LAMB WAVE MODE SELECTION FOR INCREASED SENSITIVITY TO INTERFACIAL WEAKNESSES OF ADHESIVE BONDS

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INTRODUCTION

Interface quality between layers in a layered structure is critical in fracture and fatigue analysis. A theoretical and quantitative solution to the problem from a NDE point of view would be desirable in both manufacturing and for in-service investigation of a variety of different structures. For example a great need exists to develop a reliable and efficient inspection program of adhesive bond delamination and interfacial weakness detection in aging aircraft noting that the bond degradation generally preceeds cracking in the aluminum skin, starting at the rivet holes.

Some techniques introduced earlier, such as normal beam and oblique longitudinal and/or transverse waves are useful but suffer from one major limitation, the time required to inspect large areas [1]. In search of improved sensitivity to interface weakness without using higher frequencies, shear vibrations on the interface were suggested. Higher sensitivity of transverse waves in normal incidence compared to longitudinal waves for the detection of submicron gaps filled with liquid or gas was revealed in laboratory conditions [2], and a low-frequency ultrasonic oblique-incidence technique was also proposed [3,4] and confirmed experimentally [5]. Shear vibration on an interface is also possible with guided waves [6-13], such as Rayleigh-type surface waves, Lamb-type plate waves, Love-type surface waves and/or Stoneley-type interface waves. In these guided wave approaches, a wave is sent directly through the bond area and such characteristics as amplitude of the reflected or transmitted modes, their frequency content, propagation velocity etc., are measured and correlated with the quality of the bond.

The multimode nature of Lamb waves with different cross-sectional displacement and energy distributions makes it possible by appropriate mode selection to have a concentration of shear vibrations close to the interface region, hence greater sensitivity to interfacial weakness. Here, a Lamb wave mode selection criteria are discussed with respect to both generation and reception for defect sensitivity analysis. Selection of appropriate modes and frequencies for adhesion weakness detection is suggested by either numerical analysis of the dispersion relations for different boundary conditions or by analysis of displacement and power distributions across the three-layered asymmertic adhesive structure.

MODE SELECTION BASED ON DISPERSIVE CURVE COMPARISONS

Utilization of an appropriate mode selection criteria is still an open issue. A known approach to this subject [6,9] is based on an observation of the biggest velocity change possible when comparing two sets of dispersive curves obtained from numerical solutions of different boundary-value problems. One of the solutions is based on simulation of a perfect, welded interface by assumption of a continuity of displacement and stress, both normal and tangential. The second of the solutions is based on an interfacial weakness model. Modelling of interfacial weakness is tackled by a wide variety of models starting from classical elastic smooth boundary condition for solid/solid interface [14,15] and ending with an introduction of an isotropic viscoelastic or orthotropic layer in equivalent boundary conditions [16,17]. Different models are relevant for different realistic situations. The subject of this paper is on mode selection concepts not on the suitability of the different models. Hence, for the sake of simplicity, we are presenting the dispersive curve diagram for the welded boundary conditions together with diagrams obtained for the smooth (slip) boundary conditions, which allow vanishing of tangential stress across the interface. Note, that smooth bond represents one of the possible limit cases of the finite boundary stiffness model (partial bond), when the tangential component of the boundary stiffness matrix is taken as zero, while the normal component remains large. We are conscious of the fact that a slip bond model represents a bond practically with no strength at all, but in assuming guided wave low-frequency inspection with tangential displacement component domination, such a model seems to be suitable for demonstration of a mode selection concept.

The sample results of numerical calculations for an asymmetric three-layered aluminum-to-aluminum adhesively bonded structure for different boundary conditions are presented in Fig. 1. Material and geometrical properties for the three layers are given in Table 1. An asymmetric geometrical case with different thicknesses of upper and lower adherends was considered. The relevant characteristic equation formulation, numerical details and discussion of limit cases are given in [18].

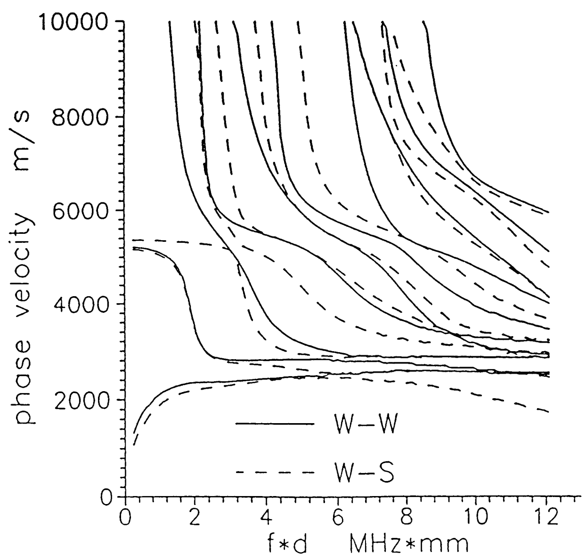

Figure 1. Dispersive curves for phase velocity in an asymmetric aluminum-to-aluminum three-layered adhesively bonded structure for two different boundary conditions : continuous lines - welded on both interfaces, broken lines - smooth on lower interface, welded on upper interface.

The dispersive curves for phase velocity were obtained for a frequency-total thickness product in the range of 0 - 12 MHz*mm for four different sets of boundary conditions on the upper and lower interfaces. For simplicity, materials were assumed as lossless from a wave propagation point of view. For a welded - welded case there are only two fundamental modes in the low-frequency limit like for a classical Lamb wave. A mode equivalent to a symmetrical Lamb mode has the plate phase velocity given in the three-layered case by the following formula:

$$c_1^2 = \frac{4\sum_{i=1}^{n} d_i G_i \left[1 - (c_{Ti} / c_{Li})^2\right]}{\sum_{i=1}^{n} d_i \rho_i} \tag{1}$$

where d_i, G_i, c_{Ti}, c_{Li}, ρ_i are respectively the thickness, shear modulus of elasticity, transverse wave velocity, longitudinal wave velocity and density of each of n = 3 layers. For boundary conditions other than perfect or welded-welded, there can be three or even four modes at the low-frequency limit. Besides a mode of flexural type, there can be two or three modes of longitudinal type with velocities characteristic for a two-layered plate and single layer or for three different single layers. For the other limit case when the frequency-total thickness product approaches infinity (the short wavelength limit) there are modes with velocity of the Rayleigh waves for upper and lower media, but additionally is the mode approaching the velocity of the bulk transverse waves of the adhesive layer. Such waves were recognized earlier [6] and named trapped modes. This mode, transporting most of the energy through the adhesive layer along the adherends, could be quite sensitive to cohesive changes in the glue line. There are, however, practical difficulties with the generation of such waves.

As discussed, an approach to mode selection is based on an observation of the biggest velocity change due to different boundary conditions. In analyzing the two sets (families) of curves for two types of boundary condition situations in Fig. 1 we can see few regions where the differences in phase velocities for the same *fd* values are pronounced. For example, there are few modes in the region above the bulk longitudinal wave velocity in aluminum that manifest large changes in the phase velocity. It could suggest that they are suitable for an interfacial weakness detection. However, one should remember that these modes are also very strongly dispersive, hence very sensitive to changes in total thickness or in thickness of glue line and additionally very strongly attenuative. They are also very difficult to generate in contact angle-beam technique with a transducer of finite size due to spreading of energy to many modes possible even for a narrow-band kind of excitation. Generally it is worth mentioning that from the dispersive curves itself we can not make any conclusions concerning excitability of individual modes. There are other problems arising from the discussed approach to mode selection. From the dispersive curves alone we can say nothing about stress and power distribution, hence judgement from the phase velocity changes with changes in boundary conditions can be misleading. There are modes with very good displacement distribution for interfacial weakness detection but with almost no energy concentration close to the interfaces. There are also problems associated with the proper interpretation of the additional modes for smooth boundary conditions in the low-frequency range. These problems can be avoided by applying different kind of boundary conditions, e.g. partial bond model at the expense of introducing additional parameters, such as values of normal and tangential bond stiffnesses.

For the above mentioned reasons we would like to consider a different approach to mode selection based on a full analysis of the cross-sectional field distributions. The proposed approach could permit together with dispersion curve variation analysis a more precise and reliable mode selection criteria for increased sensitivity to interfacial weaknesses.

MODE SELECTION BASED ON FIELD DISTRIBUTION ANALYSIS

The longitudinal u and normal w displacements, stress components σ_{zz}, σ_{xx} and σ_{xz}, and time average longitudinal power P_x per unit width were calculated across the asymmetric three-layered aluminum-to-aluminum adhesively bonded structure for each point on a dispersive curve for individual modes. The used material and geometrical data were the same as for calculation of dispersive curves (Fig.1.) and are given in Table 1. The axis x is oriented along the interfaces, the axis z is normal to the free surfaces. The P_x is defined as

$$P_x = -0.5(\sigma_{xx}\,\dot{u}^* + \sigma_{xz}\,\dot{w}^*) \qquad (2)$$

where an asterisk denotes complex conjugation.

Examples of such calculations are presented in Figs. 2-3. All data are normalized by the largest value of the relevant variable and the vertical lines denote the interfaces between the adherends and the adhesive layer.

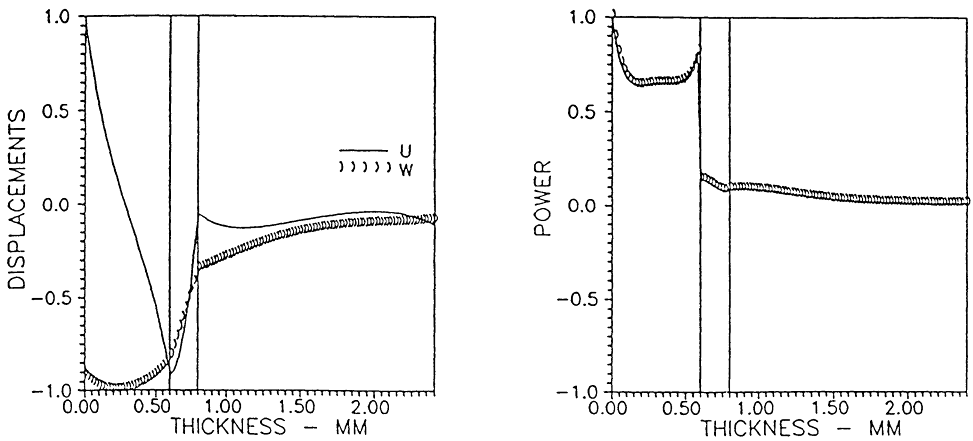

Fig. 2. Cross-sectional distributions of displacements and power for the first mode and $fd = 3$ MHz*mm; d - total thickness, f - frequency, u and w - longitudinal and normal displacement, respectively.

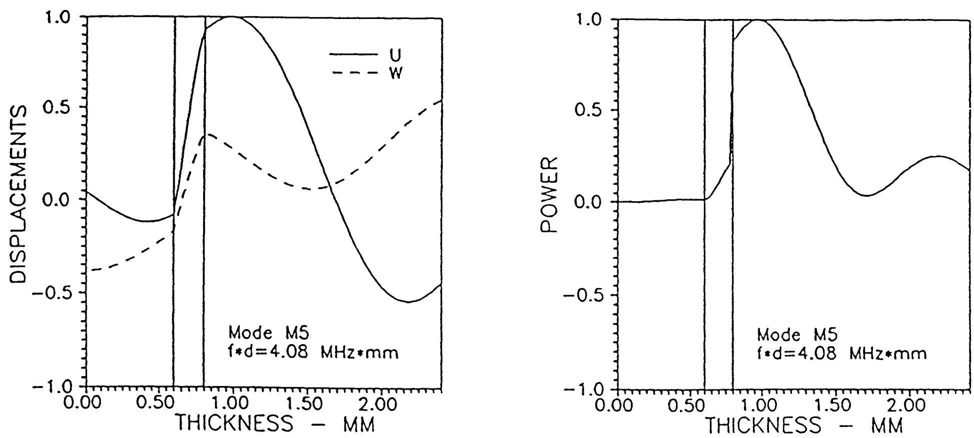

Fig. 3. Cross-sectional distributions of displacements and power for the fifth mode and fd = 4.08 MHz*mm; d - total thickness, f - frequency, u and w - longitudinal and normal displacement, respectively.

The first mode for frequency-total thickness product equal to 3 MHz*mm (Fig. 2) seems to be very suitable for interfacial weakness detection on the lower interface, i.e. on the interface between thinner adherend and adhesive layer, for two reasons. Firstly, because the amplitude of longitudinal displacement *u* reaches its maximum on that interface, and secondly, the power of propagated mode is concentrated entirely in the lower adherend. A completely opposite situation occurs for the fifth mode in the frequency-total thickness product value of 4.08 MHz*mm (Fig. 3). In this mode, both the amplitude of the longitudinal displacement and power have its maxima almost on the upper interface, i.e. on the interface between thicker adherend and adhesive layer. It would suggest the suitability of that mode for the interfacial weakness detection on the upper interface.

Unfortunately the distribution of longitudinal displacement although suitable may not be supported by enough power concentration in the inspected region. We would also like to address the problems related to mode generation. For the wedge technique of excitation of plate waves either from a liquid in the immersion version or from a solid wedge through an acoustic couplant in the contact version [19], best excitability occurs when the normal component of the displacement vector on the surface from which the plate mode would be generated reaches its maximum. Judging from Fig. 2 it happens for the lower adherend, but not for the upper one. Hence the suitable normal displacement distribution from excitability as well as from receptability viewpoint should be considered additionally. As was mentioned earlier, the modes with strong dispersion, because of poor excitability, should be avoided as well.

MODE SELECTION CRITERIA

Looking for a more objective mode selection criteria, the integrals for longitudinal displacement distribution and longitudinal power distribution for very thin layers close to both interfaces for each point on the dispersive curve of the individual modes were calculated using the following expressions:

a) for the longitudinal displacement

$$cr_u = \int_{up}^{lo} u(z)\, dz \qquad (3)$$

b) for the longitudinal power

$$cr_{px} = \int_{up}^{lo} P_x(z)\, dz \qquad (4)$$

where for the upper interface *up* = [z(2) - 0.03] in mms and *lo* = [z(2) + 0.01] in mms, while for the lower interface *up* = [z(1) - 0.01] in mms and *lo* = [z(1) + 0.03] in mms. z(1) and z(2) are the coordinates of the lower and upper interface, respectively.

The examples of such calculation for the fifth mode of plate waves propagating in the three-layered aluminum-to-aluminum adhesively bonded structure (see Table 1) for both upper and lower interface are plotted in Fig. 4. Fig. 4a shows the displacement criterion, while Fig. 4b the power criterion. Judging only from the displacement criterion, one can conclude that for this particular mode and three-layered structure the frequency-total thickness products of 4, 6 and 7.5 MHz*mm are suitable for interfacial weakness detection on the upper interface, while 5.25 MHz*mm for the lower interface. Although in analyzing the power criterion distribution for these values of *fd's* the appropriate power concentration has been found only for 4 and 7.5 MHz*mm values in the case of the upper interface, while almost none of *fd's* for the lower interface.

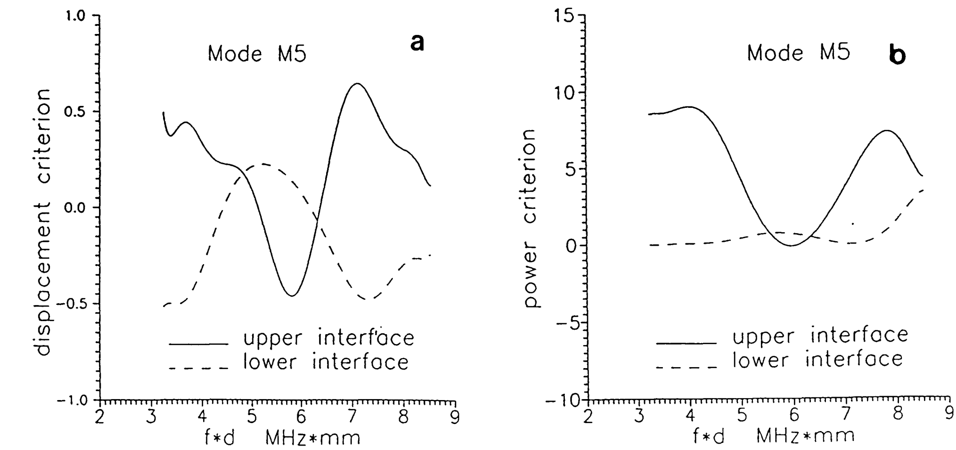

Fig. 4. Displacement (a) and power (b) criteria for the fifth mode and given range of *fd*.

To make such conclusions more readable a combined criterion was introduced. The definition of the combined criterion is given as

$$cr = cru' * crpx' , \qquad (5)$$

where cru' = |cru| >0.25 and crpx'>0 were taken arbitrary. Sample results of the combined criterion parameter distribution for the discussed earlier fifth mode is shown in Fig. 5.

It is worth mentioning that the above combined criterion can be extended to other criteria, such as the mode excitability and receptability criterion for a given technique of generation and reception or the criterion of insensitivity to the changes in the thickness of the glue line. It was shown that the last criterion eliminates frequencies close to the cut-off frequencies, as e.g. for the fifth mode in Fig. 5 for the frequencies close to 1.25 MHz.

CONCLUSIONS

Both approaches presented in this paper to the plate mode selection problem for the best sensitivity to interfacial weakness detection in multilayered structures, based on either dispersion curve comparisons and/or field distribution analysisare useful in the establishment guidelines in data acquisition and analysis. Experimental work will be required to address such problems as mode generation and reception, mode conversion and reflection and/or transmission of plate waves from discontinuities, etc.

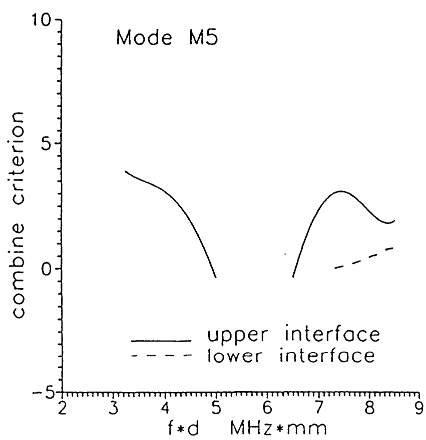

Fig. 5. Combined displacement and power criterion for the fifth mode.

Table 1. Material properties and geometrical configuration

Layer #	Material	Longitudinal velocity [m/s]	Transverse velocity[m/s]	Density [kg/m3]	Thickness [mm]
1	Aluminum	6200	3150	2700	1.6
2	Epoxy	2700	1350	2100	0.2
3	Aluminum	6200	3150	2700	0.6

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