ULTRASONIC DEFECTOSCOPY OF DAMAGED MATERIALS BY MODULATION TRANSFER METHOD : NONLINEAR PUMP-PROBE INTERACTION

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Abstract

In relation to the growing interest to the defectoscopy technique of damaged materials by nonlinear ultrasonic methods, a new approach is described. Based upon increased nonlinearity of the material due to the presence of cracks, strong interaction between independent ultrasonic waves is possible. Modulation transfer is one of the forms of this interaction. In the present work an amplitude-modulated pump wave, at a few Hertz, has been used to induce variations of the main mechanical parameters of the material. These parameters have been tested by a probe wave of smaller amplitude. Thus, the amplitude of the probe wave is influenced by the variation of the material parameters under the action of the pump, synchronously with pump amplitude.

Significant variations have been observed on the tested plates in terms of their Frequency Response Functions with and without pump (no modulation). The correlation between those variations and depth of induced amplitude modulation of the probe has been put in evidence by comparison in the spectral domain of the modulation sidelobes of the probe at different frequencies. Glass plates having limited damage zones were tested within 30-110 kHz.

Introduction

During the last decade a true revival of the nonlinear acoustics in solids has been observed. A new class of solids, the so-called "mesoscopic materials" [1] having macroscopic inhomogeneities, is concerned. Applications dealing with the detection of cracks [2-6], the monitoring of materials fatigue [7], the characterization of materials used in micro-electronics [8], have been recently described.

Recent advances are reported towards the characterization of micro-cracked materials. For instance, it has been proposed [9,10] to use for crack diagnostics the so-called "Luxembourg-Gorky effect", which consists in the transfer of low-frequency modulation from high-amplitude (pump) acoustic wave to low-amplitude initially unmodulated (probe) acoustic wave. However, the classical method to probe material nonlinearity by detecting the excitation of the harmonics (2ω, 3ω, ...) of a fundamental wave at frequency ω [11] is still very useful. Another effective method for crack detection patented more than 25 years ago [12] is based on the mixing of high frequency (ω) acoustic wave with low frequency (Ω) vibration, which leads to the excitation of side lobes at frequency $\omega \pm \Omega$. Generally speaking this is the same physical principle as for the ultrasonic parametric receiving antenna in underwater applications [13].

Innovative frequency conversion method have been proposed [14] for the diagnostics of cracks produced by thermal shock in glass. Efficient frequency mixing in damaged glass has shown that for diagnostics of cracks in solids there exist several ways to realize nonlinear sound waves interactions. One way was based on the principle of parametric antenna. The other possible way consists on implementation of the "Luxembourg-Gorky effect". The present paper provides further results following our previous work [14]. It deals with ultrasonic waves interaction illustrated by nonlinear modulation transfer.

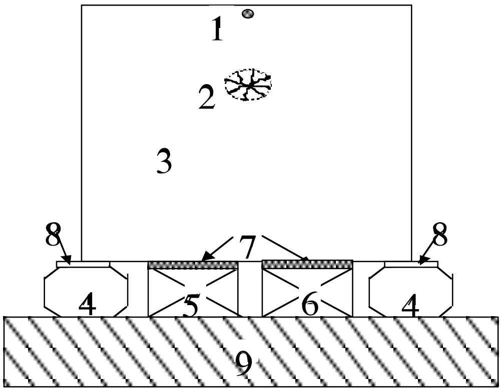


Figure 1 : Experimental set-up

Experimental set-up

The experimental set-up is described on Fig.1. There are two identical wideband piezoelectric ultrasonic transducers (5) and (6) acoustically coupled (7) to the test sample. One is used to produce a pump wave (that can be amplitude modulated by a low frequency wave). The other one emits a pure tone probe wave (that can be swept in frequency within a large band). The reverberated signal within the sample is then probed with a laser vibrometer at a chosen point (1) on the sample surface. The choice of the point is totally arbitrary. Rectangular 230x190x15 mm glass plates have been used for virgin and damaged samples. The plates were damaged through a localized thermal shock. A small zone of 1 cm in diameter and a few mm deep filled with fine cracks (2) was created for each sample (3). The elements (4) are simple mechanical supports for the sample where (9) and (8) are elastic anti-vibration isolators.

The received by the laser vibrometer signal was processed with two regimes and displayed on a vector signal analyzer. The first regime was the Frequency Response Function (FRF) of the sample when the frequency of the probe signal is swept smoothly within a chosen range and the signal amplitude received by the vibrometer is registered versus probe frequency. The other regime was FFT transformation of the received signal within a narrow window around probe signal frequency in order to obtain modulation spectra of the probe.

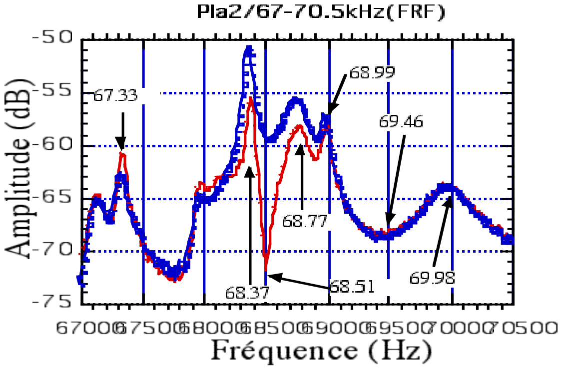
Discussion

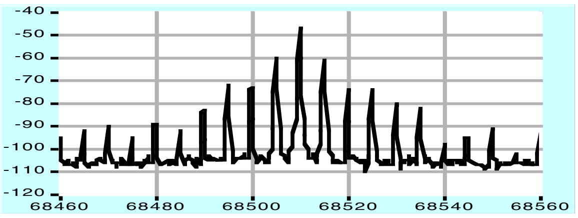
Modulation Transfer in ultrasonic waves interaction

A remarkable interaction between probe and pump signals within the damaged plates is expected as a direct consequence of manifestation of high acoustic nonlinearity of the plates with small damaged zones compared to the virgin one. It is important that the wave interaction begins at relatively weak mechanical strain induced by the ultrasonic pump wave. We estimate the strain from the displacement of the transducer surface (coupled to glass) by means of laser velocimetry. The maximum speed of surface oscillation was $v\ max$ = 25 mm/s at 100 kHz. Consequently, the largest relative strain $\varepsilon\ max$ that we were able to achieve with the used pump transducer at the maximum driving voltage was $\varepsilon\ max = v\ max / Co \approx 4 \times 10^{-6}$ (here Co = 5800 m/s is the sound velocity in glass).

It is demonstrated in the present work that a relatively weak level of ultrasonic excitation (pump) can be sufficient to detect small localized damage by monitoring phenomena due to nonlinear wave interaction. The advantage of proposed configuration is that the interaction has been realized between pump and probe waves both being within ultrasonic range. The authors suggest an alternative way of test sample excitation to the one used for instance in [1], i.e. with an ultrasonic pump wave. This way the well-known problems related to ambient low frequency noise and undesirable vibrations can be avoided.

How does the interaction between two ultrasonic waves happen in nonlinear media (damaged object)? In a few words, the pump wave, which is much stronger than probe, modifies major static mechanical parameters of material of the test object. The probe wave "feels" those parameter variations. It results in noticeable changes in probe wave amplitude (as well as in its phase). If one makes pump amplitude going slowly up and down the parameters values follow the pump simultaneously. Consequently, amplitude of the probe wave also goes up and down following the parameters variations. This way the interaction between two ultrasonic waves is produced. Amplitude modulation of the pump wave is thus transferred onto the probe wave. Of course, in the case of linear media (undamaged object) the same pump wave causes no variation to material mechanical properties (averaged over pump ultrasonic period) and no wave interaction occurs.





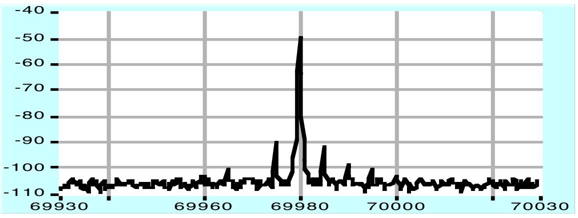


Fig.2 : FRF, Fig.3,4 : probe modulation spectra

Frequency Response Function analysis

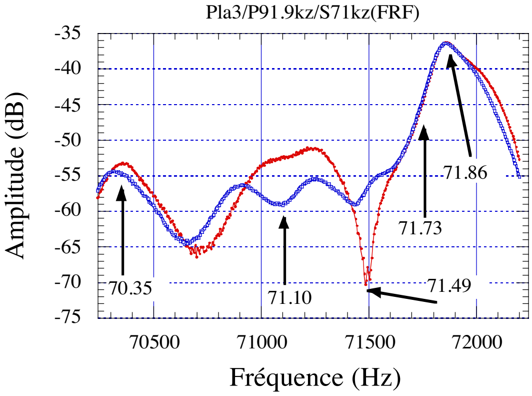
Let us illustrate the above point by analyzing the Frequency Response Function (FRF) of the plate with cracks. FRF curve shows up all plate resonances caused by the probe wave. It is a mechanical signature of the object. Fig.2 represent two superposed FRF of the same plate in the same frequency window from 67 kHz to 70,5 kHz. One curve is registered when the pump transducer was switched off. The other curve is obtained with the pump transducer exciting constantly the plate (no modulation) on its maximum amplitude at 84 kHz. FRF curves are not exactly the same with and without pump. That is a direct experimental evidence of some important changes in mechanical properties of the plate that are attributed to the action of ultrasonic pump. One can notice that some parts of both curves look very different while the other parts practically coincide. This fact can be explained by a small size of damaged zone relative to the volume of the plate. Probe wave forms a standing wave inside the plate with complex configuration of maxima and minima. Pump wave modifies material properties within the damaged zone and around it. If at a given frequency a probe minimum occurs in the zone, the probe wave does not "feel" the zone and the parts of both FRF at that frequency coincides. However, changing probe frequency leads to a re-distribution of maxima and minima within the plate and thus, the zone becomes "visible" for the probe wave which is itself influenced by the pump.

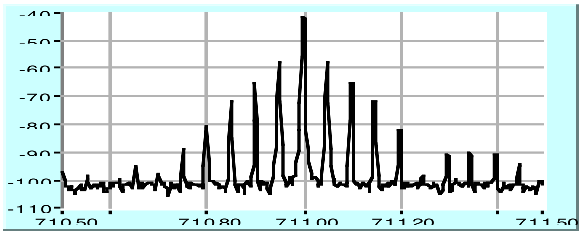
The parts of FRF curves where the difference between both of them is the most pronounced indicate the values of probe wave frequencies at which the pump-probe interaction is the best. Fig.3 and Fig.4 illustrate above mentioned interaction in the spectral domain by modulation transfer from the pump to the probe. In this case, the pump signal is amplitude modulated with a very low frequency of 5 Hertz. Probe signal (pure tone) is set up at first at 68.51 kHz which corresponds to the greatest change in FRF. Then probe frequency is moved to 69.98 kHz where both FRF coincides. The received probe signal spectrum over 68.46 - 68.56 kHz window (Fig.3) exhibits numerous high sidelobes around the central peak with 5 Hz intervals between them. The presence of strong sidelobes means existence of strong amplitude modulation of 5 Hz on the probe signal. Received signal spectrum in 69.93 - 70.03 kHz window at the second pump frequency provides totally different picture. Sidelobes are practically absent on the spectrum, the central peak of pump frequency dominates, meaning that there is no amplitude modulation transfered onto the probe wave.

The choice of pump modulation frequency is not critical; it can be higher or lower than 5 Hz leading to similar results. The only difference is the distance on the spectra between sidelobes which changes according to new modulation frequency.

To confirm that correlation between sample's FRF curve variation and the probe modulation spectra are regular, several plates with different zones of damage were tested at numerous combinations of probe and pump frequencies. Because of limited space we provide here only one additional set of data taken on another plate. Fig.5,6,7 represent correspondingly the FRF with and without non-modulated pump (95.9 kHz) in the window 70.3-72.3 kHz, and the spectra of the modulation transfer (5 Hz) from the pump onto the probe for two chosen frequencies of 71.10 kHz and 71.86 kHz. The same correlation is well seen: the parts of FRF where the difference between the curves is more pronounced always correspond to the configuration of pump and probe frequencies where interaction between probe and pump waves is stronger.

Similar tests on the undamaged plate exhibit both mentioned FRF curves which are practically identical and coincide one with the other within all tested frequency range over 30-110 kHz. As it is expected, modulation transfer spectra show up no pump-wave interaction (similar to Fig.4) at any tested combination of pump-probe frequencies.





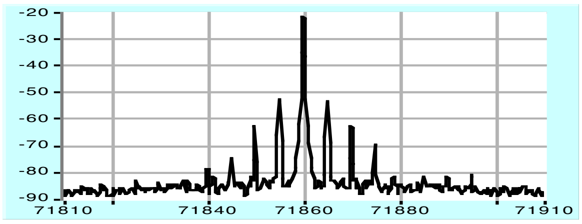


Fig.5 : FRF, Fig.6,7 : probe modulation spectra

Anomalous non-classical nonlinearity

The huge nonlinearity of the cracked glass plates is clearly of non-classical nature. We remind here that classical nonlinearity of solids is associated with weak nonlinearity of the stress/strain relationship (due to anharmonicity of interatomic potential) and with kinematic nonlinearity (due to nonlinearity of strain tensor in terms of displacement gradient). The plausible candidate providing huge nonlinearity at the cracked glass is the nonlinearity of soft contacts, existing between the lips of the cracks [2]. However at the current stage of our experiments it is difficult to discriminate between elastic nonlinearity of soft contacts and their contribution to nonlinear dissipation as well as to distinguish between different possible regimes of contact nonlinearity.

FRF approach to damage diagnostics

Based on the obtained strong correlation between nonlinear ultrasonic waves interaction, anomalous acoustic nonlinearity of damaged materials and variations induced in FRF by intense ultrasonic pump, we propose to use directly FRF analysis for microcracks detection within an object.

One has to compare two FRF of the same object, first under intense constant ultrasonic excitation and then without it (use a large band ultrasonic transducer within its frequency window). When both FRF curves totally coincide within all tested frequency window - the object is intact. If there are at least a few zones where the curves differ from each other then it indicates the presence of damage within the object.

The window should be taken large enough to cover many resonances of the object. FRF needs to be taken with a good resolution. Ultrasonic pump frequency is not critical, it can be chosen relatively free. If the pump frequency happens within one of the object resonances then induced FRF variations are greater to the case where the frequency is outside resonance (pump amplitude is constant). In any way, FRF variations will be well remarkable in both cases.

For the pump, a narrow band resonant ultrasonic transducer is better to use to gain in pump amplitude. The best detection apparatus seems to be a laser vibrometer. We used large band ultrasonic transducer for probe wave as high signal amplitude is not required for it. Other ultrasonic excitation methods can be considered to get fine FRF of the object. Finally, a particular attention should be paid to the coupling of both transducers to the object because bad acoustical contacts are themselves the sources of additional nonlinearity.

Spectral analysis of probe wave modulation can be efficiently used on its own for damage detection as was illustrated by Fig.3,4,6,7. However, each spectrum depends a lot on the choice of probe and pump frequencies that complicates analysis, numerous spectra being required. Approach via FRF is easier than spectral analysis: the choice of frequencies is less critical, one function (FRF) is sufficient to complete analysis and acquisition of FRF does not require complex electronics like spectrum analyzers.

Conclusions

Damaged glass plates have been studied with intense ultrasonic fields. Great difference between damaged and intact samples has been demonstrated by the Frequency Response Function analysis as well as in the spectral domain. Dramatic increase in ultrasonic waves interaction clearly indicates huge nonlinearity of damaged material. Anomalous non-classical nonlinearity found in such material was confirmed by pronounced manifestation of nonlinear modulation transfer phenomena.

Further studies are needed to understand better the physics and the mesoscopic mechanisms at the origin of such anomalous nonlinearity. Knowledge in this field will find many applications, particularly in nondestructive testing of the onset of micro-cracks at the very early stage. Two above proposed methods (the FRF analysis and the Modulation Transfer Method) are promising approaches to the problem.

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