Nonlinear interaction of ultrasonic waves studied with Frequency Response Function (FRF) analysis

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Introduction

A correlation between nonlinear interaction of ultrasonic waves and Frequency Response Functions (FRF) of damaged samples is described in relation to defectoscopy of damaged materials and structures by nonlinear ultrasonic methods. In order to analyze damage, there is a very sensitive and efficient method - the interaction of a powerful ultrasonic pump wave with a smaller amplitude probe wave. The presence of microcracks is responsible for the interaction because it drastically increases the nonlinearity of a material [1].

For the diagnostics of cracks produced by thermal shock in glass the frequency conversion phenomena has recently been studied [2]. Efficient frequency mixing in damaged glass has shown that for characterization of cracks in solids it exists several ways to obtain nonlinear sound waves interaction. First way is based on the principle similar to the one of parametric antenna. The other way consists on implementation of the "Luxembourg-Gorky effect" which is the phenomenon of the transfer of low-frequency modulation from high-amplitude (pump) acoustic wave to low-amplitude initially unmodulated (probe) acoustic wave in a nonlinear media.

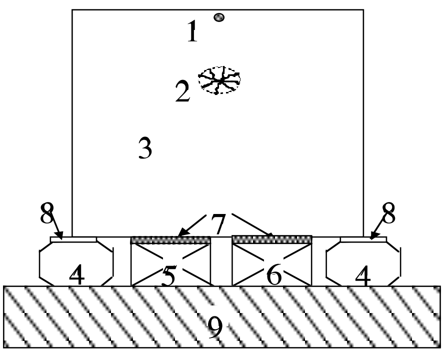


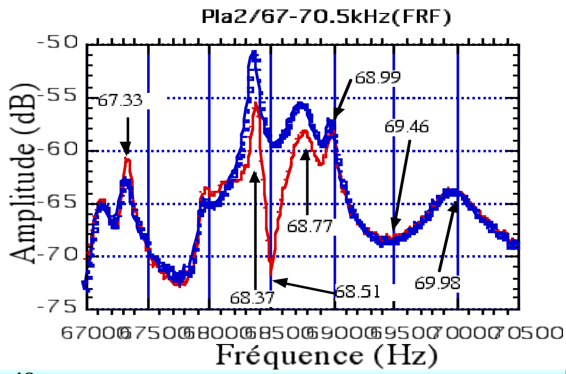
Figure 1 : Experimental set-up

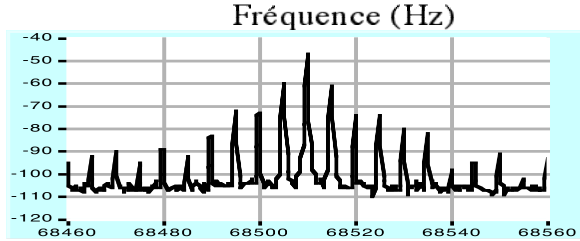
Experimental set-up and procedure

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 (3). One transducer is used to produce a pump wave (that can be amplitude modulated by a low frequency signal). 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 (1) is totally arbitrary. Rectangular 230x190x15 mm glass plates are used for virgin and damaged samples, they are tested within 30-110 kHz. 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) is created on each test sample (3). The samples are held on mechanical supports (4) with anti-vibration isolators (8),(9).

The signal received by the laser vibrometer is processed and displayed on a vector signal analyzer. The first processing regime is the acquisition of the Frequency Response Function of the sample: the frequency of the probe signal is swept smoothly within a chosen range and the signal amplitude received by the vibrometer is registered as a function of the probe frequency. The second processing regime is FFT transformation of the received signal within a narrow spectral window around central frequency of the probe signal in order to analyze the modulation spectra of the probe wave.

When the pump wave is amplitude modulated, nonlinear ultrasonic wave interaction (due to the presence of cracks) takes place in the form of a modulation transfer from the pump wave to the probe wave depending on the amount and sizes of the damaged features inside the material. The Frequency Response Functions of the plates have been recorded with and without unmodulated pump. Correlations between the FRF variations (with and without pump) and observed corresponding sidelobes on the related amplitude spectra of the probe wave (when pump is amplitude-modulated and probe is emitted as a pure sine wave) are observed and explained.





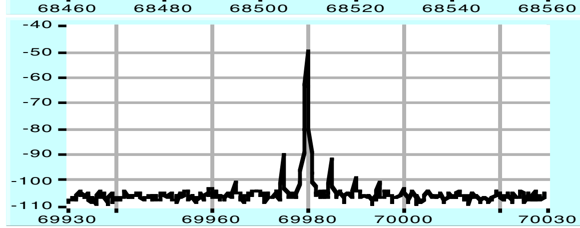
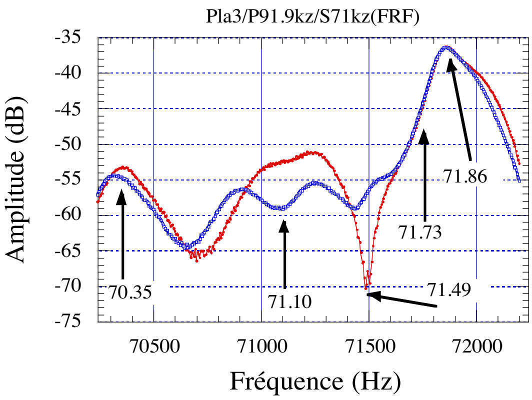
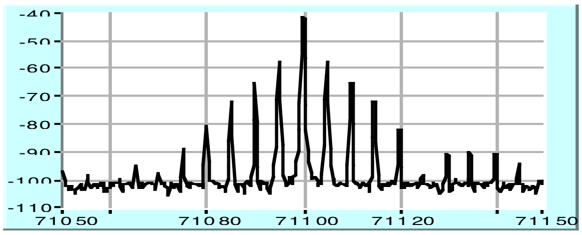


Figure 2: FRF; **Figures 3 and 4:** Probe modulation spectra





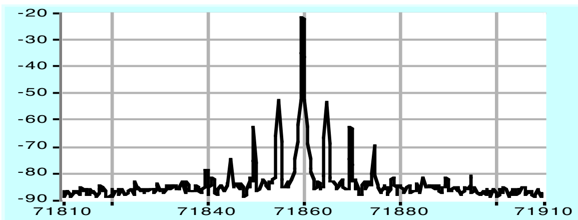


Figure 5: FRF; **Figures 6 and 7:** Probe modulation spectra

Discussion

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 ε_{max} that we were able to achieve with the used pump transducer was $\varepsilon_{max} = v_{max} / C_o \approx 4 \times 10^{-6}$ (here C_o = 5800 m/s is the sound velocity in glass). Such relatively weak level of ultrasonic excitation (pump) was sufficient for nonlinear wave interaction. The major advantage of proposed configuration is that the interaction occurs between pump and probe waves when both waves are in ultrasonic range. It allows to overcome the problems related to ambient low frequency noise and vibrations.

Frequency Response Function analysis

Let us analyze the Frequency Response Functions of damaged plate. A FRF curve shows up all plate resonances caused by the probe wave while its frequency is slowly swept. The FRF is a mechanical signature of the object. Fig.2 represents 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 while the pump transducer is constantly exciting the plate on its maximum amplitude at 84 kHz (no modulation). The 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 induced by the ultrasonic pump. One can notice that some parts of both curves look very different while the other parts practically coincide. The parts of FRF curves where the difference between the curves 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 the effect of modulation transfer from the pump to the probe. The pump signal is amplitude modulated with a very low frequency of 5 Hertz (value of the modulation frequency is not critical). Probe signal (pure tone) is set up at 68.51 kHz: that corresponds to the greatest change in FRF. Received probe signal spectrum over 68.46 - 68.56 kHz window (Fig.3) exhibits numerous high sidelobes with 5 Hz intervals around the central peak of 68.51 kHz. The presence of strong sidelobes means existence of important 5 Hz amplitude modulation on the received probe signal. Next, the probe frequency is moved to 69.98 kHz where both FRF coincides. Received signal spectrum in 69.93 - 70.03 kHz window (Fig.4) provides totally different picture. Sidelobes are practically absent on the spectrum. The central peak of 69.98 kHz probe frequency dominates, meaning that no amplitude modulation is transferred onto the probe wave.

Another plate exhibits similar behavior. Fig.5 ,6,7 represent correspondingly the FRF with and without non-modulated pump (at 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 probe 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 FRF curves (with and without pump) that coincide one with the other within all tested frequency range over 30-110 kHz, they are identical). As it is expected, modulation transfer spectra show up no pump-wave interaction (like Fig.4) at any combination of pump-probe frequencies.

Conclusions: FRF damage diagnostics

The correlation between FRF variations of the damaged objects and the depth of amplitude modulation (sidelobes) induced on the probe wave by ultrasonic pump has been put in evidence. Based on this correlation, the authors propose to use directly FRF analysis for microcracks detection.

One has to compare two FRF of the same object, first under intense constant ultrasonic excitation and then without it. When both FRF curves totally coincide within entire tested frequency range - the object is intact. If there is at least one zones where the curves differ from each other then it indicates the presence of damage within the object.

References

[1] A. Moussatov, V. Gusev and B. Castagnede, Self-induced hysteresis for nonlinear acoustic waves in cracked material, Phys. Rev. Lett., 90, 124301-04 (2003).

[2] A. Moussatov, B. Castagnede and V. Gusev, Frequency up-conversion and frequency down-conversion of acoustic waves in damaged materials, Phys. Lett. A, 301, 281-290 (2002).