COMSOL CONFERENCE
2017 ROTTERDAM

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Far COMPOSITES

3D Acoustic-Structure Interaction of Ultrasound in Fluids for the Manufacture of Graded Materials

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INTRODUCTION

Functionally Graded Materials (FGM)

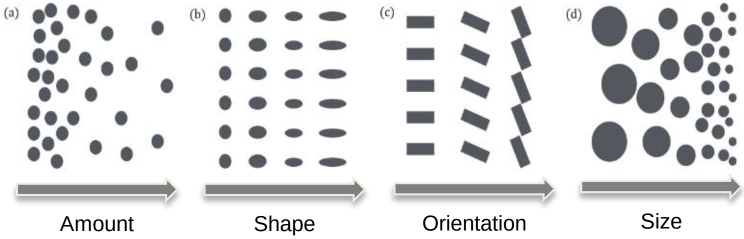
Functional gradients within materials to improve properties.

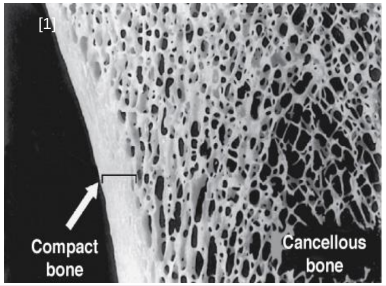
Decreasing mass whilst maintaining stiffness is a widely desired property in advanced engineering sectors.

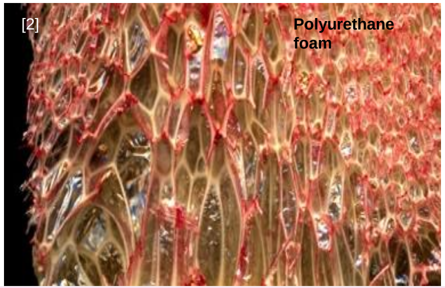
Demonstrate the control of porosity gradients for structural applications.

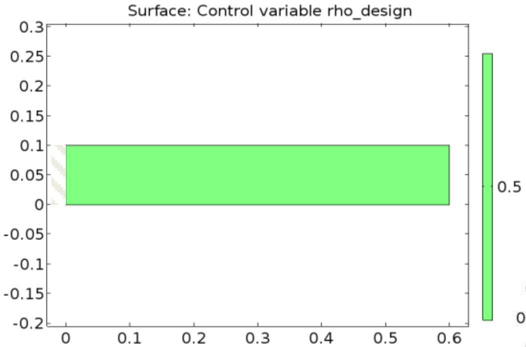
Topology optimisation designs structures for least compliance.

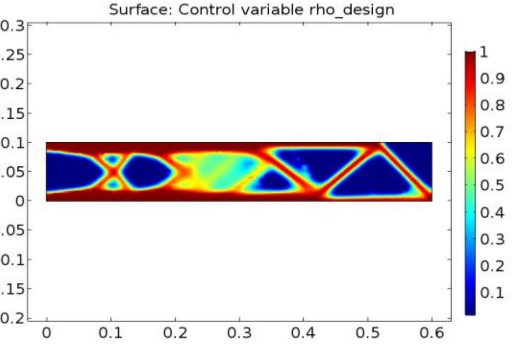
Material is redistributed within a design domain to best fit the load case.











[1] Mescher A. L. (2010) *Junqueira's Basic Histology.* 12th Edition

[2] Torres-Sanchez, C. and Corney, J. R. (2008). *Journal of Mechanical Design.* 131 1-8

Manufacture of FGM

The manufacture of graded materials is difficult for traditional methods. New methods are being researched and developed to realize optimised material distributions.

Research is exploring ultrasound as a manufacturing tool to produce porosity graded polymeric materials.

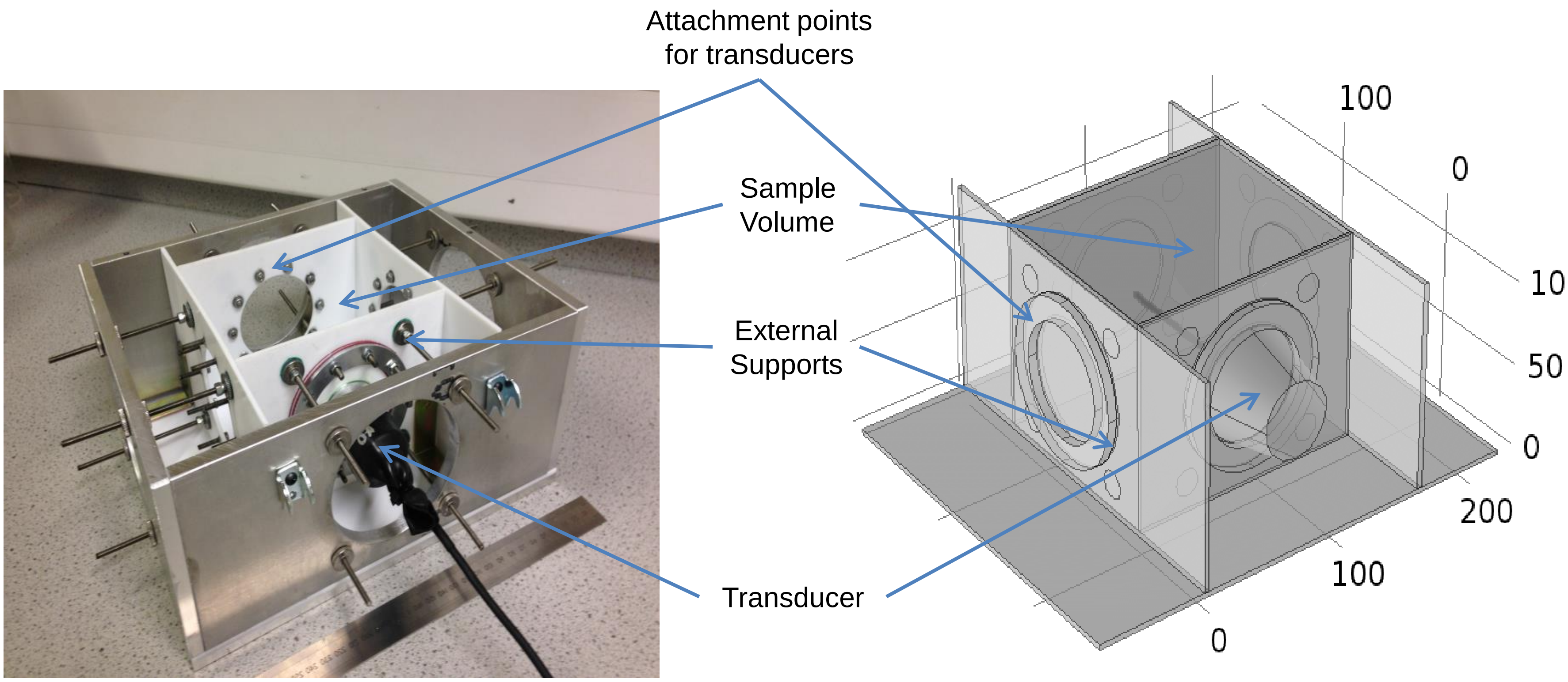
- A bubble in a standing-wave acoustic field will experience an oscillating pressure gradient
- The bubble’s volume will oscillate
- Oscillation phase and force direction is determined by size of the bubble, R_0 [3]:

$$w_0 = \frac{1}{R_0}\sqrt{\frac{3kp_0}{r}}$$

- Through this mechanism it is possible to influence the distribution of bubbles within a fluid

SIMULATION

Experimental Rig & Geometry



Attachment points for transducers

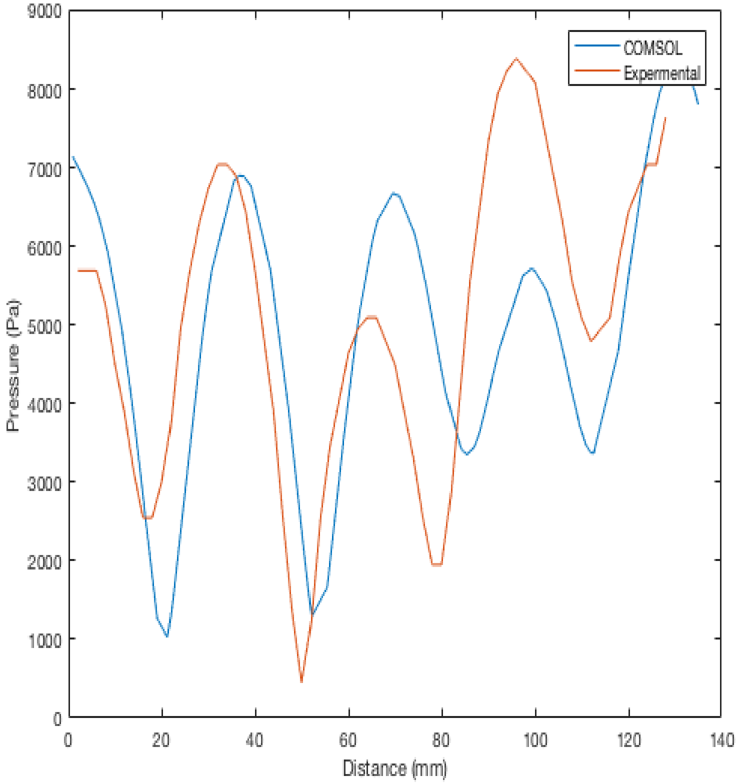
Sample Volume

External Supports

Transducer

Validation of Model

- Experimental rig was filled with deionised water and irradiated with ultrasound at known frequencies
- Hydrophone was used to measure pressure at defined locations within the fluid
- COMSOL Multiphysics model was solved for the same frequencies and the pressure distributions were compared
- Power (pressure) was found by parameter estimation using the COMSOL Optimization module



Comparison of the COMSOL results in blue with the experimental results in red for two transducers operating at 25.3 kHz.

Porous Material Model

- Investigating the effect of ultrasound on a **reacting** polymeric foam, polyurethane foam
- The Poroelastic Waves interface was used to solve Biot's equations for the coupled propagation of elastic waves in the elastic porous matrix and acoustic pressure waves in the saturating fluid
- Assuming time-harmonic displacements, Biot's equations for poroelastic waves are:

$$-r_{av}W^2u+r_fW^2U-\nabla\cdot s=0$$

$$-r_fW^2u+W^2r_c(W)U+\nabla p_f=0$$

- Biot-Willis coefficient of 1 was chosen

Animation of polyurethane foam expansion. The animation spans approximately 30 minutes.

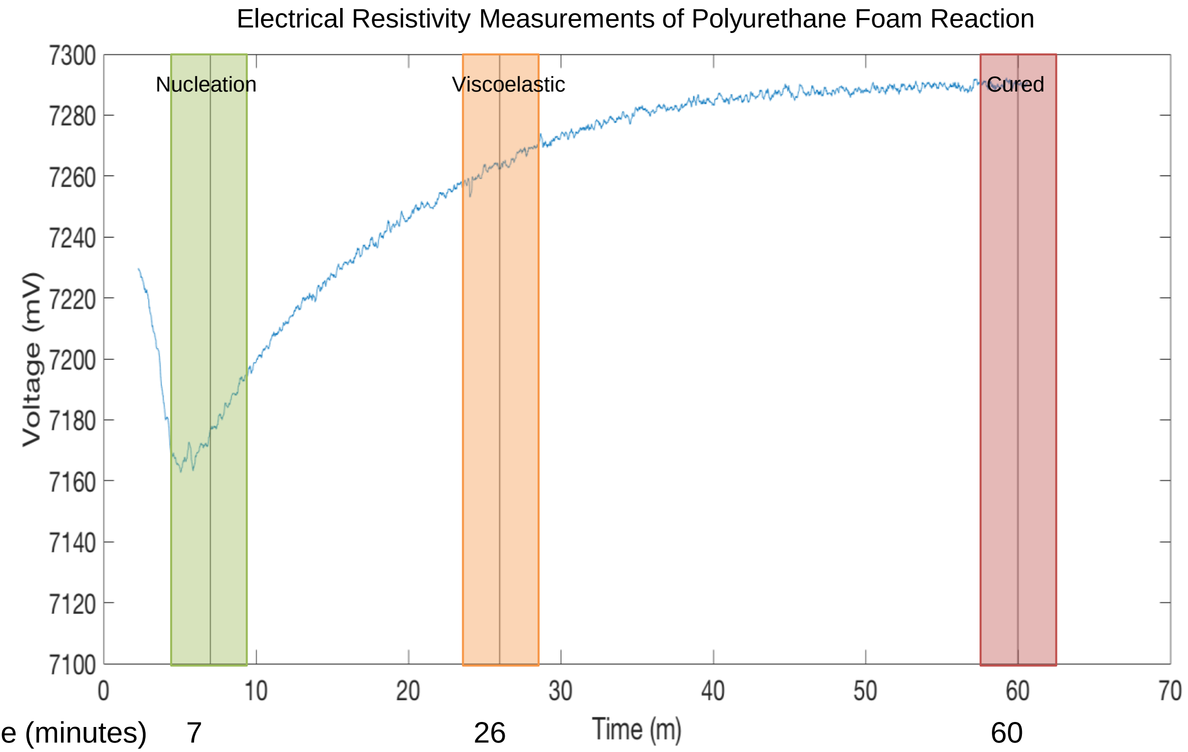
Material Properties

Three known stages of polyurethane polymerisation sequence. The model is solved at each of these separately.

Matrix properties were taken from experimental measurements.

Fluid properties were modelled as air.

*Electrical resistivity measurements were used to characterise polymer stages as in [4].

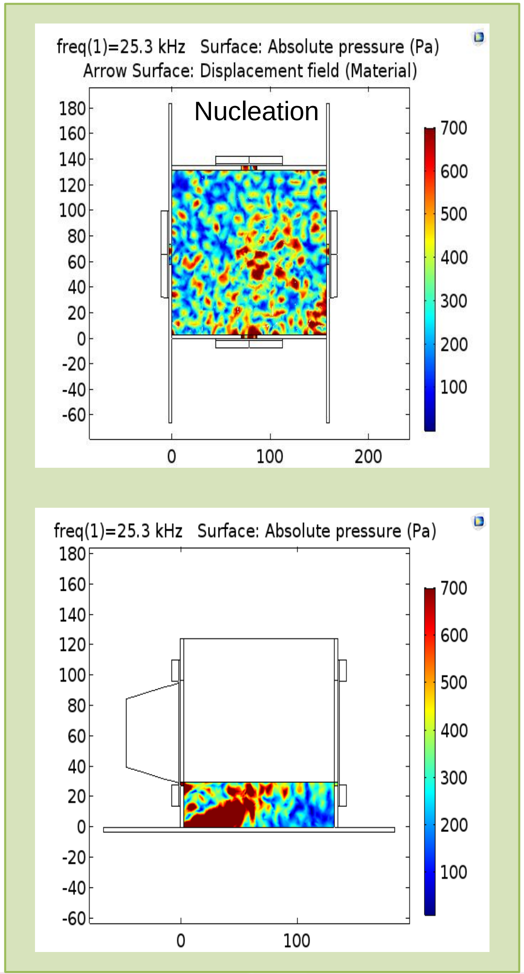

Electrical Resistivity Measurements of Polyurethane Foam Reaction

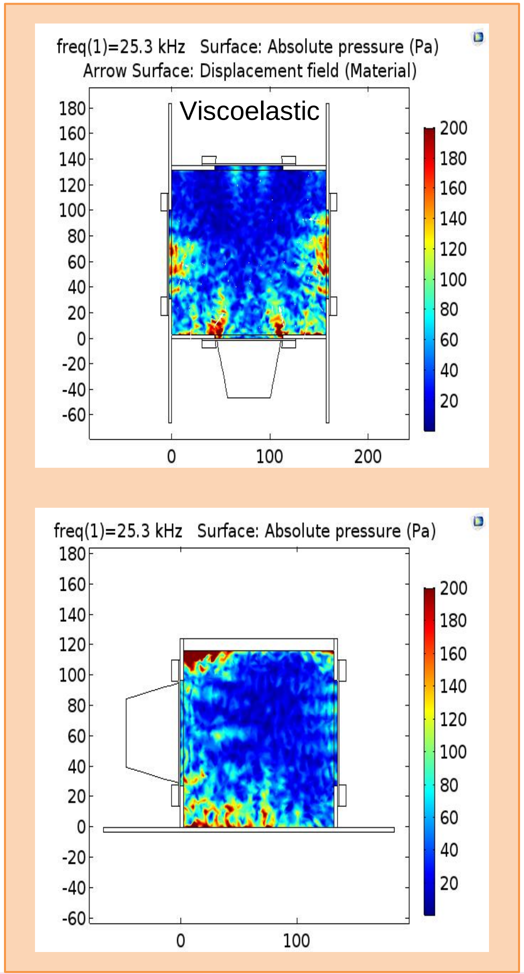
Time of cure (minutes)	7	26	60
Volume of foam (% of cure)	25	97	100
Drained Young’s modulus (Pa)	1.63E7	2.29E6	1.19E7
Foam density (kg/m^3)	663.3	108.0	99.1
Porosity	0.36	0.89	0.90
Characteristic pore size (mm)	0.2	2.0	2.0

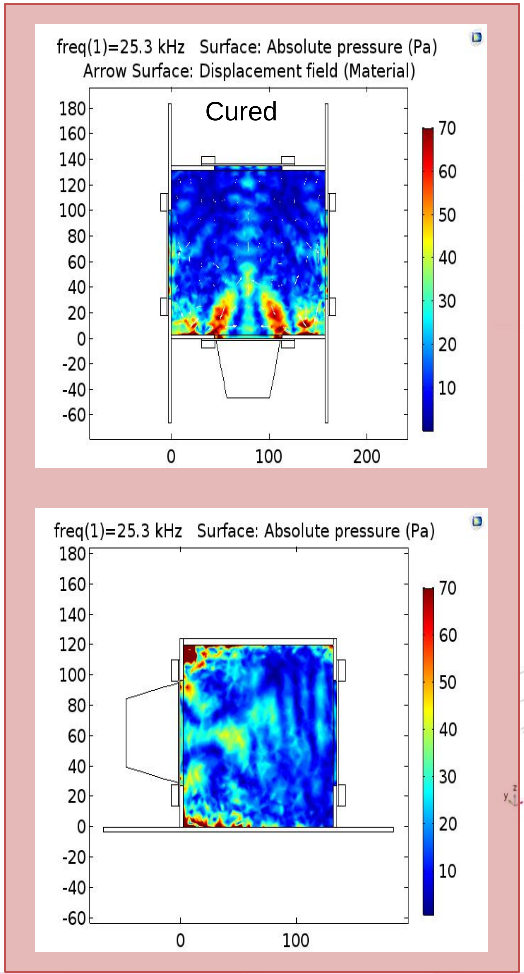
[4] Torres-Sanchez, C. and Corney, J. (2009) Identification of formation stages in a polymeric foam customised by sonication via electrical resistivity. *J. Polym. Res.* 16 461-470

RESULTS

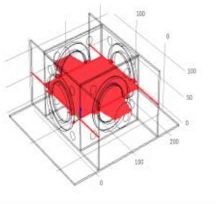
Results – 25.3 kHz 1 Transducer



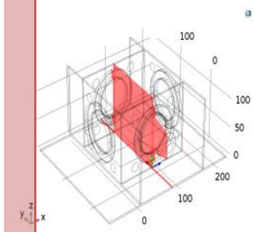


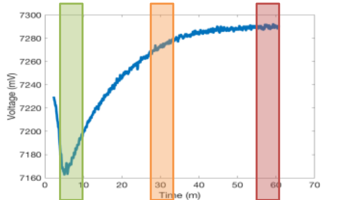


XY Plane

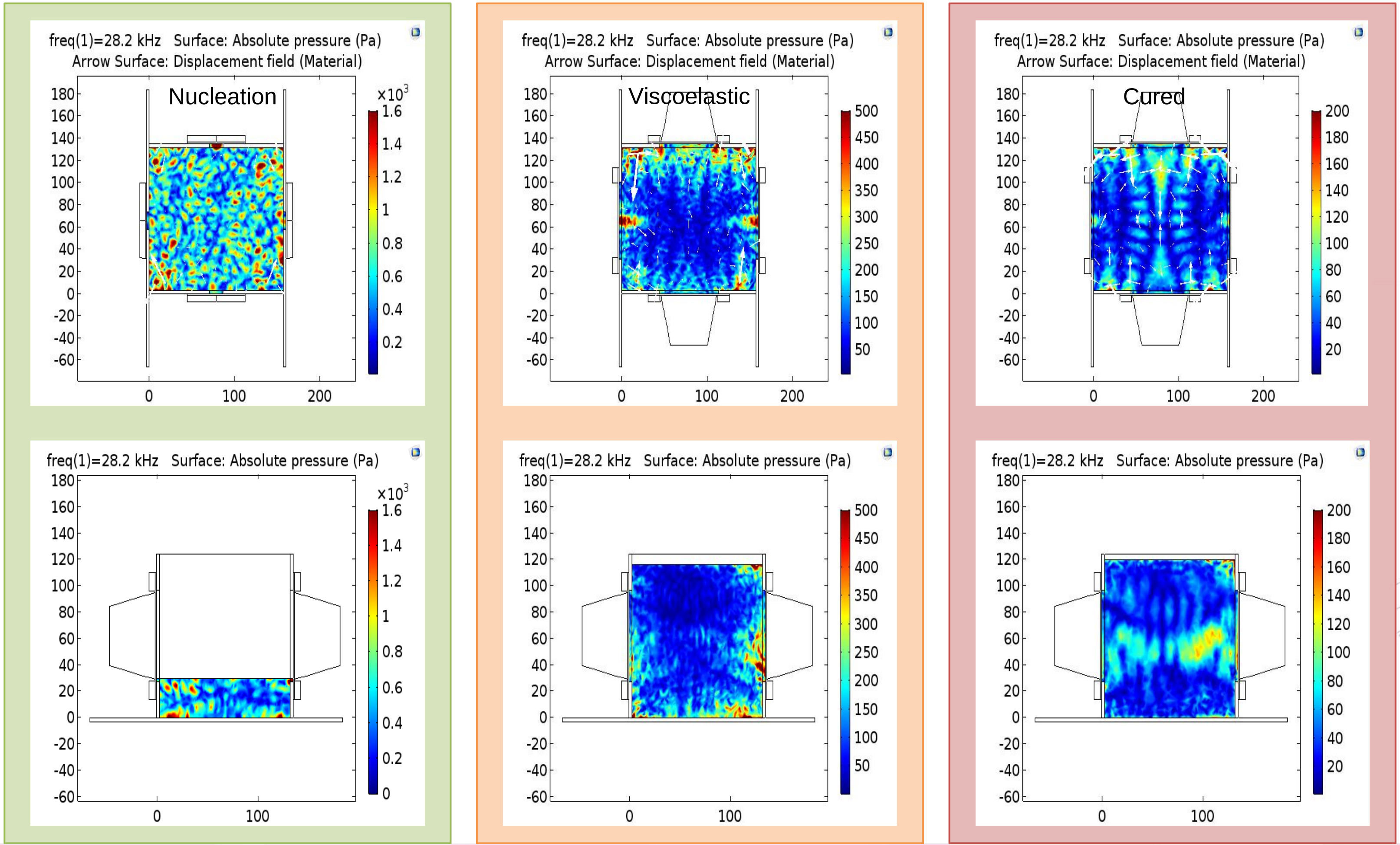


YZ Plane

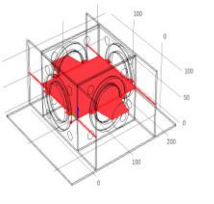




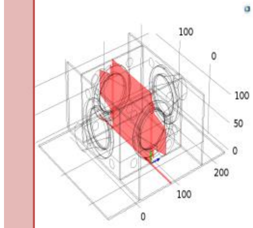
Results – 28.2 kHz 2 Transducers

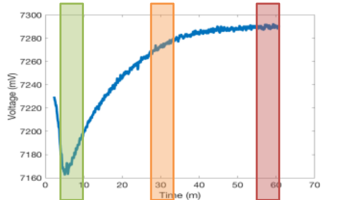


XY Plane

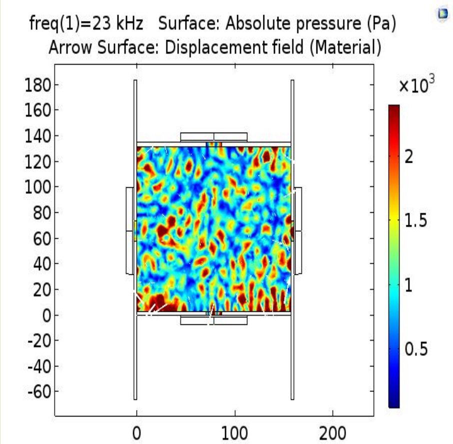


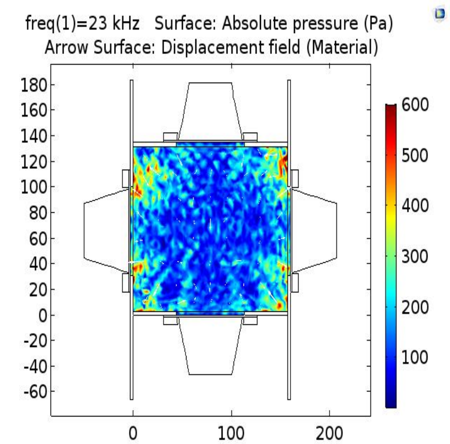
YZ Plane

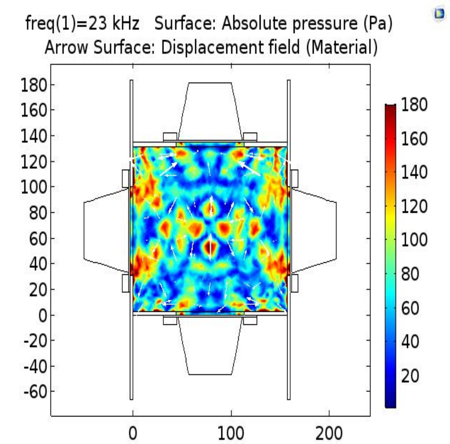




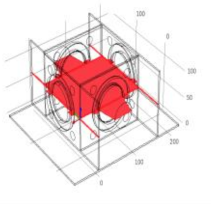
Results – 23.0 kHz 4 Transducers

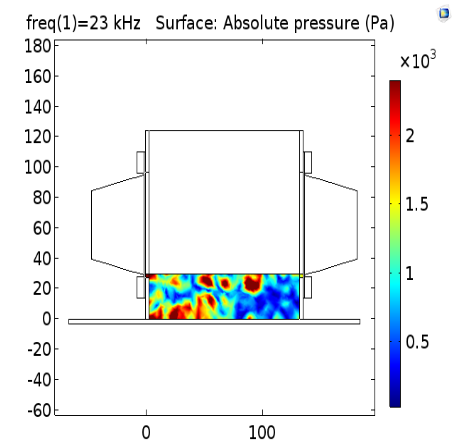

freq(1)=23 kHz Surface: Absolute pressure (Pa)
Arrow Surface: Displacement field (Material)

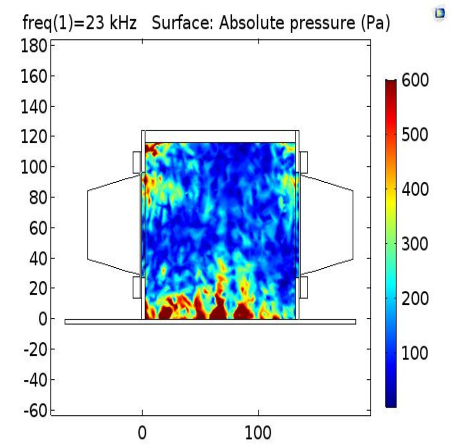

freq(1)=23 kHz Surface: Absolute pressure (Pa)
Arrow Surface: Displacement field (Material)

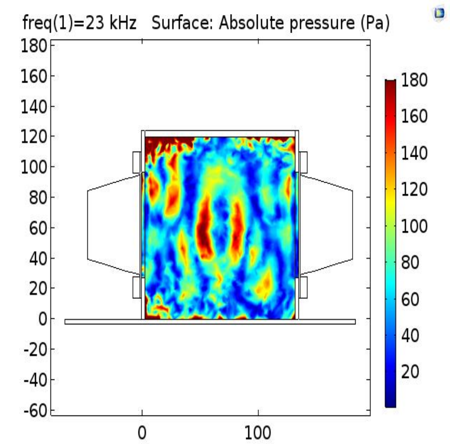

freq(1)=23 kHz Surface: Absolute pressure (Pa)
Arrow Surface: Displacement field (Material)

XY Plane

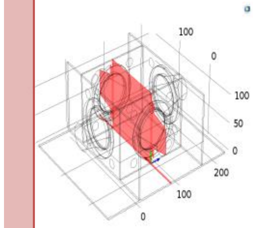


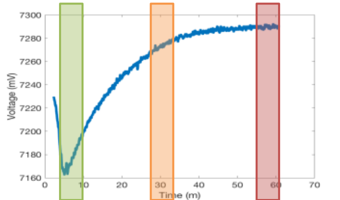

freq(1)=23 kHz Surface: Absolute pressure (Pa)


freq(1)=23 kHz Surface: Absolute pressure (Pa)


freq(1)=23 kHz Surface: Absolute pressure (Pa)

YZ Plane





CONCLUSIONS

Conclusions

The results from this simulation show that there are significant changes in the pressure fields due to the evolution of the poroelastic material at the different stages of the polymerisation of the foam.

Previous works have identified specific stages where sound can affect the foam as the rising and packing stages (from nucleation to viscoelastic). The next stages of the model are the develop the material property inputs for these stages of the foams evolution in more detail.

This model gives insight into the evolution of the foam as it polymerises

Symmetrical acoustic set-ups offer the most promise from a manufacturing perspective.

THANK YOU FOR LISTENING

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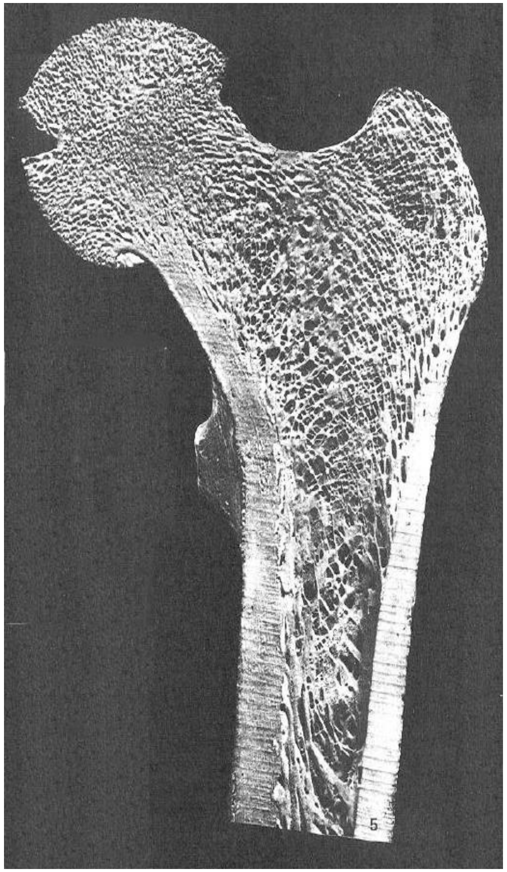
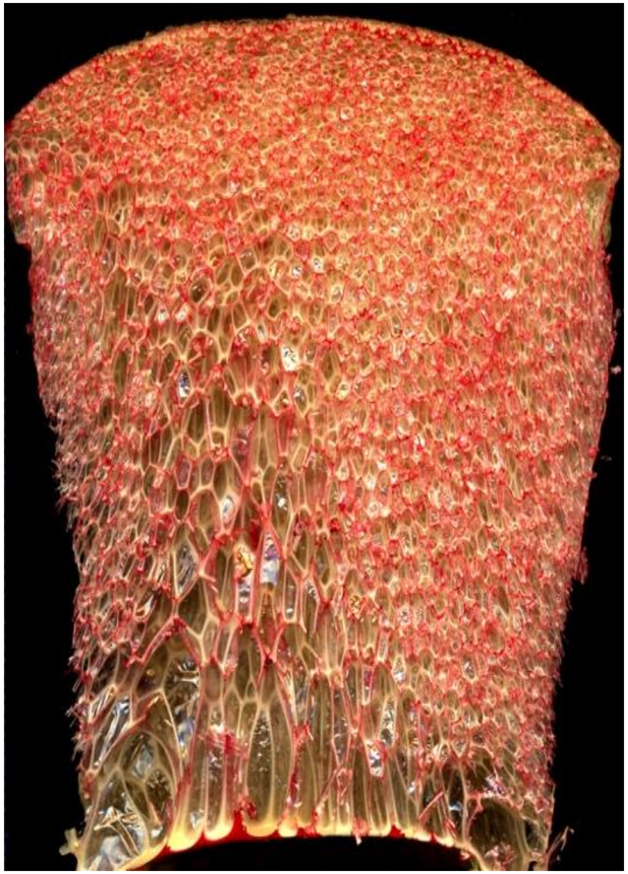
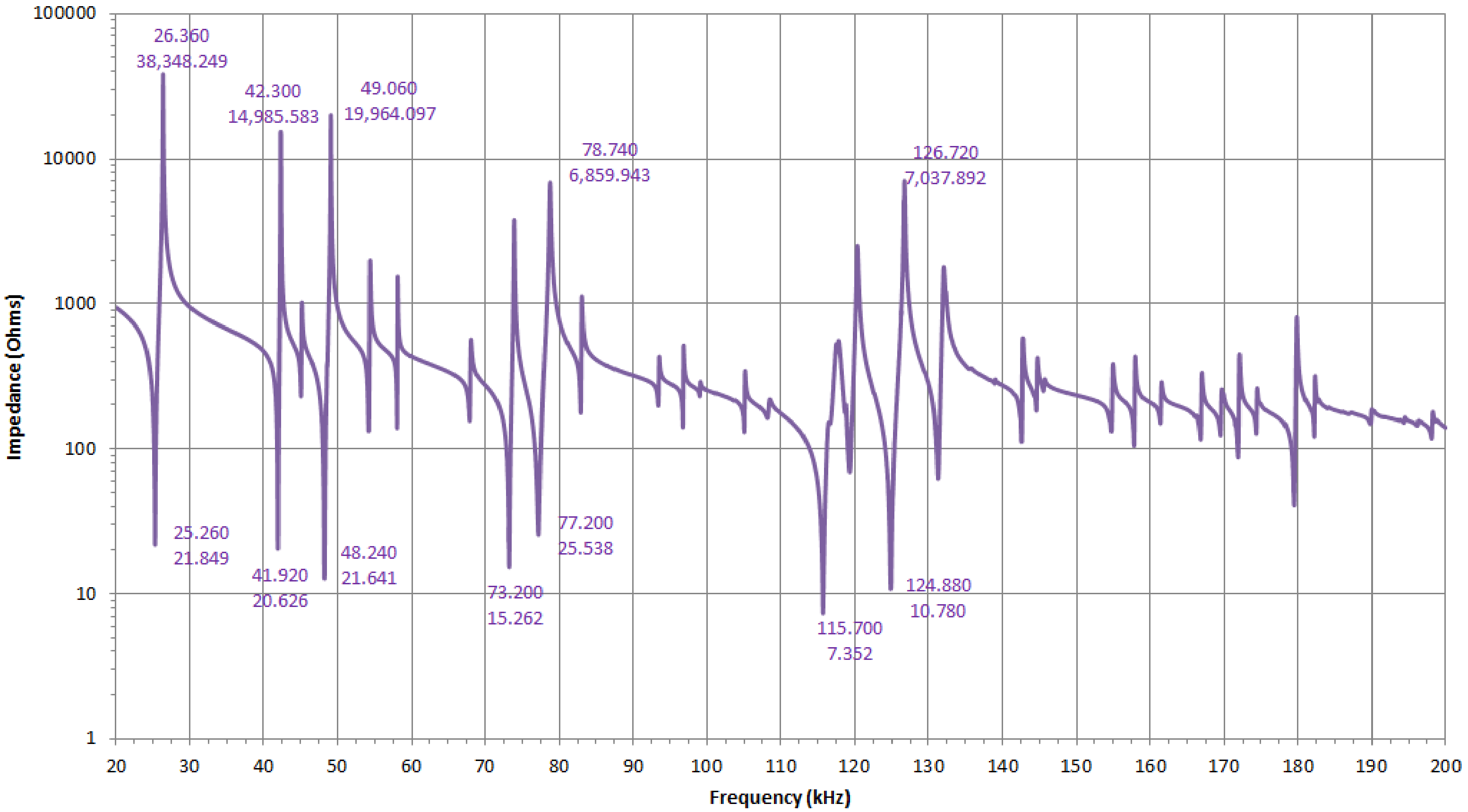


Longitudinal section of a femur. The bone orients its porous structure according to the local stress field [5].



Section of polyurethane foam with graded density as a result of acoustic pressure field [2].

[2] Torres-Sanchez, C. and Corney, J. R. (2008). *Journal of Mechanical Design.* 131 1-8
[5] Williams, P. L., R. Warwick, M. Dyson, and L. H. Bannister (1989). *Gray's anatomy* (37th ed.).ISBN 0443-02588-6



Frequency impedance figure for one transducer (25.3 kHz).

Material Properties

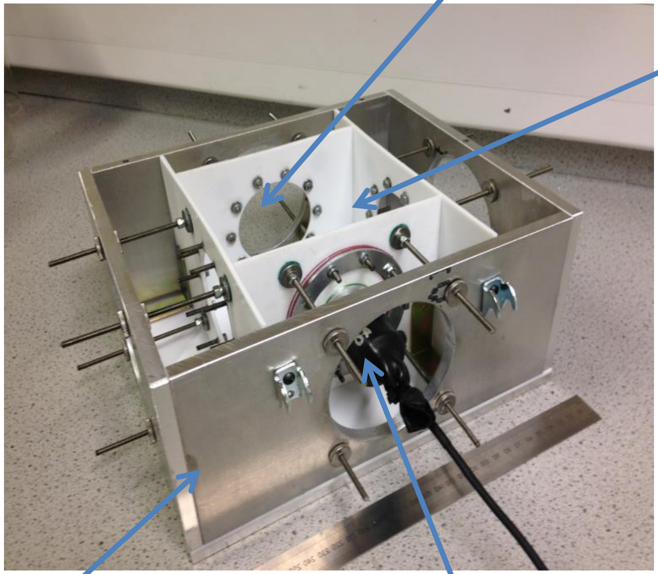
Polyurethane Foam Properties

- The polyurethane foam was modelled at three known stages of its polymerisation:
  1. Nucleation: bubble population just formed
  2. Viscoelastic: expansion complete, polymerisation still on-going, matrix material is viscoelastic
  3. Cured: rigid, cured foam structure
- Flow resistivity and tortuosity were set a 3750 N s m^{-4} and 2.5 respectively, to represent closed cell foam
- Fluid properties were modelled as air

Parameter	**Nuc.**	**Visco.**	**Cured**
Time of cure (minutes)	7	26	60
Volume of foam (% of cure)	25	97	100
Drained Young's modulus (Pa)	1.63E7	2.29E6	1.19E7
Drained Poisson's ratio	0.375	0.375	0.375
Foam density (kg/m^3)	663.3	108.0	99.1
Porosity	0.36	0.89	0.90
Characteristic pore size (mm)	0.2	2.0	2.0

The Experimental Rig

Experimental Rig



Attachment points for transducers

Sample Volume

External Structure

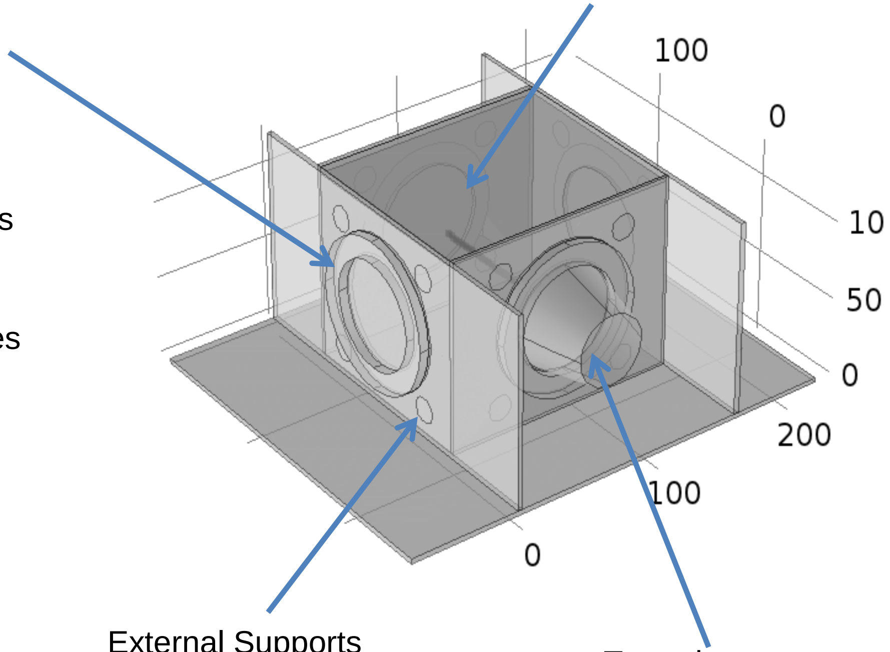
Transducer

- The rig is designed to couple the oscillations of the transducers to the fluid containing region containing the polymeric foam
- Multiple transducer configurations can be set up
- Different sample sizes can be produced
- The ultrasonic transducers are driven by signal generator(s) and amplifier(s)

The Model Geometry

Setting Up

- Structural Mechanics module
- Pressure Acoustics, Frequency Domain
- Optimization module
- External support structure approximated by stiff pads
- Transducer oscillation modelled as a prescribed displacement on outermost face
- Mutliphysics boundaries on the interface of structures and fluid
- Optimisation used for parameter estimation of the pressure amplitudes



Attachment points for transducers

Sample Volume

External Supports

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