CRACK LOCATION BY THE NONLINEAR MODULATION MODE TECHNIQUE

I. Didenkulov, N. Kurochkin, and A. Stromkov
Institute of Applied Physics of Russian Academy of Sciencies, Nizhny Novgorod, Russia
din@hydro.appl.sci-nnov.ru

Abstract

Cracks exhibit high acoustic nonlinearity. It produces different nonlinear acoustic responses, which are used for development of methods of nonlinear acoustic nondestructive testing. Simple techniques based on nonlinear responses can be used for detection of damaged objects, but cannot give information on crack location. Advanced methods allow one to measure crack position. Several nonlinear acoustic methods of crack location have been suggested. In the present paper we describe the novel modulation modal method. Experimental examples demonstrate possibilities of the method, which can be effective tool for NDT.

Introduction

Acoustic methods of nondestructive testing are widely used in industries and science. During last decade an increasing attention is being paid to development of the nonlinear acoustic diagnostic methods since it has been revealed that cracks exhibit high acoustic nonlinearity [1-3]. The nonlinear acoustic parameters of solids are much more sensitive to crack-like defects than the linear acoustic parameters (sound velocity, attenuation). Crack can produce different nonlinear acoustic responses such as higher harmonics generation or frequency mixing when ultrasound waves of different frequencies pass through or reflected from a crack and some others. These effects are used for development of the methods of nonlinear acoustic nondestructive evaluation [4-6]. Simple techniques can be used for detection of damaged objects. However, such techniques cannot give information on crack location. Advanced methods allow one to measure crack position [7]. In this paper we present results on the modulation technique of the nonlinear acoustic nondestructive testing. The modulation method is based on the effect of modulation of high-frequency acoustic wave passing through a crack by low-frequency oscillations of testing samples. Low-frequency wave changes parameters of the high-frequency probe wave propagating through the crack. The modulation coefficient (index), therefore, contains information on interaction of high- and low-frequency waves at the crack. The modulation index depends on crack position relatively to nodes and antinodes of excited low-frequency oscillation modes in a sample. In this paper we describe the novel modulation modal method for crack location.

Method

The modulation modal method of crack location is based on the fact that interaction of high-frequency acoustic wave with low-frequency oscillations of testing object takes place at the crack. Consequently, the nonlinear force, which generates the modulation frequency components act at the position of the crack. Exciting different low-frequency modes in the object one can get a set of modulation amplitude responses from the testing sample. Resonance properties of high frequency acoustic waves are usually not as strong as for low frequency oscillations, and by additional local spatial or frequency averaging the influence of those resonances on modulation indexes can be easily avoided. As a result by measurement of the modulation indexes for different low-frequency modes one can reconstruct the crack position.

Consider this method for 1-dimentional case. It may be, for example, a rod. Low-frequency (LF) longitudinal modes in such a sample for the free-boundary conditions at both ends can be written as:

$$u_n(z,t) = A_n \cdot \sin\frac{\pi n z}{l} \cdot \cos\Omega_n t\,,\ n=1,2,3,\dots\,. \qquad (1)$$

Here $u_n(z,t)$ is the displacement in the sample, l - the sample length, A_n - the amplitude, Ω_n - resonance frequencies of the modes. Suppose that u_ω is the displacement in a sample caused by the high-frequency (HF) wave propagating in it.

Without a crack in the sample the LF and HF waves do not interact to each other. If there is a crack in the sample they interact producing the modulation effect, which is proportional in the approximation of the quadratic nonlinearity to the product of $u_n(z,t)$ and u_ω:

$$\tilde{u}_n = \alpha \cdot u_n(z_0) u_\omega\,. \qquad (2)$$

Here $\tilde{u}_n$ is the amplitude of a wave, which is generated by the nonlinear force in the crack at the combination frequency components (modulation frequency components) $\omega \pm \Omega_n$. Suppose that the newly generated high-frequency waves at the combination frequencies propagate in the sample as in infinite 1-D medium. The modulation index can be derived as:

$$M_n = \frac{1}{A_n} |\tilde{u}_n / u_\omega| = \frac{\alpha |u_n(z_0)|}{A_n}\,. \qquad (3)$$

Then, introduce the parameter M as:

$$M(z,z_0)=\mathrm{sum}[|M_n \cdot \sin(kz)|]\ . \qquad (4)$$

where $k=\pi n/l$. The parameter M has a peak value at the position of the crack, that is at $z=z_0$. Additional peak, evidently, takes place at $z=l-z_0$. Spatial resolution of this technique depends on the number of excited modes of flexural oscillations.

Experiment on crack location in a string

To verify the modulation mode method we carried out 1-dimension experiments with metal strings and rods. A scheme of the first experiment is shown in figure 1.

The 2-meter string was stretched between two supports fastened to a massive metal platform. Transverse string oscillations were excited with the electromagnet 5. Electromagnetic sensor 6 was used to measure amplitudes of the string transversal oscillations. Acoustic waves (~200 kHz) in the string were generated by a piezoceramic transducer fastened to the end. A signal was registered by the another piezoceramic transducer at the opposite end of the string.

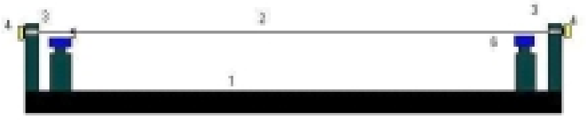

Figure 1 : A scheme of the experiment with a metal string: 1 - platform, 2 – string, 3 – supports, 4 – high frequency piezoceramic acoustic transducers (one of which is the emitting and the second is the receiving), 5 – an electromagnet for excitation of transversal string oscillations, 6 – electromagnetic sensor for measurement of the transversal string oscillation.

The string was excited step by step at the mode resonance frequencies and the modulation coefficients of high-frequency wave were measured for each of the low-frequency mode resonance. Amplitudes A_n of low-frequency modes were also measured by the electromagnetic sensor.

Experiments were done with the normal string and with a string having a small crack. A crack was made by a cut in a small drop of hard solder on the string.

The experimentally obtained mode distributions of the modulation indexes for normal string and the string with a crack are shown in figures 2 and 3. It is seen from the figures that the string with a crack has several times higher nonlinear responses than the normal one. It is obvious that artificial nonlinearity is introduced in the system in points of contact of the string with the supports. Therefore the nonlinear responses for the normal string can be considered as the background nonlinearity. One can also see that the modulation indexes are very much different for different modes in accordance with the model described by the equation (3).

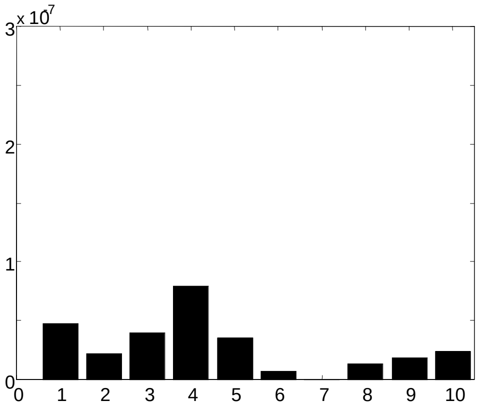

Figure 2 : Modulation coefficients for different modes. Normal string.

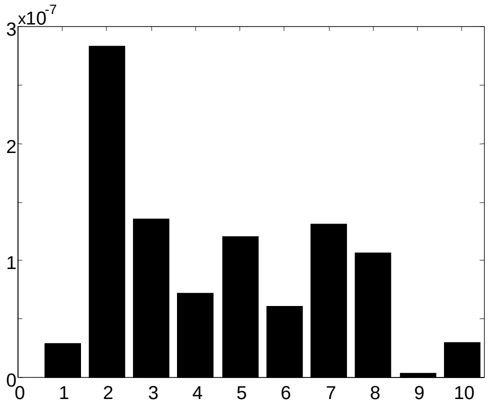

Figure 3 : Modulation coefficients for different modes. String with a crack.

Results of reconstruction of crack position by the use of the value M in accordance with the equation (4) is shown in figure 4.

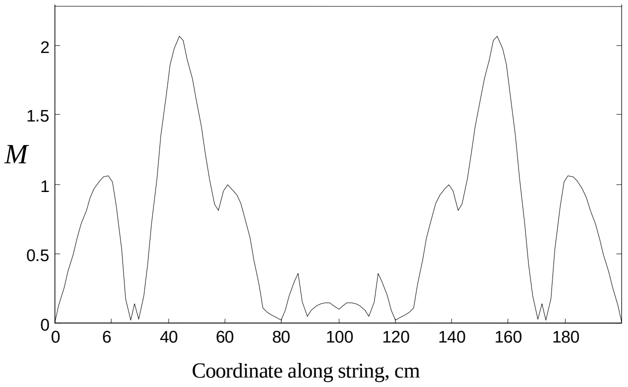

Figure 4 : Reconstruction of crack position. Horizontal axis – coordinate along the string, vertical axis – the modulus of the parameter M.

The relative nonlinear parameter is maximal at the site of the crack. Left maximum in the figure is real and the other is imaginary because of the symmetry of flexural modes on the string.

Experiment on crack location in a rod

The modulation mode method of crack location was verified also in experiments with a metal rod. A scheme of the experiment is presented in figure 5.

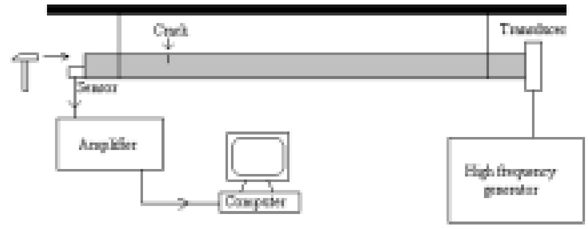

Figure 5 : A scheme of the experiment with a metal rod.

A duraluminium rod of 2.1-m length was fastened by two ropes to the support. The rod had a crack at 50 cm distance from one of ends. High-frequency piezoceramic transducer was glued to one end of the rod, and the sensor - to the another end. In this experiment the rod had free-end boundary conditions. The transducer emitted continuous longitudinal waves into the rod at the frequency about 200 kHz.

Longitudinal resonance modes were excited in the rod by the shock of hammer. They were generated simultaneously. Such a technique allows one to measure all the modulation indexes in a single experiment, as the spectrum of the registered signal contains modulation frequency components for all of the modes. For the free-end boundary conditions in the experiment with the rod longitudinal modes are described by the same functions as in equation (1). Therefore, for reconstruction of crack position in the rod one can use the same scheme, as in the previous experiment (see equation (4)). For the reconstruction of crack position in the experiment with the rod we used a modified technique. Instead of the parameter M introduce the parameter $\tilde{M}$ as follows:

$$M(z,z_0)=\mathrm{sum}[M_n \cdot \sin(kz)] \,. \qquad (5)$$

It can be easily seen that $\tilde{M}$ is not positive and also has two peaks: one is in the position of the crack at $z=z_0$ and the second at $z=l-z_0$.

Result of reconstruction of crack position in the rod made in accordance with the equation (5) is shown in figure 6.

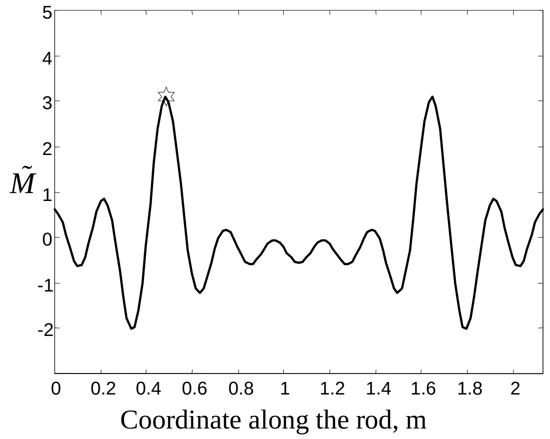

Figure 6 : Reconstruction of crack position in the rod. A star marks the real crack position.

The reconstructed crack position presented in figure 6 is in good agreement with the real crack position.

Conclusion

In this paper we considered the nonlinear acoustic modulation method for detection of cracks in solids. A simple modulation technique does not answer the question where is the crack in the damaged sample. To find place of a crack in solids the novel modulation mode method was considered. It allows one to reconstruct crack position basing on measurements of the modulation indexes for resonance low-frequency modes in the sample. This method was verified in experiments on crack location in the metal string having transversal mode oscillations, and with the metal rod having longitudinal mode oscillations. Both experiments have shown that crack position can be successfully reconstructed with the modulation mode method. The suggested technique can be prospective tool for nondestructive testing of different materials and constructions

Acknowledgement

This work was supported by RFBR (01-02-16938) and by the Research School Foundation (NS-1641.2003.2).

References

[1] O. Buck, W.L. Morris, J.N. Richardson, “Acoustic harmonic generation at unbonded interfaces and fatigue cracks”, Appl. Phys. Lett., vol. 33, pp. 371-373, 1978.

[2] A.M. Sutin, V.E. Nazarov, “Nonlinear acoustic methods of crack diagnostics”, Radiophysics & Quantum Electronics, vol. 38, pp. 109-120, 1995.

[3] L.A. Ostrovsky, P.A.Johnson, “Dynamic nonlinear elasticity in geomaterials”, La Rivista del Nuovo Cimento, vol. **24**, pp. 1-46, 2001.

[4] A.S. Korotkov, A.M. Sutin, “Modulation of ultrasound by vibrations in metal constructions

with cracks", Acoustics Letters, vol. 18, pp. 59-62, 1994.

[5] A.S. Korotkov, A.M. Sutin, "Modulation of ultrasound by vibrations in metal constructions with cracks", Acoustics Letters, vol. 18, pp. 59-62, 1994.

[6] A.E. Ekimov, I.N. Didenkulov, V.V. Kazakov, "Modulation of torsional waves in a rod with a crack", J. Acoust. Soc. Am., vol. 106, pp. 1289-1292, 1999.

[7] I.N. Didenkulov, A.M. Sutin, V.V. Kazakov, A.E. Ekimov, S.W. Yoon, "Nonlinear acoustic technique of crack location", in Nonlinear Acoustics at the turn of the Millenium (Proceedings of the ISNA-15, Goettingen, 1-4 September, 1999), Melville, New York, 2000, pp.329-332.