CHALLENGE OF ULTRASONIC SELF-INDUSED HYSTERESIS PHENOMENON IN DAMAGED MATERIALS

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Abstract

A new phenomenon of self-induced hysteresis has been observed in the interaction of bulk acoustic waves with a cracked solid. It consists in a hysteretic behaviour of material nonlinearity as a function of the incident pump wave amplitude. Hysteresis manifests itself in the self-action of the monochromatic pump wave, in the excitation of its superharmonics and of its subharmonics. The proposed theoretical models attribute the phenomenon to hysteresis in transition of the acoustically forced oscillation of cracks from a non-clapping regime to a regime of clapping contacts.

Experimental observation of self-induced hysteretic behaviour for the bulk sinusoidal acoustic wave interacting with a system of cracks inside a glass plate is reported. Neither hysteresis in harmonics excitation nor self-induced hysteresis can be attributed in our system to parametric nonlinear phenomena. We interpret the phenomena as a hysteresis of an additional mechanism of nonlinearity due to clapping contacts between crack lips. This mechanism "turns-on" and "turns-off" at different amplitudes of the pump wave.

Hysteretic behaviour of the amplitude of harmonics related to the presence of cracks in tested material presents an interesting opportunity for a new approach in Non-Destructive Evaluation of damaged materials.

Introduction

Hysteresis in elastic behaviour of materials is a well-known (but in many cases much less understood) physical phenomenon. Similarly to the studies in ferromagnetic systems [1] efficient phenomenologies have been already proposed [2, 3] for some hysteretic phenomena observed at macroscopic level, but an adequate microscopic theory is yet to be developed. The hysteresis of macroscopic stress/strain relationship in such materials as rocks, microcrystalline metals and ceramics, for example, might be attributed [3] to hysteresis of unspecified nature in mechanical behaviour of mesoscopic structural two-level elements. In accordance with theory [2, 3] the mesoscopic mechanical elements contribute to hysteresis of material nonlinearity. Because of this (in order to identify the mesoscopic elements) it is tempting to investigate the nonlinearity of material stress/strain relationship by methods of nonlinear acoustics [3, 4].

The studies of mechanical systems, which might be considered as prototypes of the individual hysteretic elements, constitute the opposite extreme limit of research activities in nonlinearity hysteresis. Using atomic force microscope (AFM) and friction force microscope hysteresis in tip/surface interaction and sliding friction can be evaluated on nanoscale (see, for example, [5] and the references therein). However there is still a significant gap between our understanding of hysteresis of artificial contacts and those of a crack imbedded in a solid matrix.

Experimental results and Discussion

We report experimental observation of self-induced hysteretic behaviour for the bulk sinusoidal acoustic wave interacting with a system of cracks inside a glass plate. Besides the effect of the self-induced hysteresis in the pump wave amplitude (at frequency ω), which have not been reported before, our observations differ from those reported earlier [6] (effects were attributed [6] to stochastic motion of cracks parametrically driven by acoustic wave) in the following important aspect. We observed, for the fixed frequency of the pump wave in a given (unmodified) experimental configuration, different thresholds for the hysteresis of superharmonics (2ω, 3ω, …) excitation and for the hysteresis of subharmonic (ω / 2) excitation (Fig. 1(a)). The threshold for superharmonics excitation was significantly lower. Consequently, neither hysteresis in harmonics excitation nor self-induced hysteresis can be attributed in our system to parametric nonlinear phenomena. We interpret the phenomena as a hysteresis of an additional mechanism of nonlinearity due to clapping contacts between crack lips. This mechanism "turns-on" and "turns-off" at different amplitudes of the pump wave. The nonlinear oscillations of contacts in our model are forced but not parametric.

The experimental study was carried out on a set of glass plates with a different quantity of cracks produced through a thermal shock. Figure 1 illustrates the hysteresis phenomena in the acoustic spectra of two different plates representing two principal cases of in-phase and of out-of-phase observation. The effect of the hysteresis has not been observed in the samples without cracks even at the highest available level of the excitation. The set-up consisted of two piezoelectric wide-band transducers firmly attached onto the opposite edges of a rectangular sample plate (230x190x18 mm). The transmitter was driven by a harmonic 111 kHz wave of 150 V p-p amplitude. The signal induced in the receiver from acoustically

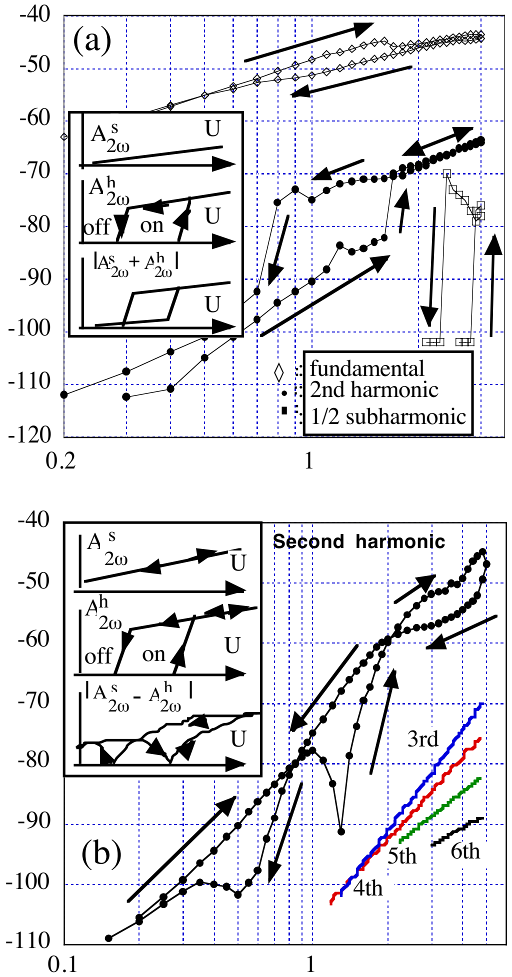

Figure 1 : Harmonics hysteresis loops obtained with intense ultrasonic pump observed in two different samples. Vertical axis: Spectral amplitude (in dB); Horizontal axis: External driving voltage (in arbitrary units, 1 a.u. = 30 Volts p-p). Inserts: $A^{s}_{2\omega}$ and $A^{h}_{2\omega}$ denote the amplitude of smoothly varying second harmonic signal, that would occur without contribution from the activated crack, and of the hysteretic part due to nonlinear mode of crack vibration, respectively; the axes are in proportion to those in the basic figure. Fig. 1 a) and Fig. 1 b) are obtained in the case of in-phase, and out-of-phase superposition of the signals, respectively.

excited cracks together with the transmitted pump wave was Fourier transformed by a vector signal analyzer (HP 89410A) having a full 100 dB dynamic range within 20 MHz bandwidth. Due to significant damage of the sample the absorption length at fundamental frequency (estimated from the additional pulsed-echo experiments) did not exceed the dimensions of the sample and the resonance phenomenon did not contribute to our observations.

Oscillation mode of each individual crack depends on the local distribution of the acoustical field. Thus the transition from linear to nonlinear mode of oscillation happens first for a single crack. In nonlinear mode the crack provides additional localized sources of superharmonics and modifies the acoustic field at fundamental frequency. The localized character of these sources is of great importance because the signal from the "activated" crack arrives to the point of observation with a phase shift depending on the relative position of the observation point and the crack. It is also important that the cracks in different positions are driven by the different superposition of the directly incident acoustic waves and the waves scattered from the boundaries and other cracks. The second harmonic curves in Fig. 1 (a) and (b) correspond to two different plates where the signal from the crack oscillating in nonlinear mode arrives to the receiver in-phase and out-of-phase with the pump wave, respectively. Pronounced hysteresis is seen both on the second harmonic curve and on the fundamental one. The inserts provide qualitative explanation of observed shapes for the second harmonic dependence on the pump amplitude in two limiting cases of the phase shift.

Hysteresis phenomena has been observed on all recorded superharmonics, up to 9ω, as well as on subharmonics, $\omega/2$. Analysis of these data provides two trends. Firstly the hysteresis threshold on the superharmonics is systematically much lower than the pump level for appearance of subharmonics, which is illustrated by the $\omega/2$ curve in Fig. 1 (a). Secondly the threshold in hysteresis phenomena on ω and 2ω is accompanied by a very efficient generation of a large number of superharmonics. This fact is illustrated in Fig. 1 (b) by four straight lines emerging from the narrow zone of the graph corresponding to the "jump-up" of the 2ω hysteresis loop. Here the experimental points for the 3rd, 4th, 5th and 6th harmonics are approximated for clarity by a linear function, thus the hysteresis loops are not seen on them.

The qualitative scenario of the observed phenomena is based also on the results of the calibration experiment. By optically measuring the vibration amplitudes at the surface of the plates, it was estimated that strain amplitudes in our experiments never exceeded 10^{-5}. This strain is too small to completely close the crack when the maximum crack length does not exceed few centimetres (as it is in our samples). Because of this we currently attribute the observed phenomenon to the hysteresis turn-on and turn-off in clapping of some intermittent contacts between crack lips. The distance between the opposite asperities at crack lips can be much smaller than the average crack opening. It is well documented in literature that nonlinearity accompanying contacts clapping is significantly higher than the elastic nonlinearity of homogeneous materials [7, 8] and is even higher than the nonlinearity of non-clapping Hertzian contacts [8, 9]. In AFM the distortion of the basic sinusoidal motion of the cantilever due to the tip hitting the sample was observed [10]. From the physics point of view this is due to very abrupt changes in the motion of clapping contacts during the impact.

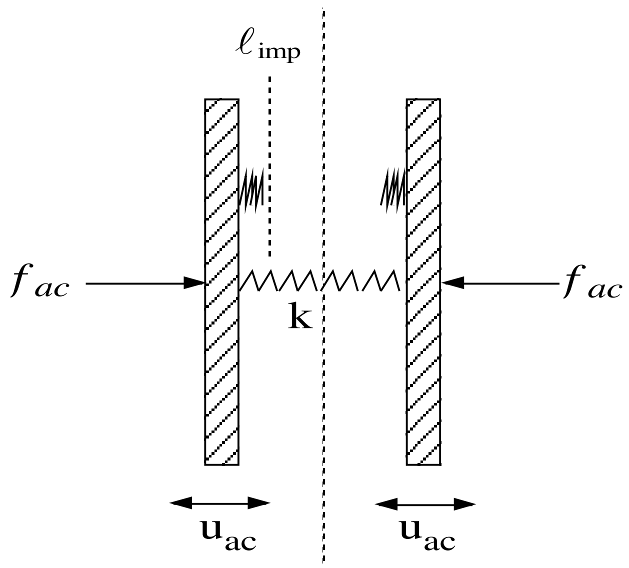

Figure 2 : Lumped element model for the clapping contacts between crack lips.

To gain a further insight in the physical nature of the observed phenomenon we model the local place of possible clapping as an oscillator imbedded in the elastic solid matrix (Fig. 2). In this lumped element model the effective masses of the interacting asperities are separated by the local crack opening width. The spring stiffness k models the rigidity of the crack (which is much less than the rigidity of the elastic matrix), u denotes the local mechanical displacement of the crack surface. The regime of the interaction between the acoustic field and the crack depends on the ratio of the acoustic wavelength λ to the characteristic crack length L.

In the case (λ / L) << 1, the acoustic field action can be modelled by local sinusoidal forces applied to the interacting asperities. Only the part of these forces, which is symmetric relative to the plane x = 0 and which may cause clapping of the contacts, is presented in Fig. 2. In the limiting case (λ / L) << 1 our model is mathematically equivalent to that of a forced impact oscillator (see [11-15] and the references therein). Our problem has also evident similarity to the phenomena occurring with a ball bouncing on a vibrating table [15, 16]. Fortunately the theory of impact oscillations is sufficiently developed to be useful for the interpretation of our experimental observations. Both the simplest model using an instantaneous impact rule [13] and a more realistic model [14] of the impact process, the Hertz contact law, demonstrate that sinusoidal non-impacting oscillation becomes unstable (with increasing force amplitude) when the oscillating masses contact for the first time. The numerical solution [14] demonstrates that subsequent increase of the force may cause restabilisation of the oscillator onto one impact motion with the same period (period one) but nonsinusoidal (nonlinear). If the amplitude of the acoustic pump wave later diminishes, the system exhibits hysteresis in returning to non-impacting period-one oscillation. The existence of a hysteretic zone where (depending on the excitation procedure) nonlinear impacting or linear non-impacting motion occurs is confirmed by experiments [17]. The described scenario provides a possible explanation for the clapping onset in our experiments, which takes place at higher acoustic amplitudes than those necessary to stop clapping. As clapping provides the additional strong mechanism of acoustic nonlinearity [7-10], this scenario explains both the threshold increase in superharmonics excitation and the observed hysteresis in superharmonic amplitudes. The hysteresis at fundamental frequency (self-induced hysteresis) may be due to hysteresis in the amplitude of contact vibration at fundamental frequency and/or due to hysteresis in fundamental wave energy losses for superharmonics excitation and intermittent contact heating (pump depletion).

If the amplitude of the acoustic pump wave continues to increase (after the clapping threshold) then at some higher excitation the transition evolves first to a period-two and then to a period-four solution, as numerically predicted [14]. This is the beginning of a period doubling cascade. It is important to note that theoretically, the hysteresis in returning from period-two (subharmonic) to period-one oscillations may take place [12]. Recently the hysteresis in subharmonic excitation was reported for a nanoscale contact [15]. The above-described scenario provides a possible physical explanation for the behaviour of the subharmonic (ω / 2) signal in our experiment (Fig. 1).

In the forced impact systems the chaotic oscillations are possible theoretically [12, 18, 19] and are observed experimentally [19]. Thus a scenario of parametric excitation hypothesized in [6] is not the only possible route to chaos in crack oscillations. The acoustic turbulence in the interaction of high-power sound with liquids was attributed to forced (and not to parametric) excitation of gas bubbles [20]. In our experiments with cracked glass the threshold conditions for chaotic vibrations have not been achieved.

In the opposite limiting case of the acoustically small crack $(\lambda / L) >> 1$ the scenario of forced motion of the crack explains observed hysteresis phenomenon as well. In this regime the crack lips oscillation precisely follows the displacement in the acoustic field (in Fig. 2 force f_{ac} can be omitted while $u = u_{ac}$). The nonlinear interaction between the crack lips in this regime causes the variation in the local crack opening depending on the amplitude of the acoustic wave. This regime of the interaction of sound with crack resembles the ultrasonic force mode in operation of AFM [21]. The clapping acts as mechanical diode, demodulating the vibrations of crack lips. The process of this type was also observed in sound reflection from solid-solid interface [8].

The authors have developped further the proposed model in order to get a solution in a compact form. The model is described in details in Moussatov et al. [22]. The behaviour predicted theoretically qualitatively reproduces observed hysteresis.

In conclusion, our experimental results and qualitative models indicate prospects for future applications of nonlinear acoustic methods in non-destructive characterization of material damage. Acoustic monitoring of cracks is an important motivation for future research. The development of a quantitative theory for crack probing by strong acoustic waves is challenging.

References

[1]. G. Bertotti, Hysteresis and Magnetism (Academic Press, New York, 1998); F. Pazmandi, G. Zarand, G. T. Zimanyi, Phys. Rev. Lett. 83, 1034 (1999).
[2]. D. J. Holcomb, J. Geophys. Res. 86 (B7), 6235 (1981).
[3]. R. A. Guyer, K. R. McCall, G. N. Boitnott, Phys. Rev. Lett. 74, 3491 (1995); R. A. Guyer, P. A. Johnson, Physics Today, 30 (April 1999).
[4]. V. E. Nazarov et al., Phys. Earth Planet. Interiors 50, 65 (1988); P. B. Nagy, Ultrasonics 36, 375 (1998); D. J. Barnard et al., J. Nondestr. Eval. 16, 77 (1997).
[5]. N. A. Burnham, A. J. Kulik, in Handbook of Micro/Nano Tribology, ed. By B. Bhushan (CRC Press, Boca Raton, 1999); E. Grecco et al., Phys. Rev. Lett. 84, 1172 (2000).
[6]. I. Yu. Solodov, B. A. Korshak, Phys. Rev. Lett. 88, 014303 (2002).
[7]. O. Buck, W. L. Morris, J. M. Richardson, Appl. Phys. Lett. 33, 371-373 (1978); J. M. Richardson, Int. Engng. Sci. 17, 73-85 (1979).
[8]. I. Yu. Solodov, Ultrasonics 36, 383-390 (1998); I. Yu. Solodov, C. A. Vu, Acoust. Phys. 9, 476-479 (1993).
[9]. I. Yu. Belyaeva, V. Yu. Zaitsev, E. M. Timanin, Acoust. Phys. 40, 789-793 (1994); V. Yu. Zaitsev, Acoust. Phys. 41, 385-391 (1995).
[10]. C. A. J. Putman, et al. Appl. Phys. Lett. 64, 2454-256 (1994).
[11]. S. W. Shaw, P. J. Holmes, Phys. Rev. Lett. 51, 89-957 (1983).
[12]. F. Peterka, J. Vacik, J. Sound. Vibr. 154, 95115 (1992).
[13]. S. Foale, Proc. R. Soc. Lond. A 347, 353-364 (1994); A. B. Nordmark, J. Sound Vibr. 145, 279-297 (1991).
[14]. S. Foale, S. R. Bishop, Nonlinear Dynamics 6, 285-299 (1994).
[15]. N. A. Burnham A. J. Kulik, G. Gremaud, G. A. D. Briggs, Phys. Rev. Lett. 74, 5092-5095 (1995).
[16]. A. B. Pippard, The Physics of Vibrations I (Cambridge University Press, Cambridge, 1978); J. Guckenheimer, P. Holmes, Nonlinear Oscillations, Dynamical Systems, and Bifurcations of Vector Fields (Springer-Verlag, New York, 1986).
[17]. S. R. Bishop, M. G. Thomson, S. Foale, Proc. R. Soc. Lond. A 452, 2579-2592 (1996).
[18]. J. M. T. Thomson, R. Ghaffari, Phys. Lett. 91 A, 5-8 (1982); S. W. Shaw, J. Appl. Mech. 52, 459-464 (1985).
[19]. F. C. Moon, Chaotic Vibrations. An Introduction for Applied Scientists and Engineers (John Wiley & Sons, New York, 1987).
[20]. W. Lauterborn, E. Cramer, Phys. Rev. Lett. 47, 1445-1448 (1981).
[21]. O. Kolosov, K. Yamanaka, Jpn. J. Appl. Phys. 32, L1095-L1098 (1993).
[22]. A. Moussatov, V. Gusev, B. Castagnede, "Self-induced hysteresis for nonlinear acoustic waves in cracked materials", Phys. Rev. Lett., 90, 124301 (2003).