Ultrasonic spectrometry and modelling that verifies shear-wave reconversion in micro- and nano-fluids

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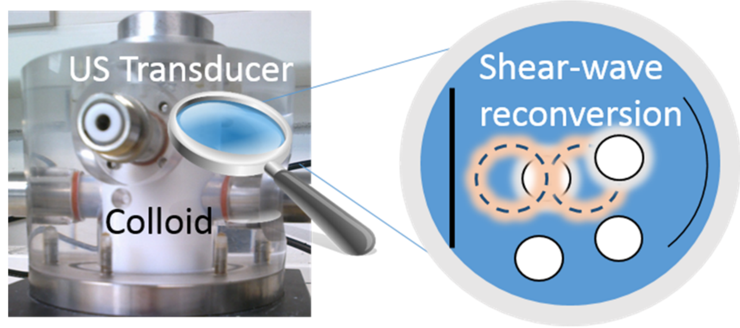
Introduction

We created an extended multiple scattering model: with inclusion of shear wave contributions



=> effective wavenumber[1,2]

Shear-waves in a suspension can reach neighbouring particles when,

- Particles approach the nanoscale
- Concentration increases

Thus, in addition to the incident compressional wave there is a shear-wave field and in proximity to other particles this can have a significant contribution to the effective wavenumber.

With this is mind we have derived a new form of the effective wavenumber, inclusive of shear wave effects

Theoretical model

Scattering coefficients:

$$T_1^{CC} = \frac{i(k_C r)^3(\hat{\rho}-1)h_2(k_S r)}{3D(k_S r)},$$

$$T_1^{CS} = -\frac{k_C r(\hat{\rho}-1)}{k_S r D(k_S r)},$$

$$T_1^{SC} = -\frac{2i}{3}(k_C r)^2 k_S r\frac{(\hat{\rho}-1)F(k_S r)}{D(k_S r)},$$

$$T_1^{SS} = -\frac{3j_2(k_s r)-2(\hat{\rho}-1)j_0(k_s r)}{D(k_S r)}, \quad b = 2r$$

$$F(k_S r) = h_2(k_S r)j_0(k_S r) - h_0(k_S r)j_2(k_S r)$$

$$Y_n = k_C b j_n'(k_C b)h_n(k_S b) - k_S b j_n(k_C b)h_n'(k_S b)$$

$$D(k_S r) = 3h_2(k_s r) - 2(\hat{\rho}-1)h_0(k_s r)$$

$$\hat{\rho} = \rho'/\rho$$

densities : dispersed silica (ρ') and a continuous phase (ρ)

k_C is the compressional wavenumber

Effective wavenumber:

$$\frac{K_{eff}^2}{k_C^2} = \left[\frac{K_C^2}{k_C^2}\right]_{LB} + \Delta_{CS}^{(2)} + \Delta_{CS}^{(3)},$$

$$\Delta_{CS}^{(2)} = -\frac{27i\phi^2}{(k_C r)^6}\frac{k_C^3 b}{(k_C^2-k_S^2)}T_1^{SC}T_1^{CS}X,$$

$$\Delta_{CS}^{(3)} = -\frac{81i\phi^3}{(k_C r)^9}\frac{k_C^6 b^2}{(k_C^2-k_S^2)^2}T_1^{SC}T_1^{CS}T_1^{SS}Y_0^2,$$

$$X = Y_0 + 2Y_2$$

compressional-compressional (T_1^{CC})

compressional-shear (T_1^{CS})

shear-compressional (T_1^{SC})

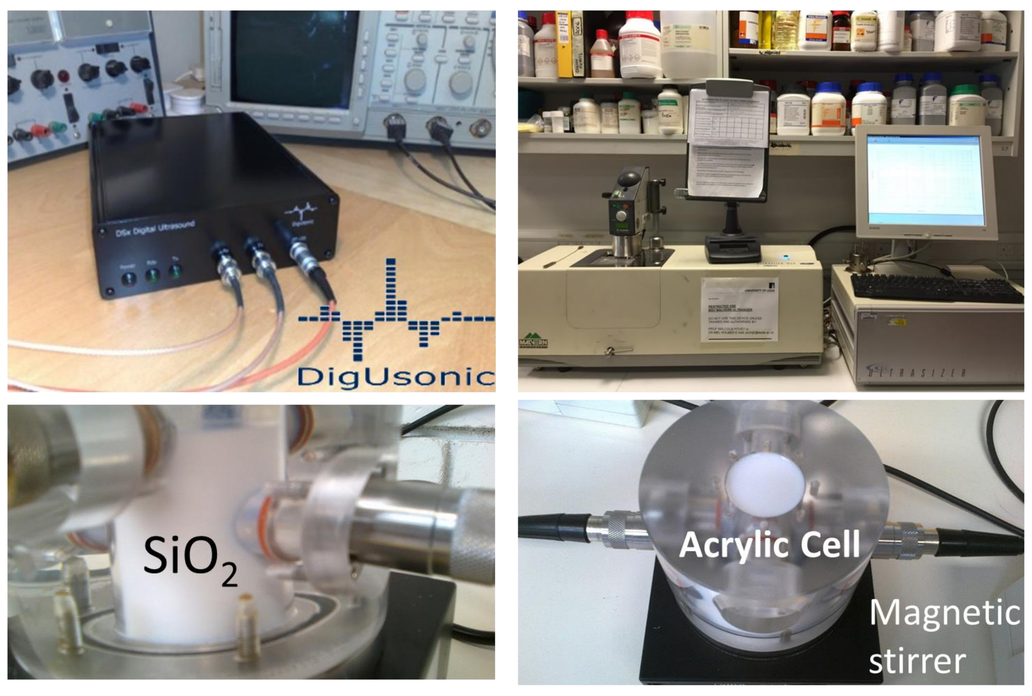
shear-shear (T_1^{SS})

$h_{0,2}$ and $j_{0,2}$ are spherical Hankel and Bessel functions

k_S is the shear-mode wavenumber

ϕ is the volume fraction

Ultrasonic Spectrometers and Samples



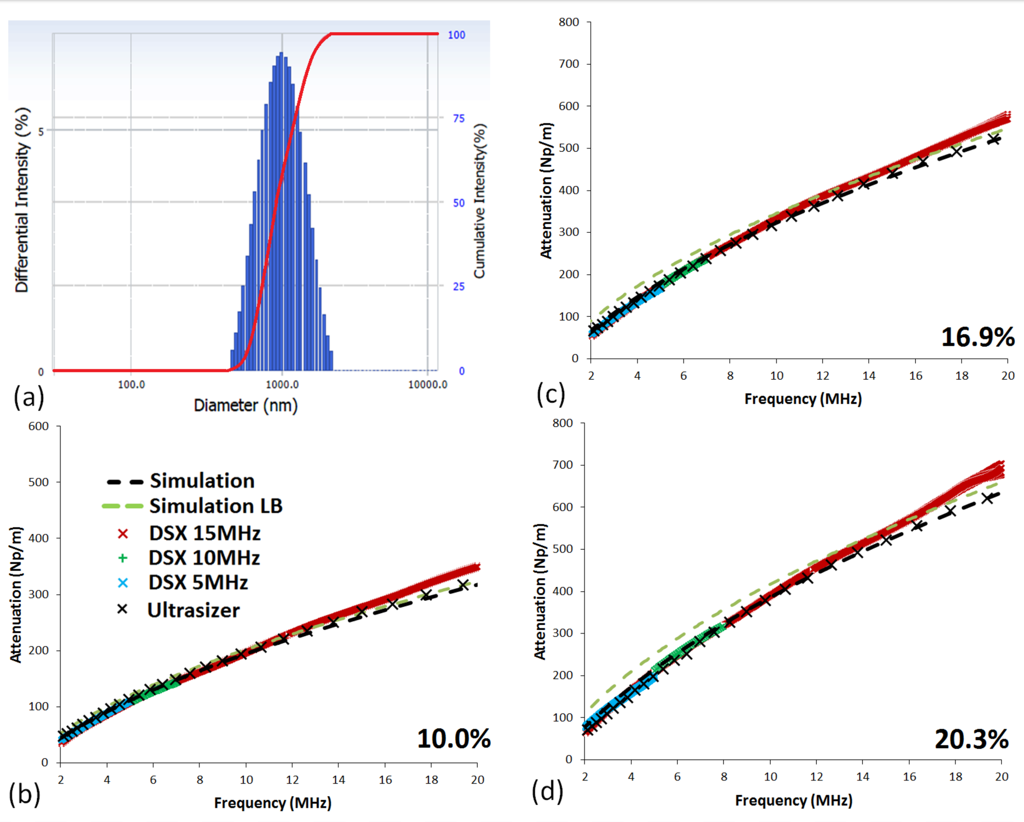
TWO TYPES OF ULTRASONIC SPECTROMETER USED:

Digusonic DSX (left)

And Ultrasizer (right)

15MHz
10MHz
5MHz

Attenuation: 1 micrometre diameter silica in water

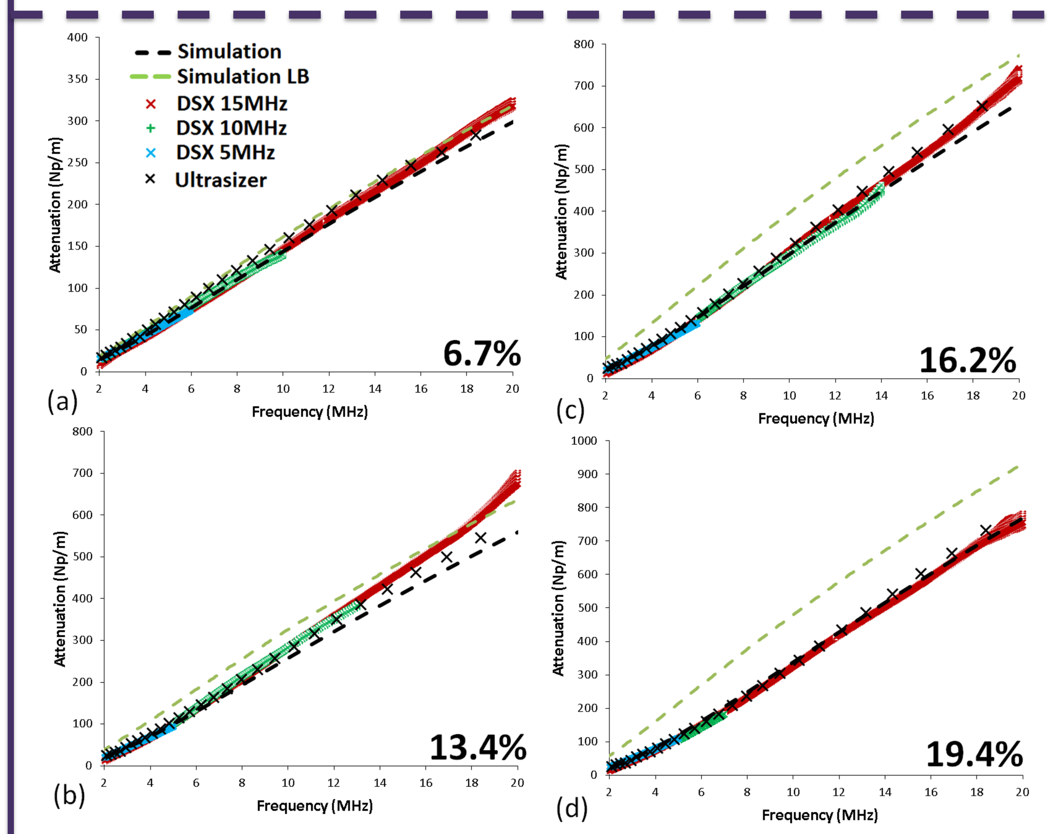


Lloyd/Berry model does not include shear wave re-scattering

Black dashed line: new shear mode reconversion model

Concentration: volume percent

Attenuation: 430nm diameter silica in water

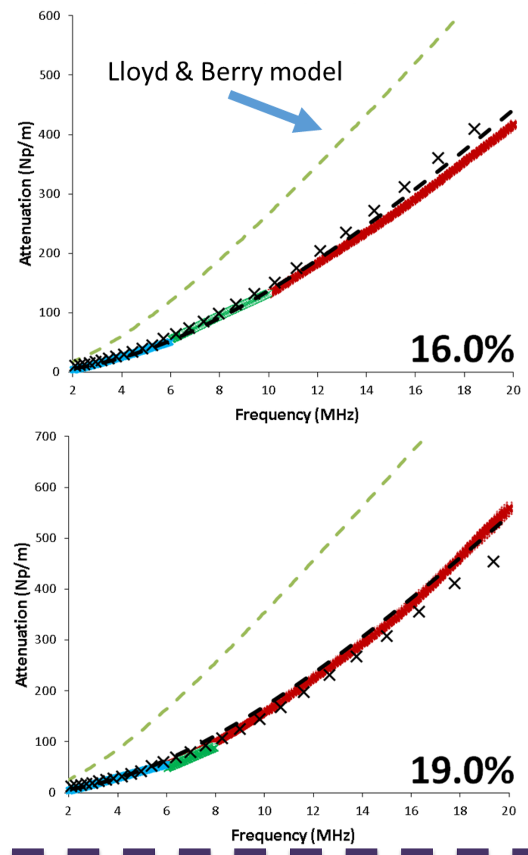


1 micron case, there was fairly close agreement between models

BUT

As particle size becomes smaller can we find shear wave effects? **Yes, through the attenuation spectra**

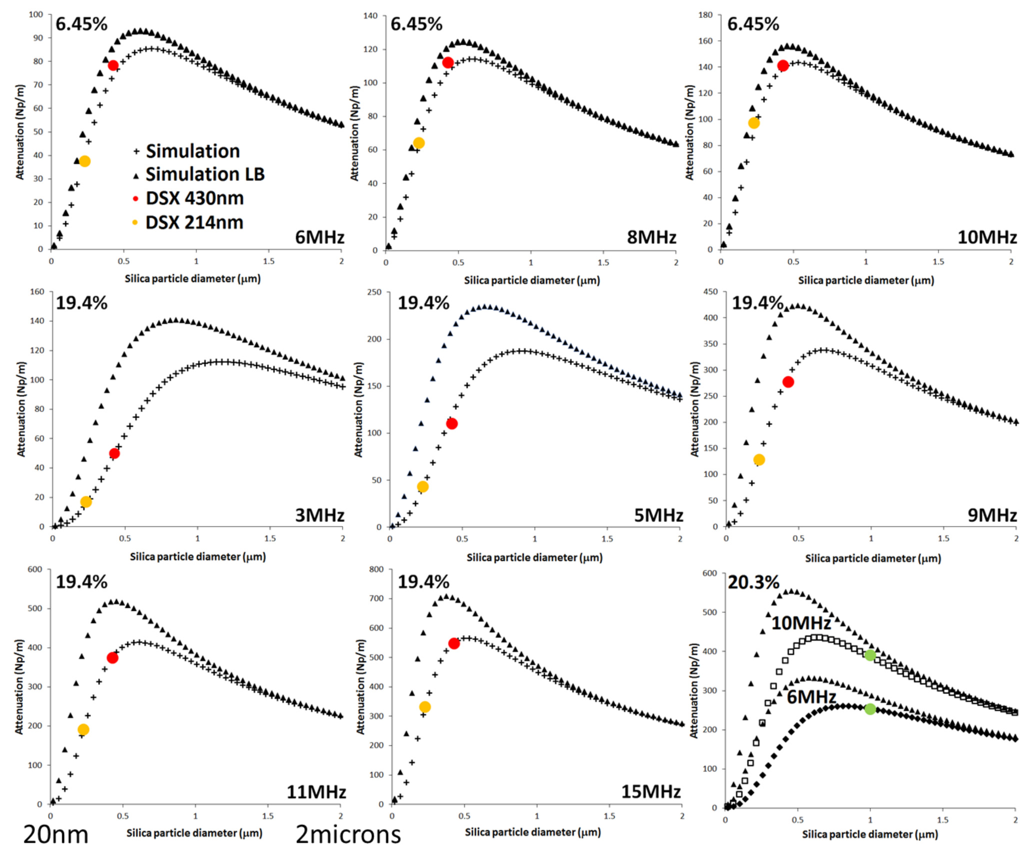
Attenuation: 214nm diameter silica in water

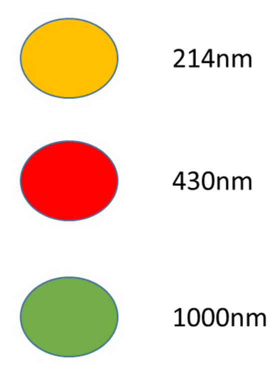


It is now clear that as particle size becomes smaller than 1 micron that shear wave effects begin to become very important in order to accurately match the true attenuation

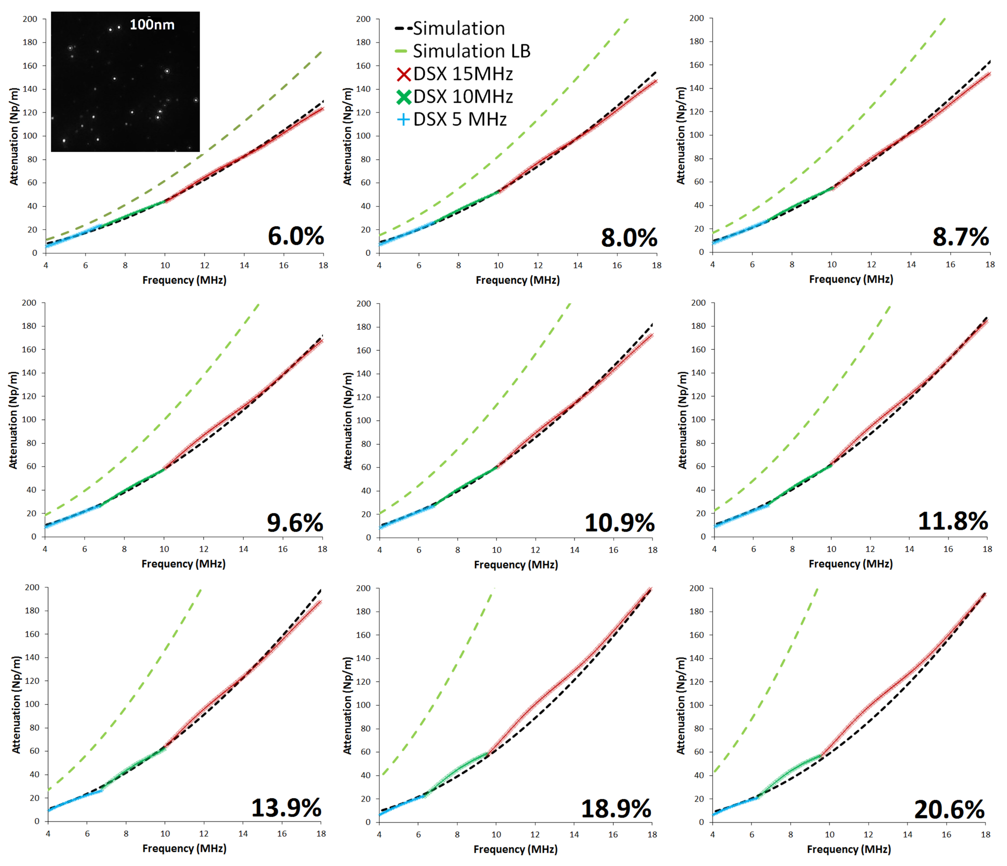
As concentrations increase the disparity between the models with and without shear waves becomes even greater.

Attenuation particle size dependency



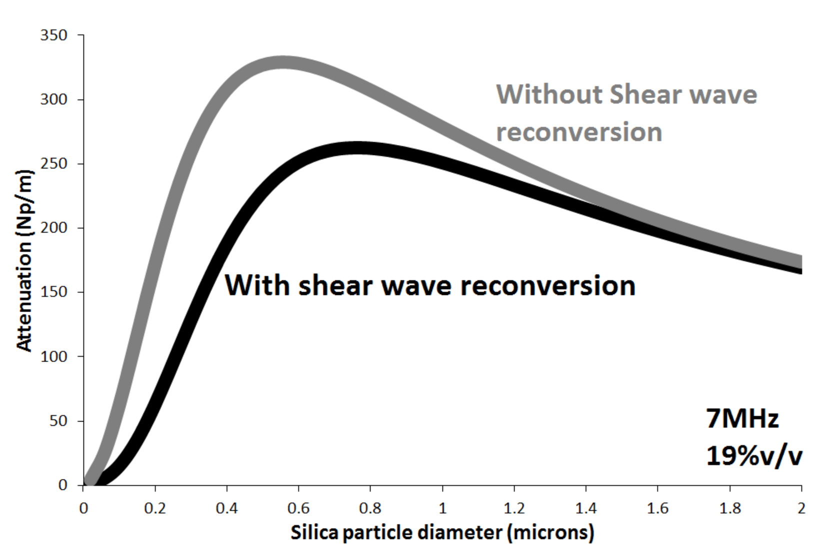


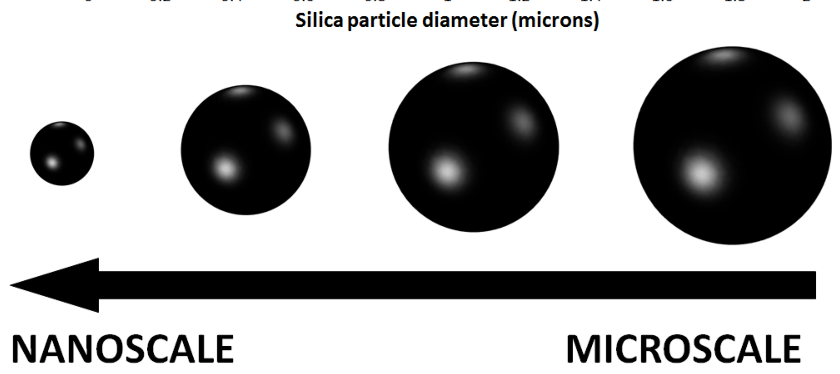
Attenuation: 100nm diameter silica in water

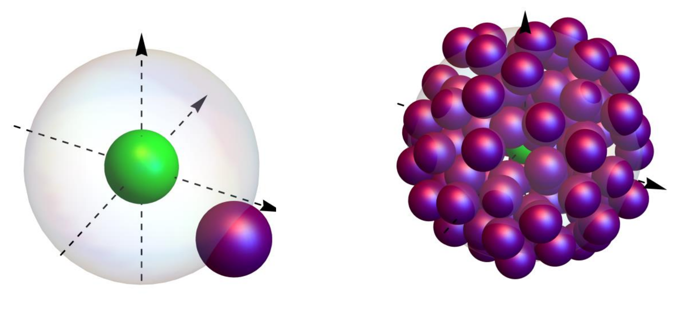


For technologically important nano-fluids, the effect is pronounced

Conclusions







- As we move to the nanoscale we must include shear wave effects in analyses of suspensions using ultrasound
- We have experimentally verified the phenomenon using two kinds of spectrometer
- The model is very good at the frequencies examined (up to 25MHz)
- We have focused on solid particles in suspension. Thermal waves also have a small effect.
- Within the range of a few shear wavelengths complex coupled particle effects emerge
- The shear effects are strongest near $k_S r$ equal to 1
- Ultrasound can even penetrate the most opaque of samples and consider them in their entirety (without dilution as in light scattering techniques).
- Thus, ultrasound spectrometry can be successfully employed for particle characterisation

REFERENCES

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2. F. Luppé, J. M. Conoir, A. N. Norris. *J. Acoust. Soc. Am.* 131, 1113-20 (2012).

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