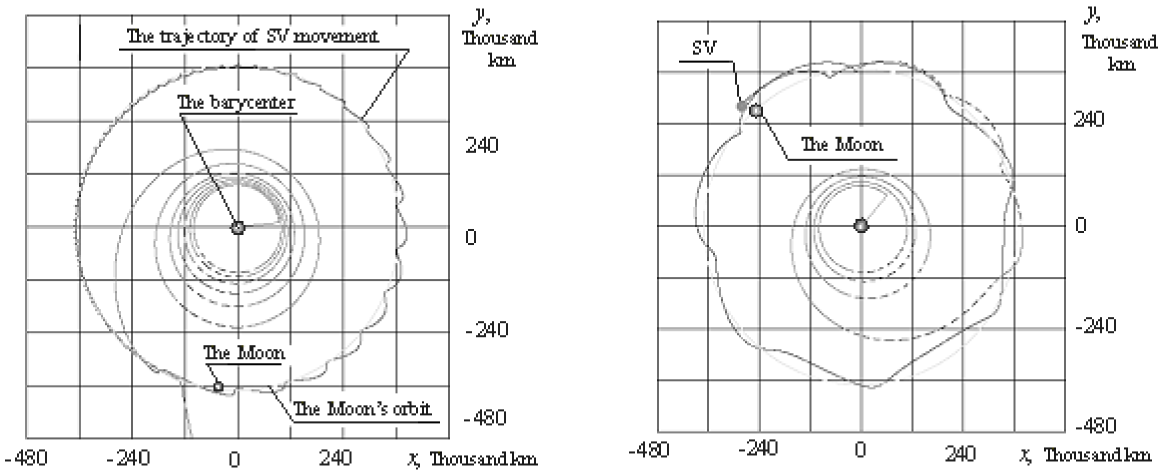
$$tg\lambda = -\frac{e \cdot \cos^2 \upsilon + 2 \cdot \cos \upsilon + e}{\sin \upsilon \cdot (1 + e \cdot \cos \upsilon)} \tag{10}$$

then if a near-circle orbit radius is not equal to the required one, the law of decrease of the largest half-axis is used [2]:

$$tg\lambda = -\frac{1 + e \cdot \cos \upsilon}{e \cdot \sin \upsilon} \tag{11}$$

3. The results of SV motion modeling

The modeling of SV movement comes to solving of Koshy's problem for system of differential movement equations, conjugate variables and optimal control. For its numerical decision the Runge-Kutta's method of fourth order with stable step was used.
Design objectives of apparatus are equal to parameters of ESA's research space vehicle SMART-1: m_0 = 400 kg, c = 15 km/s.
To solve boundary problem about optimal inhibition's migration in the Earth-Moon system modified Newton's method with automatic evaluation of convergence and variable calculation step of defining derivatives and limits on increase was applied. For decision with variable value of design objectives and edge conditions of mission the method of continuing on parameters was used.
The following results come from this paper.
It seems that the Moon gravitation greatly influenced the optimal control law and the corresponding motion trajectory. For example, fig. 2 shows the optimal Moon flyby trajectory at the angular distance of 6° starting from the circular orbit a_0 =100000 km. The motion with a turned-on engine and optimal thrust direction is shown by a solid line. Dotted line illustrates the passive SV movement trajectory after completing the mission and engine cut-off.



а) б)

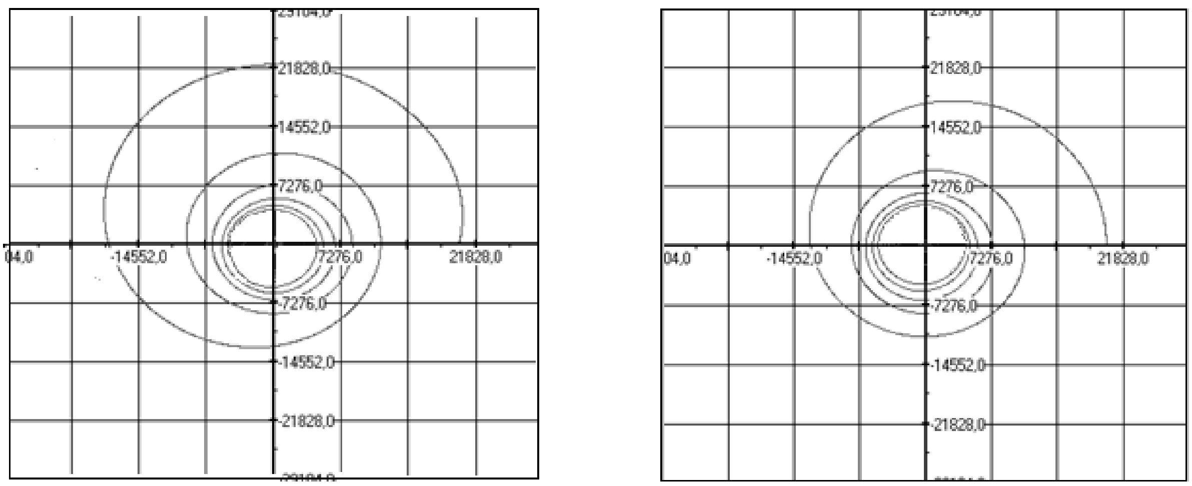
Fig. 2. The optimal fuel consumption trajectory of the Moon flyby for a SV with mass m_0 = 400 kg and electric thruster fuel discharge c = 15 km/s:

а) T = 45 days, P=0.1 N; $\Delta\varphi_0 = 6°$, $\Delta\varphi_k = 7°$, m = 21 kg;

б) T = 35 days, P=0.2 N; $\Delta\varphi_0 = 50°$, $\Delta\varphi_k = 3°$, m = 23 kg.

After SV achieves the Moon action area, recalculation of flight parameters is accomplished from the inertial polar barycenter system of coordinates to the Moon-centre system of coordinates. In accordance with methodology (described in section 2) the motion modeling is realized.

The formation of the Moon-centre orbit of SV for events a) and b) (fig. 2) is shown in the fig. 3.



а) б)

Fig. 3 – The near-centre Moon-circle orbit formation
(T = 11, 50 days, e=0.09, r=5000.00 km)

Conclusion

So the applied methodology demonstration its effectiveness for optimization of complex multiple-turn SV trajectory with law thrust engines within two bodies' gravity field. Findings may be used to solve problems of assigned the Moon-center orbit formation.

Thus, the submitted procedure demonstrated its efficiency for optimization of complex multiple-pass motion trajectories of spacecrafts with low-thrust engines in the field of attraction of two bodies. The obtained optimal control laws and corresponding motion trajectories can be used to solve the problems of formation of given selenocentric orbits.
The developed software is intended for the numerical solution of boundary problems and is based upon the algorithm of modified Newton approach. Results obtained for the problems of optimal coplanar flights in the Earth-Moon system are taken as the initial values of conjugated variables. To optimize the flights with different initial ballistic conditions and spacecrafts with different design parameters, the parameter marching method was used.
A 400 kg spacecraft with 0.1 N thrust and 15 km/s discharge velocity was considered as an example. Numerical results were obtained concerning the formation of a near-circular selenocentric orbit for the given spacecraft parameters and different initial ballistic conditions of flights.

References

1. O. Starinova. The optimization of SV with low thrust propulsion system travel in the Earth-Moon system. // The bulletin of SSC RAS № 3, 2006 – 9 p. (in Russian)
2. V. Lebedev. The calculation of movement of SV with low thrust propulsion system. - M.: CC AS UCCR, 1968.- 108 p. (in Russian)

Olga Starinova (Samara State Aerospace University named after academician S.P. Korolev**),** professor of the Department of Flight Vehicles. Scientific researches: dynamic systems' control, interplanet missions by space vehicles with low thrust propulsion systems.

Irina Materova (Samara State Aerospace University named after academician S.P. Korolev**),** postgraduate student of the Department of Flight Vehicles, investigates under guidance of Starinova Olga.

TsNIIMash and the works on reusable space system "Energia-Buran"

A.G.Milkovskiy, M.N.Kovbich
TsNIIMash Federal State Unitary Enterprise
4 Pionerskaya str., Korolev, Moscow Region, 141070, Russia

Introduction

TsNIIMash is one of the largest Russian research and test centers, which is involved in all Russian developments in rocket and space engineering and participates in most of international space Programs and Projects, in which Russia is taking part.
It should be noted that according to the Decree No.132-51 dated 16 February 1976, TsNIIMash has become the head contractor performing research of strength, aerodynamic processes, heat transfer of reusable space systems and gas dynamics of launch; it participated in preparation of Mission Control Center to make it able to work with reusable space systems.

Historical background

The Institute was established according to the USSR Council of Ministers' Decree No.1017-419 dated 13 May 1946. This laid the foundation for Russian rocket building industry. State Research Institute for Jet Armament (NII-88) was established in Kaliningrad (since 1996 – Korolev city), Moscow Region. It was founded on the basis of ordnance plant No.88 as a leading scientific and production center for the development of long-range missiles, surface-to-air missiles, long-range cruise missiles and liquid propellant engines. In 1967, it was renamed into Central Research Institute for Machine Building.
At the beginning of 1950s, works on long-range ballistic missiles supervised by General Designer S.P.Korolev were very successful. NII-88 headed this area of developments. The first success in practical astronautics showed vast capabilities of application of rockets not only for the purposes of defense, but also for the national economy. Therefore rocket and space engineering made great advances, and the Institute kept playing its head role in it.
The first flight and development tests of the first Russian strategic missile R-5 were carried out in April 1953. R-5M missile capable of carrying a nuclear warhead to the distance of 1200 km was put into service in 1956.
In different years the Institute was headed by L.R.Gonor, K.N.Rudnev, M.K.Yangel, A.S.Spiridonov, G.A.Tyulin, Yu.A.Moszhorin, V.F.Utkin, N.A.Anfimov, G.G.Raikunov, N.G.Panichkin. At present (since 21 April 2014) Alexander Grigoryevich Milkovskiy is a General Director of the Institute.
An Interdepartmental expert commission (IEC) responsible for development and testing of a new reusable space system (RSS) was founded at TsNIIMash in January 1977. The chairman of the Commission was an outstanding scientist and the head of TsNIIMash at that time U.A. Moszhorin. His deputies were the head of Central Institute of Aerohydrodynamics P.P. Svischev and the Deputy Chief of the USSR Ministry of Defense Head Department of Space Means G.S. Titov.
Thus, from the very beginning TsNIIMash became headquarters of the Commission. Scientists and specialists of the Institute provided operation of the IEC as well as scientific and technical maintenance of development works.

TsNIIMash as a head organization in the research of RSS strength analysis, studies of its dynamics, aero and gas dynamics, heat and mass transfer, thermal protection cover, was also responsible for
- component reliability, sufficiency of their on-ground tryout;
- temperature conditions, gas dynamic behavior during orbital flight;
- heat transfer and gas dynamics of launch;
- mission control center preparation;
- regular systems’ telemetry data operational processing;
- provision of information to Telegraph Agency of Soviet Union (TASS) and mission control center and launch site reporters.

A comprehensive program of using “Energia-Buran” RSS for the benefit of national defense, economics and science was designed by the IEC in conjunction with the Central Research Institute of Machine Building (TsNIIMash).

System engineering

The system engineering department of TsNIIMash (headed by S.D.Grishin) was responsible for organizing development works, announcing conclusions of the IEC and executing an expert examination of project materials on the tasks and areas of their application, the overall design and construction of the RSS. Here is the list of main specialists responsible for this work: V.I.Bondarenko, L.P.Vasilyev, V.V.Vakhnichenko, S.D.Grishin, V.V.Daev, V.I.Dorofeev, A.F.Evich, B.I.Zheltetskiy, I.F.Zhuravlev, S.F.Kostromin, V.P.Senkevich, A.V.Tselin, S.V.Chekalin. The Department also took part in system research and substantiation of tasks of development of technical proposals, draft and technical design of “Energia-Buran” system.

Before this, the Institute performed some conceptual design research of possible purposes of RSS. A team of leading specialists of TsNIIMash was formed (headed by Ya.T.Shatrov) to study the flight safety systems. It allowed the development of the required recommendations in a number of engineering proposals.

The examination of project materials based on the national system was carried out with utmost care, which had a positive impact on the timing and phasing of the design and construction work: draft design and related supplements, technical design and related supplements, number of subsequent studies aimed at ensuring the flight safety. The “Energia-Buran” system was quite different from Space Shuttle (USA). Most notably, the cruise engines of the second stage were placed not on the orbiter itself, but on the rocket cluster, i.e. the carrier and the spacecraft were functionally separated. On the first stage standardized rocket packs operating on liquid oxygen and kerosene were used. The second stage operated on oxygen and hydrogen.

These and other engineering solutions, approved and supported by the IEC, provided the national RSS with a number of advantages in comparison with the Space Shuttle system, specifically, the universality of the RSS, i.e. its adaptation to different kinds of payloads (the ability to put into orbit Buran spacecraft and other payloads).

IEC provided complex control of quality and reliability of the development, particularly at the interface of works performed by different industrial branches and departments. IEC had so much work that up to 800 specialists from different scientific and design institutions were involved into some stages of expertise. IEC work groups with participation of the institute’s specialists covered the whole complex of design works: design and construction works on separate components and the system on the whole, development of technical, launch and landing systems, on-ground experimental tryout of “Energia-Buran” RSS and its flight tests.

IEC demanded, among other, the redundancy of main vital systems and units, the development of special means of emergency protection of cruise engines, which could provide the diagnostics of state of the latter and timely cut-off of these engines in case of emergency. The Commission demanded to analyze various emergency situations and make provisions for their compensation.

More than 2000 recommendations and comments of the Commission and its work groups were accounted for providing good preparation to the system flight tests. A.A.Eremenko's department provided information to Telegraph Agency of Soviet Union (TASS) and mission control center and launch site reporters.

Before "Energia-Buran" development started, in 1972-1973, scientific and pilot-study research of problems associated with RSS control systems development were conducted. The results enabled substantiation of the concepts of building the control system and the requirements imposed on an instrument set at different phases of orbiter flight.

Works on "Energia-Buran" were conducted in cooperation with Academician Pilyugin Center, S.P.Korolev Rocket and Space Center "Energia", SPA Molniya, "Mars" Moscow Experimental Design Bureau, Yu.A.Gagarin Research and Test Cosmonaut Training Center.

Main research results were the following:

- independent verification and validation of design materials were performed by simulation modeling of controlled motion of an orbiter at the stage of descent and landing using the algorithms developed by TsNIIMash ;
- the control of the descending trajectory during the «small» return maneuver of the orbiter was developed for the purpose of landing at the main aerodrome near the launch facility in case of emergency during the initial phase of the ascent trajectory;
- capabilities to safely descent the orbiter in case of its emergency separation from the launch vehicle in the «middle» part of the launch trajectory were also studied;
- end-to-end simulation of descent and landing trajectories enabled to show the possibility of guiding and landing of the orbiter to a number of supplementary aerodromes (Dzhezkazgan, Barnaul, Abakan, Belaya, Khorol, etc.);
- the ability to use on-board satellite navigation equipment (working on the basis of Uragan station signals) for Buran orbiter after an emergency separation during the descent and landing on an emergency aerodrome were demonstrated for the first time;
- options for the orbiter crew to control the trajectory limitations and perform manually controlled descent of the orbiter were developed.

The main results were reported in materials presented by TsNIIMash and later included in the preliminary design of NPO Molniya.

The works were performed by V.S.Lobanov, V.P.Sobolev, I.G.Zelyaletdinov, E.V.Zolotarev, V.N.Zboroshenko, A.K.Stepanova, A.V.Chikhalova, N.I.Voitenko.

Strength and dynamics tryout

This work was conducted in accordance with the Comprehensive Program of experimental development adopted by NPO «Energia» in conjunction with the developers of constituent parts.

In order to implement the aforementioned program, a site for complex thermal and structural tests was built between 1982 and 1984 on the territory of TsNIIMash . At the same time test beds for static and cryogenic experiments were built with the participation of the Institute specialists at the «Progress» factory in Samara.

In 1982, an engineering and manufacturing building was constructed in order to provide specialists from the dynamics division with opportunities to produce structurally similar models, including models of Energia launch vehicle on a scale of 1:5, aiming to help carry out dynamics testing of “Energia-Buran” system.

In strength laboratories of TsNIIMash 160 full-scale assemblies of “Energia-Buran” RSS were tested; it was more than 70% of the whole amount of strength tests. A considerable part of the experiments were static tests of the feed lines on the central block and its communication nodes with the Buran, blocks A and Ya, and low-temperature static tests of intertank and tail sections of block C (Ts). Vibration tests of the propellant lines, engines RD-170 and RD-0120, a series of vibration and shock test of the panels of Block C compartments with attached equipment were conducted.

A large amount of works were carried out by TsNIIMash specialists as a part of research of loads and simulation cases of the system structure loading, research and refinement of mechanical properties of new structural, thermal-protective and thermal insulating materials. A series of strength norms for a launch vehicle, an orbiter and propulsion systems was established. Strength analysis with reference to the design features and manufacturing methods was also performed.

An interagency team of experts led by A. Karmishin was formed for testing the strength of the unique engines for the system (liquid hydrogen, significant plastic deformation, multiple engine start, etc.). It included representatives of TsNIIMash, Design Bureau KBKhA, Research Institute of Precision Instruments, Central Institute of Aviation Motors (CIAM), A.A.Blagonravov Research Institute for Machine Science (IMASH AN USSR). As a result, issues of ensuring the strength of the nozzle block in the oxyhydrogen RD-0120 engine and high reliability of the entire propulsion system of “Energia-Buran” RSS were successfully solved.

Considerable contribution to the research of “Energia-Buran” strength and dynamics was made by A.V.Karmishin, N.G.Panichkin, O.P.Klimonov, A.I.Likhoded, A.A.Malinin, A.P.Malyshev, V.V.Matveev, B.V.Mogilniy, V.P.Molchanov, M.F.Nikitin, Ya.G.Osadchiy, V.L.Popov, V.M.Sannikov, S.N.Sukhinin, E.S.Shimusyuk, V.P.Shmakov, G.N.Mikishev, B.I.Rabinovich, V.G.Stepanenko, V.I.Safronov, Yu.A.Gorbunov, E.G.Bednyashin, Yu.Yu.Shveiko.

A program to create and test structurally-similar models of the system on a scale of 1:10 and 1:5 in order to determine the dynamic characteristics of the RSS was proposed and implemented as an alternative to an expensive long-term plan of building a full-scale dynamic stand at Baikonur. The most important result of the experimental research of “Energia-Buran” dynamics properties was the revealed influence of the play in the coupling of bottom chord of interunit connections on the lowest frequencies of elastic oscillations of the structure. It enabled to quickly improve these components and eliminate the difficulties which could otherwise arise when working with already designed control system. Flight and design tests confirmed the correctness of the recommendations and the performed improvements. According to the results of these model tests, a series of considerations were set out promptly, which allowed to efficiently finalize the design and to eliminate basic difficulties of the control system.

Consequently, strength and dynamics issues related to the design features and new manufacturing techniques were successfully solved, a series of dynamics and strength tests of the system were conducted. Bench runs and flight tests were provided for the launch vehicle «Energia» in 1987 and for “Energia-Buran” RSS in 1988.

Aero and gas dynamic research

Aero and gas dynamic tryout of "Energia-Buran" RSS was carried out at the aerodynamic installations of TsNIIMash in the range of Mach numbers 0.3-14.0. 80 scale models (from 1:200 to 1:50) studied more than 200 variants of the system and its elements, about 11,000 experiments were conducted. Gas dynamics tests of launch facilities were carried out in three stages.

1. On the basis of experimental data obtained using small-scale models, the design and construction of launch systems, as well as assessment of loads impacting the rocket during launch, were performed.
2. With the use of large-scale models of launch systems (1:10) all gas-dynamic, thermal, shock wave, acoustic characteristics were elaborated; possibilities of discrete vibration processes and their parameters were investigated under scientific and methodological guidance of the Institute in conjunction with Research and Test Center of Rocket and Space Industry (former NIIKHSM) and KB SM (Design Bureau of Mechanization).
3. The Institute developed projects of field measurement systems for full-scale launch facilities. The system provided control of gas-dynamic, shock wave, thermal, acoustic and digital oscillatory processes during the launch.

To provide the required accuracy and completeness of "Energia-Buran" RSS ground tests, the existing aero and gas dynamic installations and test benches were thoroughly modified and put into operation; new testing procedures, tools, means of measuring, methods and programs for determining aero and gas dynamic characteristics of the system and its elements were also developed.

The largest contribution into aero and gas dynamics tryout of "Energia-Buran" system and its components was made by (listed alphabetically): B.G.Beloshenko, N.A.Gorbushina, S.A.Gorokhov, B.N.Dankov, Yu.A.Demyanov, T.N.Dombrovskaya, V.V.Eremin, M.N.Kazakov, B.S.Kirnasov, V.V.Kislykh, V.V.Kudryavtsev, V.I.Lagutin, V.I.Lapygin, Yu.M.Lipnitskiy, T.S.Pankova, L.F.Pelipenko, I.A.Reshetin, A.M.Semenov, A.F.Syrchin, V.A.Khotulev, A.A.Churilin, V.I.Shein.

Complex studies on heat transfer and development of thermal protection of the RSS were conducted in hypersonic installations U-6, U-7, U-11 and heat pipes of the new generation TT-1, U-15T-1, U-13VChP, U-16.

New calculated and experimental methods for studying of thermal processes of "Energia-Buran" system during the atmospheric phase were developed (spatial problems of streamlining and boundary layer, heat transfer in interference zones, influence of non-equilibrium processes, infrared thermography, etc.).

Investigation of heat transfer of Buran orbiter in hypersonic tunnels allowed specification of the spacecraft thermal scheme.

Experimental testing of combined thermal insulation of a hydrogen tank on the launch vehicle and heat protection of the orbiter was conducted (including catalyticity, endurance tests, influence of two-phase jets of engines of paired units at separation stage, etc.).

The influence of open-space environment on the characteristics of temperature-control coatings and friction units during the orbital flight phase of the spacecraft was investigated.

The behavior of structural materials in liquid hydrogen was studied.

Heat-vacuum testing of the spacecraft were conducted, including the ones in vacuum chamber (volume 8000 m^3)

N.A.Anfimov was a scientific supervisor of all the works carried out at TsNIIMash on heat transfer of "Energia-Buran" system.

The major contribution into these works was made by V.S.Avduevskiy, V.T.Alymov, G.A.Beda, V.N.Vasilyev, V.I.Vyshvanyuk, O.I.Gubanova, G.N.Zalogin, B.A.Zemlyanskiy, P.G.Itin, V.V.Kislykh, V.V.Kozelkin, R.M.Kopyatkevich, L.A.Kuzmin, V.V.Lunev, I.N.Murzinov, O.N.Ostapovich, V.L.Polunin, A.N.Rumynskiy, M.V.Savelov, V.P.Timoshenko, M.G.Trenev, V.A.Fadeev, V.G.Farafonov, N.A.Tseev, V.A.Chervakov, N.V.Chereshneva, V.N.Shebeko.

TsNIIMash specialists V.P.Danilov, G.N.Zalogin, L.A.Kuzmin and V.A.Chervakov were awarded the USSR National Prize (1988) for the development of gas-dynamic plant U13-VChP and the research made on this plant and aimed at tryout of heat-protection materials for Buran orbiter.

The Decree of CC CPSU and USSR CM issued in 1979 entrusted TsNIIMash with the development of a new mission control center (MCC-B) on the basis of MCC-M. It was supposed to control the reusable space system “Energia-Buran” at the stage of flight and development tests. Besides, TsNIIMash was responsible for the development of all the required software and mathematical support.

Flight control

The development of such a unique Buran spacecraft demanded a qualitatively new approach to the management of its flight.

A strict division of responsibilities between automatic guidance, manual control and commands given by MCC-B was necessary. In accordance with the tactical and technical requirements for the Buran spacecraft, all control modes were to be performed automatically. On the other hand, the MCC-B was provided with the complete control over all stages of flight, duplicating all the basic operations of the spacecraft systems in case of emergency situations.

It required combination of the development stages and creation of on-board and ground-based control complexes for Buran orbiter under a single automated flight control system.

Buran flight was monitored by MCC supporting services of telemetry, command software, ballistic navigation, information service, collective and individual information display, signal and power service. The operation of all services was planned and coordinated by the command post of the MCC.

The ground control system included the MCC-B TsNIIMash , a network of monitoring stations, information exchange system between the tracking stations and the MCC-B, and a satellite system of monitoring and control of Buran orbiter - Altair relay satellite - ground relay - MCC-B.

For the development of Buran Mission Control Center, V.I.Lobachev, V.A.Udaloy, V.V.Bedrintsev and V.K.Samsonov were awarded the Prize of the USSR Council of Ministers.

A large group of the Institute specialists were awarded National prizes for successful work upon the “Energia-Buran” system.

References

1. Raketno-kosmicheskaya epokha. Pamyatnye daty. / [red. Sovet: pred. Popovkin V.A. i dr.]. – Izd. 5-e, dop. i utochnennoe.- M.:Lokus Standy, 2012 – 400 s. (in Russian)
2. Cosmonavtika i raketostroenie Rossii. Biograficheskaya entsiklopedia. / [redkol.: pred. Perminov A.N. i dr.]. – M.: ZAO “Izdatelskiy dom “Stolichnaya entsiklopedia”, 2011 – 840 s. (in Russian)

3. Cosmonavtika: Entsiklopedia. / [Gl. red. V.P.Glushko i dr.]. – M.: Sov. entsiklopedia, 1985. – 528 s. (in Russian)
4. Sovetskaya kosmicheskaya initsiativa v gosudarstvennylh dokumentakh. 1946-1964 gg. [pod. red. Yu.M.Baturina]. – M.: RTSoft, 2008. – 416 s. (in Russian)
5. Kosmicheskiy nauchniy centr. (glav.red. G.G.Raikunov). – TsNIIMash, 2011. (in Russian)
6. Nauchniy centr cosmonavtiki i raketostroeniya. glav.red. academic V.F.Utkin. – TsNIIMash, 1996. (in Russian)
7. Tak eto bylo… Kniga o Yu.A.Moszhorine. – t.1, TsNIIMash , 2014, 528 s. (in Russian)
8. G.G.Raikunov. TsNIIMash – Nauchno-issledovatelskiy Centr Rossiyskoy Cosmonavtiki. Mezhd. Ross.-Amer. Journal APAAS, 2 (33), t.16, 2011. (in Russian)
9. N.G.Panichkin, M.N.Kovbich, N.Ya.Dorozhkin. Academic Vladimir Fedorovich Utkin i TsNIIMash (k 90-letiyu Glavnogo konstruktora rakety “Voevoda” – “Satana”). Mezhd. Ross.-Amer. Journal APAAS, 2(37), t.18, 2013. (in Russian)
10. G.G.Raikunov. Scientific research Centre of Russian Cosmonautics.RAJ “APAAS”, 2(33), v.16, 2011
11. N.G.Panichkin, M.N.Kovbich, N.Y.Dorozhkin. Academician V.F.Utkin and TsNIIMash (to 90-th Anniversary of General Designer of «Voevoda»-«Satan» rocket). RAJ APAAS, 2(37), v.18, 2013

Alexander Grigoryevich Milkovskiy, Candidate of Engineering Sciences (PhD), Senior Researcher, retiree colonel; graduated from Kharkov Higher Military Aviation Engineering College. In 1994-2010 A.G.Milkovskiy did his military service at the 30th Central Research Institute of Russian Ministry of Defense (Institute of Aviation and Space Engineering). Held military positions from junior researcher to head of research center (for marine aviation engineering) of the 30th TsNII of Russian Ministry of Defense. During 2010-2014, Milkovskiy managed the 4th Central Research Institute of Russian Ministry of Defense, which comprised six research institutions dealing with different research subjects. Since 21 April 2014 he is a General Director of Federal State Unitary Enterprise TsNIIMash. National awards: Medal of Order “For Merit to the Fatherland” 2nd class; “Honorable Service” XXX years Badge (on a Ribbon of Saint George).

Mikhail Nikolaevich Kovbich, specializes in the system research of information support of rocket- and space-related activities. Graduated from military school in 1988, from military academy in 1997.During the period of 1984-2011 did his military service starting from the position of company execution officer and up to the Associate Professor of the military academy department, retiree colonel. Since 2011 – Head of TsNIIMash division responsible, among all, for retrospective research of establishment and development of Russian space industry. He participates in the researches and directly controls complex studies of the improvement of information support of Russian space activity and historical research of space engineering evolution. Awarded with Medals of the Russian Ministry of Defense.

History of rocket and space technology: from the past to the present and future

A. A. Gafarov[1], E. Yu. Kuvshinova[1], I. E. Vlasov[2], L. P. Vershinina[3]

1 - SSC “Keldysh Research Center”

2 - Veterans Council of the Command and Measurement Complex (CMC)

3 - TsNIIMash (Central Research Institute of Machine Building)

Pionerskaya 4, Korolev, Moscow Region, 141000, Russia

The main results of the “History of rocket and space technology” section activity in the framework of the XXXVIII Academic Conference on Astronautics held on 28-31 January, 2014 in Moscow are presented. Along with description of historical achievements, a number of reports contain an analysis of their relationship with some present and future focus areas in the rocket and space science and technology.

B.E. Chertok, the Patriarch of the Russian space industry, noted in one of his speeches: “The study of history helps to understand the present, learns to predict the future, reveals the mechanism to achieve success.”

The meetings of the “History of rocket and space technology” section of the XXXVIII Academic Conference on Astronautics were held exactly in this aspect on 28-31 January, 2014 in Moscow. They were dedicated to the memory of Academician S.P. Korolev and other prominent Russian scientists – the pioneers in the exploration and use of outer space.

In the paper “On the Predictive Function of Historical Research”, V.I. Florov, the member of staff of the Space Engineering and Technology College, broaches a question “why historians are not professionally engaged in predictions, but professional prediction researchers are not engaged in historical investigations”. The author believes that the existing resource dynamics method “stitches together” the retrospective and perspective with networks of resource transformations organized in a hierarchical system with different aggregation levels. This approach to the integrated retrospective and prospective could expand historical researches to determine the trends in different areas of science, technology, production, everyday life and culture in general on the different aggregation levels of development processes.

The report “Steps for Creating the R-2 Long-Range Missile” by L.P. Vershinina, the staff member of the TsNIIMash, is devoted to the history of development, organization of series production and entry into service of the R-2 long-range missile. The author emphasizes several stages in the R-2 creation process. The report first presents systematic data on the cooperation of the enterprises involved in the development of the R-2 missile. According to the author, it is the R-2 which could be considered as the first Soviet ballistic missile.

S.V. Starostin, the veteran of the SSC FSUE “Keldysh Research Center”, devoted his speech to the history of creation and development of the Liquid Rocket Engines (LRE) Laboratory in the SSC FSUE “Keldysh Research Center.” He noted the most important scientific and technological achievements of the Laboratory: solving the problem of longitudinal stability of the liquid rocket engine (LRE) missile, introduction of new fuel (liquid hydrogen) into missile engineering, study of gas generators for turbine drives, low-thrust rocket engines, process in LRE pumps and turbines and materials resistance in LRE gas and fluid paths. The Liquid Rocket Engines Laboratory have created the closed-circuit LRE with afterburning, complex of LRE test benches, operational monopropellant (hydrazingas) generators for orientation and stabilization systems of the Lavochkin NPO SC.

The report “Cruise Missile Burja (Storm)” by V.E. Bugrov, the veteran of the space industry, former staff member of the RSC “Energia”, describes the creative environment in the department of propulsion in the Lavochkin NPO SC (Lavochkin Research and Production Association), where the intercontinental cruise missile “Burja” was developed with participation of the reporter. The events occurred in the course of its design, manufacture and tests are shown. Unfortunately, the “Burja” program was terminated, despite the fact that it could be continued independently. The idea to combine the missile and aircraft took a new lease of life in 1976. As a result, the “Energia-Buran” space shuttle complex was brought into being.

The presentation “Developing Second-Generation Sea-Launched Ballistic Missiles. Creating a National School of Sea-Launched Missile Engineering (1962-1974)” by R.N. Kanin, the expert of the V.P. Makeyev State Rocket Centre, demonstrates the use of a systematic approach to the development of the second-generation sea-launch ballistic missiles, and, as consequence, the growth of sea-launched strategic weapon combat capabilities to meet and exceed the international standard requirements. Also, it is noted that development works on the R-27 ballistic missile of the D-5 launch complex deployed on the submarine Project 667A and the R-29 ballistic missile of the D-9 launch complex deployed on the submarine Project 667B were realized.

A.M. Peslyak, the representative of the Russian Union of Journalists, delivered the report “Media Mirror of Space Concerns: Is it False One - or ...”. He notes that the Russian mass media pay a lot of attention to space issues. But it is necessary to take into account the motivation which generates this interest. The staff engaged in the Space Journalism is a conglomerate of youngish graduates working in editorial and television studios not very long. A number of examples are given to demonstrate the recent period specificities of reflecting the history and critical tasks of the astronautics by the Russian media.

The speech “On the methodological approach for defining role of space weapons in the military strategic balance” by E.K. Babichev, the veteran of the “Plesetsk” cosmodrome, proposes a methodological approach consisting in clarification of the space weapons (SW) place in strategic weapons systems and in comparative efficiency evaluation of the SW as part of the USSR and USA strategic weapons systems. The proposed functional approach allows to conclude that the military space parity was achieved in 1977. The author believes that this approach makes it possible to determine the role of the space component in the military strategic balance in the new historical period as well.

O.A. Skryl, the veteran of the Command and Measurement Complex (CMC), regularly participates at the section meetings. This time he presented the report “Development of the Common-Time System of the Command and Measurement Complex as a Metrological Basis for Space-Based Systems”. In the creation and development of the Command and Measurement Complex, the problem of referencing the trajectory, telemetry and special measurements performed by space airborne and ground-based systems to the common time scale moves to the forefront. The basis for implementing the universal time system can be considered the works carried out during the first R1 and R2 ballistic missiles tests at Kapustin Yar in the period from 1947 to 1956. The implementation of the high-precision universal time system for the all military services was the next step (project “Vremya” - Time). The high-precision universal time system was developed in the framework of the State Universal Time System and Standard Frequency Project (project “Tsel” - Target). Works on the Project were carried out simultaneously with creating the GLONASS navigation-and-timing complex.

This year, the theme related to the history of CMC floating complexes has been evolved. S.S. Monakov, the member of the “Veterans Council of CMC”, presented a report “Large Floating Radio Complex (LF RC) Selena-M Project” (for the 35th anniversary of putting into operation of four LF RCs: “Cosmonaut Vladislav Volkov”, “Cosmonaut Pavel Belyaev”, "Cosmonaut Georgy Dobrovolsky" and "Cosmonaut Viktor Patsaev"). The complexes were intended to receive information of all types and provide two-way radio communication with spacecraft crews and orbital stations with the Mission Control Center. The ships successfully completed their tasks in tests of the "BOR-4" spacecraft, in flight of the "Buran" space shuttle, "Salyut" and "Mir" permanent orbital stations, etc. The report was accompanied by the video of all "Selena-M" ships from the author's personal archive.

V.P. Kuznetsov, the veteran of the Great Patriotic War, fellow of RDM 4th CRI (NII-4), Doctor of Technical Sciences, laureate of the USSR State Prize, has issued yet another report on "Constraction of the Integrated Missile Range for the People's Liberation Army (PLA) of China and Its Consequent Effect." In 1957, the PRC government appealed to the leadership of the USSR with a request for assistance in developing the missile weapons. As a result, the USSR Council of Ministers adopted three Regulations, which provided designing and constructing the PLA Integrated Missile Range for testing the missile weapons. To date, China ranks second in the world in the rate of space technology and research programs development. These achievements is a great merit of the OKB-1, NII-4(Research Institute), NII-28 (Research Institute) and NII-30 (Research Institute) specialists, who laid the ground for developing the Chinese rocket and space technology.

A.P. Fursov, the member of the Veterans Council of the CMC, presented a report "On the Baikonur Cosmodrome Computation Center Veterans Memoirs Edited by B.V. Yuryev". The report is devoted to issuing the memoirs book prepared by B.V. Yuryev in 2013. This is a collection of reminiscences of the veterans of the Baikonur Cosmodrome Computation Center that celebrated its 50th anniversary in 2012. The book contains historical materials about the most interesting events of establishing the Russian space science and technology, about the participants of these events and co-authors of this book.

About 50 representatives of different companies and organizations assisted in the work of the section.

It should be noted that a number of reports contain not only analysis of historical achievements, but also an analysis of their relationship with the current state and prospects in the areas under consideration. This fully applies to the report of S.V. Starostin devoted to the activities of the LRE department in the State Scientific Center "Keldysh Research Center", to the report of E.K. Babichev devoted to the methodological approach to determination of the space weapons role in the military strategic balance, to the report of O.A. Skryl devoted to the Universal Time System of the Command and Measurement Complex, and to the report of V.P. Kuznetsov devoted to construction of the Integrated Missile Range in China.

R.N. Kanin's report on developing the second-generation sea-launched ballistic missiles is a continuation of the previous readings cycle describing the sea-launched ballistic missiles developed by the V.P. Makeev State Rocket Centre.

The reports were supplemented by presentations, illustrations and photographs. R.N. Kanin submitted videos about Viktor Makeev, the General Designer of the submarine-launched ballistic missiles, the V.P. Makeev State Rocket Center and the town of Miass where the V.P. Makeev State Rocket Center is located. The speeches provoked many questions and discussions in some cases.

Albert Akramutdinovich Gafarov, the head of section of the SSC FSUE "Keldysh Research Center", Dr. (PhD Engineering). Research interests: effectiveness of application and provision of radiation safety with the use of nuclear power in space; history of the rocket and space science and technology. kerc@elnet.msk.ru

Ekaterina Yurievna Kuvshinova, first category engineer**,** student of the branch nonresident postgraduate course of the SSC FSUE “Keldysh Research Center.” Research interests: effectiveness of the use and flight dynamics of the spacecraft equipped with nuclear power sources. kerc@elnet.msk.ru

Igor Evgenievich Vlasov, the member of the Veterans Council of the Command and Measurement Complex**,** Dr. (PhD Engineering). Research interests: history of the rocket and space technology, space navigation, dynamics of spacecraft flights. igorwl@post.ru

Lubov Pavlovna Vershinina, first category engineer of the TsNIIMash**,** postgraduate of the Institute of History and Archives. Research interests: history of the science and technology, space industry, aerospace education. vega100@mail.ru

In Memory of Vladimir Anatolyevich Kuzmin, Journal Editor

(08.12.1940 – 27.06.2014)

Vladimir Anatolyevich Kuzmin, Editor of bilingual Russian-American scientific Journal "Actual Problems of Aviation and Aerospace Systems", Kazan-Daytona Beach; ISSN 1727-6853; Dr. Prof., Academician - Full Member of the Academy of Aviation and Aeronautics Sciences, Professor at the Department of Jet Engines and Power Plants of A.N.Tupolev Kazan National Research Technical University – KAI (KNRTU-KAI) died suddenly on 27 June 2014.

Since 1958 Vladimir Anatolyevich's whole life was connected with Kazan Aviation Institute, with the Department of Air Jet Engines (AJE) (presently the Department of Jet Engines and Power Plants):

in 1958 he entered the Faculty of Aircraft Engines, in 1964 he graduated from KAI (qualification: engineer specializing in mechanics; specialty: aviation engines). In 1964 he entered a PhD program of the same department, but due to the need to deliver lectures on new courses of "Hydro and Gas Dynamics" and "Magnetic Gas Dynamics", Vladimir Anatolyevich had to terminate his full-time attendance of PhD program and start teaching alongside with extramural PhD training. His scientific supervisor was Boris Sergeevich Vinogradov, Professor of AJE Department. Vladimir Anatolyevich defended his PhD thesis in 1979. Since 1988, V.A.Kuzmin worked as an Teacher (Professor) of Air- Jet Engines Department. He successfully combined teaching and research, performed works under commercial agreements with Kazan Engine Plant Soyuz. He published over 50 research papers.

Since the very beginning of his teaching activities, V.A.Kuzmin worked much with students: since 1979, he supervised students in the university, since 1992, he worked as a Vice-Dean of Aircraft Engine Division and was responsible for students' social protection, later – as an Deputy Director of the Institute of Aviation, Land Transport and Power Engineering.

At the same time V.A.Kuzmin took an active part in organization and preparation of scientific conferences, in publication of research and methodological papers. Since 1986, he was an executive secretary of an inter-university collected volume "Gas Dynamics of Aircraft Engines".

Since 1995, V.A.Kuzmin was an Editor of bilingual Russian-American scientific Journal "Actual Problems of Aviation and Aerospace Systems", Kazan-Daytona Beach; ISSN 1727-6853.

In 1997 V.A.Kuzmin was elected a full member of the Academy of Aviation and Aeronautics Sciences (AAAS); he was elected a Co-Chairman of Volga Region AAAS Branch; he was a member of K.E.Tsiolkovskiy Russian Academy of Astronautics. Under his supervision, regular Sessions of Volga Region AAAS Branch took place; scientific Workshops Proceedings were published. He is initiator of special youth Sections in framework of regularly working United International Workshop that is organized by Russian scientific Centre of International Federation of nonlinear analysts on base of KAI (KNRTU – KAI), jointly with Academy of nonlinear analysis, with the Academy of Aviation and Aeronautics Sciences, with K.E.Tsiolkovskiy Russian Academy of Astronautics , with Federation of Astronautics of Russia.

V.A.Kuzmin was awarded:
AAAS Certificate of Honour for his valuable contribution to the education of highly - qualified specialists for aerospace industry; Diploma of K.E.Tsiolkovskiy Russian Academy of Astronautics for his outreach activities in propagating Russian Cosmonautics; K.E.Tsiolkovskiy Medal and S.P.Korolev Medal of the Federation of Astronautics of Russia for his merit to Astronautics.
Being considerate to everybody and having brilliant organizing abilities, V.A.Kuzmin possessed ability to lead away their own idea the people, to choose an optimum alternative, and to charge all his "fosterlings", colleagues and friends with the confidence…
Vladimir Anatolyevich Kuzmin was a paragon of a Teacher, a Creator and a Scientist. Being a True Patriot of KAI, he selflessly served to improve the image of KAI in his educational, editorial, public activities.
Cherished Memory on Vladimir Anatolyevich will always rest in the hearts of his colleagues, friends, disciples; it will support them in a rough time encouraging optimism and faith in triumph of moral ideals, supreme moral values laid by basic traditions of KAI (Kazan Aviation Institute) since the times of its Founder – Academician N.G.Chetaev, and very important for everyone.

KNRTU-KAI Administration
Institute of Aviations, Land Transport and Power Engineering
Department of Jet Engines and Power Plants
Academy of Aviation and Aeronautics Sciences
K.E.Tsiolkovskiy Russian Academy of Astronautics
Federation of Astronautics of Russia
Associates ,Colleagues, friends, disciples…

Представление работ

Статьи, предназначенные для публикации в журнале, должны быть поданы в трех экземплярах. Статьи направляются по указанному ниже адресу или тому члену редакционного комитета, который, по мнению автора, наиболее близок к теме работы.

Адрес: Л.К.Кузьмина, Казанский авиационный институт (КНИТУ им.А.Н.Туполева)
Адамюк, 4-6, Казань-15, 420015, РОССИЯ
Lyudmila.Kuzmina@kpfu.ru
Тел.: (7) (843) 236-16-48
http://kpfu.ru/science/journals/rasj/apaas
http://www.kcn.ru/tat_en/science/ans/journals/rasj.html

Информация о подписке

“Актуальные проблемы авиационных и аэрокосмических систем: процессы, модели, эксперимент”,
2015, т.20 (два выпуска), ISSN 1727-6853.

Стоимость годовой подписки - 6600 руб. (включая пересылку) за любой год с 1996г.

Банковские реквизиты для платежа:

ФГБОУ ВПО КНИТУ им.А.Н.Туполева - КАИ
УФК по РТ (КНИТУ-КАИ л/с 20116Х02750)
ИНН 1654003114 КПП 165501001
р/с 40501810292052000002
Отделение-НБ Республика Татарстан (БИК 049205001)
(Х – печатается латинская буква).

с указанием: Для МНЖ “Актуальные проблемы авиационных и аэрокосмических систем: процессы, модели, эксперимент”.

Пожалуйста, информируйте нас о перечислении и сообщите номер платежного поручения по электронной почте или другим способом

Manuscript Submission

Manuscripts for publication in this Journal should be submitted in triplicate to the Editorial Office or to an individual member of the Board of Associate Editors who, in the opinion of the authors, is more closely involved with the topic of the paper.

The address of the Editorial Office:

Dr.Lyudmila Kuzmina, Kazan Aviation Institute (KNRTU of A.N.Tupolev’s name)
Adamuck, 4-6, Kazan-15, 420015, RUSSIA
Lyudmila.Kuzmina@kpfu.ru
Tel.: (7) (843) 236-16-48
http://kpfu.ru/science/journals/rasj/apaas
http://www.kcn.ru/tat_en/science/ans/journals/rasj.html

Subscription information:

“Actual Problems of aviation and aerospace systems: processes, models, experiment”,
2015, vol.20 (two issues), ISSN 1727-6853.

Annual subscription rate: US$200 (subscription rates include postage/air speed delivery), for any year from 1996.

Please, send this payment to:
Kazan State Technical University
S.W.I.F.T. SABRRUMMNA1
SBERBANK
(VOLGO-VYATSKY HEAD OFFICE
NIZHNIY NOVGOROD)
ACCOUNT 40503840762020200019
FOR CREDIT TO KGTU ANTUPOLEVA

with indication: For ISE “Actual Problems of aviation and aerospace systems: processes, models, experiment”.
Please, inform us about this transfer and the wire number by e-mail.

A C T U A L   P R O B L E M S   O F   A V I A T I O N   A N D   A E R O S P A C E   S Y S T E M S

Kazan Daytona Beach

Kazan National Research Technical University of A.N.Tupolev's name - Kazan Aviation Institute, (collective member of International Federation of Nonlinear Analysts and Cosmonautics Federation of Russia) and Embry-Riddle Aeronautical University (Daytona Beach, USA) in accordance with the agreement about collaboration initiated the foundation of Russian-American scientific Journal on a broad spectrum of problems in aviation and aerospace systems. It is interdisciplinary bilingual scientific Edition, presenting the papers in areas of dynamics and flight control; theory, design and technology of aircrafts, engines; sciences on materials; information and computing systems, experimental investigations; economic and humanity problems of operation; Earth remote sensing; information satellite technology; the problems of Higher Engineering Education in area of Avia-, Aerospace systems; nanotechnology problems for Avia-, Aerospace systems,…

- The beginner authors are invited. Constructive and benevolent critique by specialists in the pages of our Journal must raise the level and quality of works of beginner investigators and stimulate the intake of fresh forces to that complicated branch of world science and engineering.

http://kpfu.ru/science/journals/rasj/apaas

http://www.kcn.ru/tat_en/science/ans/journals/rasj.html

FOR THE AUTHORS

Authors must send their works (3 clean copies, ~15 pp.), prepared to the publication, and diskette (MS Word for Windows, IBM PC). It is possible also to duplicate via e-mail the submitted paper. Text size is 160x235 (mm), Times New Roman, 12pt, one space; including the title of article, author name, name of Institute (University), full address for contacts. The upper margin is 35mm, left margin is 25mm, right margin is 25mm. Pages are numbered by pencil on the opposite side; the illustrations (format files .jpg, .gif, .bmp) are placed at the same scale as the text. Short information about the author (3-4 lines) should be given in paper end (including the area of scientific interests, the spheres of applications).

Also it is necessary the abstract of article (2p.), prepared on same rules, but without indication of address. Abstract is placed on separate pages. Authors of papers in Russian are required to supply an abstract in English (2p), also - the article variant in English.

The author reserves the right to copy his publication. The Journal may be sent to the author by his request for the separate payment or by subscription.

Our telephones (on all questions of publications,
of advertisement, of business suggestions) -

(7) (843) 236-66-92 Vladimir A.Pavlov
(7) (843) 236-16-48 Lyudmila K.Kuzmina
(7) (843) 238-44-20 Vladimir A.Kuzmin

Address: Dr. Lyudmila K.Kuzmina, Kazan National Research Technical University of A.N.Tupolev's name (Kazan Aviation Institute)
Adamuck, 4-6, Kazan-15, 420015, RUSSIA
E-mail: **Lyudmila.Kuzmina@kpfu.ru**

The Journal has been cataloged:
*in Congress Library; the Library of Congress Catalog Number (LCCN) is **97-647933***
*in British Library; the British Library Catalog Number (LCCN) is **005399143***

Published papers are reviewed in abstract Journal and abstract database of RAS All-Russian Institute of Scientific-Engineering Information
Information about Edition is entered in reference system on periodic Editions "Ulrich's Periodicals Directory" http://www.ulrichsweb.com
Electronic version of Scientific Edition is implemented in the cooperation with Kazan Federal University and set at KFU-portal
Academic, Scientific, Information Support - Ministry of Education and Science of RF

Edition is carried out with support of ABAK Operating Printing Center
Original-model is prepared for printing
in Kazan National Research Technical University of A.N.Tupolev's name
Color printing - **OPC ABAK** (licence No.0195, 03.08.2000)
Kazan, RUSSIA