MICRO-DAMAGE DETECTION USING A MODULATION TECHNIQUE BASED ON DISSIPATIVE NONLINEAR EFFECTS

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ABSTRACT. Experiments indicate that occurrence of defects in a solid may dramatically increase its nonlinearity. For diagnostic applications of this phenomenon, ample understanding of the particular nonlinear mechanism is crucial. We present experimental data on pronounced nonlinear-modulation interaction of acoustic waves in slightly damaged solids. In particular, we discuss a new variant of the nonlinear-modulation technique implying interaction of a probe wave with another, slowly modulated, stronger wave instead of conventionally used lower-frequency intensive excitation. The observed dependencies can be explained neither by conventional elastic, nor hysteretic nonlinearities. We propose a new mechanism of strongly amplitude-dependent dissipation due to acoustic wave-crack interaction, which explains the aforementioned experiments.

INTRODUCTION

Conventionally in vibro-acoustic diagnostics, nonlinear distortions are intentionally eliminated or simply neglected [1]. On the other hand, as experiments have proven, occurrence of a small amount of defects in a solid may increase its nonlinear response by orders of magnitude while the linear properties may be only slightly perturbed [2]. Therefore, nonlinear distortions of a vibrational (acoustical) signal can be used as a very structurally-sensitive indicator of damage in the sample structure [3-7]. Drastic differences in linear and nonlinear manifestations of micro-defects in solids are now confirmed by numerous experimental demonstrations, and general reasons of such a difference are comprehended theoretically (see, for example, [8]). Among other nonlinear effects the use of modulation vibro-acoustical interactions yields several advantages (see e.g., [6,9]). Such effects are normally absent in weakly nonlinear undamaged (intact) homogeneous samples and their noticeable level indicates the presence of some microstructure, for example, cracks in the investigated sample.

Previous theoretical models of modulation effects due to wave interaction on a single discontinuity-like defect [10], or in a solid resonator made of a polycrystalline medium with multiple micro-defects [11] are not sufficient to explain significant features of the experimental results in many cases (especially those obtained for single cracks that are small compared to the acoustic wavelength). Moreover, the simple intuitive deduction that a low-frequency action changes the propagation conditions through the crack for the acoustic wave is insufficient to explain satisfactory the experimental results on rather intensive modulation even for defects whose size is much smaller than the characteristic elastic wave length. In the next sections, we discuss a number of experimental data on the nonlinear modulation of an ultrasound wave by a low-frequency vibrations in a metal sample with a single small crack [9], and cross-modulation effects observed in a rod-resonator made of polycrystalline copper containing numerous intergrain defects, and in glass rods with a few thermal cracks [12,13]. The obtained data indicate clearly that nonlinear elasticity or hysteretic nonlinearities in the conventional sense cannot account for the observed effects. A new explanation based on a nonlinear-dissipative mechanism of a non-hysteretical and non-frictional type is proposed for the observed phenomena, which offer better possibilities for exploitation of nonlinear-modulation effects in damage-detection problems and material diagnostics.

EXPERIMENTS ON NONLINEAR MODULATION OF ULTRASOUND BY A LOW FREQUENCY INTENSIVE VIBRATION IN A METAL SAMPLE WITH A SINGLE CRACK

Conventional modulation of a relatively high-frequency (HF) acoustic excitation by another, low frequency (LF) intensive vibration, also called “pump”, is schematically shown in Fig.1. We observed such a modulation in the metal sample, an aluminium plate (130mm x 55 mm in sizes and 0.5 mm in thickness), which was mounted on a shaker through an intermediate piezo-actuator. The LF vibrations of the shaker and the HF oscillations of the piezo-actuator were controlled by independent signal generators, so it was possible to excite simultaneously a LF (tens of Hz) vibration and a HF (20-30 kHz) acoustic signal, and to exclude the mixing of the signals in electrical circuits and in the actuators. Vibro-acoustic response of the plate was registered by light-weight accelerometers and the forms of the accelerometer outputs were monitored by a two-channel oscilloscope and a spectrum analyzer.

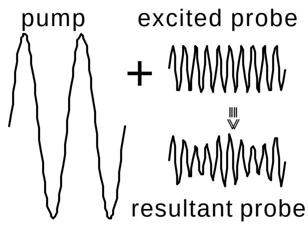

Fig.1. Schematically shown conventional noninear modulation of a probe wave caused by a low frequency pump excitation.

Figure 2 demonstrates the high contrast between the modulation spectra obtained in the reference intact sample and in the damaged one, in which a 5 mm-length crack was previously produced by intensive vibrations of the plate clamped to the shaker. Note that the modulation interaction between elastic waves or vibrations, in principle, may be attributed to different particular types of the sample nonlinearity. The latter can be either purely elastic nonlinear deviation from the linear Hooke’s law, or the effects of a hysteretic nonlinearity, or the manifestation of amplitude-dependent attenuation, that is the nonlinearity of a dissipative type. The observed modulation exhibiting multiple sidelobes, evidently, cannot be explained by conventional quadratic in strain elastic nonlinearity. “Clapping” elastic nonlinearity, in principle, may produce such multi-sidelobe spectra, but it does not suffice to induce strong enough perturbations is resonance frequencies even if the crack could be completely opened and closed under the action of the LF vibrations. Indeed, observation of direct temporal records of the probe wave (see Fig.3) indicated that the amplitude of the probe wave was strongly modulated. On the other hand, in order to produce such a strong amplitude modulation, the perturbations of the resonance frequency for the probe wave should be strong enough, that is comparable with the width of the probe wave resonance. This relative resonance width in the experiment was about 10^{-2}, whereas the elasticity perturbations due to the

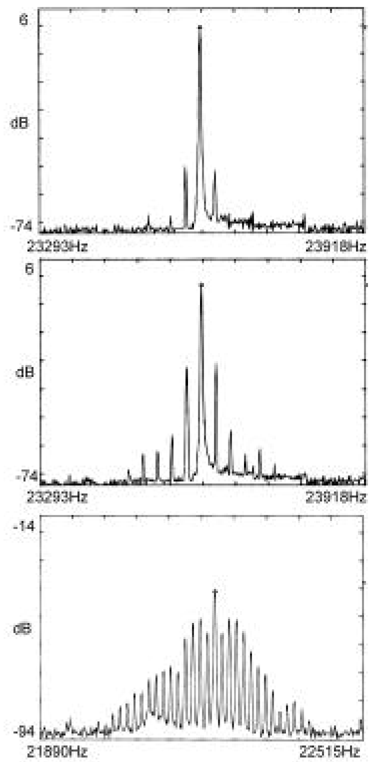

Fig. 2. Modulation spectra for the reference sample (a) and for the damaged one (b),(c).

opening and closing of the crack should be significantly smaller. Thus a purely elastic nonlinearity could not account for the observed effects. The details of the respective estimates may be found in [9].

Another type of nonlinearity, which is conventionally discussed concerning nonlinear effects in microinhomogeneous and damaged solids, is the hysteretic nonlinearity [2]. The elastic deviation of a hysteretic stress-strain dependence from the linear Hooke's law cannot explain the observed phenomena by the same reasons as purely elastic nonlinearities. The other essential feature of hysteresis is the non-zero area of the hysteresis strain-strain loop and thus the occurrence of the respective hysteretic losses. However, as the detailed experimental study [9] indicated, the modulation sidelobes were essentially linear in the amplitude of the HF probe signal. Moreover, the modulation was observed even for very weak strains (down to fractions of 10^{-9}), at which the probe wave did not exhibit noticeable hysteretic losses. Thus a conclusion was made that the most important reason of the observed strong modulation of the weak wave could be variation in the probe-wave dissipation under the action of the intensive vibration [9].

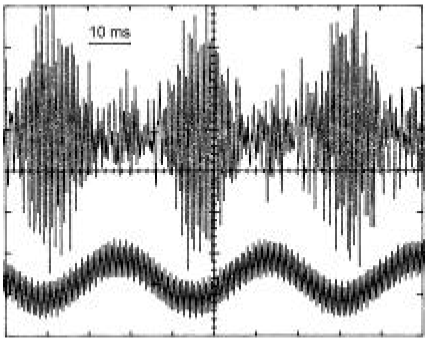

Fig.3. An example of a temporal record of the vibration in the damaged sample at a strong modulation. The lower record is the excited superposition of the LF and HF signals. The upper record is the modulated HF signal (the LF signal is filtered out).

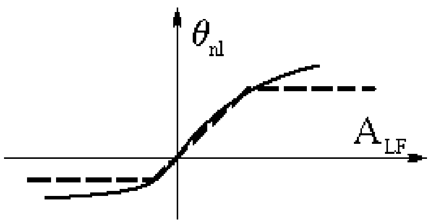

Fig. 4. Schematically shown amplitude dependence of the amplitude-dependent decrement (the solid curve) and its approximation by a piece-wise function (the dashed curve).

The variety of the observed features lead us to the conclusion that the strong LF vibration affects the magnitude of linear thermoelastic losses of the HF wave at the crack interface. Despite the small volume of the crack those losses are significantly increased due to high temperature gradients in the vicinity of the crack edges. They are determined not by the length of the acoustic wave, but by the scale of the inter-edge contacts, which is significantly less than the wavelength. A similar mechanism is responsible for the anomalously strong sound dissipation in polycrystalline media [14]. This effect alone might give the increase of the thermal losses by 2-3 orders and more (depending on the wavelength). In our case, however, there is another important strong factor, the increased amplitude of the deformation of the crack contacts, since they are much softer (up to several orders in the stiffness magnitude) compared to the stiffness of the surrounding intact material. Those combined factors could cause thermal losses at a rather small crack, which are comparable to other losses in the whole intact sample. The additional applied LF action changes the amount and stiffness of the contacts at the crack thus causing the modulation of the HF viscous-like thermal losses. Due to this mechanism, the losses of the HF wave remain linear in the amplitude of the HF excitation, although they become dependent on the LF vibration amplitude. The observed features of the modulation also lead to a conclusion that the variation in the dissipation of the probe wave is essentially asymmetrical with respect to instantaneous value of the sample deformation under the action of the LF vibration. Qualitatively this asymmetry of the decrement of the HF probe wave is shown in Fig. 4. The results of numerical simulation of the modulation spectra based on a piece-wise linear approximation of the amplitude-dependent part of the decrement agreed well with the experimentally observed features of the modulation [9].

CROSS-MODULATION NONLINEAR TECHNIQUE BASED ON THE USE OF A SLOWLY-MODULATED HIGH-FREQUENCY PUMP EXCITATION

The above-mentioned asymmetry of the amplitude-dependent dissipation is intuitively expectable, since cracks and similar defects should exhibit essentially asymmetrical response

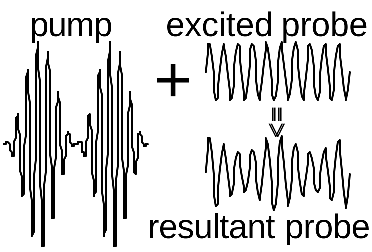

Fig. 5. Schematically shown L-G type cross-modulation of a probe wave caused by an amplitude-modulated

with respect to either compressing or stretching loads. This conclusion suggested us an idea of another variant of the nonlinear-modulation technique. Indeed, due to the asymmetrical response of the defects, even a symmetrical, sinusoidal in the simples case, strong excitation should cause appearance of a period-averaged variation in the dissipation of the defect-containing sample. Generically the same statement should be valid for period-averaged variations in the sample elasticity. Then if the stronger wave is slowly-modulated in amplitude, the period-averaged material properties should become modulated, thus causing the modulation of the second, probe wave much like in case of the conventional modulation scheme (see Fig.1.). The described nonlinear cross-modulation effect is schematically shown in Fig. 5. In this case, the modulation frequency Ω is significantly smaller than both carrier frequencies $w_{1,2}$ for the pump and probe waves, whereas the ratio between w_1 and w_2 may be quite arbitrary. Initially cross-modulation effect of such type was observed over sixty years ago in the interaction of a weak and powerful radio waves propagating in the ionosphere plasma, which was one of pioneering observations of nonlinear wave interactions. The phenomenon was called the Luxemburg-Gorky (LG) effect by the location of the powerful radio-stations, for which first observations of the effect were reported. The mechanism of the effect is essentially dissipative: the modulated powerful radio wave produces perturbations in the plasma conductivity (and thus in the radio wave dissipation) on the scale of its modulation frequency causing the appearance of the amplitude modulation of the weaker radio wave. The above discussed variation of elastic wave dissipation at cracks under the action of a strong enough wave or vibration may produce effects very similar to the LG cross-modulation of radio waves [13]. Comparison of Figs. 1 and 5 indicates that the resultant LG modulation in the appearance is rather similar to the conventional modulation. However, there are essential physical differences between these cases. Conventional modulation caused by a low-frequency action is determined by the *instantaneous* dependence of the nonlinear terms in the equation of state of the material. In contrast, the LG type cross-modulation is determined by variations in the material properties, which are *time averaged* over the pump carrier period. Therefore, the LG type cross-modulation provides an additional possibility to discern period-averaged nonlinear response of the material.

There are several other features that are not directly related to the physical mechanism of the phenomena, but are very important for implementation of practical diagnostic methods based on the LG-type cross-modulation effect. From the experimental point of view, it is normally rather advantageous to exploit resonance properties to enhance the magnitude and sensitivity of the observed effects. By these reasons, the frequency of the probe wave is often chosen close to one of sample resonances. However, in order to effectively observe the modulation it is also necessary to provide the resonance conditions for the induced modulation sidelobes of the probe wave. Apparently, the simplest way could be to choose a sufficiently low frequency pump-action, in order to provide the modulation sidelobes within the same resonance peak together with the excited probe signal. In practice, the excitation of intensive low-frequency vibrations (at frequencies of tens or even a few Hertz) may be a rather difficult technical problem, which complicates practical implementation of the nonlinear modulation spectroscopy. In contrast, in case of the LG effect, the modulation frequency is independent on frequencies of the pump and probe excitations. Therefore, the modulation frequency may be chosen arbitrary low, which readily makes it possible to put the modulation sidelobes together with the initially excited signals within the same resonance, thus providing favorable conditions for observation of the modulation. Besides, in case of the LG effect, there are no strict requirements to the high-linearity of the actuation typical for nonlinear experiments, since the parasite higher harmonics of both the pump and probe waves may be easily separated from the modulation spectral component located near the fundamental harmonic of the probe wave.

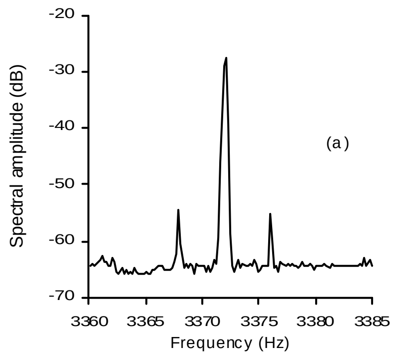

Fig. 6. Example of the modulation spectrum in the copper rod.

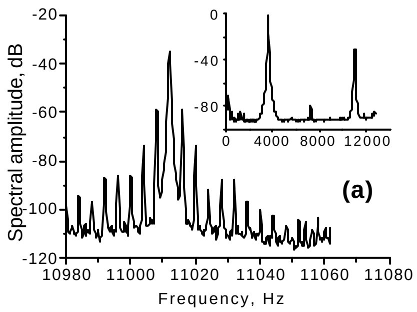

Fig. 7. Experimental spectra of the LG type cross modulation in the damaged glass rod.In the inset the lower-resolution spectra of the pump and probe waves are displayed.

We have realised an instructive experimental demonstration of the acoustic LG-effect in the form of the cross-modulation of two longitudinal modes in rod resonators. In one case the sample was a copper rod aged by strong annealing, which produced a pronounced grainy structure in the metal. Figure 6 demonstrates the modulation spectrum for a weak probe wave (strain $\sim 10^{-9}$) tuned to the first rod resonance and a slowly-modulated stronger wave (strain $\sim 10^{-7}$) tuned to the second resonance. In the reference unannealed copper and intact glass rods the modulation sidelobes were below noise at approximately the same wave amplitudes. The next example (Fig. 7) of the modulation spectrum is for the case of a damaged glass rod containing three corrugated thermally-produced cracks 2-3 mm in size (In a reference rod without cracks, the modulation sidelobes (existing due to residual parasitic nonlinearities) were 25-40 dB lower than shown in Fig.7.

For the interpretation of the observations, in the development of the qualitatively formulated above idea about the influence of the stronger wave on the thermoelastic dissipation of the second, probe, wave we considered a model of crack, containing strip-like inner contacts. Such a shape of contacts agree with direct electron- and atomic-force microscopy images of cracks normally exhibiting wavy corrugated structure of the interfaces. We applied an approximate approach similar to that [14] used for estimates of thermoelastic losses in polycrystalls and additionally took into account stress-concentration at the inner contacts. Thus we derived the following approximate expressions for thermoelastic losses in the low-frequency limit, in the high-frequency limit and at the relaxation maximum, when the thermal wave length coinsides with the width of the contact:

$$W_{LF}^{dis} = 2\pi\omega T(\alpha^2 K^2/\kappa) l^2 \tilde{L} L^2 \varepsilon^2, \quad (1)$$

$$W_{HF}^{dis} = (2\pi/\omega)\kappa T(\alpha K/C\rho)^2 \tilde{L}(L/l)^2 \varepsilon^2, \quad (2)$$

$$W_{cont}^{\max} = 2\pi T(\alpha^2 K^2/\rho C)\tilde{L} L^2 \varepsilon^2, \ \omega = \omega_l \approx \kappa/(\rho C l^2), \quad (3)$$

where ω is the wave cyclic frequency, T is the temperature, α is the temperature expansion coefficient of the solid, K is the bulk elastic modulus; ρ is the density; C is the specific heat, ε is the average strain, κ is the thermal conductivity, ω_l is the relaxation frequency for contact width l, L is the characteristic crack diameter and $\tilde{L}$ is the contact length. Note that for strip-like contacts with $\tilde{L} \sim L$ the maximal losses at the narrow contacts are roughly the same as at the whole crack. However, the relaxation frequencies for millimeter-scale cracks are fractions of Hz for most of metals, glasses or rocks, whereas for narrow contacts, this frequency can reach kHz and even MHz band. Quantitatively the estimates based on Eqs.(1)-(3) indicate that the considered thermoelastic losses at the inner contacts may readily account for the observed modulation.

The next important point for the proposed mechanism is how an excitation with strain $\varepsilon \sim 10^{-6}..10^{-5}$ may significantly affect the dissipation at the contacts. In this context, it is well known that cracks with ratio of the opening d to diameter L, may be completely closed by average strain $\varepsilon \sim d/L$, typical d/L for cracks being $10^{-2} - 10^{-4}$. However, at small loosely separated regions, local separation (or inter-penetration) $\tilde{d}$ of crack interfaces is much smaller than average separation d. Such contacts are extremely stress-sensitive, since due to the described geometry they are strongly perturbed by the average strain, which can be orders of magnitude smaller (roughly $d/\tilde{d} >> 1$ times) than the typical magnitude $\varepsilon \sim d/L \sim 10^{-3}..10^{-4}$

required to close the whole crack. Therefore, the suggested mechanism explains how pronounced amplitude-dependent variation in dissipation can be produced by quite a moderate-amplitude pump excitations.

CONCLUSION

The revealed properties of the nonlinear modulation in weakly damaged samples indicate that the effects can be explained neither by purely elastic, nor hysteretic nonlinearities. We proposed an alternative mechanism implying the modulation of thermoelastic dissipation of a weak wave at the contacting crack edges in the field of another stronger excitation. Certainly this modulation mechanism is not the unique one, and nonlinear-elastic or hysteretic mechanisms may be also important in other conditions. However, the obtained results indicate that for small cracks, which cannot perturb significantly the sample stiffness, the proposed mechanism of the nonlinear interaction plays the main role.

A new nonlinear technique of damage detection based on the effect of the so-called LG-type cross-modulation was proposed and experimentally tested. The new technique suggests a number of advantages for experimental implementation and may be a very sensitive tool for early crack detection. The revealed features of the mechanism allow for a better selection of the parameters of the vibro-acoustic action in order to provide the best conditions for defect diagnostics.

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