Sound beyond the speed of light: Measurement of negative group velocity in an acoustic loop filter

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The authors describe the experimental observation of negative group velocity propagation of sound waves through an asymmetric loop filter. The characteristics of the filter are established using impulse response and direct tunneling of narrow bandwidth Gaussian pulses. The results confirm recent theoretical predictions that faster-than-light group velocity propagation of sound is possible. Further, the results show that the spectral rephasing achieved in a loop filter is sufficient to produce negative group velocities independent of the phase velocity of the spectral components themselves. Thus, superluminal propagation is realized despite almost six orders of magnitude difference between the speeds of sound and light. © *2007 American Institute of Physics*.
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The question of wave velocity has been studied since the advent of Einstein's special theory of relativity.[1,2] A central issue is whether the speed of light in vacuum c constituted an upper limit to the group velocity—the velocity of the peak of a wave packet. The consensus of much theoretical work[3–5] is that the group velocity is not limited and, in the past few years, a number of experiments[6–9] have confirmed that it is possible for optical or electrical wave pulses to travel through absorbing, attenuating, or gain materials with group velocities greater than c. Furthermore, under appropriate conditions, the group velocity can even become negative,[10–13] a circumstance in which the peak of the tunneled pulse emerges from the output of the medium before the peak of the incident pulse has reached the input. Although most wave propagation phenomena have been explored for electromagnetic waves, there is a history of theory and experiment using ultrasonic acoustic waves.[3,14,15] Recently, it was predicted through numerical modeling[16] that faster-than-light phenomena should be observable for ultrasound pulses. In this letter we demonstrate experimentally the transmission of audio-frequency acoustic pulses through an asymmetric loop filter with group velocities that exceed the speed of light. This work is significant for two reasons. First, we confirm the theoretical prediction that, under the appropriate conditions, sound pulses can exhibit group velocities that surpass the speed of light in vacuum. Second, we demonstrate a simple passive acoustic filter system that exhibits a negative group velocity.

The mechanism by which superluminal propagation arises involves rephasing of the spectral components of a pulse by a medium that exhibits anomalous dispersion. Anomalous dispersion occurs over frequency intervals in which materials exhibit strong absorption, attenuation, or gain. The spectral components of a pulse traveling through an anomalously dispersive medium recombine in a manner such that they replicate the shape of the original pulse but are moved forward closer to the leading edge of that pulse. Because the tunneling pulse is fashioned from the leading edge of the incident pulse, it exits the sample earlier in time. The group velocity is defined by the length of the sample divided by the time taken for the peak of a pulse to traverse the sample. If anomalous dispersion is sufficiently strong the group velocity can exceed the speed of light. If the transit time is zero, the peak of the transmitted pulse exits at the same time as the peak of the incident pulse reaches the input, and the group velocity is infinite. Finally, in the case of very strong dispersion, the peak of the transmitted pulse exits before the peak of the incident pulse reaches the input, and the group velocity is negative. It is now generally agreed that all of these superluminal phenomena do not violate special relativity or causality and, in particular, it has been shown that the speed of information transmission is subluminal.[17,18] In all previous optical, microwave, or electrical demonstrations the individual spectral components of the pulse have velocities close to the speed of light and thus realizing sufficient rephasing to achieve superluminal propagation is less surprising. In the experiments described here, however, the individual spectral components travel at the speed of sound, almost six orders of magnitude slower than the speed of light and yet still experience sufficient rephasing to achieve superluminal velocities.

Experiments were conducted in a one-dimensional acoustic waveguide system constructed from 1.9 cm diameter polyvinyl chloride (PVC) pipe. The filter element being characterized was an asymmetric loop filter, a type of acoustic interference filter modeled on a similar device used in electrical measurements in coaxial cable waveguides.[12] The design and dimensions of the acoustic loop filter are shown in Fig. 1(a). The loop was created from the same type of 1.9 cm diameter PVC pipe used for the waveguide and it was connected together using commercially available right-angle and T junctions. The asymmetric loop splits the guided sound signal along two unequal length paths designated as d_L and d_S (long and short, respectively). By analogy with the electrical results reported in Ref. 12, there are two mecha-

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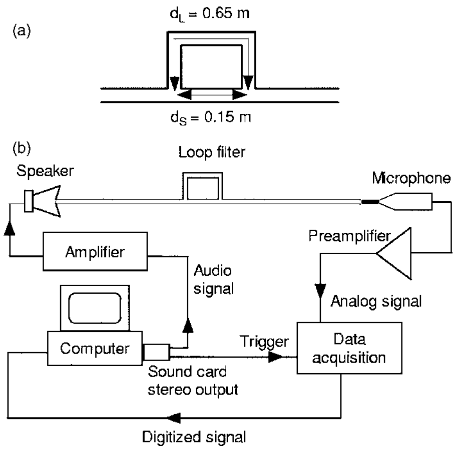

FIG. 1. (a) Dimensions of the serial loop filter. (b) Schematic of the acoustical test system.

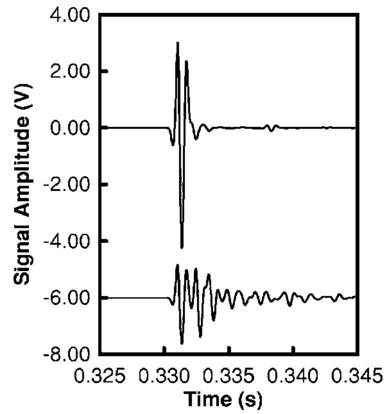

FIG. 2. Plot of the impulse as a function of time through the straight waveguide (upper plot) and through the loop filter (lower plot).

nisms by which the asymmetric loop filter results in dips in transmission. The first mechanism is due to destructive interference that results when the path length $\Delta L = d_L - d_S$ between the long and short arms differs by one-half wavelength. The second mechanism occurs due to standing wave resonances around the whole length of the loop $L = d_L + d_S$. The two mechanisms result in transmission dips at frequencies

$$f_n = (2n+1)\frac{v_s}{2\Delta L}, \tag{1}$$

$$f_m = \frac{m v_s}{L}, \tag{2}$$

where v_s is the speed of sound and n and m are positive integers.

The experiments consisted of two measurement types. First, we used very short acoustic impulses that contained a broad frequency spectrum to determine the filtering properties of our asymmetric loop structure. Fourier analysis of the impulse response led us to discover the frequency ranges in which we could expect to measure negative group delays and hence superluminal acoustic group velocities. The second part of the experiment used narrow bandwidth acoustic pulses with a Gaussian envelope to demonstrate explicitly the negative group delay. In both experiments we compared transmission through a loop filter to transmission through a straight waveguide. The straight waveguide segment that replaced the filter in the reference measurements was equal in length to the short arm of the loop filter (d_S) such that the shortest physical path between the source and detector was identical in both measurements.

The experimental configuration is shown schematically in Fig. 1. The computer sound card was used to produce an audio and a trigger signal on the respective channels of the stereo output. The audio signal was amplified and sent to the speaker (Alesis Monitor One) which was coupled to the input end of the waveguide. The audio signal was either an impulse or a narrow-band Gaussian envelope depending on the type of experiment being performed. At the output end of the waveguide, the transmitted audio signal was detected by a condenser microphone (ACO 7013), amplified, and digitized by the analog-to-digital converter (IOtech 3000 USB). The trigger signal from the second stereo channel consisted of a narrow square pulse that was routed to the trigger input in order to initiate data acquisition. To achieve high signal-to-noise ratio data we used an add-and-average technique described previously.[19] The loop filter was located in the center of a long (8 m) section of waveguide in order to provide a large time window free from multiple reflections from the discontinuities at the filter, speaker, and microphone.

Figure 2 shows the time domain data comparing transmission through a single loop filter to a straight waveguide. Figure 3 shows the frequency dependent results derived via Fourier analysis of impulse response data. The impulse and the corresponding trigger signals were created numerically in MATLAB. The impulse contained frequency components from 100 Hz out past 3 kHz allowing the frequency dependent filter response to be determined in a single experiment. Impulses were recorded after transmission through the filter and through a straight waveguide. The complex transmission function of the filter was calculated by dividing the Fourier transform of the filter impulse by that of the straight waveguide signal.[19] Figure 3(a) plots the amplitude transmission as a function of frequency derived by taking the absolute value of the complex transmission function. Sharp drops in transmission are seen at frequencies of 339, 457, 927, 1018, 1392, 1751, 1801, 2301, 2416, and 2761 Hz. These values are in excellent agreement with the predictions of Eq. (1) and in good agreement with Eq. (2) using the filter dimensions of d_S=0.15 m and d_L=0.65 m.

Figure 3(b) plots the phase delay derived from the complex transmission function. In a normally dispersive medium

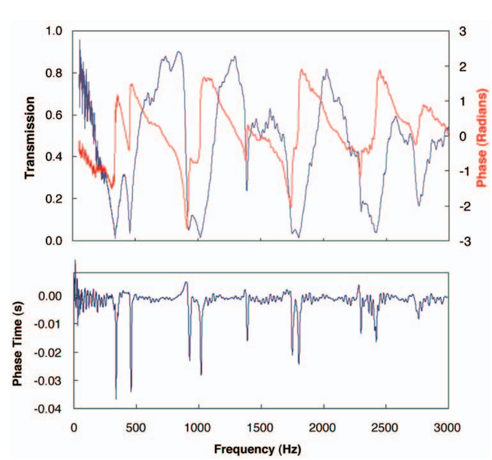

FIG. 3. (Color) Filter response as a function of frequency derived from a numerical Fourier transform of the impulse response experiments. Upper plot: (a) Transmission (blue) and (b) phase (red). Lower plot: (c) phase time.

the phase delay would be a monotonically decreasing function beginning at the origin. In the case of the loop filter the phase delay generally decreases with increasing frequency except for a series of steep positive jumps in phase. These phase jumps occur at frequencies corresponding to the transmission minima and represent regions of strong anomalous dispersion. The negative of the slope of the phase delay data with respect to angular frequency results in the phase time—the time difference for propagation through a filter compared to the straight pipe. The phase time data are plotted in Fig. 3(c), and for most frequencies, are near zero. This result is expected because the shortest direct path from source to detector is identical for both the filter and straight waveguide cases—the only difference in the filter case is the addition of the loop path in parallel. However, at the frequency intervals that exhibited strong phase jumps, the phase time dips sharply to negative values. These values are sufficiently negative to indicate that pulses whose spectral components fall within these frequency bands exhibit negative group velocities. The negative velocity value can be quantified. The time delay Δt is given by the expression

$$\Delta t = \frac{L}{v_g} - \frac{L}{v_s}, \tag{3}$$

where L is the length of the straight waveguide segment (d_S), v_s is the speed of sound (representing both phase and group velocities in the straight waveguide), and v_g is the group velocity of a narrow-band pulse through the loop filter. Solving for v_g gives

$$v_g = \frac{v_s L}{L + v_s \Delta t}. \tag{4}$$

If Δt is sufficiently negative such that $|v_s \Delta t| > L$ then the group velocity v_g is negative. The conditions for a negative group velocity are met for all of the negative phase time dips corresponding to the transmission minima shown in Fig. 3.

Although the impulse response method of determining a negative group velocity is valid, it is more convincing to perform an experiment that demonstrates the effect explicitly. Figure 4 shows the plots of a narrow bandwidth pulse centered at a frequency of 2414 Hz after propagation through a straight waveguide segment (blue plot) and through a loop filter (red plot, scaled up by a factor of 10 for clarity). The peak of the pulse that travels through the loop filter clearly arrives at an earlier time than the pulse through the straight waveguide. The time difference, determined by numerically finding the weighted center of the pulse,[20] is -0.0024 s which corresponds to a group velocity value of -52 m/s. Comparable results were obtained for pulses centered at the other transmission minima.

In conclusion we have demonstrated faster-than-light group velocity propagation for sound pulses in an asymmetric loop filter and the existence of a simple acoustic waveguide configuration in which negative group velocities can be realized. Finally, the type of path-difference interference in the loop filter, described by Eq. (1), is directly analogous

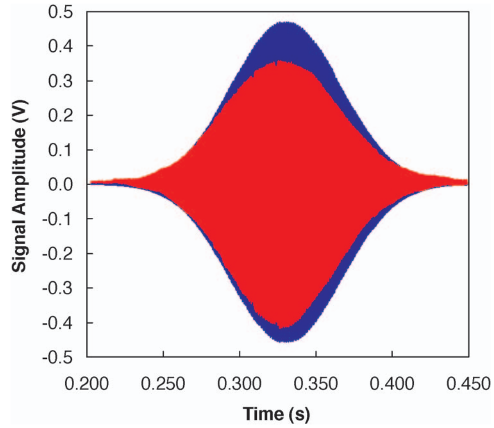

FIG. 4. (Color) Plots of Gaussian wave packet centered at 2414 Hz after transmission through straight waveguide (blue) and through a single loop filter (red). The red trace has been scaled up by a factor of 10.

to the comb filtering phenomenon in architectural acoustics[21] where direct sound from a source interferes with a strong reflection from a hard surface. Thus, the superluminal acoustic effect we have described is likely a ubiquitous but imperceptible phenomenon in the everyday world.

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