Understanding the Dynamic Response of Soft Materials in the Ultrasonic Range Using the IBUS Test

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Abstract. In this contribution, we present a study on dynamic properties of soft materials in the ultrasonic regime (20 kHz). An Image-Based Ultrasonic Shaking (IBUS) test is employed to measure visco-elastic properties of Polydimethylsiloxane (PDMS). The specimen is subjected to ultrasonic vibration at 20 kHz and the resulting deformation is recorded with a combination of ultra-high speed imaging and digital image correlation. The dynamic moduli are compared against the reference quasi-static data.

Introduction

High-power ultrasonic cutting tools have a potential to improve many surgical procedures. Compared to standard power cutting tools, they offer better precision, reduce blood loss through haemostasis and potentially can facilitate healing through ultrasonically mediated regeneration. The cutting mechanism for soft tissue relies on coaptation and coagulation through cavitation induced by the oscillating device [1].

Finite Element Analysis could be used to produce better understanding of the exact mechanical response of soft tissues under dynamic loading combining tool-driven ultrasonic excitation with pressure fields originating from cavitation. To build such models, a detailed understanding of dynamic behaviour of soft tissues is necessary. Tissues such as brain, cartilage, muscle or organs are well known to be highly sensitive to the rate of applied loading [2], but the mechanical properties at ultrasonic regime, that are available in the literature, are limited to very high frequencies (> MHz), typical of imaging scenarios, rather than power ultrasonics which reside in 20-55 kHz range.

In this contribution, we apply the Image-Based Ultrasonic Shaking (IBUS) test [3] to measure the viscoelastic properties of Polydimethylsiloxane (PDMS), including the storage and loss moduli. In short, a video of the vibrating specimen is recorded using an ultra-high speed camera (Shimadzu HPV-X) at the rate of 1 MHz and the recorded images are processed with digital image correlation (DIC) to calculate strain and accelerations fields from which material properties are extracted in a contactless manner.

Methods

A PDMS specimen is prepared using commercial silicone (Sylgard 184, Dow) by mixing the base and curing parts in 10:1 ratio. A white silicone pigment (Mouldlife) is added to the mixture to make the specimen opaque. The mixture is then thoroughly mixed and degassed in a desiccator under vacuum for 30 min until no bubbles are present in the bulk. The mixture is then poured into laser-cut moulds, forming 15 x 5 x 2 mm specimens. The moulds are then transferred to an oven and kept at 60°C for 4 hours. Before performing the experiments, the specimens are decorated with a random DIC pattern, by using a microcontact printing technique and oil-based ink (Archival, Jet-black).

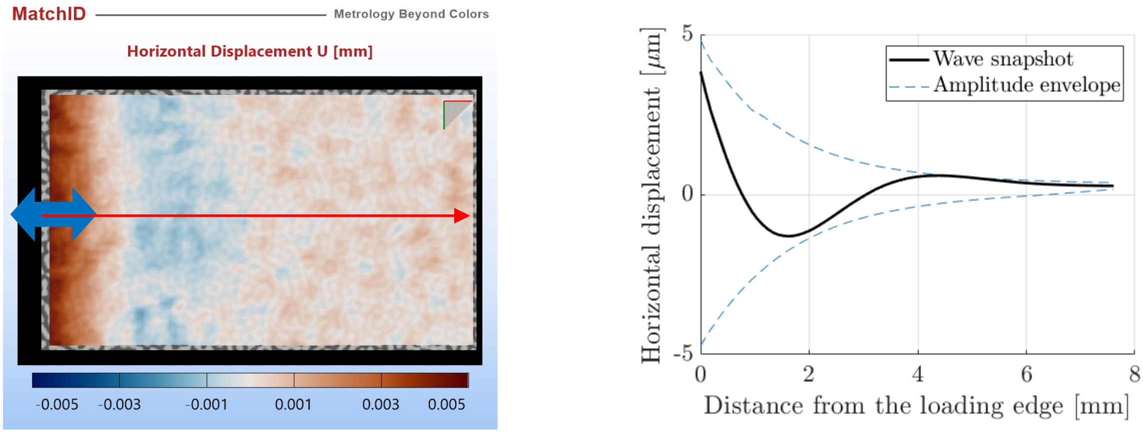
The specimen was glued to a sonotrode (SinapTec NexTgen) using a cyanoacrylate glue (Loctite, 431). The sonotrode operates at 20 kHz with controllable amplitude in the range of 2-40 µm. The oscillating specimen was observed with an ultra-high speed camera (Shimadzu HPV-X) recording the surface of the specimen at 1 MHz. Importantly, due to the small shape of the specimen, a magnification of over x1.0 was necessary, which was realised with high-magnification lens (12X, Navitar), while the appropriate lighting was achieved by employing a pulsed laser synchronised with the camera acquisition. The other side of the specimen was observed with an IR quantum detector (Telops M3k) to record the temperature increase due to viscous dissipation of ultrasonic energy.

The greyscale images captured by the camera are then processed with DIC, and strain and acceleration fields are derived from the displacement fields. These are then used in the IBUS analysis to produce average stress vs strain in each section of the specimen. The two time series are then fitted with a sine function and viscoelastic properties are calculated from the relative amplitudes and the phase shift between the two.

Results

In the first stage of the experiment, a finite element model of the test was built, based on preliminary data available [4]. This model can be used to optimise the optical system of the designed experiment. The preliminary results indicated a significant attenuation of the traveling wave, with approximately 90% attenuation of the strain amplitude in 4 mm of travel.

The finite element model informed the image deformation analysis, where synthetic DIC images are produced by deforming a speckle pattern according to the known displacement fields. This process is invaluable as it enables tracking the performance of the experimental measurements, such as necessary spatial and deformation resolutions. One of simulated images is presented in Fig. 1 (a), where the left-hand side of the specimen is subject to ultrasonic excitation. The displacement field was extracted along the red arrow to show the profile of the traveling wave and the amount of attenuation (Fig. 2 (b)). The processed fields were then used to reconstruct the stress-strain curve, which shows a lot of dissipation (Fig. 2), as expected from the data used to produce the model.



(a) (b)

Fig. 1 (a) Simulated displacement field as seen through the DIC filters. The blue arrow indicates the application ultrasonic vibration, the red arrow shows from where displacement fields were extracted from. (b) A snapshot of travelling wave through the solid. The dashed lines show approximately the amount of amplitude dampening.

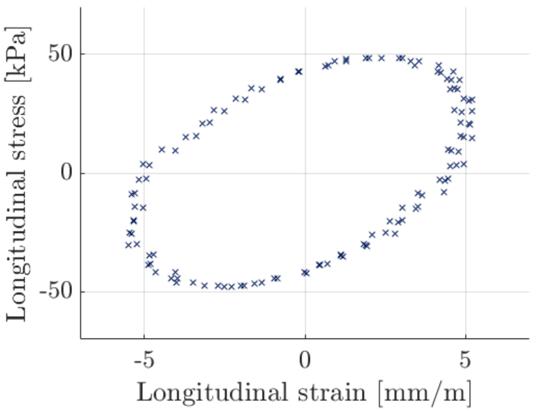


Fig. 2 Reconstructed stress-strain curve using IBUS analysis and images injected with a realistic noise.

Conclusion

In this contribution, we propose an image-based test to measure dynamic properties of soft materials (modulus ~1 MPa) in the ultrasonic range. A preliminary experiment showed significant dissipation of the traveling wave originating from the sonotrode and image simulation analysis was performed to validate the methodology and optimise the imaging setup for the future experiment. Experimental results will be presented at the conference.

References

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