NONLINAR ULTRASONIC SPECTROSCOPY OF FIRED ROOF TILES

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Abstract: Paper deals with non-linear interaction between elastic wave and structural defects in fired roof tiles. Present ultrasonic non-destructive testing methods are very sophistic, but they have some limitations for practice use. For example, it is an impossibility integral testing procedure, time demanding or practically infeasible testing of solids with inhomogenous materials or with complicate forms. In such examples it is possible to utilize measuration of non-linear effects of wave propagation and creation of higher harmonic signals in the vicinity of defects.

This paper describes measuring set-up method for non-linear effects determination. First, the short summary and comparison of various methods of nonlinear ultrasound spectroscopy is shown. It was chosen the CV method with one pure harmonic exciting signal and with evaluating of 2nd and 3rd harmonic element as a quantity of nonlinearity. The corresponding measuring set-up is described.

This method is practically applied to fried roof tiles because testing of this material is problematic by other NDT method. The selection of exciting frequency by analysis of frequency responses is shown. Measured spectrums for good tiles and for tiles with cracks shows usability of this method for rated aim.

Introduction: **A**mong the various non-destructive testing (NDT) techniques, the ultrasonic methods are perhaps the most frequently used. On the other hand, it has some limitations for practice use. For example, it is an impossibility integral testing procedure and on the account resulting elaborateness, time and financial expensiveness or practically infeasible testing of solids with inhomogenous materials. Analogical problems bring ultrasound testing of bodies with complicate forms. These and other problems of ultrasounic NDT leads to searching new methods.

New promising non-destructive testing methods are based on the non-linear behaviour of current defects and inhomogeneities regarding the elastic wave propagation processes. In a present paper, the non-linear techniques, know as NEWS (Nonlinear Elastic Wave Spectroscopy) and their effective use are discussed.

There are two groups of methods available for application: resonance and non-resonance. Bodies exhibiting strong resonance effects make it possible to study, above all, the non-linear effect of the resonance frequency shift versus exciting signal intensity. These methods are usually referred to as SIMONRAS (Single Mode Nonlinear Resonance Ultrasound or Acoustic Spectroscopy) [2-4]. The resonance methods are rather labour-intensive and require many readings to be taken (frequency response curves for various signal magnitude levels). Therefore, they are not suited for fast in-process measurements.

Non-resonance methods are used to study suppressed resonance specimens. These methods analyse the effect of non-linearities on acoustic signals propagating through them. These methods can be split into two groups. In the first group, a single ultrasound harmonic signal is employed. The non-linearity gives rise to additional signals featuring different frequencies according to Fourier expansion. In general, the amplitudes of these additional components decrease with the natural number *n*:

$$f_n = n\, f_1 \qquad \big|\, n = 0, 1, 2..\infty \,, \tag{1}$$

Nevertheless, among the emerged signals, the third harmonic appears to be most pronounced, see Fig. 1. This is why the third harmonic amplitude is pursued by most researchers, especially in electronics [7].

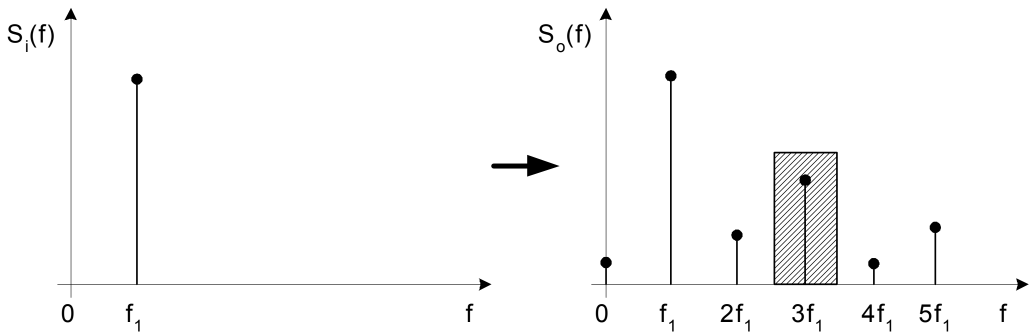


Figure 1.: Growth higher harmonic components in frequency spectra at transit pure harmonic signal through nonlinear environment with illustration of selection dominant third harmonic component by the frequency band-pass filter.

In the second case, several (usually two) ultrasound signals are applied to the specimen. The number of additional harmonic components generated is substantially higher. In addition to both exciting signals' harmonics, one gets also sum and difference frequency components.

$$f_v = \left| \pm m\, f_1 \pm n\, f_2 \right| \qquad \Big| m, n = 0, 1, 2..\infty. \qquad (2)$$

Owing to the general harmonic amplitude versus frequency curve downward slope, the first sum and difference components are most pronounced. The application domain of the ultrasound modulation spectroscopy (usually referred to as NWMS – Nonlinear Wave Modulation Spectroscopy) splits into two sub-domains, which differ from each another by the exciting frequency ratio. In the first case, two harmonic signals are employed, whose frequencies differ by several orders of value (one being called the low-frequency, the other the high-frequency signal), see Fig. 2a. This option is well suited for high-sensitivity integral measurements. In the second case, the frequency mixing principle is used. The signal frequencies are close to each other. The first difference component therefore falls into the low-frequency range as it show Fig. 2b. This option is well suited for the defect localisation.

The third, time-discrimination, method consists in applying impulse signals to the specimen (generated, e.g., by an instrumental hammer). This method does not appear to be as applicable as the above mentioned ones, because the specimen is excited by a continuous-spectrum signal (Dirac impulse spectrum) and the effect of the specimen non-linearities on the response is rather hard to detect. On the other hand, the mechanical impulse exciting signal carries much higher power than any pure harmonic electric excitation. Therefore, the measurement sensitivity is improved. These methods are especially suitable for pronounced resonance response specimens. The broad-band impulse excitation results virtually in a narrow-band or even harmonic response. Two typical practical examples can be mentioned in this respect: hammer testing of railway wagon wheel integrity and a well-known change in the spectrum of a cracked bell's sound. Beside the generation of new harmonic components, the defect induced non-linearity also results in a change of the specimen transfer characteristics and both phenomena can be analysed at a time.

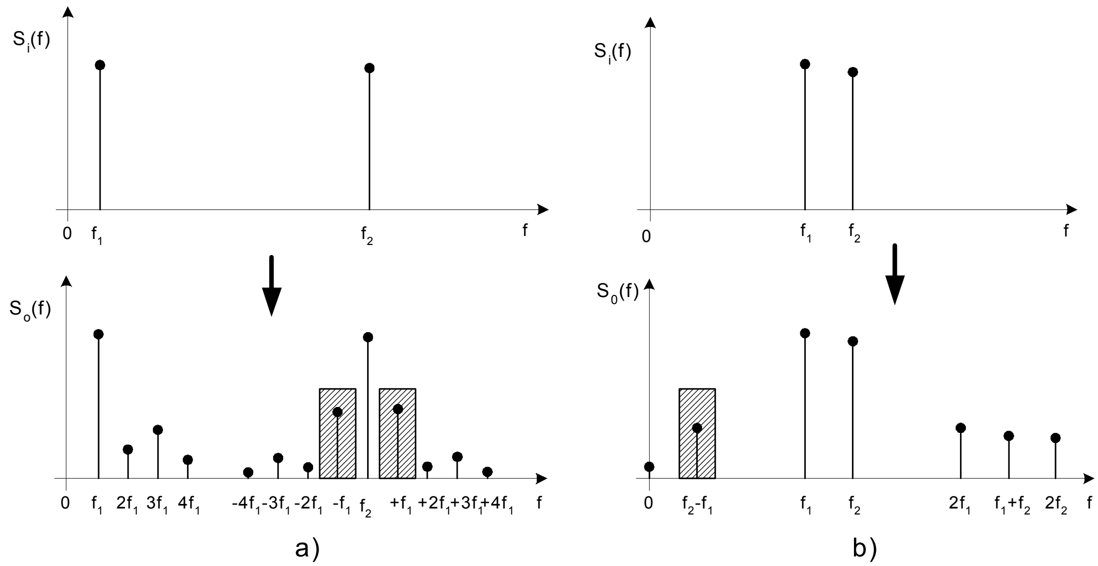


Fig. 2: Creation of new harmonic components in frequency spectra at transit two harmonic signal through nonlinear environment with demonstration of selection dominant components by frequency filter. a) event of AM modulation (with large rate of f_2/f_1), b) event of mixing (with small rate of f_2/f_1)..

Recently, various papers on both the theoretical and experimental examination of diverse methods and their applicability in some fields have been published. Most published papers as well as our experience show these methods to be highly promising for the defectoscopy and the material testing purposes in the near future.

One of the fields in which a wide application range of non-linear acoustic spectroscopy methods may be expected is civil engineering. Poor material homogeneity and, in some cases, shape complexity of some units used in the building industry, are heavily restricting the applicability of "classical" ultrasonic methods [5]. Precisely these non-linear acoustic defectoscopy methods are less susceptible to the mentioned restrictions and one may expect them to contribute to a great deal to further improvement of the defectoscopy and material testing in civil engineering

The measure equipment for CV measuring with one harmonic signal is shown in Fig. 3. It consists from two parts. The transmitter has four main blocks, generator of signal, power amplifier, low-pass filter and output transformer. The generator has simply solution but other three blocks have special requirements. The power amplifier has to offer high power with low distortion and high efficiency. Our solution of amplifier has maximum power 100 W. The low-pass filter has a minimum attenuation 60 dB for the frequency of 2nd and 3rd harmonic element. The transformer was designed for maximum power matching.

The receiving part consists above all from filters and low noise amplifiers, which are used in three ways. The first way is used for measure of 1st harmonic level. The second way uses HP filter for rejecting of the first harmonic element for increasing of dynamic range. The next two band-pass filters select signals of 2nd and 3rd harmonic elements. These three output signals are used for final evaluating. Nevertheless, the starting measures were realized by normal spectral analyser.

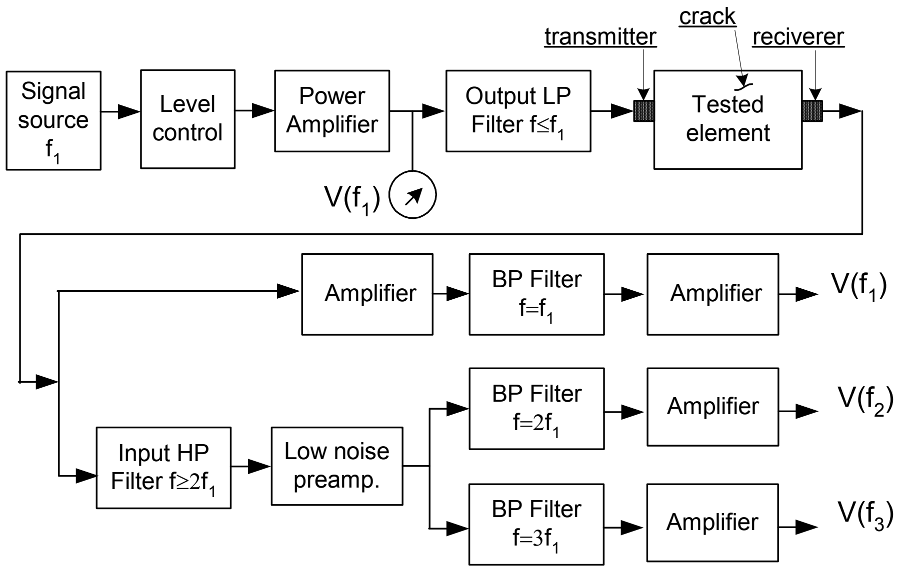
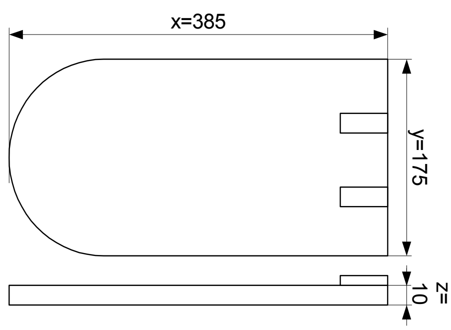


Fig. 3. Block scheme of the measure equipment



The dimensions of tiles are also very important. They are show in Fig. 4. In context of dimensions the orientations of ultrasound transmitter and receiver are important too. The orientation with longitudinal propagation of acoustic waves in z dimension we mark Z-orientation and orientation in y dimension we mark Y- orientation. We tested set of good tiles and set of tiles with cracks. This cracks were oriented mainly in Z-orientation. The set of tiles with crack was obtained by applying of thermal shocks.

Fig. 4: Main dimensions of the tile

Results: The first experiments were aimed to determine a measuring frequency. General knowledge shows a raise of the attenuation of propagation and also raise of a sensitivity to cracks for increasing of frequency. It is necessary to find the optimum compromise. Therefore we measured frequency response of the ultrasound signal way. The responses for Z-orientation and various distances of transmitter and receiver are shown in Fig. 5. Therefore it is necessary to find the optimum compromise. Therefore we measured frequency response of the ultrasound signal way. The responses for Z-orientation and various distances of transmitter and receiver are shown in Fig. 3. We can see two typical findings. First, there are fuzzy multiple resonance maximums, which corresponds to main dimensions of the tiles and the velocity of ultrasound propagation (2900 m/s). The Fig. 3 shows responses also for various distances of transmitter and receiver. And we can see, that attenuation if propagation is rising with frequency. Therefore we can consider the maximum useful frequency circa 300 kHz.

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Further problem consists with orientation of propagation and orientation of cracks. Because the largest cracks were oriented in Z-dimension, we tested also frequency dependence of propagation in Y-dimension. The Fig. 6. shows lower level of transfer and lowering of this transfer for frequencies below circa 150 kHz. These effects are caused by reducing of the contact area of transmitter and receiver with tile in this Y-orientation. These results were used for choose of the measure frequency and therefore we selected it in resonance for Z-dimension that's circa 250 kHz.

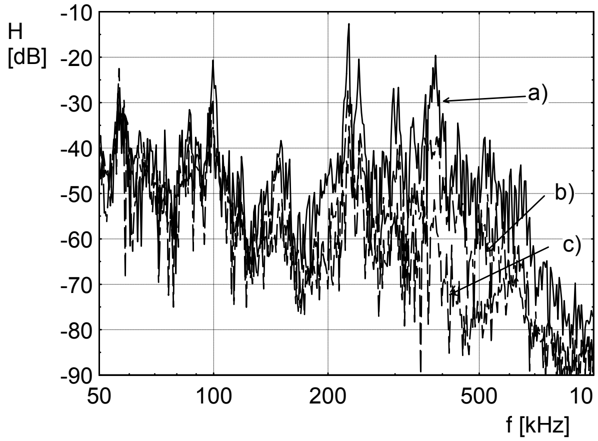

Fig. 5: Ultrasound frequency responses of the tile for Z-orientation and for various distances of transmitter and receiver: a) 30 mm, b) 80 mm, c) 300 mm

Fig. 6: Ultrasound frequency responses of the tile for Y-orientation.

The first measure of spectrum was realised for testing of THD and noise background. The metal block was used for this aim. The normal spectral analyser HP 4195A was used for this measure. As the result spectrum from Fig. 7 show, the minimum dynamic range is 80 dB (V_3 /V_1). It can be raised for 10-20 dB in case of longer time measuring. It is necessary to use the HP filter in input (see Fig.3) for higher dynamic range. Nevertheless practical measure of tiles shows that this dynamic range is sufficient. Therefore the simple measure with spectrum analyser was used in this stage.

Discussion: The typical results of spectrum for good tile and for tile with cracks are shown in Fig. 8 and Fig. 9. There are evident that 2^{nd} and 3^{rd} harmonic element are dominant for THD measure. Therefore we focus at measure of these values.

Fig. 7: Spectrum of a signal from metal block (THD and noise background)

Fig. 8: Spectrum of a signal from good tile

In further measure we tested a dependency of relative values for 2^{nd} and 3^{rd} harmonic elements (V_2-V_1 and V_3-V_1 in dB) versus exciting 1^{st} harmonic value (V_1). Typical results are shown in Fig. 8. As we can see, the differences between good and cracked tiles are evident for both harmonic elements. On the other hand, these differences are not so much high in comparison with ambiguity and errors of measured values. Therefore it is necessary to improve this method for practical use. A little better result we can obtain for Y-orientation of transmitter and receiver placing although the transfer coefficient is a little lower.

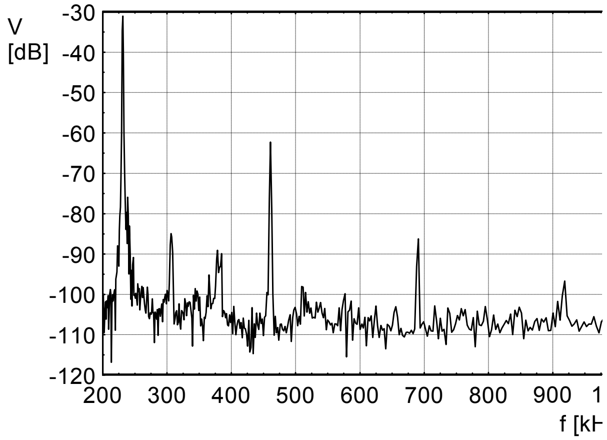

Fig. 8: Spectrum of a signal from tile with cracks

Fig. 9: Dependency of values for 2nd and 3rd harmonic (V_2-V_1 and V_3-V_1) elements versus exciting 1st harmonic value (V_1).

Conclusions: This paper describes measuring set-up method for non-linear effects determination. First, the short summary and comparison of various methods of nonlinear ultrasound spectroscopy is shown. It was chosen the CV method with one pure harmonic exciting signal and with evaluating of 2nd and 3rd harmonic element as a quantity of nonlinearity. The corresponding measuring set-up is described.

The results of the tiles testing show a possibility to practically applied this method. On the other hand, the high background distortion of inhomogenous material of tiles cases low differences between measured distortion of good and cracked tiles. Therefore it is necessary to improve this method. The ways of advancement can be in optimum placement and orientation of transmitter an receiver, optimum choose of measuring frequency, optimum value of exciting power. Also the method with limited pulse without use of resonance can be used.

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