Acoustic Characteristics of a Multifunctional Composite for Space Application - a Concept that Mimics a Natural Structure

Ashok Kumar Ghosh*
Department of Mechanical Engineering, New Mexico Tech, Socorro

Abstract
Natural structures evolve to survive and sustain. Often these structures have combinations of beneficial characteristics commonly called multifunctional. Exciting progress is being made to develop engineered systems with ideas taken from the natural world. Multifunctional systems are complex and thus very challenging in their investigation and call for highly inter-disciplinary effort encompassing breadth of science and engineering disciplines including biological sciences. This paper illustrates an effort to mimic one such multifunctional natural structure and investigate the acoustics characteristics of the same. Test results demonstrated that acoustic mass law holds good for such a complex system in a general sense. Contrary to the mass law, the rate of increase in transmission loss due to inclusion of interstitial fluid was found to be not directly proportional to the rate of increase in mass per unit area.

Key words: Natural structures, human skull, and transmission loss.

1. INTRODUCTION

Historically, dedicated and expendable vehicles are used to launch satellites into the orbit. With the increase in demand for more small satellites into the orbit, option to carry multiple satellites in any mission will be a cost and time effective solution and will be a reality in the near future.

On board optics, electronic and other delicate instrumentation make any particular satellites very fragile. Protecting the satellites against the acoustic load during launching is the most challenging aspect of any successful mission. Current protection system includes acoustic blankets, Helmholtz resonators, efficient adaptor etc.

Alliant Tech Systems (ATS) has recently developed an efficient method to significantly reduce acoustic propagation through the fairing.[1] Their protection system consists of a hollow sandwich panel temporarily filled with water, carried to a few thousand feet vertically up from the earth's surface and releasing the water from a height when this acoustic protection is no longer needed.

Air Force Research Laboratory at Kirtland, Albuquerque, New Mexico, has developed the system using hollow tubes of composite cores connected by a number of radial ribs forming one-dimensional pores. The design can accommodate water or any other fluid in the pores. They tested the system with and without water in the cores. They observed that the system could mitigate as high as 12 dB over a range of frequencies between 100 to 5000 Hz. Beyond about 6 dB reduction, noise transmission appears to be dominated by structural transmission through internal composite ribs.

In the quest to improve the ATS system, this group has directed its attention to the nature for ideas. In nature, form of a structure evolves to make it better adapted to the environment it is in. It is almost always true that these natural structures have combinations of multiple beneficial characteristics. Exciting progress is being made on developing engineered systems with ideas from the natural world. Natural systems are complex/challenging and call for highly inter-disciplinary effort encompassing breadth of science and engineering disciplines including biological sciences. Presented here is a summary of observations from experiments performed on a structure that closely resembles the human skull, under acoustic environment.

*Email: ashok@nmt.edu

Human skull bone has the similar design as that of a sandwich panel with its core being softer than the outer shells. The core layer often has the morphology of a cellular structure. Cellular materials possess combinations of mechanical, energy-absorption, thermal and acoustic properties that provide opportunities for their implementation in diverse applications [2].

Stress-strain behavior of most cellular materials has the characteristics:

- at small strains the behavior is linear-elastic;
- beyond the linear-elastic regime, lies a long stress plateau followed by a steep rise in the stress [3].

The skull has a dense outer shell (cortical bone) enclosing a central porous region (cancellous bone), filled with a viscous fluid. Pertinent characteristics of skull bone are:

- cancellous bone structure is functionally graded, open-cell, rod-like where stress is low and changes to an almost closed, shell-like structure at locations of higher stresses, and
- cancellous bone structure is piezoelectric, and it has been suggested that this is responsible for stress-induced growth, in other words, its adaptive nature.

Figure 1 includes stress-strain behavior of cancellous bone at two different relative densities and wood at one density [3]. Change in the stress-strain behavior due to variation in relative densities is similar for both of these natural structures [3]. The rate of increase in young's modulus in woods in the radial and tangential direction is three times faster than that along the axial direction. Young's modulus in the axial direction is much larger than that in the tangential and radial directions, which are roughly equal [3].

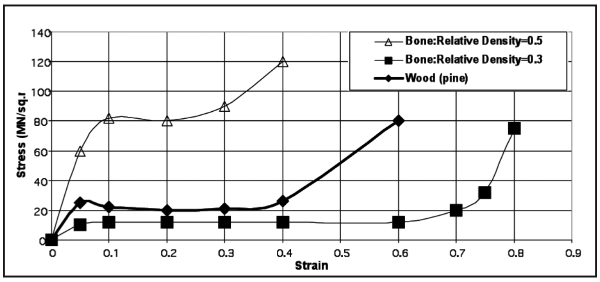

Figure 1. Comparison of compressive Stress-Strain Curves for bone and wood.

Stress-strain behavior of many artificial cellular materials (foams) used in energy absorption products like impact limiter in packaging and crush padding are similar to figure 1[3]. Foams are typically formed by generating bubbles in a liquid medium. After nucleation the bubbles grow and pack together.

When bubbles make contact with each other, a flat surface is formed that defines the boundary between two neighboring bubbles. At some point the liquid solidifies resulting in the formation of the cellular solid or foam. If the faces of the solid remain intact it becomes closed-cell

foam. If the cell walls are broken, only the cell edges remain intact then the resulting structure will be called open-cell foam. Figure 2 (a) shows a 1-dimensional cellular structure, and (b) a 3-dimensional open celled foam structure.

Relative density of cellular solid (ratio of density of cellular material to density of the solid from which the cell walls are made), can be very low, as low as 0.001. Almost any material can be foamed. Polymers, of course, are the most common. Figure 3 shows the reduction in strength and stiffness caused by porosity. The correlation between strength/stiffness loss due to porosity of the material and

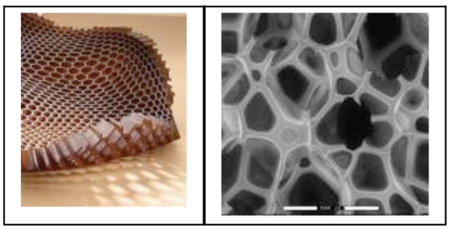

Figure 2. (a) Honey comb- A 1-D cellular structure with ends open (www.virginmedia.com); (b) 3-D open celled foam (science.nasa.gov).

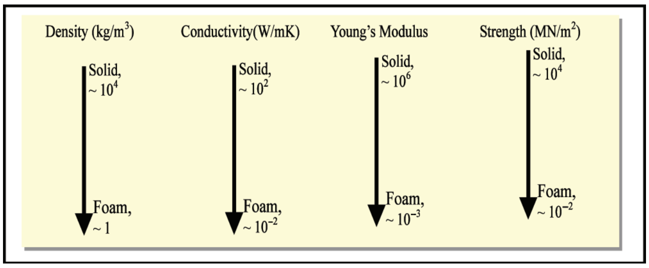

Figure 3. Variation of properties due to foaming.

making up of this loss by adding fluid is not established. The long-term goal of current test program is to establish this correlation in the quantitative term.

2. MATERIAL SELECTION

Present investigation to mimic this complex structure started with identifying and testing with available structures. Current commercial market is surveyed to select the best candidate material that resembles as close as possible with the morphology of cancellous structure of human skull. The acceptance criteria were:

- Cellular structure (open cell),
- Porosity around 90% or higher and
- Deformable.

Quick recovery adhesive backing Polyurethane foam (PUF) from McMaster-Carr supply satisfies these criteria and was thus selected for further tests. Twelve different PUF were used with following Characteristics:

- Density = 15 pcf;
- Tensile strength = Rating 2 (20psi); rating 4 (40 psi) and rating 8 (80 psi);
- Young's Modulus = 0.1 Gpa;
- Thickness = $\frac{1}{4}$", 3/16", 3/8" and $\frac{1}{2}$".

Stress-strain behavior of PUF provided by the manufacture is given in the figure 4 below.

2.1 Micro Structure

Figures 5 (a, b) show the field Emission Scanning Electron Microscopy (SEM) of the PUF used in the tests. Figure 5 (a) shows a single cell of the PUF (magnification 500) and figure 5(b) shows the interface between the foam and the sealant layer (magnification 100). Pore size ranges between 50-200 (m.

3. ACOUSTIC CHARACTERISTICS

Literature on the study of human skull (in-vivo, bony part only) as a structural shell is many, of which some have accounted for the dynamic loading environment. Fry and Barger [4] measured acoustical properties (scattering, transmission loss and reflection) through human skull structure in the frequency range of 0.25 - 2.2 MHz. Samples studied were relatively large section of human skull taken from adult, child and infant subjects. They demonstrated that the dense, outer shell acts more like a reflector and allows little to transmit inward, which eventually got absorbed by the porous middle layer. Since 1990s,

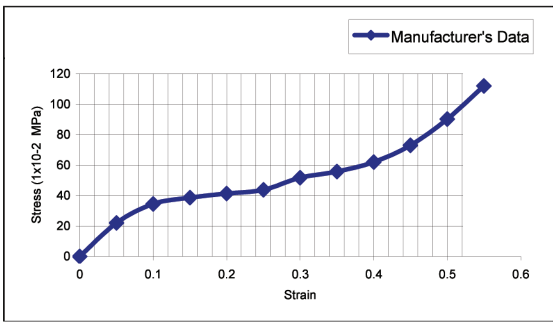

Figure 4. Stress-strain behavior of PUF

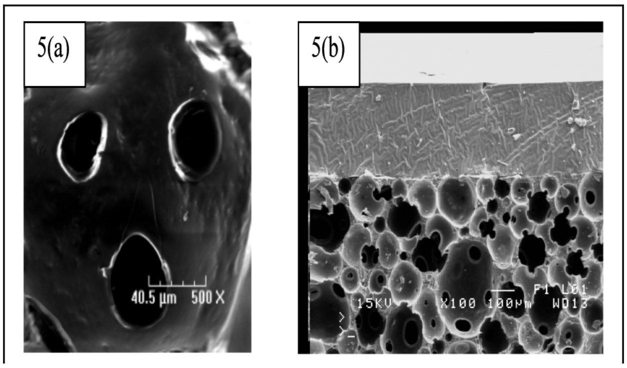

Figure 5. Microstructure of a PUF

there has been a number of workshops dealing with fluid flow in bone. Many of these investigations were related to growth and maintenance of bones [5-7].

An important acoustic characteristic of skull is its attenuation or absorption of acoustic energy. Attenuation is defined as restriction of the passage of sound to the brain. Tests were carried out using PUF with its interstitial pores filled with compatible fluids. This fluid filled composite (FFC) material absorbs incident, airborne sound waves, converting them into heat. When FFC are exposed to acoustics, the following two well known mechanisms become responsible in absorbing the acoustic energy:

Viscous-flow losses - when a structure with fluid-filled-interconnected -pores is under acoustics, there is relative motion between the fluid and the surrounding structure resulting in boundary-layer losses, and

Internal Friction - under acoustics, porous structure will compress or flex, and loss of energy takes place by internal friction.

4. TEST SETUP

Twelve samples were tested at the Air Force Research Laboratory, Kirtland, Albuquerque. The test setup consists of 6-in diameter custom-made acoustic transmission loss tube as shown in figure 6 [8]. There are two microphones on both the incident sound side of the pipe as well as the transmitted sound side of the pipe. A speaker produces a standing acoustic wave on the incident side that travels through the test sample. After passing through the sample, the two microphones on the transmitted side record the transmitted sound. On the transmitted side, the end of the pipe can either be open or closed. A loudspeaker was used to generate a plane wave field in a standing wave tube and a single microphone was used to measure the transfer functions between the signal provided to the loudspeaker and the sound pressure at the four locations as shown below.

5. OBSERVATIONS

The plot of transmission loss versus frequency for all the samples is shown in Figure 7 [8]. Legend Plate_1/4_r=2_a signifies a plate sample of 1/4” thickness made with rating 2 grade polyurethane foam where pores are filled with air i.e. as manufactured. Highest transmission loss of approximately 40 dB was noticed for 1/2” plate sample with pores filled with fluid. It is also noticed that the higher the mass per unit area of a sample, the higher the TL value. This supports the acoustic mass law. All the fluid filled samples demonstrated higher TL than that without fluid.

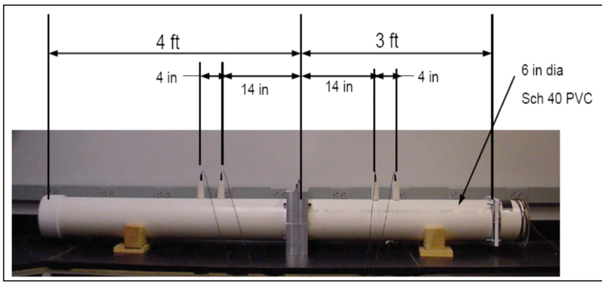

Figure 6. Transmission loss tube experimental setup

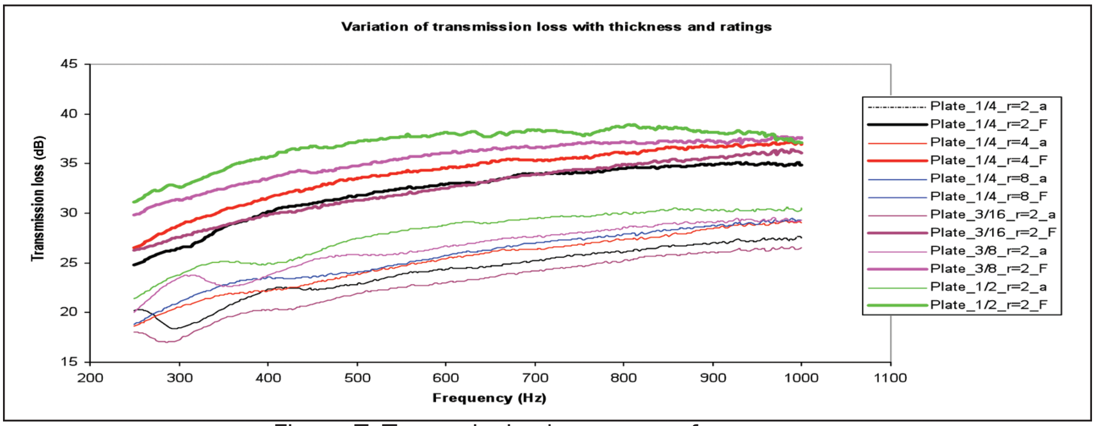

Figure 7. Transmission loss versus frequency

6. DISCUSSION

As expected, plates with higher mass per unit area of a sample, supporting the acoustic mass law, which states that transmission loss of a material is proportional to its mass per unit area and not mass per unit volume i.e. mass-density. All fluid filled samples demonstrated higher transmission loss than that by the air filled samples.

7. CONCLUSIONS

Tests were performed under acoustic environment to understand the influence of interstitial fluid on transmission loss of flat panel. Test results demonstrated that acoustic mass law holds good in a general sense. The rate of increase in transmission loss due to interstitial fluid is found to be not directly proportional to the rate of increase in mass per unit area. The sample with 3/16 in thickness yielded highest change in transmission loss.

8. ACKNOWLEDGEMENT

I acknowledge with thanks the assistance received from the Office of Naval Research for presenting this paper at the ICEAE conference at Bangalore. These being a review paper, much of the contents of this paper have appeared in Reference 8.

9. REFERENCES

[1] Higgins, J., Williams, A., and Ardelean, E. V., "Acoustic Testing of Hollow Core Fairing Designs", Proceedings of SDM, AIAA, 2005.

[2] Evans, A.G., Hutchinson, J.W. and Ashby, M.F., "Multifunctionality of cellular metal systems", progress in Materials Science, 43 (1999), 171-221.

[3] Gibson, L. J. and Ashby, M. F., Cellular Solids -Structure and Prop., Cambridge Uni. Press, 1997.

[4] Fry, F.J. and Barger, J.E., "Acoustical properties of the human skull", J. Acoustic Soc., Am., 63 (5), May 1978.

[5] Montgomery R J, Sutker B D, Bronk J T, Smith S R, Kelly P J, "Interstitial fluid flow in cortical bone", Microvascular Res, 35:295-307, 1988.

[6] McCarthy, I D, "Clearance of albumin by cortical bone and marrow. Clin Ortho related Res, 334: 24-29, 1997.

[7] Gatzka, C, Knothe U, Niederer P, Schneider E, Knothe Tate M L, "A novel ex vivo model for investigation of fluid displacements in bone after endoprosthesis implantation. J. Mater Sci mater Med 10, 801-806, 1999.

[8[Ghosh, A.K., Williams, A.D., Zucker. J.M., Mathews, J.L. and Spinhirne, N., "An Experimental Investigation into the Acoustic Characterisitcs of Fluid-filled Porous Structures – A Simplified Model of the Human Skull Cancellous Structure", J. of Experimental Mechanics (2008) 48:139-152.