Amelioration of waves and micro-vibrations by micro-buckling in open celled foam

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Abstract

Open cell polymer foam exhibits both an intrinsic micro-vibration frequency and a cut off frequency associated with resonance of the cell ribs. Compression of the foam causes regions of local buckling of ribs. Incipient buckling gives rise to negative stiffness and enhanced amelioration of waves. Transmitted wave amplitude is reduced by compression below and near the cut off frequency.

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1 Introduction

In cellular polymers, the micro-vibrations of structural elements influence the propagation of acoustic waves by dispersing the waves and producing a cut-off frequency. The cut-off frequency occurs because the structural resonance frequency of the rib elements limits the maximum frequency of waves that can pass through. Structural resonance may be modified by changing the structure itself or by an imposed strain.

Wave disturbances over a wide frequency range can be ameliorated by material damping [1]; for example, polymer foams are viscoelastic and provide substantial material damping [2]. Wave disturbances can also be reduced by local structural resonance, or by negative stiffness inclusions [3]. As for acoustic waves, layered or other periodic structures can give rise to stop bands of near zero wave transmission over ranges of frequency. The frequency usually corresponds to a sound wavelength on the order of the structure size. For tungsten wires 0.127 mm in diameter spaced 0.3 mm in aluminum alloy, the stop band begins at about 5.5 MHz [4]. For steel rods embedded in epoxy [5], a spacing of 6 mm gives a stop band from about 120 kHz to almost 300 kHz in the ultrasonic regime above 20 kHz. One difficulty with such an approach is that the attainable stop band frequencies are in the ultrasonic range; to block acoustic or sub-audio waves, the required structure size is prohibitively large to be considered in the context of materials. Cut off frequencies in the acoustic range were observed in flexible polymer foam of cell size about 1 mm to be about 2.5 kHz [6]. Ribs in polymer foam are bend-dominated so their resonance frequency corresponds to a wavelength These materials are compliant and they can be used as sound absorbers or baffles, but they not appropriate to be used as stiff structural materials. If one seeks acoustic wave blocking in stiff materials, genuinely macroscopic length scales are required. For example, in periodic shaped hard plastic rods 6 m long with shape memory inserts, similar cut-off frequencies of around a kilohertz were obtained [7].

Local resonances can give rise to negative effective mass density in composites consisting of inclusions of coated spheres, for example, with a core of lead surrounded by rubber, in a stiff light matrix [8] [9]. As the material is oscillated above the resonant frequency the dense spheres move out of phase with the input. Such an approach can block waves in certain frequency ranges as well.

In the present research, micro-buckling of cell ribs is used to obtain regions of incipient negative stiffness [10], with the aim of reducing wave transmission.

2 Experimental Methods

The foam was Z60Q open celled, 60 pores per inch, reticulated polyester foam acquired from Foamex Industries [11]. This foam is commonly used for filtration applications. An optical micrograph of the foam is shown in figure 1. The density is low, about 0.04 g/cm^3. That corresponds to 96% porosity. Test specimens were cut from a large block using a hot wire cutter. For attenuation measurements, and for detailed study of transmitted waveforms, two specimens were studied, a 14 by 2.2 by 2.4 cm specimen and a 6.2 by 2.2 by 2.4 cm specimen. A third specimen consisted of an air gap without foam, to discern the contribution of sound through the air. This is necessary because the foam is of low density and contains much air.

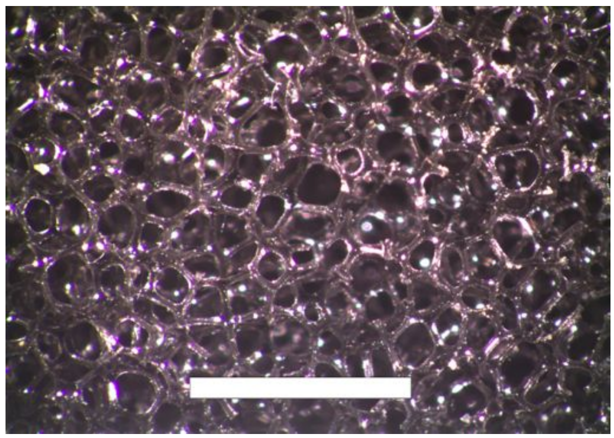


Figure 1: Optical micrograph of the foam studied in this work. The scale bar is 3 mm long.

The foam was studied by sending tone bursts of longitudinal waves through bar shaped specimens of foam. The waves were generated with a one inch diameter piezoelectric bender transducers with the input electrical signal produced by a Tektronix AFG3051C function generator. An identical bender was used to pick up the response on the other side of the specimen. The bender natural frequency was about 3 kHz, above the range required. Input and response were monitored with a Tektronix TDS 3012 digital phosphor oscilloscope. Small loudspeakers were initially tried as transducers but they did not generate sufficient signal at the higher frequencies. Phase velocity was found by measuring the time delay between sending and receiving the signal for a specimen 18.5 cm in length. The time delay from the leading edges of input and received waveforms was used to infer velocity. Attenuation was found by measuring the amplitude of the response of different lengths of specimens at the same frequency. The amplitudes were fit to the attenuation model, $A_1 = A_0 \exp(-\alpha z)$ where z is the length of the specimen, A_1 is the measured amplitude, A_0 is a scaling coefficient and α is the attenuation.

The shorter specimen was compressed 20% between the transducers to test the effects of buckling of ribs. This specimen was short enough that compression resulted in local micro-buckling of the foam and not column buckling of the specimen. The micro-buckling resulted in bands of heterogeneous deformation in the foam. In analysis of waveforms, the frequencies of the responses were found by expanding the horizontal scale of an area of interest and measuring the period of the sinusoid. A rubber specimen was also tested to exclude possible instrumental artifacts that could mimic a cut off frequency.

3 Results and discussion

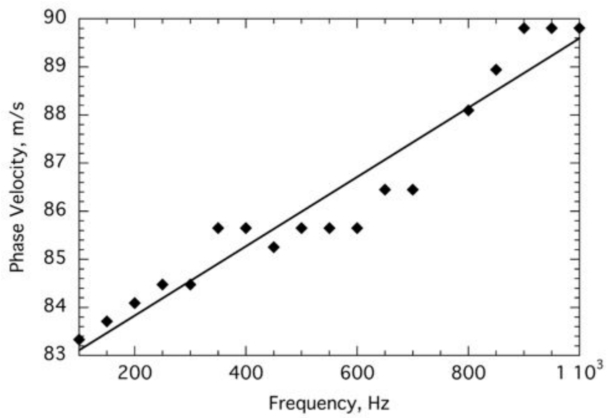
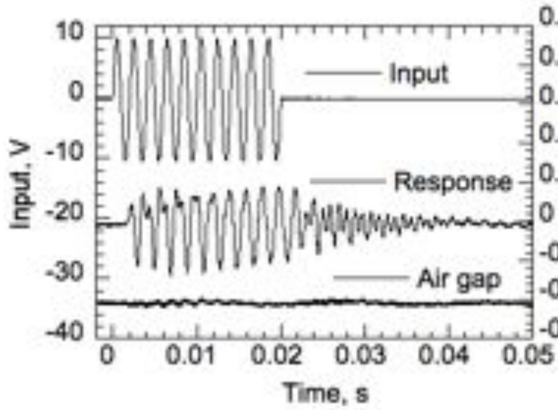
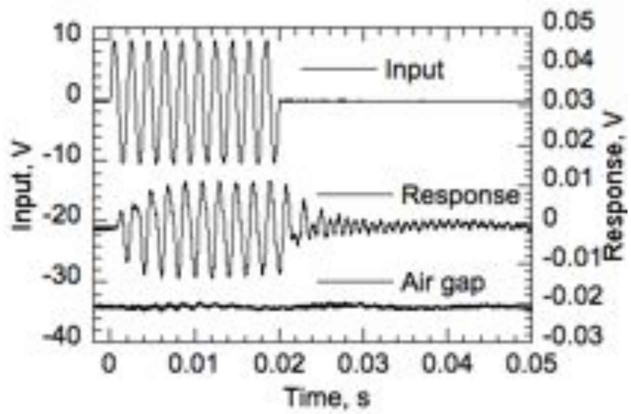


Figure 2: Below the cut off frequency, the phase velocity increases with frequency.

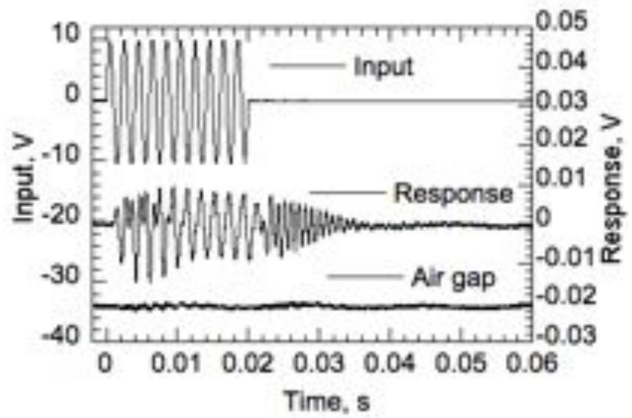
Below the cut off frequency, the phase velocity increases with frequency, shown in figure 2. Such an increase is expected in a viscoelastic material such as a polymer foam. The Young's modulus inferred from the wave speed at 300 Hz and the density is 290 kPa. At the frequencies used, the wavelength is much larger than the specimen width, so the wave velocity is the bar velocity. The modulus under quasi-static conditions will be lower as a result of the frequency dependence of modulus. The attenuation of the foam at 300 Hz it was 2.9 m^{-1}; at 500 Hz it was 3.9 m^{-1}, and at 700 Hz was 4.2 m^{-1} . At 500 Hz, below the cut-off frequency, the signal passes through the specimens at the forcing frequency, shown in figure 3. After the input, the specimen rings out at the natural frequency of ribs, at 1.0 kHz. The tone burst contains Fourier harmonics at other frequencies in addition to the driving frequency, hence the response at the micro-resonance frequency. The effect of compression was to modestly decrease the response at the driving frequency.



(a) Long Specimen, 14 cm



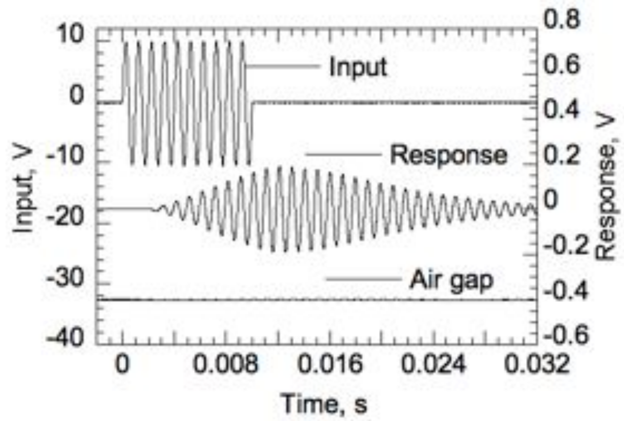
(b) Short Specimen, 6.2 cm



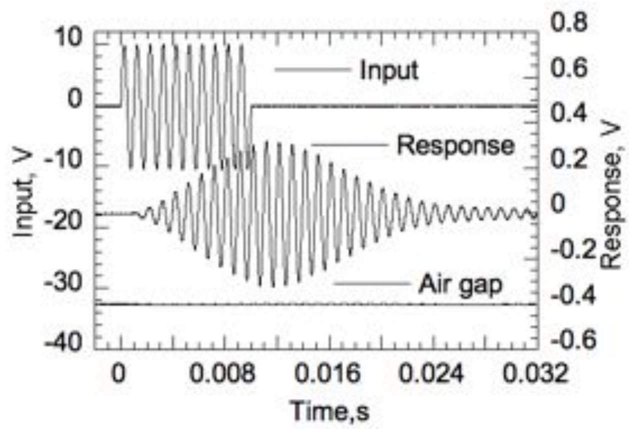
(c) Compressed Short Specimen

Figure 3: Wave transmission results at 0.5 kHz. Compression modestly decreased the response at the driving frequency.

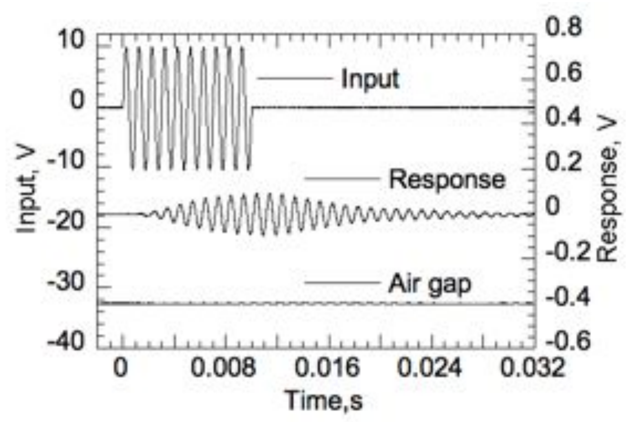
The cut-off frequency of the foam was found to be 1 kHz. Rubber, by contrast, exhibited no cut off frequency. In figure 4 the input and response of the specimens is shown for a forcing frequency of 1 kHz. Ringing at that frequency persists after the end of the pulse. The received signal was considerably stronger in this case than at the other frequencies, as indicated by the difference in scale on the right. The least amount of signal passes through the compressed specimen. This has the shortest distance for waves to pass through, so one might expect a greater transmission; however the compression results in micro-buckling of ribs which gives rise to instability, hence a region of negative incremental stiffness. This region helps to block the waves. The transmission of signal through the air is shown in these plots as well and its amplitude increases with frequency, however, it is small compared to the signal through the foam in all cases. Similar behavior was observed at 0.8 kHz and 1.2 kHz. Different compressive strains were tried; transmitted wave amplitude decreased with compressive strain up to about 14%, then was constant with increasing compression.



(a) Long Specimen, 14 cm



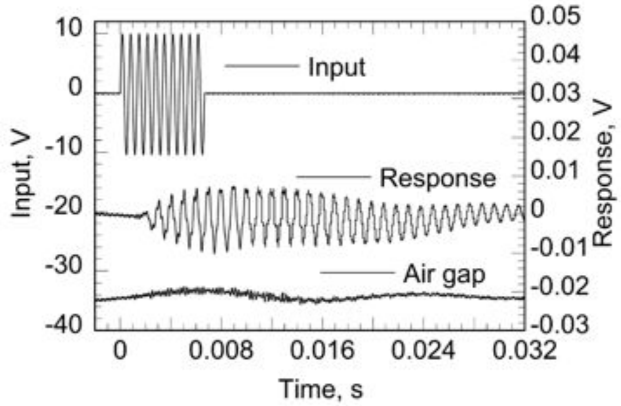
(b) Short Specimen, 6.2 cm



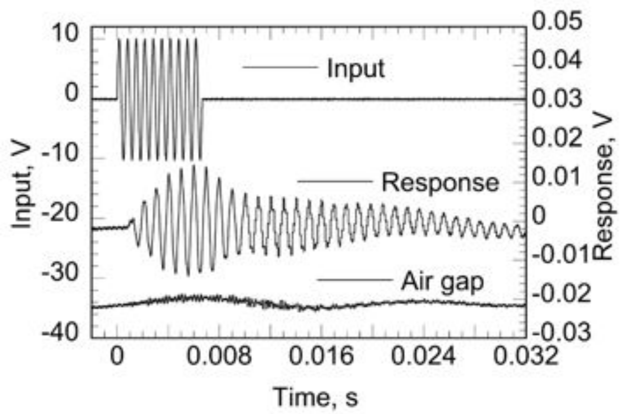
(c) Compressed Short Specimen

Figure 4: Wave transmission results at 1 kHz. Ringing due to micro-vibration occurs at the material's characteristic frequency. Compression results in reduced transmission.

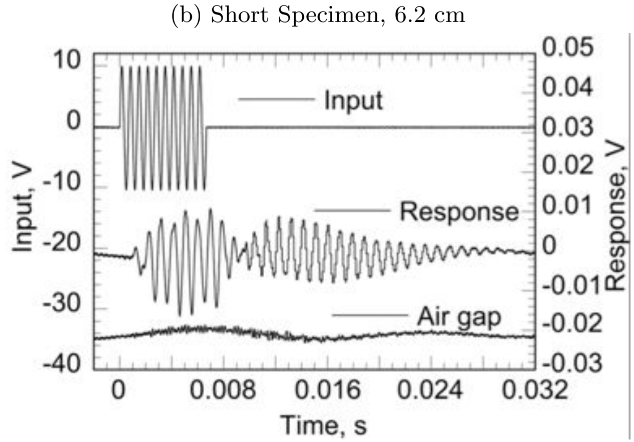
Above the cut-off frequency, the response is not at the forcing frequency, rather it comes through at 1 kHz, shown in figure 5. There is no observed response at 1.5 kHz for any of the specimens. The response is measured to be at 1 kHz for all specimens. The compressed specimen displays a beat phenomenon in the waveform. The associated difference in frequency was too small to be detected by measuring the periods of the waves. The transmission is similar between the compressed and uncompressed specimens except that the response decays faster for the compressed specimen. Compression modestly reduces the amplitude of the 1 kHz response, introduces a beat phenomenon into the 1 kHz ringing after the pulse and increases the damping of the ringing.



(a) Long Specimen, 14 cm



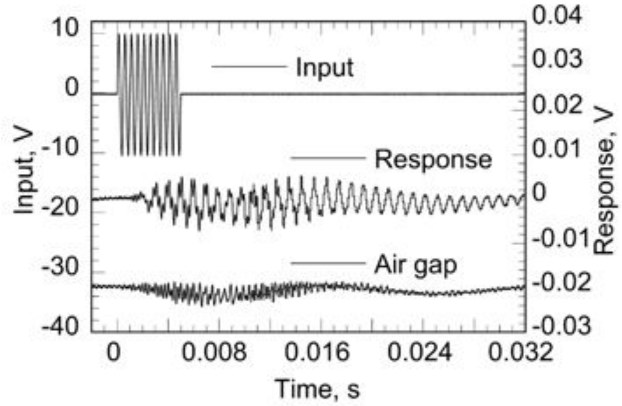
(b) Short Specimen, 6.2 cm



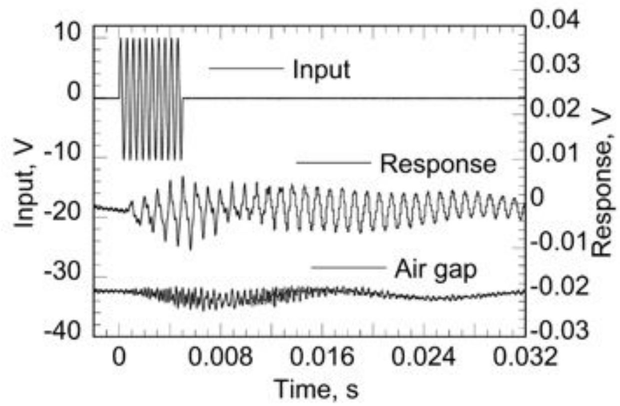
(c) Compressed Short Specimen

Figure 5: Wave transmission results with 1.5 kHz input. There is no response at 1.5 kHz. The response is measured to be at 1 kHz for all specimens.

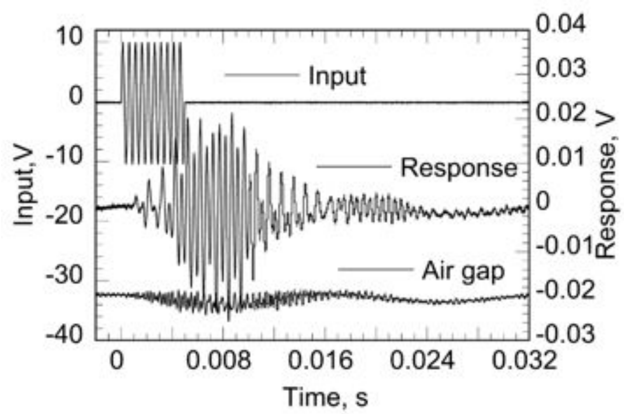
With an input at 2.0 kHz, shown in figure 6, the response of the uncompressed specimens was measured to be at 1.0 kHz. The response of the compressed specimen was predominantly at 2.0 kHz and there was more signal transmitted through the compressed specimen compared to the uncompressed.



(a) Long Specimen, 14 cm



(b) Short Specimen, 6.2 cm



(c) Compressed Short Specimen

Figure 6: Wave transmission results with 2.0 kHz input.

The 1 kHz micro-vibration response is due to the material not a length resonance because the same frequency is observed in specimens of different length.

The physical cause of a micro-vibration frequency and a cut off frequency in foam is resonant vibration of ribs comprising the foam [6]. The wavelength of waves in the foam at 1 kHz is 90 mm, compared with the cell size, 0.42 mm. The reason for the difference is that ribs in polymer foam are bend-dominated. So their resonance frequency is much lower than that of a stretch dominated structural element. An elementary model of the foam rib vibration can account for the order of magnitude of the cut off frequency. Cut off frequencies and wave dispersion can also be interpreted in the context of generalized continuum theories in which the points of the continuum not only translate as in classical elasticity or viscoelasticity but rotate and deform as well [12].

Wave dispersion in periodic structures is well known [13], originally in the context of crystal lattices. At sufficiently high frequency in elastic solids, the wave speed decreases with frequency. A similar phenomenon is obtained in generalized continua [12].

The reason for the increase in wave speed with frequency in figure 2 is as follows. The damping tan δ inferred from attenuation α via $\alpha \approx \frac{\omega}{2v} tan\delta$, is 0.26 at 300 Hz, 0.22 at 500 Hz and 0.17 at 700 Hz with v as the wave velocity and ω as the angular frequency, with $\omega = 2\pi f$ in which frequency is f. The change in modulus over a factor ten in frequency based on tan $\delta = 0.2$ is a factor of 1.34. That assumes a broad distribution of relaxation times and no internal resonances: $E(f) \propto f^n$ with $\delta = n\pi/2$. The change in modulus over a factor ten in frequency based on the dispersion in velocity in figure 2 is only a factor 1.18. The difference is attributed to the softening effect associated with the internal resonances in the material. In a purely elastic material with internal resonances, such softening gives rise to a decrease in wave speed with frequency [12] [13]. In viscoelastic materials such as the foam, this is compensated by the increase in modulus with frequency associated with damping.

The ring-down of micro-vibration of ribs corresponds to an effective damping tan $\delta = 0.035$. This is considerably smaller than damping associated with wave attenuation or wave dispersion. The internal degree of freedom revealed by rib vibration evidently experiences less damping than the bulk longitudinal wave.

As for the effect of regions of buckled ribs, the high damping observed in other negative stiffness systems arose from a snap through effect in the vicinity of the buckling transition [3]. The snap effect is not as abrupt in a high damping material such as the foam, as it is in a low damping material. Therefore the effect of the buckled regions is modest.

4 Conclusion

Micro-vibrations and a cut off frequency were observed in open celled foam. Uncompressed foam had a cut off frequency of 1 kHz. Below the cut-off frequency, the foam behaves at a viscoelastic material, with phase velocity increasing with frequency. Near and above the cut-off frequency, the foam exhibits local resonance and does not behave as a classical continuum.

Compared to the unstrained specimen, less signal was transmitted through the strained specimen below the cut-off frequency and more signal was transmitted above cut-off frequency.

5 Acknowledgements

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