TECHNICAL NOTE

A HIGH-FREQUENCY SHEAR DEVICE FOR TESTING SOFT BIOLOGICAL TISSUES

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Abstract—Accurate mechanical property data obtained at large shear deformations and high frequencies are a fundamental component of realistic numerical simulations of soft tissue injury. Although many commercial systems exist for testing shear properties of viscoelastic materials with properties similar to soft biological tissue, none are capable of determining properties at high loading rates necessary for modeling soft tissue injury. Previous custom shear testing systems, though capable of high-frequency loading, indirectly measure tissue properties by using analytical corrections for inertial effects.

To address these limitations, a new custom designed oscillatory shear testing apparatus (STA) capable of testing soft biological tissues in simple shear has been constructed and validated. Through a proper selection of sample thickness, direct measurement of material properties at high frequencies is achieved mechanistically without analytical inertial adjustments. The complex shear modulus of three mixtures of silicone gel with viscoelastic properties in a range similar to soft biological tissue was characterized in the STA over a dynamic frequency range of 20–200 Hz and validated with a commercially available solids rheometer. The frequency-dependent complex shear modulus measurements of the STA were within 10% of the rheometer measurements for all mixtures over the entire frequency range tested.

The STA represents substantive improvement over current shear testing methods by providing direct measurement of the shear behavior of soft viscoelastic materials at high frequencies. Mechanical property data gained from this device will provide a more realistic basis for numerical simulations of biological structures.

Keywords: Constitutive properties; Material properties; Biomechanics; Viscoelastic.

INTRODUCTION

The widespread growth of numerical modeling in biomechanical research has placed a heightened emphasis on accurate material property data for biological tissues. Soft biological tissues are typically characterized as rate- and temperature-dependent materials capable of large deformations. In order to gain insight into how these tissues behave in injurious loading conditions, the viscoelastic response of these materials must be quantified at high loading rates.

Shear testing techniques have been developed previously for brain because of its tendency to fail in shear (West Virginia University, 1971). Fallenstein and colleagues (Fallenstein et al., 1969) measured the dynamic complex shear modulus of human brain, but at a single low frequency of 10 Hz. Shuck and Advani (Shuck and Advani, 1972) determined the complex shear modulus of human brain by performing small-amplitude oscillatory torsion tests over a range of frequencies that included high loading rates (10–350 Hz), but their measurements included inertial effects, and from them, they computed a corrected shear modulus based on an analytical solution presented by Berry (Berry, 1958).

Linear viscoelastic materials are typically characterized by an isothermal, frequency dependence of the complex modulus. Using time temperature superposition (TTS), the frequency range can be extended to experimentally inaccessible values by exploiting the interdependence of the moduli on temperature and frequency such that increases in frequency can be related to properties measured at reduced temperatures (Ferry, 1980). Unfortunately, in porcine brain tissue, low-frequency (0.16 to 16 Hz), isothermal, oscillatory tests performed at 4 temperatures between 5 and 25°C failed to exhibit temperature-dependent changes in moduli, the fundamental temperature/frequency relationship required to employ TTS (unpublished observations). Temperatures below 5°C would have fundamentally altered tissue structure.

To address these limitations, a new custom designed oscillatory shear testing apparatus (STA) was developed to measure shear properties of tissue directly over a broad range of strains and at high frequencies. The STA described in this communication measures the shear properties of soft biological tissues directly, without analytical compensation, at high loading rates similar to those associated with rapid traumatic injury (Margulies et al., 1990). The purpose of this technical report is to describe the STA and to validate its accuracy using a synthetic gel by comparing measurements with those from a commercial rheometer.

MATERIALS AND METHODS

A custom-designed electro-mechanical device capable of shear strain amplitudes up to 20% and a frequency range of 20–200 Hz was constructed to determine the complex shear modulus of biological tissue samples. Samples of viscoelastic Sylgard silicone gel (Dow Corning, Midland, MI) were tested in the STA and in a Rheometrics™ Solids Analyzer (RSAII) (Rheometrics™ Inc., Piscataway, NJ) to validate the performance of the STA.

Three Sylgard gel mixtures with consistencies similar to soft biological tissue were prepared and tested: 1:1, 1:2, and 1:3 ratios of polymer to catalyst, respectively. Increasing proportions of catalyst produce a material of increasing stiffness. Each mixture was cast in three thicknesses (2.1, 0.75 mm) and cut into 12 x 12 mm specimens for testing in the STA. RSAII specimens (13 x 16 mm) were cut from the 1 mm thick casting.
strain by a phase angle, \( \delta \). The complex shear modulus, \( G^* = G_r + jG_v \), will respond with a periodic shear stress that leads the shear force transmitted through the specimen. Micrometers support the top plate/force transducer assembly and are used to adjust the gap between the plates to the thickness of the test specimen. To drive the system, a function generator in series with a power operational amplifier is used to excite a linear voice coil actuator (Model LA15-16-001A, range = ±0.010 in., natural frequency = 2.78 kHz, BEI Motion Systems, San Marco, CA). By varying the generator signal, the bottom plate of the oscillating assembly is displaced sinusoidally with a specified amplitude and frequency.

The STA uses a horizontal parallel plate configuration with a fixed sample gap. Plates on the outside of the specimens are driven via computer control to deliver an oscillatory shear strain. A fixed insert sandwiched between the two specimens measures the shear force transmitted through the specimens. In this study, 1 mm thick test specimens were mounted on either side of the center plate. The assembly was enclosed within a forced-convection chamber capable of precise temperature control. While strain amplitude (2.5%) and temperature were held constant, successive force and displacement measurements were taken at 10 frequencies between 16 and 0.16 Hz. This experiment was repeated over a range of temperatures (30 to -60°C in 10°C steps) so that TTS could be used to determine properties at higher frequencies.

The STA uses a horizontal parallel plate configuration with a variable sample gap. The bottom plate delivers an oscillatory displacement to the test sample and the shear force transmitted through the sample is measured at the fixed top plate (Fig. 1). The specimen and plates are housed within a high humidity chamber capable of providing a moist environment for testing biological tissue. This feature of the STA was not used in these tests, because the properties of the gel are unaffected by humidity level. Gel samples were subjected to a sequence of sinusoidal shear strains with an amplitude of 2.5% over the frequency range of 20-160 Hz in 10 Hz increments. Voltages corresponding to displacement and force values at each test frequency were obtained between -60°C and +30°C from which the master curve was constructed using the shift factors (\( \alpha_t \)) (see insert). The shift factors are well fit by the WLF equation (as shown by the linear relationship), supporting the applicability of TTS to the RSAII data.

For the RSAII, \( G_1 \) and \( G_2 \) were calculated at each frequency and temperature using equations (1) and (2). TTS was employed to shift the data along the frequency axis to create master curves of \( G_1 \) and \( G_2 \) at a reference temperature of 20°C (Fig. 2).

For the STA, shear stress, \( \tau \), and shear strain, \( \gamma \), were calculated from the following equations (Ferry, 1980):

\[
G_1 = \frac{\tau_0}{\gamma_0} \cos \delta
\]

\[
G_2 = \frac{\tau_0}{\gamma_0} \sin \delta
\]

where \( G_1 \) and \( G_2 \) represent the elastic and viscous components, respectively, \( \tau_0 \) is the amplitude of the shear stress, and \( \gamma_0 \) is the amplitude of the shear strain. This formulation neglects inertial effects of accelerating the mass of the sample.

To evaluate reproducibility of the STA measurements, two samples of each of the nine thickness/stiffness combinations (3 thicknesses, 3 stiffness mixtures) were tested in the STA. The deviation (one-half the difference between the \( G^* \) values for the two samples tested at each combination) expressed as a percentage of the mean was calculated at each frequency. The overall deviation in \( G^* \) was 7.9 ± 5.8% (mean ± S.D.). There was no systematic influence on the deviation due to frequency, sample thickness, or gel mixture. For each stiffness, an increase in sample thickness was associated with an increase in the measured force amplitude which resulted in an erroneous increase in the measured complex shear modulus (Fig 3). It is expected that tissue samples tested in the STA will be between 0.75 and 2 mm thick. For this reason, the complex shear moduli of the gels tested

![Fig. 1. Schematic diagram of the shear testing apparatus (STA).](image)

![Fig. 2. Master curve of the complex shear moduli as a function of frequency at a reference temperature of 20°C for 1:1 gel.](image)
a device to measure the high-frequency behavior of soft tissues in shear. Inertial effects associated with the mass and acceleration of the sample contribute to the force measurement at the top plate. As sample mass and frequency increase, the relative effect of inertia becomes more pronounced, and the calculated modulus increases erroneously. Ideally, inertial effects may be neglected if the sample thickness, h, is small compared to the wavelength, \( \lambda \), of the elastic shear wave in the sample (Ferry, 1980):

\[
\lambda \approx \sqrt{\frac{\rho}{\omega G'_s}}
\]

where \( G'_s \) is the storage modulus, \( \rho \) is the sample density, and \( \omega \) is the displacement frequency in Hz. For samples much thinner than \( \lambda \), inertial effects can be neglected. If not, one must evaluate the effect of the sample mass on the mechanical response of the system and introduce analytical corrections to the experimental data, such as those implemented by Shuck et al.

As \( G'_s \) decreases, \( h/\lambda \) increases and the influence of inertial effects is more pronounced. \( G'_s \) is smallest in the 1:1 gel, resulting in a \( h/\lambda = 0.16 \) for the thickest samples (2 mm), but only a \( h/\lambda < 0.08 \) for the thinner samples. The erroneous increase of calculated complex modulus due to inertial effects is evident in the thicker samples (Fig. 3). Thus we recommend reducing any error associated with sample inertia by choosing the sample thickness prudently. Because only low-frequency measurements were made in the RSAII, \( h/\lambda < 0.01 \) and inertial effects are negligible.

The STA is capable of direct measurements of the complex modulus of the material at high frequencies, without analytical adjustment. Mechanical property data gained from this device will provide a more realistic basis for numerical simulations of biological structures, an essential first step in understanding soft tissue injury.

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REFERENCES


West Virginia Department of Theoretical and Applied Mechanics (1971) Head Injury Model Construction Program Data Compilation and Review. West Virginia University.