

Trapped Scholte modes supported by soft elastic cylindrical rods underwater

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This paper documents trapped Scholte modes; nonradiative surface acoustic modes that exist on fluid-loaded elastic cylindrical rods. Unlike previously reported surfacelike waves on cylindrical rods, the Scholte modes identified here are localized to the interface between the rod and the surrounding fluid. The study investigates plastic rods submerged in water, which allows exploration of the domain where the Scholte velocity is significantly slower than the speed of sound in water. The supported Scholte modes are shown to become increasingly localized to the solid-fluid interface at high frequencies, as their phase velocities tend toward that of the Scholte wave on a planar interface. This was modeled numerically using the finite element method and experimentally verified using cast acrylic rods underwater.

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I. INTRODUCTION

On the planar interface between an isotropic solid half-space and a fluid half-space, two types of surface waves exist—the leaky Rayleigh wave and the Scholte wave.

The Rayleigh wave is a surface wave that propagates along a free surface. In other words, it propagates unattenuated along a solid-vacuum interface. The leaky Rayleigh wave [1–4], however, exists on a flat solid-fluid interface, and can be considered the Rayleigh wave of a free surface whose behavior has been altered by fluid loading. Unlike the Rayleigh wave, the leaky Rayleigh wave decays as it propagates along the interface, leaking energy into the fluid. This decaying wave has a phase speed slightly above the Rayleigh velocity for a free surface and slightly below the transverse bulk wave speed in the solid. The leaky Rayleigh wave must also propagate with a phase velocity that exceeds the speed of sound in the fluid, and as such, this wave is only allowed for solid-fluid interfaces where the transverse bulk wave speed in the solid exceeds the speed of sound in the fluid [5], with the exact threshold investigated by Mozhaev and Weihnacht [6,7].

Modes that are allowed to radiate away from an interface or waveguide are referred to as radiative. For an interface, this occurs when the phase velocity of a mode exceeds at least one of the bulk speeds of sound in one of the media, while a waveguide mode will radiate if the phase velocity exceeds a bulk speed of sound in the surrounding medium. For the leaky Rayleigh wave, the leaky Rayleigh velocity exceeds the speed of sound in the fluid c_F , and hence radiates energy into the fluid. Modes that exist below the bulk speeds of sound are known as near-field modes. They have insufficient momentum to radiate and will decay into the surrounding media. In other

words, near-field modes are trapped surface waves and propagate along the interface unattenuated.

Unlike the leaky Rayleigh wave, the other surface wave that propagates along a planar interface between a solid and a fluid, the Scholte mode [8–11], is a near-field mode. The phase velocity with which this mode travels along a single planar solid-fluid interface is referred to as the Scholte velocity in this work. It is given by the Scholte-Stoneley equation [5,9,12,13], and its value is below that of the bulk speeds of sound in the fluid and the solid.

Despite being a localized wave that is allowed for all solid-fluid interfaces [5,11], research on the Scholte mode has fostered interesting but limited application, as its velocity is very close to the speed of sound in the fluid [14–17], and therefore it closely resembles a grazing wave in the fluid. However, this is only the case for “hard” solid-fluid interfaces [18], such as the conventionally studied metal-water interface. For “soft” solid-fluid interfaces, such as a plastic-water interface, the Scholte velocity is notably slower than the speed of sound in the fluid [19] and the disturbance is no longer largely localized to the fluid, with its energy penetrating into both media [20].

In addition to the surface waves, there can exist two lateral waves in the solid at the planar boundary. These correspond to grazing transverse and longitudinal waves, traveling at the bulk transverse velocity c_T and the bulk longitudinal velocity c_L , respectively. Unlike the Rayleigh and the Scholte waves, the amplitude of lateral waves does not decay exponentially in the direction normal to the interface.

Many studies have looked at modes with surface wave-like behavior traveling along submerged solid cylindrical rods, both for the axially symmetric case and for higher circumferential orders (modes with a nonzero integer number of wavelengths about the circumference). Four classes of modes with surfacelike wave behavior have been described for metal rods underwater—Rayleigh modes, whispering gallery modes, Franz modes, and the Scholte mode [21–27]. Unless axially symmetric, these modes travel both

around the circumference of the submerged rod and along its axis.

The velocity of the Rayleigh mode [3,28] tends toward the leaky Rayleigh wave velocity at high frequencies, and it radiates energy into the surrounding water. Similarly, the phase velocity of the axially symmetric Scholte mode, sometimes called the Stoneley mode, tends toward the Scholte velocity at high frequencies. Unlike the Scholte modes documented in this work, this previously reported radially symmetric Scholte mode is not trapped. It is weakly attenuated and radiates energy tangentially into the fluid [21,22,25].

The whispering gallery modes [29] are cylindrically propagating modes associated with the solid's elastic properties. At high frequencies, the behavior and velocity of the transverse whispering gallery modes tend toward that of a lateral transverse wave along a flat boundary. Similarly, at high frequencies or in the limit of a rod with an infinite radius, the longitudinal whispering gallery modes propagate as longitudinal lateral waves.

Franz modes [30] arise due to the cylindrical geometry of the system, existing even on impenetrable cylinders. They have high attenuation levels, corresponding to energy leaking off the rod tangentially as the mode propagates, and become infinitely damped when the radius of the rod goes to infinity. These modes are described for metal rods underwater as traveling at velocities close to but less than the speed of sound in the surrounding fluid at high frequencies, with the modes becoming slower and increasingly attenuated with decreasing frequency, or with increasing circumferential order.

For the case of a planar interface between two different solid half-spaces, certain conditions permit the existence of a trapped surface wave, with behavior analogous to that of the Scholte mode on a solid-fluid interface. This wave, called the Stoneley mode [31], propagates along the interface at the Stoneley velocity, and exponentially decays into the solids on either side.

When the conditions for the Stoneley mode are met for a solid cylindrical rod embedded in an infinite solid (an infinitely clad rod) [32], there is an allowed family of Stoneley modes existing for all integer circumferential orders [33]. Unlike any of the modes identified to be traveling along a solid rod submerged in a fluid, these Stoneley modes are guided waves, and as such, they do not radiate energy into the cladding. With increasing frequency, the disturbance becomes more localized to the interface and propagates at the Stoneley velocity in the high-frequency limit.

The majority of previous studies on solid cylindrical rods submerged in a fluid [21–26] deal exclusively with the case of “hard” solid-fluid interfaces, where the Scholte velocity is very close to the speed of sound in the surrounding fluid. This present study explores the case of a “soft” interface, specifically a cast, approximately isotropic, acrylic cylindrical rod submerged in water. It investigates the behavior of trapped Scholte modes; a family of guided modes that travel unattenuated along the rod when viscous loss is neglected, with slower phase velocities than the speed of sound in the surrounding fluid. The behavior of these modes is analogous to the Stoneley modes in infinitely clad rods and has not been identified or observed much on solid cylindrical rods submerged in a fluid.

This present study investigates these modes through both finite element method (FEM) modeling and experimentation, where the Scholte modes are excited and measured propagating on acrylic rods of three different diameters submerged in water. The identification and verification of these guided waves on solid rods underwater could have useful implications for nondestructive testing [16,17,34,35]. Furthermore, increasing our understanding of how underwater acoustics interact with “soft” solid-fluid interfaces benefits the many industries that utilize underwater acoustics, including applications in sonar used by the fishing industry, oil companies, the military and the police, as well as acoustofluidics [36] used in biotechnologies and chemistry.

II. BEHAVIOR OF THE TRAPPED SCHOLTE MODES IN SOFT ELASTIC RODS UNDERWATER

The Scholte modes in this study were modeled using the finite element method in COMSOL multiphysics. The full 3D behavior of the rod system is evaluated and adequately captured by a 2D model, represented by a disk of water enclosing the circular geometry of the acrylic rod. The pressure acoustics module and the solid mechanics module, solving the acoustic and structural mechanics problems, are coupled to evaluate the problem. In the plane of the 2D model, the radial wavenumber k_r and the angular wavenumber, represented by the circumferential order number n , are defined. Out of the plane of the model, the wavenumber down the rod axis is denoted k_z . An eigenvalue model was used to evaluate the modes for a range of out-of-plane wavenumbers, returning a set of eigenfrequencies as a function of k_z .

The numerically obtained dispersion relations are presented in Fig. 1. As we are only interested in the Scholte modes, and many of the non-Scholte rod modes tend toward the transverse speed of sound c_T , all data above this sound line are not plotted.

Figure 1(a) displays the dispersive behavior of the lowest four modes supported by a 10 mm diameter rod. The lowest frequency mode, which sits below the Scholte velocity at low frequencies, is the mode with circumferential order $n = 1$, and the second lowest mode and the first mode to cross the transverse sound-line is the $n = 0$ mode. These modes do not tend to the Scholte velocity within the frequency range presented, but do converge on the Scholte sound line at higher frequencies.

The behavior of these two lowest-order modes can be compared to the coupled Scholte modes in fluid-loaded flat plates [20]. The slower antisymmetric plate mode has a comparable dispersion to the $n = 1$ rod mode, with both cases exhibiting a snaking motion. The faster symmetric breathing plate mode is analogous to the axisymmetric $n = 0$ rod mode [20].

Figure 1(b) shows the existence of modes of higher circumferential order, for a larger diameter rod (30 mm). Except for the first two modes, as discussed above, each additional mode that crosses the transverse sound line corresponds to a mode of $+1$ higher circumferential order compared with the mode below it. Also evident in this dispersion plot is that the velocity of each mode disperses to-

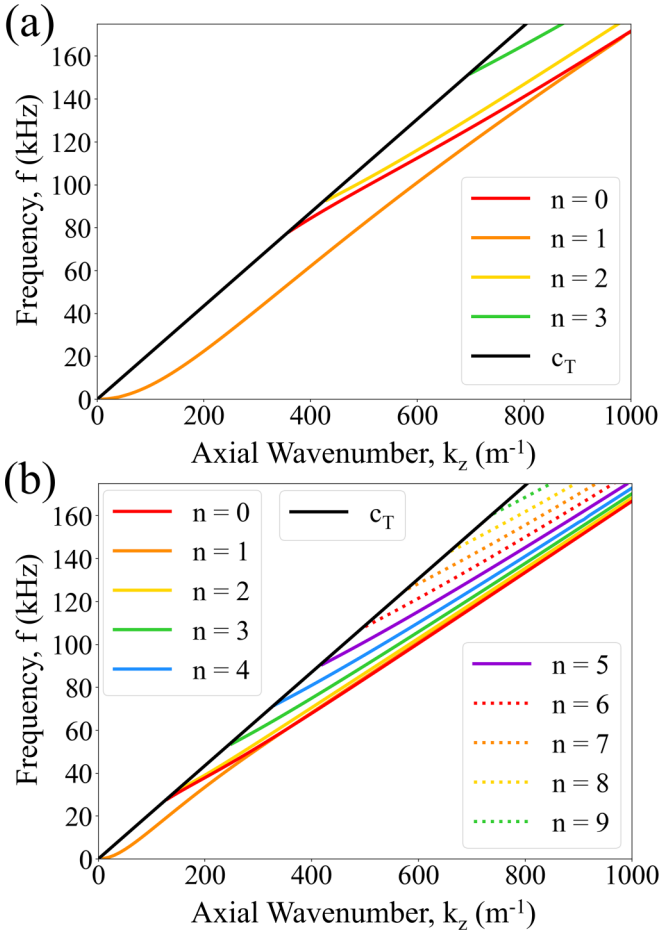


FIG. 1. Dispersion relations for the Scholte modes supported by (a) 10 mm and (b) 30 mm diameter acrylic rods underwater, together with the bulk transverse wave speed in acrylic c_T . The slowest mode, beginning below c_T , is the $n = 1$ snaking mode. The first mode to cross the c_T line is the axially symmetric $n = 0$ mode, with the modes of higher circumferential order following in increasing n .

ward the Scholte velocity c_{Sch} with increasing out-of-plane wavenumber/frequency—this behavior is also clear in the frequency-phase velocity representation (Fig. 4), introduced later.

Furthermore, in the high-frequency region, the disturbance associated with the mode becomes increasingly localized to the surface of the rod. This is demonstrated in Figs. 2 and 3, where the displacement magnitude of a 30 mm diameter acrylic rod, and the acoustic pressure in the water are presented in a color map for modes with $n = 0, 1$, and 3 . Figure 2 shows the disturbance penetrating across much of the rod at $k_z = 250 \text{ m}^{-1}$. On the other hand, Figure 3 shows that the same modes become highly localized to the interface between the rod and the surrounding fluid at larger wavenumber ($k_z = 1000 \text{ m}^{-1}$).

For acrylic underwater, the Scholte modes disperse before tending toward a limit velocity, the Scholte velocity, which is significantly slower than the speed of sound in the fluid, as clearly observed in the phase velocity-frequency plot in Fig. 4(a). Except for the slow $n = 1$ mode, the Scholte modes

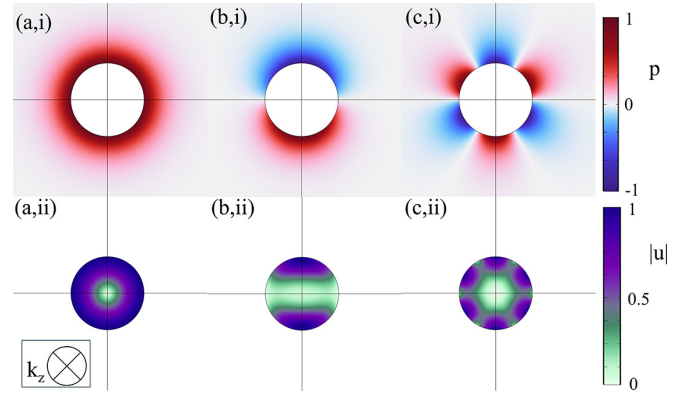


FIG. 2. The behavior of the modes for modes with circumferential order $n = (a) 0, (b) 1, (c) 3$ at $k_z = 250 \text{ m}^{-1}$ displayed in terms of (i) normalized acoustic pressure p in the water (red and blue), and (ii) normalized displacement magnitude $|u|$ in the rod (purple and green) for the 30 mm diameter rod. Here the fields of the Scholte modes are penetrating through much of the rod.

begin with phase velocities larger than the c_{Sch} , and then with increasing frequency converge on c_{Sch} .

For a planar aluminium-water interface, the Scholte velocity approximates the speed of sound in water [5,14,15,18–20]. The phase velocities for the Scholte modes for an aluminium rod with a 30 mm diameter are shown in Fig. 4(b). There are only two Scholte modes present for the aluminium rod in this frequency region, and, except for at low frequencies, the two modes sit very close to one another with their phase velocity differing from the speed of sound in water by only a fraction of a percent. As most of the studies on fluid-loaded rods to date have been done on metal rods underwater, it is plausible that the proximity of the Scholte modes to the speed of sound in water is why it has not been documented frequently.

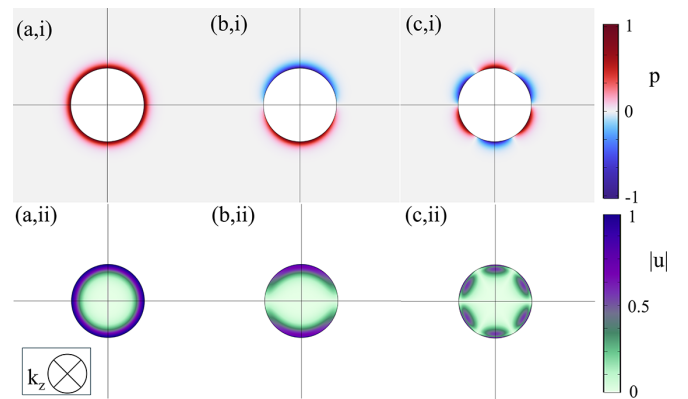


FIG. 3. The behavior of the modes for modes with circumferential order $n = (a) 0, (b) 1, (c) 3$ at $k_z = 1000 \text{ m}^{-1}$ displayed in terms of (i) normalized acoustic pressure p in the water (red and blue), and (ii) normalized displacement magnitude $|u|$ in the rod (purple and green) for the 30 mm diameter rod. Here the Scholte modes are highly localized to the surface.

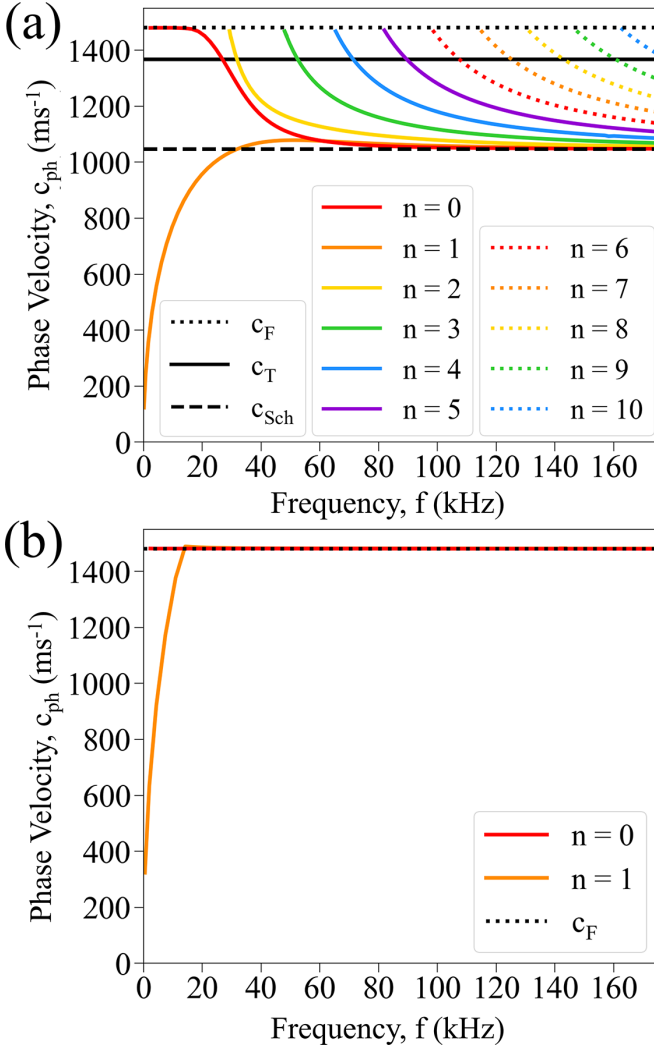


FIG. 4. Phase velocity vs frequency of the Scholte modes of a 30 mm diameter (a) acrylic rod and (b) aluminium rod. Generally, for a given frequency, the mode numbers increase with increasing frequency, except in the low frequency region of (a), where $n = 1$ is slower than $n = 0$.

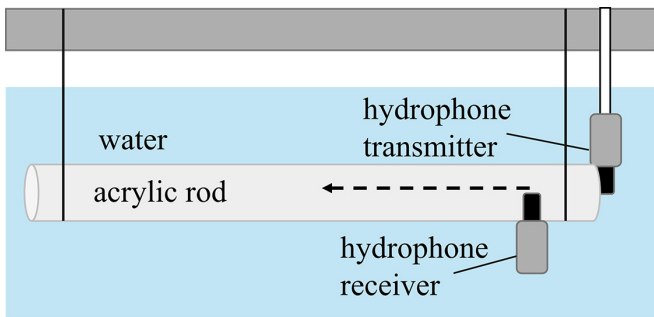


FIG. 5. A schematic of the experimental setup used to excite and detect Scholte modes in acrylic rods of diameter $d = 10$ mm, 20 mm, and 30 mm underwater. The rods were suspended in a water tank, attached to a support using nylon thread. A hydrophone is positioned at one end of the rod to excite the modes, and another hydrophone scans along the rod from a motioned scanning stage (not pictured).

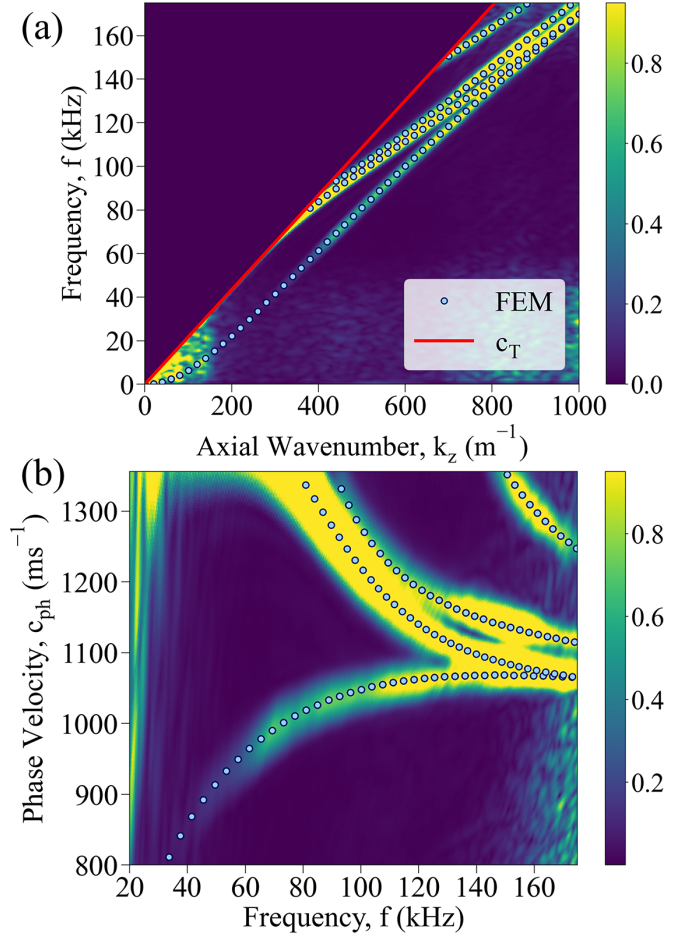


FIG. 6. Experimental data obtained for an acrylic rod of diameter $d = 10$ mm is presented as (a) a color map of the Fourier transformed data, where the peaks in Fourier amplitude, shown in yellow, indicate the dispersion of the modes, in agreement with the overlaid theoretical predictions, and the same data and theory are also presented as (b) a color map of phase velocity vs frequency.

III. EXPERIMENTAL VERIFICATION

In the experimental setup, a cast acrylic rod is suspended in a tank of water via two 0.2 mm diameter nylon threads attached to supports, as illustrated in Fig. 5.

An acoustic transceiver source (B&K Type 8103 hydrophone) was positioned approximately 1 mm away from the end of the rod and driven with a sine-Gaussian pulse (four cycles) with a central frequency of 100 kHz. The source was intentionally misaligned from the rod center to enhance coupling to modes of higher circumferential order.

An acoustic transceiver detector (B&K Type 8103 hydrophone) mounted on a motorized scanning stage was positioned approximately 0.5 mm away from the surface of the rod to detect signals propagating locally down the rod, including the near-field signal associated with the Scholte modes. The source and detector were operated using a single trigger, and the temporal signal was measured at each spatial position in a 450 mm linear scan (0.75 mm steps) and averaged over 50 repeats.

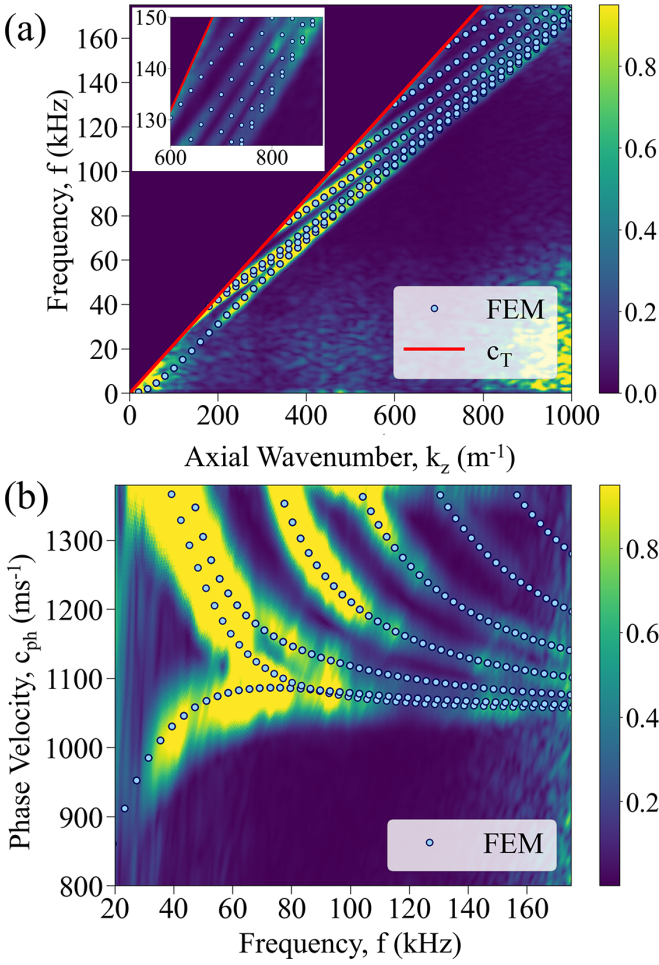


FIG. 7. Experimental data obtained for an acrylic rod of diameter $d = 20$ mm is presented as (a) a color map of the Fourier transformed data, where the peaks in Fourier amplitude, shown in yellow, indicate the dispersion of the modes, in agreement with the overlaid theoretical predictions, and the same data and theory are also presented as (b) a color map of phase velocity vs frequency.

The time-dependent data was fast Fourier transformed to obtain the phase and amplitude data for every frequency, and then a spatial Fourier transform produced the wave vector spectrum at each frequency.

Due, in part, to the existence of nodes in cylindrical rod modes, where no fluctuations in amplitude are present at certain spatial positions around the circumference, not all modes are detected by a single scan. To overcome this, the experiment was repeated several times, making small adjustments to the position of the source between each scan. These small angular and radial shifts in source position relative to the rod face change the location of the nodes, as well as the efficiency with which the different modes couple to the rod at different frequencies. Averaging the resulting experimental dispersions from several of these scans provided a more complete map of the dispersion.

The experimental results for rods of diameter 10 mm, 20 mm, and 30 mm, are presented in Figs. 6–8, respectively. The upper plot in each figure shows the measured dispersion behavior as a color map of Fourier amplitude overlaid by the theoretical dispersion curves obtained via FEM modeling.

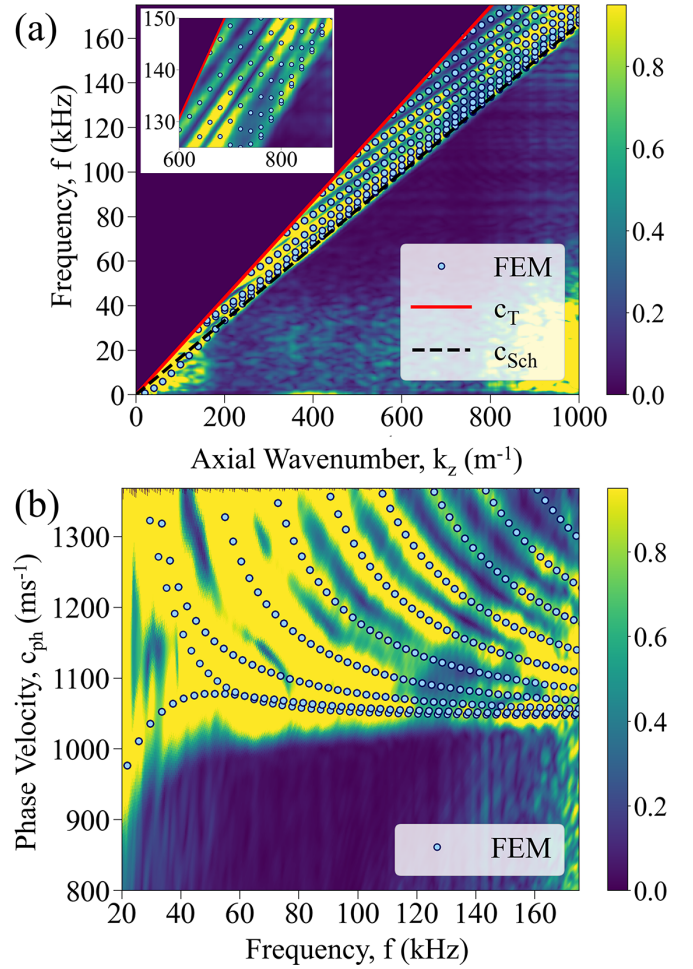


FIG. 8. Experimental data obtained for an acrylic rod of diameter $d = 30$ mm is presented as (a) a color map of the Fourier transformed data, where the peaks in Fourier amplitude, shown in yellow, indicate the dispersion of the modes, in agreement with the overlaid theoretical predictions, and the same data and theory are also presented as (b) a color map of phase velocity vs frequency.

The lower plots present the same measurement data plotted in terms of the phase velocity against frequency.

Since the focus here is on trapped Scholte modes, all data above the transverse sound line in the dispersion plots, or above the y-axis range in the phase velocity plots, are omitted. We note also that we do not expect to detect the highly attenuated Franz modes in this experiment.

Even when averaging temporal data over several scans, the results still exhibit some fluctuation of amplitude across modes and frequencies, which can be attributed to variations in coupling efficiency between the excited Scholte modes and the source, and the modal structures being detected. To minimize these effects, the Fourier amplitude of the dispersion plots has been normalized to the integral of the amplitude at each frequency, setting the peak amplitude at each frequency to unity. Additionally, any signal that is less than the mean background noise in the high wavenumber region has been set to zero to increase the visibility of the modes.

Despite this, from Figs. 7 and 8, we can see some reduction in amplitude for the modes at higher frequencies and with higher circumferential order, as these modes are increasingly

difficult to excite with this arrangement. Nevertheless, these higher-order modes are visible in the results and are particularly clear and distinct in the phase velocity plots.

All three figures show good agreement between the theoretical dispersion curves, produced by FEM, and the experimental data. For the 10 mm rod, shown in Fig. 6, the dispersion of the modes of lowest circumferential order are demonstrated. As the diameter of the rod increases, as in Figs. 7 and 8, the modes can be observed to be tending toward the Scholte velocity sound line as frequency increases, starting with the lowest circumferential order modes.

It should be noted that the three rods slightly differ in their elastic parameters, likely due to minor variations in the casting and setting process, and as such, their theoretical dispersions were determined using different elastic constants. Changing the elastic parameters accordingly produced small variations in the dispersion, resulting in a better fit between the experimental and theoretical results for each rod. For the rod with a diameter of 10 mm, the Young's modulus, E , is determined to be $E = 5.80 \pm 0.12$ GPa [35]. For the rods with diameters 20 mm and 30 mm, the respective Young's moduli are determined to be $E = 5.98 \pm 0.06$ GPa, and $E = 5.87 \pm 0.09$ GPa [35]. These values exceed the zero-frequency elastic parameters for acrylic, with the manufacturer's data sheet giving a value of 3.2 GPa. This is due to the relaxation phenomena observed in viscoelastic materials [37], such as plastics, at nonzero frequencies [38–40].

The Young's modulus was the only parameter that notably varied between the rods, and as such, it is the only parameter that was adjusted when fitting the theoretical modes to the experimental data.

IV. CONCLUSIONS

A family of trapped Scholte modes on “soft” fluid-loaded cylindrical rods underwater have been identified and experimentally observed.

These Scholte modes are a family of modes traveling with phase velocities slower than both the speeds of sound in the rod and the speed of sound in the surrounding fluid. At high frequencies, the phase velocity of these modes tends toward the Scholte velocity, and the disturbance associated with the mode becomes increasingly localized to the interface between the rod and the surrounding fluid.

The Scholte modes were excited in approximately isotropic cast acrylic cylindrical rods underwater using ultrasonic Gaussian pulses. The experimental data from time and spatial scans were used to obtain dispersion curves for these modes. A fit between the experimental and theoretical data was demonstrated, verifying the existence of the trapped Scholte modes.

This increased understanding of the near-field modes of a “soft” solid structure provides an intellectual base from which to design improvements to acoustofluidic devices and sonar sensors for a wide range of applications.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [42].

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