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Diagnosis of Metal Plates with Defects Using Laser Vibrometer

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Abstract

The method of nonlinear laser scanning vibrometry is used for diagnostics of thin cylindrical resonators of polycrystalline aluminum alloy D16 with latent defects and residual stresses. Flexural Lamb waves are used for diagnosis. The dependence of the frequency of the resonator eigenmode on the amplitude of the flexural Lamb waves in it is detected (the effect of the fast dynamics); it indicates the presence of defects in the material of the resonator. Coordinates of defects were identified by vibromodulation technique in the resonator.

Keywords: flexural lamb waves, laser scanning vibrometry, fast dynamics, vibromodulation technique;

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1. Introduction

Study of nonlinear elastic properties of solids with defects (microcracks, residual deformation, delamination in composite materials) is constantly paid much attention. On the one hand, the attention is due to interesting nonlinear elastic properties of such materials, and on the over hand, it is due to study of the possibility of creating new acoustic nondestructive testing technique, based on the principles of nonlinear acoustics. As described in the book edited by Delsanto [1], it was found that in solids with defects, besides the elastic nonlinearity associated with the anharmonicity of intermolecular forces (classical nonlinearity), an elastic structural nonlinearity is presented. The one is associated with defects in solids (nonclassical nonlinearity). Influence of defect structure on the nonlinear elastic properties of poly- and monocrystals is allegedly first investigated experimentally by Gedroits et al [2]. They showed experimentally, that defects, dislocations, microcracks, local internal stresses in isotropic solids alter

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substantially their nonlinear elastic properties. In his paper, Rudenko [3] examined the possible physical mechanisms of nonclassical nonlinearity.

The studies revealed the characteristic properties of nonclassical elastic nonlinearity: it is local, it has a threshold, and the speed of elastic waves is linearly dependent on their amplitude. It was also found that the structural nonlinearity may be substantially higher than the classical nonlinearity. This enabled Johnson et al [4] and Zaitsev et al [5] to observe a number of new interesting nonlinear acoustic effects, which can't be seen in the materials with only the classical nonlinearity.

Unfortunately, the unique diagnostic properties of nonclassical elastic nonlinearity are used insufficiently in NDE. Modern methods of elastic waves recording allow creating new techniques for the diagnosis of defective media, where all of the above diagnostic properties of nonclassical elastic nonlinearity may be implemented. For example, Solodov et al [6] used a laser vibrometer for the diagnosis of solid thin plates with flexural Lamb waves, thus not only detecting defects therein, but also determining their coordinates.

The aim of this work is the diagnosis of thin cylindrical resonator made of polycrystalline aluminum alloy D16 with defects by fast dynamics and acoustic vibromodulation techniques with flexural Lamb waves and laser vibrometer.

2. Flexural Lamb waves in thin cylindrical isotropic metal resonators

For non-destructive testing of thin resonators, antisymmetric mode A_0 of Lamb waves is used in the work. This mode has the geometric dispersion. Its phase velocity c_a is given by:

$$c_a = \sqrt[4]{\frac{E}{12\rho\left(1-\sigma^2\right)}}\sqrt{2\pi fh}\ , \tag{1}$$

where E is a Young modulus, σ is a Poisson ratio, ρ is a density of the material, f is a frequency, h is a plate thickness.

In the case of excitation of thin cylindrical resonator with free contour with harmonic force applied to its center, the waveform of the resonator eigenmodes are described by the expression:

$$Y_m(r,\phi) = [\cos(m\phi)][A_m I_m(kr) + B_m I_m(kr)] \tag{2}$$

where Y_m, A_m, B_m are magnitudes, $m = 0, 1, 2, 3\ldots$, $J_m(kr)$, $I_m(kr)$ are Bessel's function, r is a radius, φ is azimuth.

Eq. (2) with boundary condition at $r = a$ permit to define resonant frequency of resonator. Due to the velocity dispersion of flexural Lamb waves (1), the spectrum of eigenmodes of the cylindrical resonator is not equidistant and as a result, the first elastic harmonic of the fundamental mode does not coincide with the eigenmodes of the higher modes of the resonator.

3. The sample under study and experimental setup

For experimental studies, cylindrical resonator of 121 mm diameter was manufactured of polycrystalline aluminum alloy plate D16 with thickness h = 1.2 mm. The experimental setup is shown in Fig. 1a.

For excitation of the resonator with intense low-frequency flexural Lamb waves at a frequency F, we used Robotron shake table. The studied resonator is rigidly mounted to its movable part. Amplified signal with frequency F is supplied by Generator 2. High frequency probing wave is generated by a piezoelectric ceramic ring placed in the center of the resonator. The electric signal with frequency f is taken from internal Generator 1 under control of PC. Fluctuations in the sample are registered with a scanning laser Doppler vibrometer PSV-300 (by Polytec) and also recorded in PC. The spectrum of the eigenmodes of the resonator in the frequency range (160-23434) Hz was pre-measured, and characteristic shape of the resonator at certain natural frequencies are visualized (Fig. 1b). The spectrum of the natural oscillations of the resonator was not equidistant. As seen in Fig. 1b, the waveform of the resonator depends on both the radial and the angular coordinate. That is in accordance with the Eq. (2).

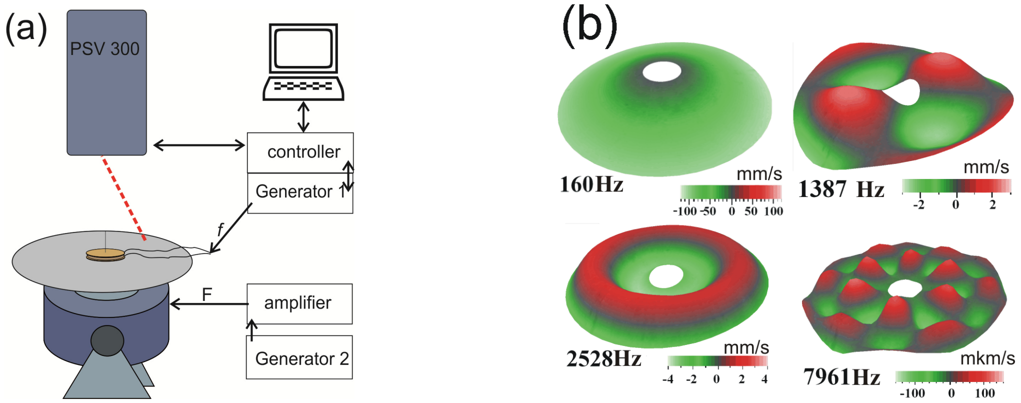

Fig. 1. (a) Experimental setup; (b) some resonator modes on its resonant frequencies.

4. Experimental results and discussion

The plate and the resonator during their manufacture may be damaged with hidden defects, which can't be observed visually. However, such defects (residual deformation, dislocations, microcracks) can cause nonclassical nonlinearity in resonators. To detect it, we used the effect of fast dynamics: dependence of the natural frequency of the resonator $f = 2481$ Hz on the amplitude of the Lamb waves U in it. Fig. 2a shows a family of resonance curves of one of the resonator modes, taken at different amplitudes of Lamb waves. The dependence of the shift of the resonance frequency of the resonator df/f_0 on the amplitude of the standing waves Lamb U is shown in Fig. 2b.

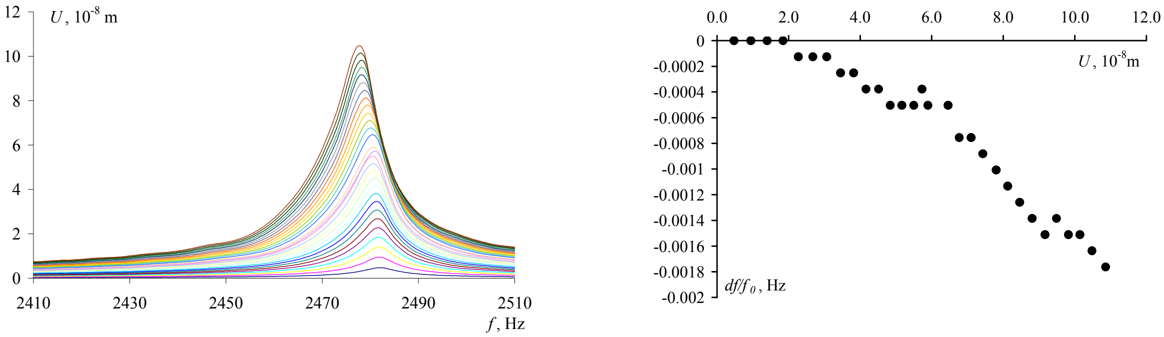

Fig. 2. (a) Resonant curves on the frequency f_0=2481 Hz at different amplitude; (b) dependence of resonant frequency shift on amplitude.

Analysis of the experimental results shown in Fig. 2b indicates the presence of a multiple sources of structural nonlinearity and threshold character of their manifestation. With increasing the amplitude of the excitation signal, an increasing number of defects begin to affect the nonlinear elastic properties of the resonator, which leads to a stepwise change in its resonant frequency. The linear dependence of the resonator frequency of the amplitude of waves in it, and its threshold character indicates the presence of defects in the resonator and related nonclassical nonlinearity (see Johnson et al [4]).

Used vibromodulation techniques allowed spotting the defects in the resonator. Two waves, intensive low-frequency wave *P(f)* and probe high-frequency wave *P(F)*, simultaneously excited in the resonator, gave a response on a nonlinear elasticity of a defect:

$$P(f \pm F) = \frac{\Gamma d}{4c^3 \rho}(f \pm F)P(f)P(F) \tag{3}$$

where c, ρ - a sound velocity and density of the material, d - a size of a defect, *P(f)*and *P(F)* stay constant; thus Γ, a local nonlinear parameter, and frequency of resulting wave *(f ± F)* are responsible for the amplitude of the response in each point. It has to be mentioned that the low-frequency signal must be strong enough to change acoustical properties of the sample.

In our experiment we used two waves: the intensive one at the lowest mode with a frequency f = 344 Hz, and probe signal at a frequency of a mode f = 75.39 kHz. Vibrations of the disk were registered with laser vibrometer.

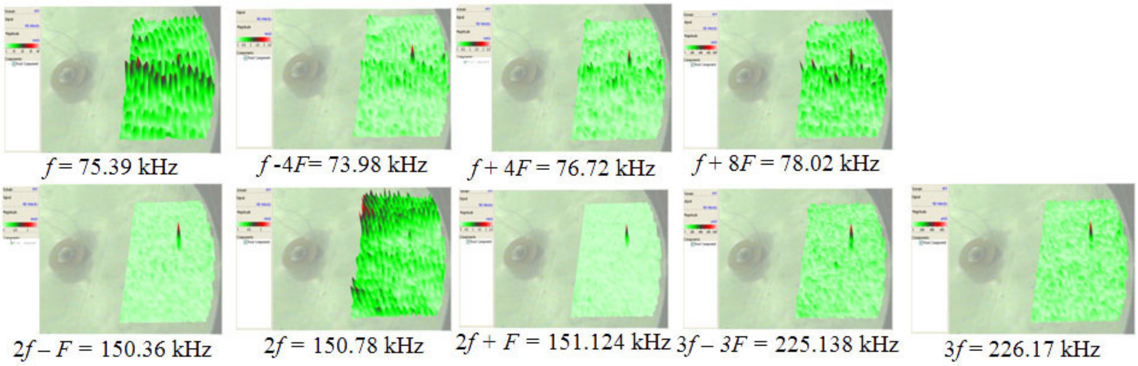
f = 75.39 kHz
f -4F= 73.98 kHz
f + 4F = 76.72 kHz
f + 8F = 78.02 kHz
2f – F = 150.36 kHz
2f = 150.78 kHz
2f + F = 151.124 kHz
3f – 3F = 225.138 kHz
3f = 226.17 kHz

Fig. 3. Probe frequency (75.39 kHz), its second and third harmonics, and cascade combination frequencies.

As shown in Fig. 3, in the local points of the resonator, vibrations of large amplitude are observed at combination frequencies. Such appearance of intense fluctuations is caused by local elastic structural nonlinearity associated with local defects (residual stress, microcracks) in the resonator. The size of these defects is different, and due to the threshold nature of the structural nonlinearity, they appear at different amplitudes of vibrations of the sample (Fig. 3). Oscillation amplitude distribution over the surface, as follows from (2) and as seen from Fig. 1b, depends on the frequency, and therefore various defects occur at different frequencies combination: one may see defects, the coordinates of which coincide with a greater amplitude of oscillation of the resonator. In addition to the combination frequencies $f \pm nF$, defects were also detected in the second and third harmonics and the corresponding combination frequencies ($2f \pm$ nF). and ($3f \pm$ nF). (Fig. 3). The signals at the harmonics of the probe signal are registered only at the simultaneous excitation of the resonator oscillation frequencies f and F.

Conclusion

The work includes diagnostics of thin cylindrical resonator made of polycrystalline aluminum alloy D16 with defects using flexural Lamb waves. The presence of non-classical elastic nonlinearity caused by defects in the resonator, and its threshold character were investigated with the effect of the fast dynamics. Coordinates of defects were determined using the method of acoustic vibromodulation. Lamb waves are registered with a laser vibrometer. At diagnosis of a resonator with defects, basic properties of nonclassical nonlinearity were used: it is much bigger than a classical nonlinearity, it has local and threshold behavior, the speed of elastic waves in media with defects are linearly dependent on their amplitude.

Acknowledgements

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