590. Detection of Internal Defects of Material on the Basis of Performance Spectral Density Analysis

Ondrej Krejcar[1], **Robert Frischer**[2]
[1]VSB Technical University of Ostrava
dept. of Measurement and Control, CAK, FEECS, Ostrava, Czech Republic
e-mail: *ondrej.krejcar@remoteworld.net*
[2]dept. of Automation and Computing in Metallurgy
VSB Technical University of Ostrava
Ostrava, Czech Republic
e-mail: *robert.frischer@vsb.cz*

(Received 20 September 2010; accepted 9 December 2010)

Abstract: The developed approach for nondestructive diagnosis of solid objects is described in this article. This is accomplished by means of software analysis of oscillatory spectra (possibly acoustic emissions,) which is formed while running the monitored device or in unexpected situations. The principle of this method is based on the analysis of spectrum from received signal, its subsequent processing in MatLab and following sample comparison in Statistica program. The last step (comparison of samples) is the most important because it enables determination with some certainty the actual condition of the examined object. The processed samples are currently compared only visually. On the other hand, in applying this approach they are subject to the analysis with the assistance of neural network (Statistica program). If correct and high-quality input data are provided to initial network, it is capable of analyzing other samples and identifying the actual condition of certain object with success rate of around 70% (minimum 70%). The instructed neural network is then able to determine whether any critical condition occurred (e.g. escape of gas from burst pipe, loosened screws in critical places, etc.). Data from accelerometer (microphone) are evaluated with the assistance of MatLab program and a special newly defined filter is implemented. This filter ensures extraction of relevant data. Analogue signal is digitized with the help of special NI I/O module PCI 6221. The correlation of the spectrum and the condition of examined material (its internal defects) are obvious after implementation of FFT. Finally, it is possible to detect defects or upcoming hazardous conditions of examined object/material by using only one device which contains HW and SW parts. This kind of detection can lead to significant financial savings in certain cases (such as continuous casting of iron, which saves hundred of thousands of USD).

Keywords: FFT; Power Spectrum; MatLab; Statistica; Defect

INTRODUCTION

The problem area of technical diagnostics is very extensive. Device maintenance and economical performance is dependent on it. This is the reason why it is important to know the actual condition of an object or the condition of its significant components. It is often impossible to determine the actual parameters of certain device, because shut-down would be uneconomical (e.g. device for continuous casting of steel, high-pressure gas pipes, or just simple engine which would be necessary to disassemble and detect fading of cylinders). Technical diagnosis replaces intuitive, empiric and systematic approach towards maintenance of certain object without taking it apart or suspending its activity. Technical diagnosis which is correctly implemented increases the reliability and safe operation of an object. The basic function of diagnosis is to determine critical places of monitored object. In these places, we are trying to install a physical quantity sensor that would characterize defect or its emergence. We detect many problems in the latter case. The placement of sensors is often impossible because of the movement of parts (either it is a linear shift or rotational motion). For example, sensors of surface clefts, which operate on the basis of magnetic fields, are very complicated, expensive and they require a specific adjusting for each type of setting. Especially clefts are critical for the majority of objects and prompt detection is crucial for the safe operation and economical reparation. This is the reason why the nondestructive approaches of diagnosis are under constant intensive development. The scheme of measured and evaluated chain is provided in Fig. 1.

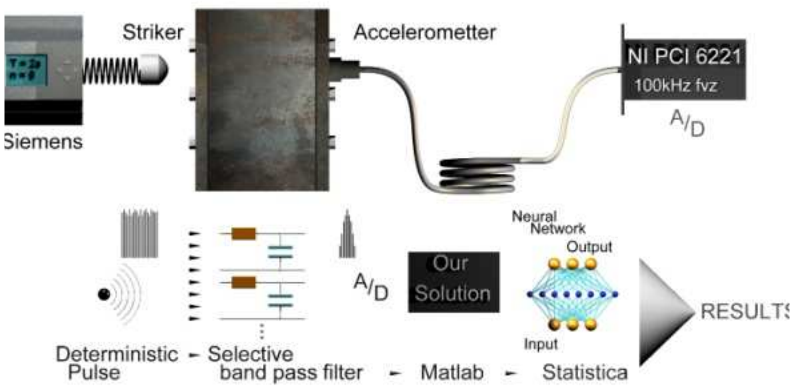

Fig. 1. Scheme of measuring network and procedure of data processing

RELATED WORK

This article is devoted to the technical diagnosis of a device, which uses analysis and evaluation of vibratory spectra or acoustic emissions. Vibratory spectrum and acoustic emissions have various causes of formation. While analyzing vibratory spectra, the response of system (of an object) to artificially-generated impulse is recorded. On the other hand, acoustic emissions mainly originate spontaneously by e.g. initiating crack on pipe surface during mechanical stressing (in plastic deformation position).

On the basis of problem definition by external company, the task of our research work was to determine whether it is possible to detect internal condition of an object on the basis of vibratory spectral analysis. It was a metallic skeleton connected by screws on edges [Fig. 1]. When loosening of screws, diagnostic system should precisely define the position or side where the screw (or simply the defect) occurs. There are many articles published on this topic [1-4]. However, mostly there are specific problems and translated solutions are closely specialized.

For example in article [4], authors are interested in a problem of crack formation in rotor and turbine blades. Their method is based on detection and analysis of acoustic emissions. The main difference between our proposed solution and the one reported in [4] is that the latter solution is trying to detect already evolved defect (crack) and our solution enables detecting of emerging crack, because it uses other source of vibrations (deterministic pulse). Whilst the formation of acoustic emission is controlled in [4] (passive method), our method aims at recording forced response on impulse. The difference is illustrated in Fig. 2.

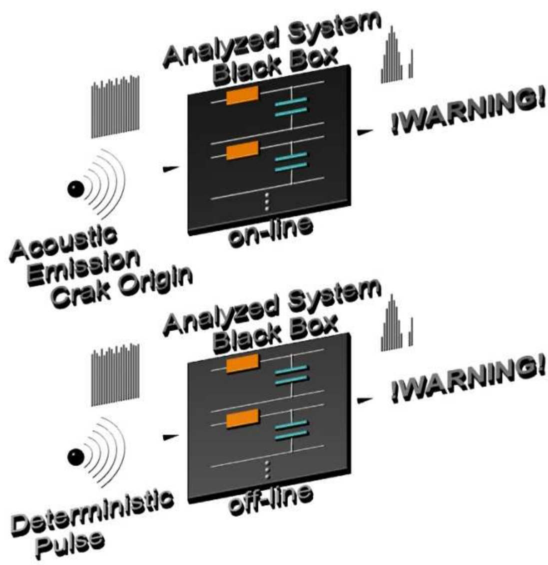

Fig. 2. The upper part illustrates online identification. Meanwhile, the bottom figure indicates our method of offline condition identification

The main advantage of our solution is the possibility of preventing the formation of limit conditions, dangerous situations and device damages. Whilst the authors of introduced article are trying to preclude greater damages during the formation of a crack, our approach seeks to forestall the condition from happening. The comparison of both approaches is given in Table 1.

Table 1. Summary of comparison of several relevant methods for internal defect detection.

Emission source	Mode	Scan type	Aiming field of application					Solution type
			Detection of forthcoming boundary states	Detection of boundary states (cracks)	Crack position determination (2D)	Complexity of application	Mobile solution	
Acoustic emission	On-line	Contact	No	Yes	No	Middle hard	No	HW+SW
Deterministic pulse	Off-line/ On-line	Contact	Yes	Yes	Yes	Middle hard	No	HW+SW
Acoustic emission	Off-line/ On-line	Contact less	No	Yes	No	Easy	Yes	SW

The third option of analysis with the assistance of acoustic emission is mentioned in Table. 1. However, it is different from [4] by being mobile. It is based on software application that is designed for mobile device. This solution is applicable for detection of engine defects in automobiles or electrical engines while applying acoustic emission analysis through the microphone input of mobile device. The range of recorded frequencies of the input is typical up to 22 kHz which is fully enough for considered application. However, this article does not engage in this solution. It will be resolved in the future.

ANALYSIS OF RESPONSE ON DETERMINISTIC PULSE

The principle of method comes from measuring of response of examined object to Dirac impulse. The first experimental results were presented in [5]. An ideal Dirac impulse is replaced by real impulse, which is generated by firing pin that is excited by magnetic field (Fig. 3).

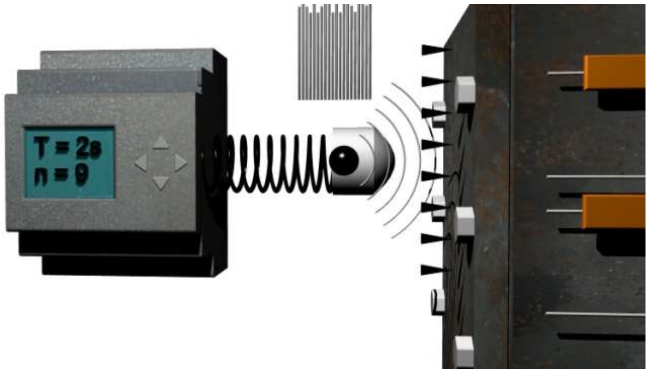

Fig. 3. Pseudo Dirac impulse realized by firing pin, which is controlled by Siemens PLC. T is a period of pulses and n is a number of pulses

This impulse is far from ideal shape but is appropriate for our purposes. Individual pulses are operated by Siemens PLC, which generates series of impulses with period of 2 s (Fig. 3). Unwanted offset and relatively uneven progress of individual strokes belong to the basic disadvantages (only when comparing amplitude covers). Number of measurements are progressively made with the goal of eliminating these defects. At least four out of nine of these measures are very similar and others show moderate or extreme anomaly or periodic defects (vibrations from surroundings, noise from amplifier etc.). Digital record is made for the whole series of measuring at once. The records of individual pulses are then extracted from the whole and saved independently (Fig. 4).

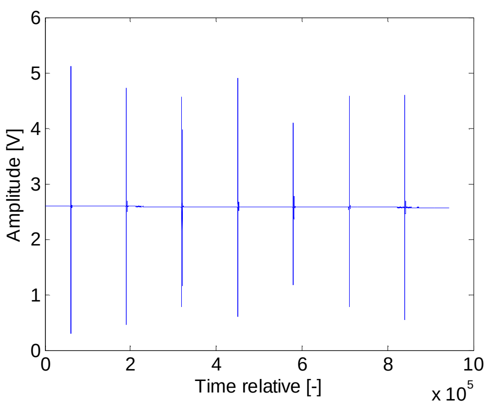

Fig. 4. Record series of measurements

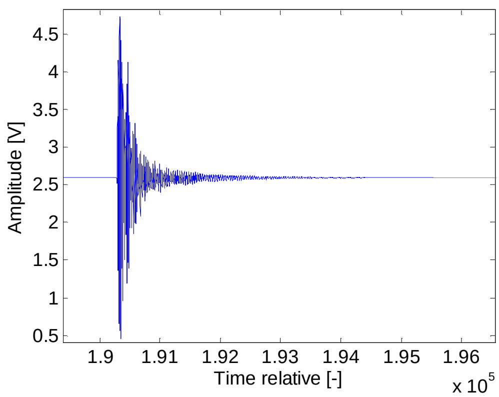

Fig. 5. Amplitude envelope of chosen response to a pulse (pulse no. 2 from Fig. 4)

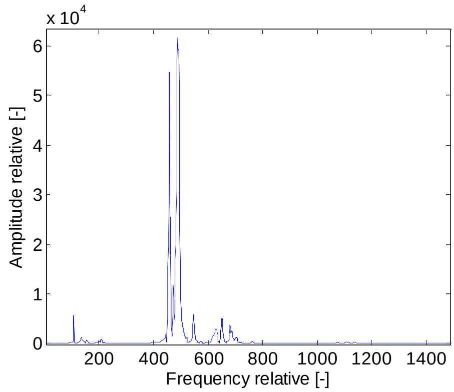

Fig. 6. Power spectrum density of given pulse without any other modification (pulse from Fig. 5)

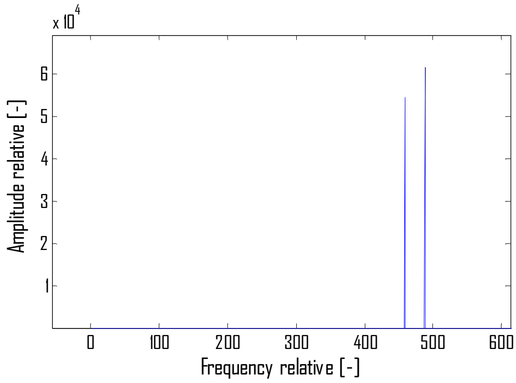

Fig. 7. Modified power spectrum density. Suggested filter was used in Matlab environment. Filter was applied on power spectrum density from Fig. 6

An impulse is a source of vibrations (or also specific acoustic emissions (6)) with wide range of frequencies (spectral density (6)). All of the components of the whole spectrum would be represented in an ideal pulse (theoretically the generator of white noise). The components up to several kHz are represented in our case. Moreover, there is uneven representation of individual components. An analyzed object behaves as a selective band-pass filter (6) after the activation of pulse or after the formation of acoustic emission. Recorded amplitude envelope is modified and FFT (Fig. 6) is applied.

Final high-performance spectral density (Power Spectral Density – PSD) is then subjected to examination and modification. Some vibrations (in certain frequencies) pass without significant changes, some are heavily suppressed. In order to work more predictably with obtained data, it is necessary to modify PSD. After the application of suggested filter, the irrelevant data are removed from PSD and the result is saved in a matrix form (Fig. 7). Suggested filter scans record of each pulse (its PSD) and searches specific values of individual spectrum components. Positions of points (their corresponding frequencies) are very important for next analysis PSD. It is quite difficult to locate these anomalies, because the signal spectrum has an odd progress (Fig. 8). Hundreds of data which did not correspond to the distribution of maximums in spectrum were received after the application of classic algorithm for determination of maximum ($f_{(x-1)} < \max > f_{(x+1)}$). While searching for the cause of algorithm malfunctioning, a simple cause was discovered. It is clear after enlarging part of the curve that it is not smooth. Modulated points created number of false (pseudo) maximums (Fig. 8) needed to be eliminated.

A newly proposed filter (described further in the article) was able to eliminate these „pseudo-maximums“. It went through the record and for the highest value in a certain area (local maximum) verified whether it is really the highest. This interval is optional and its value is inversely related to the number of maximums in the record. Moreover, this interval may be expressed as insensitivity. Its value states in which interval certain local maximum must be valid in order for its position to be clarified and saved. Furthermore, in order to remove the omnipresent noise from the signal, the local maximums with amplitude smaller than 7% of global maximum were eliminated. In this way the image was cleaned and sent to next processing stage with the assistance of neuron network. Used filter is still in development and its improvement will lead to better results.

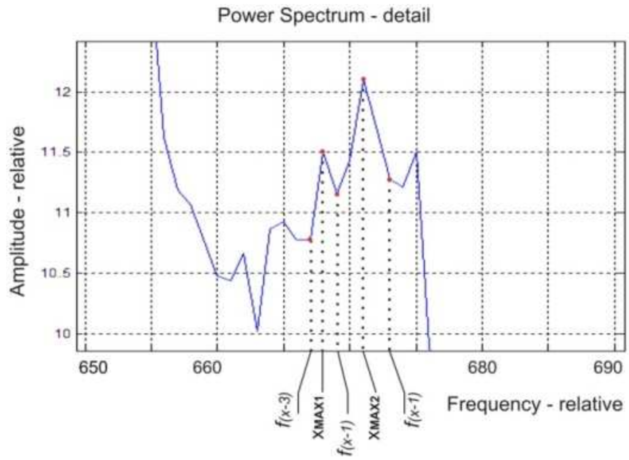

Fig. 8. False maximum during application of simple algorithm for finding maximum

IMPLEMENTATION

Scheme of measuring series is presented in Fig. 9. Vibrations are scanned with the assistance of accelerometer of type 4332 from Bruel&Kjaer. This sensor is unique by high frequency which exceeds the value of 25 kHz. Certainly there is number of cheaper accelerometer types on the market, however, most of them are suitable only for scanning of frequencies up to 600 Hz (mobile applications), which is not appropriate for declared purposes. On the other hand, they might be used in applications that do not require high frequencies of scanning, because they are often implemented in modern and smart mobile phones or PDA devices.

After the increase of signal (sensor offers only tens of mV) the signal is digitalized with the help of multi I/O card NI PCI 6221. This card disposes 16 analogue inputs with joint multiplex, which runs on 250 kHz. Only one canal which works with sample frequency of 100 kHz was used for the considered purpose. With regard to the estimated and scanned frequencies of order of tens kHz (maximum around 20 kHz) fivefold oversampling is sufficient. Driving algorithm was built in Matlab environment – Simulink and adjusted in a way that the acquired data are saved for period of 20 s. Subsequent processing of results was already running offline.

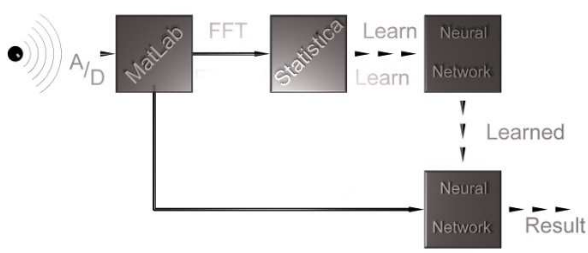

Fig. 9. Scheme of measurement network

Evaluation of algorithm is performed in MatLab. Firstly, it is necessary to extract relevant data, records of pulses and save them separately into matrix. Routine serves for this purpose. It looks for initiation of pulses and then saves identically long blocks of data into the beforehand set positions in matrix.

$$[start]_{\downarrow} i = if\ (abs(DATA(j) - DATA(j+1))) > (noise.level \cdot \sigma)$$

Where:

DATA	is a matrix with the record of pulses
i	Index of variable start, sequential number
j	sequential number of sample in the record
σ	is a constant derived from medium level of noise in signal and states that σ> 2

After extracting of individual records, fast Fourier transformation (FFT) is applied to them and its results are saved into next matrix. Each individual line of matrix corresponds to values of one pulse (its PSD). The calculation is composed of signal division into M segments which may partly overlap. From each segment (after removal of direct component and by calculating window (Fig. 10)) the middle value of quadrate of normalized and amplitude spectrum is calculated. Average is made from the results for each segment and deflections made by used window are removed. This is called the Welch‘s method of modified periodograms (5). Simplified scheme of calculation is provided in Fig. 10.

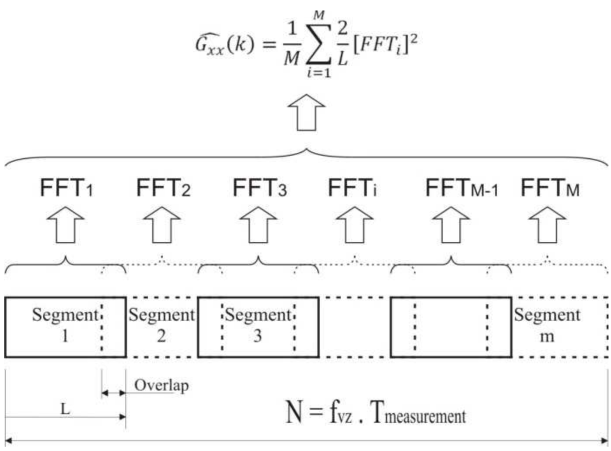

Fig. 10. Welch’s method of modified periodograms

From already made signal spectral densities, it was necessary to extract relevant data and to separate the useful signal from noise or residues formed by surrounding noise or insufficient shielding of an object from surrounding vibrations. This part is fairly challenging because it is not possible to find the suitable routine in Matlab or in literature which deals with such task. The question is how to determine the position (frequency) of individual points. These points are very important for us and directly reflect the real condition of an object. The classic definition of local maximum fails due to the aforementioned problems. It states:

$$maximum_{local} = if\left(f_{(x-1)} < f_{maximu-local} > f_{(x+1)}\right)$$

Where

$maximum_{local}$	is a position of local maximum
$f_{(x)}$	is a value of a function in point *x*

Therefore, it was necessary to find a different method. Human perception of this problem meant great inspiration. When looking on the graph of high-performance spectral density (Fig. 8), the individual maximums are obvious. After some simplification it is possible to say that perceiving of individual extremes is due to their position towards other values. Even though, the amplitudes of two sharp local maximums which are next to each other are very high, it is possible to ignore them. Although, if the local maximum is isolated and it has significantly lower amplitude than global maximum, it is perceived as sharp. Obtaining of relevant points from PSD is crucial. It is only their position which guarantees correct acquiring of neuron network or regressive detection and marking of the result. Nowadays, there is a “flag” assigned to each local maximum which states for how long the maximum is valid. In the future, the algorithm will be enlarged by the option of working in narrow zones and choosing of local maximum more correctly than it is done presently.
Value of flag is incremented in the case when

$$\uparrow n_{flag} = if\left(f_{PS(i)} > f_{PS(i-1)}\right).$$

Then position of local maximum must fulfill the following criteria

$$maximum_{lokal} = if\left(f_{PS(i)} > f_{PS(i+1)}\ AND\ n_{flag} > n_{set}\right).$$

Where

n_{flag}	Actual value of variable n which indicates operating period of given maximum
$f_{PS(i)}$	is a value of a function (curve PS) in point *i*

Individual results are saved again into rectangle matrix. With regard to the fact that filtered spectrum has number of irrelevant local maximums (noise component cannot be neglected), it is necessary to apply last modification which means removal of all local maximums that do not fulfill criterion.

$$maximum_{lokal(i)} > \rho$$
$$\rho \cong 0.07 \cdot maximum_{global}$$

Where

ρ	Constant derived from global maximum (optional)
$maximum_{global}$	Value of global maximum from given PS pulse

For verifying whether individual impulses are at least a little similar, the values of global maximums of certain calculations (in same conditions) are for better transparency arranged next to each other. The final result is a graph (Fig. 11). Furthermore, it is necessary to emphasize that values of frequencies and amplitudes are only relative. By recalculating them it is possible to obtain real values of frequencies and amplitudes. However, this is not necessary for this analysis and it would be more difficult to calculate. Therefore, the values on axis do not have units (important are only their values).

Values from each pulse that are adjusted in this way are saved into a file and presented to neuron network as teaching pattern or as useful data for detection. StatSoft program from Statistica firm was used in order to realize the neuron network. This analytic software is

© VIBROENGINEERING. JOURNAL OF VIBROENGINEERING. DECEMBER 2010. VOLUME 12, ISSUE 4. ISSN 1392-8716

primarily intended for data mining, thus for obtaining potentially useful data from data file. It uses the options and potential of neuron networks. Data are suitable for learning and therefore they are given to the network. The network studies the given method (back propagation, method of joint neurons, Levenberg-Marquardt method etc.). Studying is basically setting of weights of individual neurons. Then the examples of data are given to the network and it determines by certainty the origin of these data or competence to some whole. Graphic representation of input data for neuron network is provided in Fig. 12 and some values which are suitable for determination of neuron network are listed in Table 2. All values refer to one series of measures on equal terms.

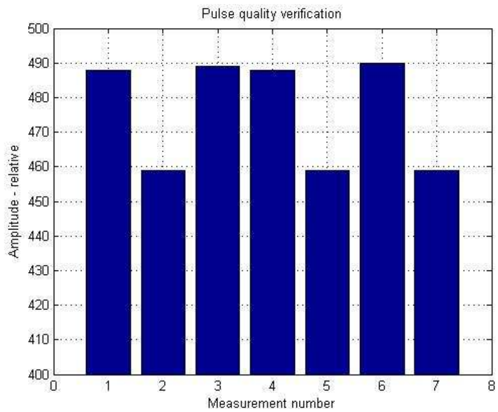

Fig. 11. Verification of pulse quality by regressive control of their major frequencies maximums derived from PS

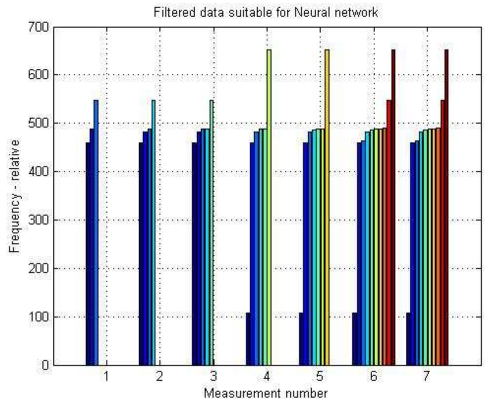

Fig. 12. Input data for neuron network. Number of major values corresponding to individual points is present in each measuring

Table 2. Example of input data for teaching the neural network (seven measurements of one specific condition of examined object)

Number of measurement	Characteristics frequencies of several measurements (measured at same conditions)			
1	459	488	550	0
2	459	485	488	550
3	459	485	488	489
4	459	485	488	489
5	459	485	487	488
6	459	485	487	488
7	459	485	487	488

TESTING AND EVALUATION OF PROPOSED SOLUTION

There is couple of major values in each measurement which correspond to individual points in signal spectrum. In this way the networks which always represent some condition of investigated object are given. It must be specified in each measurement to which condition it belongs. Samples of measurement (one or more) are presented for detection to the taught network. This detection tries to assign them retrospectively to given condition of an object. For example, the recognition of an individual on the basis of analysis of his/hers voice. Each person has a certain spectrum of voice, thus the position of local maximums is individual. If the spectral analysis is accomplished from the person’s voice, the taught neuron network would be capable of assigning certain samples to the persons. In our case, the successfulness of regressive assigning of condition samples to which it belongs is in the range of 70-80%. This value is depending on quality of measurement and inner network state, so how the network is learned. As an illustration, Fig. 13 (in right window) present results of analysis of input data, which indicates that the network determined state of the system with an accuracy of 85.71 % (which mean that 6 results from 7 were correct). Fig. 13 illustrates environment of STATISTICA program. The window called DATA_3 contains training data aggregate. Also the window called Table_3 contains testing data aggregate. Finally, the last window shows the successfulness of the assignment of testing data to original aggregate. Training data are marked by prefix U, P, L which characterizes the condition of an object, thus its inner arrangement (simulation of inner defects). Testing aggregate obtains independent data which were not used for training aggregate and serve as an input for neuron network. These data were measured on equal terms (prefix U), thus we believe that the network assigns all values to prefix U. It is possible to verify the results in a window and to find out that except one result all of the values are correctly assigned. A first value is incorrectly assigned to other condition of an object (prefix P).

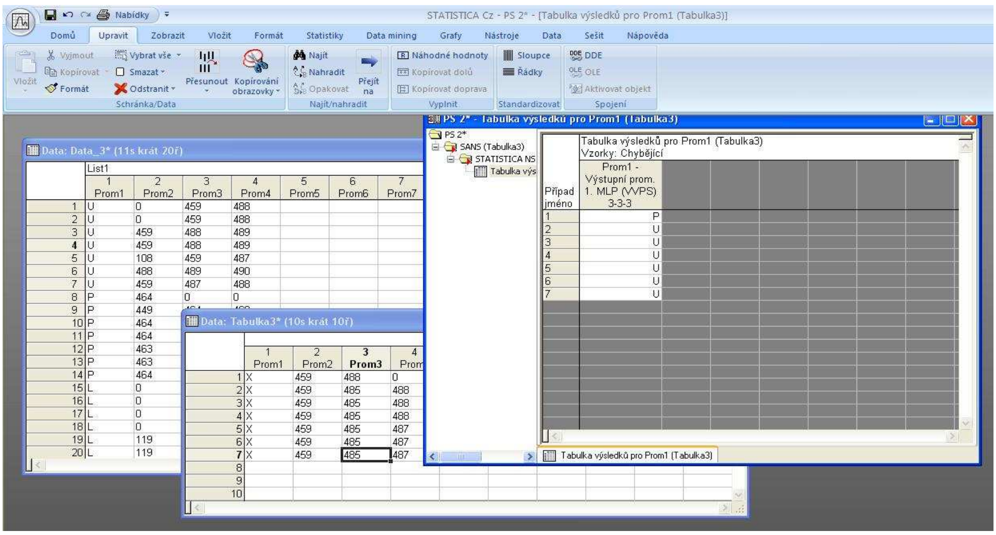

Fig. 13. The environment of Statistica program and example of input and output values

We did one series of measurements, where from 7 measurements 6 were detected correctly (85.71%). For verification of authenticity of state determination another check measurement were did on sample of 20 measurements. Successfulness of detection was in this case 16 of 20 (80%).

For relevant detection of state of examined object it is necessary to perform several measurements at a row and evaluate them as whole. From our tests it is obvious that a series of 7 measurements is sufficient. A delay of 2 s (Fig. 3) always exists between individual measurements and so it is necessary to count with 14 s of whole measurement time. For given reasons we can assume target application field for the proposed solution. These are processes with slow state changes (order of tens of seconds).

CONCLUSION

The purpose of this project is to verify whether it is possible to determine condition of monitored device (presence of inner defects or critical conditions) on the basis of analysis of vibration spectrum (acoustic emission). It is clear from measurement results that there are some similarities in the frequency interval. Another processing of results with the assistance of neural networks can be traced. The condition of an object may be established together with identification of critical condition or breakdown. Correctness of assigning individual samples to given conditions presently constitutes at minimum 80%. This number is partly dependent on the data folder which is designed for teaching of neuron network. Therefore, it is necessary to have these operational, critical or breakdown conditions well monitored. Further development of filters and modification of computational algorithms will enable increase of success rate with reliable identification of condition of an object without a necessity for shut-down or interfering into its inner structure in any other manner. Therefore, this method will be useful in those situations, when it is impossible or economically inefficient to stop system operation due to preventive maintenance or replacement of device or its part. For example, this is the case of device of fluent casting of steel (loss of hundreds of thousands, 200 tons of steel costs 200 x $2000,- = $400.000,- (7)), cracks in pipes and escapes of fluid (thousands or hundreds of thousands) or inconsistency in engine operation (price of new engine) etc.

ACKNOWLEDGEMENT

This research has been carried out under the financial support of the research grants "Centre for Applied Cybernetics", Ministry of Education of the Czech Republic under Project 1M0567 and "Safety and security of networked embedded system applications", GACR, GA 102/08/1429, Grant Agency of Czech Republic.

REFERENCES

[1] Bogorosh A. et al. Defect diagnostics in devices via acoustic emission. *Journal of Vibroengineering.* 11, 2009.

[2] He Y. Y., Zhang X. M. and Friswell M. I. Defect diagnostics in devices via acoustic emission. *Journal of vibration and acoustics-transactions of the ASME.* 2009, Vol. 11.

[3] Carpinteri A et al. Critical defect size distributions in concrete structures detected by the acoustic emission technique. *Meccanica.* 2008, Vol. 43.

[4] Volkovas V. and Dulevicius J. Acoustic emission used for detection of crack generation in propellers of turbine-pump units. *Russian journal of nondestructive testing.* April 2006, Vol. 42, 4, pp. 248-254.

[5] Krejcar O. and Frischer R. *Material Inner Defect Detection by a Vibration Spectrum Analysis.* s.l.: NJ. IEEE Conference Publishing Services, 2010. 2nd International Conference on Mechanical and Electronics Engineering, ICMEE 2010, 01. -03. August 2010, Kyoto, Japan, Volume 1. pp. 384-388. ISBN 978-1-4244-7480-6.

[6] Gheorghies C. and Thompson M. Characteristics of Acoustic Emission Signal Specific to Isolated Cracks Triggered by Scratch Tests in Stainless Steel Coatings. *Journal of adhesion science and technology.* 2008, Vol. 22.

[7] Steel Prices (US$/TON). [Online] 01 2005. [Cited: 08 25, 2010.] http://www.airproducts.com/metals_newsletter/metal3-SteelPrices.htm.