

Interaction between blast wave and reticulated foam: assessing the potential for auditory protection systems

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Abstract. Injuries to the tympanic membrane (ear drum) are particularly common in individuals subjected to blast overpressure such as military personnel engaged in conflict. Here, the interaction between blast wave and reticulated foams of varying density and thickness has been investigated using shock tube apparatus. The degree of mitigation afforded by the foam samples is discussed in relation to an injury threshold which has been suggested by others for the tympanic membrane.

1. Introduction

The minimum audible pressure of the human ear is defined as 2×10^{-5} Pa at test frequencies ranging from 1-3 KHz [1]. This results in the ability to detect one part in 10^{10} at atmospheric pressure. Consequently, the human ear is the most pressure-sensitive organ of the body and is suggested to be the first to manifest injury as a result of exposure to blast waves [2]. Breeze et al. [3] found that 53% of all evacuated military personnel that had sustained blast-induced injury in Iraq and Afghanistan between 2006 and 2009 exhibited abnormal audiogram results. However, as not all evacuated personnel received audiogram testing, it was deemed likely that the levels of auditory damage in blast victims could be higher than indicated by the study.

Sound pressure levels (SPLs) are a measure of sound intensity and are measured in units of decibels (dB) – see equation (1), where P_0 is the ambient pressure and P is the witnessed overpressure. The threshold of pain occurs at approximately 120 dB. According to equation (2), this sound intensity corresponds to a pressure of 20 Pa. However, due to the fact that the human ear responds logarithmically to sound intensity, typical gunshot loudness levels, whose maximum outputs range from roughly 160 to 170 dB, correspond to pressure levels of $\sim 2 - 6$ KPa [4]. The tympanic membrane has been noted to rupture at pressures beyond 37 KPa [5]. Consequently, as the overpressures generated in close proximity to large detonation events may reach into hundreds of Kilopascals, a clear requirement for auditory protection systems on the battlefield emerges. A key focus of this research was to examine materials that may offer hearing under normal conditions but ‘react’ upon witnessing blast overpressure. Here, the response of reticulated (open cell) foam to blast wave is investigated.

$$SPL (dB) = 10 \log_{10} \left(\frac{P_{RMS}^2}{P_0^2} \right) \quad (1)$$

$$P_{RMS} (Pascals) = P_0 \times 10^{\frac{SPL}{20}} \quad (2)$$

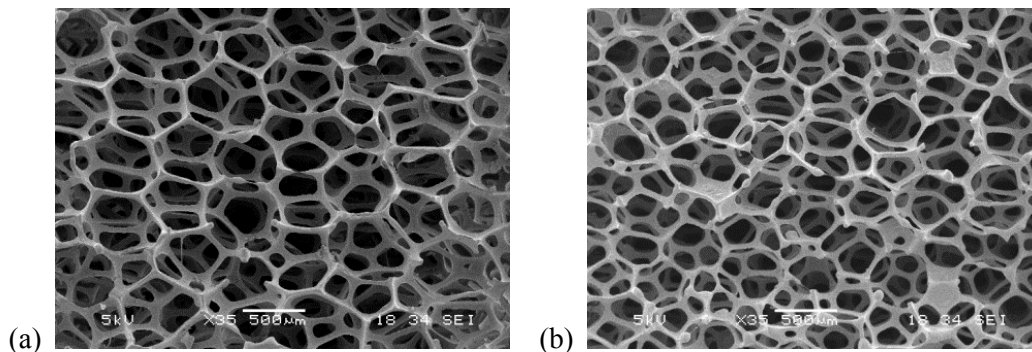


Table 1. Sound-pressure relationships (supplementary information taken from [4]).

Intensity (W/m^2)	Sound Pressure Level (dB)	P_{RMS} (Pa)	Notes
1×10^{-2}	100	2.0	
1.00	120	20.0	
1×10^2	140	200.0	
1×10^4	160	2000.0	.30 rifle and 12-gauge shotgun [4]
1×10^6	180	20,000.0	
1×10^8	200	200,000.0	Potential blast event

2. Materials

Reticulated polyurethane foams manufactured by Acoustafom Ltd (UK) were used in this experimental study. The reticulation process involves removal of the windows/faces within a regular, closed-cell polyurethane foam. This may be achieved by the ignition of gas (e.g. hydrogen) within the pore spaces of closed-cell foams under controlled heating. This leaves a skeletal frame corresponding to the contact regions between the closed cells in the pre-treated material. Reticulated foams of 65, 69, 75, and 79 ppi (pores per inch) and ranging in average density from 29-34 g/cm^3 (manufacturer values) were investigated in this work. Scanning electron micrographs of the 65 ppi and 79 ppi foams are shown in figures 1 (a) and (b), respectively (field of view $\sim 10.5 \text{ mm}^2$). The micrographs were obtained using a JEOL JSM-5610LV variable pressure scanning electron microscope. A repeating polyhedral structure is clearly apparent within the foam samples. A more comprehensive description of the structure of reticulated foams is provided by the Kelvin and Weaire–Phelan models [6].

**Figure 1.** Scanning electron micrographs of: (a) 65 ppi; and (b) 79 ppi foam samples.

As discussed, any material offering the potential for blast mitigation in the context of auditory protection should also introduce minimal effect on the natural operation of the human ear. An example of the acoustic absorption of an open-cell foam of the type investigated in this work is shown in figure 2. Acoustic absorbance (ISO: 10534-2) is typically determined by obtaining a frequency response function between two microphones in a tube that is sufficiently massive that transmission of noise and vibrations does not affect measurements. In addition to the reflective coefficient, the absorption coefficient and normalized impedance for a test material may be determined from the frequency response function. The absorbance coefficient (α) and normal impedance (Z_n) of the sample material may be calculated using equations (3) and (4), where R is the experimentally-determined reflection coefficient. It seems reasonable to suggest that the peak absorption for reticulated foams exhibiting porosity characteristics similar to those investigated in this work should lie between approximately 3.5 and 4.5 KHz (e.g. mid-high frequency range occupied by a snare drum).

$$\alpha = 1 - |R|^2 \quad (3)$$

$$Z_n = \frac{1+R}{1-R} \quad (4)$$

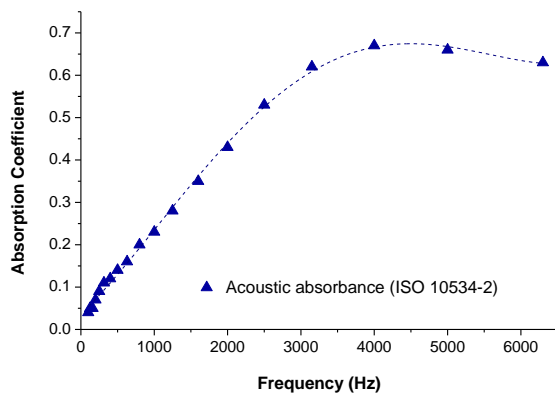


Figure 2. An example of the acoustic absorbance of reticulated, polyurethane foam with porosity characteristics equivalent to the materials investigated in this work. Measurements taken with a Type 4206 B&K Absorption Tube and a Type 3560 Pulse Analyser.

3. Experimental Setup

Blast wave interaction with reticulated polyurethane foams of 65, 69, 75, and 79 ppi was investigated using a 3 m long, 60 mm bore steel shock tube. All foams were manufactured to thicknesses of 40, 70, and 80 mm. The pressure-time histories of the interactions were measured using a Dytran® 2300V1 pressure transducer exhibiting a sensitivity of 21.4 mV/psi. A schematic for the experimental setup is shown in figure 3. Foam samples of 100 cm² were gripped between two (locked-position) steel plates. Each plate had a Ø 60 mm cut-out which was aligned with the bore of the shock tube. In an attempt to assess the effects of standoff distance (an important factor when considering the design implications of potential auditory protection devices) pressure output was measured at distances of 5 and 40 mm from the rear surface of the foam samples.

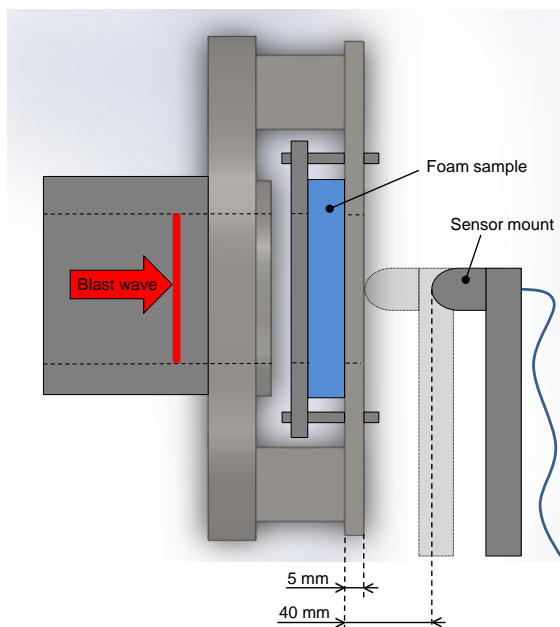


Figure 3. Experimental setup (Note: 5 and 40 mm standoff distances).

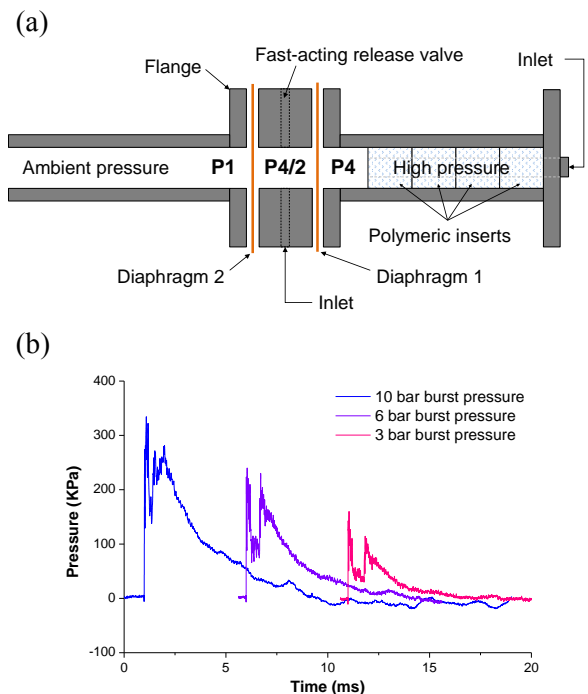


Figure 4. (a) Double diaphragm arrangement with variable driver volume; (b) output pressures from minimal (approx. 107 cm³) driver volume (no foam).

A double-diaphragm bursting arrangement was used in all experiments (see figure 4(a)). This allowed for accurate control of the firing pressure via solenoid, i.e. controlled evacuation of region P4\2 in figure 4(a). Diaphragms were comprised of aluminium (40 μm thick) or Mylar[®] (23, 50, and 100 μm thick). This allowed for burst pressures of 2, 3, 6, or 10 bar, respectively. The duration of the shock pulse was minimized via inclusion of polyethylene inserts within the driver section of the shock tube. In general, a long pulse duration is achieved using a large volume of driver gas, while short pulses are achieved using a reduced driver volume. In all cases here, a minimal driver volume of $\sim 107\text{ cm}^3$ was used. Consequently, the resultant shock pulses are suggested to be more representative of blast waves in an open environment, i.e. those conforming to the Friedlander waveform [7].

While providing an accurate method for firing the shock tube, and hence reproducibility of shock pressure, the double diaphragm setup also provided a double shock to the sample. Rupture of diaphragm 2 (see figure 4(a)) is initiated by the blast wave formed upon rupture of diaphragm 1. This likely causes a secondary, rearward compression wave that is reflected when it reaches the polymeric insert boundary. The temporal separation of the incident and reflected shocks at the shock tube outlet was noted as being dependent on the volume of polymeric inserts used in an experiment, thus reinforcing this hypothesis. The wave separation for a 2.0 bar shot is shown in figures 5 (a) and (b). The waves are approximately 1.5 milliseconds apart, matching the incident pressure-time history shown in figure 6.

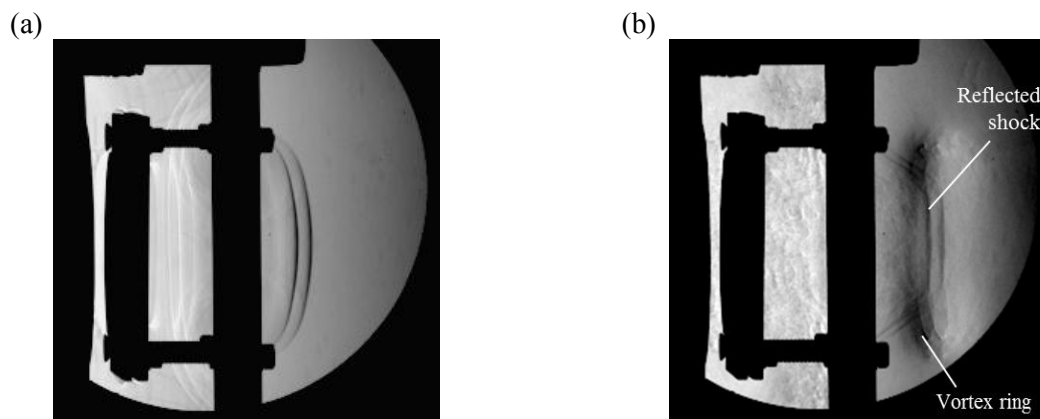


Figure 5. (a) incident shock; (b) reflected shock seen penetrating the vortex ring.

The schlieren images shown in figures 5(a) and (b) were captured using a single mirror system ($f = 1.84\text{ m}$), which was illuminated using a Cree[®] CXA2011 X-Lamp[®] LED array. In this setup the light was not parallel and it traversed the region of disturbance twice. Consequently, a slight off-axis deviation has resulted in a doubled image. Single mirror systems are also susceptible to the effects of coma. Such features are clearly observed in the schlieren images presented here.

4. Results and Discussion

Our initial experiments sought to assess the effects of standoff distance on the measured pressure profile. Notably, any system used to protect the tympanic membrane will likely be required to sit in close proximity to the outer ear. Figure 6 shows the pressure profiles resulting when the sensor was placed 5 mm from the rear surface of 40, 70 and 80 mm thick samples of the 65 ppi foam. The incident pressure profile is also shown in figure 6. Signals for the incident and transmitted pressure profiles were smoothed using 150 and 100 pt. adjacent averaging filters, respectively.

The ideal gas description of a shock tube allows the pressure in a shock wave through an ideal gas to be determined from initial known conditions and the shock speed – see equation (5). By assuming a value of $\gamma = 1.4$ (diatomic gas), and using the calculated shock velocity ($M = 1.21$), the pressure in the shock equates to 154 KPa. However, the reflected shock pressure measured by the sensor in the bull-

nose mount represents a much smaller interaction area than a flange-mounted sensor, i.e. a closed shock tube configuration. Consequently, the measured reflected pressure (approximately 90-100 KPa) is markedly lower than the calculated value. Other sources of error between the calculated and measured output pressure will likely include the effects of temperature and friction, which have been neglected in this ideal gas assumption.

$$\frac{P_2}{P_1} = \frac{2\gamma M_1^2 - (\gamma - 1)}{(\gamma + 1)} \quad (5)$$

The (indicated) magnitude of the shock transmitted through the foam samples in this configuration is significantly lower than that of the incident wave(s). In addition, with as little as 40 mm of sample material, the transmitted component of the shock sits well below the threshold at which rupture of the tympanic membrane has been suggested to occur [5]. The large pressure pulses recorded behind the transmitted shock pulse were caused by sample contact with the sensor (5 mm from the rear of the samples). In a complimentary set of experiments, where the pressure sensor was placed 40 mm from the rear surface of the foam samples, the ‘ramped’ wave was not detected behind the shock. Schlieren capture of the loading events confirmed that the ramped regions were caused by displacement of the foam samples, i.e. sample contact with the sensor.

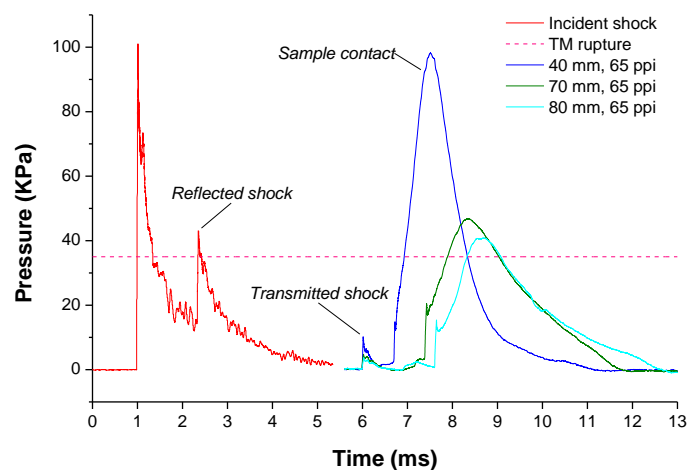


Figure 6. Minimal standoff (5 mm) pressure-time histories
Note: 2.0 bar burst pressure.

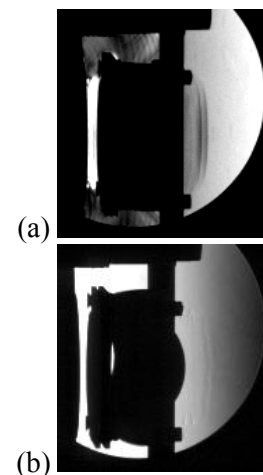


Figure 7. (a) Shock emerging from foam sample; (b) maximum displacement.

In light of the data presented in figure 6, where the (indicated) magnitude of the transmitted shock is seen to sit significantly below the incident profile, further experiments were conducted using a cylindrical chamber manufactured out of polycarbonate. This chamber was intended to mimic the basic geometry of an ear-cup and hence yield data that was more representative of a ‘real world’ device. Data from 40 mm thick 65 and 79 ppi foam experiments using the polycarbonate capsule is shown in figure 8. A schematic for the capsule setup is shown in figure 9. A number of features are worth noting in the capsule data. Firstly, the magnitudes of the transmitted waves for the two foam porosities are roughly equivalent, both to one another and to the incident shock pulses. While the traces are clearly more ramped in appearance than the incident waves, which suggests disruption of the shock fronts (both incident and internally reflected shocks), their durations are also similar to the incident pulses. It seems reasonable to suggest that the reflected shock pressure in the capsule arrangement is more representative of the transmitted pressure history than the bull-nose sensor mount. This may be due to the disruptive geometry of the bull-nose mount, which contrasts with the much larger, planar interaction surface promoted when using the closed polycarbonate chamber.

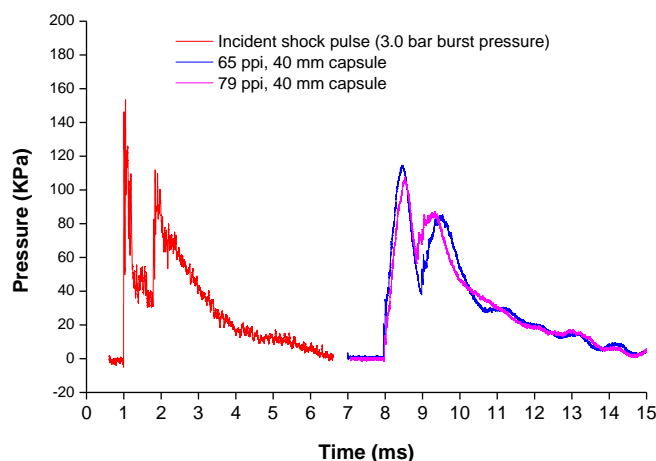


Figure 8. Polycarbonate chamber data.

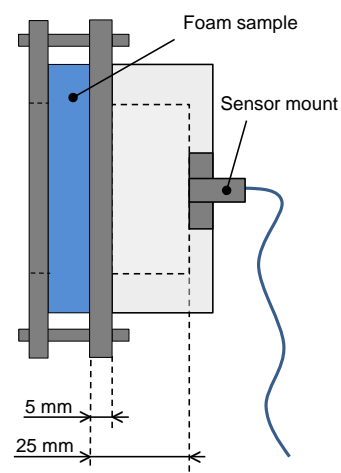


Figure 9. Schematic of polycarbonate chamber arrangement.

5. Conclusions and Future Work

Two arrangements seeking to characterize the interaction between blast wave and reticulated foam samples have been presented. A polycarbonate chamber, which was deemed to be more representative of a ‘real world’ auditory protection device, has shown that the inclusion of 40 mm of reticulated polyurethane foam does not significantly reduce peak overpressures. Other auditory protection devices may be considered in future testing. Potentially, digital technologies that detect an incoming blast wave and initiate counter-measures may be used to prevent blast-induced auditory damage in future systems. Such technologies might, for example, apply an electrical current to an adaptive material resulting in the closure of pore spaces.

Acknowledgements

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