THE USE OF PERMANENTLY-MOUNTED SURFACE TRANSDUCERS TO CHARACTERIZE LAMB WAVE PROPAGATION

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Abstract

For a few years, the concept of integrated health monitoring of aeronautic structures has become an important issue. For a number of reasons, Lamb waves are considered to be a promising solution. In every aspect of the research activities about this concept, the use of a way of characterizing acoustic fields on the surface of the structure is essential. A solution proposed here is the use of surface-bonded piezoelectric transducers. However, since the presence of such a transducer constitutes a local heterogeneity, it is thus susceptible of locally modifying the Lamb waves propagation and thus leading to erroneous or misinterpreted results. The aim of this work was to characterize, quantify and then minimize the influence of the bonded transducer on the wave propagation. As a result, conditions under which characterization of the surface acoustic field could be considered reliable have been established.

1. Introduction

Lamb waves have been considered for several years to be a very convenient way of performing structural health monitoring of plate-shaped structures. Long range propagation and sensitivity to virtually any kind of material defects are among their most attractive properties.

From a fundamental point of view, precise characterization of the Lamb wave field present at a given position of the monitored structure is a key issue. Indeed, quantitative experimental characterization and interpretation of Lamb wave generation [1], interaction with damage [2], as well as material evaluation [3] require a way of measuring surface displacements related to Lamb wave propagation.

On this purpose, classical tools are laser interferometers [4] and mobile wedge transducers [5]. Interferometers are able to measure normal surface displacement but quality of the results depends on the optical reflection factor of the studied surface, which leads to relatively poor signal-to-noise ratios when used on dark materials such as carbon-epoxy composites. On the other hand wedge transducers require the use of a coupling medium, which makes measurements hardly reproducible. Moreover interpretation of signals is generally not straightforward. An alternative solution is the use of surface-bonded piezoelectric transducers. Provided proper surface state is ensured, permanent attachment of a thin piezoelectric element is relatively simple and reproducible enough. Besides, in the context of integrated health monitoring, this kind of receiver is best suited.

When used as a single element and in a non-resonant way, a convenient surface-attached piezoelectric transducer should be able to provide a voltage signal representative of the global displacement field on the surface. Another possibility is the use of multi-element transducers. In this case, additional information is obtained, since the contribution of each propagating mode can be extracted using the two-dimensional Fourier transform technique (2D-FT) [6-9].

However, unlike the laser probe and wedge transducer methods, the use of surface-attached piezoelectric elements constitutes a rather intrusive measurement technique. Indeed, the presence of the attached transducer introduces necessarily a local modification of the boundary conditions of the structure. Consequently, perturbations in the acoustic field to be measured are possible. In the multi-element case, degradation of the wavenumber information due to some inter-element interaction or cross-coupling is also a probability [10].

In a first part, example of a surface-attached multi-element transducer will be presented in order to illustrate the above-mentioned problems. Then, results of a numerical modelling of the same experimental configuration will be presented. Finally, by exploiting these results, design rules of convenient receivers for the considered application will be deduced.

2. Multi-element example

In a previous work [7], application of the 2D-FT using surface-attached multi-element transducers has been presented. The same example will be used here for illustrating purposes.

The piezoelectric elements that constitute the receiver were chosen so that their resonance frequencies are well beyond the frequency domain of the emitted excitation. In this way, they are expected to have a relatively flat frequency response inside the considered bandwidth. Hence, their dimensions are 15*1*1mm^3. As shown in Figure 1, an array of 32 of these elements has been bonded with a 2-mm inter-element distance to the surface of a 3-mm thick aluminium plate.

The emitter used in this application was a 4-mm wide and 1-mm thick piezoelectric element that was surface-coupled at a distance of 10 cm from the first element of the receiving array. The applied excitation signal was a 5-cycle sinusoid at the central frequency 300 kHz.

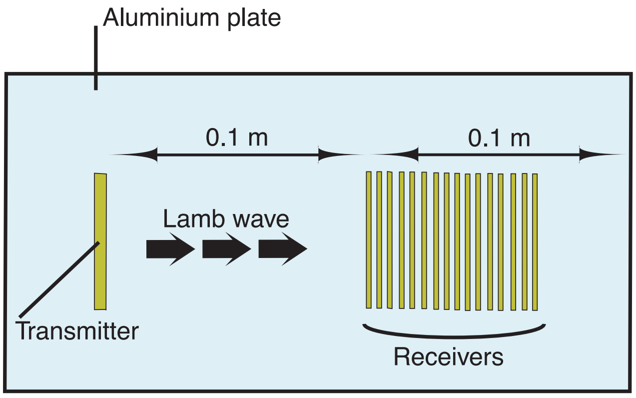

Figure 1 : Experimental set-up

As shown in [7], encouraging results have been obtained and 2D-FT using this technique has been proved feasible. However, presence of some anomalous artifacts has been noticed in the results. In particular, wavenumber values that did not correspond to any known Lamb wave at the considered frequency have appeared to have non-negligible contributions in some 2D-FT results.

Influence of the receiving elements themselves on the wave propagation seems a likely interpretation of such apparently anomalous behaviors. The presence of these surface-bonded elements constitutes a local heterogeneity in the waveguide structure. The consequence of it would be the presence of partial reflections, locally degraded wave propagation and possible mode conversions at each element, which would result in perturbations in the waveforms measured by the receiving array.

To verify and complement this interpretation, we will focus on the signal acquired at a single element among the other elements constituting the array. Hence, Figure 2 shows the signal received at the first element (closest from the emitting transducer).

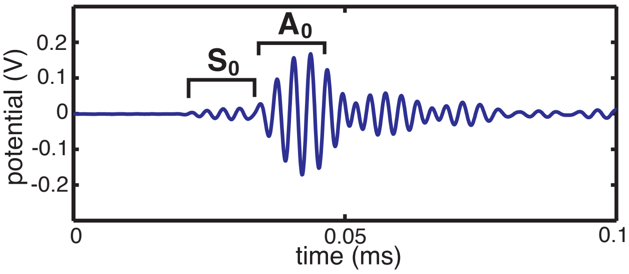

Figure 2 : Measured electric potential at the first element of the receiver array

According to the theoretical group velocity dispersion curves (Figure 3), only two, almost non-dispersive, modes should be present for the considered frequency range (around 300 kHz).

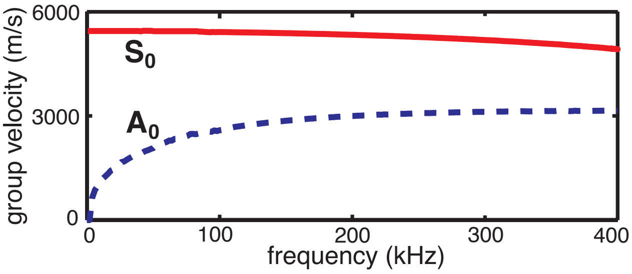

Figure 3 : Group velocity dispersion curves

Then, prediction of the individual time-of-flights enables to identify the first two wavepackets in Figure 2 as S_0 and A_0 respectively. As can be seen, additional wavepackets arriving after the A_0 packet are present in the received signal. Since the dispersion of the two generated waves is negligible and no other mode can be propagated, these parasitic contributions should be related to the influence of the neighbor receiving elements in the array. Reflection and back-propagation seem to be the most evident effects.

3. Numerical modelling and interpretation

In order to better identify and then minimize these parasitic effects, a finite element modeling (FEM) of an emitter-plate-receiver configuration as close as possible to the actual experimental set-up has been performed.

Since the length of every piezoelectric element considered in the present application is large compared to width and thickness, a two-dimensional plane strain model has been used (Figure 4). To make the prediction even more accurate, a post-processing correction has been applied to account for the slight beam divergence effects of the emitted waves [11]. The considered distance between the receiver array and the right hand plate edge has been chosen sufficiently large to avoid edge reflection contributions in the predicted transient signals. To simplify the model, perfect adhesion conditions (displacement and stress continuity) between the aluminium plate and the piezoelectric elements have been assumed. The FEM code used here is ATILA. It has been previously validated in many other related applications [12].

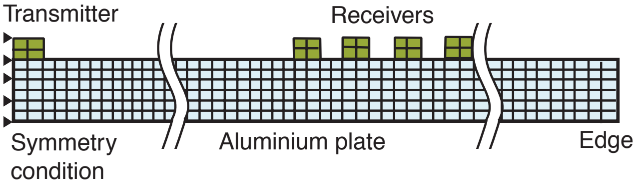

Figure 4 : Description finite element modelling

The predicted signal at the electrodes of the first receiving element is shown in Figure 5. S_0 and A_0 contributions can be easily identified. Here again, presence of the additional parasitic wavepackets is manifest.

Qualitative comparison with the corresponding experimental signal of Figure 2 appears to be satisfactory. The discrepancy in the signal amplitudes as well as the very slight differences in the A_0 and S_0 waveforms can easily be explained by the fact that the emitting transducer is not rigidly bonded on the plate surface, but rather coupled using a greasy coupling medium.

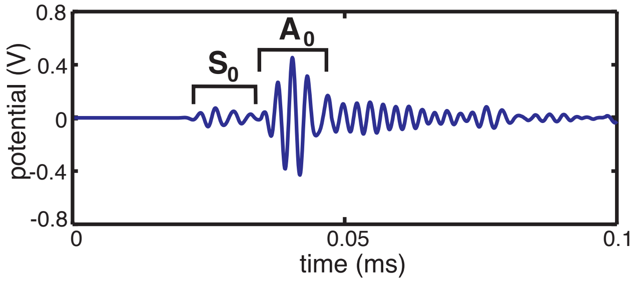

Figure 5 : Predicted electric potential at the first element of the receiver array (1 mm thickness)

Interpretation of these FEM results shows that the additional wavepackets cannot be justified by experimental hazards such as uncertain bonding conditions of the receivers or reflections on the plate edges. This tends to confirm that effects related to the very presence of the receiving elements themselves are the only sensible explanation of the observed perturbations.

4. Optimization of receivers

Solution to reduce the above-mentioned parasitic artifacts is to use piezoelectric elements that would have a lower influence on Lamb wave propagation. For a given piezoelectric material, the choice of the optimization parameters is then reduced to the width and the thickness of the receiving elements. Since the 1-mm width already corresponds to a small fraction of the wavelengths in presence, only the influence of thickness will be considered here. Practically, the use of thinner piezoelectric elements should lead to the reduction of local heterogeneities by approaching the case of a continuous waveguide.

Thus a finite element modelling of the same configuration as in section 3, except the receiver thickness is reduced down to 300 µm, has been performed. Signal at the first receiving element is presented in Figure 6. The respective wavepackets of S_0 and A_0 modes are clearly visible. Relative mode amplitudes are very different from the previous case (Figure 5), which confirms that the interaction between the incident waves and a piezoelectric element is very dependent on its thickness.

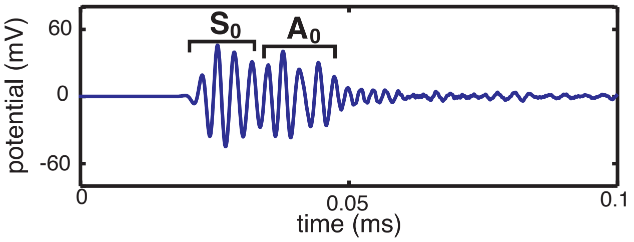

Figure 6 : Predicted electric potential at the first element of the receiver array (300 µm thickness)

Besides, as expected, contribution of the additional wavepackets related to reflections from the neighbor elements appears to be considerably reduced. Unlike the previous 1-mm thickness case, this implies that the presence of the thin piezoelectric element corresponds only to a rather negligible perturbation in the waveguide behavior. As a consequence, the measured signal should be quite representative of the actual surface displacement field of the plate.

Since the thickness and lateral dimensions of the bonded transducer are very different, its corresponding vibration modes are strongly uncoupled. Considering the frequency range applied in the present application, the transducer should thus be more sensitive to the transverse surface displacement.

Hence the “free” surface displacement field has been computed using the FEM. The very same emitting conditions have been ensured except no receiver is bonded. The signal displayed in Fig. 7 thus corresponds to the transverse displacement at the precise location where the first receiving element was positioned in the previous modeling.

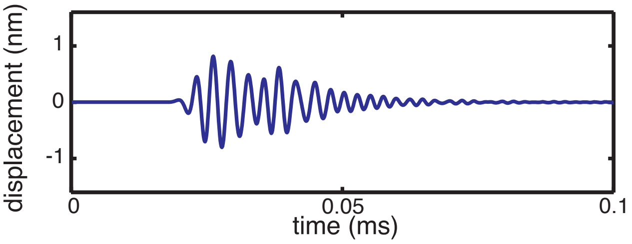

Figure 7 : Predicted free tangential surface displacement

In Figure 6 and 7, both the relative amplitudes and the individual mode waveforms appear to be very similar indeed.

Additional tests have been performed using different piezoelectric receivers with thickness between 300 µm and 1 mm. In these cases, clear influence of the transducer presence on the received waveforms has been observed. For the sake of conciseness, the corresponding results have not been detailed in this paper.

Consequently, in the particular experimental conditions presented here, transducers with thickness 300 µm or below have been demonstrated to be suitable sensors for measuring and characterizing the surface displacement fields related to Lamb wave propagation in the plate.

5. Conclusion

In this paper, the possibility of using permanently-bonded piezoelectric receivers to characterize Lamb wave displacement fields has been investigated. Quantitative conditions have been established for the design of transducers that do not perturb the acoustic fields to be measured.

For the example considered, a value of the transducer thickness / plate thickness ratio in the range 0 to 0.1 has been proved acceptable, provided the transducer width is small compared to the smallest propagating wavelength.

Using such receivers, it has been shown that a response directly proportional to the free surface displacement field could be obtained. In the multi-element case, unperturbed and reliable 2D-FT results are also achievable.

Future works should focus on further experimental validation and generalization of the established criteria.

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