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## Can Microcantilevers Probe the High-frequency Viscoelastic Properties of Fluids?

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### Abstract

Vibrating microcantilevers are used as microrheometers to investigate the high-frequency viscoelasticity of 20-cP silicone oil. This fluid exhibits a surprisingly pronounced viscoelasticity at high frequency with moduli in the range of  $10^2$ - $10^5$  Pa.

**Introduction** Viscoelastic materials, such as mayonnaise and ketchup, are time-dependent and exhibit both elastic and viscous characteristics when undergoing deformation. However, viscoelastic effects also exist in Newtonian liquids (e.g., water) under special conditions of measurement, such as very high frequencies [1]. Such a high-frequency range (on the order of kHz) cannot be reached using conventional mechanical rheometers. For example, water has been proved to be a Newtonian fluid only over the rheometer frequency domain ( $<200$  Hz). Recently, AFM provided highly accurate measurements of the hydrodynamic interaction between a fluid and the probe [2]. Belmiloud et al. [3] proposed an analytical model based on a simplified hydrodynamic function [4] to estimate the viscosity using a vibrating silicon-based microcantilever. This non-destructive method overcomes the limitations on the frequency range introduced by mechanical rheometer use.

For the first time, we present here extended analytical equations based on the approach introduced previously [3] to calculate the viscoelastic moduli (the elastic,  $G'$ , and viscous,  $G''$ , moduli) over a large frequency range. Silicone oils are usually used as a model for Newtonian fluids. Here, a rheogram of 20-cP silicone oil over a frequency range of 0.001-100 kHz is shown and follows the development of the viscoelasticity with the frequency.

**Method** Out-of-plane dynamic spectra of microcantilevers (provided by LAAS, Toulouse) with different dimensions ( $L \times b \times h = 1430 \times 285 \times 20 \mu\text{m}^3$  and  $500 \times 100 \times 20 \mu\text{m}^3$ ;  $L$ ,  $b$ , and  $h$  are the length, width and thickness of the microcantilever) immersed in a 20-cP silicone oil (Sigma Aldrich) have been measured using a Scanning Laser Doppler Vibrometer (MSA-500 Micro-System Analyzer from Polytec).

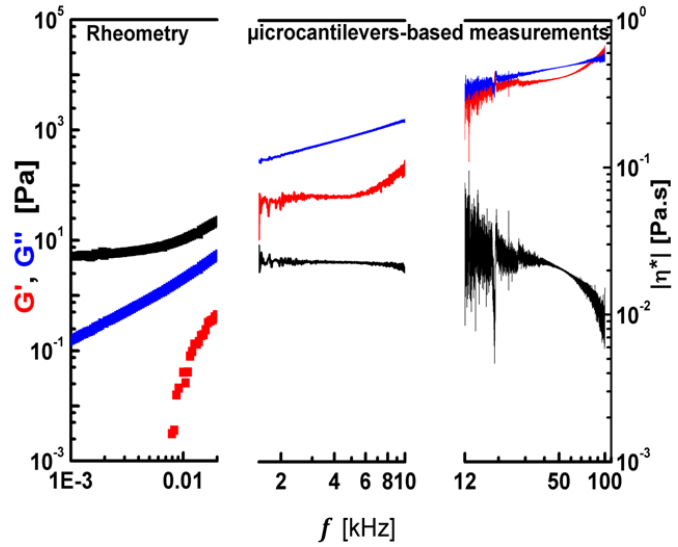
The model introduced by Belmiloud et al. [3] is based on  $G'$  tending to zero. However, the 20-cP silicone oil has a measurable  $G'$  at low frequencies (Fig. 1). Thus, the following new equations [5] for the estimation of the viscoelastic moduli, which take into consideration the importance of elastic behavior of the fluids, are required:

$$G' = \frac{[D(\underline{g}_2\omega - C) + B^2]Z - B\underline{g}_1}{D^2Z} \quad G'' = \frac{\underline{g}_1 - BZ}{D}$$

$$\text{where } D = \frac{\pi b_2}{2\omega}, \quad B = \frac{\pi b b_1 \sqrt{\rho_f}}{2\sqrt{2}}, \quad C = \frac{\pi \rho_f b^2}{4} \omega, \quad Z = \sqrt{\frac{-(B^2 + 2D(\underline{g}_2\omega - C)) + \sqrt{(B^2 + 2D(\underline{g}_2\omega - C))^2 + 4D^2 \underline{g}_1^2}}{2D^2}}$$

The fluid density ( ) has to be known to calculate the elastic ( $G'$ ) and viscous ( $G''$ ) moduli over the angular frequency ( $\omega$ ), where  $\underline{g}_1$  and  $\underline{g}_2$  are related to the imaginary and real parts of the hydrodynamic function, and  $b_1$  ( $=3.8018$ ) and  $b_2$  ( $=2.7364$ ) are Maali's parameters [4].

**Results and Discussion** Figure 1 shows the development of viscoelasticity of 20-cP silicone oil over a large frequency range ( $10^{-3}$ - $10^2$  kHz). The material behaves as a viscoelastic liquid since  $G''$  always predominates  $G'$ . At ca 85 kHz, a  $G''$ - $G'$  crossover is seen to occur, beyond which the material is a viscoelastic solid ( $G'' < G'$ ). Concomitantly, the complex viscosity  $|\eta^*|$  is independent of the frequency until the crossover frequency where the viscosity begins to decrease exhibiting non-Newtonian (shear-thinning) behavior. The behaviors of moduli in the ranges 20-1500 Hz and 10-12 kHz are not shown because we have yet to fabricate cantilevers with specific dimensions to cover these frequency ranges.



**Fig. 1.** Variation of the elastic ( $G'$ ) and viscous ( $G''$ ) moduli of 20 cP silicone oil over large frequency range -at 19°C: the low- $f$  data are obtained by rheometer, the intermediate and high- $f$  data are calculated by our equations using two cantilevers:  $1430 \times 285 \times 20 \mu\text{m}^3$ , and  $500 \times 100 \times 20 \mu\text{m}^3$ , respectively.

**Conclusion and Perspective** Vibrating microcantilevers can be used to probe the high-frequency viscoelastic behavior of fluids. However, the results are sensitive to some parameters in the analytical model [6], a point which is under investigation and will appear in a future work.

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