

Investigation of nonlinear bulk viscoelasticity in complex media using dynamic acoustoelasticity

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Introduction

- ❖ Few tools have been developed for industrial quality control of textures. The use of non-contact techniques, based on acoustic waves, offers obvious advantages in food-processing or cosmetics industries : health & safety, non-destructive testing, continuous inline measurement.
- ❖ The Dynamic AcoustoElastic Testing (DAET) assesses the nonlinear viscoelastic properties of materials in response to a bulk compression/expansion stress. In this study, we present several applications of DAET method in complex media.

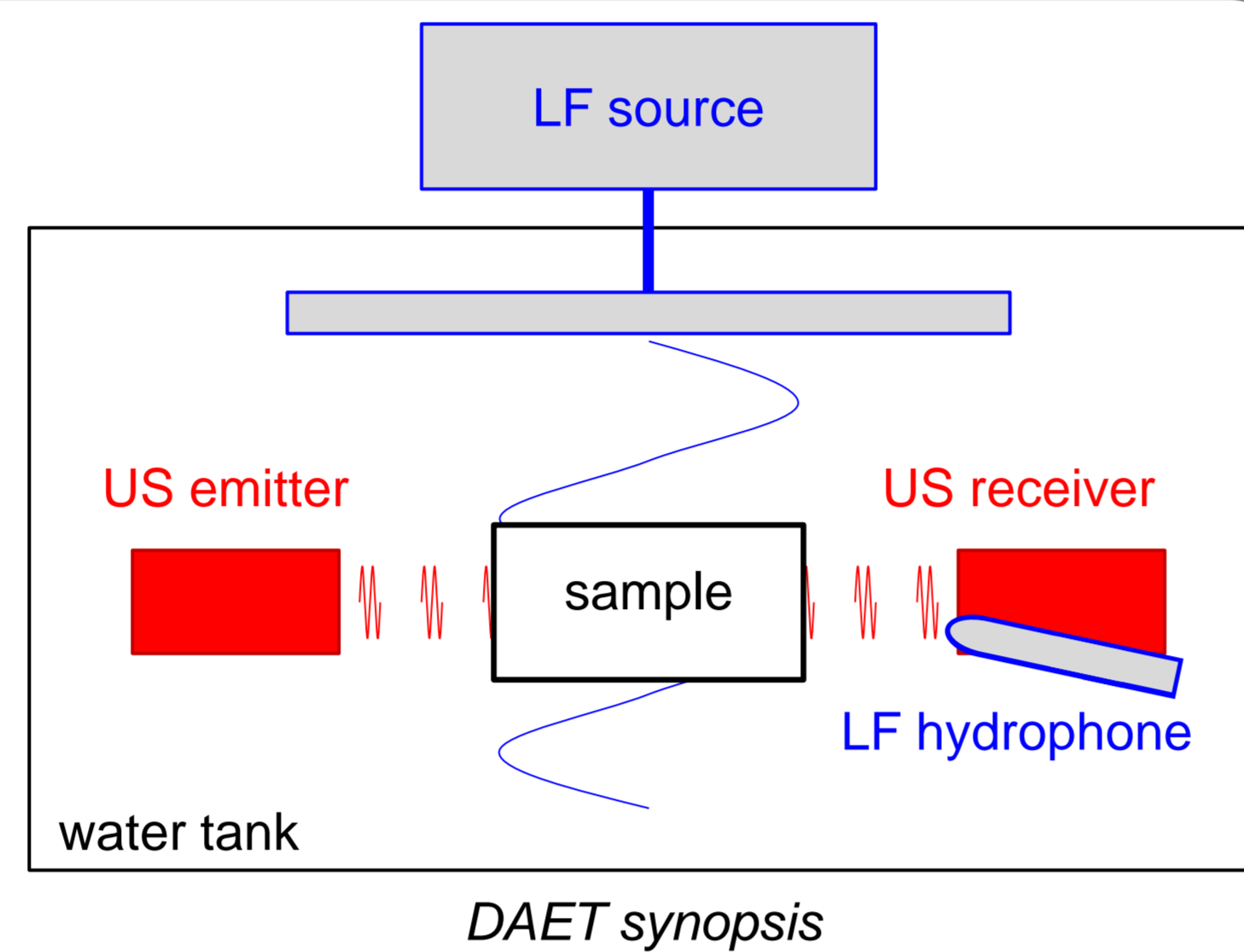
Keywords:

Non-contact
Acoustic rheology
Nonlinear viscoelasticity

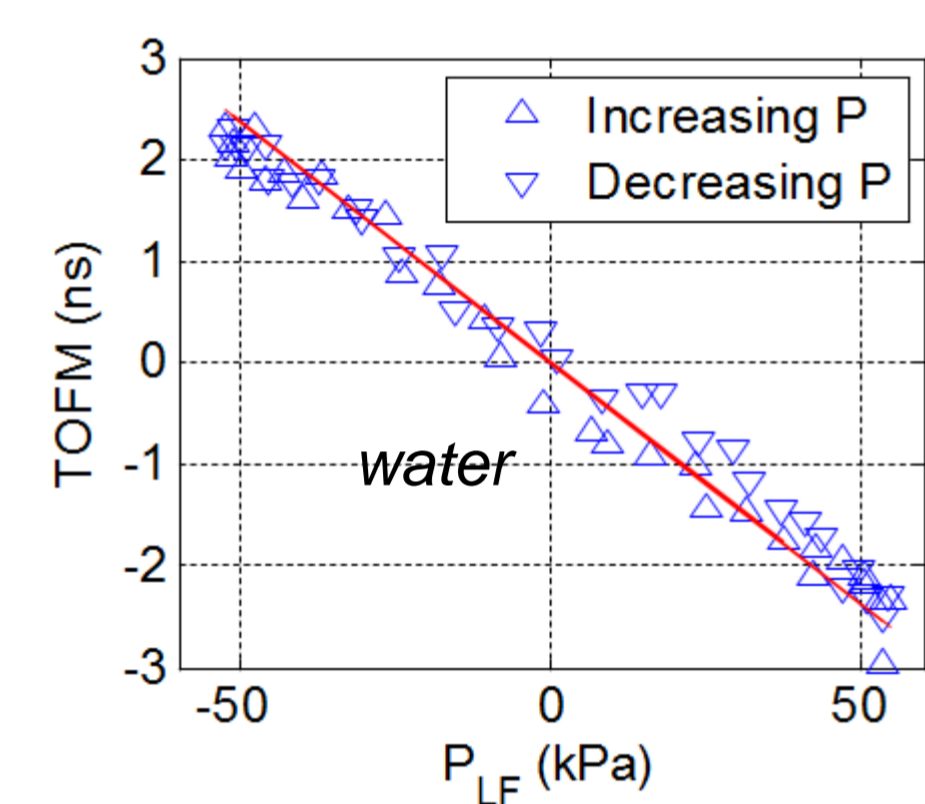
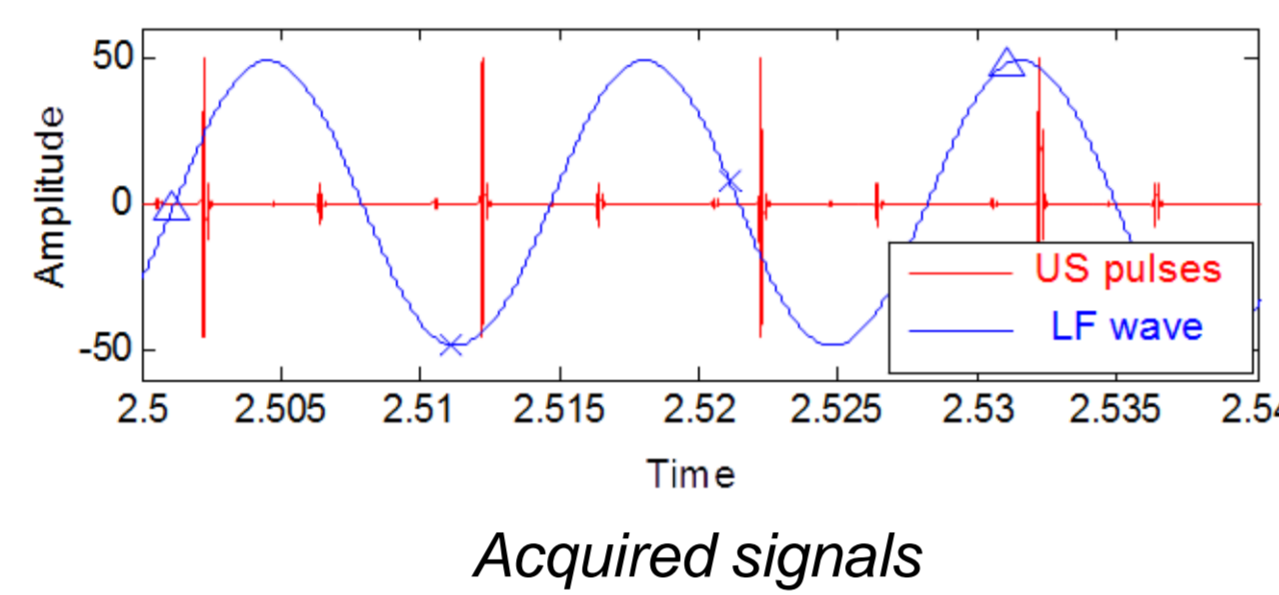
DAET method

❖ Interaction between two acoustic waves :

- Low-frequency sinusoidal wave (LF, 4kHz) to successively compress and expand the medium,
- Ultrasound longitudinal pulses (US, 1 MHz) to probe this medium at different pressure values imposed by the LF wave.



❖ Measurement of the Time of Flight Modulations (TOFM) of the US pulses, induced by the variations of the applied LF pressure: $TOFM = TOF_{P_{LF}} - TOF_0$



❖ DAET diagram: plot of TOFM as a function of LF pressure

$$\Rightarrow TOFM^* \approx -\frac{L}{c_0^2} \Delta c^* \approx -\frac{L}{2\rho_0 c_0^3} \Delta M^*$$

with c the celerity, L the length propagation, ρ the density and $M^* = \rho c^2$ the complex longitudinal modulus

Nonlinear viscoelastic parameters

$$M^* = A^* - B^* \varepsilon + C^* \frac{\varepsilon^2}{2} - \dots$$

$$\Rightarrow \Delta M^* = -B^* \varepsilon + C^* \frac{\varepsilon^2}{2} - \dots = -(B + j\omega\eta_B) \varepsilon + (C + j\omega\eta_C) \frac{\varepsilon^2}{2} - \dots$$

❖ From the measured TOFM, we identify nonlinear viscoelastic parameters:

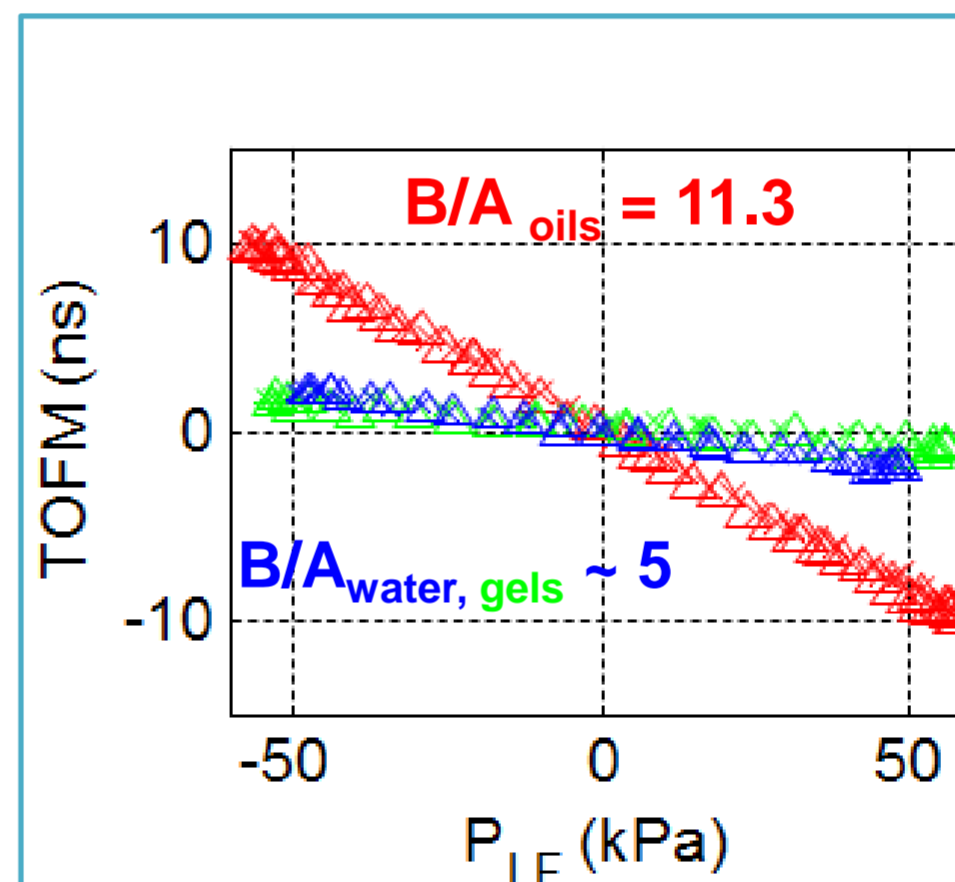
$$TOFM = -\frac{L}{2\rho_0 c_0^3} \text{Re} \left\{ \left(\frac{B}{A} + j \frac{\omega\eta_B}{A} \right) \Delta P + \left(\frac{C}{A} + j \frac{\omega\eta_C}{A} \right) \frac{\Delta P^2}{2A} \right\}$$

Elastic parameters (B/A , C/A)

Viscous parameters ($\omega\eta_B/A$, $\omega\eta_C/A$)

Validation in Fluids

HOMOGENEOUS MEDIA



Water, Carbomer gels, Silicon oils :

Low values of $B^* \Rightarrow$ homogeneous media

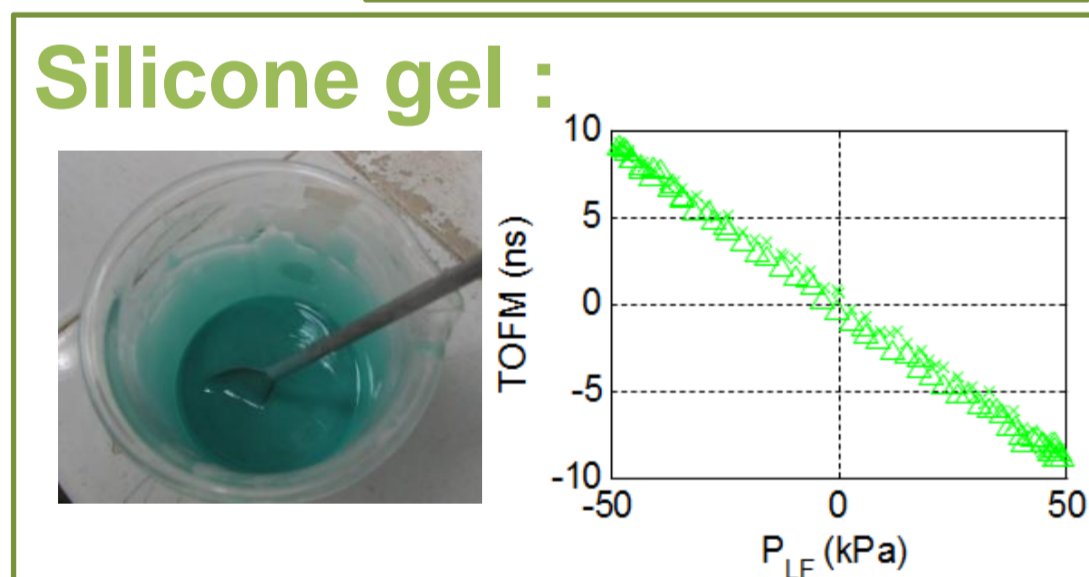
$$\frac{B}{A} < 15$$

$$\frac{\omega\eta_B}{A} < 1$$

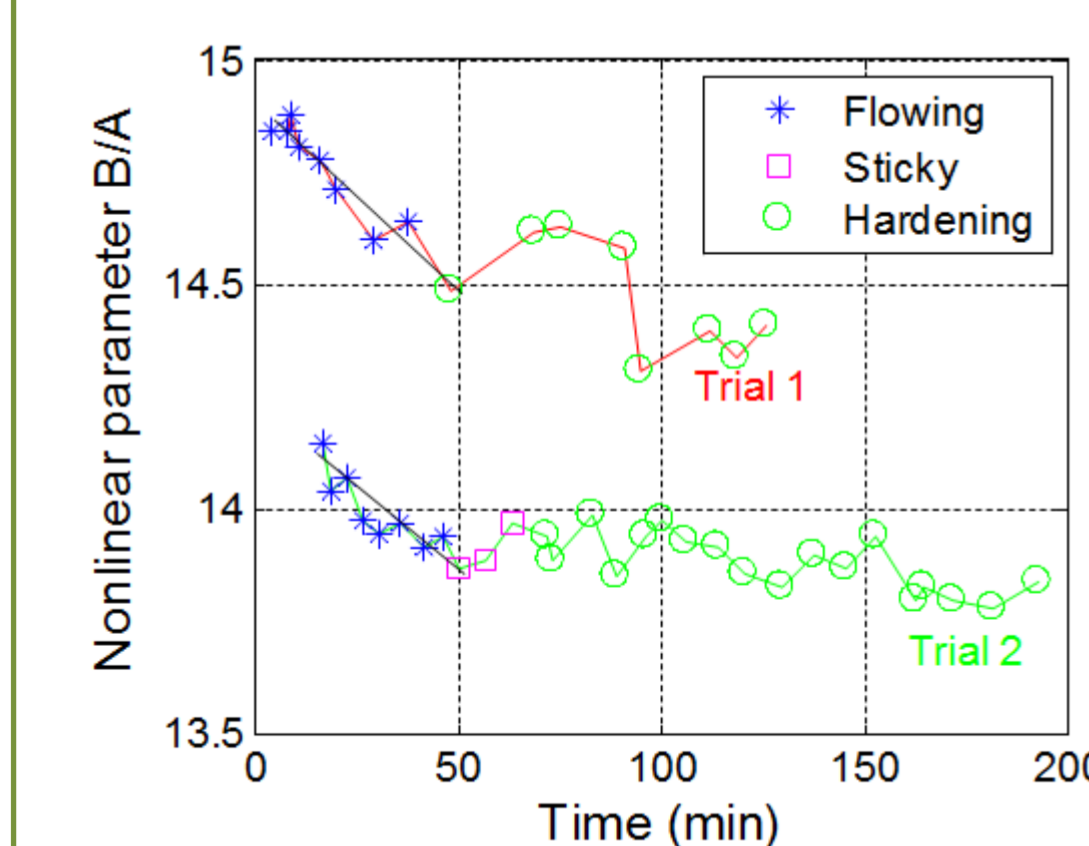
Governed by fluid nature

Results in Complex media

POLYMERIZATION

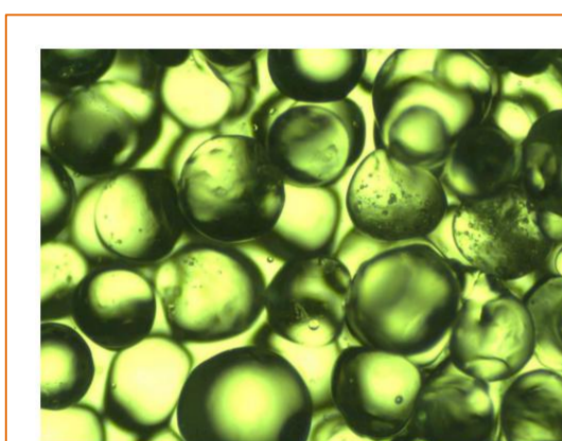


❖ Silicon hardening kinetics :
Gel time determination

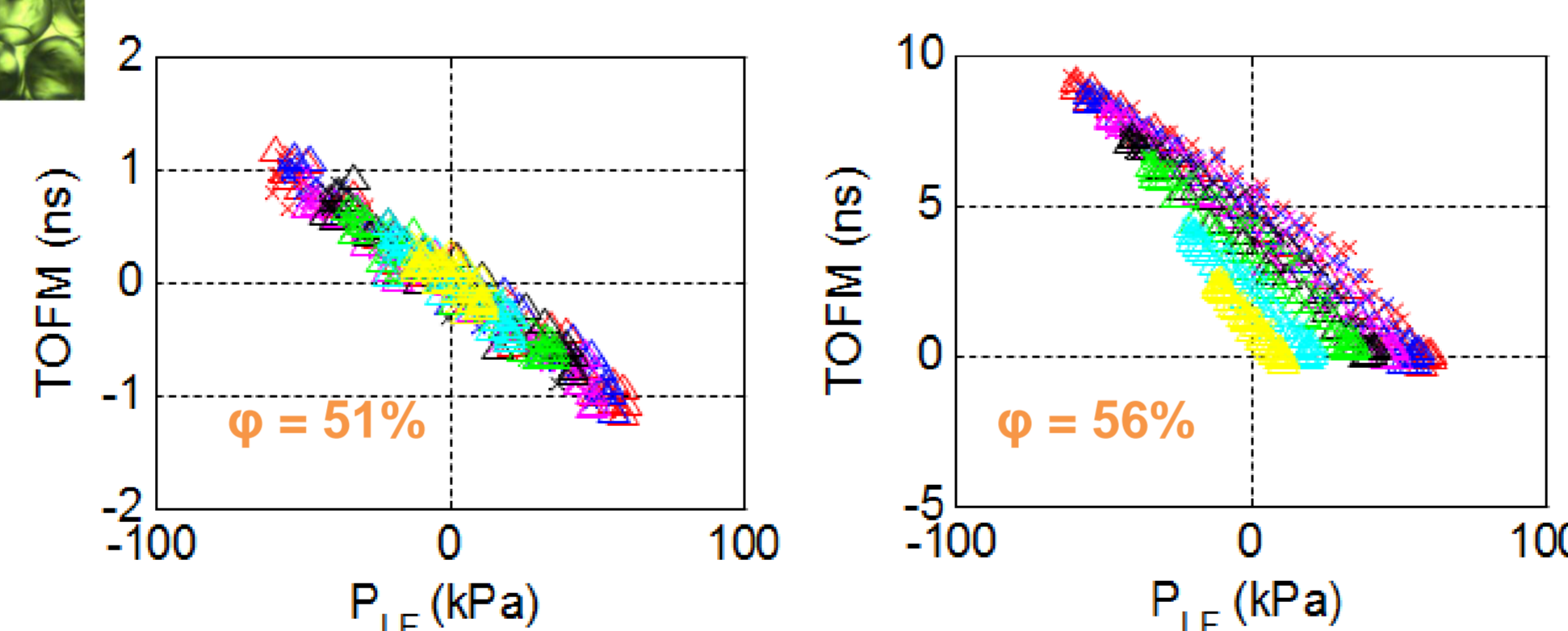


Governed by chemical bonds

GRANULAR MEDIA



250 μm glass beads in gelatin :



No beads contact (B^*)

Beads contact (B^* , C^*)

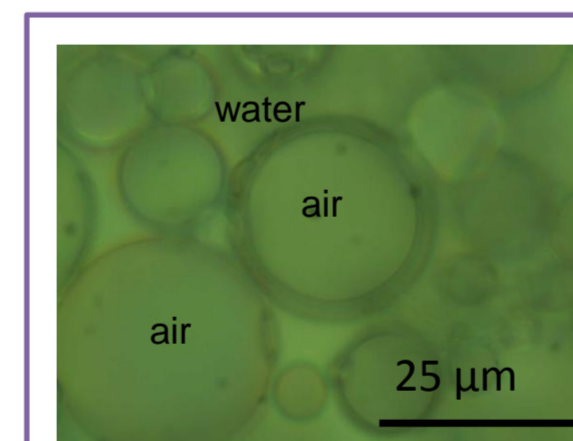
| | |
|------------------|----------------|
| B/A | $12,2 \pm 0,2$ |
| $\omega\eta_B/A$ | $-0,5 \pm 0,7$ |
| Offset (ns) | $0,0 \pm 0,1$ |

| | |
|------------------|---------------|
| B/A | 68 ± 13 |
| $\omega\eta_B/A$ | 14 ± 3 |
| $C/A (x10^6)$ | 2 ± 1 |
| Offset (ns) | $3,9 \pm 1,1$ |

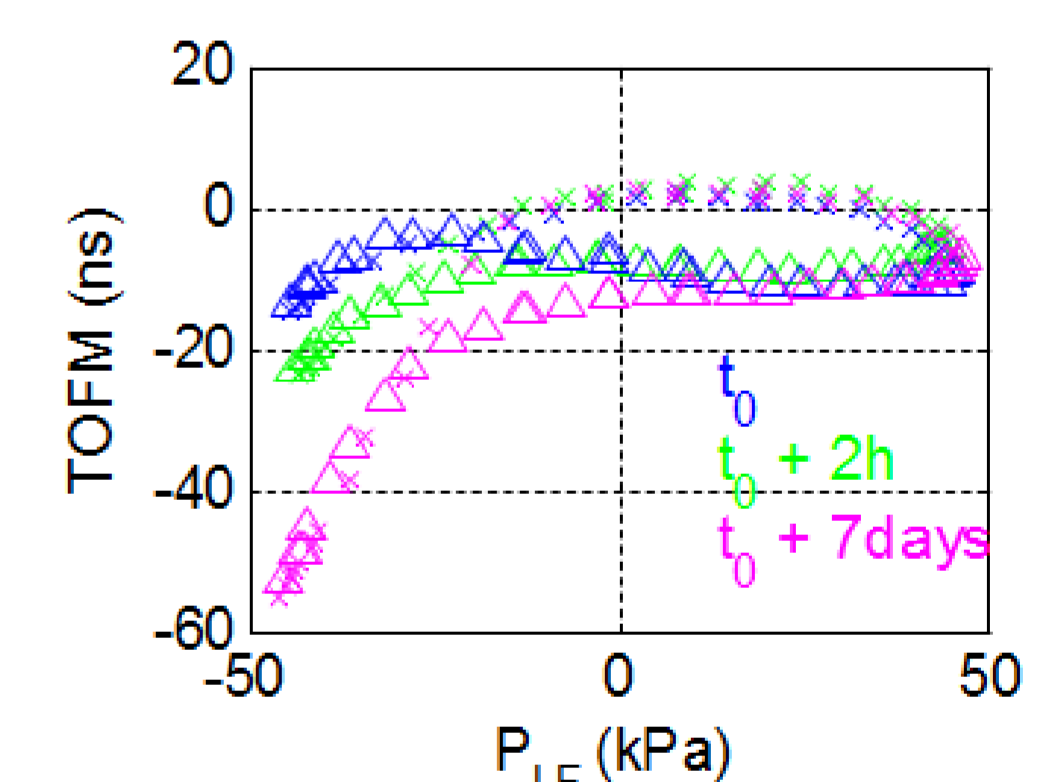
❖ Sensitivity to a percolation threshold

Governed by beads contact

AIR-BASED MEDIA

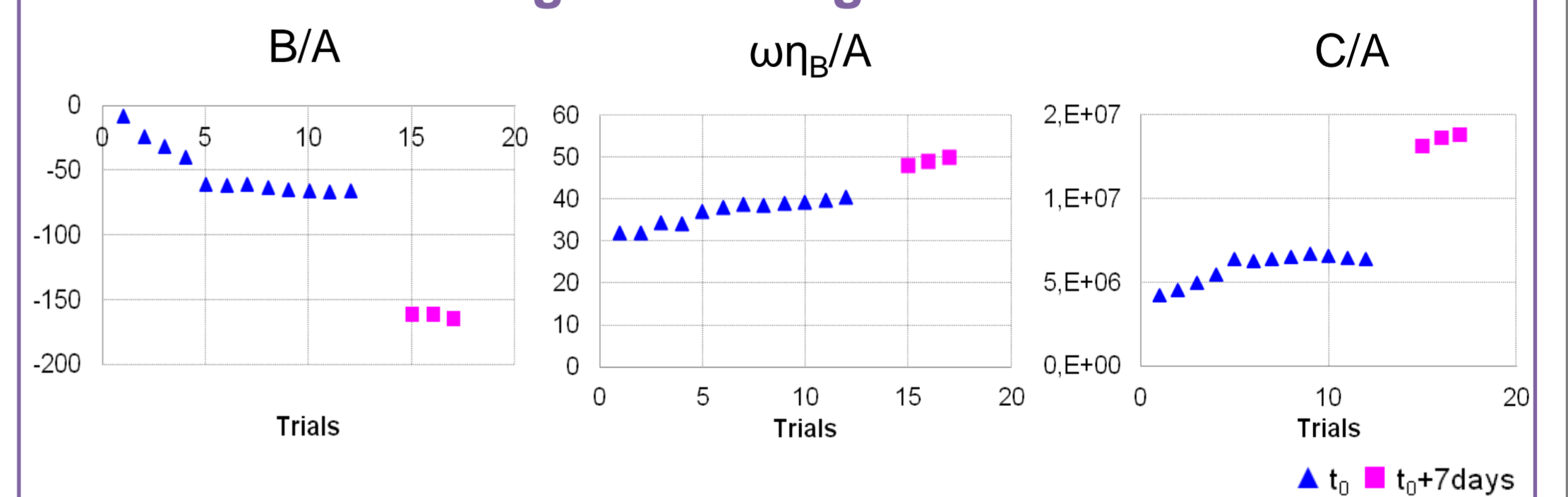


Hollow glass beads in water :



❖ High values of B^* , C^* and D^*
 \Rightarrow air presence

❖ Efficient creaming monitoring :



Governed by air and beads contact

Conclusion and perspectives

- ❖ The DAET method measures with a good reproducibility the variations of the bulk viscoelastic modulus, through the quantification of nonlinear elastic and viscous parameters.
- ❖ Homogeneous fluids exhibit classical viscoelastic nonlinearities (1st order B^*) and complex media nonclassical viscoelastic nonlinearities (until 3 orders B^* , C^* , D^*).
- ❖ This method appears to be an interesting alternative to conventional rheometry, especially for the characterization of these complex fluids.
- ❖ A similar work has to be done on the RAM data related to an attenuation of US pulses (thanks to a nonlinear Kramers-Kronig relationship ?...)