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**ULTRASONIC PARAMETRIC IMAGING OF METALLIC SAMPLES
USING NONLINEAR ACOUSTIC MEASUREMENTS**

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A calibrated contact phase modulation method [1] have been developed in the laboratory. Nonlinear effects coming from parametric interaction of an high and a low frequency waves can be measured as a phase modulation of the HF acoustic beam. According to the NDE needs, the nonlinearity in samples with interfaces, coming from aeronautic industries (two layers of aluminum bonded by an epoxy thin layer), must be measured. In order to meet these needs, our method has been extended. Thanks to additional measurements of reflection coefficient, calibration procedure, based on the self-reciprocity principle applied to the LF transducer, has led us to obtain absolute value of the LF particle velocity at the bonded interface. To know the feasibility of this extension, preliminary results of nonlinear parameter have been obtained in bi-layer samples considering the propagation inside the layer only. An image have been created by slope values of phase modulation obtained from 25 regularly spaced measurements.

1. Introduction

In this work, according to the needs of NDE in aeronautic industry, we propose to extend a phase modulation method [1] to samples having high impedance mismatch between two layered samples manufactured by CDE Dassault Aviation (two layers of aluminum bonded by an epoxy thin layer). This in-situ method and associate calibration procedure was previously validated in homogenous media (fluids, fused silica, aluminum). Two kinds of sticking are analysed: an healthy adhesive epoxy layer which is completely polymerized between two pieces of aluminum (E2) and a damaged one whose polymerization was interrupted during the process (F2). For the measurement in homogenous media [1], parametric interaction is achieved between the HF wave which is reflected from the edge of the sample and the LF wave which is emitted at this edge during the HF wave reflection. With bonded aluminum samples, new aspects have enhanced the difficulty:

- What is the influence of the adhesive epoxy layer on the HF wave propagation through the sample?
- How can the LF transducer be calibrated?

In this work, the feasibility of our measurement in these samples is investigated, and in particular the LF particle velocity on adhesive epoxy interface and the phase modulation of the HF wave which is reflected on this interface are studied.

2. Theory of parametric interaction

The interactions between a low frequency (LF) wave and an high frequency (HF) wave produce spectral components at frequencies $f_{\pm} = f_{HF} \pm f_{LF}$. The aim of parametric interaction is to measure the LF field by detecting the spectral components. In the case of weak interactions and high frequency ratio (i.e. $f_{LF} \ll f_{HF}$), harmonic generation at frequencies f_{\pm} can be measured as a phase modulation of the acoustic beam [2]. The high frequency phase modulation is interpreted as a local HF frequency velocity variation $\Delta c_{HF}(x, t)$ resulting from the LF field presence. The HF celerity variation, coming from two simultaneous effects (thermal coupling, with the thermodynamic coefficient γ , and convection [3]), is time and spatial dependent

$$\Delta c_{HF}(x, t) = \frac{\gamma - 1}{2\rho_0 c_0} p_{LF}(x, t) + v_{LF}(x, t), \quad (1)$$

where $\rho_0 = 2700 \text{ kg.m}^{-3}$ is the density, $c_0 = 6400 \text{ m.s}^{-1}$ the celerity in the medium (aluminum), and $p_{LF}(x, t)$ and $v_{LF}(x, t)$ are respectively the pressure and particle velocity of the LF wave.

With hypothesis of plane waves, the phase of the HF wave φ_{HF} can be calculated as the integration along the propagation path of length L :

$$\varphi_{HF} = \int_0^L \frac{\omega_{HF}}{c_{HF}(x, t)} dx = \frac{\omega_{HF} L}{c_0} - \frac{\beta}{\rho_0 c_0^3} p_{LF}^{\max} \omega_{HF} L \cos(\omega_{LF} t_0) = \frac{\omega_{HF} L}{c_0} - \Delta\varphi_0 \cos(\omega_{LF} t_0), \quad (2)$$

where ω_{HF} and ω_{LF} are the HF and LF angular frequencies, $c_{HF}(x, t) = c_0 + \Delta c_{HF}(x, t)$ is the HF celerity in the medium, and β is the nonlinear parameter defined by:

$$\beta = \frac{\gamma + 1}{2} = - \left(\frac{3}{2} + \frac{c_{111}}{2c_{11}} \right). \quad (3)$$

Using the impedance relation for plane waves $p_{LF}^{\max} = \rho_0 c_0 v_{LF}^{\max}$ and Eq.(2), the nonlinear parameter β is extracted [4]:

$$\beta = \frac{c_0^2}{\omega_{HF} L} \left(\frac{\Delta\varphi_0}{v_{LF}^{\max}} \right). \quad (4)$$

This parameter is determined via measurements of two parameters: the phase modulation index $\Delta\varphi_0$ and the LF particle velocity v_{LF}^{\max} .

3. Low Frequency particle velocity measurements

3a. Extended metrology for LF calibration with bonded interface

In order to determine the LF particle velocity $v_{LF}^{\max}(t)$ on the adhesive interface which is emitted by the LF transducer, a self-reciprocity calibration [1] is extended (**Fig. 1a**). The determination of LF particle velocity in time domain $v_{LF}^{\max}(t)$ is given by:

$$v_{LF}^{\max}(t) = FFT^{-1} \left[H_v(f) I_{out}(f) (1 + R(f)) e^{\alpha_{LF} d_2} \right], \quad (5)$$

where:

$$H_v(f) = \sqrt{-\frac{1}{2AZ_0} \frac{E_{in}}{I_{out}} \frac{1}{D(f)R(f)}} e^{(jk + \alpha_{LF})d_2}, \quad (6)$$

with A is the effective transducer radiating area, Z_0 is the acoustic impedance of the media, E_{in} is the Thévenin-equivalent voltage source of the amplifier, I_{out} is the output electrical current, d_2 is the thickness, α_{LF} is the LF wave attenuation into the sample and $D(f)$ is the exact diffraction correction for transmitter and receiver (neglected in our case). FFT^{-1} stands for inverse Fast Fourier Transform. The originality of our work consists in taking into account $R(f)$, the reflection coefficient of the adhesive epoxy layer, defined by:

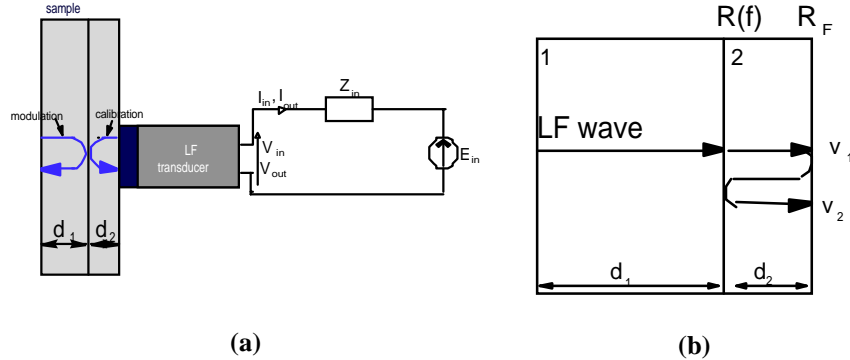


Fig. 1. Contact self-reciprocity calibration (a) and reflection coefficient $R(f)$ measurement (b) setup in bi-layered samples.

$$R(f) = \frac{v_2(f)}{R_F v_1(f)} e^{(\alpha_{LF} + jk)2d_2}, \quad (7)$$

where R_F is the reflection coefficient of the sample surface, $v_1(f)$ and $v_2(f)$ are defined respectively as the velocities of the first and the second echoes of the

transmission through the layer (**Fig. 1b**). Thus, a preliminary determination of this coefficient is necessary to know the LF particle velocity on the adhesive interface.

3b. Reflection coefficient $R(f)$ measurements

A new setup has been built in order to take into account the presence of epoxy layer and to extract interface reflection coefficient $R(f)$ with absolute laser measurements (**Fig. 2**). LF *Technisonic* planar transducer (0.25") is driven by a 1.45 MHz burst created by an HP3314A waveform generator and amplified by an ENI A500 60dB amplifier. Using a *Polytec OFV 505* laser, $v_1(f)$ (the particle velocity of the transmitted wave through the interface) is acquired. In the same acquisition, $v_2(f)$ (the particle velocity reflected by the sample edge and then by the interface) is also measured (**Fig. 1b**). Then the reflection coefficient $R(f)$ is computed using Eq.(7). In order to realize an image of the reflection coefficient in each sample, a motorized displacement system *Owis DC500* is used to move the sample between the laser and the transducer (**Fig. 2**).

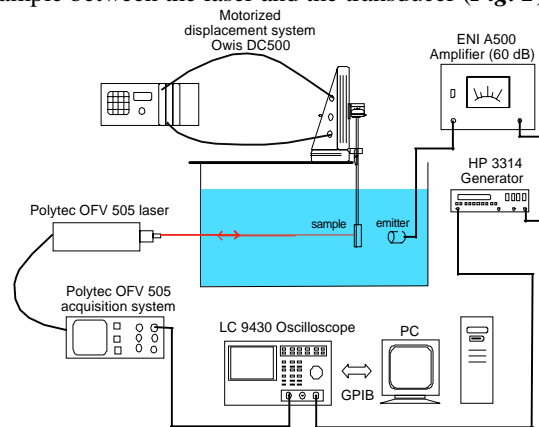


Fig. 2. Experimental setup for reflection coefficient $R(f)$ measurement with laser.

Signal processing of measurements are realized on computer with *Matlab* software. For each measurement (total: 36×36), echoes are separated and FFT is calculated. Then a 36×36 matrix of reflection coefficients are obtained. Each of these coefficients is dependent of the frequency in the frequency bandwidth of the transducer, comprised between 0.4 MHz and 2 MHz. To visualise the reflection coefficient discrepancies between the healthy adhesive epoxy layer and the damaged one, images of this coefficient at 1.45MHz are realized (**Fig. 3**).

Strong variations of the reflection coefficient $R(f)$ can be observed close to the edges of the sample. These are artifacts due to diffraction of the

sound beam. In spite of this, zone of interest (ZOI) can be defined (as shown on **Fig. 3**). In these ZOI, a mean of reflection coefficient $R(f)$ is calculated leading to: $|R_{mean}^{E2}| = 0.43$ in the healthy sample and $|R_{mean}^{F2}| = 0.58$ in the damaged one.

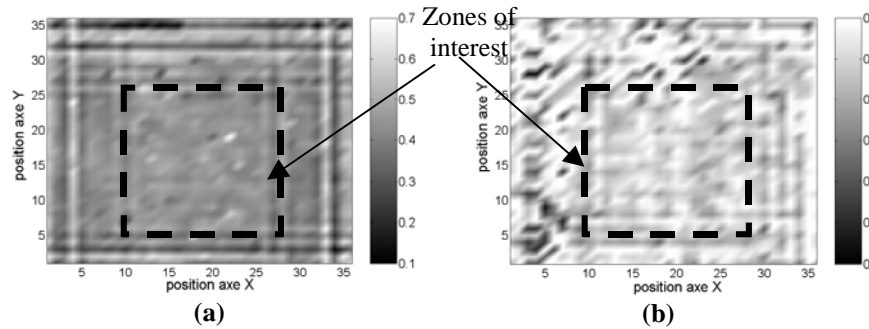
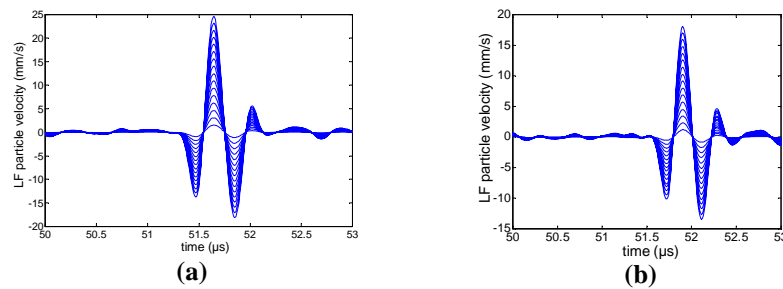


Fig. 3. Imaging of the reflection coefficient modulus $|R(f)|$ at 1.45 MHz for a bi-layered sample with healthy (a) and damaged (b) adhesive epoxy layers.

Thus, for the two samples, a mean $R(f)$ has been determined showing, as expected, a higher reflection coefficient in the damaged bonded sample. For the moment, no local variation of $R(f)$ on a single sample are detected. These results enable the determination of the particle velocity of the LF wave.

3c. LF particle velocity results

Thanks to the reflection coefficient previously determined and the measurement of the four electrical parameters (V_{in} , I_{in} , V_{out} , I_{out}), it is possible to determine the LF particle velocity on the adhesive interface (Eq.(5) and Eq.(6)).



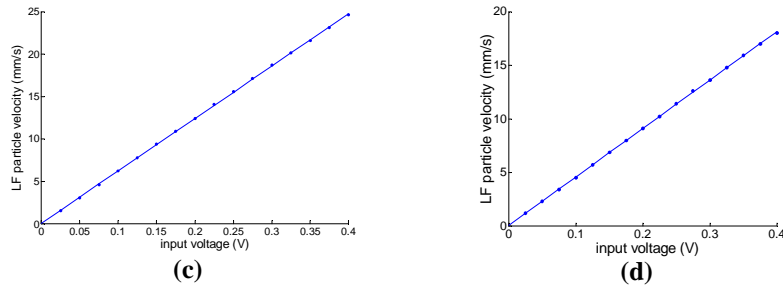


Fig. 4. Time evolutions of LF particle velocity for (a) healthy sample (E2) and (b) damaged sample (F2) and their amplitudes (c) and (d) respectively versus LF input voltages.

As shown on **Fig. 4**, low frequency particle velocities have the same behaviour for the two samples. Only the amplitudes are different. This means that $R(f)$ can be considered constant in the bandwidth. The ratio of amplitude is about 1.4 and is consistent with the Eq.(5) and Eq.(6) and the $|R_{mean}|$ calculated in §0 which give 1.57. Thus, a calibration has been obtained in the bonded samples using a preliminary $R(f)$ measurement.

4. Phase modulation measurements

The experimental setup (**Fig. 5**) which has been published elsewhere [1],

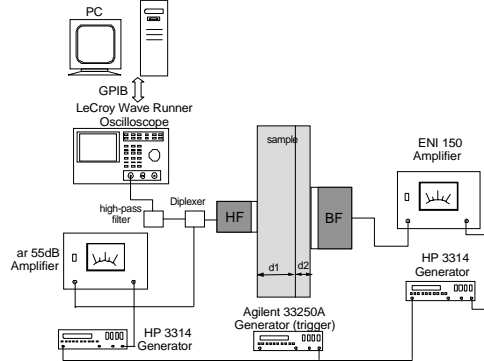


Fig. 5. Experimental setup for contact phase modulation measurement was modified by the amplification of the HF wave (in order to enhance signal to noise ratio by an *ar 55-dB* amplifier). HF *Panasonic* planar contact transducer (0.25") was driven by a 15 MHz tone-burst (about $N=30$ periods) created by an HP3314A waveform generator. After propagation in the sample, the HF wave is reflected by the interface (adhesive epoxy layer). A LF pulse, generated by an HP3314A is amplified by a 55-dB amplifier (ENI A150) before transmission to the transducer. Both HP3314A generators are triggered by an HP33250A

waveform generator, so that the reflected HF acoustic wave interacts collinearly with the LF pulse during its back propagation in the thickness d_1 (Fig. 1a). The received signal is filtered in order to eliminate the LF signal detected (to avoid the electric interactions), transmitted through a Ritec diplexer to an oscilloscope and saved on a computer via GPIB link.

Before amplifications, input voltage applied towards the transducers takes values between 25 and 400 mV for LF one and 100 mV for the HF. The frequencies are 2.2 MHz and 15 MHz respectively. Results of phase modulation are shown on Fig. 6.

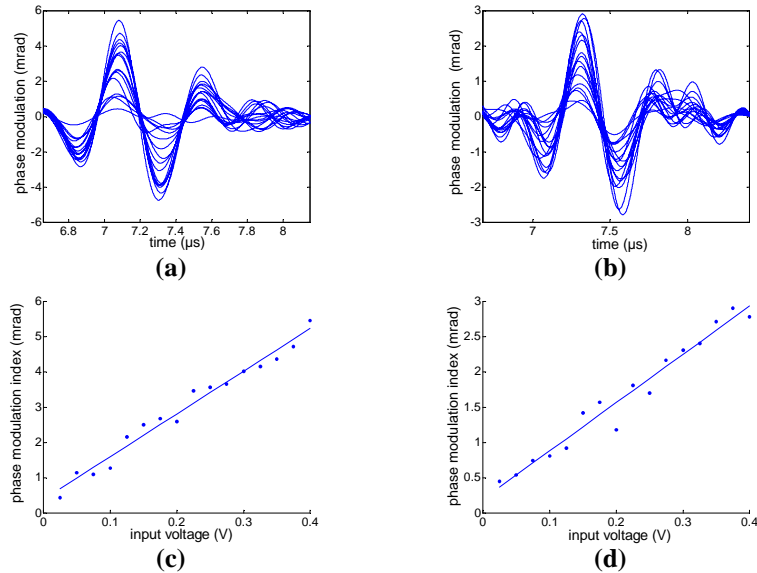


Fig. 6. Time evolutions of phase modulation for (a) healthy sample (E2) and (b) damaged sample (F2) and (c) and (d) correspondent.

The shape of the detected modulation is in good agreement with the LF wave shape. But the strong attenuation (transmission through the adhesive layer) in bonded samples decreases the SNR and thus the phase modulation amplitude (as shown on Fig. 6a and Fig. 6b). The amplitudes of phase modulation increase fairly linearly with the input voltage (as shown on Fig. 6c and Fig. 6d). The amplitude of modulation obtained in the damaged bonded sample is lower than expected. This is mainly due to the low SNR of this measurement. Phase modulation index $\Delta\varphi_0$, which has to be measured for β evaluation, is the slope of phase modulation amplitude versus input voltage.

5. Results

In order to check the feasibility of the overall measurements, we have done a comparison between the nonlinear parameter β in an homogenous reference aluminum sample and in our bonded aluminum samples, considering that the measurement in bonded sample only characterize the aluminum nonlinearity. For the reference sample $\beta_{Al} = 7.3$, for the healthy bonded sample $\beta_{E2} = 6.7$ and for the damaged bonded sample $\beta_{F2} = 4.9$. Results in the reference sample and in the healthy bonded sample are in good agreement, showing the feasibility of modulation measurement in bonded layer (given a sufficient transmission coefficient). In the damaged bonded sample, the influence of the interface is too strong and measurement does not lead to the proper β value, because of the low SNR.

Moreover, as shown in *Fig. 7a*, slope values of phase modulation have been obtained from 25 regularly spaced measurements in order to build an image. It can be observed that peripheral measurements (out of ZOI) are strongly divergent due to the diffraction of the LF transducer.

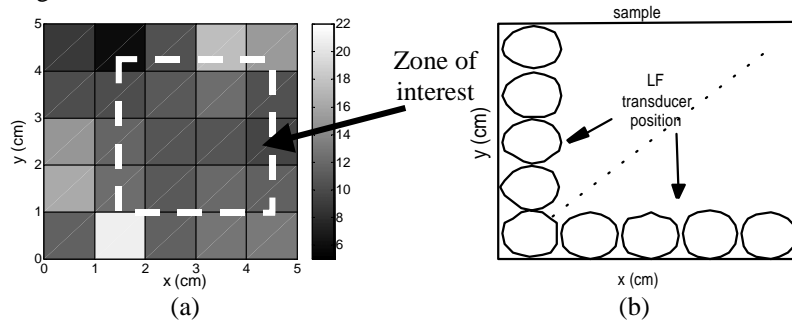


Fig. 7. Imaging of the phase modulation slope for a bi-layered sample with a healthy adhesive epoxy layer (E2). The figure is built with a set of 5×5 measurements (b). Both HF and LF transducers were moved assuming the same alignment.

In the zone of interest, the modulation index is quite constant and in agreement with measurement in §0.

6. Conclusion and perspectives

In this work, LF transducer calibration has been extended to bi-layered sample but problems have appeared especially in the phase modulation measurement. In spite of these problems, nonlinear parameter results are obtained in healthy bonded sample.

Follow on works include an optimization of the SNR to obtain β from weakly bonded layer sample (as F2) and measure the reflection coefficient in

contact in order to have a β image of the samples. Then, our goal will be to investigate the influence of the interface on parametric interaction and on β .

7. Acknowledgement

The authors acknowledge H. Trétout, J.-Y. Marin and E. Guillorit, from CDE Dassault Aviation, for providing samples. This work has been supported by the EC Sixth Framework Programme AERONEWS: Specific Targeted Research: FP6-502927(<http://www.kulak.be/AERONEWS>)

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I.N.Didenkulov¹, L.M.Kustov², N.V.Pronchatov-Rubtsov², A.A.Stromkov² METHODS OF THE NONLINEAR ACOUSTIC VISION OF OBJECTS AND DEFECTS

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Nonlinear acoustic methods are found increasing applications during the last decade. In this paper we describe methods of acoustic imaging based on the nonlinear effects: the combination acoustic scattering and the modulation of high-frequency acoustic wave by low-frequency wave. Acoustic vision of objects at the difference frequency was studied using bubbles as strongly nonlinear scatterers. The experiments were carried out in a water tank with metal objects covered with electrolysis microbubbles to produce highly nonlinear scattering from the object surfaces. Images of the objects were obtained. The nonlinear scattering by bubbles was also used to obtain an image of the cavitation flow. Nonlinear acoustic vision of small (in the scale of wavelength) defects is possible when tomography schemes are applied. We used the method of nonlinear modulation modal spectroscopy for defectoscopy of cracks in metal samples. Results of investigation demonstrate possibilities of the nonlinear acoustic techniques in nondestructive testing of different media.

1. Introduction

Methods of acoustic imaging have been elaborated for quite a long time. They are mainly based on the use of linearly scattered waves from an object. Some objects, such as gas bubbles in fluids [1-3] or cracks in solids [4-6], are