Air-Coupled Ultrasonics: Modelling and Experimental Studies for Thick Composite Liners

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Abstract

Composite materials have gained importance in various fields because of their properties like higher specific strength, higher specific stiffness, corrosion resistance etc. They are used as ablative nozzle liners in aerospace sector for functioning under high thermal and erosive environments. Quality assurance is very important for these composite liners, being critical components of launch vehicles and rockets. Defects like delaminations, low density regions can significantly change the erosion rate of these liners thereby leading to mission failure. Till now, radiography testing (RT) has been the primary NDT technique for composite liners. Thicker and larger diameter nozzle liners need very high energy for taking tangential radiography thereby necessitating linear accelerators. Ultrasonic testing (UT) is introduced with the aim of reducing/ replacing radiographic testing. UT using liquid couplant is to be avoided while testing because of the porous nature of these composite liners, as the liquid couplant may ingress inside the liner thereby affecting performance and further processing.

In this paper, the application of air-coupled ultrasonic system for the NDT of nozzle liners using through transmission mode is discussed. Air-coupled Ultrasonics is an emerging non-contact ultrasonic technique which avoids the physical contact between the transducer and material being tested. The transducers and equipment are designed to reduce the energy losses occurring due to acoustic impedance mismatches. Finite element analysis is performed using the general-purpose finite element package-ABAQUS® to simulate the wave propagation in composites with air-coupling and to study the interaction of wave with defects in composites. Experimental studies are carried out on composite specimens. A specially designed seven axis manipulator system is used for the quick scanning of the nozzle liners with air-coupled transducers.

Keywords: Air-coupled Ultrasonics, Ablative nozzle liners, Through-transmission mode.

1. Introduction

Composite materials are increasingly being used in many applications. They offer many advantages such as specific strength, specific stiffness, directional tailorability etc. and are the preferred ones for the structural applications. Because of their thermal, ablative and fire retardant properties, they are used in applications such as ablative nozzle liners for functioning under very high thermal and erosive environments. Generally ablative composites are used in the nozzles of solid motor of a rocket or a launch vehicle to sustain the high temperature and velocity of the combustion gases. Silica phenolic and carbon phenolic composites are commonly used for making nozzle liners.

In this paper, the application of air-coupled ultrasonic system for the NDT of nozzle liners using through transmission mode is discussed. Modelling and simulation is done using general purpose Finite Element package, ABAQUS® for the generation of waves in composite material with air-coupling and to study the interaction of the wave with defect in composites. The simulation results are qualitatively compared with that of experiments. The application of air-coupled ultrasonic system for the NDT of nozzle liners using through transmission mode is presented. Defect detected with air-coupled through transmission mode are compared with that of radiography and other ultrasonic techniques.

2. Feasibility of ultrasonic testing on Ablative composite liners

Ultrasonic testing operates based upon wave-material interaction phenomena and is an established method of non-destructive testing. By propagating a wave in a given medium, information about the medium can be obtained analyzing the transmitted or reflected signals. Ultrasonics are used to detect variations in structure, presence of cracks or other physical discontinuities, measure the thickness of materials and coatings and determining other characteristics of industrial products. It is used to locate critical discontinuities such as delaminations and debonds in composite products.

2.1 Conventional Ultrasonics with liquid couplant:

Conventional UT with liquid couplant may be conducted either by the pulse-echo technique or the through transmission technique. Pulse echo technique uses a single transducer. A flaw is indicated by the presence of a reflected signal ahead of the back wall echo. Through-transmission technique uses two transducers, with the transmitter on one side and the receiver on the other side of the component under test. A flaw is indicated by the reduction or absence of a transmitted signal. It also gives very good sensitivity but needs access on both sides of the component and perfect
alignment of two transducers. UT using liquid couplant is to be avoided while testing composite liners because of their porous nature, as the liquid couplant may ingress inside the liners thereby affecting performance and further processing.

2.2 Dry coupled Ultrasonics:

In dry coupled Ultrasonics, special soft rubber tipped probes, silicon rubbers are used thereby avoiding the liquid couplant. Dry coupled pulse echo technique is feasible for small sizes of the components. Even though it is easier compared to through transmission technique, it is not applicable for non-uniform thickness and higher thickness components. In such cases through transmission dry-coupled through transmission technique is adapted using soft tipped rubber probe or roller probes. Application of roller probes in through transmission mode make the testing faster and easier when compared to the soft tipped probes. Since the probes are pressed against the product, proper care needs to be taken to keep this pressure within limits.

2.3 Non contact Ultrasonics:

Researchers have tried to develop non-contact methods for material characterization by utilizing the wave phenomena, which includes optics, sound, thermal, X-ray and magnetic resonance. Laser Ultrasonics, Electro Magnetic Acoustic Transducers (EMAT’s) and Air-coupled Ultrasonics are among those methods tried to achieve the non-contact testing [1].

3. Air- coupled Ultrasonics

Air Coupled Ultrasonics is recently developed ultrasound technique that uses air or gas as coupling medium. The development of air-coupled mode would allow many more applications of ultrasound in characterizing porous and hygroscopic materials and also in medical diagnosis. But, the realities that defy air-coupled ultrasonics are very high acoustic impedance mismatch between the coupling medium (air) and the test medium. Acoustic impedance, \( Z \) is given by the product of material density and velocity of ultrasound through the material. Extremely high attenuation of ultrasound in air further aggravates the difficulty. However, for air-coupled ultrasonics to become a reality, we need the transducers and electronic systems sensitive enough to transmit and detect ultrasound without contact with the test medium. When ultrasound travels from a medium with low acoustic impedance to one of high acoustic impedance, only a fraction of the energy is transmitted to the latter.

\[
T = \frac{4Z_1 Z_2}{(Z_1 + Z_2)^2}
\]

where \( T \) – Transmission coefficient in the medium of propagation
\( Z_1 \) – acoustic impedance in air
\( Z_2 \) – acoustic impedance in test medium

Energy transferred in the medium = 20 log \( T \) (dB)

Transmission coefficients and energy transfer in selected materials at various interfaces in the non-contact mode are compared by Mahesh C. Bhardwaj [1]. By using combinations of improvement in transducers as well as equipment design, air coupled technology has now become a practical inspection tool. Buckley [2] and Mahesh C. Bhardwaj [3] give a detailed description of these advancements.

4. Modelling and Simulation studies

Modelling and simulations studies play an important role in

- Obtaining physical insight of the problem
- Optimization of experimental parameters for effective testing
- Interpretation of experimental data

Castings et al. [4] have worked on the numerical model for generation of waves in anisotropic media from a finite air-coupled transducer and studied the interaction of waves with defect. In our studies, we have tried modelling and simulation using commercial finite element package ABAQUS® for the generation and propagation of wave in composite plate using air-coupled through transmission mode. ABAQUS® explicit dynamics procedure is employed for simulating wave propagation. Explicit schemes, as used in ABAQUS®/Explicit, obtain values for dynamic quantities at time, \( t + \Delta t \) based entirely on available values at time, \( t \). The equations of motion for the body are integrated using the explicit central difference integration rule [5].

4.1 Wave generation in Air medium

Initially, modelling trials are done to simulate wave propagation in air medium which is used as coupling agent in air-coupled ultrasonics. 2D planar modelling of air domain is done and corresponding acoustic properties like bulk modulus and density are defined. Though the air medium is modelled with definite control volume, infinite medium is simulated by assigning non-reflecting planar interaction properties on either sides as represented in the Fig. 1. Two dynamic, explicit steps namely excitation and propagation are defined. During excitation step, hanning pulse with excitation

![Fig. 1: Modelling of Air domain](image)
frequency of 400 KHz and 15 cycles is applied on a node at one end and the wave propagation in air medium is analysed during propagation step.

The hanning pulse is denoted graphically in the Fig. 2. The air domain is discretized spatially into elements of dimensions around $1/20^{th}$ of the wavelength of the propagating wave in the media at the given excitation frequency. Then, the magnitude of acoustic pressure is measured at various distances away from the transmitter end. The results indicate that there is a reduction in amplitude along the length, which is contributed by attenuation of energy in air. Otherwise, there is no change in the signature of acoustic wave.

### 4.2 Wave generation in composite plate

Then, modelling is performed to generate wave in composite plate using Air-coupled through transmission mode. 2-D modelling of composite plate and the air column (coupling medium) are done as represented in the Fig. 3. 2-D modelling is done with the assumption of plane-strain condition i.e., the dimension in third direction (axis perpendicular to the paper) is assumed to be of infinite length. Transmitter and receiver strip are coupled to composite plate using air column by applying tying constraints. Material orientation and properties are also defined for composite plate, being anisotropic in nature.

CPE4R (4-noded bilinear plane strain quadrilateral with reduced integration) is chosen for meshing composite plate and AC2D4R (4-noded linear 2-D acoustic quadrilateral with reduced integration) is chosen for air medium. Two dynamic steps namely excitation and propagation are defined. During excitation step, acoustic pressure is applied over a transmitter strip. During the propagation step, the wave gets propagated from transmitter to receiver through composite plate. After analysis, the magnitude of acoustic pressure averaged over the receiver strip is determined. Later, simulation is done to study the effect of composite thickness on wave propagation. Composite plates of 10 mm, 20 mm and 30 mm thickness are modelled and analysis is performed for each case. The analysis results infer that magnitude of acoustic pressure at receiver end reduces with increase in composite thickness. The normalised acoustic pressure at receiver end are tabulated below (Table 1)

<table>
<thead>
<tr>
<th>Liner thickness modelled ($\times 10^{-3} m$)</th>
<th>Acoustic pressure at receiver end ($N/m^2$)</th>
<th>Normalised value for Acoustic pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.12158E-13</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>5.78924E-14</td>
<td>0.516167</td>
</tr>
<tr>
<td>30</td>
<td>4.31477E-14</td>
<td>0.384704</td>
</tr>
</tbody>
</table>

### 4.3 Interaction of wave with defect in composite plate

Modelling is done to study the interaction of wave with defect in composite plate as shown in Fig. 4. While modelling the plate, material is removed over a small area in order to simulate a delamination like defect in composite plate. Then, the defect of same size is modelled assigning acoustic properties as that of air and it is constrained to the composite plate by tying all the four sides. Excitation step and propagation steps are defined as earlier and the interaction of wave with the defect is studied during the propagation step. After analysis, the magnitude of acoustic pressure averaged over the receiver strip is determined. The simulation results show that there is a reduction in acoustic pressure magnitude at receiver end, when the defect is introduced in

![Fig. 3 : Modelling of Composite plate and air-coupled transducers](image3.png)

![Fig. 4 : Modelling of Composite plate with defect](image4.png)
the plate. Amplitude of acoustic pressure measured at receiver end is less than 1 percent that of amplitude obtained without defect.

5. Experimental studies

For our experimental studies we have used QMI SONDA007CX equipment with 400 kHz transducers. Air-coupled ultrasound typically operates at frequencies below 1 MHz, above this the sound transmission in air reduces, and more importantly, scattering losses in many materials become unacceptably high (2). Through transmission configuration is adapted to carry out the experiments. A carbon phenolic specimen with built-in defect is taken. The transducers are aligned on either side of the specimen and they are slightly adjusted by swiveling till the maximum amplitude is obtained. The aim is to study the change in signal amplitude over good and defect regions. Scanning is done by keeping the probes stationary and moving the specimen. The amplitude of the signals obtained over the defect region is about 10 % that of amplitude obtained over the good region, which qualitatively confirms the results obtained in our simulation studies (0.014 %). The major reasons for the variation between simulation and experiments could be due to the modelling constraints as follows:

i) Hanning pulse of 400 KHz frequency is used in simulation studies whereas tone-burst pulse of 400 KHz frequency is used in experiments.
ii) Planar transducers are modelled in simulation whereas focussed transducers are used in experiments.

6. Application

Air coupled ultrasonics find real application in detecting the delaminations occurring in large, thick composite liners. One of the carbon phenolic divergent nozzle liners is found to have many delaminations. Using dry coupled pulse echo technique the delaminated regions are mapped. Then air coupled equipment is used to find these defects. The results are matching and have given us very good confidence of applying this technique on further products. 7- axis manipulator is realised for precise positioning and orientation of the probes while testing the nozzle liners. The surface of the liner can be covered in two ways.

1. Linear scanning: traversing of the probes at incremental positions of table rotation.
2. Circumferential scanning: rotation of the table by keeping the probes fixed at incremental positions.

Results correlate well with those obtained by UT using roller probes as well as RT. Fig.5 shows testing of a nozzle liner. By keeping the transducers at constant distance, attenuation increases by increase in material thickness and at the same time, it reduces as the air travel distance between the transducers reduces. This factor is taken into consideration while testing.

7. Conclusions

In the defect detection and characterization, ultrasonic testing with air as couplant is one of the most significant developments. Simulation and experimental studies are carried out to have better understanding of air-coupled ultrasonics and their results are compared. The variation between simulation and experiment is due to modelling constraints. Further, studies are being carried out to improve the modelling. Composite nozzle liners are scanned using air-coupled ultrasonic system. Results are found to be matching with those obtained by RT and UT with dry coupled roller probes. Time reduction in testing is the most impressive factor compared to the dry coupled UT. Also this reduces the uncertainties in the application of pressure in the dry coupled probes. With the confidence gained in these tests, RT can be reduced to a minimum for many of the nozzle liners.

8. Acknowledgements

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References

5. ABAQUS® User Manual