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Acoustic performance of a voided soft medium under hydrostatic pressure

Christopher Levin (1), Gyani Shankar Sharma (1), Ian MacGillivray (2), Alex Skvortsov (2), Nicole Kessissoglou (1)

(1) School of Mechanical and Manufacturing Engineering, UNSW Sydney, Sydney, Australia
(2) Maritime Division, Defence Science and Technology Group, Melbourne, Australia

ABSTRACT
The effect of hydrostatic pressure on the acoustic performance of a metamaterial attached to a rigid backing and submerged in water is presented. The metamaterial design consists of a polydimethylsiloxane (PDMS) matrix embedded with an array of spherical voids. A nonlinear finite element model is developed that considers deformation of the voided inclusions caused by hydrostatic pressure as well as the rheology of the viscoelastic material. An increase in the hydrostatic pressure is shown to significantly affect the volume of the voids which in turn affects the sound reflection from the coating. Results from the numerical model developed here are compared with results from the literature, showing good agreement.

1 INTRODUCTION
Acoustic metamaterials are engineered composite structures designed using distributions of inclusions in a host material. Metamaterials exhibit unusual acoustic properties that go beyond those of their bulk ingredients. One application of acoustic metamaterials is as an external coating on a marine vessel to reduce underwater noise. However, in a marine environment, the coating is subject to harsh conditions such as hydrostatic pressure. While there are numerous studies on acoustic coatings for underwater applications (for example, see Leroy et al. (2009), Calvo et al. (2015), Sharma et al. (2017, 2019) and references therein), few studies have considered the effect of hydrostatic pressure. An early study by Gaunaurd et al. (1984) reported that hydrostatic pressure significantly affects the material properties as well as the acoustic performance of a viscoelastic material containing cavities. In a recent study, Thieury et al. (2019) showed that an acoustic coating becomes hard under high hydrostatic pressure, reducing its intended performance. In this work, a numerical model is developed to investigate the effect of hydrostatic pressure on the acoustic performance of a voided soft medium submerged in water.

2 METHODOLOGY
Figure 1 schematically shows a three-dimensional model of an air-filled spherical cavity in PDMS subject to a normally incident plane acoustic wave. The fluid medium on the incidence side is water and a rigid backing of infinite extent is applied on the transmission side of PDMS to represent a perfect reflector. The PDMS and rigid backing are modelled as solid domains using the Structural Mechanics module. The voided inclusion and water on the incidence side are modelled as fluid domains using the Pressure Acoustics module. Interactions between the PDMS, water and the voided inclusions are modelled using a structure-acoustic boundary condition at the solid-fluid interfaces. Interactions between the soft medium and rigid backing are modelled using a continuity boundary condition. Periodic boundary conditions are applied on all lateral faces of the unit cell to simulate a square lattice arrangement of voids. The model has perfectly matched layer boundary conditions on both its incidence and transmission sides to ensure anechoic termination of outgoing waves.

The numerical procedure comprises a two-step pre-stressed frequency analysis using the finite element software COMSOL Multiphysics. In the first step, the hydrostatic pressure is applied at the interface between the water and PDMS using an auxiliary sweep in increments of 0.05 MPa up to 0.7 MPa. This initial stationary step considers geometric non-linearity and enables the stress, strain and deformation imparted to the PDMS matrix and the voided spherical inclusions to be captured. The effect of hydrostatic pressure on the rheology of the PDMS is modelled using a fractional Zener model and a temperature shift function described by the Williams-Landel-Ferry (WLF). These models account for the viscoelasticity of the material under uniaxial compression caused by the hydrostatic pressure, the effect of temperature and the frequency dependent response of PDMS. Information obtained from the first step was utilised in the second step corresponding to a linear harmonic analysis, in which an incident plane wave was prescribed using a background pressure field in the fluid domain.

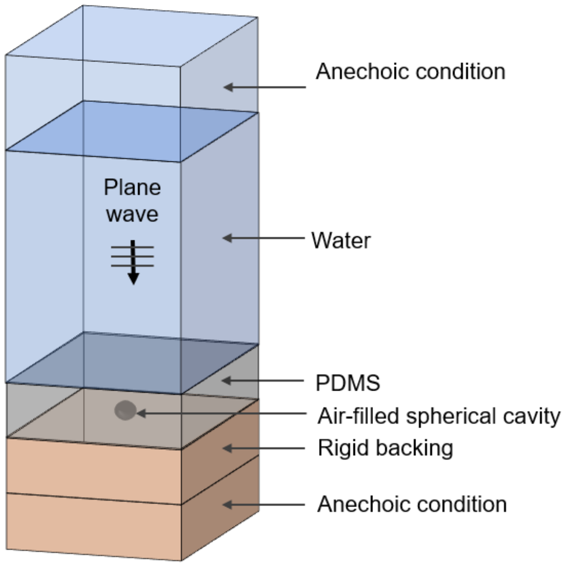

Figure 1: Schematic diagram of a unit cell of the acoustic coating.

3 RESULTS AND DISCUSSION

The unit cell of the PDMS domain had dimensions of 185mm x 185mm × 50mm. The radius of the voided inclusion was 9 mm. The PDMS has density of 1100 kg/m^3, bulk modulus of 2 GPa and shear modulus of 1.5 MPa. Typical material properties for water and air were used. The geometric and material properties as well as the input parameters to the fractional Zener and WLF models were taken from Thieury et al. (2019). The values utilised in the fractional Zener model correspond to a shear modulus of 100 MPa, relaxation time of 3.5 μs and fractional order of 0.6. In the WLF model, the reference temperature is 273.15 K, WLF constant 1 is 10 and WLF constant 2 is 100 K.

Figure 2 presents the reduction in volume of the spherical voids in response to uniaxial compression of the PDMS under hydrostatic pressure. The reflectance of the acoustic coating in Figure 3 was initially assessed in the absence of hydrostatic pressure and compared with results from Thieury et al. (2019). A trough in the reflectance is observed around a discrete frequency attributed to a mass-spring resonance, where the voided PDMS contributes to the stiffness and the rigid backing contributes to the mass, as reported previously in Sharma et al. (2019). Good agreement between results obtained from our numerical model and results from Thieury et al. (2019) is observed for the entire range of hydrostatic pressure (Figure 2) and for the reflectance (Figure 3).

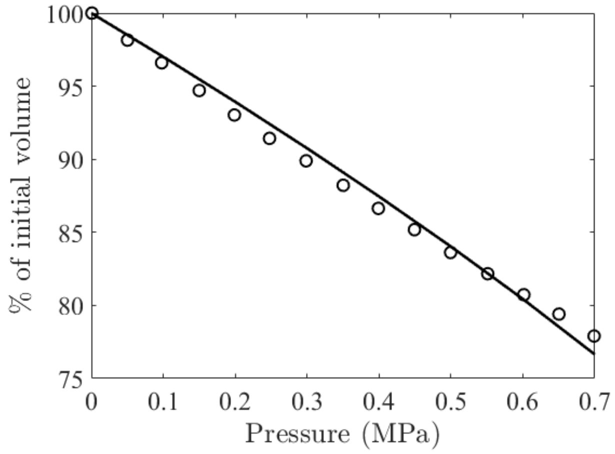

Figure 2: Percentage reduction in inclusion volume arising from an increase in hydrostatic pressure obtained numerically (solid line) and from Thieury et al. (2019) (circles).

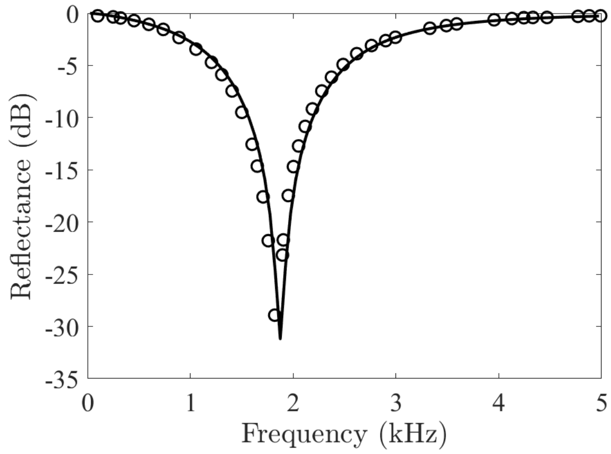

Figure 3: Reflectance (in dB) of the acoustic coating in the absence of hydrostatic pressure obtained numerically (solid line) and from Thieury et al. (2019) (circles).

Deformation of the void obtained in the first step of the pre-stressed analysis arising from uniaxial application of hydrostatic pressure is shown in Figures 4 and 5 at hydrostatic pressures of 0.3 MPa and 0.7 MPa, respectively. As expected, greater deformation occurs on the top of the void closest to the source of uniaxial pressure. An increase in deformation and corresponding reduction in volume of the inclusion from its undeformed state occurs with an increase in hydrostatic pressure, as shown previously in Figure 2.

Figures 6 and 7 respectively present the effect of hydrostatic pressure on the reflectance and absorption of the acoustic coating. An increase in hydrostatic pressure causes the mass-spring resonance to shift to a lower frequency. Further, an increase in hydrostatic pressure results in a reduction in the amplitude of the reflectance, thus indicating an increase in sound reflection. The amplitude of the absorption coefficient also slightly reduces although the reduction is less obvious. The reduction in the mass-spring resonance frequency for a reduction in volume occupied by the void is in contrast to results in the absence of hydrostatic pressure, for which a reduction in void diameter results in an increase in the frequency of the mass-spring resonance.

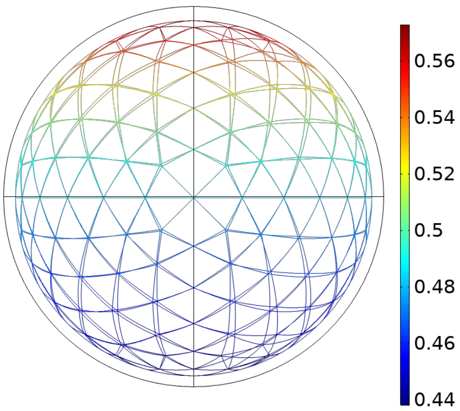

Figure 4: Deformation (in mm) of the inclusion resulting from uniaxial compression of the PDMS at a hydrostatic pressure of 0.3 MPa. The undeformed geometry is represented by the black circle.

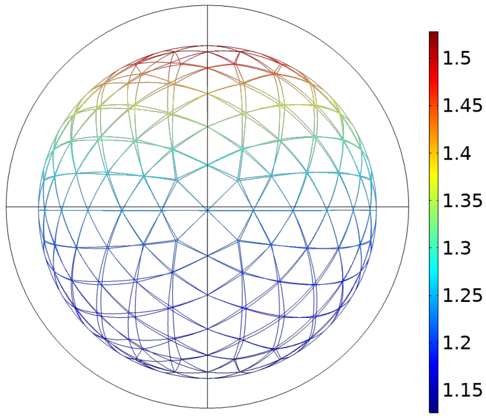

Figure 5: Deformation (in mm) of the inclusion resulting from uniaxial compression of the PDMS at a hydrostatic pressure of 0.7 MPa. The undeformed geometry is represented by the black circle.

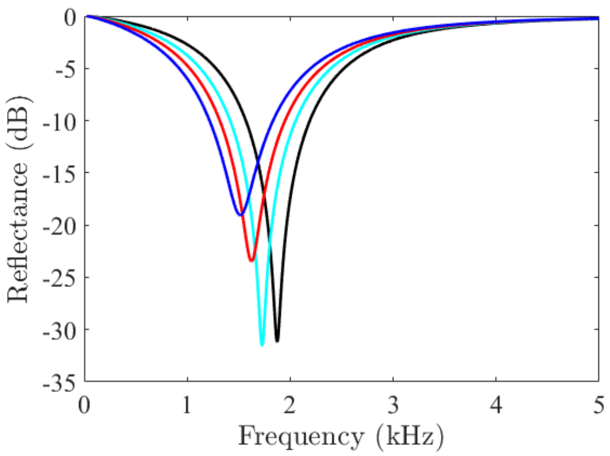

Figure 6: Reflectance (in dB) of the acoustic coating in the absence of hydrostatic pressure (black line) and under hydrostatic pressure of 0.3 MPa (cyan line), 0.5 MPa (red line) and 0.7 MPa (blue line).

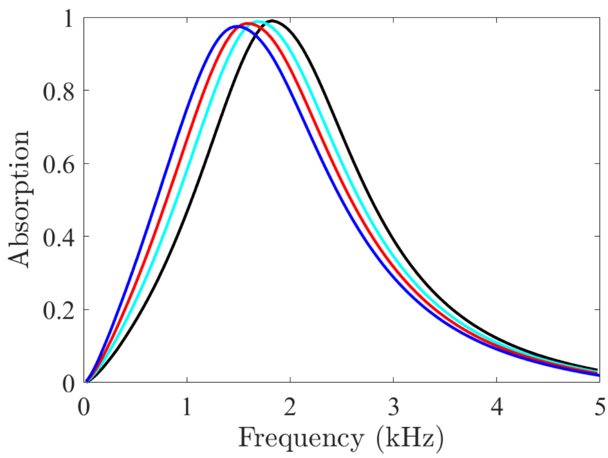

Figure 7: Absorption coefficient of the acoustic coating in the absence of hydrostatic pressure (black line) and under hydrostatic pressure of 0.3 MPa (cyan line), 0.5 MPa (red line) and 0.7 MPa (blue line).

The shift in mass-spring resonance is investigated in what follows. Figures 8 and 9 present the reflectance and absorption of the coating for the original sized voided inclusion without hydrostatic pressure, the same coating under hydrostatic pressure of 0.7 MPa, and of a coating without hydrostatic pressure but with a reduced size void to match the volume of the deformed voided inclusion of the original coating under hydrostatic pressure. For the coating with the original voided inclusion, the presence of hydrostatic pressure causes the mass-spring resonance frequency to decrease. In contrast, a smaller sized void in the absence of hydrostatic pressure shows an increase in the mass-spring resonance frequency. These results highlight that hydrostatic pressure has a significant effect on the rheology of the PDMS, which in turn has a dramatic effect on the mass-spring resonance frequency.

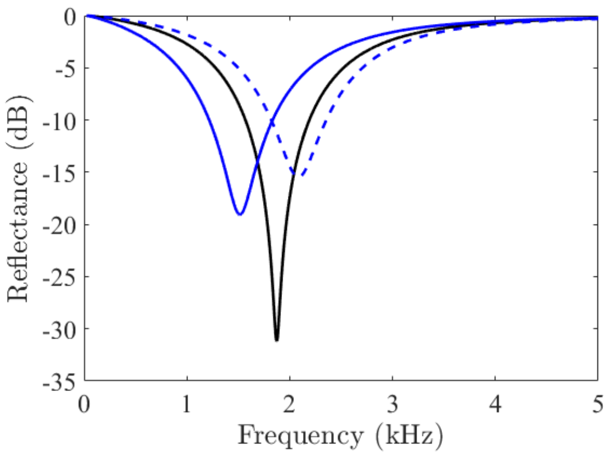

Figure 8: Reflectance (in dB) of the acoustic coating for the original sized voided inclusion in the absence of hydrostatic pressure (black line), for the same coating under hydrostatic pressure of 0.7 MPa (blue line), and of a coating without hydrostatic pressure but with a reduced size void (dashed blue line).

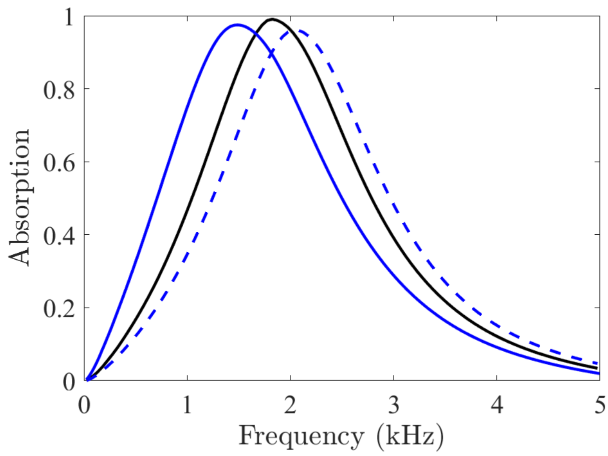

Figure 9: Absorption coefficient of the acoustic coating for the original sized voided inclusion in the absence of hydrostatic pressure (black line), for the same coating under hydrostatic pressure of 0.7 MPa (blue line), and of a coating without hydrostatic pressure but with a reduced size void (dashed blue line).

4 SUMMARY

A numerical model of a soft medium embedded with a matrix of voided inclusions and attached to a rigid backing has been developed. The acoustic performance of the coating was examined in terms of its absorption coefficient and reflectance. Application of hydrostatic pressure to the voided soft medium was observed to affect both the volume of the inclusion and the rheology of the PDMS. Results show that variation in the rheology of the soft elastic medium has a greater effect on the frequency of mass-spring resonance and as such, should be taken into account in the development of metamaterial coatings for targeted underwater noise reduction.

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