Nondestructive evaluation of adhesive joints by using nonlinear ultrasonics

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Abstract. Adhesive bonding technology has now gained much attention in many industries as a very versatile assembling technique. However, to be used for structural joining and critical application, high reliability is needed. Thus, efficient non-destructive control strategy should be proposed to evaluate the nominal bonding quality but also possible progressive in-service degradations. Promising results have been presented in the literature using ultrasound-based methods. While linear ultrasound is efficient to detect decohesion or voids in a structure, it barely sensitive to bond strength. In this work, we present a method to generate high amplitude plane wave, which may produce nonlinear phenomenon that are able to reveal kissing bonds or other types of adhesion defects. In this purpose a method based on a chaotic cavity transducer has been developed to generate high energy plane wave. Then the method is evaluated on metallic bonds with bonding defects. Combined with the pulse inversion technique, nonlinear phenomenon can be measured in the form of harmonic generation in the defect zone. We use this method to image a defect created by spraying PTFE on one adherent prior to bonding.

1. Introduction
Structural adhesion can be used to replace rivets, it leads to lighter structural weight, better stress repartition and can be used to assemble different materials such as composite. Adhesive bonding technology has therefore gained much attention in many industries, specifically aeronautic [1]. Efficient non-destructive control strategy is needed to evaluate the nominal bonding quality and to detect defects [2]. Defects can be either ’cohesive’ or ’adhesive’. Cohesive defects are exclusively located in the bond line, and encompass many different types e.g. voids or cracks. Adhesive (or interfacial) defects are located at the interface between the adhesive layer and the substrate. Apart from complete disbonds, these interfacial defects may correspond to a weak adhesion, due to inappropriate surface treatments of the substrates, e.g. presence of pollutant on the substrate surface before assembly. Such pollution can also lead to the well-known ’kissing bond’ where substrate and adhesive layer are in contact without any bonding. These interfacial defects are the most critical for the industries, and therefore the aim of the present work is to develop a non-destructive method able to detect them.

Ultrasound nondestructive methods have been developed for decades now to assess the bond strength, however none is available for industrial inspection yet. Some recent methods exhibit promising results such as inspection using Zero-Group Velocity Lamb Modes [3, 4], plane-wave inversion [5], or Laser Shock Adhesion Testing (LASAT) [6]. Nonlinear ultrasound has also been recently studied to assess bond quality, using vibroacoustic modulation method (VAM) [7]. This
method combines the emission of a pump-frequency at low-frequency and of an ultrasonic wave at orders of magnitude higher frequency. When contact defects are present in the specimen under test, mechanisms such as contact, decohesion or friction activated by the pump wave in the defect regions induce a nonlinear response. In [7], the method is shown to be able to detect kissing bond, the latter being introduced in a bond using a Teflon insert, and being also detected with a conventional C-Scan measurement on a reflection amplitude image. Nonetheless, this research suggests that nonlinearities can be measured in bonds with adhesion defect. The present work presents a method based on a chaotic cavity transducer to induce CAN (contact acoustic nonlinearities [8]) in the case of a weak interface in a metallic bond.

2. Sample preparation
Two bonds of the same dimensions were prepared namely 200 mm long and 200 mm wide, with a thickness of 2 mm per adherent. Non-supported, epoxy based, structural adhesive film AF191 (see adhesive datasheet in [9]), was used to bond the aluminum plates. Bond line thickness was controlled by applying a 100µm thick, PTFE coated fiberglass fabric close to the edges of the plates. Bonded substrates were then put in a vacuum bag and cured inside an autoclave. Curing conditions were adopted as specified by the adhesive manufacturer (3M). An adhesion defect was introduced in one of the samples by spraying PTFE molecules to the substrate prior to bonding. This procedure results in a weak interface in the polluted-region.

3. Linear nondestructive methods
Two different linear ultrasound-based nondestructive methods were used in order to try to detect the interfacial defect.

3.1. Immersion measurement
A C-Scan ultrasound measurement is a conventional nondestructive testing method for the inspection of defects in structures. Both specimen are inspected with a 15 MHz piezoelectric transducer in pulse-echo mode, driven by a M2M MultiX electronic system. Figure 1 represents the reflected amplitude at the interface, with the red line representing the defect position. Figure 2 represents two A-Scans: one extracted above the defect free region, the other above the defect region. The various echoes are reflections either on the bond interface or on the bottom or top of the adherents. The amplitude of the bond interface echo is not sensitive to the bond strength in this case.

3.2. Guided waves
Guided waves are also used as a conventional nondestructive testing method and have been used previously for adhesion evaluation [2]. Guided waves are indeed known to be sensitive to all material properties (ultrasound velocities, density...) and specimen geometry (thickness of various layers). A simulation study showed that high resolution dispersion curves are needed in order to observe weak fluctuations of Lamb mode waves in such bonds [18]. Therefore a new dispersion curves imaging technique called Multichannel MUSIC (MUltiple SIgnal Classification) was developed to improve existing methods like 2D-FT and SVD-based method [12]. This algorithm (detailed in [12]) enables low-energy modes detection and a better wavenumber-resolution. It consists in an appropriate post-processing of the inter-element response matrix of a linear phased array placed in contact with the sample with coupling gel. Here, the experiment is performed with a 10MHz linear phased array with 128 elements and a 0.35mm pitch, put in contact of the sample either above the defect area, or above the reference sample. Then, dispersion curves are computed using the multichannel MUSIC algorithm with 20 emitters and 108 receivers, see
Figure 1. C-Scan of the specimen with the adhesion defect, red lines delimit the extension of the polluted region.

Figure 2. Two A-scans one in a reference plate with no defect, and one above the defect.

Figure 3. As it can be observed, the dispersion curves retrieved on the defect-free sample and the weak adhesion region overlap almost perfectly.

Figure 3. Dispersion curves retrieved on experimental data using the Multichannel MUSIC-algorithm: reference bonded sample (red) and weak adhesion defect (blue).

As a conclusion, the weak interface introduced in one of the bonded samples could not be detected using the considered linear ultrasound inspection techniques. A new method has to be defined in order to detect interfacial defects accurately. As it was previously mentioned, when high amplitude ultrasound interacts with contact defects, nonlinear phenomenon may occur. Nonlinear acoustics require high-pressure in order to reach a sufficient level to activate this
phenomenon and make it possible to detect the signal nonlinear component [23]. Usually, high-power electronics are used as an input to piezoelectric transducers, which creates undesirable nonlinear components in the signal. In this paper, another approach is derived from the work of Montaldo et al. [14] to create high amplitude displacement with low voltage piezoelectric transducer, namely the chaotic cavity transducer.

4. The chaotic cavity transducer
The concept of chaotic cavity transducer combines one or several transducers glued on a chaotic cavity with the time reversal technique. A chaotic cavity is a highly reverberant medium, with ergodic properties. In this work, of the cavity is an aluminium 5cm cube similar in geometry to an existing cavity found in the literature [14]. The cube is machined on one corner to create a concave sphere (see a 2D representation figure 6), conveying to this object chaotic properties.

Prior to inspection with the cavity, a calibration procedure is needed, also called learning phase in the framework of Time Reversal experiments. All impulse responses between each transducer glued on the cavity and a given point at the surface of the cavity where energy focusing is needed have to be measured. In a second step, the impulse responses are time-reversed and reemitted by the transducers, leading to a high energy focusing at the said point. Very long signals are thus recompressed into short pulses at focus location and time, thus reaching high-pressure pulses [13]. Moreover, this process can be used to reach high quality spatial focusing. Chaotic Cavities have been used for a couple of years now, mainly in the medical domain, with a special interest for shock wave ultrasound therapy techniques [20]. It was also applied more recently to NDT inspections [16].

In the present work, two 1.27cm diameter Sofranel transducers with a central frequency of 500kHz were glued with Salol on the cavity, a laser interferometer (Polytec) is used to measure the normal displacement on the surface of the cavity. All impulse responses are measured successively between each transducer and each point of the surface of the cavity that will act as a virtual source in the second step. More precisely, the virtual source surface is a 100mm square sampled as a 1mm grid in both directions. These impulse responses are linearly combined to generate a locally plane wave at the time of refocusing, with a spatial apodisation as shown in figure 4 (on the left). There exists several time-reversal based methods: classical, deconvolution, inverse filter, clipping [15], and in this work the one-bit method is used for the focusing step because it increases significantly the normal displacement amplitude at focus. To ensure linearity of the emission process, the amplitudes of the electric signals sent to the transducers are limited to 70Vpp during both learning phase and focusing phase. Prior to reemission by the transducers, a 200kHz wide bandpass filter centred on 500kHz is applied to the signals. Figure 4 (on the left) presents the spatial apodisation applied to the impulse response database (half-width is 6.28mm), and in the middle the normal displacement measured on the surface of the cavity at the focusing time. As it can be noticed, the shape of the plane-wave is broadly conserved.

A sample is then placed in contact with the cavity (with echographic coupling gel inbetween), and the normal displacement is measured on the free surface of the sample during the focusing step, see figure 6 on the right. Putting the specimen on the cavity modifies one boundary condition which may alter the time reversal process; however, due to the strong impedance mismatch between Aluminium and coupling gel, an energy focusing is still observed with an amplitude of around 12nm measured after transmission through the bonded structure. This amplitude should be sufficient to reveal CAN defects in a bonded joint [17]. The main advantage of this set-up is the possibility to perform pulse inversion [19] as the piezoelectric transducers are submitted to low voltage (≤70Vpp) as opposed to usual high power ultrasound experiments.
Another already mentioned advantage of the use of a chaotic cavity is that no nonlinear component is emitted by the chaotic cavity transducer itself. Indeed, it allows us to control exactly the frequency content of the desired output.

Figure 4. From left to right: spatial apodisation applied to the database, measured displacement on the cavity, and signal measured after transmission through the bonded joint.

A flow chart (figure 5) summarizes all steps needed in order to perform the adhesion testing (impulse response measurement, Time-Reversal of impulse response, combination of impulse response to focus energy on a chosen surface instead of on a single point, and lastly inspection of a specimen placed on top of the chaotic cavity).

Figure 5. US nonlinear adhesion testing method using a chaotic cavity transducer: a flow chart.

5. Nonlinear measurements
The chaotic cavity is then used as a high-amplitude plane wave transducer. The bonded specimen are placed on the cavity, coupled with a regular coupling gel. Then, the interferometer performs a standard C-Scan on the opposite surface of the specimen, and for each interferometer position the emitted signal location varies so that the laser is always above the maximum point of the emitted plane wave (see figure 6). Actually, in the hypothesis of a ergodic cavity, a similar amplitude can be reached at focusing time when focusing at any point of the cavity, which is indeed observed here in the limit of some acceptable variance (10%). As mentioned previously, the pulse inversion technique is also applied at each controlled point in the second focusing step [19, 23] meaning that at each point two measurements are performed, with emission of the appropriate signal and then the emission of its opposite. Both signals measured by the interferometer are summed to reduce the amplitude of the linear response of the system and
enhance the nonlinear one. A Fourier Transform is applied to the resulting signal on a time-window centered at the refocusing time. Figure 6 presents a scheme of the experimental setup.

Figure 7 represents the Fourier transforms of the residual signals after summing the pulse inverted signals, measured on either a reference sample (blue line) or a weak bond (orange line). As it can be noticed, in the signal measured on the reference bonded sample, only the fundamental frequency is present, whereas the signal measured on the polluted sample displays harmonics. If a simple 10% threshold is applied to the amplitude of the Fourier transforms (in the frequency bandwidth [800,1200]kHz) of the residual signals, the width of the created defect is correctly retrieved, as presented in Figure 8.

In nonlinear acoustics, a variety of nonlinear acoustic parameters can be defined to characterize a material [22]. In this work, a nonlinear acoustic parameter noted $\beta$ is defined as the ratio of the amplitude of the harmonic of the residual signal to the amplitude of the fundamental frequency before pulse inversion, see Equation 1. Figure 9 represents the nonlinear parameter in both cases: sample bonded after interface pollution or good bonding (i.e. reference sample) as a function of the maximum voltage applied to the piezoelectric sensors glued on the cavity during the time reversal second step. As it can be observed, the reference level of the
harmonic amplitude remains low, around 5% whereas the one corresponding to the defect keeps increasing with the input voltage. Figure 10 represents $\beta$ measured while the maximum input voltage on both transducers is 70Vpp in a zone of 40mm*3mm. As it can be seen, the defect width can be retrieved once again but some false negative are present meaning that $\beta$ is low at some points even in the region of the defect. This could be due to the fact that the pollutant was not deposited uniformly as it was sprayed so the defect is not expected to display a uniform nonlinear ultrasonic response.

$$\beta = \frac{A_2}{A_1}$$ (1)

6. Conclusion and perspectives
In this work, we focused on the inspection of an interfacial defect in a thin bonded joint, with a 2 mm thick adherent and 0.1 mm thick adhesive. The defect was introduced by spraying PTFE locally on one substrate prior to bonding. A conventional C-Scan performed at 15 MHz was not sensitive enough to detect the defect. An imaging method based on the MUSIC algorithm was also tested but the measured Lamb modes were not sensitive to the adhesion defect. Subsequently, a method was developed using a chaotic cavity transducer for nonlinear ultrasonic measurements. High amplitude displacement is obtained on the cavity surface after time reversal. The cavity is then used to activate CAN of the weak bond defect. The defect was detected and a nonlinear parameter was defined. The main concern of this experimental protocol is to ensure a good coupling between the chaotic cavity transducer and the specimen. On-going work is to perfect it, and verify the repeatability of the process with the measurements of different bonded joints, with different type of weak bond defects (PTFE spray, finger stain etc.). Two main areas of research can result from this experiment: nonlinear modeling and simulations in order to fit the acoustic nonlinear parameter to contact models to perform adhesion quality inversion, and mechanical testing in order to correlate these nondestructive results to destructive ones.

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