Evidence for two compressional waves in fluid-saturated poroelastic materials

Keith Attenborough

Ho-Chul Shin

Shahram Taherzadeh

Rederivations of Biot Theory

J. L. Auriault,
Int. J. Engng. Sci. 18, 775–785 (1980)

Burridge and Keller
JASA **70**(4) 1140 – 1146 (1981)

J. L. Auriault, L. Borne and R. Chambon, JASA, **77**(5), 1641–1650 (1985)

R.P. Gilbert and A. Mikeli´c Nonlinear Analysis, Theory, Methods and applications, **40**, pp. 185–212, (2000)

G. Maximov, SAPEM, 2011

Biot's theory valid if

$\left(\text{viscous skin depth/wavelength}\right)^2 \ll 1$

Slow wave propagates if
viscous skin depth/pore size < 1
Assuming a characteristic pore size of 0.0001 m 'slow' waves will propagate:

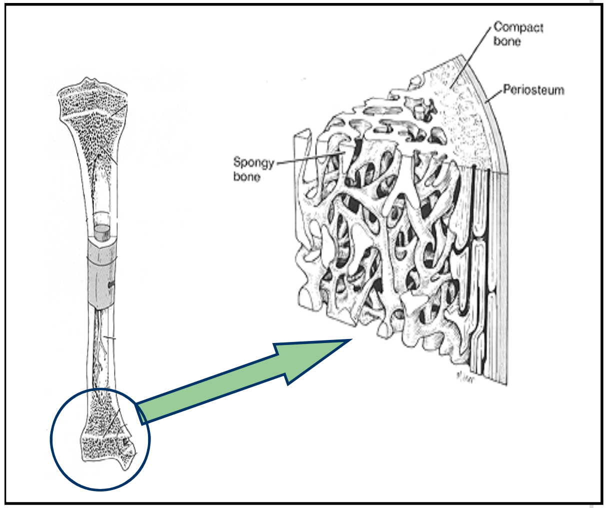
- in air-filled media above 500 Hz
- in water-filled media above 30 Hz

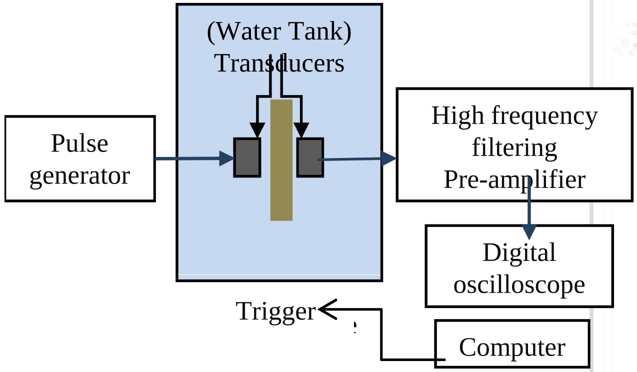
See also D. Smeulders J. Eng. Mech. ASCE 908 – 917 September (2005)

Unambiguous evidence for ***two*** *compressional waves should show separate wave arrivals in pulse transmission measurements*

Waves transmitted in water-filled bone

Z. E. A. Fellah, J. Y. Chapelon, S. Berger, W. Lauriks and C. Depollier,
J. Acoust. Soc. Am. **116** 61 – 73 (2004)





(Water Tank) Transducers

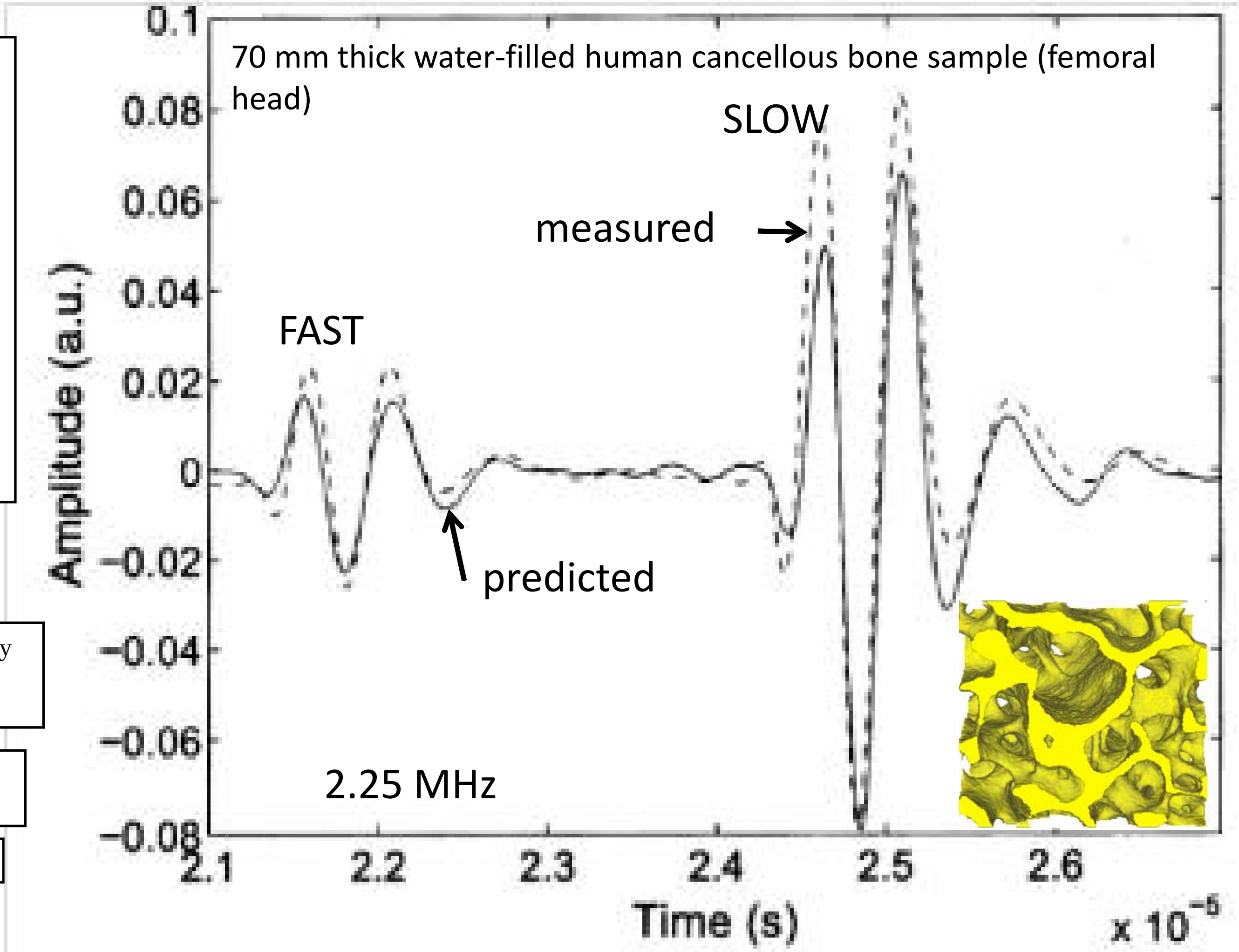
Pulse generator

High frequency filtering Pre-amplifier

Digital oscilloscope

Trigger

Computer



70 mm thick water-filled human cancellous bone sample (femoral head)

SLOW

measured

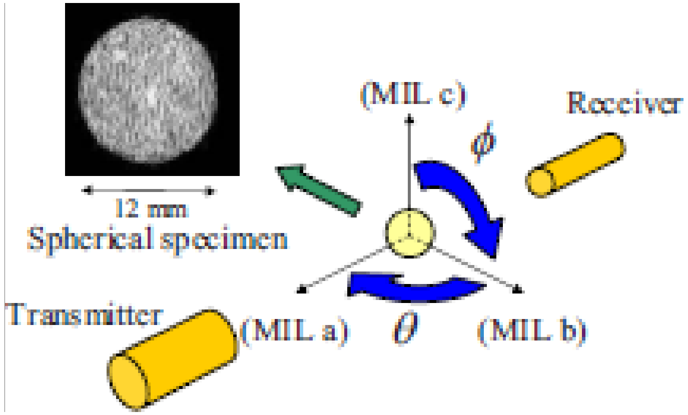
FAST

predicted

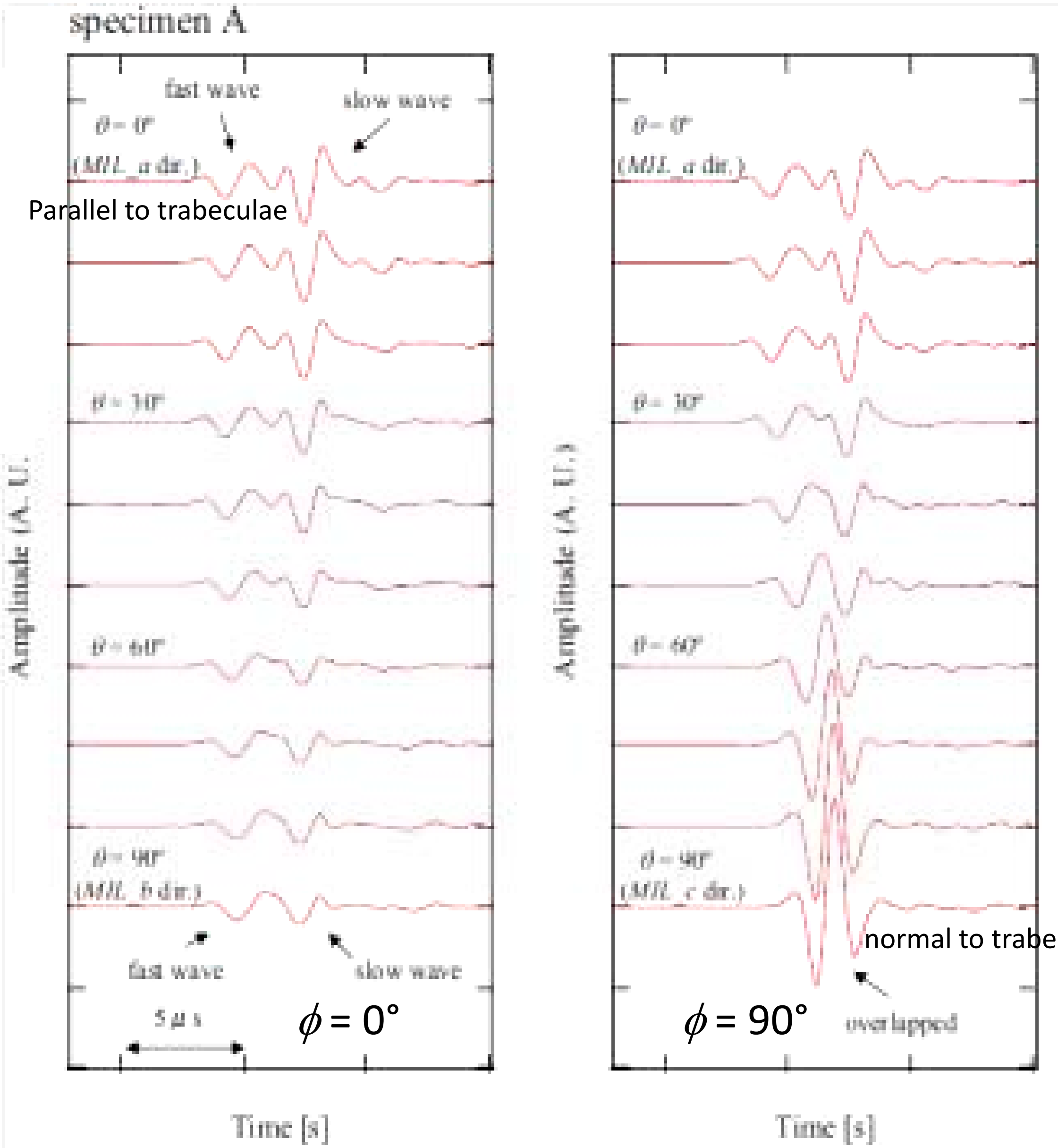
2.25 MHz

pore and trabeculae sizes are on the order of mm

Bone anisotropy effects



K. Mizuno, H. Somiya, T. Kubo, M. Matsukawa and T. Otani "Influence of cancellous bone microstructure on two ultrasonic wave propagations in bovine femur: An *in vitro* study", J. Acoust. Soc. Am. **128** 3181–3189 (2010)



Parallel to trabeculae

normal to trabeculae

$\phi = 0°$

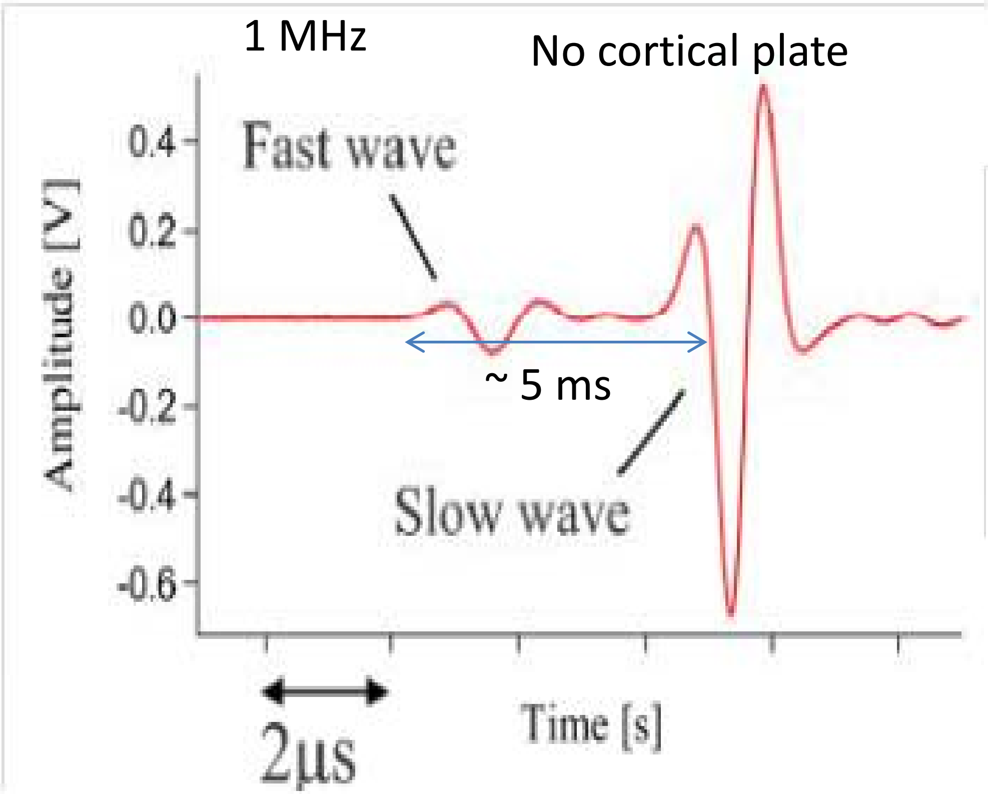
$\phi = 90°$

Influence of cortical bone outer layers

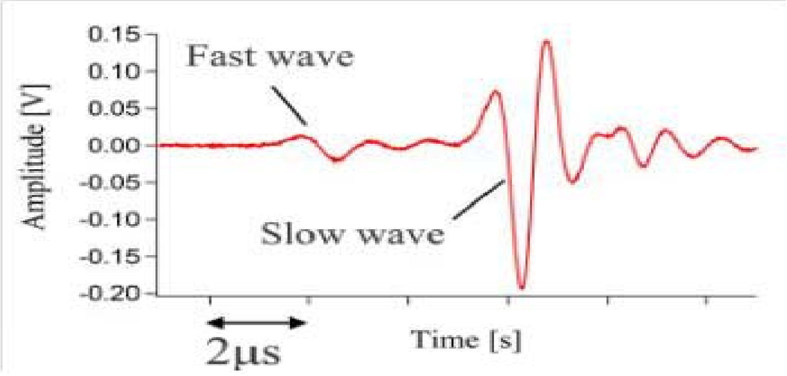
1×45.2×12.9 (thick) mm water-filled cancellous bone sample

1 MHz

No cortical plate

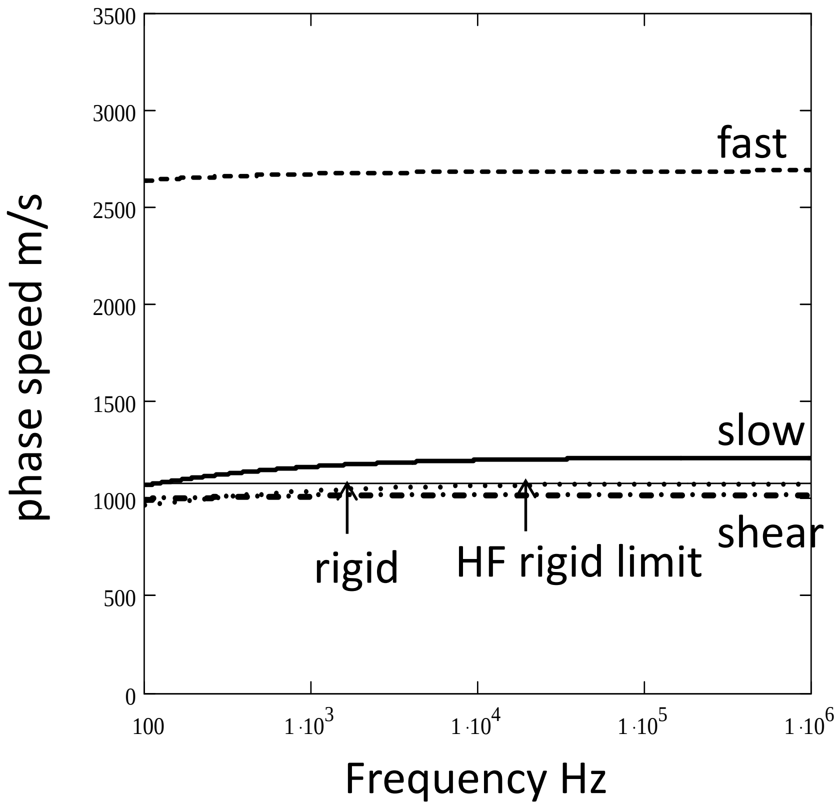


1.9 mm cortical plate

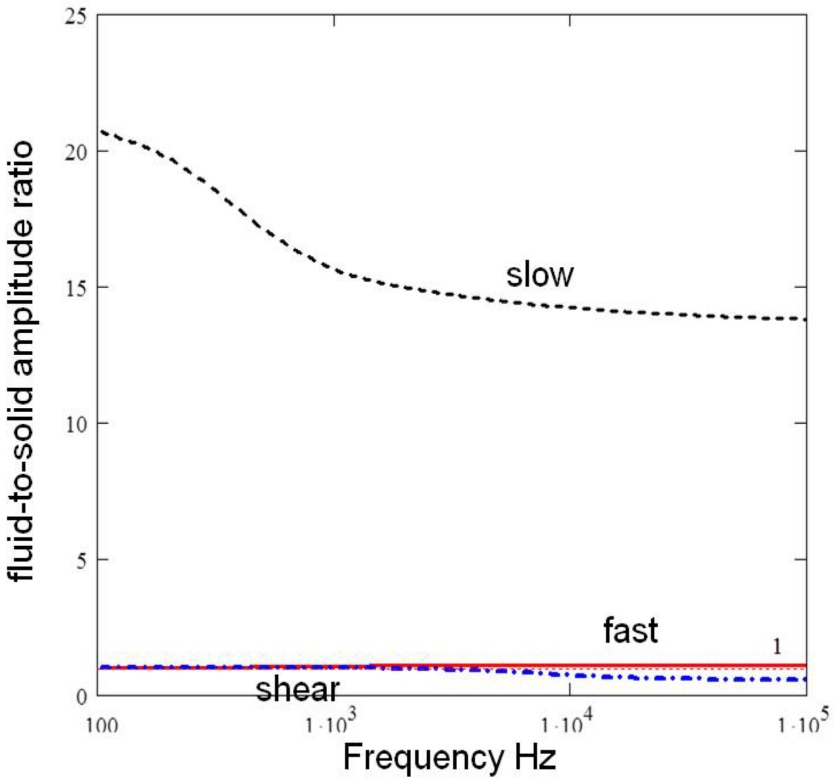


K. Mizuno, Y. Nagatani, K. Yamashita and M. Matsukawa, “Propagation of two longitudinal waves in a cancellous bone with the closed pore boundary”, J. Acoust. Soc. Am. Express Letter DOI: 10.1121/1.3607196 (2011)

Biot-slit-pore predictions of wave speeds and amplitude ratios in **Water-filled bone**



1500 m/s difference in phase speed implies about 6 μs difference in arrival time over 12 mm



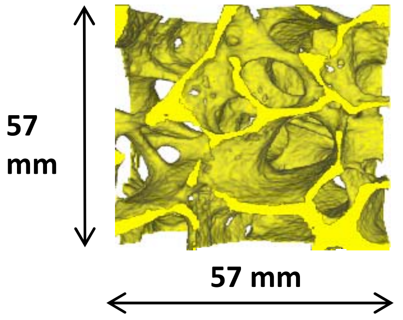
'slow' wave has 15 – 20 × larger fluid borne component than 'fast' wave

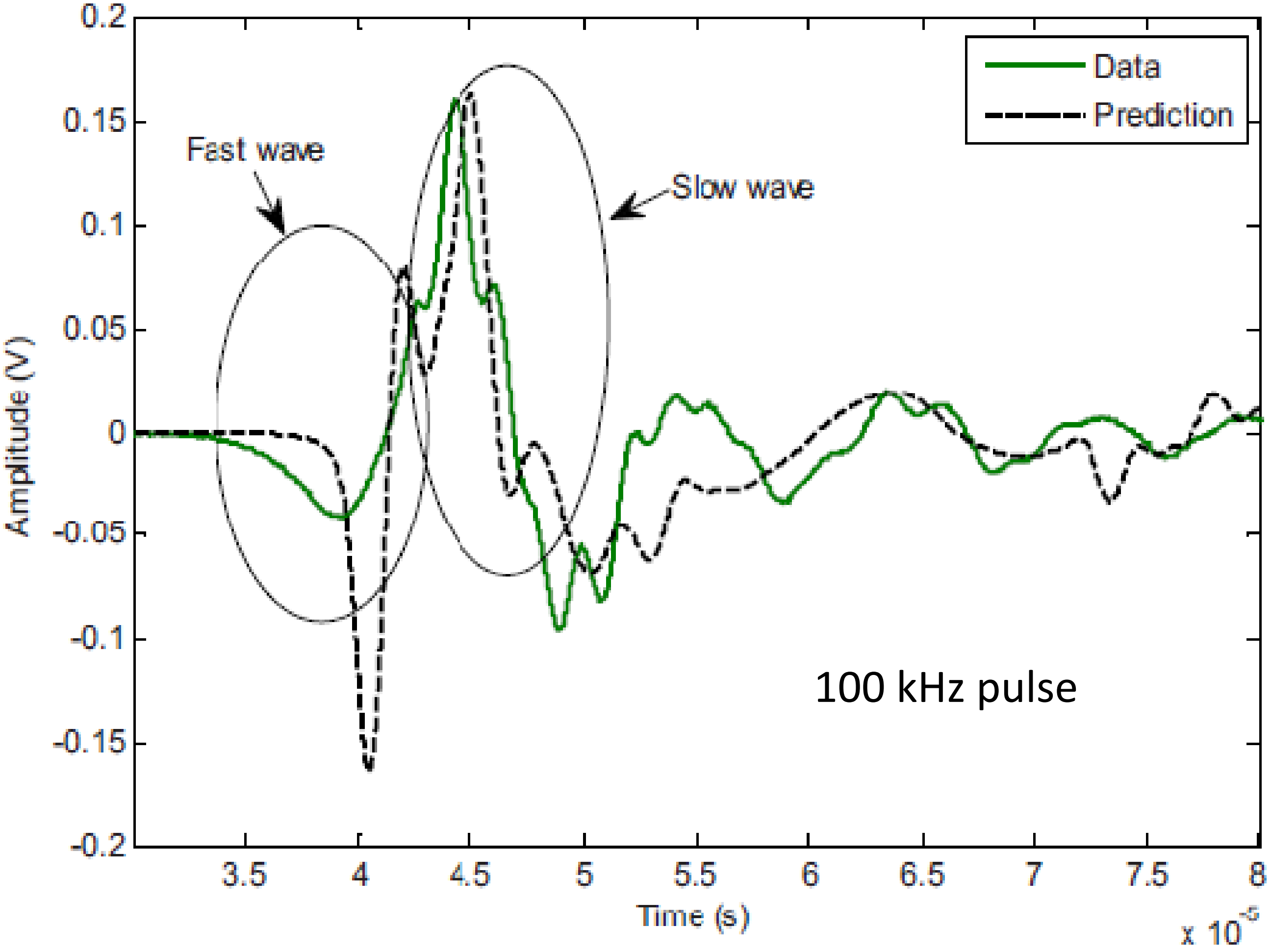
Water-filled bone replicas

A
stereolithographical
bone replica

ILIAC CREST

13× scale



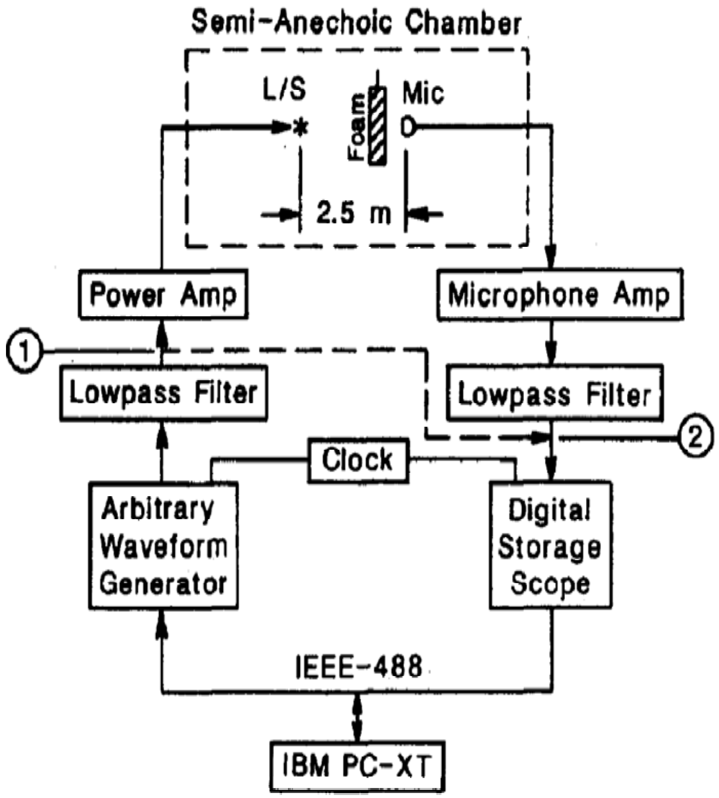


100 kHz pulse

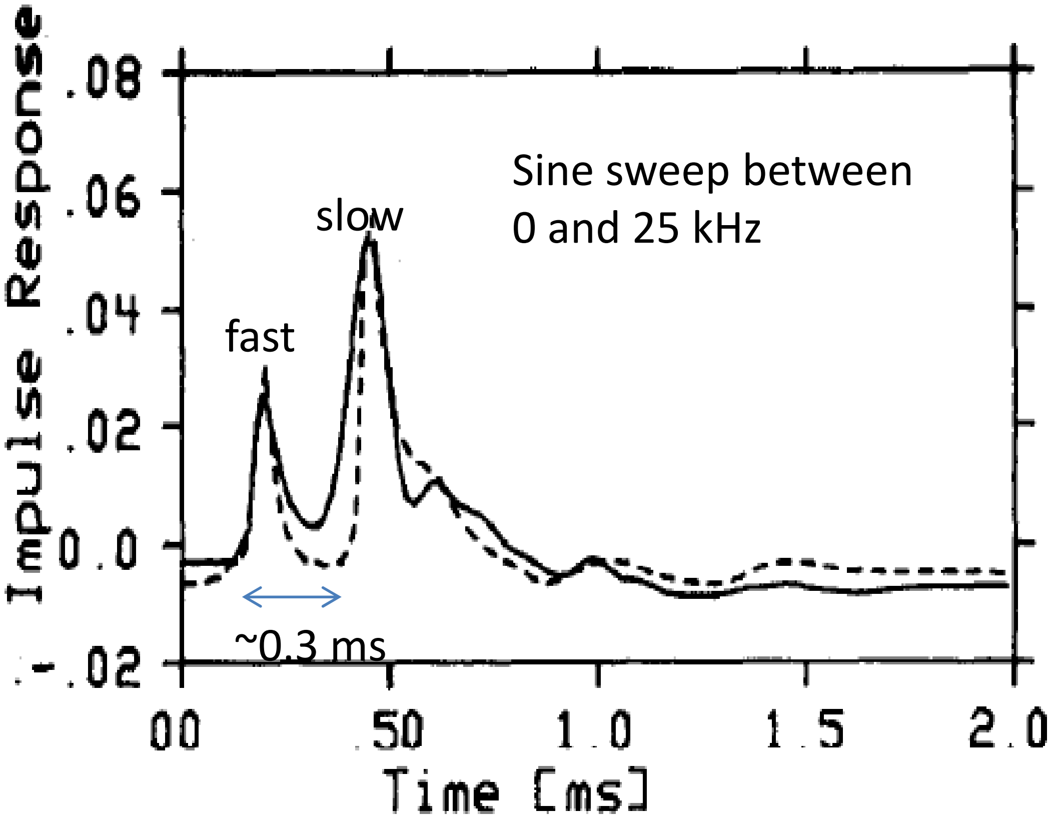
H. Aygun, K.Attenborough, W. Lauriks and C. M. Langton, "Ultrasonic wave propagation in stereolithographical bone replicas", J. Acoust. Soc. Am. **127**(6) 3781–3789 (2010)

Air-filled partially reticulated polyurethane foam

J. S. Bolton and E. R. Green, “Normal Incidence Sound Transmission through Double-Panel Systems Lined with Relatively Stiff, Partially Reticulated Polyurethane Foam”, Applied Acoustics **39** 23 – 51 (1993)



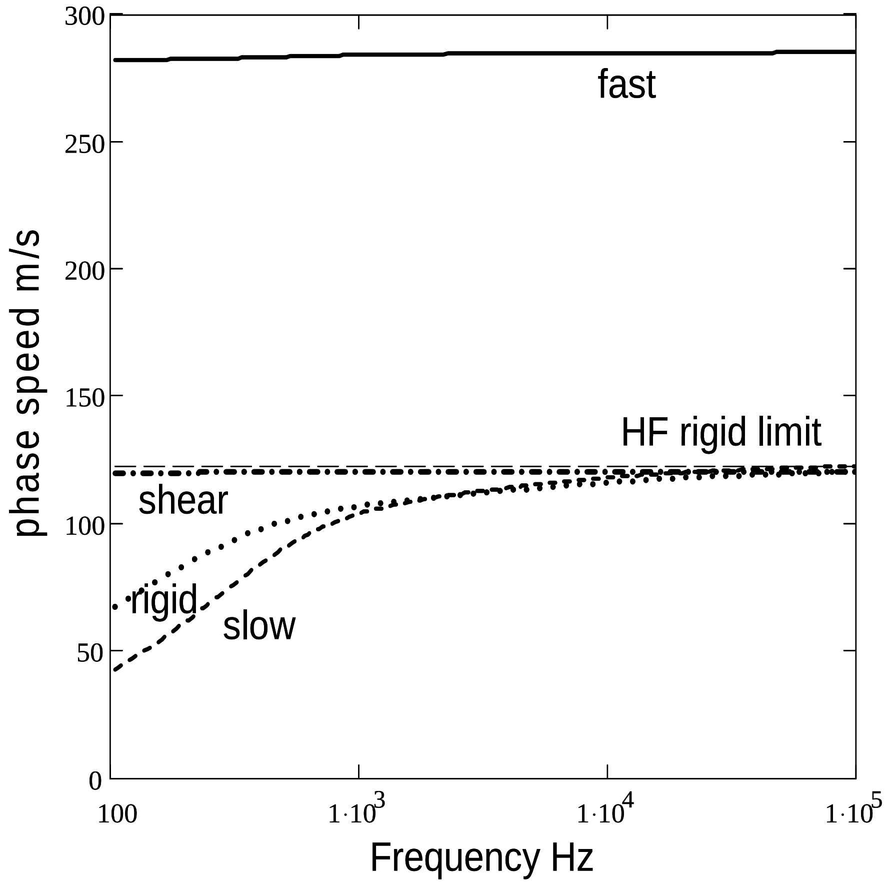
Foam sheet 1.4 m × 1.5 m × 5 cm (thick) hung in anechoic chamber

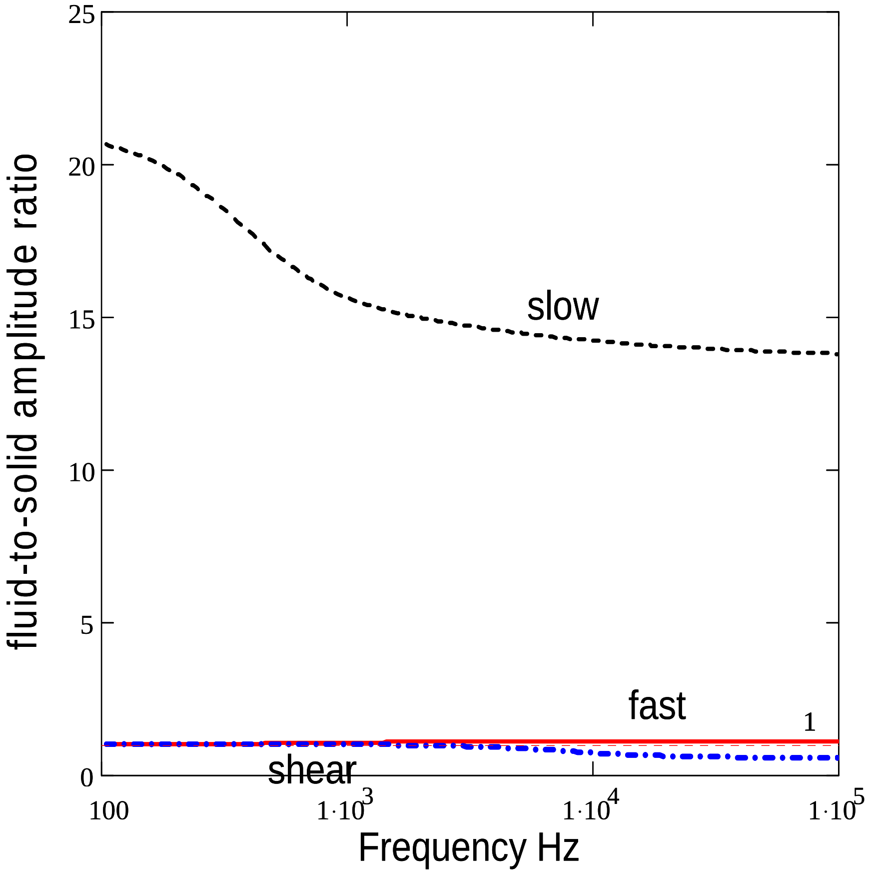


Sine sweep between 0 and 25 kHz

- estimated bulk modulus 1700 kPa, flow res. 25 kPasm^{-2}
- Considerable post-processing needed
- Fitted tortuosity value rather high (7.8)

Biot (identical pore) predictions for wave speeds and amplitudes

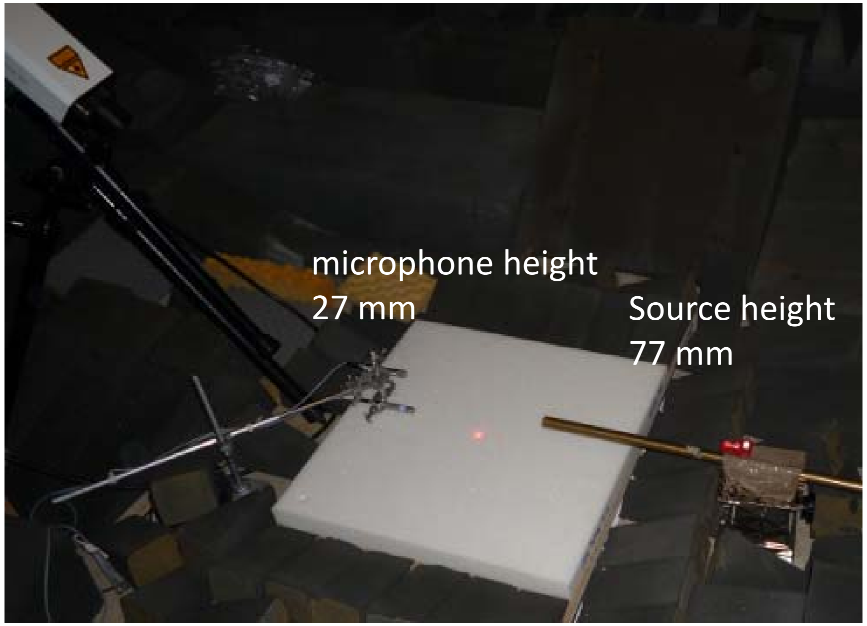


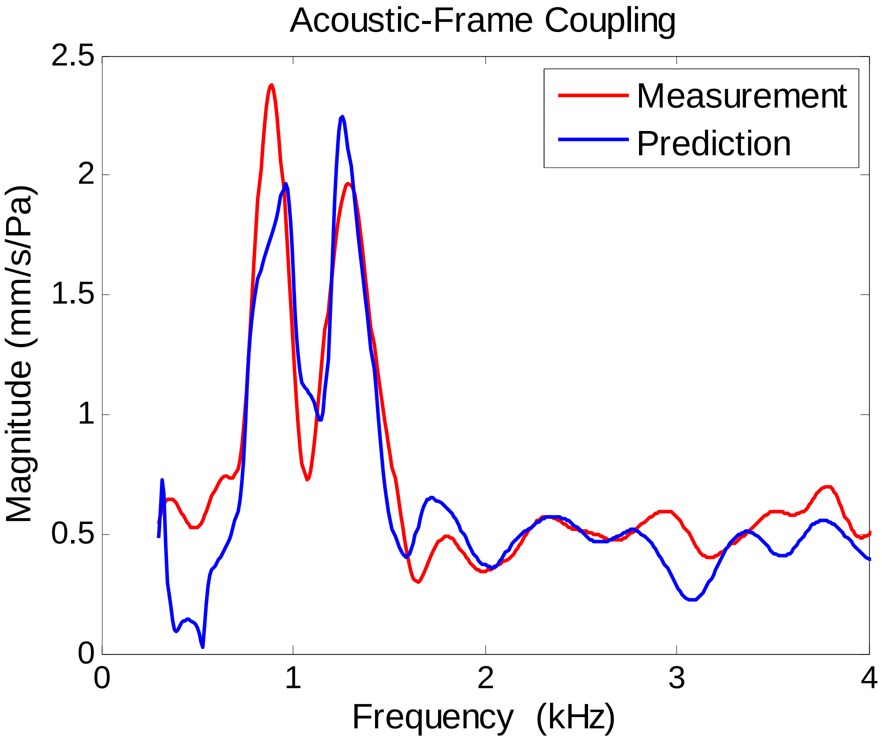


150 m/s difference in speeds implies about 0.33 ms difference in arrival times

'slow' wave has much larger fluid-borne component than 'fast'

Parameters deduced from acoustic-to-frame coupling spectra and acoustic level difference spectra





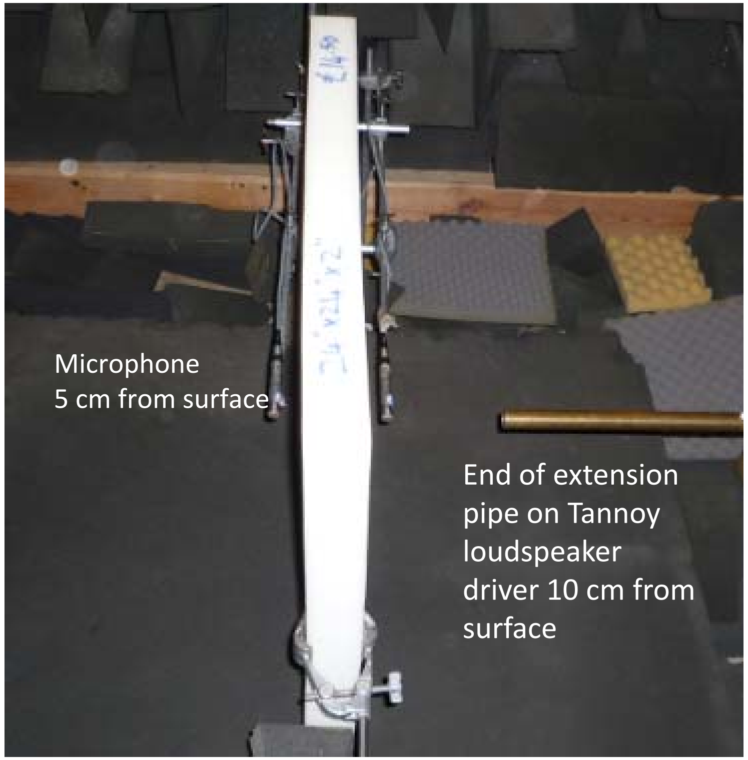
Source-microphone separation 295 mm
Source-LDV spot separation 154 mm
LDV beam incidence angle 44°

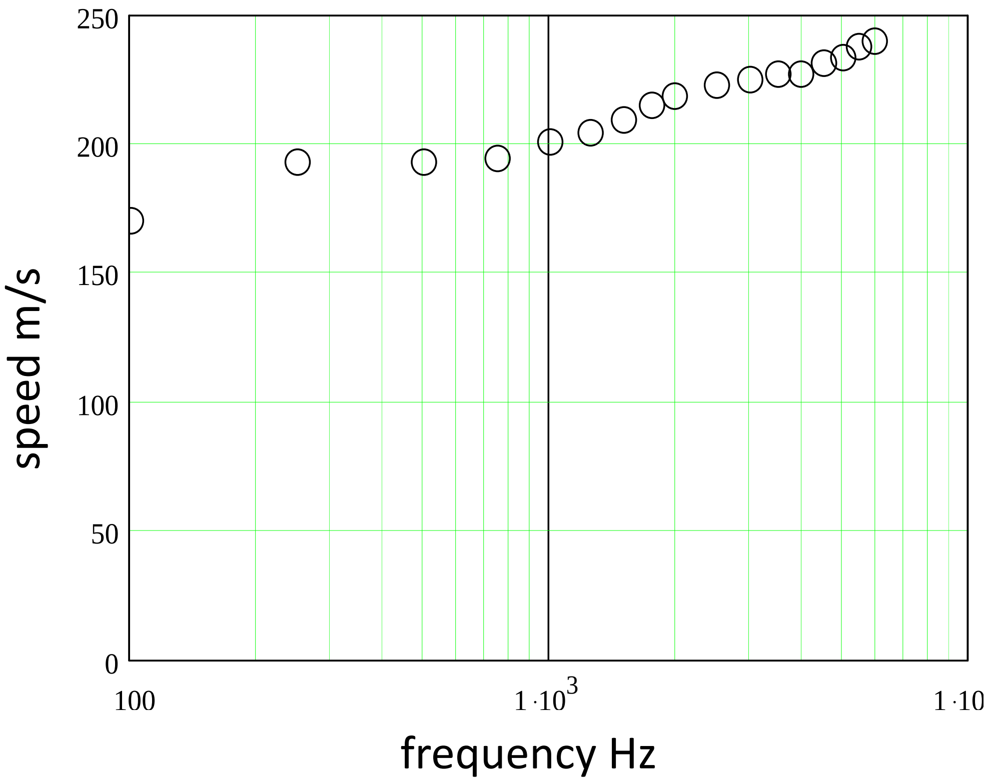
Procedure and parameter deduction algorithm was reported by Ho-Chul Shin on Wednesday

Parameter	**Deduced value**
Flow resistivity	**8.76 kPa s/m^2**
Porosity	0.98
Bulk modulus	**690 kPa**
Shear modulus	11.5 kPa
Loss factor	0.045
Bulk density	23.9 kg/m^3

Acoustic pulse transmission measurement

single cycle sine wave pulses (→ group rather than phase speeds)

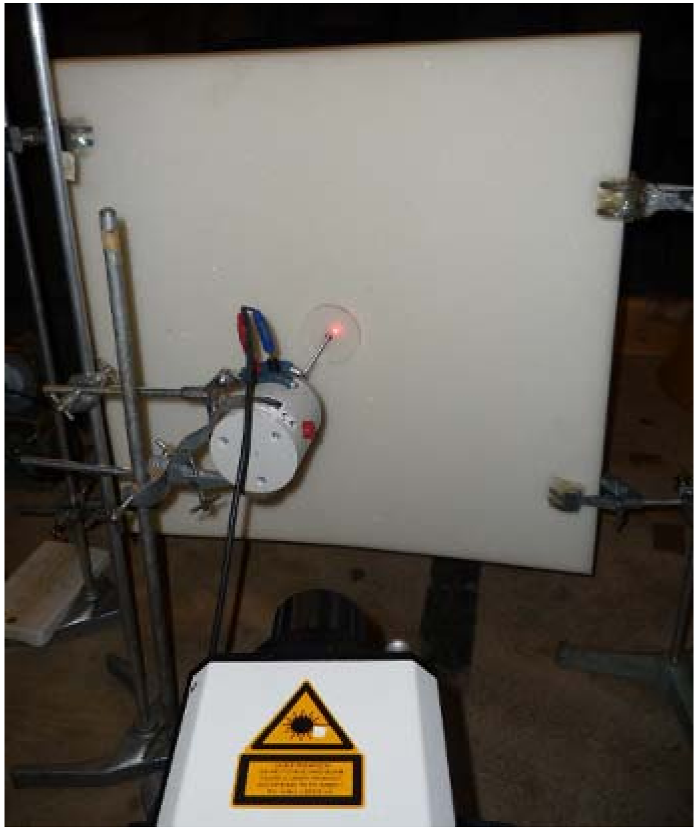


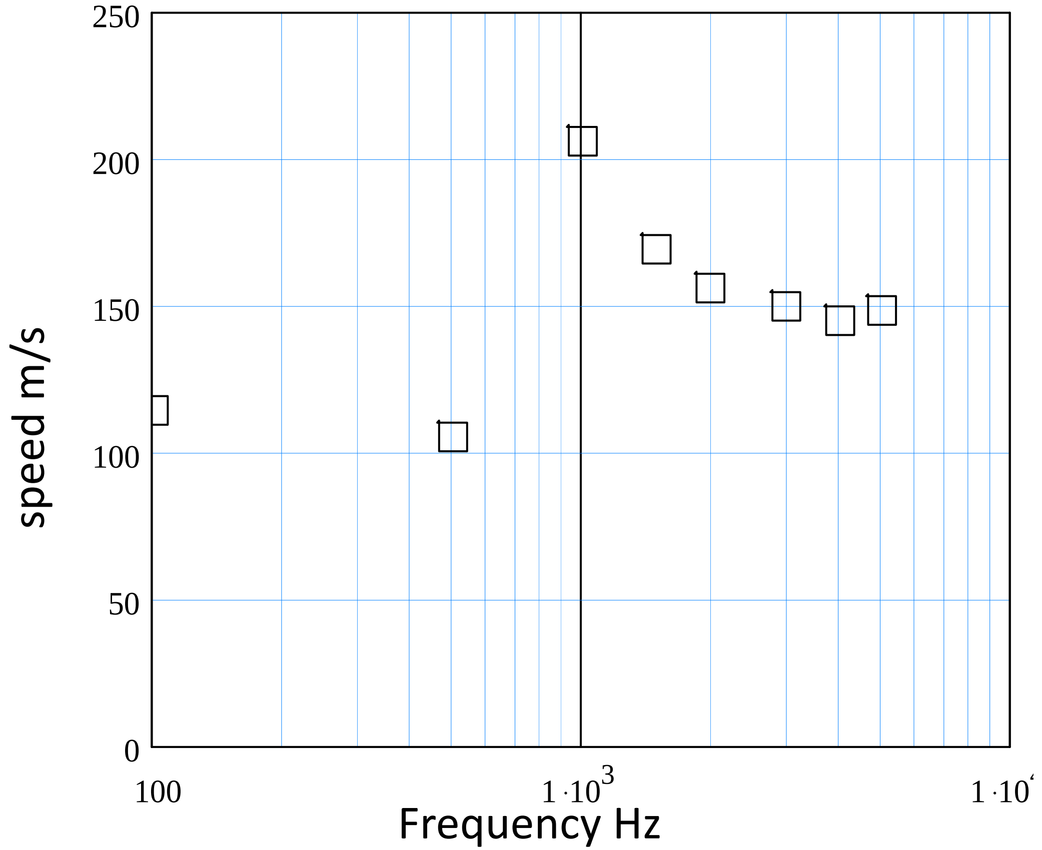


Freely supported foam plate (605 mm x 605 mm x 49-mm thick)

All the tests (output and input) were controlled by Matlab Data Acquisition toolbox and National Instruments acquisition card.

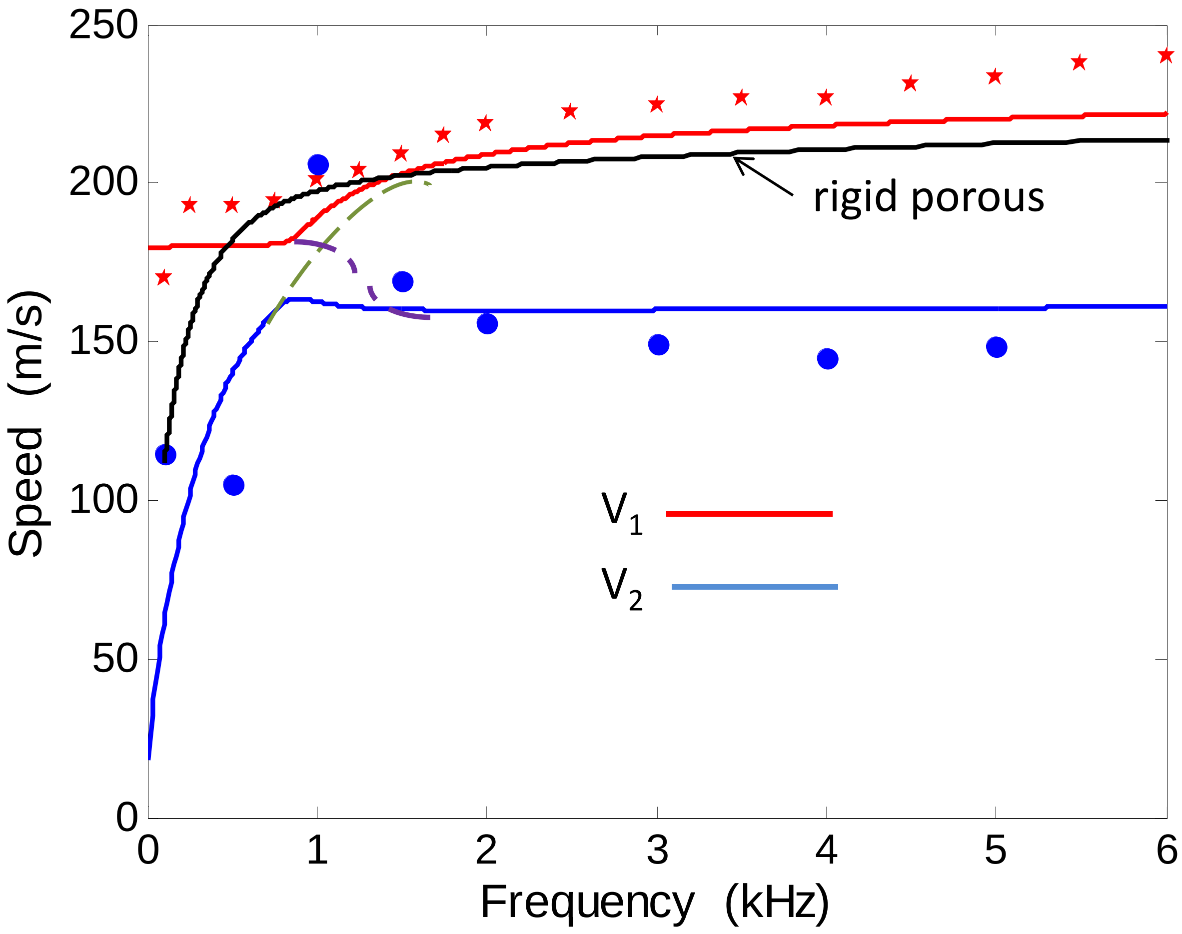
mechanical excitation transmission measurement

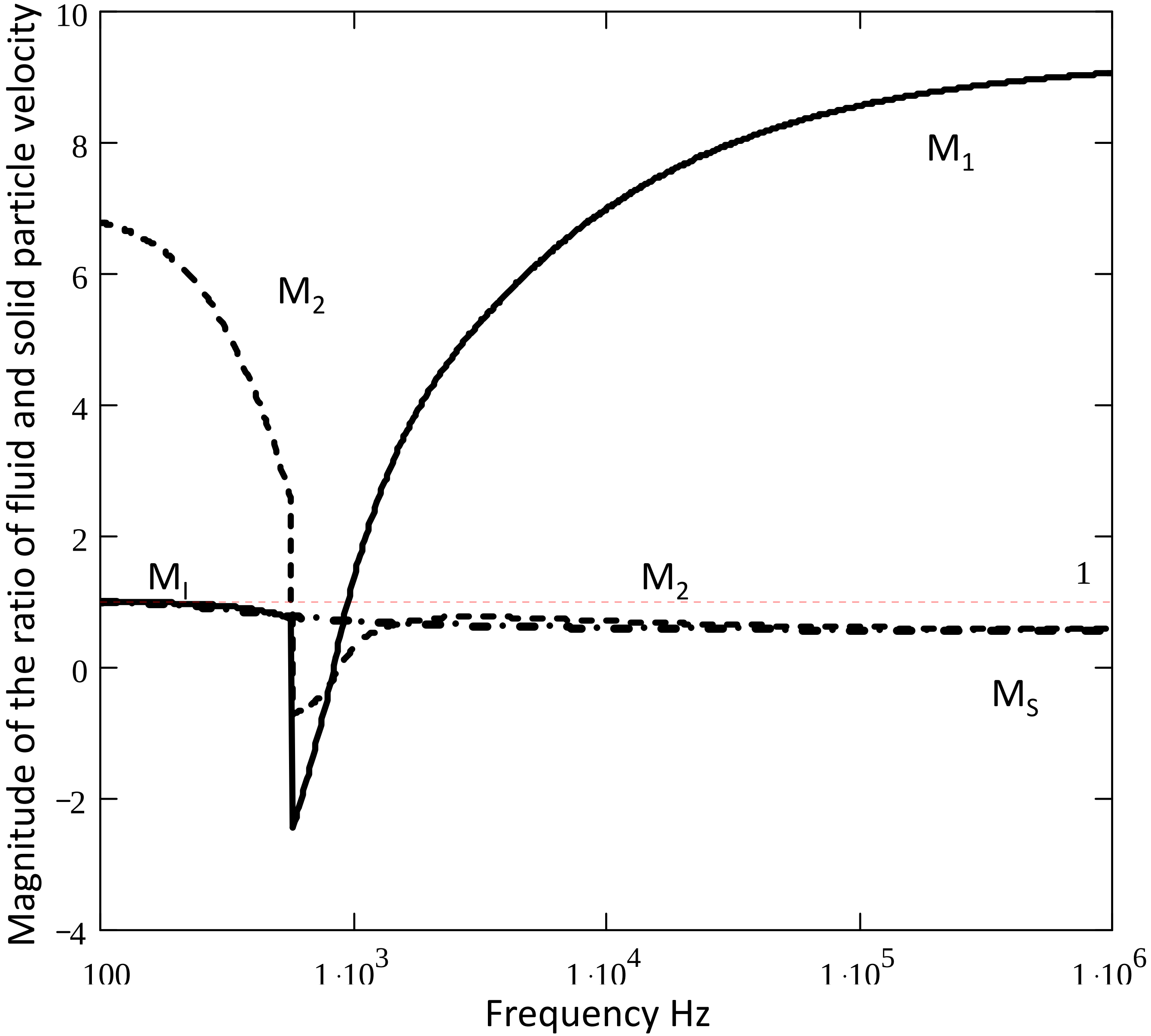




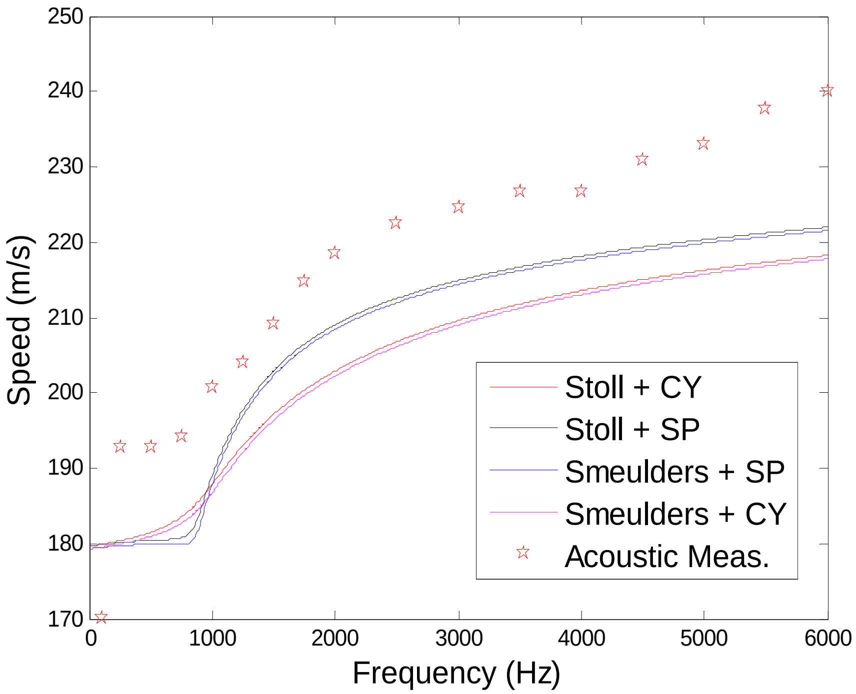
Mechanical excitation (single cycle sine wave pulses) by a shaker in physical contact with the foam through a 20 cm long thread attached to a circular perspex plate (70 mm diameter and 6mm thick).
LDV measurements were made on source side and receiver side.
NB Rayleigh–type wave measured also

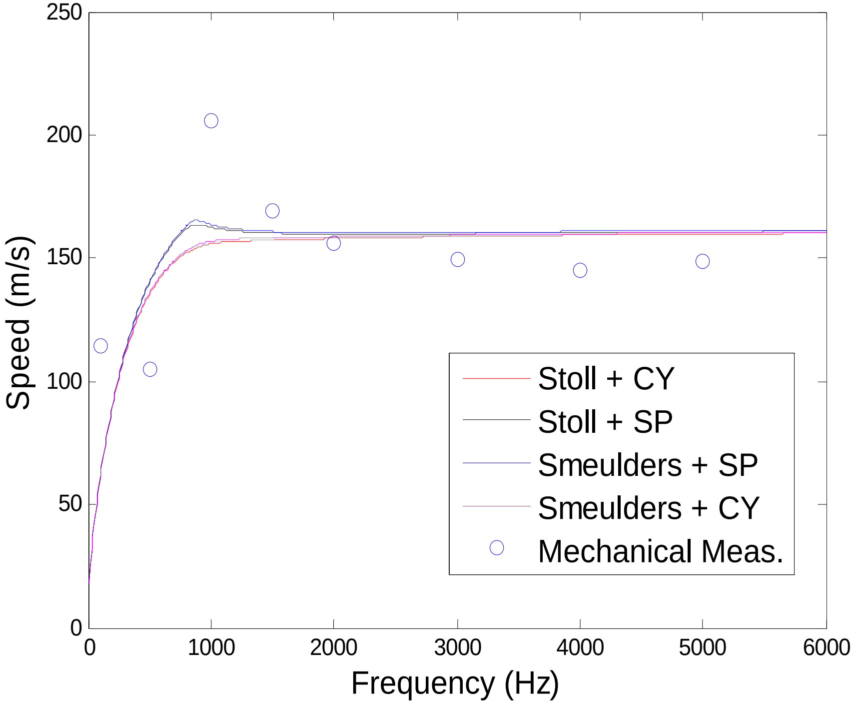
Comparisons between data and Biot-slit-pore predictions




Magnitude of the ratio of fluid and solid particle velocity
10
8
6
4
2
0
−2
−4
M$_2$
M$_1$
M$_l$
M$_2$
1
M$_S$
100
$1 \cdot 10^3$
$1 \cdot 10^4$
$1 \cdot 10^5$
$1 \cdot 10^6$
Frequency Hz

Slit v cylindrical pores in foam





CONCLUSIONS

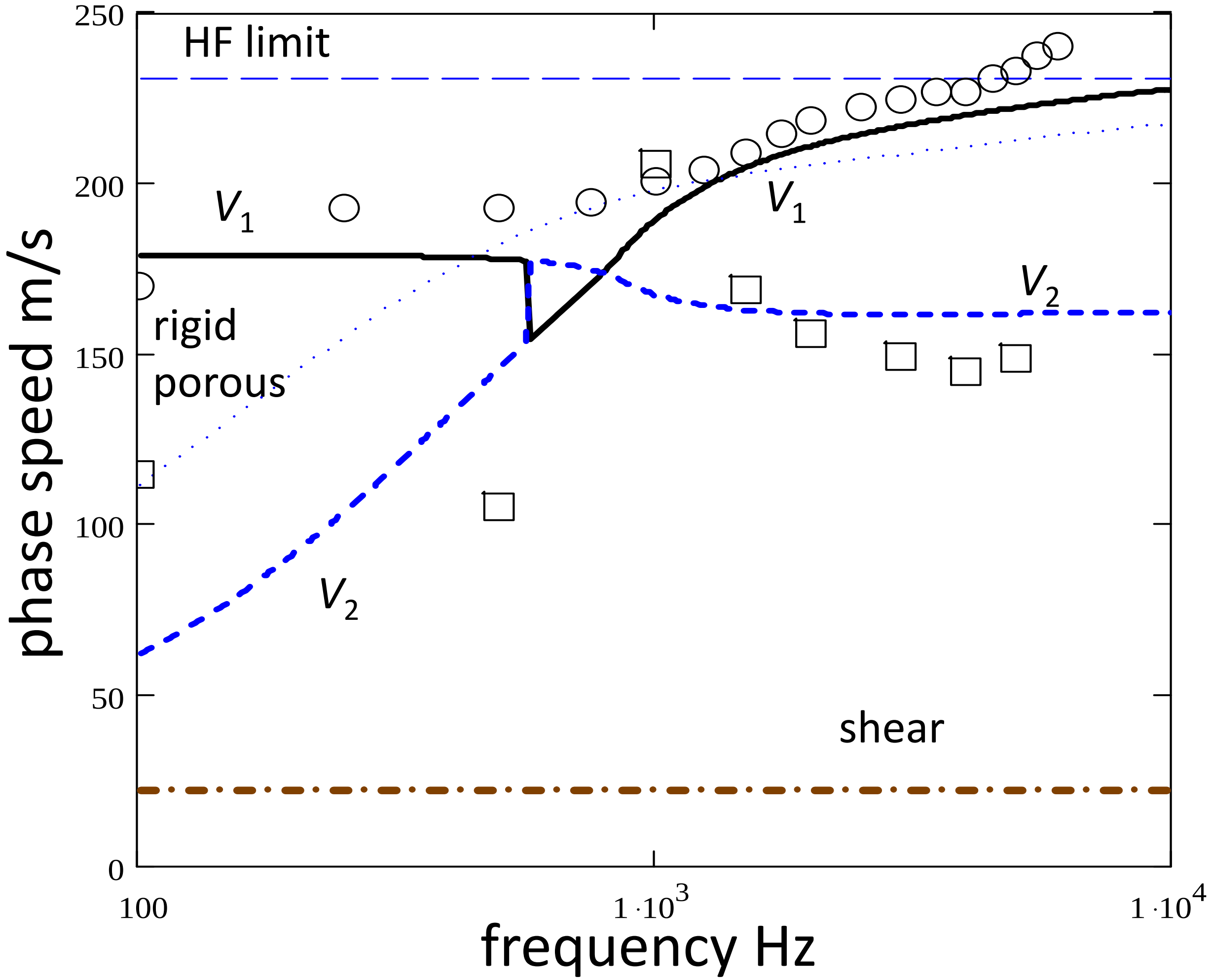
- There is unambiguous evidence for two compressional wave types from ultrasonic transmission measurements on water-filled bone

- The response of air-filled solid materials with relatively rigid frames to acoustic excitation is dominated by the mainly fluid-borne wave

- Experiments using different forms of excitation on relatively flexible air-filled partially-reticulated polyurethane form show the existence of two compressional wave types but with overlapping properties in different frequency ranges

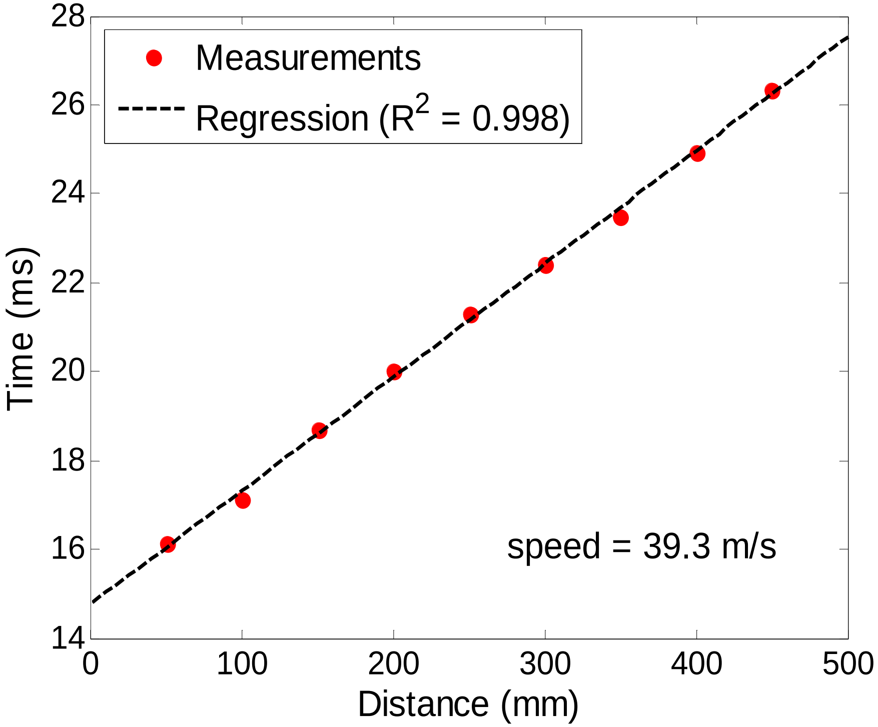
- Biot theory provides an understanding the data and can be used to deduce material properties

Biot (identical slit pore) predictions for wave speeds

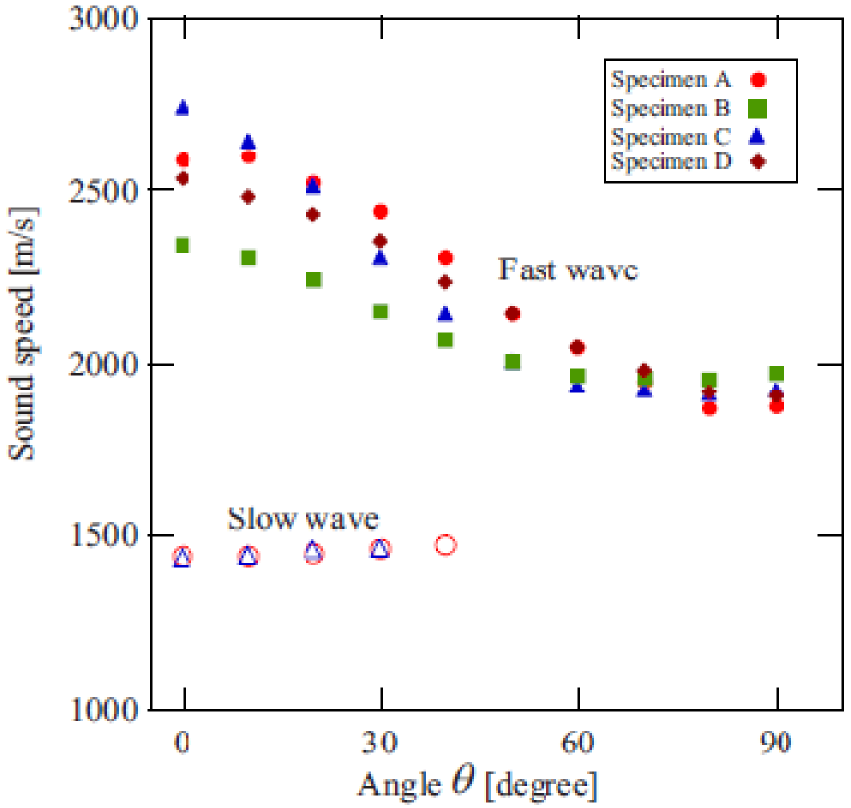


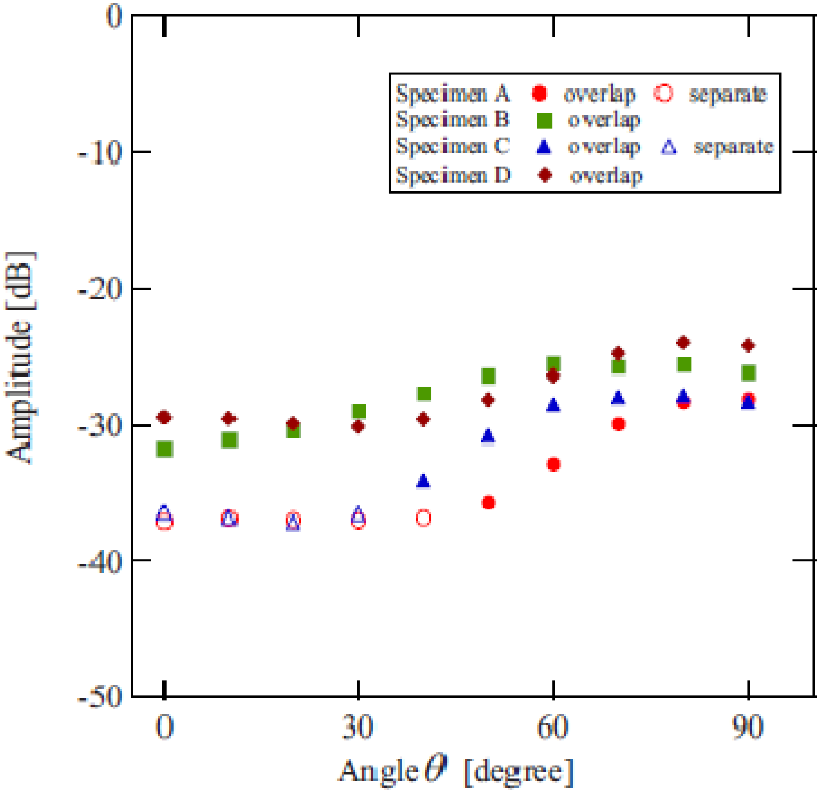
Time of flight surface transmission measurement

mechanical point excitation using shaker (one cycle at 4 kHz).
LDV point moved to different distances from excitation i.e. every 5 cm (position shown is 45 cm away from the excitation point)



Influence of bone anisotropy





Specimens A and C are more anisotropic than B and D