A Numerical study on proper mode and frequency selection for riveted lap joints inspection using Lamb waves.

Mohammad. H. SOORGEE
Nondestructive Testing Lab. Faculty of Mechanical and Energy Engineering, Shahid Beheshti University, Tehran, Iran. Phone: +98 21 7393 2707, Fax: +98 21 7731 1446, Email: mh_soorgee@sbu.ac.ir

Abstract:
Riveted and bolted lap joints are widely used in aircrafts and other shell like structures. Inspection of such joints is of interest, as the joint holes are stress concentration zones and fatigue cracks can be existed beside these holes. One of the most suitable tools for such an inspection is Lamb wave technique, which must be tuned for a better and more sensitive inspection. As a Lamb mode interacts a lap joint, it would be partially transmitted as well as partially reflected. The key point here is if one is looking for damage in the target plate (the plate which the actuator is not bonded on), the transmission coefficient of the propagated wave should be maximized for more sensitivity on target plate inspection. In this paper a 2D numerical model, simulated in ABAQUS FEM package is employed in order to study Lamb modes behavior while interacting a lap joint. Several simulations are done for a preselected lap length, plate thickness and joint contact pressure, while changing the mode and frequency. It has been shown that the fundamental antisymmetric mode is more transmitted from the joint rather than the symmetric mode. It is seen that the transmission coefficient of the Ao Lamb modes depends on the wavelength as well as the wave structure.

Keywords: ultrasonic testing (UT), Lamb waves, crack depth, transmission, reflection

1 Introduction

Structural Health Monitoring (SHM) of bolted or riveted lap joints is a very important step of structural integrity, due to the need for crack detection in there joints. Circular holes made for bolt or rivet connection, have great potential of fatigue crack growth beside them, as they are stress concentration zones. So, inspection of such lap joints is of interest. Among several methods for lap joints inspection, ultrasonic guided waves have suitable characteristics like large area inspection capability, possibility of being used as permanent SHM tool, and high sensitivity, and can be employed for such a purpose. A complete review of ultrasonic guided waves theory and applications can be found in [1, 2 and 3].

Several researchers focused on fatigue crack detection in lap joints. He and Guan [4] focused on multi-feature integration method for crack detection in riveted lap joint, while selecting a mode and frequency based on available 300 KHz piezoelectric discs. Bao and Giurgiutiu [5] have performed a valuable experimental and numerical study on the effect of fastener load on Lamb modes propagation through lap joints, while repeating the tests for several frequencies. They have shown that in several frequencies and several fastener load, the wave behavior changes. Lanza and Pizzo [6] worked on adhesively bonded lap joint and showed that Ao mode is more suitable for such a joint inspection.

The problem of lap joint inspection is a challenging Lamb wave inspection problem. In order to reach higher sensitivity, the transmitted wave from the lap joint must be maximized. So, one should look for a proper mode and frequency that causes larger
transmission through the joint. The subject of this paper is to numerically investigate several wavelengths for a predefined lap joint, and study the effect of the wavelength in each fundamental mode on transmission coefficients. The problem is described in the next section.

2 Problem definition

As stated before, the goal of the work is to study the effect of the excited Lamb modes wavelength on transmission of the wave through a lap joint. A two dimensional plain strain FE model has been considered for this purpose as shown in Figure 1. A pair of 2mm thickness aluminum plates, E=69 GPA and v=0.33, with 20 mm overlap length, representing the lap joint is simulated in ABAQUS. A uniform pressure, P=10 MPa, has been applied on both sides of the overlap area, as a simple model of the rivet load. Moreover, a surface to surface contact with the coefficient of friction equal to 0.1 has been defined in the overlap region, between two plates.

![Figure 1: Geometry of the problem, 2mm thickness aluminum plates, dimensions are in (mm)](image)

In order to excite pure Lamb modes, a four element comb transducer has been considered, simulating by piezoelectric layers in implicit FE method. Based on the fundamentals of comb transducers, in case of simultaneous excitation of all comb elements, the distance between elements must be equal to desired wavelength, as shown in Figure 1. Two receivers, R1 and R2, have been also modeled using quadrilateral plain strain piezoelectric elements, CPE4E.

3 Dispersion and wave length study

As the effect of the wavelength of two fundamental Lamb modes, A₀ and S₀, on the interaction of the wave with the lap joint is to be studied here, excitation frequency of each Lamb mode that leads to propagating the wave with predefined wavelength should be extracted. This has been done by intersecting the inclined line, representing the desired wavelength, in the phase velocity dispersion curve with each Lamb mode dispersion curve, as some samples are shown in Figure 2.

<table>
<thead>
<tr>
<th>Mode</th>
<th>λ (mm)</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>A₀</td>
<td>f (KHz)</td>
<td>605</td>
<td>449</td>
<td>347</td>
<td>276</td>
<td>224</td>
<td>186</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>Cg (m/sec)</td>
<td>3076</td>
<td>3019</td>
<td>2927</td>
<td>2813</td>
<td>2688</td>
<td>2556</td>
<td>2425</td>
</tr>
<tr>
<td>S₀</td>
<td>f (KHz)</td>
<td>1094</td>
<td>959</td>
<td>835</td>
<td>731</td>
<td>648</td>
<td>580</td>
<td>525</td>
</tr>
<tr>
<td></td>
<td>Cg (m/sec)</td>
<td>2138</td>
<td>3185</td>
<td>4040</td>
<td>4508</td>
<td>4766</td>
<td>4920</td>
<td>5019</td>
</tr>
</tbody>
</table>
Seven wavelengths for each fundamental Lamb modes, A₀ and S₀, have been considered, and excitation frequencies and group velocity of each mode has been obtained via dispersion analysis, and shown in Table 1.

Figure 2: Sample wavelength analysis on dispersion curve

So, for example, in order to excite pure S₀ mode with the wavelength equal to 7mm, the excitation frequency of the comb transducer, should be 731 KHz. Several Finite Element (FE) simulations have been performed which is discussed later.

4 Finite element simulation
A 2D finite element model has been developed using ASBAQUIS FE software. Implicit dynamic has been utilized for simulation with time increment equal to 1x10⁻⁷ sec, in order to provide enough samples for data recording. Piezoelectric material with d₃₁=-250x10⁻¹² and d₃₃=500x10⁻¹² m/v has been considered for transducers model. Tie constraints have been defined between piezoelectric transducers and plates. A three step modeling approach has been selected, the first step was a static step, constraining all parts while defining contact and tie constraints. The second step also was a static step, for applying pressure load, as a simple representation of the fastener. The third step was a dynamic implicit, in which actuators have been fired with a 300 volts-5 cycle tone burst at desired frequency and wave propagation has been simulated.

Figure 3: Deformation scaled snapshots from wave propagation, A₀ mode excited, λ=7mm, y coordinate is also scaled 3 times

R1 and R2 electric potential (EPOT) nodal variable has been captured and summed up over all nodes of the piezoelectric part, as sensor signal. Scaled snapshots from wave propagation is shown in Figure 3, from wave approaching, interacting with, reflecting from and transmitting through the lap joint, for the case which A₀ mode has been excited with λ=7mm. As it is seen in Figure 3-b, as the wave arrived at the lap region, the deformed configuration of the bottom plate, acts as an excitation for the target plate, and
began to excite the far left side of the second (or target) plate. Although the wave propagated in the first plate has been excited with narrow band excitation signal (5 cycle tone burst at the frequency of 276 KHz for the case shown in Figure 3), but the second plate has not essentially excited at this frequency. The displacement pattern shown in Figure 3-c and d, confirms this fact.

Moreover, the generated waves in the second (or target) plate, seems to be affected by the wave structure of the generated wave in the first plate. Figure 4 shows the plate scaled deformation while \( A_0 \) mode propagates, and out of plane displacement component of each case is given in the figure. As it is seen, as the wave length increases, the magnitude of the out of plane displacement (U2) of the plate increases, consequently make the expectation that the transmitted wave amplitude must be increases, too. In order to compare the effect of the wave length and mode on transmitted wave, receiver's signals are captured, which is presented in the next section.

![Figure 4: Scaled snapshots from \( A_0 \) Lamb mode approaching the lap joint for several wavelengths, focusing on the out of plane displacements](image)

The variation of U2 with respect to \( \lambda \) is shown in Figure 5. As it is seen, the \( A_0 \) mode has considerably larger out of plane displacement comparing to \( S_0 \), as expected from theoretical aspects of Lamb modes. Thus it is expected that the \( A_0 \) will transmitted more than the \( S_0 \).

![Figure 5: Variation of the out of plane displacement on the plate surface vs. wavelength for \( A_0 \) and \( S_0 \) modes](image)
5 Results and discussion

It is more interesting to focus on signals got from R1 and R2, for more accurate investigation. These signals have been normalized by dividing the whole signal by the peak to peak amplitude of desired mode related peak in R1. Figure 6-a shows the signal got from R1 while $S_0$ mode has been excited at $f=1094$ KHz, in order to achieve $\lambda=4$ mm. Figure 6-b shows R2 signal for the same case.

![Normalized signals](image.png)

Figure 6: Normalized signals got from R1 and R2 for the case $\lambda=4$ mm, for both $A_0$ and $S_0$ modes excitation and their frequency content

The Fast Fourier Transform (FFT) of these signals are shown in Figure 6-e and 6-f. As it is seen, the transmitted wave signals (R2- signal) has the same bandwidth with the excited signal for $S_0$ mode at $\lambda=4$ mm. The same fact happens for $A_0$ mode, at $\lambda=4$ mm, as seen in Figure 6-c and 6-d for normalized amplitude and Figure 6-f and 6-g for frequency content. Although the band width of R2 signal for $A_0$ mode is larger than R1 for $A_0$.

The amplitude of signals can be also compared. The transmission coefficient (TC) can be defined as below:

$$TC_S = \frac{P_{2PA(R2)}-S_0\text{ mode peak}}{P_{2PA(R1)}-S_0\text{ mode peak}} \quad S_0 \text{ excitation} \quad (1)$$

$$TC_A = \frac{P_{2PA(R2)}-A_0\text{ mode peak}}{P_{2PA(R1)}-A_0\text{ mode peak}} \quad A_0 \text{ excitation} \quad (2)$$

$TC_S$ stands for $S_0$ mode transmission coefficient and $TC_A$ stands for $A_0$ mode transmission coefficient.

Based on the definition presented in Eq. (1) and Eq. (2), the transmission coefficient of $A_0$ mode is larger than the $S_0$, for $\lambda=4$ mm, as extracted from Figure 6-b and 6-d.
The same discussion can be done for other wavelengths. The results for $\lambda=7\text{mm}$ and $\lambda=10\text{ mm}$ are shown in Figure 7 and Figure 8 respectively.

![Normalized signals](image)

Figure 7: Normalized signals got from R1 and R2 for the case $\lambda=7\text{mm}$, for both $A_0$ and $S_0$ modes excitation and their frequency content

![Normalized signals](image)

Figure 8: Normalized signals got from R1 and R2 for the case $\lambda=10\text{mm}$, for both $A_0$ and $S_0$ modes excitation and their frequency content

As it is seen in Figure 7-b and 7-d, for $\lambda=7\text{mm}$, the transmitted $A_0$ mode has a larger transmission coefficient than the $S_0$, $T_{CA}>T_{CS}$, the same is true for $\lambda=10\text{mm}$, based on Figure 8-b and 8-d. This is observed for all wave lengths simulated in this work. So it can be concluded that the transmission coefficient of $A_0$ mode is larger than the $S_0$, for the same wavelength.
But as the wavelength increases, the band width of transmitted waves increases, too. This can be obtained from Figure 7-f and 7-h, comparing to Figure 7-e and 7-g, respectively. Moreover, comparing Figure 7-f with 7-h, shows that the amount of increase in the band width for S₀ mode is smaller than the A₀, for λ=7mm. As the wavelength increases more, it is hardly possible to find transmitted wave packet related peak, especially for A₀ mode, as shown in Figure 8-d.

Figure 8 shows signals for the case λ=10mm, which is half of the overlap distance. So the wave length is in the same order with the overlap zone length. In this case, the deformation of the overlap area causes a non-uniform excitation of the second plate, and a wide band acoustic wave propagates in the target plate. R2 signal shown in Figure 8-d and its frequency content shown in Figure 8-h confirm this phenomena. So although A₀ mode transmits more than S₀, but as the wavelength increases, multiple modes are excited in the second plate that makes the signal interpretation difficult.

6 Conclusions
The effects of the wavelength and propagating mode on the transmission coefficient of Lamb modes from a lap joint have been numerically investigated. It has been shown that the fundamental anti-symmetric Lamb mode (A₀) has larger transmission coefficient from the lap joint comparing the symmetric mode, S₀, with the same wave length. Also for both modes, as the wave length increases, the band width of the transmitted wave signal increases, which means multiple modes are excited in the target plate. So in order to inspect a lap joint, the paradigm of smaller wavelength and smaller TC should be optimized.

7 References