THERMAL EXPANSION AND ITS EFFECT ON THE NORMAL FORCE FOR A MODIFIED FORCE REBALANCE TRANSDUCER

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Abstract

Prior work in this laboratory [Niemiec, et al, J. Rheology, 40, 323-334 (1996)] showed that anomalous normal forces could arise in rotary shear measurements when thermal expansion of the force rebalance transducer (FRT) superimposed a squeezing flow on the shear flow. Transducer heating results from the current to the magnetic coils in the FRT necessary to counteract the applied torque. Partly due to this work, the manufacturer redesigned the transducer by replacing stainless steel components with Invar, an alloy with a very low coefficient of thermal expansion. Tests on the new transducer show that the thermal expansion is significantly reduced. The behavior of the new transducer is described.

Introduction

Accurate characterization of material properties is critical for modeling the behavior of polymeric materials both during and after processing. One important aspect of nonlinear polymer behavior is the development of normal stresses in shearing flows of melts and solutions [1,2]. In principle, a rotary rheometer equipped with cone and plate fixtures provides a method to accurately measure both the viscosity and the first normal stress behaviors. With suitable grips, the rotary rheometer can also be used to measure the torsional response of solid polymers. Normal stresses also arise in the torsional deformation of solid polymers; the resulting torque and normal force can be used to investigate suitable strain energy density functions for such materials [3,4,5].

One critical requirement for accurate measurements with the rotary rheometer is that the geometry remains constant during an experiment. Changes in the axial position of the fixtures will affect both the shear and normal stress measurements, but will be seen most clearly in the normal stresses when testing fluids with significant elasticity or when testing solid polymers. Prior work in this laboratory [6] investigated anomalous normal stresses that arose in rotary shearing measurements of polymeric fluids and in torsion of glassy polymers. These anomalous normal stresses were caused by thermal expansion of the force rebalance transducer in the Rheometric Scientific RMS-800.[1] This paper concerns a similar investigation into the behavior of a redesigned force rebalance transducer available on the Rheometric Scientific ARES rheometer.

The force rebalance transducer (FRT) consists of a core element floating in an air-bearing housing, with electromagnetic forces used to counteract any applied torque and/or normal force, thus holding the axial and rotational position of the transducer core fixed. The magnitudes of the applied torque and/or normal force are calculated from the current flowing to the electromagnets. This transducer design has several advantages. Because the range of motion is very small, the position detectors can be very sensitive, and the deviation from the null position can be detected and counteracted very accurately. The compliance of the transducer is governed by the compliance of the structure (test fixture and transducer core) between the specimen and the position detector; since the test fixtures and transducer core are very stiff, the total compliance of the transducer is very low. There are, however, two significant potential problems with the force rebalance transducer. The first problem occurs when relatively large torques and/or normal forces are applied over an extended period of time. In these situations, the high electrical current to the magnetic coils necessary to counteract the applied loading leads to heating, causing thermal expansion of the transducer elements. While the position of the axial null-position sensor is held fixed, the length of transducer core and test fixture between the sensor and the specimen can expand, which will decrease the gap in cone and plate or parallel plate fixtures. The second problem arises because the null position is enforced through an active control system. The active system can be subject to unwanted resonance if the natural frequency of the mechanical response of the rheometer and specimen together is similar to the frequency of the control loop. We have had difficulty with audible resonance with the new FRT when trying to load relatively stiff fluids into test geometries with small gaps and/or large-diameter plates. We are working with the manufacturer to determine if retuning the control loop parameters can alleviate this problem.

The magnitude of the thermal expansion problem in the earlier experiments can be seen in Figure 1 (data replotted from Figure 3 of [6]). With no specimen in the apparatus, a constant torque of 0.1 Nm was applied to the transducer using the calibration fixture (the capacity of the transducer was 0.2

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[1] Certain commercial materials and equipment are identified in this paper to specify adequately the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply necessarily that the product is the best available for the purpose.

Nm). The axial displacement of the transducer core relative to the bottom fixture was measured using a dial gauge. It can be seen that over a forty-minute period the thermal expansion of the transducer caused the upper fixture to move toward the lower fixture by about 18 μm (the measurements were not extended to investigate the steady-state behavior for this apparatus). Clearly, a change in the gap of 18 μm (or more) could be very significant in a cone and plate geometry, which typically requires gaps on the order of 50 μm.

Following the earlier investigation, four possibilities were suggested for solving the problem of thermal expansion [6]. The first suggestion was to incorporate an environmental housing and control system to maintain a constant temperature within the transducer. The second suggestion was to construct the transducer from components with a lower coefficient of thermal expansion. The third suggestion was to include an active heating element within the transducer; the power to the heater would be varied inversely to the (measured) power supplied to the electromagnets in such a way that the total heat dissipated would remain constant. The fourth suggestion was to move the axial null-position sensor as close as possible to the position where the fixtures are connected to the transducer, thus limiting the length of the structure between the sample and the null-position sensor that can expand. The first attempt to improve the behavior of the FRT was to adopt the second suggestion and replace the 316 stainless steel components with Invar, an iron/nickel alloy. The 316 stainless steel has a linear thermal expansion coefficient of 15.9 μm/(m °C) between 0 °C and 100 °C [7, page 34], while Invar has a linear thermal expansion coefficient of 1.02 μm/(m °C) for a quenched and tempered heat treatment [7, page 794]. The new transducer with Invar components is evaluated below.

Experimental

The thermal expansion of the new transducer in response to an applied torque was measured using a Lucas Schaevitz 050 MHR linear variable differential transformer (LVDT). The LVDT was attached to the motor, which was held in a fixed position. The core of the LVDT was attached to the calibration fixture, which was mounted on the transducer. A 500 g weight connected to the 2.5 cm arm of the calibration fixture was used to apply a moment of 0.123 Nm (1250 g·cm). The transducer torque capacity is 0.197 Nm (2000 g·cm) and the normal force capacity is 19.7 N (2000 g). The LVDT signal was conditioned using a Lucas Schaevitz ATA 101 Analog Transducer Amplifier and recorded with a Keithley 197 Autoranging Microvolt Digital Multimeter, which can record up to 100 data points separated by a specified time interval. The slope of the LVDT voltage output was calibrated to be 62.15 mV/μm with a standard uncertainty of 0.06 mV/μm. The combined standard uncertainty of a single measurement is calculated to be 0.28 μm. The experiments were performed as follows. Before attaching the weight, the multimeter was set to record voltages at 1 minute intervals. After waiting for 10 minutes to record the initial position of the FRT, the weight was attached to the calibration fixture. After 100 minutes, the data was extracted from the multimeter and it was reset to take data at 10 minute intervals. On the following day, an unloading experiment was performed following the same steps except that the weight was instead removed from the calibration fixture. A curtain of polyethylene sheeting was placed around the rheometer test section in an effort to minimize thermal fluctuations from air currents in that area. The section of the rheometer containing the FRT was left open to the room atmosphere. Also note that the FRT air bearing is always supplied by air at 0.4 MPa (60 psi), which is passed through a refrigerated compressed air dryer, so it is at a temperature somewhat below ambient.

An attempt was also made to reproduce the "squeezing flow" experiment performed in the earlier investigation [6]. In this type of experiment, a fluid is loaded in a cone and plate fixture, and the motor again holds the lower plate fixed, so there is no motion of the fluid at all. A constant torque is applied to the transducer using a weight connected to a moment arm attached to the upper cone fixture, and the normal force caused by thermal expansion of the transducer is recorded. In the earlier investigation [6], a silicone melt was used for the squeezing flow experiment. In that case, the applied torque was similar to the result from a steady shear experiment at approximately 50 s^{-1}, and the normal force caused by thermal expansion was of a magnitude similar to that measured in the shearing experiment. With the new transducer, we were unable to load the silicone melt in any cone and plate fixture because of the transducer resonance problem described above. Instead, we used a solution of polyisobutylene dissolved in normal hexadecane in a 50 mm diameter, 0.04 radian cone and plate, with an applied torque of 0.127 Nm (1290 g·cm). Note that for this fluid, the applied torque corresponds to a shear rate that is much higher than could be measured in practice, while the normal force caused by the thermal expansion is much smaller than normal forces observed in typical shearing flows. The problem of thermal expansion will be most pronounced for stiffer materials in large diameter fixtures at small gaps, but these conditions have not yet been investigated with the new transducer because of the resonance problem.

Results and Discussion

For the thermal expansion experiments, the initial position for each loading experiment was reset to zero, while for the unloading experiments, the initial position was shifted to 4.8 μm, which was the average position measured at the end of the loading experiments. Three repeat loading experiments and three repeat unloading experiments are plotted in Figure 2. In the loading experiments, the gap first decreases by about 2 μm in a time of 15 to 20 minutes, and then expands to an apparent steady-state value about 5 μm larger than the initial position. The manufacturer suggested that this behavior is likely a result of different rates of heating and expansion of the FRT core and housing [8]. Initially, the core expands, decreasing the gap, while the housing expands more slowly, increasing the gap until the temperature and displacement reach an approximate steady state. The unloading experiments show a similar two-stage process which is not quite a mirror image of the loading experiments. Based on earlier experiments, it is expected that the thermal expansion is a nonlinear function of applied torque [6]. The response is also clearly dependent on the details of the heat transfer, which is why the loading and unloading are not mirror images. The strong effect of the nature of the heat transfer can be seen even more clearly in Figure 3, which shows the results of a single loading experiment. At a time of 400 minutes after the torque was applied, a power fluctuation at NIST caused a failure in the control of the room temperature, leading to a relatively large change in the measured displacement behavior. At a time of 600 minutes, it appears that the temperature control was resumed, and the transducer displacement was similar to the tests in Figure 2 at a time of 1000 minutes after application of the torque. Unfortunately, we were not monitoring the room temperature at the time so it is impossible to state the magnitude of the temperature change, but is probably only on the order of a few degrees at most.

Two repeat squeezing flow experiments for the polyisobutylene solution in a cone and plate geometry are shown in Figure 4, which plots the normal force measured by the rheometer against the time after connecting the weight to the moment arm. The standard uncertainty in the normal force measurement for this experiment is 0.1 N. Again, the motor was held fixed, so there is no shear applied to the fluid. These experiments do not seem to reflect the initial downward motion of the transducer core seen in Figure 2, but they do show a response to the increase in the gap as the housing expands. The negative normal force indicates that a tension is developed as the gap widens. It might be that the fluid damps out some of the short time motion, or that the difference in the fixtures for the two tests changes the details of the heat flow sufficiently to change the response. The calibration fixture used in the experiments in Figures 2 and 3 is more massive and compact than the hollow cylindrical shaft of the cone fixture.

Conclusion

While the force rebalance transducer has many advantages, the power dissipated in counteracting large torques and normal forces can lead to heating and subsequent thermal expansion of the transducer components. However, the thermal expansion of the redesigned FRT with Invar components is significantly reduced compared to the earlier transducer that used stainless steel components. For a torque of approximately half the 0.2 Nm capacity of either transducer, the displacement caused by thermal expansion has been reduced from 18 µm (or more) to 5µm. Displacements of that magnitude may still be significant for some materials tested in cone and plate geometries, which typically require gaps on the order of 50 µm. Such displacements might also be evident in tests with solid polymers. The new rheometer and FRT combination has also demonstrated the additional problem of audible resonance when trying to test stiffer samples, which results when the active control of the transducer matches the natural frequency of the mechanical linkage between sample and rheometer. The problem is evident with stiffer materials, larger diameter fixtures and smaller gaps. The squeezing flow experiment does demonstrate that the sample response is affected by the thermal expansion. However, the test using the polyisobutylene solution is somewhat artificial, in that the applied torque could not be achieved in a typical test. In order to provide a suitable test, we would need to load a higher viscosity fluid in the cone and plate fixture, which has not been possible because of the problem with resonance in the transducer.

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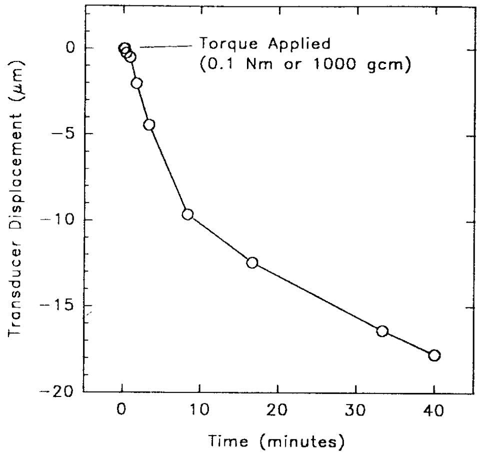

Figure 1. Axial displacement of the force rebalance transducer resulting from thermal expansion in response to an applied torque of 0.1 Nm. Data taken from Figure 3 of [6], and replotted on a linear time scale. These measurements were made on a Rheometric Scientific RMS-800 rheometer.

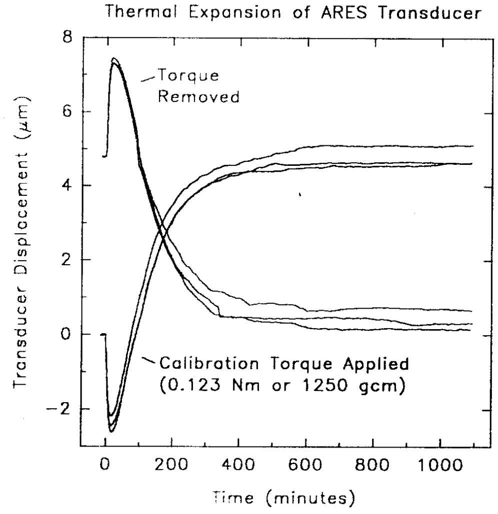

Figure 2. Axial displacement of the force rebalance transducer resulting from thermal expansion of the transducer core and housing in response to an applied torque of 0.123 Nm, and the subsequent contraction in response to removal of the torque. These measurements were made on the redesigned FRT with Invar components in a Rheometric Scientific ARES rheometer.

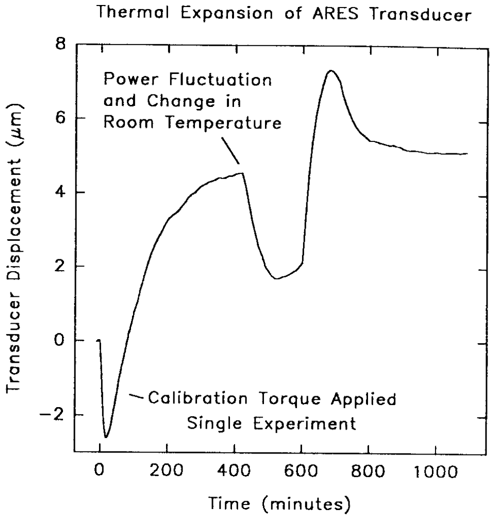

Figure 3. Axial displacement of the ARES force rebalance transducer resulting from thermal expansion in response to an applied torque of 0.123 Nm. Similar to the curves in Figure 2, except that a power fluctuation at NIST affected the room temperature. The thermal expansion depends strongly on the details of the heat flow in the apparatus.

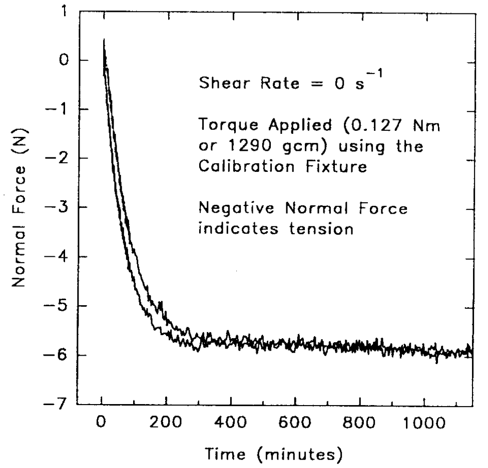

Figure 4. Force developed in a polyisobutylene solution in a cone and plate fixture caused by thermal expansion of the FRT in response to an applied torque of 0.127 Nm. There is no shearing of the fluid. The negative normal force indicates tension (negative pressure), consistent with the increase in gap seen in Figure 2.