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Application of the Generalized Mean Value Function for Detection of Defects in Metal Cylindrical Slugs

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Abstract

In this paper we present a free-oscillation method for acoustic detection of defects in metal rods. For detection of normal rods from rods with defects we use a treatment procedure based on the statistics of the fractional moments. This procedure allows to extract the quanti-tative information from the acoustic signals that are propagated in cylindrical slugs after mechanical strike and having different defects. This information allows separating normal rods (without defects) from the rods having different cuts and differentiating the saw-cut defects with different depth from each other. The analysis of data obtained from this research shows that the proposed method of the fractional moments can be applied for quantitative ”reading” of envelopes of different acoustic signals that are obtained by means of free-oscillation method and propagated in dense medium having local defects.

1 Introduction

Rejection of intermediates before machining is one of the main problem in production optimization. For the selection of necessary intermediates that satisfy necessary requirements/criteria one can use nondestructive testing methods. There are many different nondestructive testing methods that are used in different manufacturing: magnetic methods [1], capillary [2], eddy current [3], acoustic [4], radiation [5], optical [6] and etc. Each of them has its own range of applicability conditioned by cost,

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possibility of application, sensitivity and adaptability. Another important point in testing procedure lies in the processing and analysis of data obtained after application of nondestructive testing method. Frequently, the recorded data forms a large set and are "polluted" strongly by random fluctuations (known as a 'noise') that make difficult them for extraction of significant information that is associated, in particular, with identification of the desired defect located in the given intermediate. One of the most ancient method of acoustic monitoring is acoustic free-oscillation method [7]. The main advantages of this method are: 1) possibility of integral control of the complex high-curvature shape intermediates; 2) there is no need for preliminary control surface preparing; 3) quickness of the desired results achieved. The essential drawback of this method is sensitivity to the way of securing the intermediate and to the place and direction of the excitation force. Usually acoustic free-oscillation method is used in conjunction with the Fourier analysis [8]. Fourier analysis has its own area of applicability and some essential drawbacks. Two basic drawbacks are listed below: 1) assumption about the normal distribution of the noises; 2) uncontrollable errors injections during its application.

In this work we are trying to use another signal processing procedure that does not contain assumptions about the nature of the probability distribution function and does not create uncontrollable errors during its application. This procedure is based on the use of the generalized mean value (GMV)-function that has demonstrated its applicability for reliable selection of different probability distributions [9].

2 Experiment

The objects of investigation represent themselves 7 steel cylindrical rods with radius $R = 8$ mm and length $L = 300$ mm mounted on special supports. Six of them have transversal saw-cuts with penetration depth 1, 2, 3, 4, 5 and 6 mm, accordingly. These saw-cuts simulates different defects with different depths. The seventh rod is considered as the normal one and it does not contain this type of defect.

Experimental setup for investigation of the rods is depicted on figure 1. This setup is mounted on vibration isolating table (concrete plate with rubber dampers) and contains the following elements: base stand, rod laying device, striker assembly and microphone.

During experiment rods were fixed on H-frame supports that were made from transformer steel. These supports were fastened on vertical stands that, in turn, were fixed on vibration isolating table. Impact (strike contact) was made in the center of the rods and the proper acoustic response was registered by the use of microphone and ADC connected with personal computer.

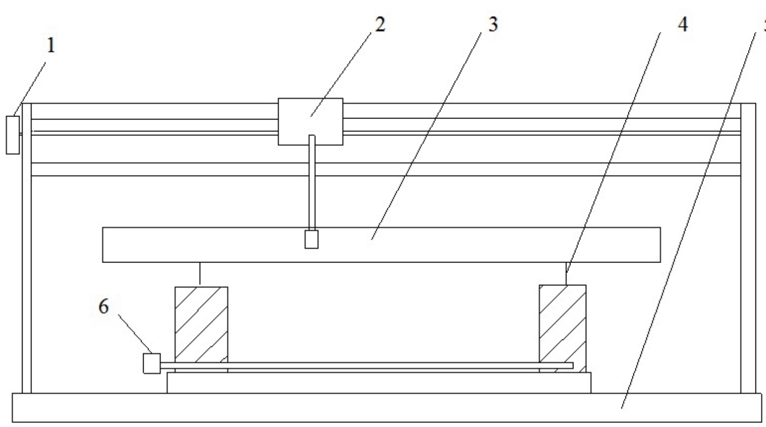

Fig. 1 Experimental setup for investigation of the rods. (1 - external screw for changing position of the striker; 2 - striker assembly; 3 - investigated rod; 4 - knife supports; 5 - base stand; 6 - screw for regulation of the distance between supports).

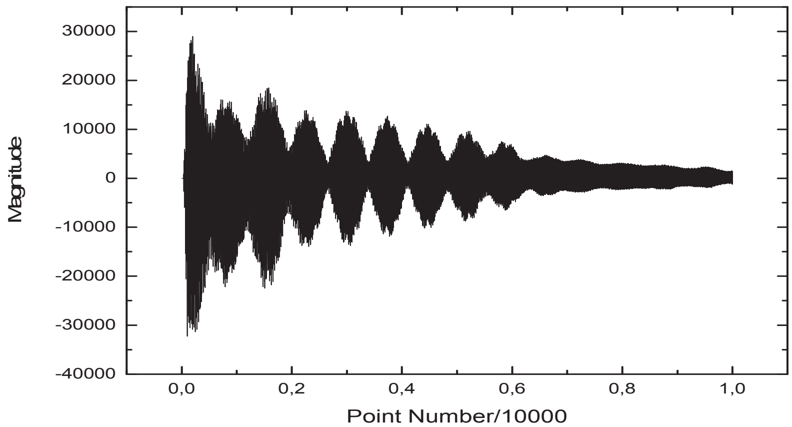

Fig. 2 Acoustic response registered from rod without defect.

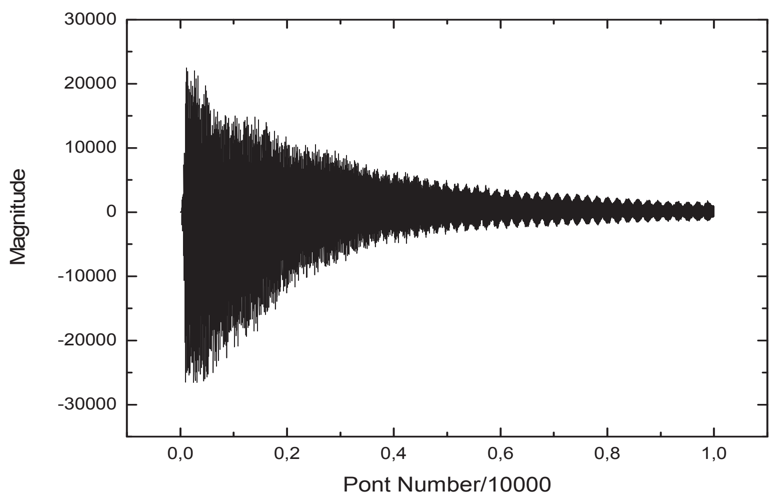

Fig. 3 Acoustic response recorded from a rod with the saw-cut defect having the depth 5 mm.

On figures 2 and 3 one can see examples of acoustic responses from rods without defect and with defect having saw-cut form and depth 5 mm.

For each rod we obtained 40 samples of acoustic data.

3 Description of the signal processing procedure

The idea of this treatment is to extract significant information that can be presented in an arbitrary form for differentiation of rods having saw-cut defects with different depth from each other and from normal rod without defect. For solution of this problem we apply the GMV- function.

This approach has been initially suggested by one of the authors (RRN) in paper [10]. It is based on idea of generalization of the arithmetic mean value and takes into consideration the total set of moments including the fractional and even complex values. The integer (or fractional) moment of the pth order is determined as:

$$\Delta_p \equiv \Delta(m_p) = \frac{1}{N}\sum_{j=1}^{N}(\tilde{y}_j)^{m_p}\,,\; 0 \le m_p \le Mx. \tag{1}$$

where N is the number of points in the sampling considered, m signifies the order of the moment and y – values of the points in the sampling.

The GMV-function is related to the moment of the pth order by means of relationship.

$$GMV_N(m_p) = [\Delta(m_p)]^{1/m_p} \tag{2}$$

This function reproduces the harmonic mean ($m_p = -1$), geometric mean (obtained in the limit $m_p \to 0$), arithmetic mean ($m_p = 1$) as partial cases. The GMV-function is increasing (monotonous) function and at $m_p \to \infty$ GMV-function recovers the right limit of the sequence ($\tilde{y}_{\max} = ymx$) and in the opposite case (at $m_p \to -\infty$) it coincides with another limiting value $\tilde{y}_{\min} = ymn$. Mathematically, these properties are expressed by the following expressions

$$\begin{aligned} &GMV_N(m_1) > GMV_N(m_2),\; if\; m_1 > m_2, \\ &\lim_{m\to\pm\infty} GMV_N(m) = \begin{pmatrix} ymx \\ ymn \end{pmatrix}. \end{aligned} \tag{3}$$

This function has a remarkable property, viz., being presented in the plot $G2_N(m) = G1_N(m)$ it demonstrates the statistical proximity of two random sequences compared if they satisfy to the linear relationship of the type

$$GMV2_N(m) = \lambda GMV1_N(m) + b. \tag{4}$$

The linear relationship (4) can be chosen as a quantitative criterion for verification of the statistical proximity for two arbitrary random sequences compared. However, for detection of the statistical proximity it is necessary to calculate expressions (2) for two sequences and plot them with respect to each other for approximate verification of expression (4).

The normalized moments (1) can be fitted by the linear combination of the exponential functions [10] that was successfully demonstrated recently in differentiation of different 3D-video films [11]

$$\Delta_p = a_0 + \sum_{i=1}^{S} a_i \exp(\lambda_i p). \tag{5}$$

Here the upper limit S of this exponential decomposition is defined by the accuracy of the fitting procedure applied. Application of this function shows [11] that for the most cases it is sufficient to use $S = 3$. So, using the GMV- function and function (5) one can “read” quantitatively any signal (with trend or without trend) in terms of the fitting parameters a_i and λ_i figuring in expression (5).

The first step in the proposed signal processing algorithm is data preparation. Under the “data preparation” we mean extraction of the data that have informative significance for detection of the desired defects.

Let N be the total length of the considered data set $\{y_i = y(t_i)\}$ (forming in our case the considered acoustic response). This sequence can be divided into M consecutive “segments” each one lasting m samples, that is $M = [N/m]$. Now, let $\{P_i\} \equiv \{p_i(1), p_i(1), \ldots, p_i(m)\}$ be the i-th segment. Reduction of this “cloud” of points to two incident points translates into the calculation of two typical points for each segment:

$$p_i^{\mathrm{up}} = \max\{P_i\}, p_i^{\mathrm{dn}} = \min\{P_i\},\; i = 1..N. \tag{6}$$

The so obtained subsets, that is $F^{\mathrm{up}} = \{p_1^{\mathrm{up}}, p_2^{\mathrm{up}}, \ldots, p_M^{\mathrm{up}}\}$ and $F^{\mathrm{dn}} = \{p_1^{\mathrm{dn}}, p_2^{\mathrm{dn}}, \ldots, p_M^{\mathrm{dn}}\}$ form two curves, describing the data trend on a compressed time scale (with a compression factor of m). If F^{up} and F^{dn}

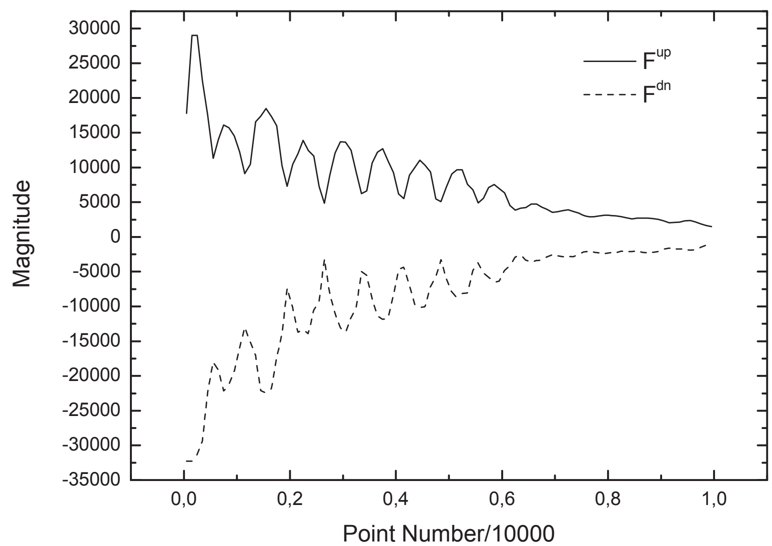

Fig. 4 Curves F^{up} and F^{dn} from rod without defect.

keep their values very close each other, then it serves as an indication of the invariance of the data set under analysis, with respect to self-similar transformations [12]. This is an advantage, because the properties of the whole set can be inferred by using much less data samples.

Please note that, if observed, this behavior is independent on the value of m, which anyway should be kept in a proper range to keep the statistical similarity of the compressed subsets. Choosing a too high value of m would translate in a lower value of M with a consequent very strong data compression and this surely destroys the possibility of detecting the data trend at a smaller time scale. On the other side, m cannot be too small, to allow capturing the low-frequency behavior of the data set under analysis. An empirical rule of thumb for a correct choice of m is based on the following compromise: the number M of the compressed data samples should be less than $N/3$ (i.e., at least three original samples per compressed sample), and at the same time it should be greater than $30 \div 40$. That is:

$$30 \div 40 \le M \le \frac{N}{3} \Rightarrow 3 \le m \le \frac{N}{40} \div \frac{N}{30}. \tag{7}$$

Application of this procedure (6) to the raw acoustic data (presented on figures 2 and 3) gives us curves Fup and Fdn presented on figures 4 and 5 ($m = 100$).

On figures 6, 7 and 8 one can see curves obtained as difference between F^{up} and F^{dn}:

$$DF = F^{\mathrm{up}} - F^{\mathrm{dn}}. \tag{8}$$

Comparing figures 6, 7 and 8 one can see that DF curves become smoother with increasing of the saw-cut depth.

The second step of our proposed signal processing algorithm is normalization procedure

$$Normalized\,DF = \frac{DF - MeanValue(DF)}{StDev(DF)} + 10, \tag{9}$$

where $MeanValue(DF)$ represents the mean value calculated from curve DF and $StDev(DF)$ represents the standard deviation value calculated from curve DF.

The third step of our proposed signal processing algorithm is calculation of the GMV functions using normalized curves (9) as input data. As it has been mentioned above for each rod we get 40 samples of acoustic data. Then after calculation of the GMV-function (2) to the normalized data expressed by

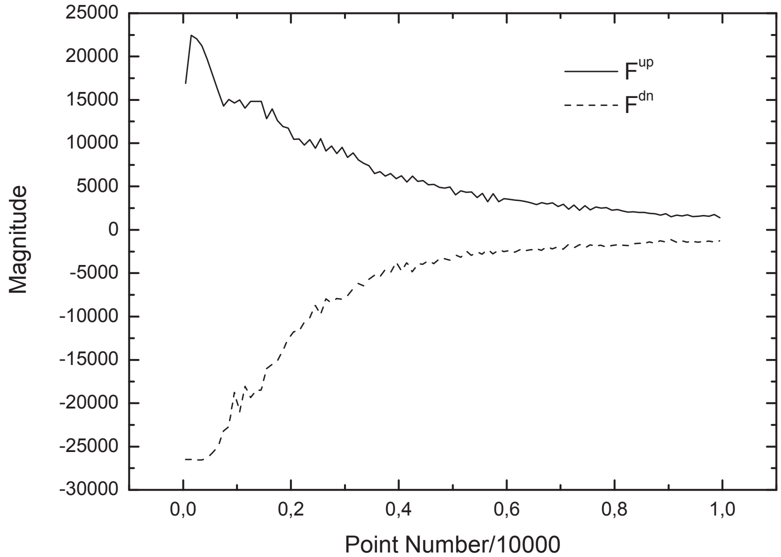

Fig. 5 Curves Fup and Fdn from rod with saw cut 5 mm.

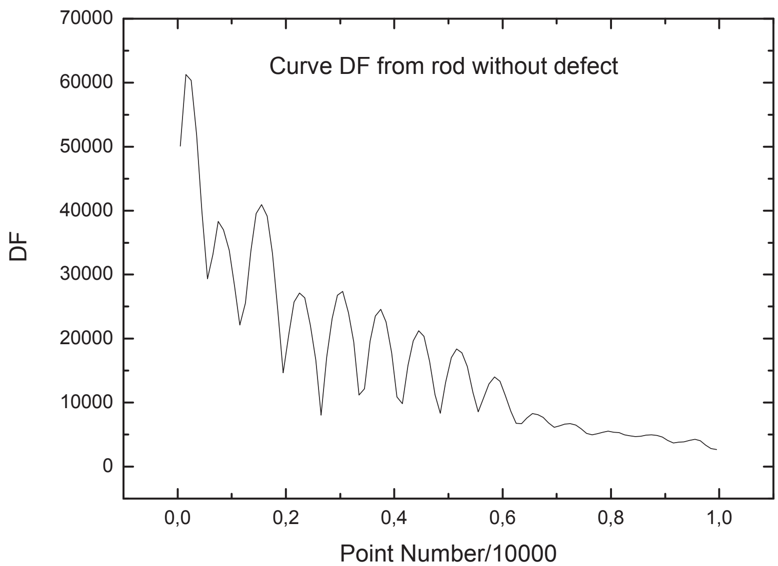

Fig. 6 Curve DF from rod without defect.

(9) we get 40 GMV-curves for each rod. After that one can get the mean function from the set of the GMV-functions corresponding to each rod. On figure 9 one can see the averaged curves obtained from each sampling of the GMV-function for seven rods (one normal rod without defect and six rods with saw-cuts with depths 1, 2, 3, 4, 5 and 6 mm, accordingly).

On the next figure 10 one can see the part of previous figure 9 for more clarity.

Here one can see the direct correlation between saw-cut depths and position of the averaged mean value function. As one can see from this plot the smallest saw-cut defect with depth 1 mm cannot be differentiated; while others starting from 2 mm can be definitely differentiated for forming of the desired calibration curve (the relative distance between the limiting values, right-hand side of figures 9 and 10) of the rods with respect to the depth of the defect:

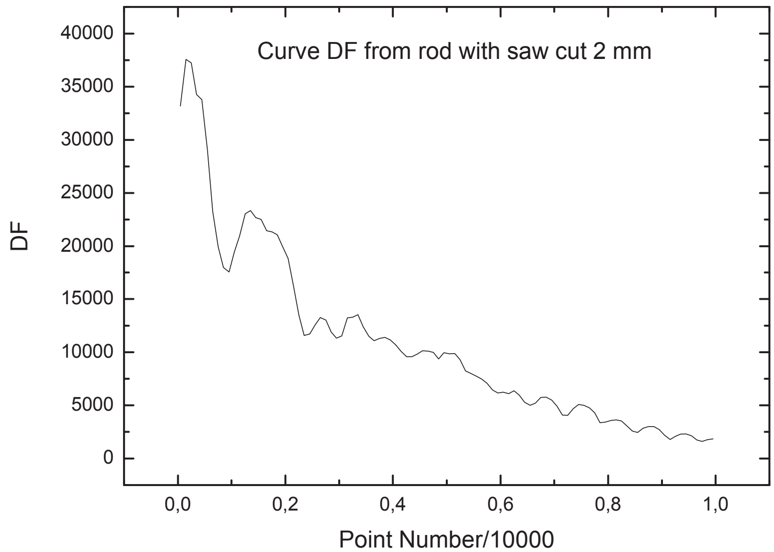

Fig. 7 Curve DF from rod with saw cut 2 mm.

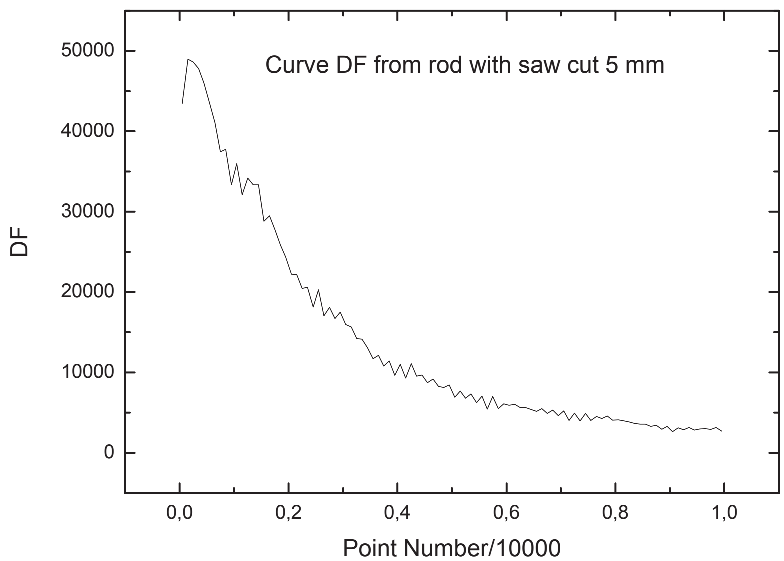

Fig. 8 Curve DF from rod with saw cut 5 mm.

$$Calibration(sawcut\ depth) = \frac{GMV(sawcut, p = 500) - GMV(normal, p = 500)}{0.5 \cdot (GMV(sawcut, p = 500) + GMV(normal, p = 500))}. \tag{10}$$

Below on figure 11 one can see the desired calibration curve calculated from expression (10).

4 Results and conclusions

The basic result of this work can be formulated as follows. It becomes possible to present a novel signal processing algorithm based on the specific behavior of the GMV-function. This algorithm helps to extract the significant and quantitative information from the acoustic signals that are propagated inside metal cylindrical slugs having saw-cut defects with different depths. This information allows to

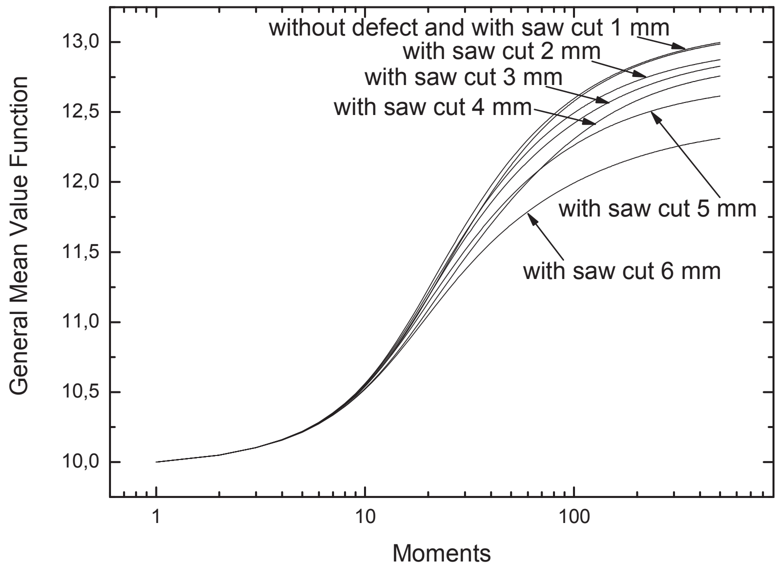

Fig. 9 Averaged general mean value functions for seven rods (one rod without defect and six rods with saw cuts with depths 1, 2, 3, 4, 5 and 6 mm).

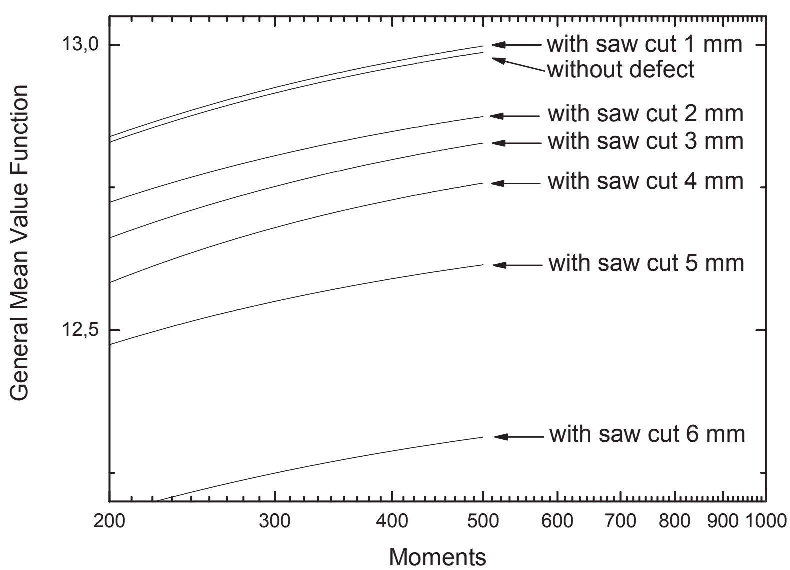

Fig. 10 The part of figure 9 - averaged general mean value functions for seven rods (one rod without defect and six rods with saw cuts with depths 1, 2, 3, 4, 5 and 6 mm).

distinguish normal rods/intermediates (without defects) from rods with saw-cut defect and construct the desired calibration curve (see figure 10) that helps to differentiate the rods with different saw-cuts depths from each other.

The conclusion of this preliminary study is that the proposed signal processing method is suited to be employed for acoustic signals acquired in frame of free-oscillation method in order to detect and evaluate defects in metal rods. We think that proposed signal processing algorithm can be used as a basic and simple procedure for development a really powerful, efficient and reliable signal processing method for detection of different defects (not only transversal saw cuts but also inner cavities) in essential improving of the free-oscillation method drawbacks.

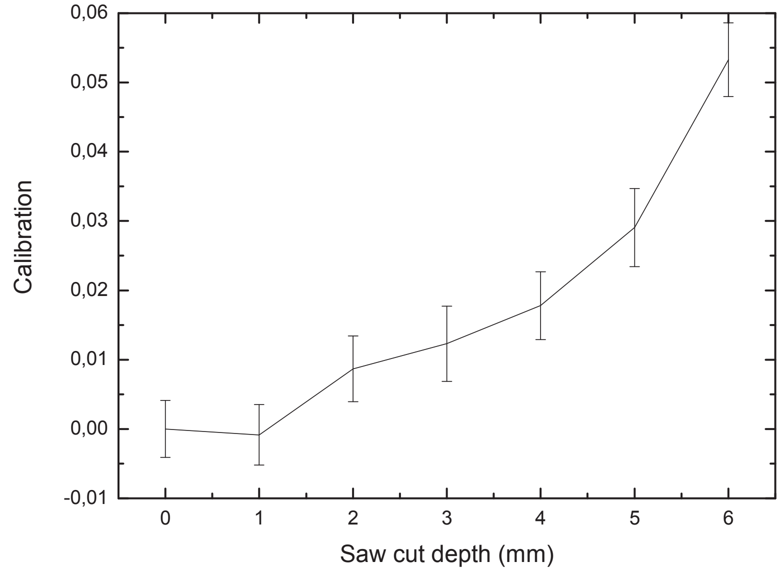

Fig. 11 Calibration curve with respect to saw cut depth.

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