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Subsonic Rayleigh wave resonances on solid polymer spheres in Water and Backscattering Enhancements Associated with Tunneling: Experiments, Models, and the Relative Significance of Material and Radiation Damping

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Abstract

Rayleigh waves on typical solid "plastic" polymers have phase velocities which are less than the speed of sound in water. One consequence is that when a solid sphere or shell made of such a material is placed in water, the backscattering mechanisms can differ from the situation for ordinary solids. For example, since the Rayleigh waves on a sphere are subsonic waves instead of leaky waves, the scattering processes need to be modeled as acoustic tunneling through an evanescent region. We have experimentally confirmed the existence of the resulting resonance and backscattering enhancements. Experiments and computations also support the extension of a tunneling model previously developed for quasi-flexural waves on thin metallic shells [L. G. Zhang, N. H. Sun, and P. L. Marston, J. Acoust. Soc. Am. **91**, 1862-1874 (1992)]. For the case of PMMA spheres studied, the intrinsic material damping can significantly affect the scattering. Some models were tested for the combined effects of material and radiation damping. The material damping was sufficiently small for the quadrupole mode that the observed enhancement may be useful for sonar calibration targets as an alternative to liquid-filled shells. [Work support by the Office of Naval Research.]

Transcript

DR. HEFNER: I am following up on Dr. Marston's talk this morning. He mentioned that we are interested in looking at the scattering of sound from plastic and polymer objects in water, looking specifically at the kinds of enhancements you can get with the backscattering of sound.

[Transparencies 1 and 2]

Just to remind you, for these types of materials, the shear and Rayleigh wave velocities are much less than what is typically found for metals and, even more importantly, they are much less than the speed of sound in water, which greatly changes the types of scattering mechanisms that one would expect.

Also, the specular reflection off of these kinds of plastic objects is very small and typically you would not expect much re-radiation back to the source. However, if you look at the exact form function of the backscattering amplitude for, say, a solid acrylic sphere, you find as a function of normalized frequency that you get a very large backscattering enhancement at low frequencies, much larger than you would expect for a solid steel sphere (shown at the bottom of the screen there).

It suggests that there is some type of elastic scattering mechanism present here. We believe that this type of enhancement is due to coupling between the incident sound wave and the subsonic Rayleigh wave resonances. This largest peak, for one of our spheres, which was a 2" diameter solid acrylic sphere, occurs at 15.9 kHz (I will show some data for that sphere in a second).

As I said, the incident sound is coupling into these subsonic Rayleigh waves on the sphere and, to predict the backscattering --

[Transparency 3]

-- we used a model that had been used previously for subsonic waves excited on solid metallic shells. Looking at the diagram, our incident sound wave reaches the point shown here at the top of the sphere, then couples energy into these subsonic Rayleigh waves by tunneling through the evanescent field. The Rayleigh wave then travels around the back side of the sphere, tunneling energy back through the evanescent field, and re-radiating sound as it travels around. Finally it reaches this point, labeled D2, and it re-radiates sound in the backward direction, which can be detected at the source location.

We are going to use this to approximate the Rayleigh wave contribution to the form function for the acrylic sphere. However in most polymers one has to pay attention to the material absorption, since it is much larger than what one usually finds in metals.

[Transparency 4]

To determine whether or not it would be necessary to account for this in the ray approximation, we introduced the attenuation into the longitudinal and shear wave numbers in the form function, to see how much affect the attenuation was going to have.

So making the shear and longitudinal wave numbers complex, we can compare the exact form function without material absorption, shown in the top graph here, with the form function were we have added the absorption, the bottom graph. You can see that for higher frequencies absorption really affects the resonances and suppresses a majority of the response, whereas the enhancements at the low frequencies are relatively unaffected, although there is still a change in the amplitudes and the Q's of those resonances. Hence it is important and we decided to add that into the theory to see if we could account for it.

[Transparencies 5 and 6]

To check it experimentally, to make sure that this really was the case, we took a 2" diameter acrylic sphere, placed it in one of the large tanks and, using a PVDF sheet source, ensonified the sphere with 10 cycles around where we expected to find the resonance -- this first resonance, which is at 15.9 kHz. These graphs show the response of the sphere measured at the hydrophone some distance away for frequencies going up to and then past the resonance.

As you can see, as we get closer and closer to the resonance, this exponential decay, the tail of the resonance that we have excited gets larger and larger until it reaches its max at the value that we expected. So this large resonance is there and we measured the Q to be about 9.31, very low compared to what everybody else has been looking at today, but that is due to this large radiation damping.

[Transparency 7]

To approximate the Rayleigh wave contribution, we look at the partial wave series solution, which I have discussed before, that form function that told us the backscattering amplitude. Using the Sommerfeld-Watson transform we can take the denominator and put it in the form of a characteristic equation, by making the index complex and, from that, we can extract the phase velocity for the various waves in the sphere, Rayleigh, whispering gallery, et cetera. Our focus here is just on the Rayleigh wave. We can also get the damping coefficient for that particular wave as well.

Once we do that, we can substitute it into a form function contribution that is a ray approximation to each circumnavigation of the Rayleigh wave. These can then be summed to find the total contribution to the backscattering form function.

To incorporate the material absorption into this equation, we can do the same thing we did before. We can make the longitudinal and shear wave numbers complex as we did before, put them into the characteristic equation we were solving, and get out the new phase velocity and damping term which will now have both the radiation damping and the material absorption as it travels around the sphere.

Another way we can introduce material absorption into the ray approximation is to assume that the absorption is not going to affect the phase velocity very much and hence is simply additive to the radiation damping -- we tried that here below (just showing you the new terms).

To determine the material absorption we looked at the fluid-loaded acrylic half-space and used that value for the absorption -- there -- which we then added to the radiation damping.

[Transparency 8]

Going back, when we solve the characteristic equation with material absorption, we find the phase velocity for the Rayleigh wave, given in this top graph. You see that at higher frequencies it goes over to the half-space Rayleigh velocity, as one would expect. Plotted here is both with and without the material absorption results, and they are very, very close to one another. This means that the approximation I was discussing just a minute ago -- might be valid in that the Rayleigh velocity changes very little with the addition of absorption.

At the bottom here in this somewhat complicated graph we have the damping for the Rayleigh wave. The solid curve here is the calculation without the material absorption, so this is just radiation damping. You see we have a large peak right around where we found our enhancement as we might expect. This long-short dashed line here is the material absorption for the fluid-loaded half-space, which we can then add to the radiation damping to get this short dashed curve at the top.

Just below that, this long dashed curve, is the calculation where we have added material absorption and solved the characteristic equation exactly. These lines are not quite identical but they are very close, which suggests that that approximation might be useful.

[Transparency 9]

With all this information we can calculate the approximate ray synthesis to find the contribution to the form function of these subsonic Rayleigh waves, which is given at the top here. Each of these individual peaks are Rayleigh wave resonances, he first being the quadrapole mode.

If I compare that to the exact form function, given down here at the bottom, we find that these peaks overlap fairly well. The dashed line is the exact form function with material absorption. However, this is without the specular reflection contribution subtracted. With that subtraction these 2 curves are a little bit closer but not significantly so. It seems to correspond fairly well to what we would expect. Hence we are fairly certain that we have identified these as subsonic Rayleigh wave resonances.

[Transparency 10]

We also decided to check ourselves and do a measurement of the form function experimentally with the acrylic sphere I discussed before, using a 1-3 piezocomposite transducer running in a frequency range of about 30 to 60 kHz. At the bottom here we made measurements for 2 spheres. The first has a 1" diameter and the second has a 2" diameter sphere.

The triangles correspond to the 1" diameter sphere while the diamonds correspond to the 2" diameter sphere. The reason we chose this particular frequency range, and hence have divided the graph up like this is that at these low frequencies we must be concerned about reflections from the surface and the sides of the tank.

As you can see, we find fairly good correspondence to what we measured in the form function, which is reassuring; it means that these resonances are there and we can see them.

[Transparencies 11 and 12]

A potential application of these resonances, especially this large enhancement, is that it might be possible to use it for a passive sonar target. If we consider the target strength of this type of sphere, we can choose our sphere radius so that the frequency of interest corresponds to the largest resonance of the acrylic sphere and we can get large target strengths at relatively low frequencies. This could be useful in replacing the passive sonar targets that they have used in the past, which depended on glory scattering with CFCs. With the recent ban on CFCs, there is an effort to find alternative targets and this may be a possibility.

[Transparency 13]

I am going to talk now about something a little bit different. In looking at polymers, we decided to consider scattering from an acrylic shell. There are two properties of polymers, and acrylics, specifically, that make this scattering quite different from what one expects for metals.

The first which we encountered in the solid sphere was that the Rayleigh velocity is much less than the speed of sound in water. Looking at the Lamb wave spectrum, the symmetric wave has to pass through the sonic line here and then go over to the Rayleigh wave velocity.

Normally for metals it is the A_0 dispersion curve that has to pass up through the speed of sound in water, so this is not what one usually encounters. Also, there is a second interesting property in that the density of the material is very close to that of water, which means that the fluid loading is not just simply a small perturbation any more; it is actually very large and has a significant effect on the waves that travel through that material.

[Transparency 14]

I will address both of those. First, just looking at the effect of the low Rayleigh velocity on the symmetric wave, we recall that for a metal plate in water, the A_0 wave divides into 2 branches; the a_0 wave and the a_0- wave (the a_0- is subsonic, the a_0 wave is supersonic).

If we look at the S_0 wave, we find the same thing happens. Once again, as the S_0 wave passes through the speed-of-sound line in water it divides into 2 branches, one subsonic and one supersonic.

This is plotted for an artificial density of water of 0.2 and we will see in a minute why I chose that value, but this just illustrates that a similar effect emerges.

[Transparency 15]

If I let the density of water go to its normal value of 1, we find some strange things happening. If I run the code to find the phase velocity, I get something that looks like this. Instead of going down to the Rayleigh velocity immediately, it actually goes up past this line here, which is the longitudinal wave velocity, and interacts with the higher order symmetric waves, until finally it drops down to the Rayleigh wave velocity.

This has been studied by Rokhlin and Freedman and essentially what is happening is that as you increase the density of water and move toward stronger and stronger fluid loading, it restricts the surface motion of the plate. Finally, if you have infinite fluid loading, the surfaces experience mixed boundary conditions and the S_0 wave goes over to a longitudinal wave running down the plate.

So the symmetric wave is beginning to move up to this line to try to run along the longitudinal phase velocity. In the process, there are relatively complicated interactions that create some very strange dispersion curves.

[Transparency 16]

If we look at a fluid-loaded shell, a 5% acrylic shell in water, we find these same things happen and they are going to greatly affect the scattering from the shell. This solid line here, and the dashed lines, are for an artificial density of water, a density of 0.01. We see the same splitting of the dispersion curve and, as we let water go up to its normal value, we find that these 2 lines move apart -- this is what I call the S_0- down here -- and then the dashed line up here is the S_0 wave, which begins to turn up as we saw for the plate.

However, the program that performs this calculation does not like it because the damping becomes very large and the code dies on me. So this is as far as we can go there, but it gives me a good sense of what is happening. If we look at the damping, we find this increases very much for this top curve and as this line passes close to the speed of sound in water, large damping and then it drops off down below. These are all going to produce different kinds of enhancements.

[Transparency 17]

However, all of these enhancements are going to happen for higher frequencies than what we expected for the solid sphere and the material absorption is going to greatly suppress these features.

There are various features, such as this one here, which may still be present. We think this one is due to a backward wave or a wave that has a negative group velocity, so when the wave is incident on the shell, it turns down and, instead of going around the back side of the shell, travels along the front and then re-radiates back very quickly. It does not remain with the material for very long before it scatters sound back. Hence there is not much absorption there and we may expect to see this effect. This was observed previously by Greg Kaduchak for a stainless steel shell (I have it plotted here for a 7.5% shell, just to show you that it is present).

These are some of the things we might expect and some of the strange things that one runs into when scattering sound from acrylic objects in water.

[Transparency 18]

This is just a summary for you to look at. Thank you.

DR. MCPHERSON: Is the surface wave, as it comes around the back side, radiating all the way around?

DR. HEFNER: Yes, it is losing energy as it travels around there. Once one reaches the point where it can send energy back, then that is when one can detect it. Every time it is moving around there it is re-radiating more and more sound.

DR. HARGROVE: I think the question that was just asked is a point that is often missed when you are concentrating on what is the backscatter but, in fact, this has an enhanced radiation isotropically around, doesn't it?

DR. HEFNER: Yes.

DR. HARGROVE: You are only summing up what comes in the back, correct?

DR. HEFNER: Right, but we have to take into account what happens as it travels, the amount of loss as it travels around, to figure out those amplitudes.

Thank you.