OPTIMIZATION OF PZT ACTUATOR/SENSOR ARRAY FOR MONITORING OF AIRCRAFT FUSELAGE PANEL USING ULTRASONIC LAMB WAVES

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Abstract
The paper deals with design of permanently mounted PZT actuator/sensor array for corrosion damage detection, localization and size evaluation on an Aluminum alloy aircraft fuselage panel. Properties of commercially available PZT actuators are studied in the first part. In particular, frequency tuning capability of the PZTs is especially analyzed. The aim of the analysis is to provide required data for selection of appropriate sensor type for a particular application. As part of the analysis several test measurements were completed. Results of the measurements are presented and discussed in the paper as well. Finally, configuration of the sensor array including sensor array position, type of sensor, and Lamb wave excitation parameters is discussed and proposed.

Key words: fuselage panel, corrosion, Lamb waves, PZT actuator, phased array, optimization

1. Introduction
Ultrasound has been proven as a powerful tool for Non-Destructive Testing (NDT) in many branches of industry [1]. In particular, ultrasonic Lamb waves have been shown as effective means for monitoring structural integrity of plate like structures [2]. Lamb waves are guided elastic waves that can travel in a solid plate with free boundaries at their top and bottom surfaces. During their propagation through the solid plate structure, they form several symmetric and antisymmetric modes related to the plate thickness and acoustic frequency of the waves. The phase velocity of these modes is dependent on frequency and described graphically by a set of dispersion curves. An advantage of Lamb waves is that they can propagate for long distances in plate structures. Moreover, in contrast to the conventional method where inspection of the structure is made point by point, a line is inspected at each position of the transducer. Therefore, Lamb waves provide significant time savings and can form the basis of an approach to actively monitor a plate structures without moving the transducer.

The paper aims at design of PZT actuator/sensor array for in-situ monitoring of corrosion damage on an Aluminum alloy aircraft fuselage panel. Schematic drawing of the panel is depicted in Figure 1. It is a part of L-410 UVP-E airplane which is all-metal high-wing monoplane powered by two turboprop engines. The airplane is certified in the commuter category in accordance with FAR 23 requirements. The panel cut was taken from the rear part of the aircraft fuselage in the area of toilet. The location is
exposed to adverse corrosive environment due to leakage of corrosive liquids from the toilet. Moreover, the location is hard to reach for visual or other types of NDT inspection. A series of preliminary tests was conducted separately on the skin plate and stringer under various corrosion conditions to analyze corrosion behavior of basic materials and panel surface protection. It was found that we can expect emergence of corrosion mainly in the contact between fuselage skin and stringers, with the most critical location for emergence of corrosion damage given by the position of the tacking rivets.

2. Frequency Tuning of PZT Sensor/Actuator
Recent development in Structure Health Monitoring (SHM) revealed advantages of small, low weight, and low cost PZT actuators, which can be permanently fixed, integrated, or embedded into the monitored structure [3]. The PZT actuators permanently installed on the structure or even integrated into structure during its fabrication allow periodical or continuous monitoring of critical structural elements which are hard to reach for common inspection NDT techniques. Moreover, the PZT actuators, in contrast to common ultrasonic transducers, can be frequency-tuned to achieve optimal detection conditions for particular structure and defect type [4]. There are specific requirements for use of PZT actuators arising from particular applications. 1. actuator dimensions should be small enough to allow formation of phased arrays; 2. actuator should operate in appropriate frequency range to allow frequency tuning for particular material type and thickness (100-700kHz); 3. cost of the actuator should be reasonable enough for use in phased arrays with large number of elements without possibility of reuse after array installation. Based on these criteria, Noliac’s shear plate PZT actuators were selected for the experiments. The actuator properties are summarized in Table 1. These actuators are more efficient in generation

![Figure 1 Drawing of the test specimen - L-410 UVP-E fuselage panel (dimensions in millimeters).](image)

### Table 1 Parameters of used Noliac’s PZT actuators.

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<tbody>
<tr>
<td>CSAP01</td>
<td>2</td>
<td>2</td>
<td>0.5</td>
<td>+/- 320</td>
<td>1.5</td>
<td>133</td>
</tr>
<tr>
<td>CSAP02</td>
<td>5</td>
<td>5</td>
<td>0.5</td>
<td>+/- 320</td>
<td>1.5</td>
<td>830</td>
</tr>
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of S modes of Lamb waves than A modes. S modes are appropriate for detection of through-the-thickness defects whereas A modes are better for detection of surface defects. Further, S0 mode is less dispersive in required frequency range and it propagates at higher velocity than A0 mode so that mode separation in time domain can be utilized.

A model of the Lamb waves tuning mechanism with PZT transducers is described in [4]. The principle of the PZT’s frequency tuning is based on the fact that maximum coupling between transducer and investigated structure is achieved when the active PZT’s dimension length equals the half wavelength of a particular Lamb wave mode. Since Lamb wave modes wavelengths vary with frequency, the tuning of certain modes at certain frequencies can thus be achieved. Results of the modeling for CSAP01 and CSAP02 actuators on Aluminum plate with 0.8 mm thickness are presented in Figure 2. The theoretical results were experimentally verified. Comparison of predicted and experimental amplitudes for S0 and A0 modes generated by CSAP02 actuator on 0.8 mm Al plate is shown in Figure 3. Differences between prediction and experimental data are caused by some assumptions in model design (e.g. ideal bonding between actuator and plate), measuring equipment, and/or measurement assessment. The locations of minima and maxima of the curves are more significant than the exact shape, which are reproduced well in the experimental results.

![Figure 2](image_url) Predicted Lamb wave response of a 0.8 mm aluminum plate under CSAP02 excitation: strain response.
3. Optimization of Phased Array Sensor

Utilization of phased arrays allows application of advanced digital signal processing algorithms for ultrasonic beam steering and focusing. For our purpose we use Synthetic Aperture Focusing Technique (SAFT) and/or Embedded Ultrasonic Structure radar (EUSR) that are both based on well known delay-and-sum approach [5]. Utilization of the phased array together with the advanced signal processing improves signal/noise ratio and spatial resolution of the defect detection system.

The spatial resolution of the ultrasonic defect detection system based on Lamb waves and digital ultrasonic beam steering/focusing using delay-and-sum approach can be expressed by means of the imaging system Point Spread Function (PSF). The PSF can be obtained either experimentally or using a mathematical model. A mathematical model for the PSF estimation which accounts for position variability can be found in [6]. Using the model the position variable PSF is defined as

$$ I(r, r_0) = \int_{-\frac{A}{2}}^{\frac{A}{2}} \frac{x(u)e^{i2\pi fu}}{\sqrt{r_s - r_0}^2} dr_s $$

where $x(u)$ is ultrasound pulse envelope, $A$ is transducer aperture, $f$ ultrasound pulse frequency, $c$ ultrasound velocity for investigated material, $r$ is position variable for the PSF evaluation, $r_0$ is position vector of the center of the position variable PSF and $r_s$ represents position vector of single transducer elements. Based on the mathematical

![Figure 3 Comparison of theoretical tuning (normalized strain) and experimental data (normalized Volts) for CSAP02, 0.8 mm Aluminum plate.](image-url)
model, we can say that the PSF is given by wavelength of the Lamb wave in the interrogated material, and geometrical configuration of the phased array sensor elements. Generally, higher ultrasonic pulse frequency and closer elements in the array result in better spatial resolution. However, due to dispersion properties of Lamb waves the situation is a little bit complicated. The wave velocity of Lamb waves vary with its frequency. The relationship is given by so called dispersion curves, which describe the dependence of the ultrasonic wave velocity on the wave frequency-plate thickness product for individual Lamb wave modes. An example of dispersion curves for A0 and S0 modes for Aluminum 2024-T4 plate of 0.8 mm thickness is shown in the Figure 4a). For every wave frequency at least two (A0 and S0) modes are excited and with increasing wave frequency number of modes increases. For particular mode there are areas which are less or more dispersive. Figure 4b) shows variability of wave wavelength with wave frequency for the modes.

Excitation pulse main frequency, ultrasonic pulse wavelength and actuator spacing should be taken into account to control the spatial resolution. The shear plate actuators we are using for the Lamb wave generation produce dominant S modes. Therefore, properties of S modes were considered for determination of the above mentioned parameters. In particular, S0 mode was used in our application. First, pitch between individual actuators was limited by their geometrical dimensions, which are 2 x 2 mm for SCAP01, and 5 x 5 mm for CSAP02. Regarding that, it was reasonable to define minimal pitch equal to 5 mm for CSAP01, and 10 mm for CSAP02, respectively. By contrast, the pitch should be smaller than one half of the ultrasonic pulse wavelength to prevent emergence of false artifacts in resulting ultrasonic image. This requirement gave minimal value of the wavelength for particular sensor pitch, which was 10 mm for 5 mm pitch and 20 mm for 10 mm pitch, respectively. Using dispersion curve for S0 mode (Figure 4b) maximal mean frequency of excitation pulse was defined for both the values of inter-element pitch. The limiting frequency was 550 kHz for 5 mm pitch, and 280 kHz for 10 mm pitch. Finally, the pulse excitation frequency was adjusted with regard to Lamb wave response as a function of the pulse frequency, which is shown in Figure 2,
Table 2 Selected combinations of parameters for Lamb wave excitation.

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Pitch [mm]</th>
<th>Wavelength [mm]</th>
<th>Frequency [kHz]</th>
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<tbody>
<tr>
<td>CSAP01</td>
<td>5</td>
<td>&gt;10</td>
<td>&lt;550 (450 or 250 optimal)</td>
</tr>
<tr>
<td>CSAP01</td>
<td>10</td>
<td>&gt;20</td>
<td>&lt;280 (250 optimal)</td>
</tr>
<tr>
<td>CSAP02</td>
<td>10</td>
<td>&gt;20</td>
<td>&lt;280 (280 optimal)</td>
</tr>
</tbody>
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or possibly Figure 3 including experimental results. Selected excitation pulse frequency was a trade-off between maximal response for S0 mode and maximal separation of S0 and A0 modes, i.e. maximal S0/A0 amplitudes ratio. Applicable combinations of actuator type, inter-element pitch, ultrasonic pulse wavelength, and excitation pulse frequency are summarized in Table 2.

The last aspect which needed to be set was spatial distribution of the individual actuators in the phased array. The issue was thoroughly analyzed in [7]. For this work, a 2D arrangement of the actuators in square array of 5 x 5 actuators was selected. Such an array arrangement should provide good beam steering capability with reasonable number of actuators, thereby with acceptable number of signals for the following digital processing.

Results of modeling of the PSF for measurement configurations from Table 2 are shown in Figure 5. The spatial distribution of the PSF size is represented as full width at half maximum (FWHM). Asterisks (‘*’) in the figures indicate locations at which the PSFs are calculated, i.e. centers of the PSFs.

4. Results and Conclusions

Phased sensor array configuration for monitoring of aircraft fuselage panel was designed in the paper. The paper deals with selection of the individual sensor/actuator type, draft of optimal parameters of the actuator excitation pulse, and geometrical arrangement of the sensor/actuators in the array.

Analysis of properties of a single sensor PZT element was performed in the first part of the paper. A mathematical model was used for modeling of the sensor efficiency in generation of A0 and S0 Lamb wave modes in dependence on the excitation pulse main frequency. Results provided by the theoretical model were verified by experimental measurements on a simple plate. The model allowed identification of excitation frequency for particular sensor and material of the monitored panel which is optimal from the point of view of separation of individual Lamb wave modes. Excitation of the sensor using the optimal frequency results in generation of just one dominant Lamb wave mode which is beneficial for further advanced processing of the ultrasound signal. Further, appropriate sensor/actuator layout was proposed with regard to the actuator excitation frequency identified in the previous step. Several layouts were proposed and resulting PSF describing process of ultrasound image formation by means of delay-and-sum approach was mathematically modeled.
Figure 5 Spatial distribution of the PSF: a) pitch = 10mm, pulse frequency = 250kHz, 1x5 phased array; b) pitch = 10mm, pulse frequency = 250kHz, 5x5 phased array; c) pitch = 5mm, pulse frequency = 250kHz, 1x5 phased array; d) pitch = 5mm, pulse frequency = 250kHz, 5x5 phased array; e) pitch = 5mm, pulse frequency = 450kHz, 1x5 phased array; d) pitch = 5mm, pulse frequency = 450kHz, 5x5 phased array.
Results of the modeling are shown in the Figure 5. The presented results demonstrate shortcomings of the 1D sensors arrangement in comparison to 2D sensor layout. First, it is not possible to recognize whether defect is located in front of or behind the sensor array. Second, focusing capability of 1D sensor array quickly deteriorates with steering angle diverging from the sensor array main axis. Interplay between sensor spacing, pulse excitation frequency, and spatial resolution of the processed ultrasound image can be observed as well. It is obvious that configuration with 5 mm inter-element pitch (fig 5 c and d) provides worse steering/focusing capability than the configuration with 10 mm inter-element pitch (fig 5 a and b) at the same pulse frequency. The worsening is due to smaller aperture of the phased array when the same number of the sensors/actuators is used as in the case of the larger pitch. Finally, the same 5 mm pitch was used but with higher excitation pulse frequency, i.e. shorter wavelength. We can conclude that this arrangement provides similar spatial resolution in the radial direction to the ultrasonic beam propagation as the one with 10 mm pitch. However, improvement in the spatial resolution in the axial direction – direction parallel to the beam propagation – can be observed.

5. References

6. Acknowledgement
The presented work has been supported by the Ministry of Industry and Trade of Czech Republic by grant project no. FR-TI1//274 under framework program TIP.