

RESONANT MODES IN CENTRIFUGALLY CAST STAINLESS STEEL (CCSS) PIPES

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INTRODUCTION

Lamb-waves are the elliptically polarized resonant modes of propagation in an isotropic solid plate with free boundaries. For a given plate thickness d and an ultrasonic frequency f , there exist a finite number of such propagation modes described by the associated phase velocity. A complete description of this dispersion structure is typically given in the form of a set of dispersion curves, one for each resonant mode, showing the variation of the Lamb-wave phase velocity as a function of the product fd . In general, Lamb-wave modes can be grouped into two fundamental types: symmetric modes or antisymmetric modes, depending on whether their displacement vector is symmetric or antisymmetric with respect to the median plane of the solid plate.

The resonant modes of a CCSS pipe are more general because a pipe is a cylindrical shell and, in the case of columnar-grain CCSS, has to be treated as an anisotropic medium. In this paper, we will evaluate how the resonant modes of a CCSS pipe deviate from those of an isotropic plate. The deviation due to either the material anisotropy or the cylindrical curvature will be examined. We will focus on the Lamb-type modes of a thick cylindrical shell and will model the CCSS as a transversely isotropic plate. For reference, a quick review of the dispersion properties of an isotropic plate will be provided.

ISOTROPIC PLATE

Consider an isotropic solid plate of thickness $d = 2h$. The dispersion relation of Lamb waves can be decoupled into two equations to describe the symmetric and antisymmetric modes separately [1]:

$$\begin{aligned} \frac{\tanh(khp)}{\tanh(khq)} &= \frac{r^2}{4pq} \quad (\text{symmetric}), \\ \frac{\tanh(khq)}{\tanh(khp)} &= \frac{r^2}{4pq} \quad (\text{antisymmetric}), \end{aligned} \tag{1}$$

where

$$p^2 = 1 - c^2/v_d^2,$$

$$q^2 = 1 - c^2/v_s^2,$$

$$r = 2 - c^2/v_s^2,$$

in which k is the wave number, c phase velocity, v_d compressional wave velocity and v_s shear wave velocity. From Eq.(1), we plotted in Fig.1 a set of dispersion curves for an isotropic SS303 plate. The curves of the symmetric modes are labeled S_n 's and the antisymmetric ones are labeled A_n 's. We observe that the two lowest modes A_0 and S_0 are distinct at low fd and start to merge into one as the Rayleigh surface-wave mode for $fd \geq 5.0$ MHz-mm. All non-zero modes asymptotically approach the limit $c = v_s$ as fd becomes very large. On the other hand, in the limit of $c \rightarrow \infty$, fd asymptotically approaches $(n/2)v_d$ or $(n/2)v_s$, where n is a positive integer. Each of these fd values corresponds to the so-called cut-off frequency for that particular mode.

TRANSVERSELY ISOTROPIC PLATE

A critical characteristic of CCSS is the material anisotropy introduced by its columnar grains. If Lamb waves are to be used for inspecting CCSS pipes, the effect of this anisotropy on the structure of the resonant modes should be examined. The directional grain microstructure can be adequately modeled as a transversely isotropic material with the axis of isotropy being perpendicular to the median plane of the plate. In this case, the authors have shown [2] that the dispersion relation could also be decoupled into two equations for two mode types:

$$\frac{\tanh(\phi_1)}{\tanh(\phi_2)} = \frac{M_2 \Sigma_1}{M_1 \Sigma_2} \quad (\text{symmetric}),$$

$$\frac{\tanh(\phi_2)}{\tanh(\phi_1)} = \frac{M_2 \Sigma_1}{M_1 \Sigma_2} \quad (\text{antisymmetric}).$$
(2)

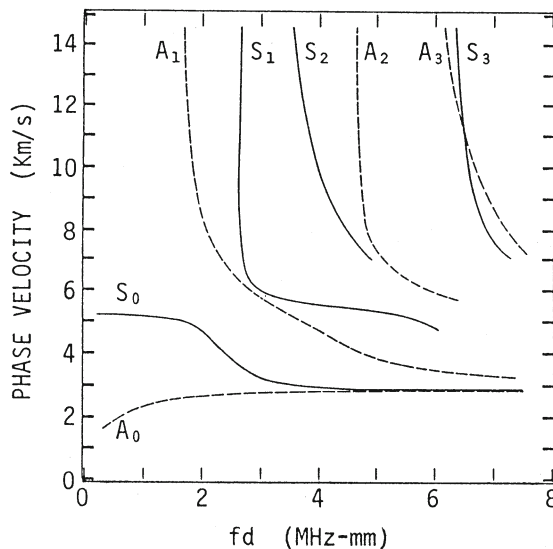


Fig.1. Dispersion Curves of an SS303 Plate.

The new variables introduced in Eq.(2) were defined [2] in terms of the stiffness constants C_{11} , C_{13} , C_{33} , C_{44} and C_{66} of a medium of hexagonal symmetry. It was also shown [2] that Eq.(2) was reducible to Eq.(1) when the stiffness constants of an isotropic plate were substituted into Eq.(2). The values of the stiffness constants for columnar-grain CCSS were estimated from the measurements of the phase velocity on CCSS samples performed recently by the EPRI NDE Center [3]. A root-finding numerical algorithm for complex functions was developed and applied to Eq.(2) to determine the dispersion curves of a transversely isotropic plate. The results are presented in Fig.2 for CCSS in the form of phase velocity versus fd .

In general, the dispersion structure of a transversely isotropic plate exhibits the same fundamental features. The resonant modes clearly fall into two groups: symmetric and antisymmetric. The two lowest modes do not have cut-off frequencies, and merge into one as fd exceeds 3 MHz-mm. The modes of higher orders again are represented by the similar curves, especially in the asymptotic limits of large fd and phase velocity. One should note that the S_0 and A_0 curves as well as the S_1 and A_1 curves cross over each other at a certain fd value. For comparison with an isotropic plate, the dispersion curves of the three lowest symmetric modes for columnar-grain CCSS and SS303 are plotted together in Fig.3. The dispersion curves for the S_0 and S_1 modes are essentially the same for both materials. For the S_2 mode, the anisotropic dispersion curve deviates significantly from the isotropic one. With respect to the antisymmetric modes, Fig.4 shows that the A_0 mode dispersion curve is basically unchanged, while the A_1 mode dispersion curve displays noticeable deviation from that for the isotropic case, although to a much lesser extent in comparison with the S_2 mode. These results, therefore, lead to the conclusion that the resonant modes of low orders, especially the A_0 , S_0 , A_1 and S_1 modes, are not strongly influenced by the anisotropy of a transversely isotropic plate.

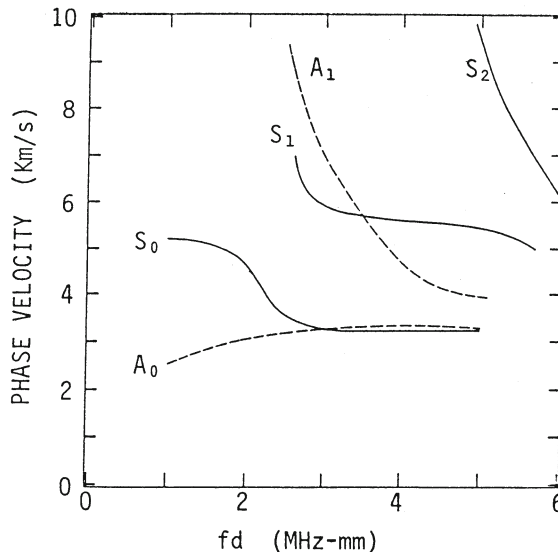


Fig.2. Dispersion Curves of a Columnar-Grain CCSS Plate.

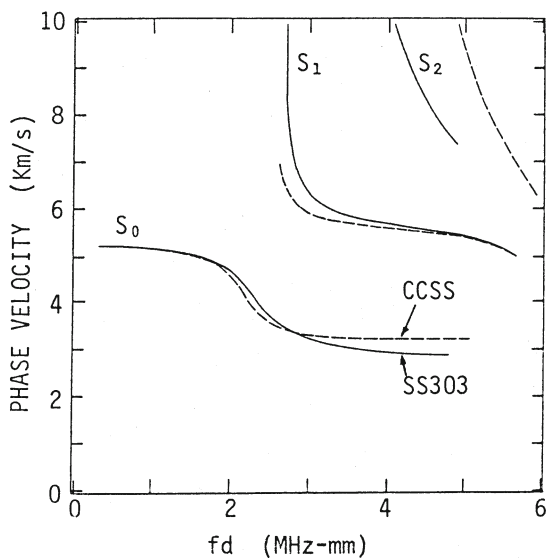


Fig. 3. Comparison of Symmetric Modes in SS303 and Columnar-Grain CCSS.

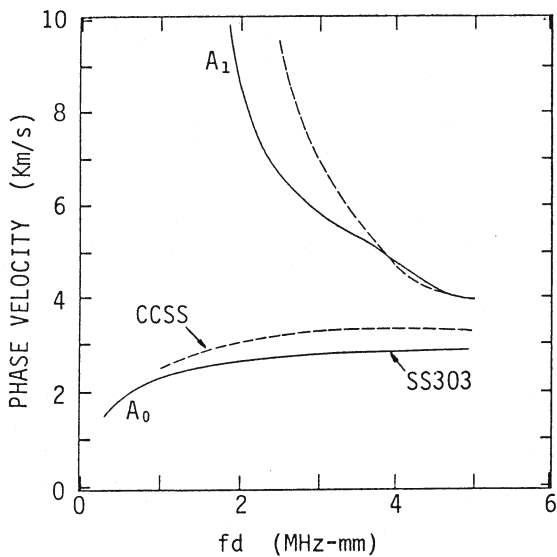


Fig. 4. Comparison of Antisymmetric Modes in SS303 and Columnar-Grain CCSS.

CURVATURE EFFECT ON LAMB WAVES

The resonant modes of an isotropic cylindrical shell has been studied extensively. In this paper, the research is focused on how these modes are related to the Lamb-wave modes of an isotropic plate. The question of interest is whether the basic understanding of Lamb waves is still applicable in the presence of moderate curvature. In other words, we are interested in finding out how the curvature affects the Lamb-wave mode structure. Fundamentally, the resonant modes of a cylindrical shell belong to two groups: one group propagating in the r - z plane and the other in the r - θ plane of the (r,θ,z) cylindrical coordinate system. The resonant modes of each group can be divided further into two types: one type unique to the geometry of a cylindrical shell and the other reducible to the Lamb-wave modes of a flat plate. The two sets of resonant modes which are reducible to Lamb waves are normally known as the planar and axial modes. The axial modes propagate along the length of the cylinder and the planar ones propagate circumferentially. In order to estimate the curvature effect on Lamb waves, we determined numerically the dispersion curves of the axial modes from the exact dispersion relation for such modes which has been derived previously [2]. The pipe dimensions are taken to be 2.625" thickness and 33.375" I.D. and the materials is the isotropic SS303. The results are plotted in Fig.5 for the three lowest modes and compared with those of a flat plate of the same thickness. It is clear from this figure that the two sets of dispersion curves are practically identical, except for the A_0 curves in the low fd range, where the cylindrical shell mode slightly deviates from the flat plate one.

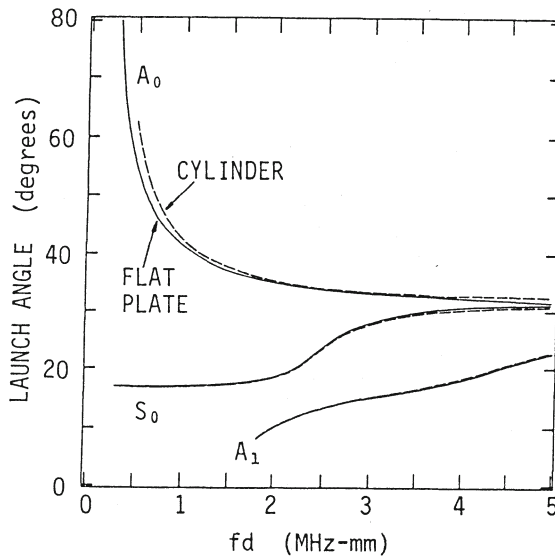


Fig. 5. Comparison of the Axial Modes of a Cylindrical Shell with the Lamb-Wave Modes of a Flat Plate.

CONCLUSION

In using Lamb waves for inspection of CCSS pipes, we were concerned with the effects of the cylindrical curvature and the columnar-grain anisotropy on the Lamb-wave dispersion characteristics. The research results presented in this paper indicate that the cylindrical curvature does not significantly change the Lamb-wave mode structure within the typical pipe dimensions under consideration. With respect to the CCSS anisotropy, there exists some deviation from the isotropic case. However, if only the low-ordered modes (A_0 , S_0 , A_1 and S_1) are used, this deviation is minimal.

ACKNOWLEDGMENT

The presented research was sponsored by the Electric Power Research Institute under Contract No. 2405-23.

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