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Research of Acoustic Emission Testing Method with Application to Monitored for Wind Turbines

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Abstract

Acoustic Emission method of nondestructive check is based on exertion wave radiation and their registration during fast local material structure reorganization. It is used as a means of analysis of materials, constructions, productions control and diagnosis during operating time. In the article, it is applied to structural health monitoring of Wind Turbines. Acoustic emission testing is based condition monitoring system uses data already collected at the wind turbine controller. It is an effective way to monitor wind turbines for early warning of failures and performance issues. We used a number of measurements to develop anomaly detection algorithms and investigated classification techniques using clustering algorithms and principal components analysis for capturing fault signatures. When registering signal amplitude it is required to consider its frequency distribution connecting each amplitude rate with the corresponding vibration rate. The correlation and signal to noise ratio were evaluated by the algorithm based on frequency spectrum. Classical method of frequency distortion influence exclusion consists of FRF calculation with subsequent adjustment of received signals spectral characteristics.

Keywords: *NDT, acoustic emission, wind turbines, spectral characteristics, FRF*

1. Introduction

Material acoustic emission is the process of producing elastic waves, provoked by local dynamic reconstruction of its structure. Acoustic emission method allows detecting and registering of only developing defects, prompting to classify them not by the size but by the danger level [1-3]. Besides, it is the most sensible method of nondestructive testing (NDT). All above mentioned gives acoustic emission method undeniable advantage which unfortunately is hard to always realize. The situation makes the usual NDT specialist at best having passed the course in the process of qualification, become the experimentalist. Such transformation is hard for some people, and that is the main reason of the non-usage of acoustic emission method. It still used by small number of people and wide sphere for scientific researches. The existent expert NDT reference aids recommend using twenty six parameters, eighteen of which are primary. The number of secondary parameters used by researchers in their work is kiting with each new thesis and has exceeded reasonable limit [4-6].

Acoustic emission (AE) method of nondestructive check is based on exertion wave radiation and their registration during fast local material structure reorganization. Acoustic emission method is used as a means of analysis of materials, constructions, productions control and diagnosis during operating time. Its important advantages over other control methods are that it only reacts upon upcoming really dangerous defects and its ability to scan large areas or the whole of product without scanning it by a transducer [7-10].

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Rapid release of strain energy takes place and elastic waves are generated when the structure of a metal is altered, and this can be analyzed by acoustic emission (AE). The primary sources of AE in WTs are the generation and propagation of cracks, and the technique has been found to detect some faults earlier than others such as vibration analysis [11-12]. The measurement and interpretation of AE parameters for fault detection in racially loaded ball bearings has been demonstrated at different speed ranges in. In addition, the application of AE for the detection of bearing failures has been presented. Acoustic monitoring has some similarities with vibration monitoring but whereas "vibration sensors are mounted on the component involved" so as to detect movement, acoustic sensors are attached with flexible glue with low attenuation and record sound directly. AE sensors have been used successfully not only in the monitoring of bearings and gearboxes but also for damage detection in blades of a WT as discussed in. Its application is also possible to an in service WT for a real-time rotating blade [13-15]. Nondestructive testing techniques using acoustic waves to improve the safety of wind turbine blades are presented, and to enable the assessment of the damage criticality for blades of small WT based on AE data in. The use of AE is gradually growing for both FD of rotating WT components as well as blades.

The opposition of two great powers inspired the studies of acoustic emission phenomenon; there was no special equipment for that. The peculiarities of acoustic emission signals forming and propagation (complex spectrum, low energy level, wide frequency and dynamic range, *etc.*,) raise the demands to measuring equipment. Acoustic emission equipment should have high sensibility, high amplification coefficient, and minimal noise level and introduce minimal distortions. Ionizing emission detecting equipment met all these requirements that time. These devices were called intensimeters and the value measured using them – intensity. This was very convenient for detecting the particles with foregone energy characteristics. At that it was meant that to get the actual values of ionizing emissions intensity it is necessary to multiply the result by the correction factor depending on the converter type, as well as registered ionizing emission type and energy. In the process of using this type of electronic equipment to detect acoustic emission such sharpness was lost. As a result, the most common acoustic emission signals parameter is the intensity or the counting rate became deficient of physical content [16-17]. Contrary to ionizing emissions the number of impulses per time unit here is by no means connected to the intensity of ultrasonic wave propagated on the deformable body.

We carried out experiments which have demonstrated that applying acoustic emission parameters based on impulses reading for quantitative acoustic emission description principles invariably results in low researches results precision. Such situation in measurements may occur in the presence of not excluded systematic inaccuracies and bear the evidence of incorrectness of such measurements due to improper choice of physical units characterizing acoustic emission properties [18]. If to compare main acoustic emission measurement units with the International System of units, it can be seen that generally accepted acoustic units are almost never used for acoustic emission description. All existing normative documents starting from GOST 2763-83 and ending with rather up-to-date RD 03-131-97 and RD 03-299-99 recommend using parameters based on impulses counting. Solid body is a random set of structural formations. Viewing it in one scale level it can be considered as a set of grains on the surface of failure. The grains can be of a random shape. Crack development process is easy to consider as a process of successive destruction of its separate structural formations. Each impulse will have individual properties reflecting grain's individual shape and size. The sequence of mentioned impulses will thus compose AE process. From what has been said we can conclude that the energy of AE signal of the developing crack will be irregularly distributed along the frequency band. The irregularity will be of a random nature as every AE signal with its spectrum will be unique composition due to formation and development features. These facts were many times established and this is the reason why energy and amplitude properties of the signal should be measured in broad band, taking into account all frequency components. Besides, while material destruction acoustic waves (AE signals) undergo serious changes when they spread along the survey item. AE signal in receiver point is a sum of signals from different paths. As a result the wave shape becomes distorted and impulse signals duration increases by hundreds and thousand times.

2. Experimental Data

Experimental studies results inconsistence and huge measuring inaccuracies apply not only to parameters based on impulses counting. Such parameters as AE signal maximum value (amplitude), AE signal average power, AE signal energy, the physical sense of which is beyond exception, are measured by modern acoustic emission systems with abnormally large error. Just receiving converter calibration error is 30%, adding thereto converter unit error and physical quantity measuring error. In the process of metering parameters registration these errors at least double. But this is still not the determining factor. The main error and variability source is the unwillingness of the researches to work in broad band. And we can understand them – in the process of receiving converter pass band spread its sensibility decreases. Up to this day they failed to create broad pass band converter with suitable characteristics. These forces the users to work in narrow band, having measuring error in the above mentioned parameters exceed 100%, thus loosing the meaning of the measurements. Researchers try to solve this problem demonstrating miracles of ingenuity. This results in the variety of parameters, the physical sense of which can be hardly explained.

The author based on spectral analysis of the research studies of acoustic emission features of different materials demonstrated the inconsistency of using traditional parameters when analyzing narrow band acoustic emission signals, and several times proved that in his further research works. The situation is paradoxical. It turns out that it is simply impossible to measure the majority of acoustic emission parameters. We talk only about detecting an event, the validity of which should be first proved. The situation makes the usual NDT specialist at best having passed the course in the process of qualification, become the experimentalist. Such transformation is hard for some people, and that is the main reason of the non-usage of acoustic emission method. It still used by small number of people and wide sphere for scientific researches. We are bound to analyze only the part of a collective process which appears to be above the equipment sensitivity threshold. This fact gives rise to multiple speculations and scientific fantasies. Mostly we can only see the tip of an iceberg and the rest data is left behind-the-scenes, under sensitivity threshold. As a result, even genuine values of such AE signal physical quantities as pulse height and energy are frequently do not allow establishing any correlations. We need comprehensive knowledge of process physics to evaluate the whole process by available data. It is important to realize that forming of the "tip" is indissolubly related to sensibility and frequency characteristic of a converter, method and accuracy of converter positioning, AE properties of a material and wave characteristics of a survey item, as well as to loading dynamics and structural in homogeneity of the material. We also have to take into consideration that AE formation process is comprised by several simultaneous processes part of which are auxiliary and depend on environmental conditions.

Experimental analysis outputs of different materials acoustic emission behaviors are shown in works. During ceramic materials testing a broadband piezoelectric transducer was used. It has transfer characteristic with uniform vibration speed of shear mode, it's gain flatness does not exceed 4dB within 0.1 – 1.6 MHz range. For comparison and analysis of spectrograms derived they were normalized according to the given criterion:

$$S_n(f_i) = S(f_i) / \bar{S}(f_i)_{\max} \quad (1)$$

Where f_i - discrete frequency of channel i, $s(f_i)$ - wavelength characteristic of channel i.

For "broadbandness" estimation of input signal the normalized spectrum's energy parameter was used:

$$^{j}E_{n} = \sum_{i=1}^{n} \left[{^{j}S_{n}(f_{i})} \right]^{2} \tag{2}$$

Where j is a spectrogram's serial number in the data block.

The energy of input signal was determined from:

$$^{j}E = K_{n} \left[U_{IN} \, {^{j}S(f_{i})_{\max}} \right]^{2} {^{j}E_{n}} \tag{3}$$

Where U_{IN} is a value of spectrum analyzer's input sensitivity and K_n is proportionality coefficient.

Spectral function's "irregularity" was estimated by the middle value of the interval between extremes ^{j}T. An energy response value of an absolute deviation between $^{j}E_{n}$ and $^{j-1}E_{n}$ was used for the variability estimation.

Also static characteristics was found for secondary parameters $^{j}E_{n}$ and ^{j}T:

$$E_{av} = \frac{1}{z} \sum_{j=1}^{z} {^{j}E_{n}} \tag{4}$$

$$G_{E} = \frac{1}{z-1} \sum_{j=1}^{z} \left| {^{j}E_{n}} - E_{av} \right|^{2} \tag{5}$$

$$\Delta_{E} = t_{\alpha}(z) \sqrt{\frac{G_{E}}{z}} \tag{6}$$

Where E_{av}, G_E, Δ_E are the average value, dispersion and confidence interval of energy response $^{j}E_{n}$.

$$T_{av} = \frac{1}{z} \sum_{j=1}^{z} {^{j}T} \tag{7}$$

$$G_{T} = \frac{1}{z-1} \sum_{j=1}^{z} {^{j}T} - T_{av} \Big|^{2} \tag{8}$$

$$\Delta_{T} = t_{\alpha}(z) \sqrt{\frac{G_{T}}{z}} \tag{9}$$

Where T_{av}, G_T, Δ_T are the average value, dispersion and confidence interval for ^{j}T.

Analysis results of acoustic emission signal's wavelength characteristics from different ceramic material's static tests on four-point bending are shown in Figure 1.

Spectrograms obtained were joined into data blocks by time tag. Block number is equal to sample's number. For each data block static characteristics were determined:

$$S_{av}(j) = \frac{1}{n} \sum_{i=1}^{n} S_{i}(j) \tag{10}$$

Where $S_{av}(j)$ is the average value of spectrum constituent's amplitude, n is the number of spectrograms in data block:

$$G_{S}(j) = \frac{1}{n-1} \sum_{i=1}^{n} \left| S_{i}(i,j) - S_{av}(j) \right|^{2} \tag{11}$$

Where $G_S(j)$ is a dispersion of spectrum constituents amplitude

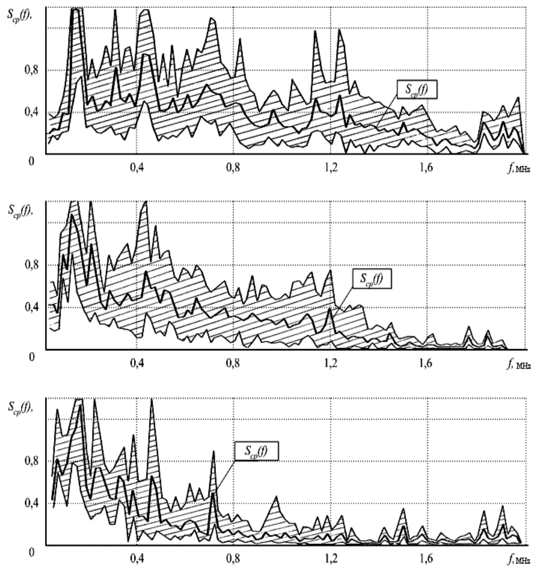

Figure 1. Spectral Function $S_{cp}(f_i)$ and Tolerance Range for a – Silicon Nitride, b – Corundum Refractory, c – Alumina-Boron Nitride

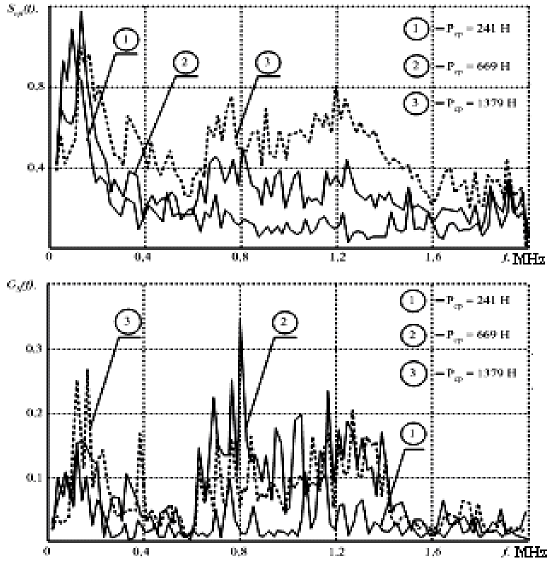

Figure 2. Graphs of Spectrum Function $S_{cp}(f_i)$ and Dispersion Function $G_s(f_i)$ with Different Values of Stress Effort P

On the basis of results of material's static analysis, obtained in different deformation stages, it was possible to make comparative analysis of acoustic emission signal's wavelength characteristics. By analyzing graphs (Figure 2, top) it becomes clear on which frequency there are the greatest changes. Analyzing graphs (Figure 2, bottom) in different stages of stress allows to describe wavelength characteristic changes of signals registered.

As shown in the given example increase of high-frequency component of is caused by increase in and the greatest changes in the signal's spectrum happen in the middle part. This allows to select optimal values of band center and bandwidth of frequency analysis channels and to substantiate the selected number of them.

As is well-known, spectrum of signals sum equals sum of spectra, hence effective width of summarized signal spectrum should not increase. However, its distortion is considerable. Transfer properties of the acoustic tract are described by frequency response function (FRF). Classical method of frequency distortion influence exclusion consists of FRF calculation with subsequent adjustment of received signals spectral characteristics. Plane shape objects FRF can be calculated theoretically. Let us do FRF calculations for a long rod.

Metal or ceramic survey item, as well as other items made of high elasticity material can be calculated with high accuracy by linear systems. In a general way spectral characteristic module of the signal taken from converter output is defined by the following formula:

$$S_{np}(\omega) = S_u(\omega) \cdot K_{mp}(\omega) \cdot K_{np}(\omega) \qquad (12)$$

Meanings of the symbols: $S_{np}(\omega)$ and $S_u(\omega)$ are spectral characteristic module of the converter output signal and AE source respectively; $K_{mp}(\omega)$ and $K_{np}(\omega)$ stand for FRF of acoustic tract and converter respectively.

With the help of distributed parameters system mathematical apparatus it is possible to find complex transfer rating coefficient for the separate type of the wave for survey unit (long rod) FRF structure effect qualitative and quantitative assessment:

$$K_{CT}(j\omega) = \frac{ch\left[\gamma(j\omega)\cdot(l-x)\right]}{sh\left[\gamma(j\omega)\cdot l\right]} \qquad (13)$$

Meanings of the symbols: $\gamma(j\omega) = \alpha(\omega) + j\beta(\omega)$; $\alpha(\omega)$ - acoustic signal fading coefficient; $\beta(\omega) = 2\pi/\lambda = \omega/v$ - phase coefficient; v - acoustic wave propagation velocity; λ - length of the wave; x - signal source coordinate; l - rod length.

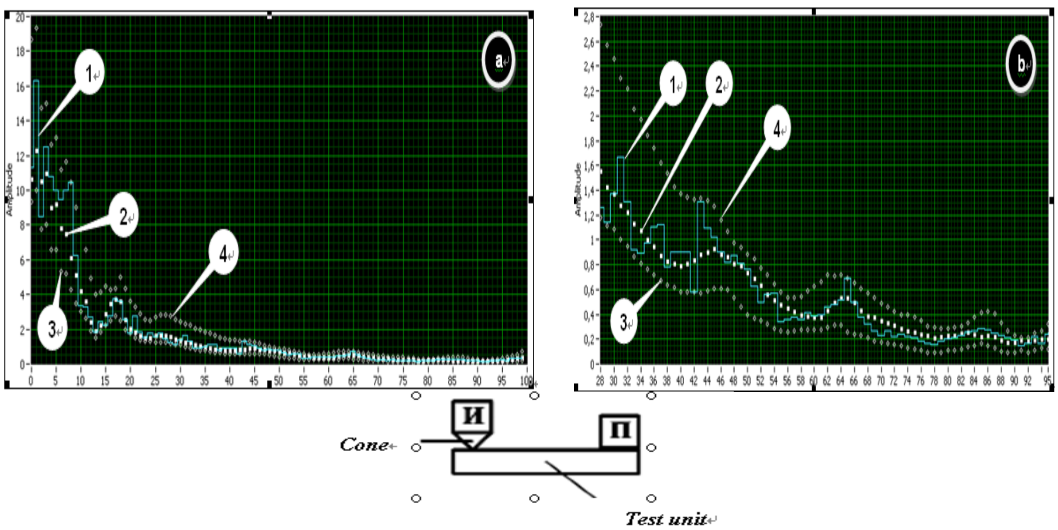

Figure 3. FRF of the Test Unit within 20-2000 kHz (a) and 560-1880 kHz(b) Frequency Bands. Frequency-response Curves are Smoothed with $\Delta f \cong 10$ kHz (curve 1) and $\Delta f \cong 100$ kHz (curve 2) in Acceptable Value Range (curve 3, 4)

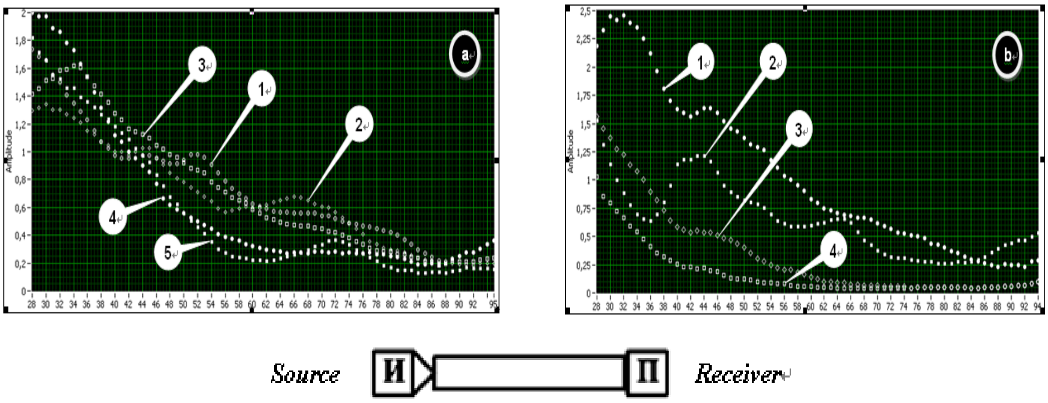

Figure4. (a) FRF of S-C-T-R (signal source-cone-test unit-receiver) System within 20-2000 kHz; (b) Range and Adjusted FRF of the Test Unit within 560-1880 kHz range, 1- electrical Insulator Porcelain; 2- silicium nitride; 3- alumina refractory; 4- alumina-boron nitride

Figure 3 displays experimentally acquired FRF of 0.12m-long square ceramic rods. Acquired curves are definitely of exponential nature, which gives evidence to the fact that the model (2) is not perfect. This model along with other factors makes no allowance for fading frequency dependence. For more precise estimation of fading dependence on frequency the positive verification range is limited to 560-1880 kHz range. This allows evaluating FRF of the test unit with the 30% max error. Fading frequency qualities depend not only on geometry of the sample and converter positioning but also on material properties of the sample.

Figure 4 represents adjusted frequency characteristics of the signals passed through different samples made of various materials: curve 1 - electrical insulator porcelain, 2 - alumina-boron nitride, 3 - alumina refractory, 4 - silicium nitride. Frequency characteristics of mentioned materials differ significantly.

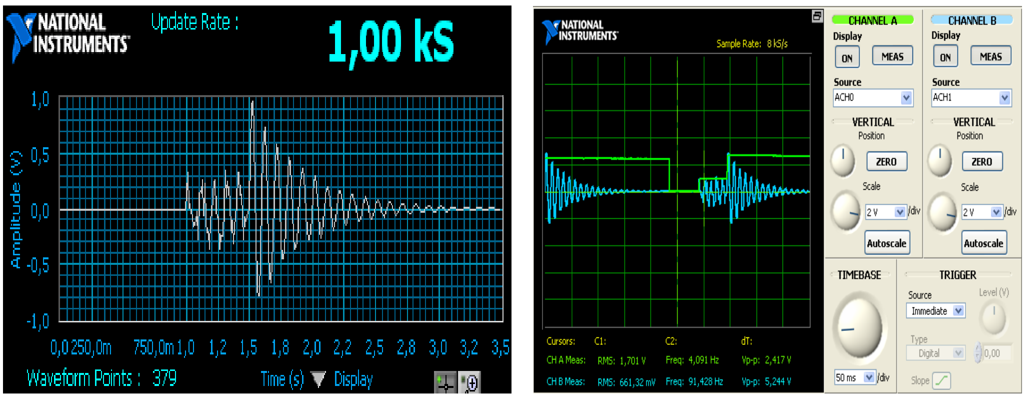

Figure 5. Measured Area of the Rectified AE Signal Envelop Registration

Figures 5 at all stage of functioning of algorithm of identification there is adaptive adjustment St according to an average level of noise. It occurs by means of adjusting in the parameter, determining sensitivity of process detection of pulses acoustical emission. When signal acoustical emission is found out, reception of a pulse with simultaneous calculation of its various parameters and search of the end of signal begins. Settlement parameters allow estimating a degree of the danger, the registered pulse. Danger of a pulse is estimate quantitatively, that allows classifying at enough low degree of danger a pulse as noise.

3. Conclusion

The spectrum of AE signals is one of the most informative of its characteristics. Knowledge of the spectral characteristics necessary to optimize the receiving channels of AE devices, the construction of generators AE signals, as well as to evaluate other characteristics of the signals, for which it is difficult to make direct measurements. The advantage of spectral analysis is that the shape of the spectral characteristics (SC) can be performed recognition AE signals in noise, to classify AE signals on the types of sources, as well as the identification of their parameters with the parameters of mechanical loading. In addition, the composition of the analyzing equipment always includes input measuring acoustic-electric transducer.

Conclusions made are fortified by performed theoretical and experimental analysis of AE signal spectrum properties and FRF samples. Taking into consideration all above mentioned I think that:

1. It is necessary to separate the detectors which are the majority of modern means of acoustic emission control from the measuring equipment and in new researches make special reference to measuring the limited amount of parameters having physical sense.
2. It is required to bring into sync the acoustic emission measurement units and International systems of units, abandon the parameters based on impulses counting, or use correction factor when detecting each separate impulse.
3. When registering signal amplitude it is required to consider its frequency distribution connecting each amplitude rate with the corresponding vibration rate.
4. It is strictly contraindicated to measure signal energy in narrow band, naming such measures as "energetic parameters". Energetic parameters as the acoustic emission energy itself may be obtained only based on the whole spectrum analysis.
5. It is required to create the commission with the purpose to draw out general provisions of the normative document that would determine the rules of acoustic emission control organization and performance rules as well as specify main requirements to acoustic emission equipment.

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