ACOUSTICS 2025 JOONDALUP
SOUNDS OF THE SUNSET COAST

Innovating Acoustic Materials: A Multi-Layered Gradient Impedance System for Underwater Applications

Gleny Chirima, Van-Tan Truong, Dean Marinucci, Hannah Spratling, Steve Burke, Ian MacGillivray, Matthew Ibrahim, Joseph Dominguez and Gyani Sharma

Platforms Division, Defence Science and Technology Group, 506 Lorimer St, Fishermans Bend VIC 3207 AUSTRALIA

ABSTRACT
Effective acoustic impedance matching is essential for high-performance underwater acoustic systems. This study presents a novel multi-layered viscoelastic material system, developed using a polyurethane (PU) matrix embedded with both high-density particles and hollow microspheres. The objective was to simultaneously match the acoustic impedance of water and attenuate broadband acoustic signals through graded transmission loss across layers.Each layer was precisely engineered to target specific acoustic properties using combinations of barium sulphate and Expancel microspheres consisting of a polymer shell encapsulating a gas. A methodology was developed to measure frequency-dependent attenuation using a two-thickness immersion technique, coupled with polynomial fitting to generate broadband attenuation profiles. Experimental validation was achieved through ultrasonic scanning and instrumented acoustic pressure tank testing under hydrostatic conditions. Strong agreement between modelled and measured responses confirmed the accuracy and robustness of the material design and characterisation approach.

1 INTRODUCTION
Underwater acoustic materials are becoming increasingly important for managing sound propagation and supporting underwater communication systems. Effective materials must often address two critical acoustic performance parameters—impedance matching to water to minimise reflections at the interface, and broadband attenuation to suppress transmitted signals over a wide frequency range. Most traditional pure polymer-based acoustic materials struggle to meet both requirements simultaneously.

Recent developments in functionally graded materials (FGMs) and multi-layered impedance systems have demonstrated the ability to tailor wave propagation characteristics. Studies such as Fu et al. (2021) and Feng et al. (2020) have explored the use of polymer composites embedded with fillers to alter acoustic impedance and enhance viscoelastic losses. Discrete multilayer structures, as discussed by Xu et al. (2016), offer fabrication advantages over continuous gradients while enabling similar performance. The incorporation of microspheres has been shown to introduce significant frequency-dependent attenuation due to their shell elasticity and size-dependent scattering (Baird et al., 1999; Matis et al., 2020).

This work builds upon these principles by developing a scalable multi-layer PU composite system with tuneable acoustic properties. Particular attention is given to attenuation measurement and modelling techniques, and validation under simulated underwater conditions.

2 METHODS
Erapol CC5/65 PU was selected for its elastomeric properties and ease of processing. To manipulate the acoustic impedance:
-Barium sulphate ($BaSO_4$, 4500 kg/m³) was used to control density and stiffness.
-Expancel 920 DET 40 d25 microspheres (25 kg/m³) were used to reduce impedance and enhance attenuation.
-Sample dimensions for ultrasonic immersion tank measurements were 120 x 120 mm with thicknesses of 5 and 10 mm.
-Sample dimensions for pressure tank measurements were 245 x 245 x 5 mm

Formulations ranged from 5–20% by volume of fillers. Neat PU served as a baseline. Layer design followed a strategy where the first layer matched water's impedance (~1.5 MRayl), while subsequent layers had progressively higher impedance and attenuation.

Speed of sound measurements were performed using a TecScan Scan-3D ultrasonic immersion robotic scanner, equipped with a pair of transducers operating in pulse-echo mode. The system consists of a large immersion tank filled with water at room temperature, robotic scanning heads, and TecView 2 software for automated data collection and analysis. The transducers were positioned in the far field to avoid wave interference, which would otherwise affect accuracy.

A two-thickness immersion method adapted from Umchid (2008) was implemented using an ultrasonic immersion scanner for the purposes of measuring attenuation. Four matched transducer pairs (0.5, 1, 2.25, and 5 MHz) captured the time-domain signals, later transformed using FFT for frequency-domain attenuation analysis.

The attenuation coefficient α was calculated using:

$$\propto = \frac{20}{d_1 - d_2} \ln\left(\frac{V_{d1}}{V_{d2}}\right) \quad \text{dB/cm} \qquad (1)$$

where d_1 is the thickness of specimen 1, d_2 is the thickness of specimen 2, V_{d1} is the peak-to-peak signal height transmitted through the first specimen, and V_{d2} is the peak-to-peak signal height transmitted through the second specimen.

A contiguous attenuation curve across 0.5–5 MHz by transforming time domain data to frequency domain and combining results from multiple probes. The attenuation fit plot was then used to model the multi-layer system.

Pressure tank testing was conducted at 100 kPa to verify attenuation behaviour thus complementing the ultrasonic immersion technique. This validated the methodology's robustness and enabled cross-verification of the ultrasonic scanner-derived attenuation values.

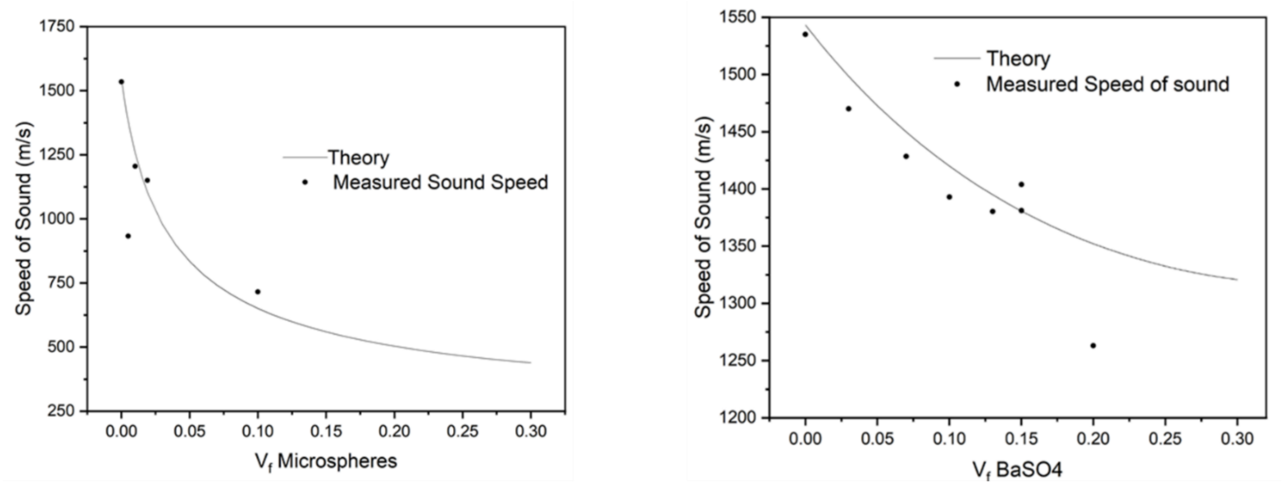
3. RESULTS AND DISCUSSION

Neat PU showed a sound speed of ~1450 m/s. The incorporation of expancel reduced both sound speed and impedance, enabling effective impedance matching to water. $BaSO_4$ increased density and impedance, reaching >2.5 MRayl at 15% volume fraction. Predictions using the Kerner (1956) model agreed well with experimental measurements, confirming model applicability.

The speed of sound of samples containing microspheres decreases with increase in volume fraction, Figure 1(a). The measured data aligns well with the theoretical predictions (Kerner, 1956). The speed of sound for PU with barium sulphate additives is shown in Figure 1 (b). The speed of sound for PU filled with BaSO4 initially drops and is expected to reach a minimum before it starts to increase. Challenges in dispersing barium sulphate at high volume fractions (>0.2) likely contributed to the observed reduction in the measured sound speed, Figure 1(b). This deviation also helped establish a practical upper limit of filler content for producing high quality PU samples.

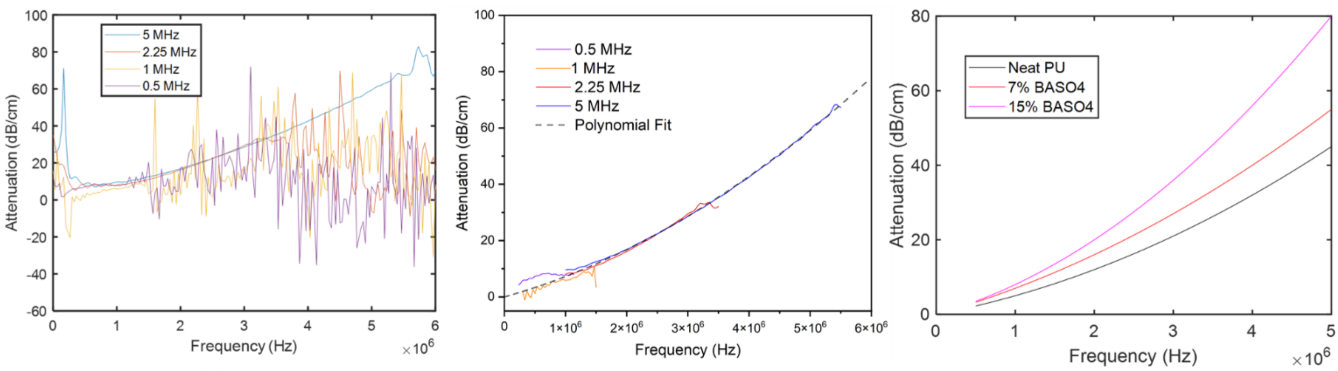
Frequency-domain attenuation data from individual probes [Figure 2(a)] were bandwidth filtered, stitched into a continuous 0–5 MHz curve and fitted with a polynomial [Figure 2(b)]. Attenuation was found to increase with frequency and filler content [Figure 2(c)], as expected. The resulting fits were used to model the acoustic response of the multilayer system.

In addition, larger samples (240 x 240 x 5 mm) were tested in a hydrophone and transducer-equipped acoustic pressure tank, that enabled the lower frequency range to be extended to 0.2 MHz and below, thus complementing the ultrasonic frequency range (0.5 MHz to 5 MHz). The attenuation data from the pressure tank was extrapolated to predict the attenuation up to 5 MHz frequency. The ultrasonic immersion tank data compared well to the extrapolated pressure tank data confirming the consistency of the measurement techniques and sample quality. Pressure tank measurements at 0.5 MHz confirmed attenuation trends within ±7% of ultrasonic scanner-derived values, validating the experimental protocol.



(a) (b)

Figure 1:(a) Decrease in measured sound speed for PU with microsphere content and (b) Decrease in measured sound speed for PU with volume fraction (V_f) of $BaSO_4$ content. The solid line represents the theoretical value obtained from applying Kerner's theory. Points are experimental data. Measurements taken from ultrasonic immersion tank.



(a) (b) (c)

Figure 2: (a) Plot showing the individual probe data in frequency domain (b) Stitched individual probe data forming contiguous curve for the 7% BaSO4 sample with polynomial fit and (c) Attenuation fitted curves for Neat PU, 7% BaSO4 and 15% BaSO4 samples.

Table 1: Summary of Ultrasonic Immersion Tank vs. Pressure Tank Attenuation Data at 0.5 MHz

Material	Attenuation (dB/cm) @ 0.5 MHz Pressure Tank (0.1MPa)	Attenuation (dB/cm)@ 0.5 MHz - TecScan
Neat PU	1.74	1.61
PU + 10% BaSO4	18.3	19.83

4. CONCLUSION

A scalable multilayer PU-based acoustic material with tailored impedance and frequency-dependent attenuation was developed. Core contributions include:
- Demonstration of impedance control using $BaSO_4$ and microspheres
- Development of a robust, broadband attenuation measurement and fitting methodology
- Validation through ultrasonic scanning and pressure tank testing

This system is suitable for broadband underwater acoustic insulation and effective sound energy management. Future work will focus on full-scale underwater testing and modelling of samples containing microspheres and $BaSO_4$.

ACKNOWLEDGEMENTS
The author gratefully acknowledges the financial support provided through the 2024–25 DSTG Chief Defence Scientist Fellowship program.

REFERENCES

Baird, A.M. et al. (1999). Wave propagation in viscoelastic media with fluid-filled microspheres. JASA, 105(3), 1527–1539.
Feng, Y. et al. (2020). Acoustic behaviour of composites with gradient impedance. Mater. Des., 193, 108870.
Fu, Y. et al. (2021). A review on polymer-based materials for underwater sound absorption. Polymer Testing, 96, 107115.
Kerner, E.H. (1956). Elastic properties of composite media. Proc. Phys. Soc. B, 69, 808–813.
Matis, B.R. et al. (2020). Critical role of microsphere shell on acoustic performance. Langmuir, 36, 5787–5792.
Umchid, S. (2008). Frequency dependent ultrasonic attenuation measurement. ISBME.
Xu, D. et al. (2016). Fabrication of acoustic gradient composites. Comp. Sci. Tech., 122, 90–96.