NEW POSSIBILITIES OF NON-DESTRUCTIVE TESTING OF CERAMIC SPECIMEN INTEGRITY

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The article deals with results of our experimental study focused on new methods of nonlinear ultrasonic spectroscopy for detection of structure integrity damage in ceramic material usage. The tested samples are excited by harmonic ultrasonic signals. In case of cracks presentation in the material structure they cause strong nonlinear dynamic effects accompanying the elastic waves propagation which can be demonstrated by occurrence of new harmonic components in the response spectra. The frequency spectral analysis of the sample response enables us to identify the damaged material structure. Two methods were applied: method with one exciting harmonic ultrasonic signal and the second method with two exciting harmonic ultrasonic signals. There were analyzed undamaged specimens and also specimens containing defects of cracks type. Intact specimen measurement results proved that non-homogeneity of ceramic material is not source of nonlinear effects accompanying elastic waves propagation. Dynamic material response of samples with damaged material integrity was demonstrated by formation of new frequency components in the response frequency spectra. For experimental verification of these methods we used ceramic cladding elements from secondary materials and ceiling slabs, and that is why they can be used for testing structure integrity of ceramic materials.

INTRODUCTION

New principle of non-destructive testing of ceramic materials is presented [1-3]. The method is based on measuring nonlinear effects of wave propagation and creation of higher harmonic signals in the vicinity of structure defects. Tested sample is excited by harmonic ultrasonic signal. There are two groups of methods for the exciting signal:

In the first group, a single ultrasound harmonic signal is employed. The nonlinearity 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*:

$$f_n = n\,F_1 \qquad |n = 0, 1, 2... \infty \tag{1}$$

Nevertheless, among the emerged signals, the third harmonic appears to be most emphasized, see Figure 1. This is why the third harmonic amplitude is pursued by most researchers, especially in electronics [4].

In the second case, several (usually two) ultrasound signals are applied to the specimen. The number of addi-

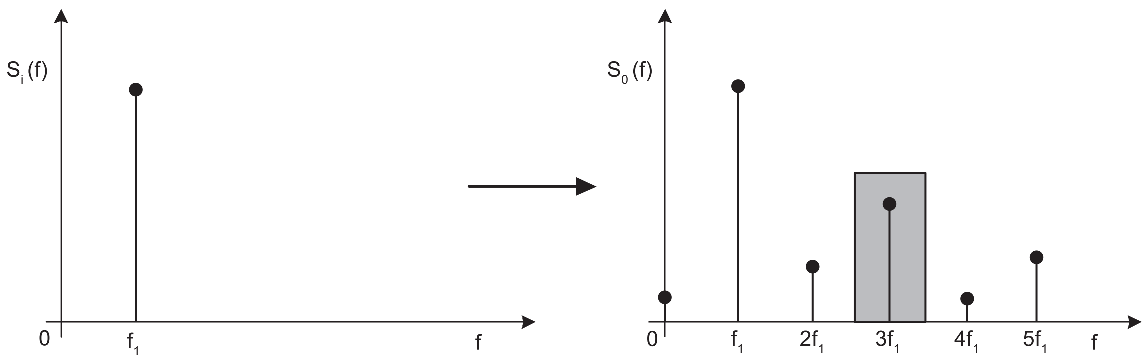


Figure 1. Growth higher harmonic components in frequency spectra at transit pure harmonic signal through nonlinear environment with illustration of dominant third harmonic component selection by the frequency band-pass filter.

tional harmonic components generated is substantially higher. In addition to both exciting signals' harmonics, one gets also sum and difference frequency components.

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

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 Figure 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 given in Figure 2b. This option is well suited for the defect localization. But the essential requirement is that wave intensity of at least one of these signals must be so high so that the atoms of defect interface make distinct anharmonic oscillations resulting in modulation.

Experimental evidence for the highly nonlinear behaviour of microcracked and damaged materials has existed for years from experiments of static stress-strain behaviour and dynamic nonlinear wave interaction. Recently, various papers on both the theoretical and experimental examination of diverse methods and their applicability in some fields have been published. One of the fields in which a wide application range of nonlinear ultrasonic 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 [9]. Precisely these nonlinear ultrasonic 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.

RESULTS AND DISCUSSION

This paper deals with application of both above given nonlinear ultrasonic methods for the tests of ceramic materials structure integrity. We used samples of two different ceramic materials. The specimens under test were small cladding elements made of secondary materials and bulkier ceiling slabs Hourdis.

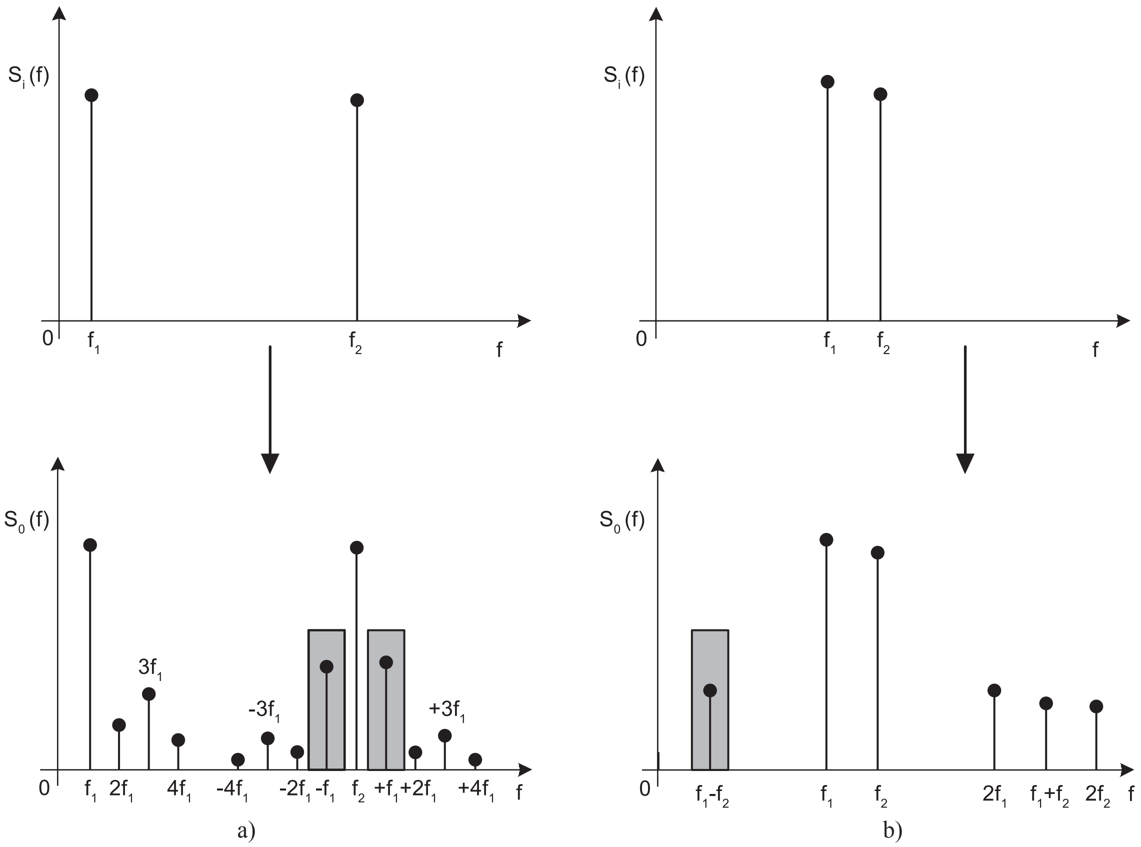


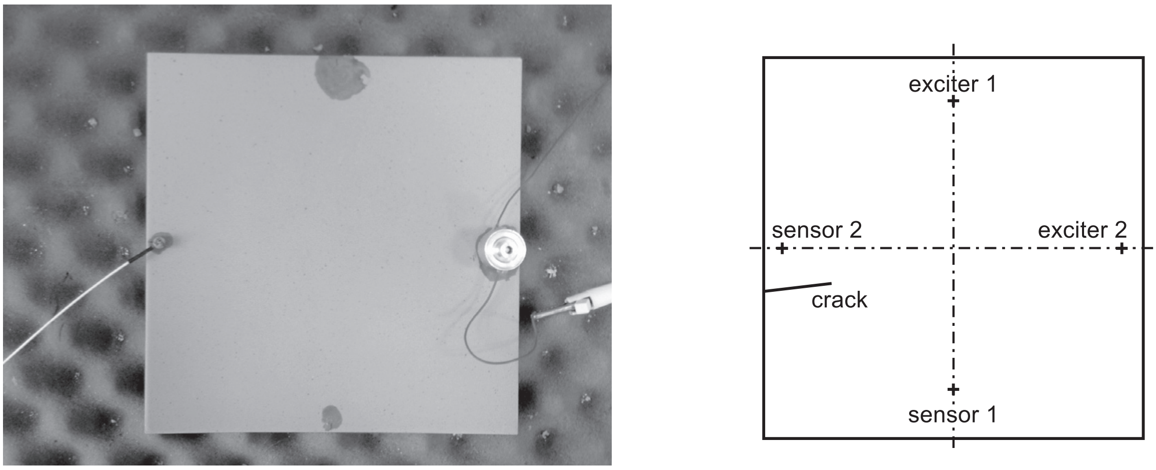
Figure 2. Creation of new harmonic components in frequency spectra at transit two harmonic signals through nonlinear environment with demonstration of selection dominant components by frequency filter. a) event of AM modulation (with large rate of f_2/f_1), b) event of mixing (with small rate of f_2/f_1).

Ceramic cladding elements

In the first phase were tested the samples of ceramic cladding elements containing fly-ash-argilic-body. The nominal dimensions of the samples used in the present study were 150 mm × 150 mm × 4 mm. We tested two type specimens: with intact structure and specimens containing a visible crack. Two mutually perpendicular orientations of the exciter and the sensor (position 1 and position 2) were tested, as it is shown in Figure 3. An ultrasonic generator with a frequency f = 29 kHz was used as a transmitter to generate a harmonic ultrasonic wave in the specimens [5]. The intact specimens, denoted B1, were checked whether or not the non-homogenous material structure containing the fly-ash-argilic body was the source of nonlinear phenomena in the course of signal propagation. The effect of the structure defect (crack) on the propagating signal properties was studied on B2 specimen.

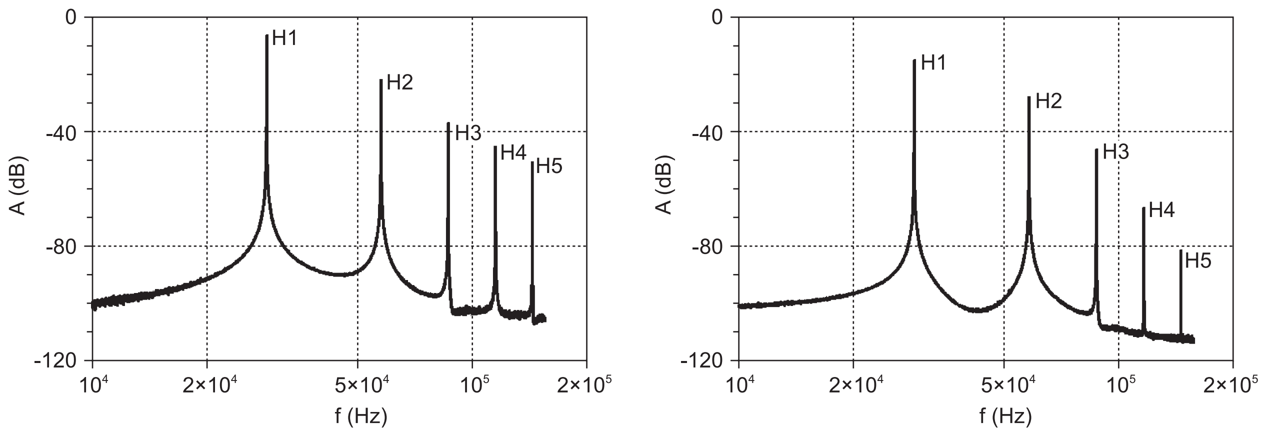
Results are represented by frequency spectra of specimens transmitting characteristics in the following Figures. Figure 4 corresponds to undamaged B1 specimen measurement for both orientation exciter and sensor according Figure 3b. Both measurement variants have one feature in common: The harmonic component amplitudes decrease with the serial number n increase, giving evidence of the fact that the inhomogeneous material makes no source of nonlinear phenomena.

Figure 5 shows the results of our measurements taken on a crack-containing specimen, denoted B2. Structural defects of the specimen took effect on the transfer function for both measurement positions. In the case shown in Figure 5a, position 1, the third harmonic H3 reaches the maximum value. The fifth harmonic H5 does not follow the previous (intact specimen) trend, either, as its amplitude exceeds that of the fourth harmonic H4. In Figure 5b diagram, position 2, the sensor has been placed near the crack (Figure 3b). The degraded structure effect is evident again. In this case, the second harmonic component H2 is the dominating frequency. Its amplitude exceeds that of the first harmonic H1 (exciting frequency). In addition, the fifth harmonic H5 frequency amplitude exceeds the fourth harmonic H4 frequency amplitude again.



a) b)

Figure 3. a) B1 specimen under test. b) Marking two positions, B2 specimen.



a) Exciter and sensor position 1

b) Exciter and sensor position 2

Figure 4. Response frequency spectra of an undamaged specimen B1.

Ceiling slabs Hourdis

In the second phase the measured objects were Hurdis ceiling slabs of dimensions 117 × 25 × 7.5 cm^3. Specimens with undamaged structure and specimens with cracks were tested. In this case we used two methods. Primarily a single harmonic ultrasonic signal method was applied with exciting signal of a frequency f = 23 kHz [6]. Transfer functions were studied from the viewpoint of nonlinear effect occurrence and the effect of exciter-to-sensor configuration (sensor positions 1 and 2). Position 1 - sensor was placed in the centre of longitudinal axes, position 2 - sensor was placed on opposite edge to exciter.

Secondly method with two exciting signals of nonlinear ultrasonic spectroscopy was applied. The above described frequency mixing principle was used, where the signal frequencies are close to each other and their first difference component therefore falls into the low-frequency range. In the case of our experiment, the frequency difference fell into a frequency range below 5 kHz (see Figure 2b). The relatively high difference between exciting signal frequencies and their first difference component enables direct detecting of this difference component, which was realized by an analogue high-dynamic-range (up to over 120 dB) pre-filtering network. The experiment layout is shown in Figure 6.

The results obtained from an intact ceiling slab are shown in Figures 7 and 8. The diagram in Figure 7, representing single harmonic signal usage, shows clearly the amplitude decrease with the growing component order, with no nonlinear effects for both measured positions. Next Figure 8 shows the result of our measurement of intact slab to which two ultrasonic signals f_1 = 19 kHz, f_2 = 23 kHz have been applied. A difference component of a frequency Δf = 4 kHz was looked for. It is clear from the diagram that no inter-modulation of the two ultrasonic signals takes place, which gives evidence of the structure integrity of the slab under test.

Measurement of a crack-containing slab is shown in Figures 9 and 10 analogously. The measurement results obtained from single harmonic signal usage are shown in Figure 9. The third harmonic appeared to have grown up, being higher than or comparable with that of the second harmonic. The fourth and fifth harmonics have disappeared entirely. Next Figure 10 represents measurement results from two signals method. The exciting frequencies f_1 = 19 kHz, f_2 = 23 kHz were used again. The predominating magnitude of the amplitude occurring at difference component Δf = 4 kHz is due to the presence of a defect in the specimen structure.

CONCLUSIONS

Our experiments have been aimed at examining the structure integrity of ceramic specimens on the basis of nonlinear ultrasonic spectroscopy. Two specimen sets of two different ceramic materials have been tested. The first set included small cladding elements made of secondary materials and the second set included bulkier ceiling slabs Hourdis. The both sets contained intact specimens and specimens with damaged structure, containing visible crack.

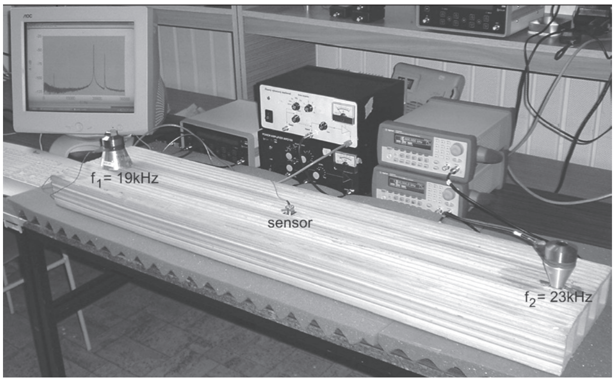
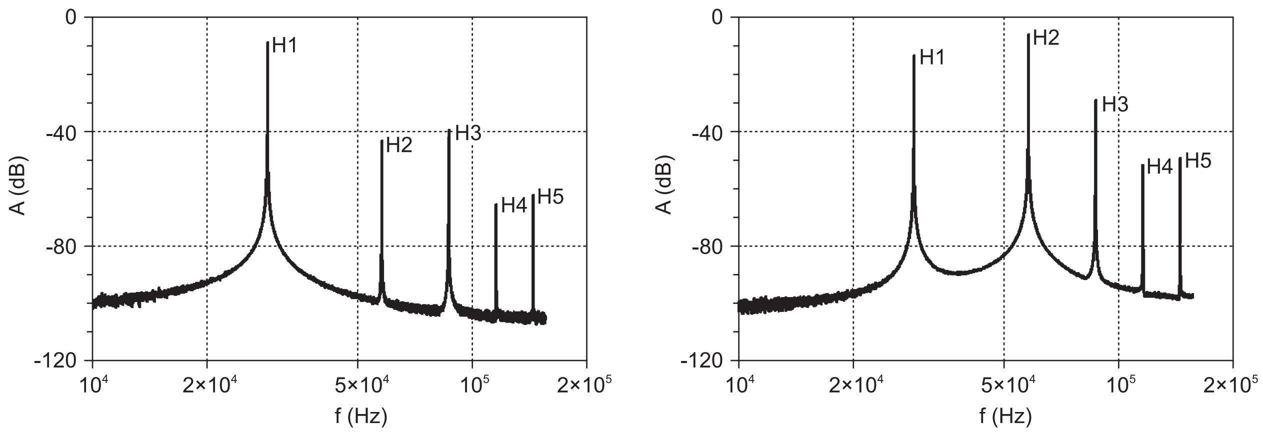


Figure 6. Photograph of experiment layout - method of two signals.



a) Exciter and sensor position 1

b) Exciter and sensor position 2

Figure 5. Response frequency spectra of a damaged specimen B2.

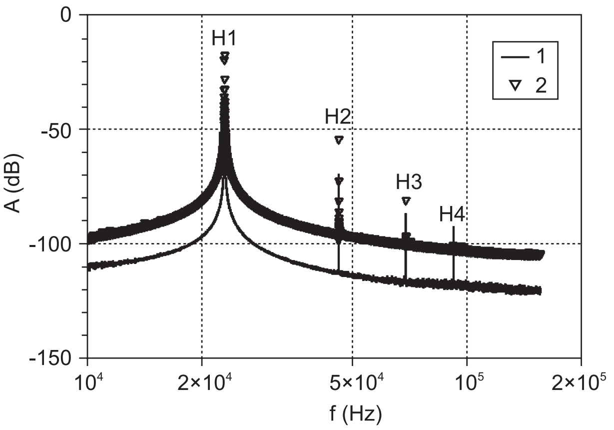


Figure 7. Response frequency spectra of an undamaged ceiling slab, single exciting signal.

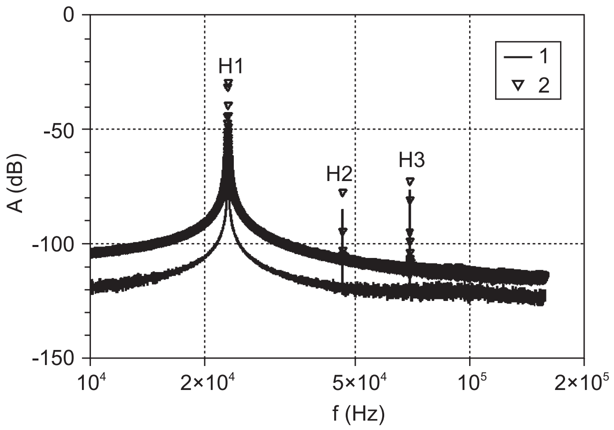


Figure 9. Response frequency spectra of a damaged ceiling slab, single exciting signal.

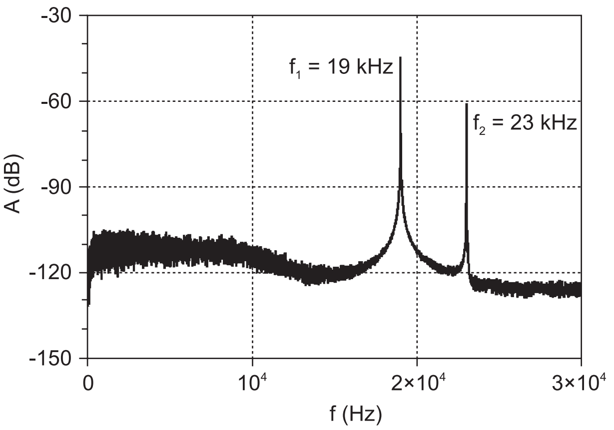


Figure 8. Response frequency spectrum of an undamaged ceiling slab, two exciting signals.

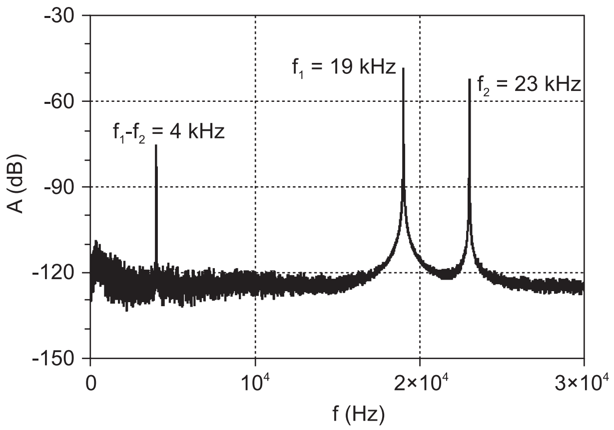


Figure 10. Response frequency spectrum obtained from a damaged ceiling slab, two exciting signals.

The presented results indicate that the nonlinear response of a ceramic material when damaged is extremely large when compared to an undamaged ceramic material. Therefore, acoustic diagnostic methods that look primarily for nonlinear phenomena such as wave distortion by creation of harmonics and multiplication of waves of different frequencies have a strong potential in damage detection. In undamaged ceramic materials the nonlinear phenomena are very weak.

Our measurements of intact specimens have shown that the effect of a ceramic material inhomogeneity being substantially lower than for common defects. The nonlinear phenomena have been remarkably large in damaged materials.

The measurement results obtained from the distorted-structure specimens have given evidence that the defects in the material structure were producing nonlinear effects in the signal transmission. The structural integrity distortion affected the transfer characteristic frequency spectra of crack-containing specimens.

Both methods outlined in this paper are fast and efficient, and proved to be very effective in discerning an undamaged samples and sample with small crack. We verified that it can be applied to any type of shapes and dimensions.

In the near future, we expect that the methodology of nonlinear elastic wave spectroscopy techniques will be developed and applied for various materials testing procedures. Their impact on the economy and safety can be enormous. Nonlinear methods may be implemented in application as diverse as general production quality control and monitoring fatigue damage in composites and structures.

Acknowledgements

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