A mechatronic shearing device : Piezorheometer

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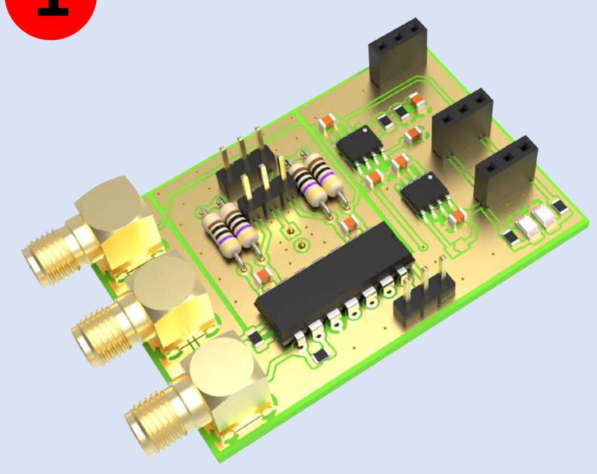
Description

This prototype rheometer is specifically designed to finely analyze the mechanical behavior of materials under controlled deformation. It is built around two opposing stacks of piezoelectric crystals: one applies mechanical deformation while the other accurately measures the material's response. The sample is confined between two glass slides, each fixed to one piezo stack.

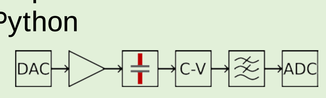
Moreover, a larger amplitude piezoelectric device is used to apply deformations in 1 µm increments up to 100 µm, so-called preshear, gradually bringing the sample into a plastic deformation regime. This deformation induces anisotropy of the sample. Once this state is reached, a small shear deformation (~100 nm) is applied to probe the material's elastic behavior. The resulting shear modulus, G', measured along any direction relative to the preshear, is normalized by a reference modulus G_0 measured without prior deformation. The G'/G_0 ratio highlights the impact of plastic pre-conditioning on material stiffness.

1



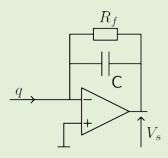
Control:

- Generation of arbitrary waveforms for the excitation piezo
- Acquisition on NI board using Python



Charge-to-voltage converter:

- Output voltage proportional to charge
- Operational amplifier with low input current
- Very high leakage resistance
- Low cutoff frequency



$$f_c = \frac{1}{2\pi R_f C}$$

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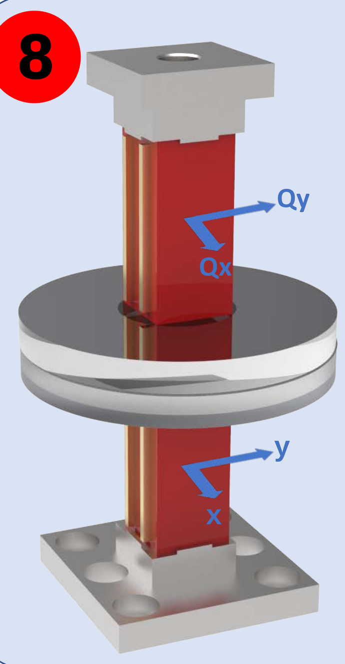

Sample cell:

The sample cell consists of two metallized glass disks (Edmund Optics Ø40x3, 4–6λ), each bonded with epoxy to a multilayer piezoelectric actuator (P.I. PICMA Plus Stack, travel range 0–5 µm, resolution 1 nm). Bonding is performed within a jig to ensure perpendicularity and parallelism within 0.01 mm. The internal surface is textured by sandblasting, achieving a surface roughness of Ra 0.5–1.6. The lower cell acts as the displacement generator, while the upper cell serves as the measurement probe.

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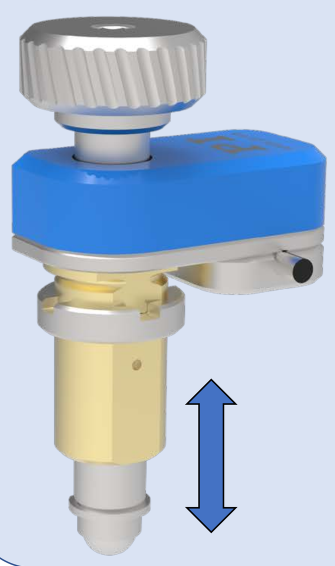

Parallelism control:

Piezoelectric micromotors (P.I. N470.12VY) with a 7 mm stroke and 20 µm precision enable fine adjustment of the sample cell's parallelism and gap, following the three position measurements taken using the CSH05FL-CRm1.4 capacitive sensors (see below)

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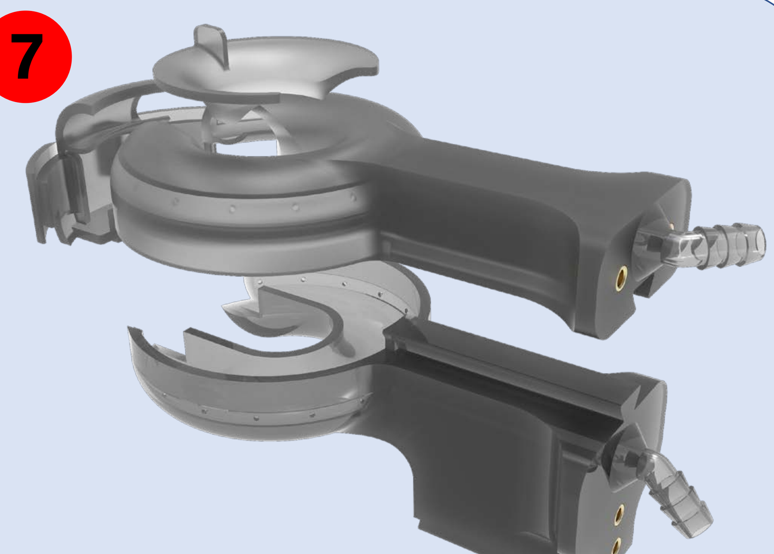

Environment control:

To prevent evaporation of the aqueous fraction of the sample, this four-part enclosure made of PETG using FDM 3D printing is equipped with channels that diffuse air at 80% humidity near the sample, under low pressure and flow rate. It is retractable to allow for sample insertion and also for performing measurements and adjusting the tilt of the upper part of the piezorheometer.

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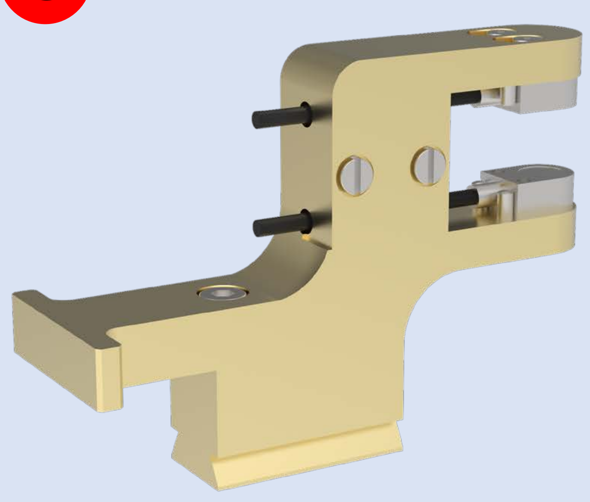

Parallelism measurement:

This component, equipped with two capacitive sensors (Micro-Epsilon CSH05FL-CRm1.4), enables precise measurement of the position of the glass discs that form the sample cell at three positions spaced 120° apart. This allows for adjustment of the disc parallelism with 0.01% accuracy, as well as setting the inter-disc gap to 100 µm ±1 µm.

6

Noise control:

The enclosure, made from 8 mm thick high-density MDF panels inserted into aluminum profile grooves (30x30), and lined with acoustic foam, serves to isolate the piezorheometer from airborne noise. It is also equipped with a multi-cable feedthrough (Ikotek 4824) to route power and control cables to the outside of the enclosure.

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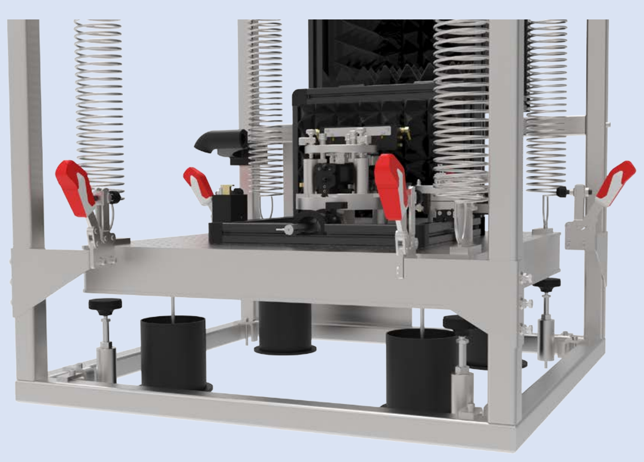

Vibrations control:

To isolate structure-borne noise: suspension using four high-deflection spiral springs (Ø = 65 mm, L_0 = 584 mm, L_1 = 1200 mm, k = 0.112 N/mm) isolates the optical breadboard on which the piezorheometer is mounted. Damping of the springs is achieved using four cylinders (Ø = 40 mm), each immersed in a reservoir filled with silicone oil (µ = 5 Pa·s at 25°C). This creates a low-pass filter with a cutoff frequency of 3 Hz

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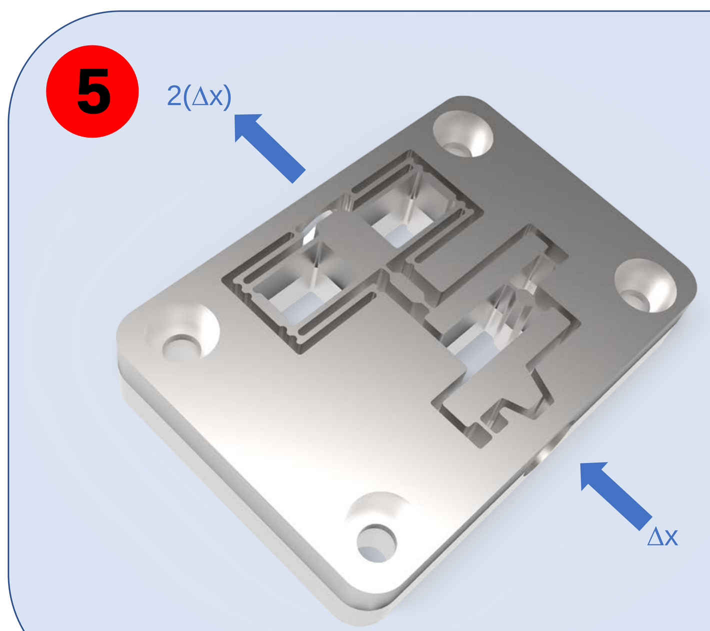

Compliant part (stroke doubling) :

This compliant part (EDM-machined) doubles the apparent stroke (190 µm → 400 µm) of the piezoelectric shear actuator (PSt150-10-200 VS15 Preloaded Linear Actuators) thanks to double-lever amplification. However, the precision is reduced by the same factor, resulting in a step resolution of 2 µm.

Results

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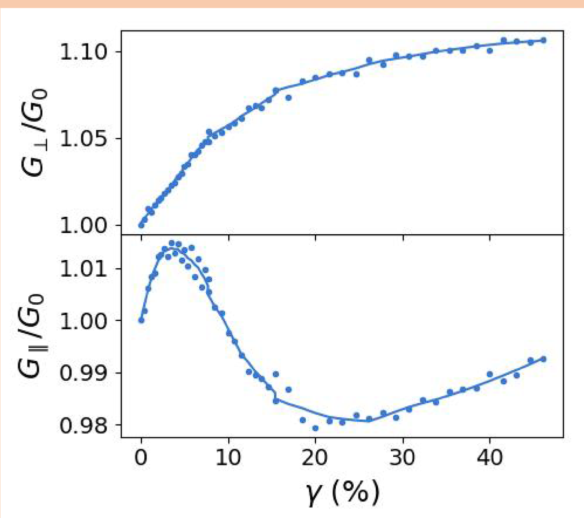

The device allows to measure the anisotropy of the linear response of the material as a function of the preshear amplitude.

The system under study is a concentrated emulsion of oil droplets in water, at a volume fraction ϕ=70%.

The evolutions of the apparent elastic modulus in the direction parallel to the preshear direction (bottom graph), and normal to it (top graph), as a function of the preshear amplitude, are represented : the emulsion becomes softer along the direction of the preshear, while its elastic modulus increases along the normal direction.

References

[1] N.Beyer, L.Engel, B.Michel, and P.Hébraud*, *Soft Matter* **2025**, *21*, 8919–8925

[2] Thanasis Athanasiou, Günter K. Auernhammer, Dimitris Vlassopoulos, George Petekidis. *Rheologica Acta* **2019**, *58*, 619-637

[3] Frederic Blanc,Francois Peters, Jurriaan J.J. Gillissen, Michael E. Cates, Sandra Bosio, Camille Benarroche, and Romain Mari, *Phys.Rev.Lett.,* 130, 118202, **2023**

[4] B. Schroyen, J. W.Swan, P. Van Puyvelde and J. Vermant, *Soft Matter*, **2017**, *43*

[5] Gero L. Hermsdorf , Sven A. Szilagyi , Sebastian Rösch , Erik Schäffer. Rev.Sci.Instrum. **2019**, *90*, 015113,