The Complete Measurement System for Crack Detection and Identification

Ryszard Sikora, Piotr Baniukiewicz

***Abstract* — In this paper authors present automatic system for crack detection and identification. The eddy current multifrequency method was used for crack detection. The depth of cracks was modeled by neuro-fuzzy network.**

I. Introduction

The problem of data analyzing, obtained from various measurement systems, has crucial meaning in process of correct results interpretation. In the eddy current nondestructive testing systems, results of measurements contain important information about cracks in internal structure of materials. The complete measurement system presented in this paper consists of flaws detection module (hardware) and recognition module (software). Both modules cooperate together. Unified software makes process of material testing fully automatic. Besides spectrogram, the estimated parameters of crack are given as results of measurements. The continuous sensor movement and very short time of data analyzing guarantee a real time measurements. The multifrequency NDT methods [1] are used to test good and weakly conductive materials such as: ferromagnetic and non-ferromagnetic metals. The right choice of work parameters of testing system such as: testing frequency, type of used sensor, algorithms used to analysis of obtained data, makes use of multifrequency method in testing materials with various electromagnetic proprieties: steels, copper and its alloys, brass, aluminium, Inconel 600, titan and more possible. Various types of discontinuities can be detected, mainly the surface discontinuities and subsurface discontinuities with small dimensions and varied shapes. Most of critical tensions, caused by fatigue of material, are concentrated on the surface of material. Multifrequency NDT methods are used in industry for testing half-finished and finished products. These methods use the eddy currents effect. One of the main feature of eddy current is the skin effect, it is associated with the usage of AC sources to energize converters. The skin effect depends on the concentration of currents on and under the surface. Depth of material penetration with eddy currents is a function of conductivity of material, magnetic permeability and frequency. The shape of current's paths depends on the internal structure of material. The output signal will contain the same harmonics as the signal, which energized the excitation coil. The output signal produced by eddy currents depends on their amplitude and, as a result, from internal structure of material.

Data obtained during measurements don't give useful information about crack, except fact of its existing. Further analysis provides more useful information about crack e.g. its depth or size. The parameter based identifying algorithms are used in recognizing module. These algorithms can recognize only main crack parameters such as depth and length. The crack profile is not recognized.

II. The basics of measurement system

Analysis of amplitudes of signal's harmonics, obtained from the sensor, makes detection of discontinuities in material possible. In practice, the FFT algorithm is often used to separate a harmonics of the output signal. The FFT can produce various errors, typical for numerical algorithms, especially when number of samples is small. Theoretically, to obtain a correct Fourier transform of signal, we should analyze an infinite numbers of signal's periods. If not, many unwanted effects can appear in the output signal. Of course, the analysis of the infinite numbers of signal's periods is impossible in real systems, but we should trend to analyze a maximal possible amount of signal's periods. In the case of analyzing low-frequency signals, this method can drastically increase amount of time required for material testing (long time A/D conversion). For example, while using frequency of 25 Hz during testing the material, we need about 2 sec, to obtain fifty signal's periods. This means, that the sensor must be stopped on each testing point for 2 seconds. Practically hundreds testing points exist on the surface of material. It depends on the step, with which the sensor is moving over the material (typically 0.2 - 1 mm). The long time of A/D conversion is a reason for the use of a step-by-step movement. The NDT system, which uses a continuous movement of sensor, is difficult to realize in practice. In many cases the technique of digital filtering is used for the analysis of the harmonics of the signal. The digital filters have many features. We are able to design practically any filter with any phase and amplitude characteristic, but these implementation of filters always require a lower or higher computation power of computers.

The presented system uses selective analog filters and can improve measurement speed. It avoids numerical analysis of the signal like the FFT algorithm, and it is not dependent on the computation power of the used computer. The center frequencies of filters are tuned to values suitable for aluminum, but the construction of the system makes the changes of center frequencies possible, when other materials are scanned. In the current version the system can work

Authors are with the Chair of Theoretical Electrotechnics and Computer Science, Technical University of Szczecin, ul. Sikorskiego 37, 70-313 Szczecin, Poland, e-mails: rs@ps.pl, *baniuk@ps.pl*

with fourteen frequencies, but it has modular construction so this range can be improved in easy way.

III. MEASUREMENT SYSTEM

The main constructional principles of the system were: high selectivity and ability to work in real time, with continuous (not step by step) sensor movement over the material. Figure 1 shows a block diagram of the constructed unit.

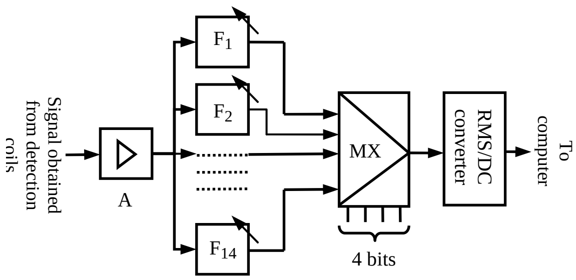

Fig.1. Block diagram of system, A – amplifier, F_{1-14} – analog filters, MX – multiplexer

The group of fourteen selective analog filters is the main part of the system. These filters extract required harmonics from input signal. The monolithic RMS/DC converter calculates RMS value of selected sinusoidal component and gives equivalent DC voltage on its output. Actually analyzed harmonic is selected by multiplexer MX (analog switch). The multiplexer is controlled by computer and specialized software. The main advantage of applied filters is maximally narrow amplitude characteristic. The selective characteristic makes use of close testing frequencies possible and guarantees that neighboring frequencies don’t disturb different channels. The elliptic functions were used for approximation. This gave better results in case of low-order structures than the usage of Butterworth’s or Chebyshev’s approximation. The filters phase shift can be ignored because only RMS value of sinusoidal components is collected and analyzed.

The construction of filters is based on LTC1264 integrated circuit. These circuits are very flexible and make creation of various filters with various characteristic possible. The use of integrated circuits instead of operational amplifiers causes the higher temperature stability of the whole system and better stability of its point of work. One LTC1264 consist of four second-order filters. They can be connected in various configurations. The main advantage of LTC1264 is that the center frequency depends on the external clock frequency. The change of clock causes retuning of the filters. The dependency between clock signal and center frequency of the filter is given by Equ. 1

$$F_0 = \frac{f_c}{b} \qquad (1)$$

Where b – unique coefficient determined on the stage of design, F_0 - center frequency of passband filter, f_c – clock frequency. The coefficient b depends on the configuration of the filter. It is set by external connected resistors. Each filter in block has different coefficient b. The block of filter is controlled by the same clock signal. It gives different center frequency F_0 for each filter in block. Change of the clock frequency extorts changes of center frequencies in all filters. The mutual ratios of these frequencies between all filters are always constant. On the basis above principles fourteen filters were projected with the following center frequencies: 20, 60, 100, 120, 140, 160, 180, 200, 220, 260, 300, 340, 380, 420 Hz. The width of passband of filters ranges from 6Hz for lower frequencies to 16Hz for higher frequencies. These parameters are caused by technological limitations of LTC1264, especially by nonstandard resistors values. The maximal clock frequency came to 5 MHz. The signal distortions appear for higher values of clock frequency.

The multiplexer is used for multiplex signals from filters to RMS converter. The active input is determined by 4-bits address bus, which is driven by computer. This part has significant influence on total measurement time, so the fast analog audio/video switch was used. The maximal delay period between channel switching equals to 220 µs. The RMS converter computes RMS value from selected harmonic. The usage of only one converter for all filters guarantee constant computing characteristic and minimalize total cost of the system.

IV. MEASUREMENTS

Figure 2 shows the complete measurement system. All parts of the system are driven by the computer and specialized software written in Matlab language.

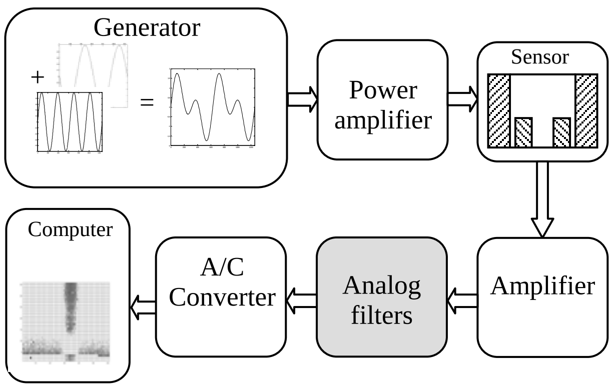

Fig. 2. The complete measurement system

The sensor consists of one excitation coil and two detection coils. The excitation coil is energized by AC current from arbitrary generator. The detection coils are sensitive to a normal vector of magnetic flux. The data used in experiments were obtained from measurements performed on test specimens (INCONEL600 plates). The specimen plate was 1.25 mm thin. The flaws were made by electro discharge machining. Each flaw was a notch of 0.2 mm width and length of 1, 2, 5 or 7 mm. The relative depth each of them ranged from 20 % to 100 %. During measurements the sensor and flaws were on the same material side. The probe was moved along the flaw with step of 0.5 mm. The lift-off was about 0.25 mm.

V. Recognition of crack parameters

The algorithms used in this method can only recognize crack main parameters, such as depth and size but the profile of the crack remains unrecognized. Parametric identification means that a parameter α was found and described by the measurement data. This parameter should and did closely depend on crack depth. The authors obtained proper results when the parameter α was simply defined by (2).

$$\alpha = \frac{f}{U_{\max}} \tag{2}$$

The U_{max} is the maximal value of signal caused by crack; f stands for the frequency for which signal U_{max} appears. The dependence of the parameter α on the crack depth is shown in Fig. 3 (for crack length of 5 mm).

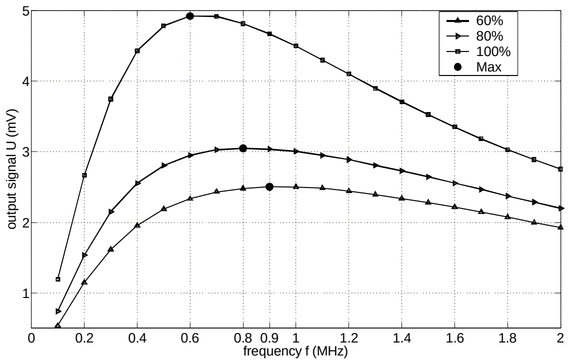

Fig. 3. Output signal in function of frequency. The parameter α is defined for points marked by black point

The ANFIS [2] Neural-Fuzzy System was used to recognize crack depth. The measurement data set was divided into two parts: training set (60% of all data) and test set (30% of all data). In the process of learning network the cracks depths included in the training set were already known. The FL system consists of one input and one output. The parameter α was given to the input, the percentage value of crack depth was obtained from the output.

The problem of choosing of membership functions was also considered. Membership function (MF) is a curve that defines how each point in the input space is mapped onto a membership value (or degree of membership) between 0 and 1. The shape of MF has a significant meaning for the system behavior. The efficiency of the training process depends on chosen MF as well. In case of simple systems, appropriate MF might be selected manually. For advanced systems, such as presented by authors, the simulation of the system behavior is the best way to obtain good results for different MFs. The number of MFs is also significant for the system accuracy, especially in recognition problems. Too many MFs causes that the training error converges to 0 but large recognition error might appear for data that didn’t belong to training set. Authors have made simulations of 40 FL systems in combinations of 8 different MF and different numbers of MF. Simulations were done for crack length of 1, 2, 5, 7 mm. Figure 4 shows results of simulations. The membership functions used during simulation are given in Table I.

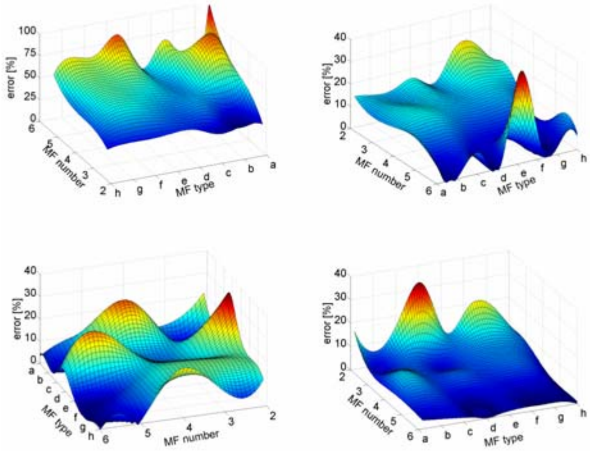

Fig. 4. Error of crack recognition in function of various MF and its number

As one can see the most significant errors appear for small crack due to higher distortions in signal obtained from sensor. The following membership functions were analyzed (Tab. 1.).

Table I. Analyzed MF

Symbol	MF Type	Symbol	MF Type
a	Triangular	e	Bell
b	Trapezoidal	f	Diff - Sigmoid
c	Gaussian	g	Prod - Sigmoid
d	2 - Gaussian	h	Pi - Shaped

The parameters that gave minimal error for all cases were considered as the optimal parameters. The low errors were obtained for membership function composed of the difference between two sigmoid functions (diff-sigmoid), and function composed of the product of two sigmoidally-shaped membership functions. (prod-sigmoid) [3]. The number of used MFs comes to 5. The prod-sigmoid function was used in further experiments. The input values of α were normalized to maximal value of each spectrogram. The maximal value corresponds with crack depth of 100%. The training set consists of input-output pairs. It includes all cases of cracks depth and length. The ANFIS model of FL was trained according to principles given above. The training time don’t exceed 30 second on Pentium IV class machine. The evaluate time is less than second.

VI. Results

The cracks used during experiments weren’t contained in the training set. Table II shows relative average error of recognition various lengths of cracks.

Table II. Algorithm accuracy

Crack length [mm]	Error [%]
1	4.69
2	0.50
5	1.97
7	0.59

Further, the two typical cases were analyzed: 1) the changes of lift-off and 2) noise in data. The changes of lift-off during measurements are caused by roughness of material surface, vibrations of sensor or other mechanical parts of system. The changes of lift-off were simulated by numerical modifying of data. The three kinds of surface slope were analyzed: along the sensor path, crosswise and diagonal. Figure 5 shows results for first two cases.

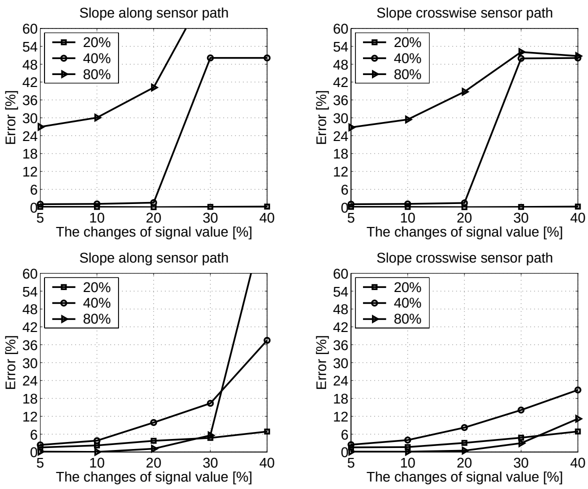

Fig. 5. Results of flaws recognition for different material slope. Upper figures were obtained for crack length of 1 mm, lower for 7 mm. The changes of the output signal value (x axis) were caused by different material slope.

Figure 6 shows results obtained for diagonal slope. As one can see, cracks of 5 mm and of 7 mm give larger errors than small cracks. It is a caused by a higher influence of the slope on longer crack than on short one. These errors are also caused by a very weak signal obtained for such a small crack and also by the resolution of the sensor used. Therefore, the relationship α mentioned before is not so strictly fulfilled.

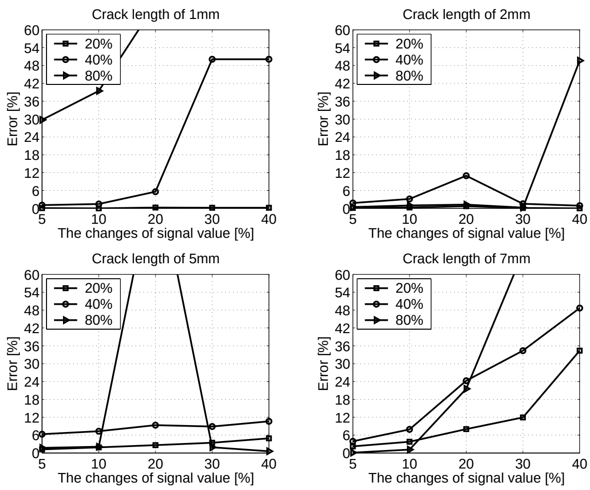

Fig. 6. Results of flaws recognition in case of diagonal material slope.

In the second case the white noise was added to data. Then accuracy of recognition was tested. Figure 7 shows obtained results.

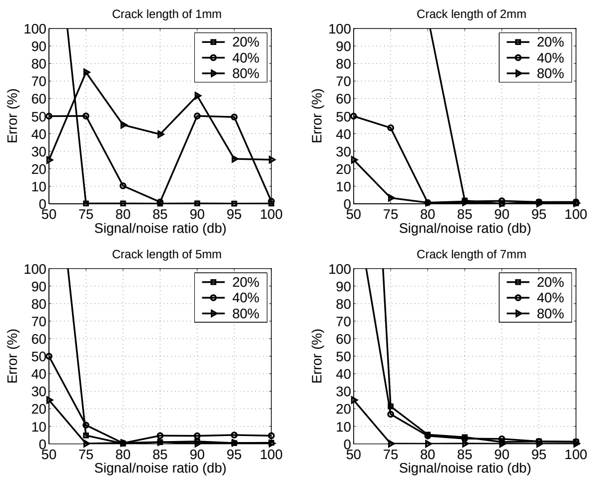

Fig. 7. The errors for various kinds of crack versus noising of data

Such as in previous cases, the maximal error appears for small cracks. Generally, the system shows good tolerance for noisy data.

VII. Conclusion

The system presented by authors can be used for crack detection and recognition. The process of material testing and data post processing don't require a high computation power of computer. The recognition algorithm is very simple and accurate. It can be applied directly to data obtained during measurements. The method presented can be used for fast finding basic parameters of the cracks

References

[1] Chady T., Enokizono M., Todaka T., Tsuchida Y., Sikora R., Flaws detection and characterization using the multi-frequency excitation and spectrogram ECT method, Electromagnetic nondestructive evaluation IV (2000), 87-94

[2] Jang R., ANFIS: Adaptive-Network-Based Fuzzy Inferencje System, IEEE Transactions on Systems, Man, and Cybernetics 23 (1998), n.3, 665-685

[3] Fuzzy Logic Toolbox manual