Nonlinear modulation methods of structural damage detection based on dissipative nonlinear effects

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Abstract

The nonlinear vibro-acoustic response of solid samples containing quite a small amount of defects can be anomalously high in magnitude compared to the case of undamaged intact solids. Functional dependencies of the nonlinear effects often exhibit rather interesting behavior which cannot be explained by manifestations of conventional nonlinear elasticity or hysteretic nonlinearity of the material. In this paper, experimental evidences of another, essentially nonlinear-dissipative mechanism responsible for nonlinear vibro-acoustic interactions in defect-containing solids are presented. In particular, experimental results on nonlinearity-induced cross-modulation of a high-frequency (HF) *f*=15…30 kHz signal by a low-frequency (LF) *F*=20-60 Hz vibration in an aluminium plate with a small single crack are reported. Comparison with a reference sample (the identical plate without a crack) has proven that the presence of such a small defect can be easily detected due to its nonlinear manifestations. It is demonstrated that under proper choice of the sounding signal parameters, the effect level can be so pronounced that the amplitude of the modulation side-lobes originated due to the nonlinearity exceeds the amplitude of the fundamental harmonic of the HF signal. Similar modulation effects were observed in polycrystalline metal samples using a new variant of modulation technique exploited amplitude-modulated intensive HF excitation instead of the LF vibration used in the first experiment. Main features of the observed phenomena are pointed out, their physical explanation based on a nonlinear-dissipative mechanism is suggested and some simulation results are also presented.

1. Introduction

Nonlinear vibrational and acoustical effects in solids with micro-inhomogeneities have been attracting ever increasing attention during last years in view of their possible applications in diagnostic problems [1-9]. Conventionally in vibro-acoustic diagnostics, nonlinear distortions are intentionally eliminated or simply neglected [10]. 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 [11]. Therefore, nonlinear distortions of a vibrational (acoustical) signal can be used as a very structurally-sensitive indicator of damage in the sample structure. Drastic differences in linear and nonlinear manifestations of micro-defects in solids are now confirmed by numerous experimental demonstrations [12-14], and general reasons of such a difference are comprehended theoretically (see, for example, [15]).

When setting up practical diagnostics, one should realize that, although the level of nonlinear distortions in a damaged solid sample can be significantly increased due to the influence of the defects, the magnitude of the nonlinearity-induced signal components can remain small compared to the linear ones. Therefore, one should avoid masking nonlinear distortions both in electrical circuits and in vibro-acoustical actuators and sensors, and choose the most sensitive and, at the same time, robust nonlinear effects to observe. From that point of view, the use of modulation vibro-acoustical effects yields several advantages

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(see e.g., [4,6]). Since the first observations of the nonlinear modulation effects [4,6], a whole series of experimental demonstrations of the effect was carried out in different conditions [12,16,17]. 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 [7], or in a solid resonator made of a polycrystalline medium with multiple micro-defects [12] 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.

In the next sections, experimental results are presented on the nonlinear modulation effects in a metal sample with a single small crack [18] and similar effects observed in a rod-resonator made of polycrystalline copper containing numerous intergrain defects [19]. 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, and some simulation results are also presented, which offer better possibilities for exploitation of nonlinear-modulation effects in damage-detection problems and material diagnostics.

2. Experiment with a metal sample containing a small single crack

Experimental setup.

The experimental set-up is schematically shown in Fig. 1. Sample (1), an aluminium plate (130mm x 55 mm in sizes and 0.5 mm in thickness), was mounted on a shaker (2) through an intermediate piezo-actuator (3). The LF vibrations of the shaker and the HF oscillations of the piezo-actuator were controlled by independent signal generators (4), (5). Therefore it was possible to excite simultaneously a

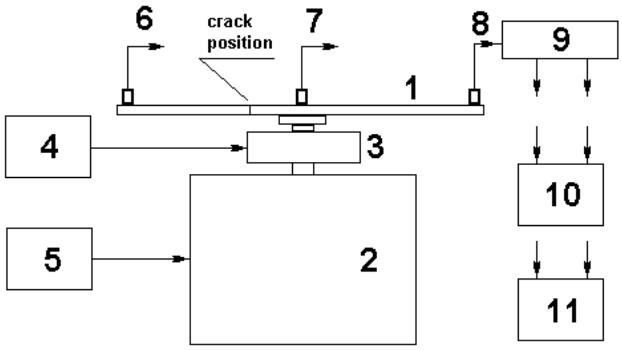

Fig.1. Scheme of the experimental set-up.

LF vibration and a HF acoustic signal, and to exclude the mixing of the signals in electrical circuits and in the actuators. The plate was tightly glued in its center to the piezo-actuator. Vibro-acoustic response of the plate was registered by light-weight accelerometers (6),(7),(8) located at the plate edges and in the center. The accelerations of the side-accelerometers (6) and (8) were proportional to the amplitude of the time derivative of strain in the plate material. After amplifier (9) the forms of the accelerometer outputs were monitored by a two-channel oscilloscope (10), and their spectrum was analyzed by a two-channel signal analyzer (11).

Two initially identical samples were used in the study. One plate without defects served as a reference one. The second plate had a small transversal crack 5 mm in length located at 50 mm from one of short plate edges. The crack was previously produced due to vibrational fatigue at intensive vibrations of the plate clamped to the shaker.

The shaker excited the lowest bending mode of the plate. Resonant frequencies of HF vibrations were influenced by the exact position of the accelerometers and by the position of the connection with the exciter. However, for the effects described below exact identification of the HF modes was not very important.

Note finally that the strain amplitude of the LF vibration was always higher (by an order of magnitude or more) than the amplitude of the HF vibration. Unlike the strain itself the time derivative of the strain for the LF vibration could be already comparable with that of the HF oscillations due to the large difference in the high and low frequencies ($f / F \approx 500..800$).

The observation of the cross-modulation of the HF signal by the LF vibrations, which were simultaneously excited in the plates, was used to detect nonlinearity of the samples. Both plates were exposed to the same excitation levels in the same frequency band. The response of accelerometer 7 located at the connection region may be considered as an "input" signal and the signals of the side accelerometers 6 and 8 correspond to an "output". In response to the LF vibration the plates behaved rather similar: the lowest bending resonance of the both plates was between 50-60 Hz. Both, the LF and the HF resonance frequencies changed by several percents when the positions of the accelerometers and of the connection region were changed by a few centimeters. Thus there was no definite distinction between the plates in their linear response. Quite different was the situation for the nonlinear response at the higher frequencies.

First, the HF response of the undamaged sample was studied. Under simultaneous excitation of both frequencies, weak modulation side-lobes at $f \pm F$ were observed around the fundamental frequency f. The amplitude of the side-lobes increased proportionally to the excitation amplitudes at both initial frequencies. The modulation was distinguishable at the side accelerometers 6 and 8 (see Fig. 1), and it was practically below the noise level for the central accelerometer (that is for the input excitation). For different frequencies f within the band 15-40 kHz, the level of the modulation varied only slightly. However, even at a higher excitation level of the LF vibration, the level of the side-lobes remained 60..40 dB lower than the central line *f*. A typical example of the spectrum at intensive excitation of the reference intact sample is shown in Fig. 2. In the figure, the difference in the level of the side-lobes compared to the central line is about $-51..-55\,\text{dB}$.

For the damaged sample under analogous excitation conditions, the cross-modulation looked significantly different both quantitatively and qualitatively. First, the level of the modulation side-lobes was considerably higher (20 or even up to 50 dB). Second, in most cases, the modulation spectrum contained significant amount of higher side-lobes at frequencies $f \pm nF$, sometimes with numbers n up to 10..15. An example of such a rich spectrum is shown in Fig. 3. The level of the LF vibration was even significantly lower compared to the case shown in Fig.2.

It is interesting to note that sometimes the level of the 2-nd and 3-rd order side-lobes was even higher

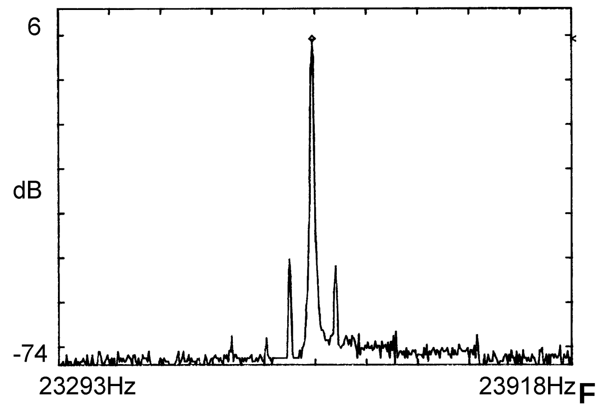

Fig.2. Modulation spectrum for the reference sample.

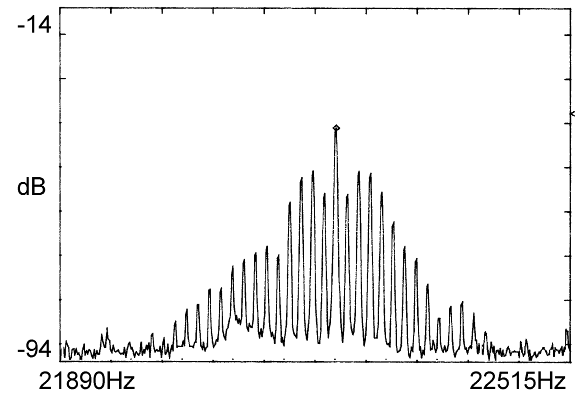

Fig.3. Example of a very rich spectrum with strong higher-order side-lobes in the damaged sample.

compared to the 1-st order ones. The spectral features varied significantly with change of the HF, but the level of the side-lobes always was at least by 10..15 times higher than in the reference sample. At some frequencies the modulation was extremely strong, so that the central (fundamental) spectral line was by several dB lower than the side-lobes. However, in all cases the nonlinear response of the damaged sample was drastically different from that of the undamaged reference plate.

At some frequencies the change of the amplitude was rather significant not only for the spectral side-lobes, but for the fundamental harmonic also. It is interesting to note that mostly it was the decrease, but in some cases increase was also observed. We shall return to such phenomena in the discussion in the following section.

Finally, besides the time-averaged spectral parameters, the set-up allowed for direct observation of the temporal dependence of the HF signal level at different phases of the LF vibration. An example of such a time-record made by a 2-channel digital oscilloscope is shown in Fig.4.

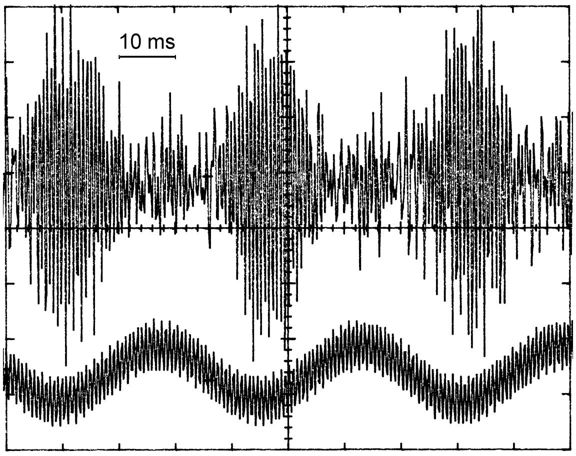

Fig.4. Temporal record of the vibration in the damaged sample at a strong modulation. The lower record is the excited superposition of the LF and HF signals measured by accelerometer 7. The upper record is the modulated HF signal received by accelerometer 8 (the LF signal is filtered out).

The lower record corresponds to the "input" signal of accelerometer 7 where both the LF and the HF signals are present. The upper record shows the output of accelerometer 8, but the LF signal component is filtered-out by a high-pass filter. There is a strong modulation of the HF output signal. In the spectral representation, such a modulation corresponded to the occurrence of strong multiple side-lobes as shown in Fig. 3.

Summarising the experimental data, it may be concluded that introduction of a weak damage (a small fatigue crack) caused drastic increase in nonlinear vibro-acoustic response of the damaged sample. Those effects allow for easy distinction between the damaged and the intact reference sample. In the next section in order to reveal the mechanism of the modulation, we shall discuss in more detail the main features of the observed phenomena.

Are elastic and hysteretic nonlinearities sufficient to explain the observed modulation?

The answer to this question is not evident since, in principle, pure elastic nonlinearity of contacts between the crack edges may cause both phase and amplitude modulation of a wave transmitting through the crack. Such a problem was analyzed, for example, in [7]. It was mentioned that for small deformation of a crack under the influence of the LF vibration, one may use the Tailor expansion of the effective relation between the stress applied to the crack and its strain. Then, the main (first) nonlinear term in the "stress-strain" relation should be quadratic in the deformation. However, this term is not sufficient to explain the occurrence of numerous intensive side-lobes $f \pm nF$ in the modulation spectrum due to the interaction of initial excitations with frequencies F and f. One may argue that those components could be attributed to the existence of initial LF spectral components nF (n=2,3…) which are transformed to higher frequencies $f \pm nF$ due to the quadratic nonlinearity. Indeed, several higher components nF occurred in the initial spectrum of the LF excitation, but their initial level was too small to explain the very high level of the side-lobes (like in Fig. 3). The same discrepancy was observed in the experiments [17] on vibro-acoustic cross modulation due to a crack-like defect for torsional HF and logitudinal LF waves in a rod-sample.

To estimate the maximal elastic influence of a crack in the considered case, one may use the following approach. For this purpose it is enough to compare the extreme cases when the crack is totally closed and totally opened under the LF action. The plate for such an estimate could be considered as a quasi-one-dimensional structure along its longer axis. Thus the conventional perturbation procedure yields for the shift of the resonance frequencies:

$$\frac{\delta\omega_n}{\omega_n} = \frac{1}{2}\frac{\int_0^L \frac{\delta E(x)}{E_0}\varphi_n^2(x)dx}{\int_0^L \varphi_n^2(x)dx} \qquad (1)$$

where the normal modes for free ends of the plate are given by

$$\varphi_n(x) = \sin(\pi n x / L), \qquad (2)$$

and the perturbation $\delta E(x)$ of the effective stiffness of the plate may be approximated in the following simple form:

$$\delta E(x) = \begin{cases} -\Delta E, & \text{at} \quad x \in [x_0, x_0 + l] \\ 0, & \text{at} \quad x \notin [x_0, x_0 + l] \end{cases} \qquad (3)$$

here x_0 is the crack position, and l corresponds to its thickness. The value of the decrease ΔE is easily related to the defect geometry. As the crack cuts the whole thickness of the plate, the maximal value of the decrease of the axial stiffness is determined by the the lengh h of the crack:

$$\Delta E / E_0 \approx h / H, \qquad (4)$$

where H is the plate width. For quantitative estimation of the maximal possible influence of the crack, it is enough to take into account that $\sin^2(\pi n x_0 / L) \le 1$. The crack thickness l in the experiment was not larger than 0.1mm, thus for the plate axial length $L \approx 130\text{mm}$, we obtain that the ratio $l / L \le 7.7 \cdot 10^{-4}$. Further, taking into account the crack length $h \le 5\text{mm}$ and the plate width $H \approx 50\text{mm}$, equation (1) yields that the ratio $\Delta E / E_0 \approx h / H \le 10^{-1}$. Then one obtains for the maximal expected shift of the resonant frequency:

$$\left|\delta\omega_n / \omega_n\right| = \left|\delta f_n / f_n\right| \le 7.7 \cdot 10^{-5}, \qquad (5)$$

where $f_n = \omega_n / (2\pi)$. When the experimental frequency value f_n is about 20 kHz, this corresponds to the maximal possible shift of normal mode frequencies by about 0.5…1 Hz. Typical width Δf_n of the resonance peaks in the experiment was about 150…200Hz (which corresponded to the quality factor $Q = \Delta f_n / f_n = 100...150$). Therefore, in order to explain the observed strong modulation effects by a shift of the resonance frequency, the resonance shift δf_n, should be comparable with the width Δf_n of the resonances ($\delta f_n \approx 10..100 Hz$), which is almost by 2 orders of magnitude higher than the maximal estimate (5). It can be readily shown that the same estimate (1) is valid either for the HF longitudinal or bending waves in the plate.

The above mentioned qualitative features of the modulation and the quantitative discrepancies between the estimates and the measurements lead to the conclusion that the observed effects could not be explained by purely elastic nonlinear effects. On the other hand, the character of the dependencies of the amplitudes of the modulation-sidelobes on the amplitudes of the intensive LF and the HF excitations (details of these measurements may be found in paper [18]) indicated that they can not be attributed to hysteretical losses of the HF probe signal.

Instead, the onset of the experimental data could be readily explained if we admit that the observed modulation was caused by some nonlinear mechanism of the LF vibration influence upon the losses of the HF frequency wave. It seems probable that the strong LF vibration changes the magnitude of linear thermoelastic losses of the HF wave in the crack's vicinity. 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 not determined 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 (see [20]). 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. This is a well known effect, for example, for cracked glass. 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. Then, for the HF signal, the total decrement θ (that is conventionally defined as a value inversely proportional to the quality factor $Q = \pi / \theta$) can be written in the form: $\theta = \theta_l + \theta_n$. Here θ_l corresponds to linear losses when the amplitude of the LF action tends to zero and $\theta_n = \theta_n(A_{LF})$ corresponds to the change of the decrement due to the influence of the LF vibrations. Main features of the dependence $\theta_n(A_{LF})$ can be revealed by investigating the modulation at a given HF excitation level and different LF vibration amplitudes. At lower LF vibration amplitudes, there was no noticeable decrease of the fundamental HF harmonic, though the 1-st order modulation side-lobes were already quite explicit. With increase of the LF vibration amplitude, higher-order side-lobes also appeared and the decrease of the central HF spectral line became clear. These measurements allowed us to estimate the period-averaged functional amplitude behaviour of $< \theta_n(A_{LF}) >$. Typical magnitudes of the nonlinear decrement were estimated by comparison with the initial linear decrements, which were determined via the widths of the HF resonances. For example, the HF resonance peak width $\Delta f \approx 200 Hz$ at -3dB level gave for the resonance Q-factor the estimate $Q = \Delta f / f \approx 100$ at zero LF amplitude, whereas at the highest applied LF amplitude, the HF signal amplitude decreased up to 30%, which corresponded to the decrease of the Q-factor to approximately $Q \approx 75$.

In addition to the spectral (time-averaged) measurements, we took into account the direct temporal observation of the amplitude modulation of the HF signal, as presented, for example, in Fig. 4. The figure shows that there was significant difference in the amplitude of the HF signal at different half-periods of the LF action. The latter fact indicates that the transversal structure of the crack was essentially asymmetrical. Indeed in case of a symmetrical crack structure there should not be such a difference between bending of the plate at positive and negative angles. If the crack were symmetrical, only even modulation harmonics $f \pm 2F, f \pm 4F, \ldots$ should be observed. In reality, at low excitation, mainly the first modulation harmonics $f \pm F$ were noticeable instead of $f \pm 2F$.

In order to explain those spectral and temporal properties one should admit that at lower amplitudes, the nonlinear additive θ_{nl} is almost an anti-symmetrical function and it is almost linear in the LF deformation: $\theta_n(A_{LF}) \propto A_{LF}$. Such a law looks rather natural as the first term of the expansion of $\theta_n(A_{LF})$ into the Tailor series at $A_{LF} \to 0$; see, for example, Fig.5. In this figure, the solid line shows the above mentioned features of the nonlinear variation of the HF losses: almost linear dependence at lower amplitudes, the asymmetry and the trend to saturation at higher amplitudes. For numerical simulation, it is convenient to approximate such a dependence by a piecewise linear function (the dashed line in the figure).

Resonance effects and numerical simulation

Resonant effects are also essential for the comprehension of the experimental results. As the modulation frequency (in most cases about 15-30 Hz) was by an order of magnitude smaller than the width of the resonance peaks, it is possible to consider the influence of the LF vibration as a quasi-static action. Then, in the maximum of a resonance peak, it is possible to estimate the HF sample response $A_{HF}(t)$ (and than to obtain the modulation spectrum) by simple multiplication of the HF sinusoidal input signal and the Q- factor which is influenced by the LF vibration:

$$A_{HF} \propto \sin(2\pi f \cdot t) \cdot Q(t) = \frac{\pi \cdot \sin(2\pi f \cdot t)}{\theta_l + \theta_{nl}\left(A_{LF}^0 \sin(2\pi F \cdot t)\right)}, \quad (9)$$

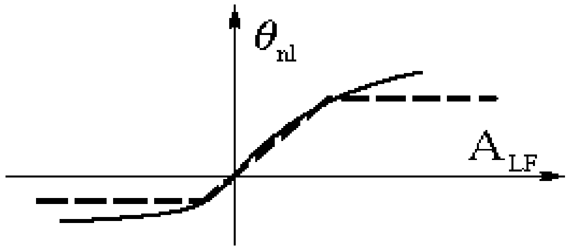

Fig.5. Schematically shown amplitude dependence of the nonlinear losses (the solid curve) and its approximation by a piece-wise function (the dashed curve).

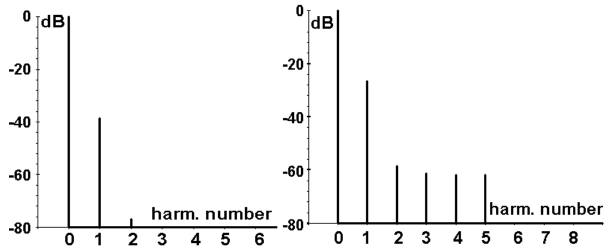

Fig.6. Example of the simulation of the modulation spectra at lower (left) and higher (right) LF vibration amplitudes.

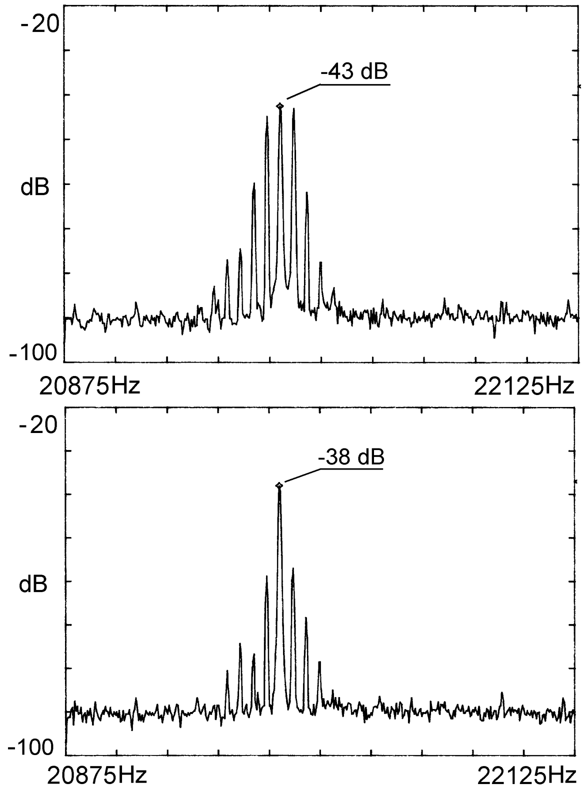

Fig. 7. The modulation spectrum for the damaged sample before (upper record) and after (lower record) the introduction of additional losses by sticking the rubber strips.

For the numerical simulation it is convenient to use the piecewise linear approximation of $\theta_{nl}(A_{LF})$ as shown in Fig.5 Examples of the calculations are presented in Fig.6.

In the figure, for lower LF vibration amplitudes, only the first side-lobes are noticeably present (left plot in Fig. 6), and at higher level, multiple $f \pm nF$ side-lobes pronouncedly appear (right plot in Fig. 6).

In addition to the resonance case, another convenient possibility to observe the modulation is the use of narrow anti-resonances. For a deep enough anti-resonance, the fundamental harmonic tuned to the anti-resonance frequency can be suppressed while the side-lobes could become even higher. Such a case was shown in Fig. 3 and was obtained just at one of the sample anti-resonances. Unlike a resonance, in an anti-resonance, additional losses can cause increase of the amplitude at the fundamental frequency instead of decrease.

The above mentioned features of the anti-resonance case gave a possibility to verify the conclusion on the decisive role of the dissipation factor by carrying out the following instructive experiment. First, the HF excitation was tuned to an anti-resonance of the damaged plate, and a strong modulation spectrum (see Fig.7a) was obtained. Then several light and soft porous rubber strips were stuck to the plate surface to introduce additional HF losses with minimal perturbation of the sample mass and stiffness. As a result, the sample Q-factor decreased almost twice and the relative level of the modulation side-lobes decreased by about 20dB, which should not happen if the nonlinear elasticity were responsible for the modulation. Besides the decrease of the modulation side-lobes, the introduction of additional losses caused increase in the amplitude of the fundamental harmonic (approximately by 5 dB), which was expected for the anti-resonance case (see Fig.7b).

Thus the variety of the observed dependencies and the modulation features was self-consistently explained by the suggested nonlinear-dissipative mechanism.

3. Modulation experiments with metallic rod-resonator samples made of metals with pronounced polycrystalline structure.

In these experiments, resonant longitudinal vibrations at lower modes were excited in rod resonators with one free and the other rigidly fixed boundary. The rods were cut of annealed copper which possessed a pronounced polycrystalline structure. Typical photo of the metal grainy microstructure is shown in Fig. 8.

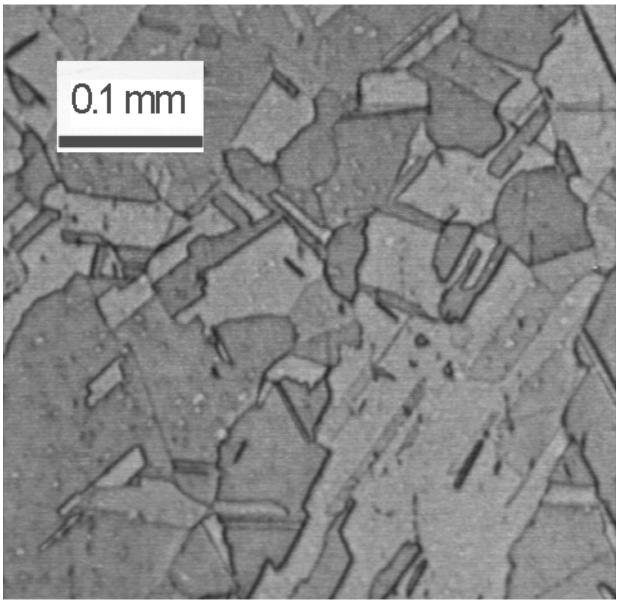

Fig. 8. Example of the material microstructure.

Presence of the inter-grain defects changed significantly the onset of material acoustic parameters, including, linear absorption/dispersion, nonlinear elasticity, hysteretical properties and nonlinear dissipation of a non-hysteretical type. Detailed discussions of the mechanisms of the microstructure influence on the above mentioned properties may be found in other publications by the authors [18]. In fact, in the above sections we considered the manifestation of the same mechanism [18] in case of a single defect in the sample. The powerful action (which is also called "pump" by analogy with nonlinear optic effects) was a LF vibration which influenced instantaneous losses for the other probe weak HF signal, thus producing the modulation of this probe wave. For the present discussion of the nonlinear-modulation effects it is essential that the stronger excitation may vary not only instantaneous magnitudes of the material parameters (like in the above described modulation experiments), but also produce period averaged variation. This period-averaged effect is determined by the odd-in-strain part of the defect's nonlinearity, which is typical for such defects as Hertz contacts, micro-cracks, etc. Such a period-averaged action may be produced by a powerful pump action with a frequency comparable with the frequency of the probe signal. The pump frequency may be even higher than that of the probe wave in contracts to the LF pump used in the previous

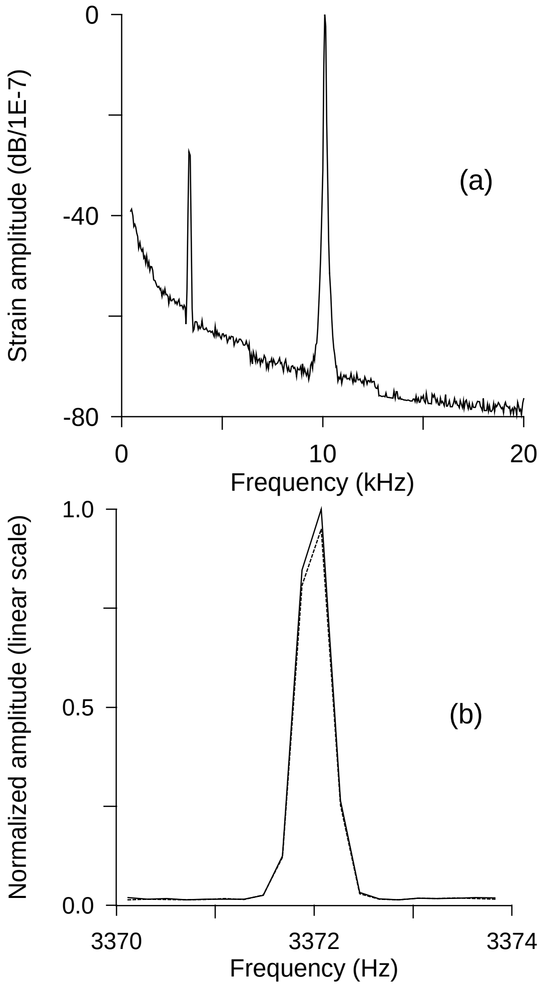

Fig.9 Supression of the probe wave under the action of the pump wave due to the dissipative nonlinearity of the material.

(a) the spectrum at the bi-harmonical excitation, the probe LF signal tuned to the 1-resonance, and the HF pump tuned to the 2-nd resonance at 3-times higher frequency;

(b) spectral zoom for the LF probe wave without the HF pump (the solid line) and in the presence of the HF pump (the dashed line).

sections. For example, a stronger resonant excitation in a rod may increase the dissipation in the material, thus causing decrease in amplitude of another weak probe resonant wave. This effect is really observed in such microinhomogeneous materials even at rather moderate pump-wave-strain about 10^{-7} (see example presented in Fig. 9).

It should be stressed that the decrease in the probe wave amplitude shown in Fig.9b is not caused by the nonlinear variation in the resonance frequency for the probe wave, but is due to the nonlinear variation in the dissipation. The influence of the resonance shift was excluded, since we intentionally used rather low level of the pump, whereas the probe wave was tuned to the very maximum of the resonance where the tangent of the

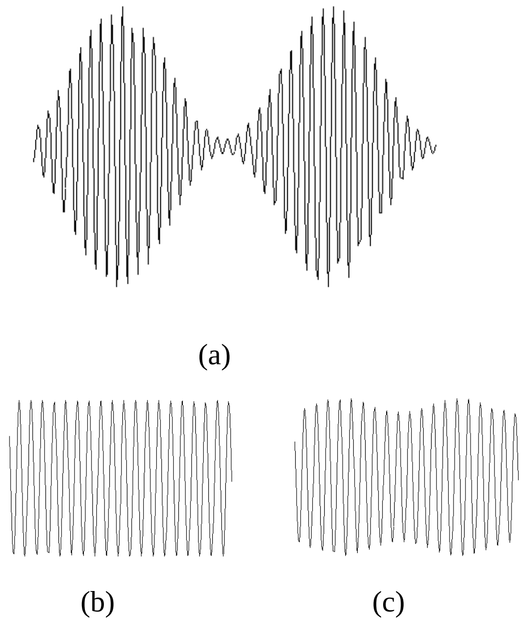

Fig. 10. Schematically shown principle of the method: (a) - the strong (pump) modulated wave; (b) - the excitation signal for the weak probe wave; (c) - appearance of the probe-wave modulation due to the material nonlinearity.

resonance curve has zero slope (see detailed discussions of the experimental conditions in reference [19]).

This method of observation of the nonlinear interaction, however, has only an academic interest, since it requires too many experimental precautions. We suggested another, practically more convenient possibility, namely, to observe the nonlinearity-produced modulation of the probe signal using a *modulated* pump wave with a relatively HF carrier frequency. The method is schematically shown in Fig.10. In this case, due to the dependence of the time-averaged material absorption on the amplitude of the modulated the pump wave, the probe wave should also acquire a modulation. The carrier frequencies of both waves in such a modulation method may be comparable, and the carrier frequency of the pump may be even higher than the probe-wave frequency.

The corresponding example for the same frequencies and amplitudes of the probe and the pump waves as in Fig.9a, but with additional sinusoidal 100% amplitude modulation of the pump wave at frequency 4 Hz , is shown in Fig.11a. The modulation side-lobes of the probe wave are clearly seen even though we intentionally used a rather weak pump level, which proves high sensitivity of the effect. The level of the sidelobes is about $-28\pm 1dB$ (that is about 4% of the central line

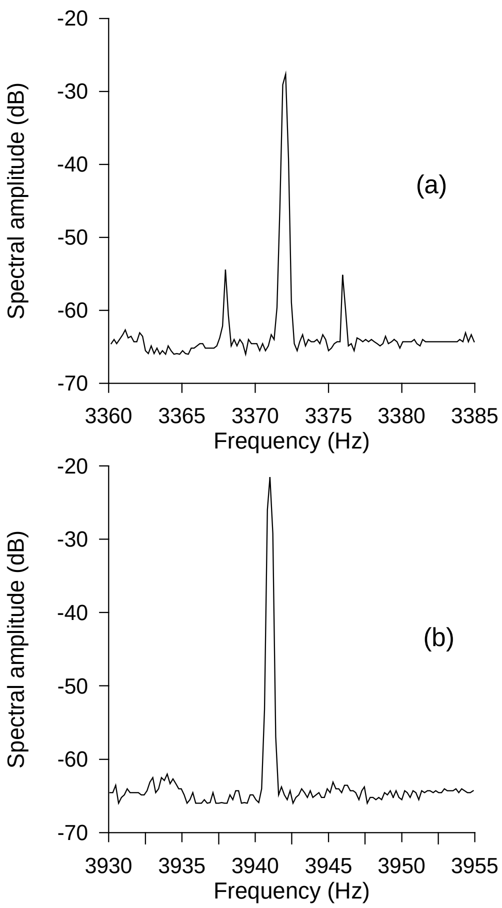

Fig. 10. An example of the modulation spectrum obtained in the microinhomogeneous copper rod (a) and the similar spectrum without signs of modulation obtained at similar conditions in the reference homogeneous rod made of glass (b).

amplitude), and agree well with the magnitude of the static decrease in the probe wave amplitude shown in Fig.9b. For comparison, another spectrum obtained for a reference rod made of glass (a homogeneous material with weak atomic nonlinearity) is presented in Fig.11b and displays no sign of such a modulation.

In the appearance this effect is similar to the modulation method discussed in the first part of the report and based on the direct use of a LF pump action. However, often the excitation of a relatively intensive vibration at such a low frequency is a difficult technical problem, so the use of the suggested method based on the modulated high frequency pump wave can be more advantageous in diagnostical applications. The effect of the amplitude-dependent attenuation does not require spatial synchronism and can be observed both for co-propagating and counter-propagating waves. When the interaction length is large enough, the resultant amplitude modulation can be rather strong even at small variation in the decrement, which seems to be very promising for practical nonlinear methods of acoustic and seismic diagnostics.

4. Conclusion

Experimental results presented in the paper are an interesting example of a rather strong nonlinear vibro-acoustic interaction. The obtained data showed that such nonlinear effects could be effectively used for detection of even small crack-like defects in a metal sample. The performed estimates proved that the influence of the crack upon the change of the sample linear stiffness (and, therefore, upon conventionally measured resonance frequencies) was negligibly small and could be hardly detected by conventional linear methods.

The observed onset of properties of the nonlinear modulation effects could be self-consistently explained by the influence of the LF vibration upon thermal viscous-like losses of the weak HF oscillations due to deformation of the contacting crack edges. Certainly this dissipative mechanism is not the unique one, and at different conditions, other mechanisms (that is conventional elastic or hysteretic nonlinear effects) may be also important. 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. Therefore the use of nonlinear effects associated with the modulation of the dissipation might be a very effective tool for crack diagnostics. 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.

Note finally, that the described study was aimed primarily at revealing the mechanism of the nonlinear response of a small amount of crack-like defects in a solid, while the important question about the damage location was omitted. In principle, a combination of a time-gating procedure (which is conventional for linear ultrasonic NDT) with the observation of nonlinearity-induced signal components can be suggested to provide spatial resolution in nonlinear diagnostics. Such a principle was discussed, for example, in paper [7]. However, simple time-gating can eliminate resonance effects, the use of which is very advantageous for high sensitivity of crack detection. Alternatively, in order to provide spatial resolution by mean of local excitation of a defect, resonance vibration modes with different shapes can be used. Therefore, it is difficult to suggest a universal solution, and particular cases of sample geometry and defect type require special consideration.

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