DETAILED ANALYSIS OF IMPACT-ECHO SIGNALS OF SPECIMENS WITH NONLINEAR EFFECTS

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Abstract
This simple NDT method uses impact pulse as a simple wide-spectrum excitation for spectral analysis. Usually the frequencies of resonance components from impact-echo (I-E) signal are compared with standard forms and their deviations signalize non-ideality and defects. This NDT method is very cheap and effective especially for small bodies with expressive resonance properties, but it has a small sensitivity to relatively small defects and it cannot identify cracks. The new improved method consists in utilize of nonlinear acoustic properties of bodies with cracks (good known as SIMONRUS etc.) when the resonance frequencies depends on excitation. On the other hand, the complex analysis of full I-E signal is very complicated because there are among others tens of dominant harmonic components. Therefore we designed a program for detailed time-frequency analysis of I-E signals. We applied not only "single-mode model" with frequency shift, but also "multi-mode model" with nonlinear effects and also phase plane. By this way we obtain time dependencies of some harmonic components with marked low frequency periodicity.

1. Introduction

The Impact Echo is very good known method of NDT, e.g. [1], [2] etc. It is used in two basic ways. First, it is utilized similarly as classical ultrasound defectoscopy with evaluation of echo time from the damage. The second way uses impact pulse as wide-spectrum excitation for spectral analysis. The obtained frequency resonance components correspond to dimensions of the tested body. Frequencies of these components are compared with standard forms and their deviations signalize non-idealities and defects. This NDT method is very cheap and effective especially for small bodies with expressive resonance properties. On the other hand this method has a small sensitivity to relatively small cracks. It is interesting that this method doesn't use the same principle as the good known crack detection by human hearing because this one needn't standard forms for comparison. The discussed improving of this method consists in utilize of nonlinear acoustic properties of bodies with cracks (good known as SIMONRUS, RAS etc. [3] - [7]) when the resonance frequencies depend on excitation. Therefore the customary use of Fourier Transformation to all recorded sound of impact echo brings inconvenient averaging of this effect with the main part of the recording time when the intensity of excitation is low.

This reasons lead to design of new method I-E signal analysis [8]. It consists in time-frequency spectral analysis, when time axis corresponds to level of excitation. By this way the frequency shifts of dominant natural resonances can be evaluated as a function of excitation, similarly as for SIMONRUS method. Experimental verification of these ideas showed supposed frequency shift. On the other hand the measured signals were more complicated and therefore we supposed that there is more information in the I-E signal. Therefore we started works with more complex analysis of this signal.

2. Some resources for detailed analysis of the I-E signal

2.1. Modeling of this effect

The solving of this problem needs two basic resources. The first one consists in suitable model of this effect. It is also necessary to use suitable mathematic methods with a computer program for signal modeling and analysis as the second important resource.

Nowadays we use these two models of this effect:

- "single-mode model" – with frequency shift,
- "multi-mode model" – with nonlinear effects.

In the first step we used a "single-mode model" (as SIMONRUS [3]) with effect of frequency shift of independent dominant resonant components for high level of excitation. As it is mentioned above, this model shows some results, but it is so much simple and deficiently corresponds to complexity of measured I-E signal.

Therefore now we have used the "multi-mode model" with considering nonlinear effects for non-harmonic (multi-mode) excitation. This approach is based on creating of new harmonic components in nonlinear environs under excitation of more harmonic components. This model is more suitable for time-frequency domain spectrogram obtained for measured I-E signal.

As it was mentioned, it is necessary to use suitable mathematical methods with computer program for signal modeling and analysis. Because our modeling is based first of all on time-frequency spectrograms, we use various forms of short-time FFT (STFFT). In this case, it is important to determinate a time interval for STFFT. Because the principle of indefinites limits the frequency accuracy for short time interval and time accuracy for high frequency resolution, we use and combine two basic approach:

- long time interval for STFFT
- short time interval for STFFT

Except of the time-frequency domain we use also "phase plane" because it is good known instrument for analysis of nonlinear inertial systems. This "time" image of I-E signal also shows some interesting information as it will be discussed.

2.2 Program for I-E signal analysis

This program calculate and displays first of all spectrograms of I-E signals and it use various algorithms of STFFT. As was discussed above, it enables setting

- duration of the time interval for STFFT,
- time of shifting step,
- others parameters of spectral analysis.

The complexity of spectrograms needs other functions as

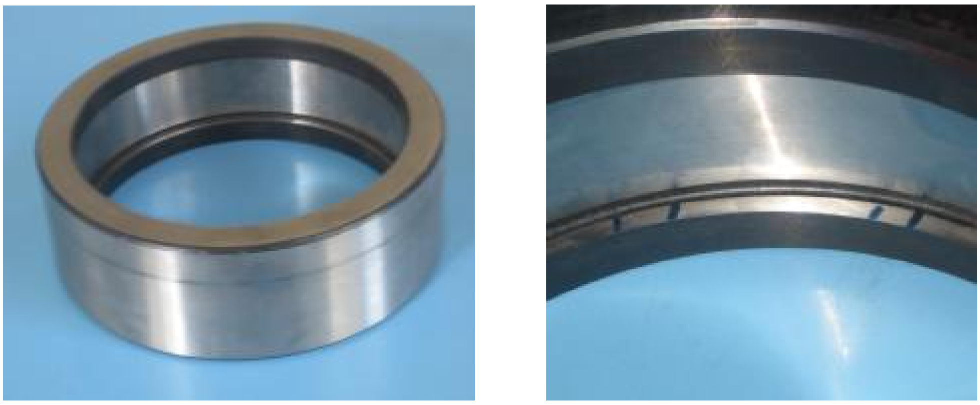
- detection of dominate frequency components as peaks in spectrum,
- separation of individual dependencies of dominate frequency components,
- extraction of individual dependencies with zooming.

As the further possibility, the program offers different variant of I-E signal evaluation by displaying on phase plane.

3. Experimental results

3.1. Tested samples and apparatus

This method was verified with a set of four samples of steel bearing cage with diameter 220 mm (see Fig. 1a). One sample has two little cracks (cca 1 mm) in the inner side of internal border of cage (see Fig. 1b). The second one has not any failure and two others have any changes without cracks.



a) b)
Fig. 1. Tested sample of steel bearing cage (a), detail with place of two cracks (b).

The testing apparatus was very simple. We used a microphone with frequency range up to 100 kHz, appropriate preamplifier and 16-bit acquisition system for PC. The impact was realized by little mechanical hammer. We use two places for impact. The first place was at side of the cage and the second was in the middle of periphery of the cage. We supposed that the first case is more effectual.

3.2. Spectrograms for short time interval of STFFT

This variant of spectral analysis enables describes quick frequency changes of spectral components with low resolution of frequency. Therefore an appearance of two near frequency components is evaluated as one component with frequency shift. We tested by this way our samples with and without cracks. The Fig. 2 and 3 shows spectrograms of I-E signal for impact at side of the cage with and without cracks. As we can see, the spectrogram of the failed sample (Fig. 2) has evidence differences in comparison with the spectrogram of the other one (Fig. 3). Especially, time dependencies for the first three dominant components (cca 8, 12 and 26 kHz) are evidently different. Typically, the dependencies of frequencies for failed sample are more unstable.

It is necessary to remark that setting of various parameters for STFFT can affect of the image of spectrogram, first of all the number of frequency components. In this case we use the spectrogram wit low number of components. It shows more telling for the first quick view.

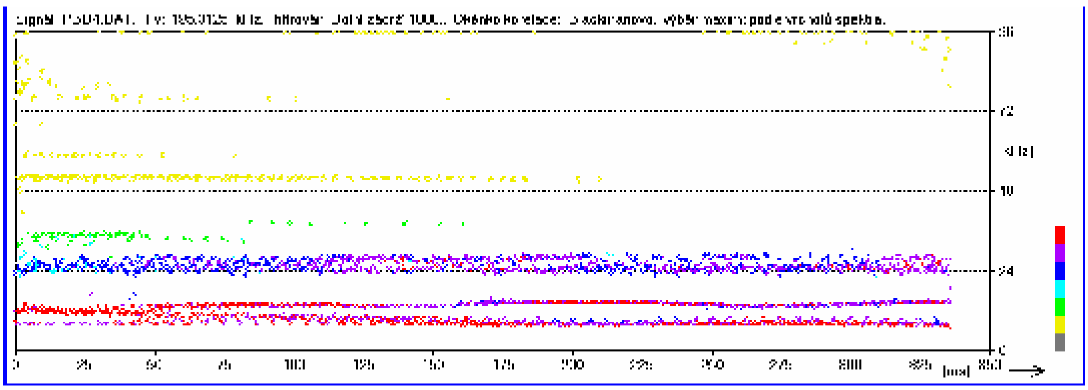


Fig. 2. Spectrogram of the failed sample, short time interval, for impact at side of the cage.

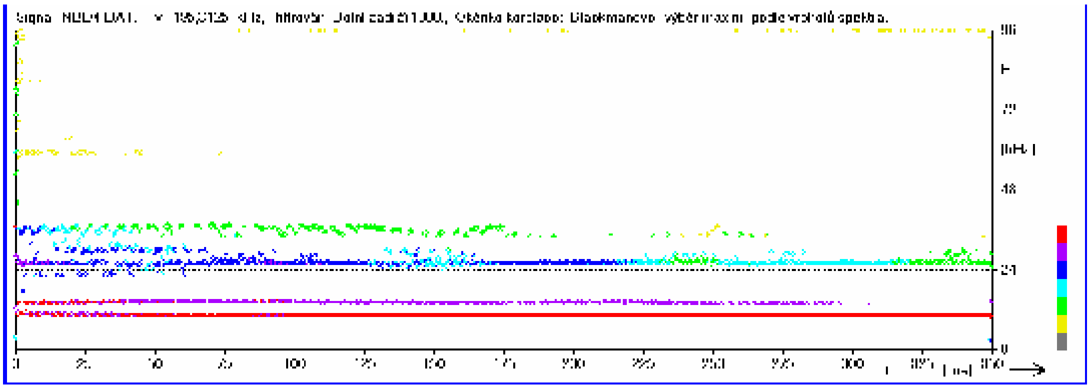


Fig. 3. Spectrogram of the good sample, short time interval, for impact at side of the cage.

We tested also influence of the impact magnitude to spectrogram of the damaged sample. As the Fig. 4 shows, this influence is not so much important.

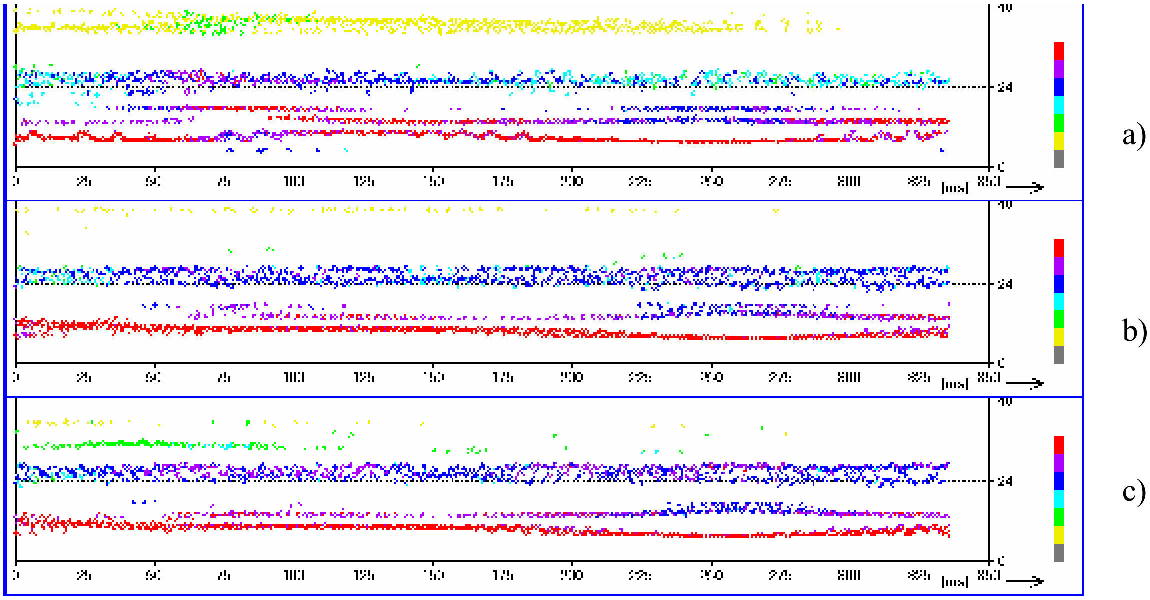


Fig. 4. Spectrograms of the failed sample, variant equivalent magnitudes: a) 9, b) 15, c) 23.

In the next step we compared good and damaged sample for impact excitation on place in the middle of periphery of the cage. We supposed that the nonlinear effect of the cracks in the I-E signal is inferior, because the excitation of the place with cracks is considerably lover in comparison wit the first case. This hypothesis corresponds to measured spectrograms in Fig. 5 and 6. Nevertheless also this example shows differences between good and failed sample.

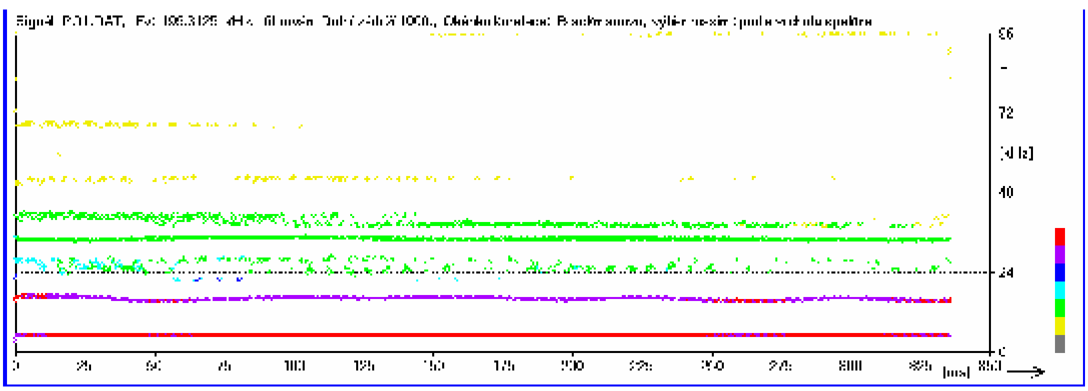


Fig. 5. Spectrogram of the failed sample, short time interval, for impact at side of the cage.

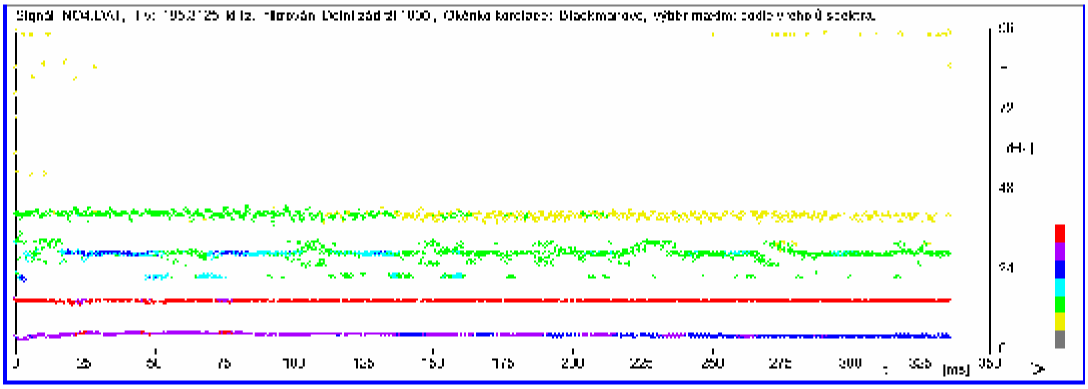


Fig. 6. Spectrogram of the good sample, short time interval, for impact at side of the cage.

3.3. Spectrograms for long time interval of STFFT

The results for spectral analysis with short time interval of STFFT don't enable fine spectral resolution for more precise detection of single harmonic components. Therefore we use STFFT with long time interval with an aim to obtain deeper understanding of nonlinear properties of the cracks to creation and changes of single harmonic components.

As examples of the results for damaged and good sample shows (see Fig. 7 and 8), the spectrograms are more complex. On the other hand the differences between both samples are less evident for the first view because the spectrograms displays more clearly the changes of frequencies than changes of magnitudes. Nevertheless also in this case we can see differences between spectrograms of good and failed samples. Further the frequency instability of 1^{st} and 2^{nd} harmonic components in Fig. 2 corresponds to magnitude instability of partial harmonic components (1^{st} - 4^{th}) in Fig. 7. From this point of view, the equivalent harmonic components for good sample have higher magnitude stability.

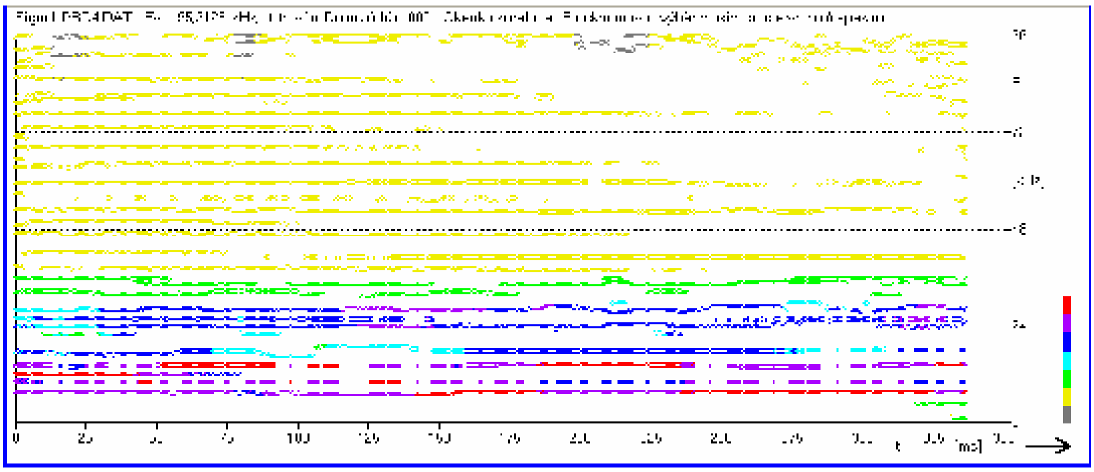


Fig. 7. Spectrogram of the failed sample, long interval, for impact at side of the cage.

On the other hand, it isn't simply to identify a creation of new harmonic components as a mixing product of incidence of two or more harmonic components to nonlinear environment with cracks. The reason of this problem consists in two facts. First, there are very much variants of combinations frequency components and these components have lower magnitude in comparison with considered excitation components.

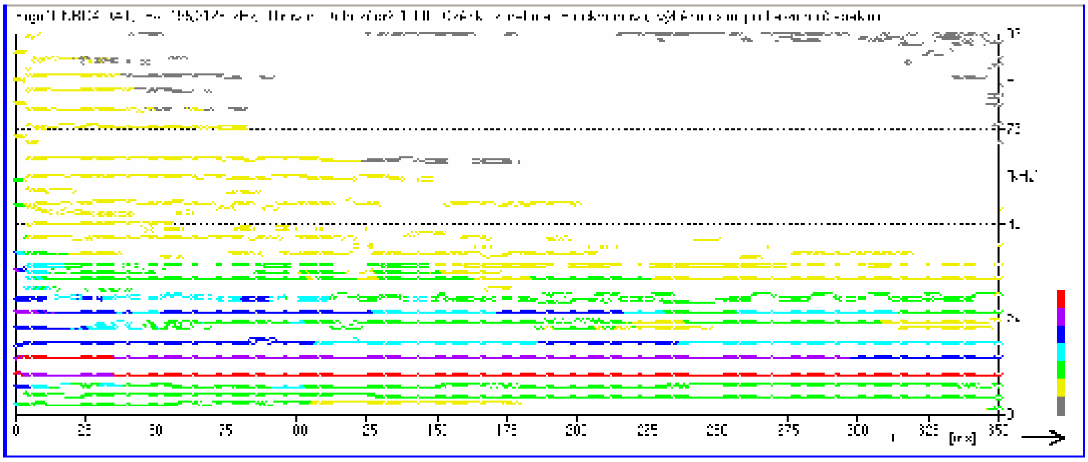


Fig. 8. Spectrogram of the good sample, long interval, for impact at side of the cage.

3.4. Detailed analysis of selected harmonic components for long time interval of STFFT

The further detailed analysis of the spectrograms for long time interval of STFFT shows interesting time dependencies for some harmonic components as 22 kHz (Fig. 9 and 10) and 28 kHz (Fig. 11 and 12) .

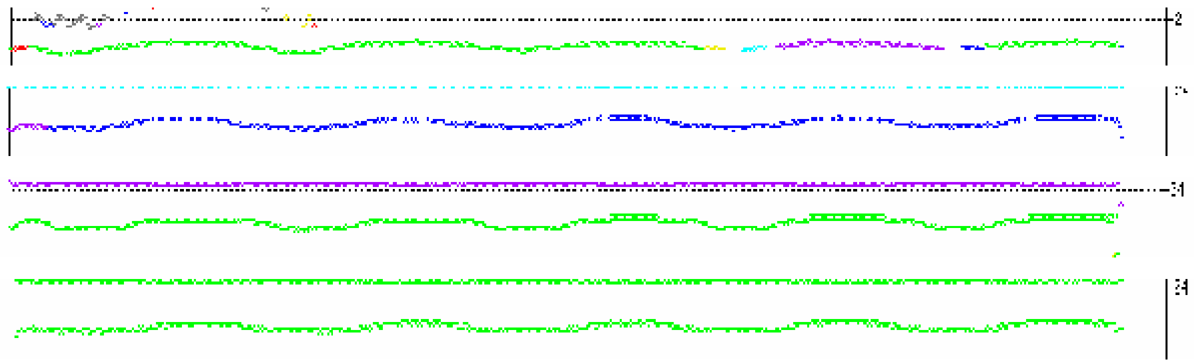


Fig. 9. Dependencies of harmonic components 22 kHz of the failed sample, four variants.

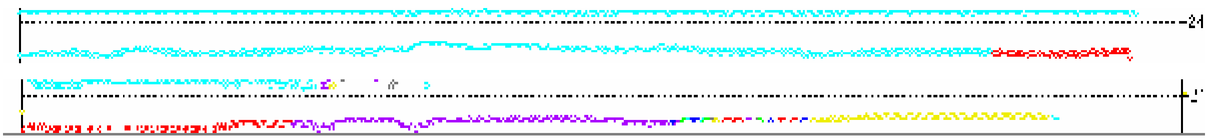


Fig. 10. Dependencies of harmonic components 22 kHz of the good sample, two variants.

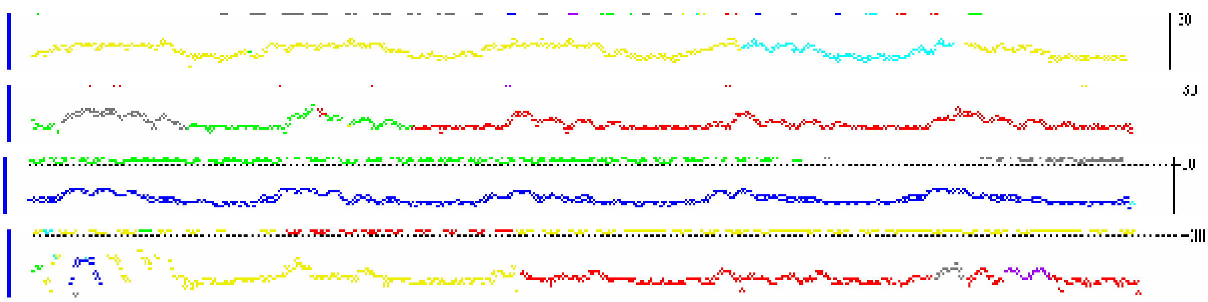


Fig. 11. Dependencies of harmonic components 28 kHz of the failed sample, four variants.

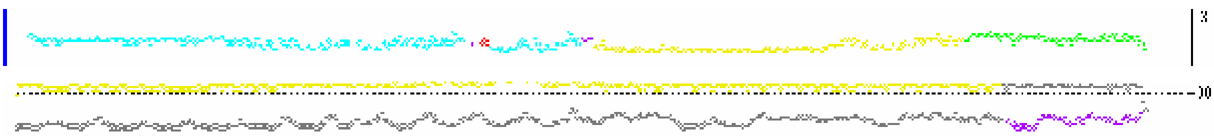


Fig. 12. Dependencies of harmonic components 28 kHz of the good sample, two variants.

There is interesting the very long time periodicity (c. 70 ms) for both cases, but it has different phases. We cannot explain the reason of this effect in this time, because the direct connection of this period with the geometric dimensions of rings and considered ultrasound velocity is not clearly evident.

3.5. Frequency compression of I-E signal for human hearing

Because we locate the most interesting frequency component (22 kHz, 28 kHz) out of human hearing range, we try to arrange the I-E signal for human hearing by frequency compression and by frequency filters for this aim. Therefore we append to our mentioned program the new part for it. Practical experiments show that for optimum compression coefficient (c. 0.3) we was able to hear difference between good and damaged samples.

4. Conclusions

The new approach to analysis of impact echo signal offers new possibilities and advantages for NDT exploitation. Till this time used methods apply spectral analysis (FFT) to whole record of I-E. Therefore they have relatively low sensitivity and low resolution of fails. The main idea of new way consists in more complex analysis of I-E signals.

On the other hand, the complex analysis of full I-E signal is very complicated because there are among others tens of dominant harmonic components. Therefore it is necessary to use a suitable model of this effect and suitable mathematic methods with computer program for signal modeling and analysis. Nowadays we prefer the use - “multi-mode model” – with nonlinear effects before “single-mode model” – with frequency shift. Further we combined STFFT with long and short time interval for elimination of the principle of indefinites.

We designed new program which calculate and displays first of all spectrograms of I-E signals and it use various algorithms of STFFT. It enables setting duration of the time interval and a time of shifting step for STFFT and other parameters of spectral analysis.

It has other functions as detection of dominate frequency components, separation of individual dependencies of dominate frequency components etc. The program also offers I-E signal evaluation by displaying on phase plane.

The proposed methods were verified at samples of steel bearing cage with and without small cracks. The results for small time interval of STFFT and optimum setting of other parameters of program show quite good resolution of spectrograms for failed and good tested samples because the creation and magnitude instability of new harmonic components bring frequency instability of equivalent harmonic components obtained for low frequency resolution. On the other hand the spectrograms obtained for long time interval of STFFT shows more finely spectrum with individual components. By this way we find harmonic components with a marked periodic instability of frequency.

Because the located unstable frequency components wasout of human hearing range (22 kHz, 28 kHz), we append to our mentioned program with frequency compression and by frequency filters for arrange the I-E signal for human hearing. Practical experiments show that we was able to hear difference between good and damaged samples.

NDT applicability of this new approach to analysis of I-E signal was confirmed. Our consecutive work will be directed to optimize and work off the discussed procedures for practical use.

Acknowledgements

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