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Application of a pseudo-3D modeling to Lamb waves generation by a surface-bonded apodized transducer: Experimental results

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Abstract—The objective of this paper is to predict the ultrasonic field radiated by piezoelectric transducers with finite dimensions in an isotropic plate. This prediction allows a good understanding of physical phenomenon of Lamb wave propagation used on the Integrated Structural Health Monitoring System. In order to describe correctly the radiated field, the stress field in the length direction of the transducer has been supposed to have a parabolic shape. The displacement field generated at the surface of an aluminum plate by a surface-mounted PZT transducer excited by a 5-cycle, Hanning-windowed sinusoid signal, has been measured for different directions, using a laser interferometer. Experimental and numerical results are successfully compared.

Lamb wave, Structural Health Monitoring

I. INTRODUCTION

Built-in ultrasound interrogation systems are seen as a promising solution for structural health-monitoring of civil and aeronautical structures. In this context, integration of small piezoelectric transducers into plates is of particular interest. The generated Lamb waves can be used to monitor large areas of the plate. The modeling of a full Lamb-wave emission and reception system, including a piezoelectric emitter and a piezoelectric receiver, can be done in a relatively simple and flexible way [1]. First, the emitter behavior and the Lamb wave propagation are predicted using a two-dimensional (2D) hybrid finite element-normal mode expansion model. The receiver electrical response can be obtained from a finite element computation with prescribed displacements [1]. Then, a numerical correction is applied to the 2D results to account for the in-plane radiation divergence caused by the finite length of the emitter. In order to describe correctly the radiated field, the stress field in the length direction of the transducer has been supposed to have a parabolic shape. This choice, which is a common way of taking into account apodization of a transducer, allows ensuring stress continuity at the transducer edges. This work is a continuation of the paper published about pseudo-3D modeling technique [2, 3]. In the following the modeling of the receiver will not be shown and only the displacement field for different directions (at point P, see Fig. 1) will be shown.

A complete summary of guided Lamb waves for identification of damage in composite structures can be found in reference [4].

The displacement field generated at the surface of an aluminum plate by a surface-mounted PZT transducer excited by a 5-cycle, Hanning-windowed sinusoid signal, has been measured for different directions, using a laser interferometer. The predicted displacement fields obtained by pseudo-3D modeling technique are successfully compared the measurement one.

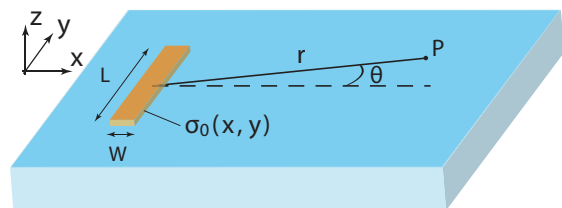


Figure 1. Description of the 3D problem geometry

II. PSEUDO-3D MODELING PRINCIPLE

Let us consider an isotropic plate with thickness d excited by a given harmonic stress $\sigma_0(x, y)$ applied on its upper surface. The excitation area S is supposed to be rectangular shaped, with length L and width W as indicated in Fig. 1. As discussed in previous papers [2], some conditions are required for the application of the pseudo-3D modeling. They are reminded below:

1. The reception point P is in the far field
2. The source stress $\sigma_0(x, y)$ can be expressed in the form:

$$\sigma_0(x, y) = \sigma_{0,x}(x)\sigma_{0,y}(y) \quad (1)$$

3. The angle θ and/or the ratio W/λ_n (where λ_n is the wavelength of the considered n th Lamb mode) have to be small. More precisely, this condition is summarized by:

$$g\left(\frac{W}{\lambda_n}, \theta\right) = 4\pi \frac{W}{\lambda_n} \sin^2\left(\frac{\theta}{2}\right) \ll 1 \quad (2)$$

Then, as shown in *Ref. 2*, the 3D field u_n^{3D} in the plate can be expressed, for a given n th Lamb wave mode, as the product of a 2D modal term and a directivity term α_n :

$$u_n^{3D}(r, \theta) = \alpha_n(r, \theta) A_n u_n e^{jk_n r}, \quad (3)$$

with:

$$\alpha_n(r, \theta) = \frac{1-j}{2\pi} \sqrt{\frac{k_n}{r}} \int_{-L/2}^{+L/2} \sigma_{oy}(y) e^{-jk_n y \sin \theta} dy \quad (4)$$

where k_n, A_n and u_n are the wave number, modal amplitude and modal displacement field of the n th Lamb mode, respectively.

III. APPLICATION TO A BONDED TRANSDUCER

In the case where the excitation is caused by a piezoelectric transducer bonded on the plate surface, the amplitude A_n associated to each propagating mode (Eq. 3) can be computed by using a two-dimensional, plane strain hybrid modeling technique [5], which will not be reminded here.

The stress profile σ_{oy} , necessary for the computation of α_n (Eq. 4), is zero outside the interval $-L/2 \leq y \leq L/2$ and unknown under the transducer. Its exact determination would require the full 3D modeling that we precisely intend to avoid. If L is significantly larger than W , the simplest hypothesis is to consider σ_{oy} as uniform. Then, the directivity α_n is easily determined from Eq. 4 and the signal received at point P with polar coordinates (r, θ) can be obtained by adding the results given for each mode by Eq. 3.

This modeling principle is illustrated in the example presented below. It corresponds to a PZT transducer with $T = 1 \text{ mm}$, $W = 4 \text{ mm}$ and $L = 20 \text{ mm}$ stuck at the surface of a 1-mm thick aluminum plate and excited by a 5-cycle, Hanning-windowed sinusoid signal with a central frequency $f = 700 \text{ kHz}$. The reception point P is located at $r = 63 \text{ mm}$ and $\theta = 0^\circ$, which makes conditions #1 and #3 (see section II) ensured. The normal displacement obtained by the pseudo-3D model (Fig. 2.a) is compared to the result of a full-3D finite element modeling (Fig. 2.b).

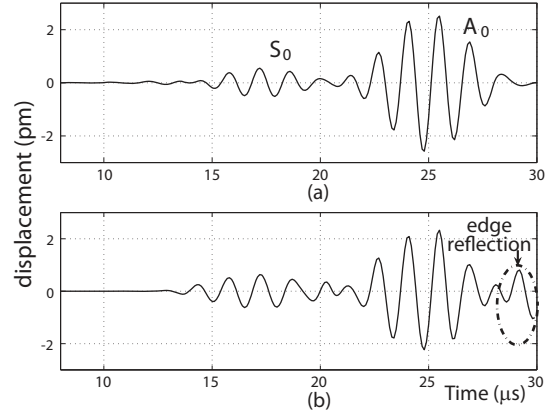


Figure 2. Theoretical normal displacement at point P for $\theta = 0^\circ$. (a) From pseudo-3D modeling. (b) From 3D FEM

A very good agreement can be observed between both results. In particular, the amplitude of each mode is correctly predicted by the pseudo-3D method. The remaining oscillations after 0.028 ms in Fig. 2.b corresponds to the wave reflection at the edge of the plate (which is necessarily limited in the FEM model) and should not be taken into account. This example, along with other cases presented previously [4], constitute a clear validation of the method, at least when the measurement point belongs to the transducer axis.

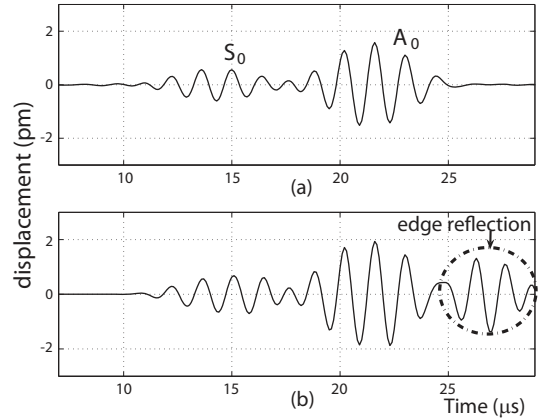


Figure 3. Theoretical normal displacement at point P for $\theta = 5^\circ$. (a) From pseudo-3D modeling. (b) From 3D FEM observed (especially for the A_0 mode).

In a second example, the same configuration has been considered, except a slightly off-axis reception point is considered with $\theta = 5^\circ$. In that case, $g \leq 0.03$ (Eq. 2) and thus condition #3 is respected. Here again, the pseudo-3D result has been compared to a 3D-FEM result (Fig. 3.a and 3.b, respectively).

In that case, although all applicability conditions #1, #2 and #3 are respected, a clear amplitude mismatch is observed (especially for the A_0 mode). Thus, obviously, application of the pseudo-3D model, such as presented above, leads to erroneous results as soon as $\theta \neq 0^\circ$.

However, the results presented in a previous paper [2] demonstrate that this problem does not occur when a known stress distribution is applied at the transducer location. Consequently, this is the estimation of σ_0 that should be questioned here. Since σ_{ox} is numerically computed and then incorporated in A_n (see Eq. 3) using a fully-validated technique [5, 6], the source of the problem is likely to be σ_{oy} .

Thus, instead of a basic uniform profile, a parabolic shape will be tried for σ_{oy} . This choice is justified by two simple arguments. First, since it allows to ensure stress continuity at the transducer edges ($\sigma_o = 0$ at $y = \pm L/2$), it is likely to be a more physically acceptable solution. And second, a parabolic function is a quite common way of taking into account apodization of a transducer.

Fig. 4 below is intended to show clearly the influence of σ_{oy} on the results provided by the pseudo-3D model. For better visibility, only the A_0 contribution has been represented. Fig. 4.a corresponds to the results computed with the uniform profile for $\theta = 5^\circ$ (and thus is nothing more than a zoomed version of Fig. 3). Fig. 4.b corresponds to the results for $\theta = 5^\circ$ as well, but with the parabolic profile.

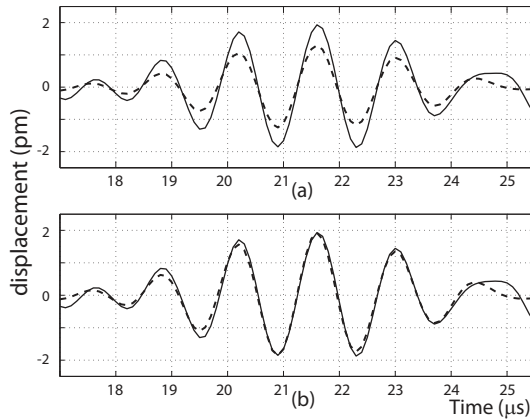


Figure 4. Theoretical normal displacement at point P for $\theta = 5^\circ$, computed using the pseudo-3D model (dashed line) and 3D-FEM (solid line). (a) σ_{oy} is uniform-shaped. (b) σ_{oy} is parabolic-shaped.

Though quite convincing, the very good matching observed in Fig. 4.b should be confirmed for higher angles. Therefore a last example is presented in Fig. 5. Here, the excitation frequency is 200 kHz and the reception point is located at $r = 63\text{mm}$ and $\theta = 22^\circ$. Here again, the comparison between the 3D-FEM and pseudo-3D results is very satisfying. The fact that the maximum value of function g (Eq. 2) is approximately 0.26, which is less favorable as referred to condition #3, only makes the matching slightly less perfect than in the previous case.

In conclusion, the directivity computed using a parabolic shape for σ_{oy} appears to be quite representative of the actual radiation of the transducer. Then, this is what will be considered in all future pseudo-3D modeling.

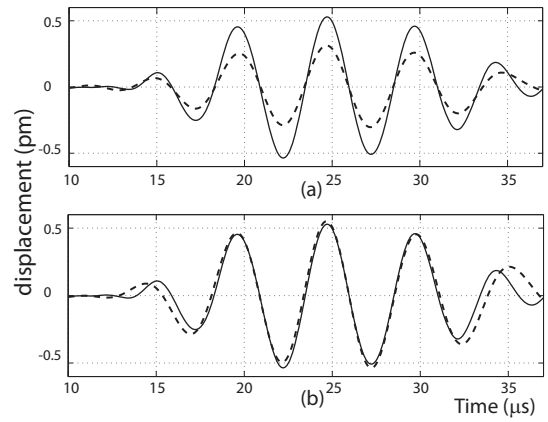


Figure 5. Same as Fig. 4, but for $\theta = 22^\circ$.

IV. EXPERIMENTAL RESULTS

The experimental setup considered in this study consisted of a 7-mm wide, 43-mm long and 1-mm thick PZT transducer stuck on the surface of a 6-mm thick aluminum plate. The excitation signal is a 5-cycle, Hanning-windowed sinusoid waveform at 200 kHz and of 10 V amplitude. The normal displacement at the surface of the plate has been measured using a laser interferometer. The measurement points considered are represented in Fig. 6. They correspond to the following locations: P_1 ($r = 135\text{ mm}$, $\theta = 0^\circ$), P_2 ($r = 133\text{ mm}$, $\theta = 10^\circ$), P_3 ($r = 130\text{ mm}$, $\theta = 20^\circ$), P_4 ($r = 125\text{ mm}$, $\theta = 30^\circ$).

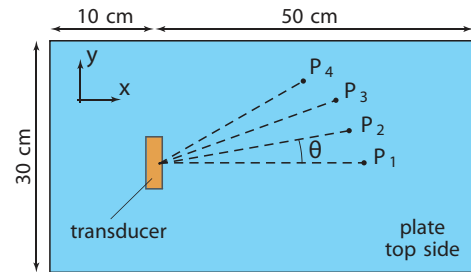


Figure 6. Description of the experimental setup and locations of the measurement points.

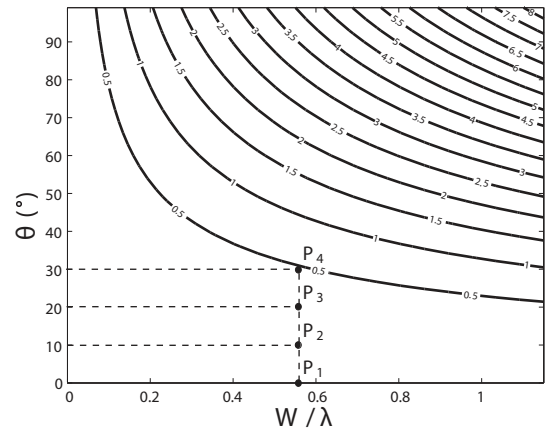


Figure 7. Contour plot of the function $g(W/\lambda, \theta)$

For each location, the maximum value (this means for the smallest wavelength) of the function g defined in Eq. 2 has been reported into Fig. 7, corresponding to a level-curve representation of $g(W/\lambda, \theta)$. This is a quick way of knowing to which extent condition #3 (see section II) is satisfied.

Then in Fig. 8, the experimental results have been compared to the corresponding pseudo-3D predictions. Naturally, as discussed in the previous section, a parabolic shape has been imposed in the model to σ_{oy} . Globally, the results appear to be very satisfying both in terms of absolute amplitude and waveform shape. Reception points P3 and P4 are too close from the plate edge to allow a complete time separation of the direct and reflected signals. Still, the significant wave packets in Fig. 8.c and d are not polluted and interpretation of the results is fully valuable. Logically, the amplitude for each mode reach a maximum for $\theta = 0^\circ$ and is decreased as θ increased. Since A_0 has a smaller wavelength than S_0 , its radiation is also more directive. Accordingly then, the ratio between the S_0 and A_0 amplitudes is increasing as θ is increased.

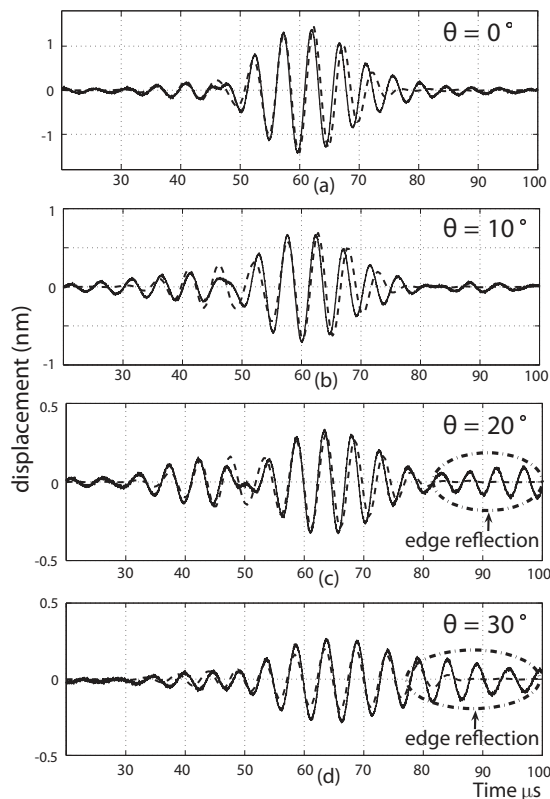


Figure 8. Comparison between pseudo-3D (dashed line) and measurement (solid line) results. (a) Point P_1 , (b) Point P_2 , (c) Point P_3 , (d) Point P_4 .

Additionally, it can be remarked that the theoretical condition #3 [2] about function g is not so restrictive. In practice a value of g less than 0.3 leads to good results.

V. CONCLUSION

The work presented in this paper consisted in an application of a pseudo-3D technique to the modeling of Lamb wave generation by a surface-bonded transducer. First, the excitation by the transducer and the subsequent modal fields are predicted in the sagittal plane using a 2D hybrid method. Then, the directivity in the plane of the plate can be computed separately for each mode. The stress profile along the third dimension (i.e. the transducer length) has been proved satisfyingly described by a parabolic function. Experimental and numerical results are in good agreement. This model has many advantages. One can firstly quote its ease of use, secondly the results can be easily interpreted and it enables to save calculation time. Moreover, its flexibility should make it possible to relatively easily take into account important additional physical effects in practice. One can in particular quote plate anisotropy, attenuation and interaction of these Lamb waves with defects.

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