An adjustable acoustic metamaterial cell using a magnetic membrane for tuneable resonance

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ABSTRACT

One of the most exciting challenges in acoustic metamaterial (AMM) research is to incorporate tuneability, for example where the resonance of the AMM can be actively adjusted, whilst also ensuring ease of manufacture. Many of the challenges in realising physical AMM prototypes, such as ensuring small feature sizes, introducing specific material characteristics, and enabling scale-up fabrication, remain significant barriers in the design of AMMs in general. As such, the dynamic control of device response is an ongoing obstacle in the field of AMMs. One option for practical AMM implementation in the future is to mitigate some of these barriers by enabling adaptable resonant properties to tailor device response. To this end, this research demonstrates the design, fabrication, and characterisation of an adjustable magnetic AMM cell using stereolithography with a bespoke superparamagnetic resin. To underpin the experimental approach, a mathematical model able to predict the behaviour of the adjustable AMM is developed and implemented, for which the mechanical properties of the AMM membrane were experimentally measured and used to define the model. This research demonstrates a 3D-printable magnetic AMM cell able to perform sub-100 Hz acoustic resonant tuning. The developed superparamagnetic formulation recorded a magnetisation of saturation of 2.4 emu/g, coercivity of 5 mT, and a Young's modulus of 17.89 MPa. The device is thus ultra-subwavelength (/77.5) and displays magnetically-actuated resonant tuneability from 88.73 Hz – 86.63 Hz with a consistent 12 dB increase in resonance.

Supplementary Table S1 - Definitions

Definitions and Values used in the Mathematical Model			
Variable	Symbol	Value	Units
Density of Air	ρ_{air}	1.293[1]	Kg/m^3
Speed of Sound in Air	c_{air}	344[2]	m/s
Height of Helmholtz Resonator Neck	h_{neck}	2.5×10^{-3}	m
Area of Neck Opening	S_{neck}	3.1416×10^{-4}	m
Volume of HR Cavity	V_{cavity}	1.3273×10^{-5}	m^3
Density of Membrane	ρ_{mem}	1185.23	Kg/m^3
Thickness of Membrane	h	2.6×10^{-4}	m
Nth solution to the Bessel function of the 1st kind, 0th order ($n = 1$)	μ_n	2.405[3]	-
Membrane Radius	a	13×10^{-3}	m
Fundamental/Natural Frequency of Membrane	ω_{mem}	-	$Rads/s$
Damping Ratio of Membrane	ζ_n	0.005	-
Viscous Damping Coefficient	c_d	-	Ns/m
Volume Velocity of HR air at Neck	U_1	-	m^3/s
Volume Velocity of air around Membrane for 1st mode	x_2	-	m^3/s
Normal Displacement of Membrane	z	-	m
Time Elapsed	t	-	s
Force of Acoustic Excitation	F_1	0	N
Frequency of Excitation	ω_F	-	$Rads/s$
Acoustic Fundamental Resonant Frequency of Device	ω	-	$Rads/s$
Flexural Stiffness of membrane	D	-	Nm
Tension per unit Length	T	-	N/m
Mechanical Pre-stress	T_1		N/m
Magnetic Pre-stress	T_2	-	N/m
Applied Force to Membrane	F_2	-	N
Young's Modulus of Membrane	E	17.89×10^6	N/m^2
Poisson's Ratio of Membrane	υ	0.35	-
Magnetisation of Saturation per unit Volume	M	2.8446×10^3	A/m^2
Applied Magnetic Field Strength	H	-	A/m
Vacuum Permeability	μ_0	$4\pi \times 10^{-7}$[4]	N/A^2
Magnetic body Force on Membrane (Normal force per unit area)	P_0	-	N/m^2

References

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Supplementary Table S2 - Magnetic Sample Specifications

Custom Resin Samples (100-50nm Fe3O4, 3.5%wt)			
Poling Regime	Density (Kg/m^3)	Mass Capsule **(g)**	Mass Sample **(g)**
None	1185.23	0.041	0.023
150°C, 2hrs	1185.23	0.041	0.017
300°C, 2hrs	1185.23	0.041	0.023

Supplementary Table S3 - Measured magnetic field from each array of magnets tested in this experiment.

No. Magnets	**0**	**1**	**2**	**3**	**4**	**5**	**6**
Maximum Magnetic Field **(mT)**	0	160	263	321	356	399	422
Minimum Magnetic Field **(mT)**	0	85	151	240	273	301	363
Average Magnetic Field **(mT)**	0	122.5	207	280.5	314.5	350	392.5

Supplementary Figure S1 - Clamped membrane undergoing measurements to capture the 1st resonant mode in Polytec's MSA-100-3D Micro System Analyzer.