NONLINEAR ACOUSTIC TECHNIQUE FOR CRACK DETECTION

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It has been relatively recently known that cracks have high nonlinear elasticity. It causes different nonlinear acoustic responses such as higher harmonics generation or nonlinear modulation of an ultrasound wave passing through or reflected from a crack by low frequency vibrations of a testing object. These effects are used for the development of methods of nonlinear acoustic nondestructive evaluation (NANDE). Simple NANDE technique can be used for detection of damaged objects. However such technique cannot give information on crack location. Advanced methods allow one to measure crack position. In this paper methods of crack detection and location are considered. They are based on modulation of high-frequency acoustic wave passed through the crack by low-frequency vibrations of testing object. Location techniques are based on modulation of acoustic pulses reflected from a crack. Experimental examples demonstrate that the nonlinear acoustic techniques can be effective for nondestructive testing of different objects.

INTRODUCTION

It is known that nonlinearity of materials with cracklike defects can be several orders higher than that of undefected materials [1,2]. It makes possible different applications in NDE. Nonlinear acoustic nondestructive evaluation (NANDE) techniques such as generation of harmonics or modulation high-frequency acoustic waves by low-frequency vibrations has been recently introduced as a new tool for nondestructive inspection of defective and fractured materials [2,3]. The earlier developed NANDE techniques can only detect cracks and damage but can not give information on crack location in tested object. The crack location methods are based on combination of pulse and modulation techniques - modulation of acoustic pulses reflected from a crack by vibrations [4,5]. The first method employs the modulation of a single ultrasound pulse by rather high frequency vibration. This modulation is observed inside one ultrasound pulse. The second, the advanced technique utilizes the modulation of long pulse sequence.

NONLINEAR ACOUSTIC DIAGNOSTICS

We experimentally studied nonlinear acoustic diagnostics of concrete beams. A scheme is shown in Fig.1.

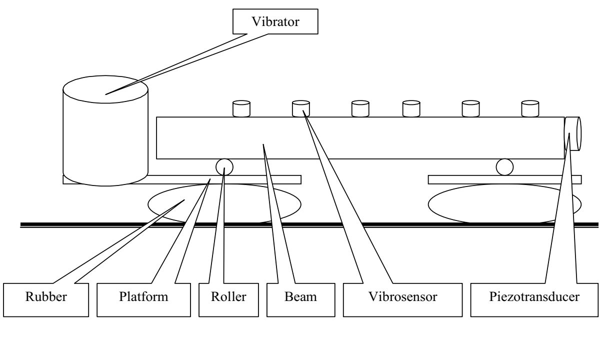

Fig.1. A scheme of experiments with concrete beams.

Four concrete beams ($100 \cdot 15 \cdot 15$ cm^3) were used in experiments. The beam #1 has spherical flaw of 3-cm diameter, the beam #2 – transverse artificially made crack, the beam #3 is the reference has no defects, and the beam #4 has a reinforcement inside. It was studied the modulation of high-frequency (16 kHz) acoustic waves generated with the piezotransducer by low frequency flexural beam vibrations excited with the vibrator at the resonance frequencies of the first and the second modes. Corresponding diagrams of beam oscillation are shown in Fig.2. Nonlinear interaction of high-frequency and low-frequency waves in concrete beams due to

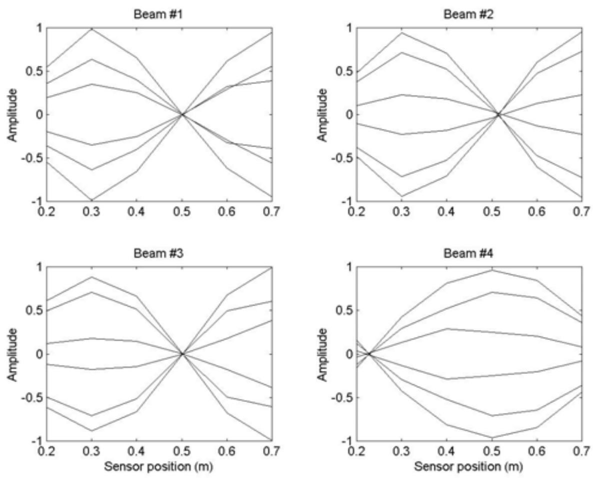

Fig.2. Diagrams of flexural resonance vibrations of beams.

defects causes effect of modulation, which is revealed by arising of combination frequencies, i.e. the lateral frequencies in spectra of signals from sensors, shown as example in Fig.3.

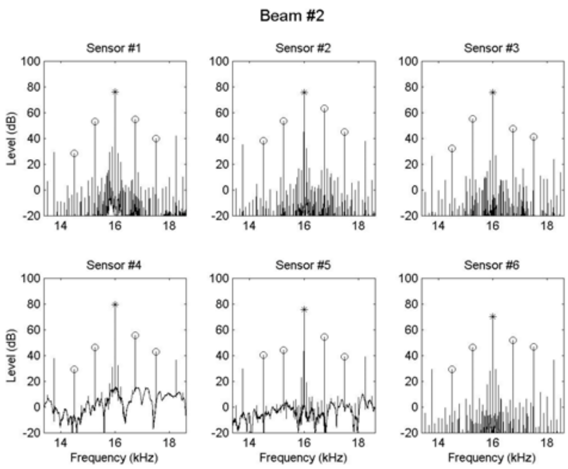

Fig.3. Spectra of signals registered by sensors along the beam #2.

It is seen from Fig.3 that the modulation effect is complex: there are many lateral frequency components. It is due to nonquadratic nonlinearity of crack. The modulation coefficient, which is the difference between levels of the 1-st lateral (modulation) frequency components and the high frequency component for the beam #2 is about –(15-20) dB. Measurements of spectra were done for all concrete beams. They have revealed, that the modulation index can be used as the nondestructive testing criterion. The acoustic nonlinearity is due contact nonlinear elasticity between crack sides or between concrete and reinforcement. The normalized (to the reference beam) modulation indexes for tested beams are shown in Fig.4.

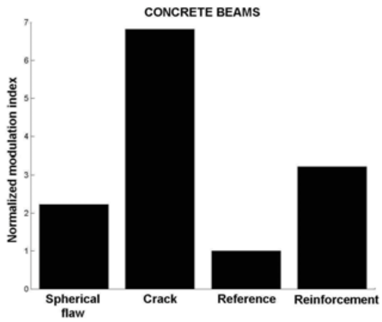

Fig.4. Normalized modulation indexes for concrete beams with different defects.

CRACK LOCATION METHODS

Schemes of two methods of crack location are shown in Fig. 5. In the single pulse modulation method (upper) the high-frequency (HF) tone-burst acoustic pulse of carrier frequency f and low-frequency (LF) CW acoustic wave of frequency F are

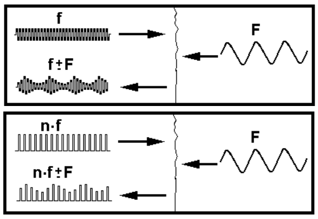

Fig.5. Schemes of single pulse (upper) and pulse series (lower) techniques of crack location.

input into the sample. Reflected from a crack HF pulse becomes modulated by low frequency due to nonlinearity of crack. Acoustically linear defects can not produce nonlinear responses. It makes possible to identify reflections from cracks among others. The distance r from the HF transducer to the crack can be obtained from pulse travel time t: $r=ct/2$ (c is the sound velocity). To detect single pulse modulation the pulse duration must satisfy the relation $F\tau>1$.

A scheme of the advanced method, i.e. the pulse series modulation method is shown in Fig.5 (lower). HF radiator emits a sequence of short pulses of duration τ and the repetition rate F_r, and the duration T_s of a sequence. Then, the nonlinear modulation can be obtained not for single pulse but rather for the entire pulse sequence. In this case the crack location and the spatial resolution are given by the same expressions as for single pulse location technique. The position of crack can be measured by strobing of receiving signal with the strobe duration equal to τ and changeable time delay. In the present method the necessary condition of detection of modulation is as follows: $FT_s>1$, which is not so strong as for single pulse location technique. From the other side the pulse series modulation technique has disadvantage - the possibility of ambiguous location due to many times reflections of each pulse from the sample ends. The detection of modulation in the sequence can be done directly with the observation of modulation frequency components in the spectrum of received pulse series or with the use of the peak detector [5]. In this case the signal after detector is the sum of constant value, which is proportional to the amplitude of the received pulses and the modulation signal of frequency F, which amplitude is proportional to modulation amplitude in the received pulse sequence. With the Fourie analysis one can easily measure the modulation coefficient, which is the ratio of value of spectral component at the frequency F and the magnitude of zero-frequency component. Experiments were done with duraluminium rods of 91 cm length at the carrier frequency 1.2 MHz, and τ=20 μs, F_r=293 Hz [5]. An example of defect location with the use of LF-vibrator at F=10 Hz is shown in Fig.6. One can see that the pulse sequence reflected from acoustically linear cut, has no modulation while the sequence reflected from the crack has the modulation.

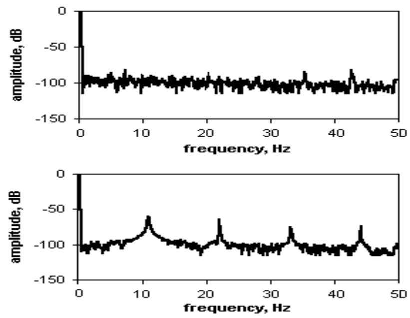

Fig.6. Spectra of signals obtained by the pulse sequence modulation method in rods with acoustically linear defect (upper) and with the crack (lower).

In the problem of crack location it is important to improve spatial resolution and detectability especially for testing objects of complicated shape. In this case acoustic waves in the sample are scattered from obstacles and roughnesses at the surface and inside the sample, producing reverberation field in the sample. For this case advanced technique can be applied. It is based on the use of pseudo-random signals, in particular M-sequences.

CONCLUSION

The nonlinear acoustic nondestructive testing technique was studied for concrete beams. It was shown that the modulation method could be used for NDE of damage in concrete constructions. This technique allows one to detect damaged samples. For location of cracks in a construction two versions of the nonlinear acoustic pulse modulation technique were considered. Nonlinear acoustic methods can be effective tools for nondestructive testing.

This work was supported by ISTC (project 1369) and in part by RFBR (01-02-16938, 00-15-96741). Authors appreciate DFG for support.

REFERENCES

1. Buck, O., Morris, W.L., Richardson, J.N., *Appl.Phys.Letters*, **33**, 371-373 (1978).
2. Sutin, A.M., Nazarov, V.E., *Radiophysics & Quantum Electronics*, **38**, 109-120 (1995).
3. Didenkulov I.N., Ekimov, A.E., Kazakov, V.V., *Acoustical Physics*, **44**, 621-627 (1998).
4. Kim, J.P., Kim, E.J., Yoon, S.W., Sutin, A.M., *JASA*, **101**, 3029-3030 (1997).
5. Didenkulov I.N., Sutin A.M., Kazakov V.V., Ekimov A.E., Yoon S.W. Nonlinear acoustic technique of crack location, in *Nonlinear Acoustics at the turn of the Millenium*. Eds.:W.Lauterborn, T.Kurz. Melville, New York, 2000, pp.329-332.