RESONANT VIBRATIONS OF METALLIC INSERTS IN HONEYCOMB SANDWICH

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ABSTRACT Resonant frequencies of a circular disc are calculated and are used to understand the observations made by low frequency air-coupled ultrasonic NDE. Metallic inserts are routinely embedded into honeycomb sandwiches panels as hard points. These circular inserts can be the location of debonding between the inserts and the face sheet. During air-coupled ultrasonic inspection it was observed that these insert were able to transmit surprisingly large amplitude of ultrasound. A thin plate of titanium was able to transmit a very week signal while the thick metallic inserts (e.g., 1.9 cm thick, 3.81 cm diameter titanium), transmitted a large acoustic signal. The experimental and analytic study of the geometrical effects of inserts is presented in this work. Finite Element Analysis (FEA) was performed on the inserts and the results compared with the experimental observations. At the longitudinal natural resonant frequencies of the insert the transmission efficiency of air-coupled ultrasound was very high.

INTRODUCTION

Composite sandwich panels are used in the aerospace construction. Honeycomb core material, such as Nomex, fiberglass, or aluminum is sandwiched between two face-sheets normally made from a composite material or aluminum. The core is very light and acts as a spacer between the two face-sheets and as a result a very light but extremely stiff panel results. Since the inter-plate region is very weak and largely air, inserts are placed as attachment points. These hard points are used for the application of external loads and attachments of other structural members to the sandwich panels. Normally these inserts are circular discs as any other shape would have corners which can cut through the thin face-sheets. These inserts are bonded to the core but it is more important for them to be properly bonded to the face-sheets. Any debonding between the inserts and the face-sheets will very quickly spread to the weak core material. It is imperative to inspect this bonding by a reliable NDE method. In many aerospace applications the application of an ultrasonic couplant [1] between the transducer and the part is not permitted. Hence this investigation was performed using air-coupled through transmission ultrasound (ACTTU). These transducers operate at low frequencies and so they add a complication to the inspection. The natural frequency of the structures could be in the operating frequency and knowingly or unknowingly the user can induce resonance in the system and mislead the inspection.

Loss of air-coupled signal through plates

The reflection and transmission coefficients of sound depend on the impedance($\rho c_{L,}$ where ρ is density and c_L is the longitudinal wave velocity) mismatch between the incident and the transmission medium. The density of air being small, the mismatch is large for air/solid interface. As a result the air-coupled transducer systems will have a large signal loss. These observations have been confirmed by the following studies with ACTTU system and through a variety of composite and metal plates.[2] A 120 kHz ACTTU signal loss through a 0.4 mil thick Saran Wrap is 25 dB, while for a 0.635 cm thick aluminum plate this insertion loss increases to 82 dB. Based on these observations it is not possible to get any significant signal through a thick titanium insert. The experiments however show that a significant amount of signal is observed through the insert. This presence of this signal can be explained by the phenomenon of resonance of the insert. In the proper resonant mode, even though the signal does not pass through the insert, it sets up a resonance and results in the vibrations which result in secondary vibrations with frequency equal to the incident ultrasonic signals and thus show up as transmitted signal.

AIR-COUPLED ULTRASOUND RESULTS

ACTTU C-scan was performed on a variety of aluminum cylinders with varying diameters and lengths. The equipment used to obtain the results presented in this paper was the Sonda-007CX AirScan from QMI, Inc.[3]. C-scan images were produced by using a commercially available raster scanning system from Sonix, Inc.[4] The transducers used were piezo-ceramic and ranged in frequency from 120 kHz to 400 kHz. The cylinders were placed between two cardboard sheets to block direct transmission of sound between the transducers.

C-scans were then performed on the specimens. Figure 1 shows a series of C-scans for a particular family of cylinders performed with a 120 kHz transducer. The three cylinders shown in the figure each have a thickness of 1.27 cm and diameters of 1.9,2.54, and 3.81 cm respectively.

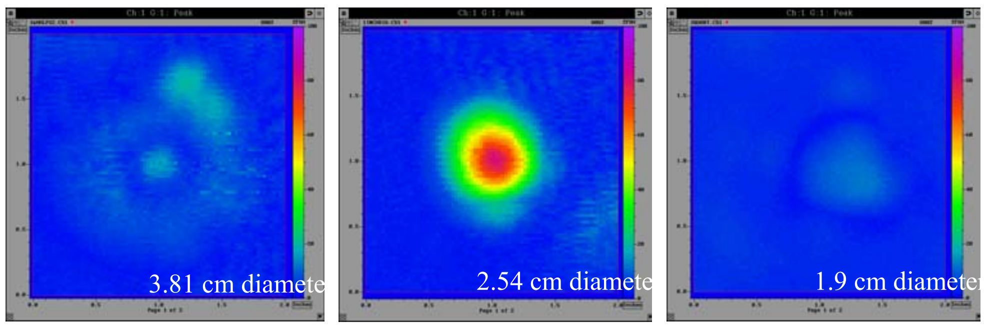

Figure-1 C-scan of 1.27 cm thick cylinders. Transducer center frequency 120 kHz.

The maximum transmitted amplitude for the 2.54 cm diameter cylinder is 5.3 times greater than the signal through the 3.81 cm diameter cylinder and 4.8 times greater than the signal through the 1.9 cm diameter cylinder. Since the cylinders are all made from the same material and have the same thickness, the losses due to insertion and attenuation are identical.

Figure-2 shows the c-scan for two panels, first where the inserts are bonded to the face sheets and second, where the bonding does not exist. The signal amplitude for the bonded inserts is excellent and this technique can be an efficient non-destructive testing method. When we combine the results of figure 1 and 2 then we have a dilemma. On one hand the NDE is possible (fig. 2) but on the other hand the wrong diameter of the insert will give false results (fig. 1).

A theoretical investigation to and understand the signal transmission through the insert is described next.

THEORETICAL INVESTIGATION

The Finite Element (FE) technique was used to determine the theoretical natural frequencies of aluminum cylinders. It has been experimentally determined that a cylinder of aluminum transmits the signal at certain frequencies only. From this observation it can be conjectured that at this frequency the size, shape, and the mass of the cylinder is such that either the energy is transmitted or the cylinder resonates at this frequency and thus facilitates the energy transmission.

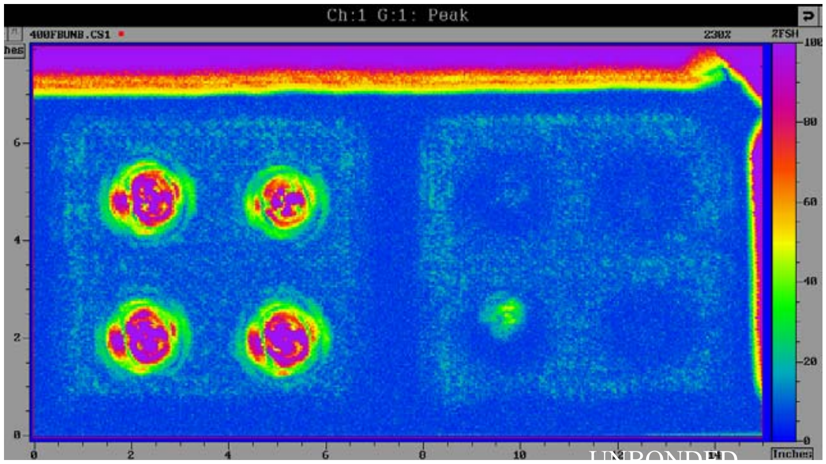

Figure-2C-scan of two panels containing embedded metallic cylinders. The panel on the left contains 4 well bonded cylinders. The panel on the right contains 4 un-bonded cylinders.

A FE model (ANSYS, Inc.[5]) was developed using 10-node isoparametric solid elements with three degrees-of-freedom at each node. The cylinder with material properties of aluminum was assumed to be vibrating in free-free mode. This does not represent the real state of the cylinder glued in honeycomb, as the adhesive on the circumferential side would provide some support. This is to be kept in mind when comparing results with experimental values. It is to be noted that the vibration modes of interest is such that the circumferential displacement does not contribute significantly.

The natural frequencies of this cylinder were obtained and some of the mode shapes over the range of interest of the experimental study are presented in Figure 3. The modes at 96.0 kHz and 170.9 kHz have the diameter expansion and contraction. Along with this the faces of the cylinder also undergo expansion and contraction along the axis of the cylinder. These modes show that the energy transfer in the axial direction is possible. On the other hand at 138.2 kHz the face folds while at 151.9 kHz the cylinder changes from a circular to elliptical form with very little out-of-plane movement of the cylinder faces. Hence in these modes the axial energy transmission would not be possible.

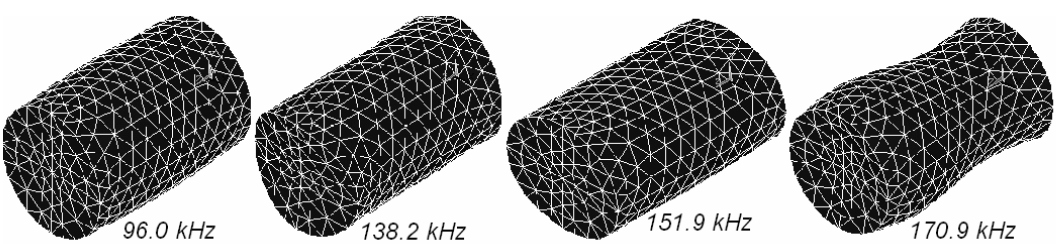

Figure-3 Some of the selected vibration modes of a 1.52 cm dia, 2.54 cm thick cylinder

These Finite Element results were validated with the theoretical results obtained from equations (1) ref. [6], the frequency of a plate can be calculated from;

$$\omega = \frac{\lambda}{R^2}\sqrt{\frac{D}{\rho h}} \quad \text{with} \quad D = \frac{Eh^3}{12(1-\nu^2)} \tag{1}$$

where: R is the cylinder radius, h is the cylinder length, ρ is the mass density, λ is the frequency parameter (a function of cylinder thickness and density), D is the flexural rigidity of the plate, and E and ν are the material's Elastic modulus and Poisson's ratio.

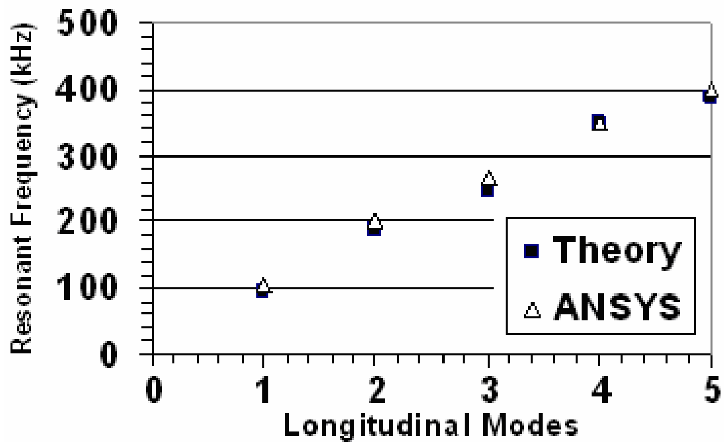

Figure-3 Comparison between theory and FEA solutions for a disc 2.54 cm dia and 1.76 cm thick.

The frequency parameter can be obtained by using Mindlin's[7] potential functions in the governing equations of motion. It was observed that the above given relation worked well when the plate was thin to moderately thick. A comparison between the Finite Element analysis and the theoretical analysis for various modes of vibrations is as shown in Fig. 3. The results show an excellent agreement. The results deviated when the plate became thick. Hence for this work we relied on the Finite Element analysis.

Figure 4 shows the resonant frequency plots as a function of disc thickness for three disc diameters as obtained by FEA. Based on these curves we can now discuss the ACTTU results. The difference in transmitted amplitude is due to the fact that only the 2.54 cm diameter cylinder has a resonant frequency close to the center frequency of the scanning transducers. The curved line in Figure 5 shows the theoretical first longitudinal natural frequency of a 1.27 cm long cylinder over a range of cylinder diameters. It can be seen that for a cylinder of this length, a 120 kHz probe is best suited for examining cylinders with a diameter of slightly over 2.54 cm in length.

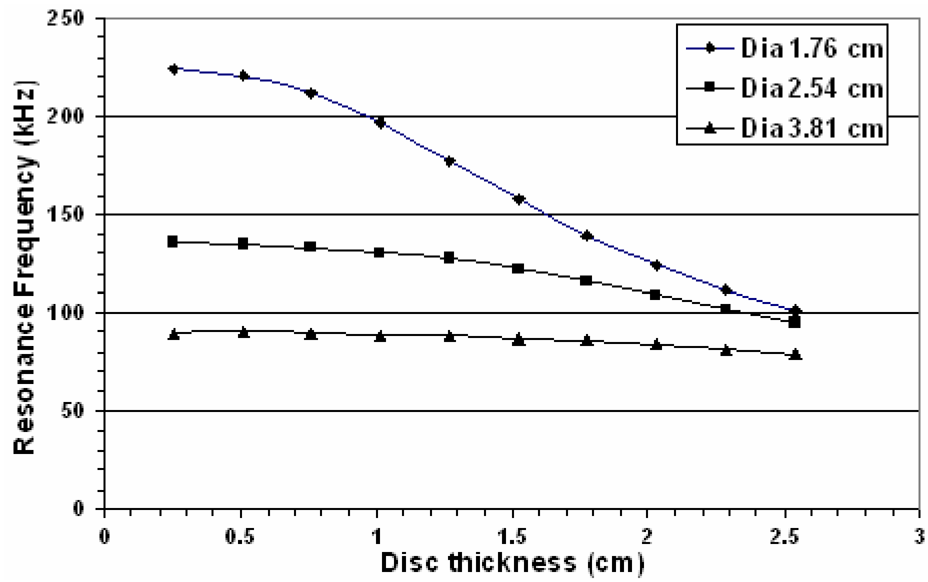

Figure-4 Resonant frequency as a function of disc thickness.

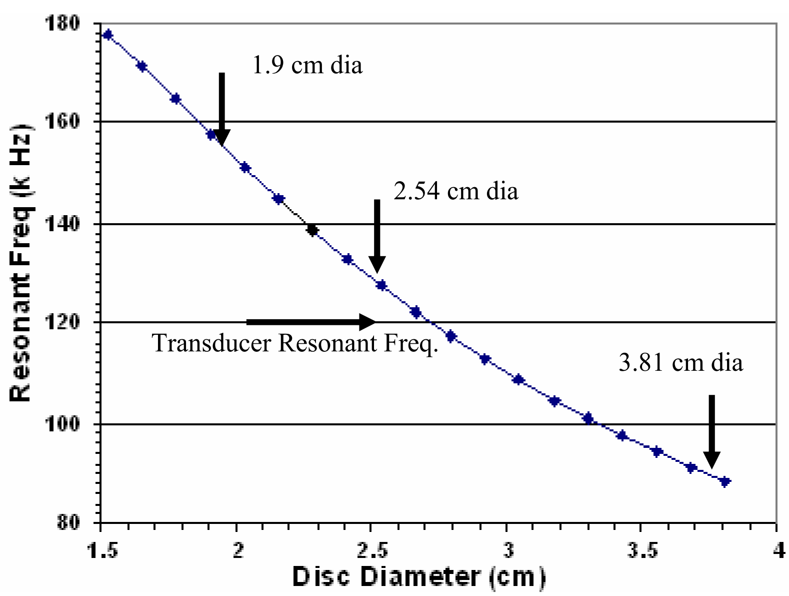

Figure-5 Resonant longitudinal frequency for cylinders with a thickness of 1.27 cm

Thus, for the purpose of NDE it becomes important to know the dimensions and the material properties of the disc. Without which the proper inspection frequency can not be determined.

EXPERIMENTAL VERIFICATION

The schematic of the experimental set up is shown in Fig. 6. The charge output accelerometer attached to the aluminum cylinders was connected to a charge amplifier, and power supply. The aluminum cylinders were suspended from a lightweight string in order to allow free vibration of the cylinder. The accelerometer was attached to the cylinders at the center of one cylinder face. The cylinder was then carefully tapped near the center of the opposite face. This test set-up was selected in order to induce longitudinal vibration in the cylinder. The output of the accelerometer was fed to a digital oscilloscope with FFT capability.

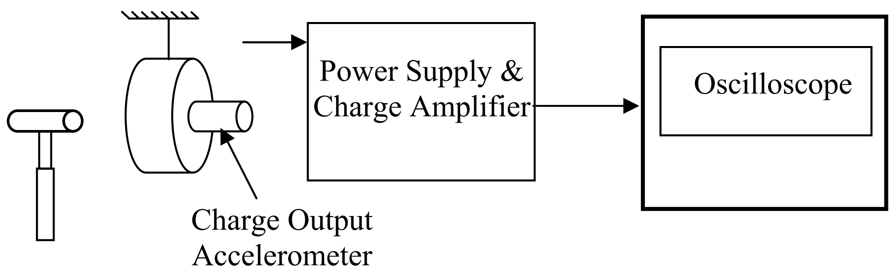

Figure-6 Test set-up for experimental modal testing of cylinders.

Figure 7 shows the experimental and FE results for an aluminum cylinder with a diameter of one inch and a thickness of one inch. The FE results are shown as vertical lines superimposed on several power spectrum FFTs. The test results obtained from the experimental investigation of longitudinal frequencies of the aluminum cylinders compared favorably to the theoretical frequencies obtained with ANSYS. First longitudinal natural frequency obtained with ANSYS agreed the experimental natural frequency with a variation of approximately 2%. The higher order natural frequencies varied by approximately 5%, possibly due to the effect the added mass of the accelerometer had on the experimental determination of frequency of the system.

CONCLUSIONS

Proper selection of the testing frequency is very important in air-coupled through transmission ultrasound inspection of thick metal parts. The testing frequency should be such that it excites resonance in the part. By matching the longitudinal natural frequencies of the insert with the inspection frequency of the ACTTU, an investigation of the bond condition of the cylinder and the facesheets can be made. An example of this is shown in Figure 2.[1]

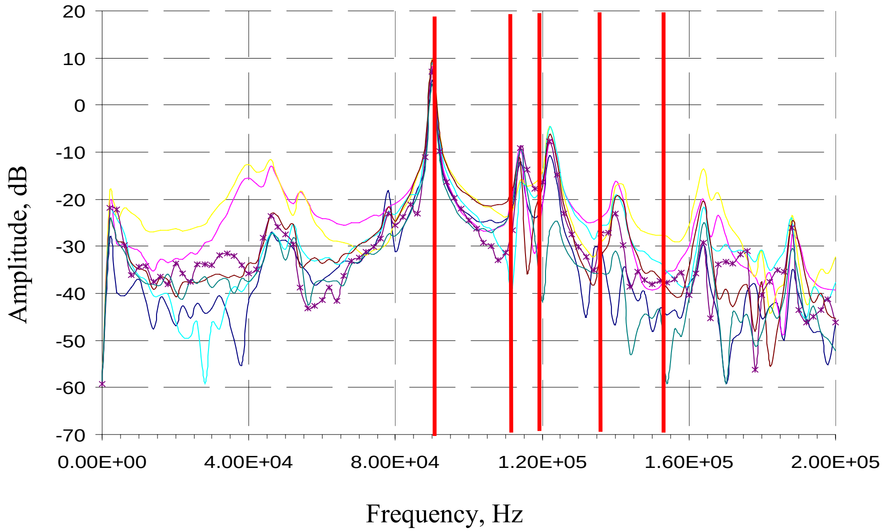

Figure-7 Longitudinal vibration frequency spectrums of a 2.54 cm long, 2.54 cm diameter aluminum cylinder along with predicted natural frequencies from ANSYS (Vertical Lines).

ACKNOWLEDGMENT

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