Study of Rubber bearings and its applicability in precision machines

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Introduction

We have investigated the use of thin rubber sheets or laminates of metal and rubber sheets as bearings in precision positioning systems. Such bearings have the potential to replace more conventional flexures fabricated for instance from metal. Rubber bearings also potentially have advantages in for example ease and low-cost of fabrication, overload robustness, and compact form.

To study the properties of these we have designed the test fixture shown in Figure 1. This fixture allows us to measure the shear and compression characteristics of these bearings in its static sense, as a function of frequency, and of various design parameters.

![Figure 1: Rubber test fixture solid model and fabricated fixture (shear test assembly shown)](image)

On the basis of the experimental results a rotary precision positioning system utilizing a rotary laminated rubber bearing was designed, fabricated and tested. The bearing of this device consists of multiple laminates of metal and rubber sheets packaged within a preload mechanism.

Rubber Test Results

The rubber test fixture uses a voice coil actuator to apply either a compression or shear force to the rubber specimen and a capacitance gage to measure the strain. The compression sample is preloaded prior to testing with the aid of a preload flexure, and the shear sample is preloaded with the aid of a clamp type sample holder.

The tests of the rubber specimens in compression have shown a fairly linear behavior of the compression stiffness within the tested strain of 0.013%. Experimental results show that the compression stiffness increases significantly with the shape factor $S$, being this increment proportional to the shape factor squared $S^2$. The results have shown that this increase of compression stiffness depends strongly on the adequate bonding of the load carrying surfaces. The ratio of the high to low frequency complex compression modulus $E_{HF}/E_{LF}$ has shown to be between 7 and 9 for the tested samples, as seen in Figure 2 (a).
The tests of rubber specimens in shear have shown a linear behavior of the shear stiffness within the tested strain of 1.6%. The increase of complex modulus in shear $G_{HF}/G_{LF}$ is much higher than the compression one, being of a factor of 30 to 240 for the tested materials. Figure 2 (b) shows the complex shear modulus of Neoprene for different shore hardness. The application of preload increases the static $G$ and low frequency shear modulus $G_{LF}$. As a consequence the application of preload reduces the $G_{HF}/G_{LF}$ ratio. Samples with higher shore hardness show higher increment of $G_{LF}$ with preload pressure, as shown in Figure 3.

The experimentally measured hysteresis consequent of a sinusoidal excitation, give an indication of the loss involved in the cyclic deformation of rubber, as shown in Figure 4 (a). The loss factor calculated from the hysteresis loops, has shown that materials with lower shore hardness exhibit higher loss factor $\eta$ than the ones with higher shore hardness.

The shear step response of the rubber specimens have a rapid elastic-type response within the order of 0.1 ms followed by a slow creep process lasting seconds, as shown in Figure 4 (b). Variation in the shore hardness has shown minimum effect on the shear step response of the tested specimens.
Fatigue tests performed on Silicone SH35A and Neoprene SH80A have shown no signs of fatigue after being subject to $294 \times 10^6$ and $207 \times 10^6$ cycles, while subject to cyclic shear strains on the order of 0.16% and 0.004%, respectively. These fatigue tests show the tested rubber specimens possess remarkable fatigue life properties for the tested strains.

Rotary Precision Positioning System

The performance of the Rotary Fast Tool Servo (RFTS) designed and fabricated by Montesanti [1], intended for diamond turning, is used as a reference for the design of ours. His RFTS uses flexural bearings, and is driven by the same actuator used in our design. Montesanti’s RFTS has a maximum stroke of 50 um pk-pk at low frequencies and has demonstrated a 2.5 um pk-pk stroke at 2 kHz while under operation.

For the design of our RFTS the tool tip stiffness of 20 N/um (for a design work load of 4.5 N) is taken into consideration. The goal of our design is to obtain a maximum stroke of 50 um pk-pk at low frequencies and a stroke on the order of 1 um pk-pk at 1 kHz. A closed-loop bandwidth within the range of 1 - 10 kHz is desired. Also because of possible overloads, a design radial load of 20 N is considered.

The design of the RFTS includes preload of the rubber bearings with the aid of a compact preload mechanism to assure the bearing radial stiffness. This preload mechanism permits adjustment of the static and low frequency torsional stiffness of the rubber bearings, by increasing the bearings shear modulus with the applied preload.

Silicone and Neoprene proved to have the best dynamic properties to be used as a rubber bearing, because of having the lower increment of complex shear stiffness with frequency. The downside of Silicone is
the bonding of the rubber to metal surfaces. As noted by Petrie [2], silicone rubber is characterized of being a low surface energy material, which are generally difficult to bond with adhesives, recommending the use of silicone adhesives. Also experimentation showed that the thinnest strong bonds obtained with silicone adhesives where of 0.1 mm. On the other hand strong bonds as thin as 0.02 mm could be obtained when bonding Neoprene rubber to metal sheets when using a rubber toughened cyanoacrylate.

The chosen rubber for the RFTS rubber bearings is Neoprene Shore 80A, being this the one that permits the greater adjustment of its shear modulus by the application of preload, as shown in Figure 3. Its complex shear modulus as a function of frequency is shown in Figure 2 (b).

The chosen actuator for the RFTS is a Model 6880 Galvanometer Optical Scanner from Cambridge Technology, INC. This is a moving-magnet actuator, having no saturation torque limit and very little electrical inductance.

The designed RFTS, shown in Figure 5 permits an open loop maximum stroke of 45 um pk-pk at 1 Hz and 0.8 um pk-pk at 1 kHz. The predicted open loop maximum stroke was of 60 um pk-pk at 1 Hz and 1.6 um pk-pk at 1 kHz. The maximum stroke prediction is within one order of magnitude of the experimental ones, being 30% off on the case of the stroke at 1 Hz and 100% off for the stroke at 1 kHz. This is an acceptable prediction of performance for the first prototype of this type of machine using rubber bearings. But further testing of the rubber bearings with testing conditions closer to the operating conditions is suggested, to make more accurate predictions.

The closed loop bandwidth of the Rotary Fast Tool Servo obtained with a simple proportional controller is 970 Hz, as shown in Figure 6 (a), which is close to the desired 1 kHz to 10 kHz bandwidth. The small signal step response is shown in Figure 6 (b). The maximum stroke obtained when using the proportional controller are of 31 um pk-pk at 1 Hz and 0.3 um pk-pk at 800 Hz. Also the closed loop tool tip stiffness is around 70 N/um, which is well within the required 20 N/um for precision diamond turning [1].

References
