

## PART 6. Lamb Waves

The theory of lamb waves was originally developed by Horace Lamb in 1916 to describe the characteristics of waves propagating in plates.<sup>48</sup> Frequently, they are also referred to as plate waves. Lamb waves can be generated in a plate with free boundaries with an infinite number of modes for both symmetric and antisymmetric displacements within the layer. The symmetric modes are also called longitudinal modes because the average displacement over the thickness of the plate or layer is in the longitudinal direction. The antisymmetric modes are observed to exhibit average displacement in the transverse direction and these modes are also called flexural modes.<sup>49,50</sup> The infinite number of modes exists for a specific plate thickness and acoustic frequency which are identified by their respective phase velocities. Figure 50 shows a typical example of generating lamb waves in a solid plate using an angle wedge. The normal way to describe the propagation characteristics is by the use of dispersion curves based on the plate mode phase velocity as a function of the product of frequency times thickness. The dispersion curves are normally labeled as S0, A0, S1, A1 and so forth, depending on whether the mode is symmetric or antisymmetric.

Although the dispersion diagrams are very complex, they can be simplified by using the incidence angle of the exciting wave to determine which mode is to be dominant. A particular lamb wave can be excited if the phase velocity of the incident longitudinal wave is equal to phase velocity for the particular mode.

The phase velocity of the incident longitudinal wave is then given by:

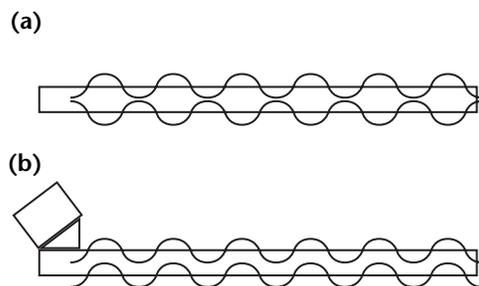
$$(38) \quad V_p = \frac{V_L}{\sin \phi}$$

where  $V_L$  is the group velocity of the incident longitudinal wave,  $V_p$  is the phase velocity of the incident longitudinal wave and  $\phi$  is the angle of incidence of the incident longitudinal wave.

Lamb waves are extremely useful for detection of cracks in thin sheet materials and tubular products. Extensive developments in the applications of lamb waves provides a foundation for the inspection of many industrial products in aerospace, pipe and transportation. The generation of lamb waves can be performed using contact transducers, optical, electromagnetic, magnetostrictive, and air coupled transducers.

Magnetostrictive transducers operate by producing a small change in the physical dimensions of ferromagnetic materials, resulting in a deformation of crystalline parameters.<sup>51</sup> Applying high frequency power to the transducers then produces ultrasonic waves in the material. Lamb waves are produced when thin or tubular materials are excited by high frequency oscillations. The technique also works with nonferromagnetic samples: a ferromagnetic sheet, such as nickel, is bonded to the nonferromagnetic sample being tested. The lamb waves generated in this manner can be used to detect cracks or other material characteristics in areas away from the excitation source because the waves propagate along the sample for long distances. When used this way, the ultrasonic waves are also called *guided waves*. Technology using guided waves developed into a very useful ultrasonic test technique in the 1990s and is expected to continue to develop in the twenty-first century.<sup>52</sup> For example, new sensor development introduces smaller transducers, such as capacitive micromachined devices,<sup>53</sup> air coupling<sup>54</sup> and new characterization studies on the lamb wave modes propagating in plate structures.<sup>55</sup>

**FIGURE 50.** Lamb wave propagating in plate: (a) symmetric; (b) antisymmetric.



loading around the circumference of a pipe. See elsewhere<sup>63</sup> for more details on flexural modes. Note in Fig. 54 that attenuation does not always increase as frequency is increased as in a usual bulk wave problem. Some modes attenuate more quickly than others. Note the dotted curve for the L(0,3) mode in this case. One of the mode's attenuations improved significantly with higher frequency but this is the surface wave on the uncoated side of the pipe. For other modes, for higher frequency, the wave amplitudes are significantly reduced.

All guided wave problems have associated with them the development of appropriate dispersion curves and corresponding wave structures. Of thousands of points on a dispersion curve, only certain ones lead to a valid test — for example, those with greatest penetration power; with maximum displacement on

the outer, center or inner surface; with only in-plane vibration on the surface to avoid leakage into a fluid; or with minimum power at an interface between a pipe and a coating. A sample set of wave structure curves are illustrated in Fig. 55 to illustrate this point. In this case, the S0 mode propagation in an aluminum plate is considered. Notice the in-plane vibration behavior across the thickness compared to the out-of-plane motion. The wave structure changes from point to point along every mode on a dispersion curve. The characteristics of every point on each dispersion curve are different, primarily with respect to wave structure, a critical feature for the development of an efficient test technique for a particular structure. Notice that for an  $f \cdot d$  value (value of frequency  $f$  times thickness  $d$ ) of 0.5, the in-plane displacement is totally dominant across the thickness with

FIGURE 53. Dispersion curves for a traction free aluminum plate: (a) phase velocity dispersion curves; (b) group velocity dispersion curves.

