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It is known that when scattering from elastic shells, a large resonance resonance is produced at frequencies corresponding to values in which the flexural phase velocity is roughly equal to the speed of sound in the fluid. A systematic analysis indicates that the large response is due mainly to water born waves (labeled A waves) which have narrow half-widths and manifest themselves as pronounces spikes in the form function as well as weaker flexural resonances (labeled A0) which have rather large half-widths and produce an envelop effect due to overlapping resonances over a broad frequency range. These results are analyzed within the context of a new time domain resonance scattering theory and are shown to produce characteristic transient return signals. From these signals it is possible to calculate both the half-width of the A waves as well as their group velocities.

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Scattering in the Time Domain from Submerged Elastic Shells at Coincidence Frequencies

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Abstract

It is known that when scattering from elastic shells, a large resonance resonance is produced at frequencies corresponding to values in which the flexural phase velocity is roughly equal to the speed of sound in the fluid. A systematic analysis indicates that the large response is due mainly to water born waves (labeled A waves) which have narrow half-widths and manifest themselves as pronounces spikes in the form function as well as weaker flexural resonances (labled A0) which have rather large half-widths and produce an envelop effect due to overlapping resonances over a broad frequency range. These results are analyzed within the context of a new time domain resonance scattering theory and are shown to produce characteristic transient return signals. From these signals it is possible to calculate both the half-width of the A waves as well as their group velocities.

Introduction

Resonances are characterized by the fact that they occur at discrete values of frequency and when they occur, a distinct event takes place. The event is usually distinguishable and can be related to a particular process. Our interest in this paper is to determine the nature a grouping of resonances in some frequency band in the time domain for back scattering from submerged elastic targets. The frequency domain case has been investigated for many years for submerged elastic spheres and infinite cylinders for both solids and shells. The nature of back scattered returns is well understood and quite predictable for the frequency domain case. In contrast, time domain solutions which encompass the frequency region for which resonances are present are not so well understood in the context of a resonance scattering theory[1-3] (RST). In this paper we outline a time domain theory based on RST techniques and set some conditions that enable one to make unique interpretations of results. We then apply the results for the problem of time domain solutions at coincidence frequency (the frequency at which the phase velocity of the flexural wave is equal to the speed of sound in the fluid) and show interesting results for that region. We interpret the results within the context of the theory outlined in the following section.

Time Domain Resonance Scattering Theory:

The partial wave series that emerges from normal mode theory for separable geometries can be represented in distinct partial waves or modes. It has been shown that a representation due to a distinct mode { n } can be written in the form:

$$f_n(\theta) = \frac{2}{ka} e^{2i\xi_n^{(r)}} \left\{ \frac{(\frac{1}{2})\Gamma_n^{(r)}}{\chi - \chi_n^{(r)} + (\frac{i}{2})\Gamma_n^{(r)}} + e^{-i\xi_n^{(r)}} \sin\xi_n^{(r)} \right\}$$

where $\chi = ka$ $\chi_n^{(r)}$ is the nth resonance

and

$(\frac{1}{2})\Gamma_n^{(r)}$ is the resonance half-width

Were $e^{2i\xi_n^{(r)}} = -\frac{h_n^{(2)}(x)}{h_n^{(1)}(x)}$

Here, we have absorbed the 2n+1 factor into the expression. We now consider the type of pulses useful in determining a resonance in the time domain. There are numerous ways to do this but we limit ourselves the following form which allows us to isolate a particular frequency region and at the same time limit the pulse time.

$$p(t) = \cos(\omega_0 t)e^{-\alpha t^2} = \cos(ka_0 s)e^{-\alpha s^2}$$

where $s = ct / a$ and $k = 2\pi / \lambda$

Here, we refer to ω_0 as the carrier frequency. The Fourier transform of this function is gi and the scattered signal in the time domain is then Ps in the expression below:

If we perform a Fourier transform on the modal components we arrive at the following expression:

$$\int_{-\infty}^{\infty} \frac{(\frac{1}{2})\Gamma_n^{(r)}}{\chi - \chi_n^{(r)} + (\frac{i}{2})\Gamma_n^{(r)}} e^{-i\chi s} d\chi = (\frac{1}{2})\Gamma_n^{(r)} \sin(\chi_n^{(r)} s)e^{-(\frac{1}{2})\Gamma_n^{(r)}}$$

That is, at a resonance the time domain solution is simply the product of the half width times a sinusoidal function times an exponential damping factor. The time domain solution for a nest of resonances (N-m) is then of the form:

$$p(s) = \sum_{n=m}^{N} \left(\frac{1}{2}\right)\Gamma_n^{(r)} \mathrm{Sin}(\chi_n^{(r)} s)\, e^{-\left(\frac{1}{2}\right)\Gamma_n^{(r)}}$$

The remaining contributions due to the backscatter are small.

Now let us make the following assumptions, which for certain situations are realistic. We assume that we are in a resonance region for which the resonance widths are fairly constant and the resonance spacing is fairly uniform.[4]

These assumptions then lead to the following:

$$P(s) = 2^M (\mathrm{Sin}(\chi_{ave}^{(r)} S)\{\mathrm{Cos}(\Delta\chi^{(r)} s / 2)\}^M e^{s\Gamma/2}$$

$$\text{where} \qquad \chi_{ave}^{(r)} = \frac{1}{2M} \sum_{i=n}^{n+2M} \chi_i^{(r)}$$

It is seen from the above expressions that:

a) The half-width is associated with the decay of the response in the time domain solution: the response decreases exponentially with increasing value of the half-width. This is not altogether unexpected since narrow resonances are associated with long ringing times and is analogous to well defined energies being associated with long half-lives in quantum physics cases.

b) The larger the number of adjacent resonances (2M) sensed, the more sharply defined the return pulse or envelope function (the beats) and the more enhanced the return signal. Under appropriate conditions we can get the group velocity of a specific type of resonance.

c) The larger the carrier frequency the more oscillatory the signal within the envelop.

d) If several adjacent resonances sensed by a signal are different in character in the region of the carrier frequency then it becomes difficult to interpret results in terms of a group velocity associated with a particular resonance type; attempts at such interpretations could lead to erroneous results. For example, if one senses two resonances, one a Rayleigh resonance and one a whispering gallery resonance, the extraction of a group velocity associated with a specific resonance type resonance would lead to error.

Additional expressions can be obtained in a manner similar to the above development, but we will end our excursus here and apply the results in the interpretation of the following cases.

Time Domain Backscattering From at Coincidence Resonance.

At low frequencies in a submerged fluid, antisymmetric Lamb waves or flexural waves do not yield resonances until the phase velocity of the flexural wave is about equal to the speed of sound in the ambient fluid [5,6]. The value in frequency for which this happens is referred to as the coincidence frequency. There are, however, subsonic fluid borne waves which produce sharp [5,6] (fluid borne) resonances below the coincidence frequency. We will refer to these fluid borne waves as pseudo-Stoneley waves and the related resonances pseudo-Stoneley resonances, consistent with the terminology of Ref. 6. The " pseudo-Stoneley " resonances are well defined in partial wave space, usually corresponding to only one partial wave mode number and a very narrow half-width with a dispersive phase velocity which approaches the speed of sound in the fluid with increasing frequency. They diminish in significance at the point for which the flexural resonances begin to dominate. It has been observed that, both for flat plates which are fluid loaded on one side and for submerged shells, at coincidence one observes a very strong response. The associated resonance region has been referred to as the strong flexurals[7] in the literature and can be interpreted in terms of a singularity that occurs when the wave number in the fluid is equal to that of the flexural wave on the surface of the object[8]. Although, this interpretation is an idealization, since it would correspond to infinite loading at the surface, it is none the less a fairly reliable picture of what is happening. Indeed, at that point there is a phase change as well which accounts for the envelope of the resonance curve at coincidence (shown here) where the waves are in phase until coincidence and out of phase afterwards. Our interest here is in examining the time domain responce since we expect the conditions of described in the previous section to be partially met over a broad frequency range and thus to yield a strong coherent responce with a carrier frequency in the neighborhood of the frequency at coincidence. Accordingly, we examine the case of CW pings for two examples for which one expects coincidence resonances to arise. This is certainly suggested by the strong responses in Figs. 1b and 2b at the ka values 113 and 87, respectively, for steel and WC. Further, we use Mindlin-Timoshenko [8] thick plate theory to determine the value for which the flexural phase velocity will equal the ambient speed of sound in water. The expressions we use are from flat plate theory but they prove to be quite reliable in predicting the phase velocity for the curved surfaces of the spheres at the frequency limits in the vicinity of the value at coincidence frequency. It is remarkable that they in fact do predict the frequency range in the figures which match the strong flexurals. We determine that the expression for the phase velocity is:

$$v_f = \frac{v_{pl}\left[\left\{(\Gamma-1)^2\left(\frac{\omega}{\Omega}\right)^4 + 4\left(\frac{\omega}{\Omega}\right)^2\right\}^{1/2} - (\Gamma+1)\left(\frac{\omega}{\Omega}\right)^2\right]^{1/2}}{\left[2\left(1-\Gamma\left(\frac{\omega}{\Omega}\right)^2\right)\right]^{1/2}}$$

where $\Omega = \dfrac{C_p\sqrt{12}}{h}$ $\qquad \Gamma = 2.65(1 + 1.5\nu + 0.75\nu^2)$

and $\dfrac{\omega}{\Omega} = \dfrac{(Ka)V_w\left(\frac{h}{a}\right)}{C_p\sqrt{12}}$

and $C_p = C_s\sqrt{\dfrac{2}{1-\nu}}$

Here C_s is the shear speed and ν is the poisson ratio of the material. The ratio (h/a) is a thickness parameter and V_w is the speed of sound in water. The remaining defining expressions in the equations are discussed in Ref. 8. For the cases presented here (h/a) is 0.01 where a is the radius of the sphere. The group velocity is determined by us to be

$$\frac{d\omega}{dk} = \frac{\left[2C_p^{\,2} - (\Gamma + 1)v_t^{\,2}\right]\left(\frac{\omega}{\Omega}\right)^2}{12v_t^{\,3}C_p^{\,2} + \left\{(\Gamma + 1)C_p^{\,2}v_t - 2\Gamma v_t^{\,3}\right\}\left(\frac{\omega}{\Omega}\right)^2}$$

In both Figs. 3 and 4 the phase and group velocities are plotted for ka values out to 200 for 1% thick steel and WC shells.

We now examine the time domain calculations. For the first example we examine the steel shell of 1% thickness, illustrated in Fig. 1a. In this case we observe a well defined envelope with pronounced oscillations within the envelope consistent with expressions in the previous section. The enhancement due to the factor 2^M is obvious both here and in Fig. 2a. We can obtain the group velocity from the peak to peak distance. The results leads to a value of 2.23 km/sec. The expression for flexural waves predicts a value of 2.53 km/sec at coincidence and a range of 2.44-2.68 km/sec. over the ka range of 100-140 where the strong flexurals are significant. In that range the phase velocity ranges from 1.37-1.58 km/sec. The values of the predicted and extracted group velocities are not in extremely good agreement; the disagreement is about 12%. This may be due in part to the fact that flat plate theory may be in error or inadequate for spherical fluid-loaded targets, the conditions in the previous section are not well met and there must be a mixture of pseudo-Stonley waves leaking into the fluid. We have determined the group velocity of the pseudo-Stonley wave for this case to be 2.16 km/sec based on plate theory. Moreover the phase velocity is in the range from 88% to 98% of the speed of sound in the fluid. This value of group velocity is within 3% of the extracted value from the time domain solution. Moreover the pseudo-Stonley resonances have very narrow widths while the flexural resonances are quite large. The conditions in the previous section would indicate that the flexural resonances would rapidly dampen while the pseudo-Stonley resonances would attenuate solely. Thus, based on the similarity of the extracted group velocity on that of the pseudo-Stonley wave and the conditions in the previous section we conclude that the time domain calculations in Fig. 1a represent pseudo-Stonley resonances.

The final example is for the WC shell of 1% thickness. The results here are consistent with that of the steel case and are illustrated in Fig. 2b. Here the group velocity was extracted to be 2.33km/sec. as opposed to the plate theory value of 2.65km/sec for flexural waves. The range of values for the group velocities predicted from the flat plate theory was from 2.49-2.78 km/sec over the ka range of 74-102. Here again the difference was 12% between plate theory and the extracted value. On the other hand, the group velocity for pseudo-Stonley waves is 2.26 which is within 3% of the extracted value. As in the previous example the pseudo-Stonley resonances are quite narrow while the flexural resonances are broad and we conclude that the results of Fig. 2b represent predominantly pseudo-Stonley resonances.

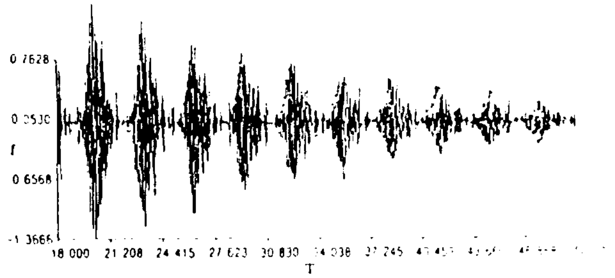


Fig. 1A. Time Domain Solution of 1% Thick Steel Spherical Shell at Coincidence CW Ping

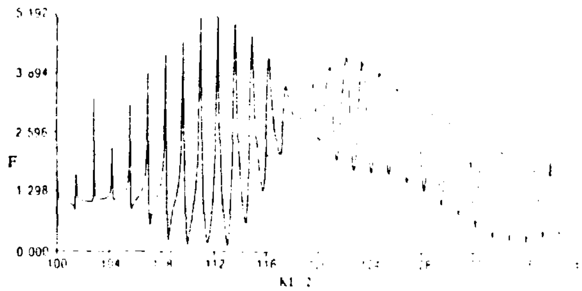


Fig. 1B. Frequency Domain Solution of 1% Thick Steel Spherical Shell at Coincidence

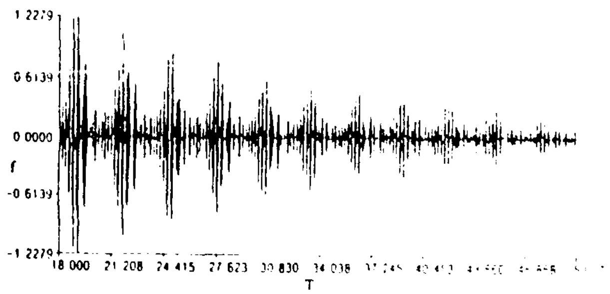


Fig. 2A. Time Domain Solution of 1% Thick WC Spherical Shell at Coincidence CW Ping

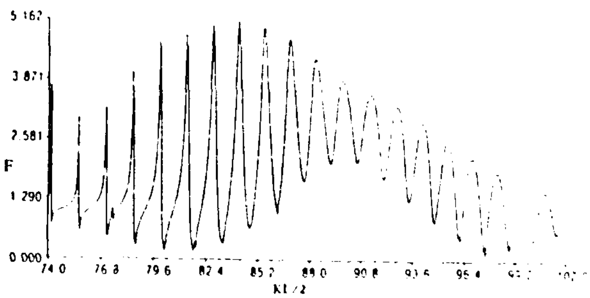
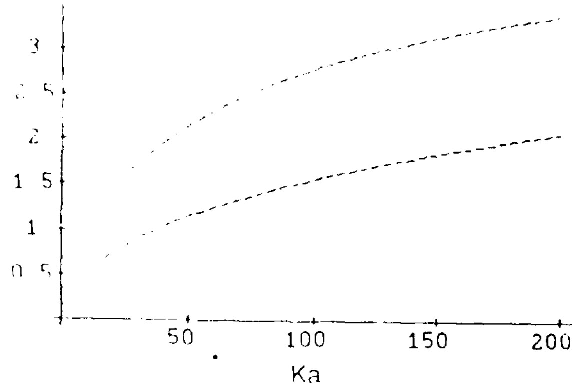
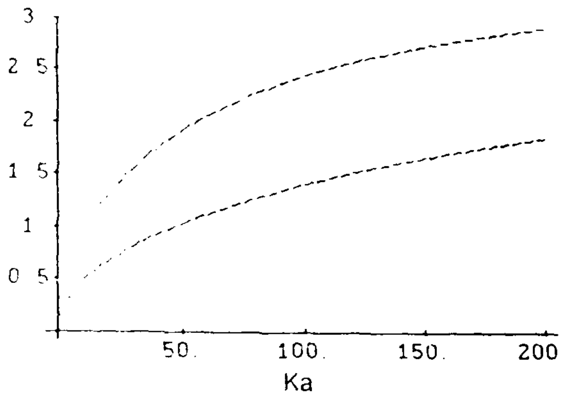


Fig. 2B. Time Domain Solution of 1% Thick WC Spherical Shell at Coincidence CW Ping



3. Phase and group velocites for steel 1% thick shell. Upper curve is for phase velocity.



4. Phase and group velocites for WC 1% thick shell. Upper curve is for phase velocity.

Conclusions

We conclude this section by commenting on the above results. We believe that the results shown here demonstrate that if proper conditions are met in time domain studies quite reliable and interesting interpretations can be made, while it is easy to come to erroneous conclusions when the proper conditions are not met. The trick obviously is to control the pulse times as well as the carrier frequency if one wishes to interpret such quantities as group velocities correctly. Further, there can obviously be conditions for which it is not possible to make sense of a group velocity within the context of a particular type of phenomena (i.e. Lamb waves, Rayleigh waves, etc.) particularly for narrow frequency bands in which different types of resonances are sensed. In particular, one should not interpret an envelope function as being associated with a particular group velocity which can be used to extract the group velocity of a particular type of resonance. Finally, it is difficult to see how the presence of a single resonance or for that matter very low frequency resonance scattering where phase velocities are highly dispersive and resonance widths are usually quite variable can lead to unambiguous results.

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