OPTI 521 Synopsis of

An instrument for generation and control of sub-micron motion

by Alson E. Hatheway

Synopsis by Eric H. Frater

INTRODUCTION

This document provides a synopsis of the technical report *An instrument for generation and control of sub-micron motion,* by Alson E. Hatheway. The transducer described in this report is intrinsically stiff, stable and athermal. It employs “calibrated elasticity” to produce highly repeatable displacements with one angstrom resolution across a one micron total range. The transducer is constructed of 6061-T6 and uses a micrometer with one inch total range and .0001 inch resolution to drive the displacements.

BACKGROUND

There are many approaches to precision positioning and each has inherent and practical advantages and disadvantages. Micrometers are used for many positioning applications because they are easy to integrate and operate. However, thread manufacturing reaches a practical limit at a pitch of 100 threads per inch and this limits manual micrometers to controlling displacements greater than or equal to 0.5 microns, at best.

Levers may be used to improve a micrometer’s resolution by creating a reduction ratio between displacements of the drive and displacements of the driven body. Increasing the reduction ratio of a lever either requires using a longer lever or positioning the driven body at a point closer to the fulcrum. Space limitations on lever length and difficulty positioning the driven body closer than about .010 inches to the fulcrum define the practical limits for mechanical advantage in a lever.

Differential screws suffer cyclic run-out errors caused by thread imperfections in manufacturing. These cyclic errors introduce an oscillating axial component to the displacements, and in practice a differential drive offers an improvement in precision of less than one order of magnitude over conventional threads.

Piezoelectric transducers offer a fundamentally different mechanism for driving a linear displacement. Applying a small voltage change across a quartz crystal can produce motions in the range of angstroms or less. The most severe limitation of the piezoelectric transducer is severe hysteresis that causes repeatability errors of 5-10% of the full range of travel. This effect is mitigated by monitoring displacements with an optical encoder or capacitive micrometer to provide feedback for the positioning system. Ultimately the positioning repeatability is limited by the resolution of the feedback sensor, and thermal effects in the crystal and sensor may introduce a thermal drift as large as .015 micrometers per degree Celsius.

The motion control limitations discussed above provide motivation for the use of a calibrated elastic device as a precision transducer.

PRINCIPLES OF CALIBRATED ELASTIC DEVICES

The transducer discussed in this paper uses the elastic properties of an extended body to generate small motions. Unlike the lever, an elastic body exhibits a different kind of reduction ratio for an applied displacement or load. For an elastic body the applied load may be a force, moment, or a displacement applied at a given point. We consider the response deformation of the body at some other point of interest, and define “effectiveness ratios” as

$$ER_L = \frac{\text{response deformation}}{\text{applied load}}$$

$$ER_D = \frac{\text{response deformation}}{\text{applied displacement}} \quad [1]$$

These ratios may have many different units depending on the form of deformation or displacement (translation, rotation) and applied load (force, moment). It is important to realize, as we will see in the example of cantilever beam deflection, that these effectiveness ratios do not yield a reciprocal relationship between the point of load or displacement and the point of deformation. This is inherently different than the lever.

Consider the cantilever shown below in Figure 1. If the end of the cantilever is displaced vertically by y_1, the response deformation of the cantilever at point 2 will yield a vertical displacement y_2. However, if a displacement y_2 equal to the previous response deformation is applied at point 2, we will not observe a response displacement y_1 equal to the previously applied displacement.

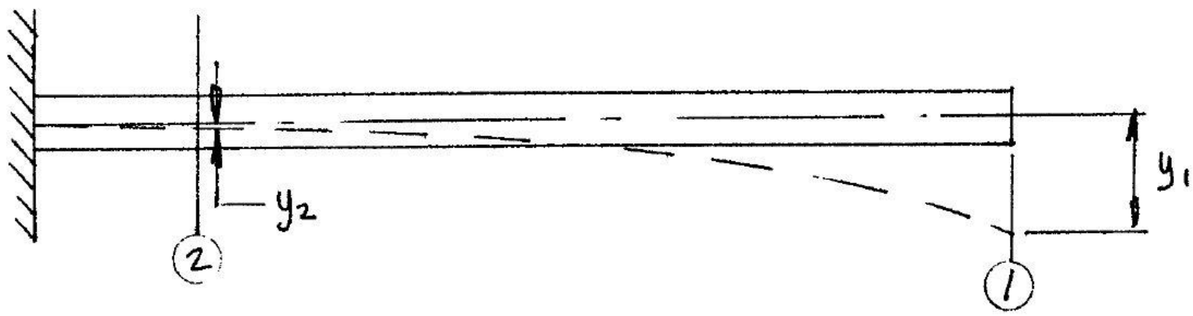

Figure 1: Vertical displacements along an elastic cantilever beam [1]

For an extended elastic body, each point in the body will experience up to six degrees of freedom. A system of flexures can be used to transmit only one translational or rotational motion between a point in the elastic body and a mounting interface. In the discussion that follows we consider a flexure system that transmits motion of translation along one axis.

TRANSDUCER USING CALIBRATED ELASTICITY

The device shown in Figure 2 is a transducer that uses calibrated elasticity to drive a small translational motion. Applying a known displacement with the micrometer bends the two beams in the transducer body. This bending imparts reaction moments and forces on each beam at their base where they are coupled to the rest of the transducer body. The transducer is fastened to a fixed structure at the interface with the two 10-32 UNF threaded holes. The mounting block with the two 8-32 UNC tapped holes is the actuated portion of the transducer. The flexure system employed in this design leaves the block unconstrained in the direction along the length of the thin beam. The axial reaction force at the base of the thin beam causes an elastic deformation of the base of the transducer body such that the small mounting block translates relative to the fixed interface. The reaction moment and the orthogonal component of the reaction force do not couple into a motion of the mounting block, because the flexures only allow motion of translation in one direction.

In practice, the motion is only *nearly* purely translational, but the flexure design shown in Figure 2 leads to an attenuation of the rotational component of motion at the block by more than two orders of magnitude. The design is optimized for a transducer body constructed from 6061-T6 and generates a 1 micron linear displacement at the block for a 1 inch applied displacement by the micrometer. Given a micrometer resolution of .0001 inch, the device achieves one angstrom resolution in translations of the block.

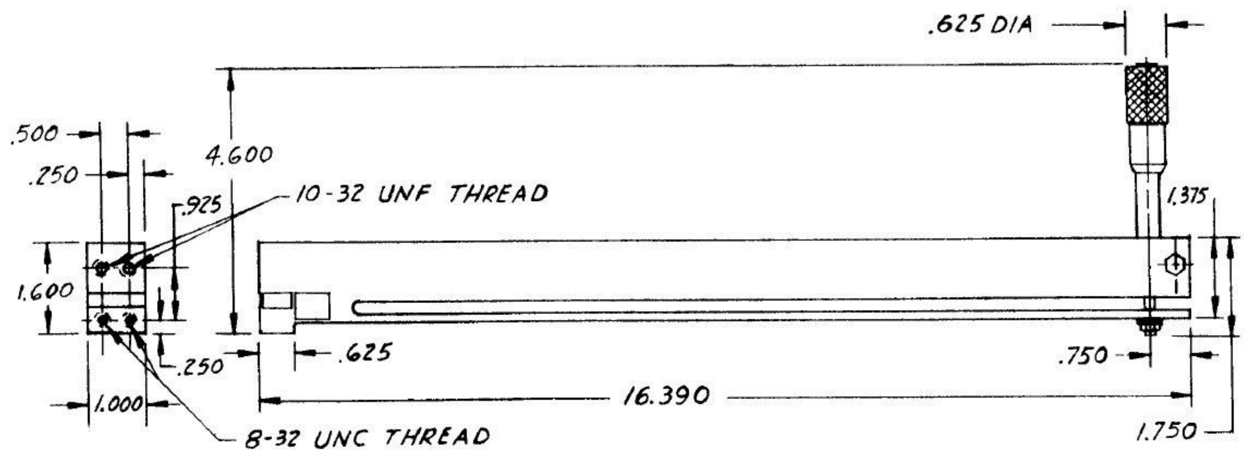

Figure 2: 6061-T6 actuator with one micron range and one angstrom resolution [1]

The micrometer threads are always under a preload reaction force from the beam bending, so this actuator is relatively free of backlash. In addition, the actuator exhibits no perceptible amount of hysteresis provided that all stresses in the transducer body are kept well below the yield strength of the material. If the transducer is made of a material that exhibits no measureable yielding over a sizable range of stress, the transducer may be designed such that it has no hysteresis. The stiffness of the actuator will depend on its flexure design, and removing the flexures altogether will give the stiffest design. However, increasing the stiffness in this way will compromise the quality of the nearly pure translation.

THERMAL EFFECTS

There are three sources of thermal sensitivity for the system described above: thermal expansion of the transducer body, changes to the modulus of elasticity with temperature, and thermal effects on the loading mechanism.

The two mounting interfaces on the transducer should be coplanar to mitigate the influence of thermal expansion of the transducer body. Since the body is made out of one type of material, thermal expansion will only cause positioning errors if these interfaces are not coplanar. Although the interfaces will not be coplanar after a known displacement is applied, positioning errors will be on the order of ppm/°C of the relative displacements of the interfaces. For this transducer this effect will be negligible for temperature changes less than about 100°C.

If the loading mechanism is constructed of a different material than the transducer body, then the differential expansion of the loading mechanism will change the deformation angle of the beams. This will introduce an error in the translation, but the (generally) small relative expansion of the mechanism is scaled down by the effectiveness ratio of the mechanism. Given the effectiveness ratio $(1\times10^{-6})/(2.54\times10^{-2}) \sim .00004$ for the cantilever described above, we find that the scaling of the small asymmetric expansion will result in a negligible effect on positioning for small temperature changes.

The change in the modulus of elasticity of steel or aluminum is about 2% over a 100°C temperature change. For an elastic transducer with an applied load, rather than an applied displacement, the response deformation will scale with the modulus of elasticity. Therefore, if an applied load must be used then the transducer body should be made out of a material with minimal change in modulus of elasticity over the operating temperature range. For an applied displacement there is no error introduced by this effect.

FLEXURE DESIGN

The flexure design is a critical component of this transducer system, and it is important to realize the sensitivity of flexure performance in terms of its construction parameters. A potential application for this transducer is precision athermal positioning of reflective optical components. In this generalized application changes in angle of the mounting interface on translation must be minimized for the device to be effective. According to Hatheway, pitch and yaw rotations of the body we mount on a monolithic flexure stage will depend on errors of unequal flexure lengths, unequal span lengths, non-parallel neutral axes of the flexures, and non-parallel principal axes of inertia of the flexures. [2] The resulting pitch and yaw errors are shown in Table 1, where Tz is

Parasitic Motion:	Flexure Influences
Rx (pitch)	$-3\Delta S Tz/2SL - 3\Delta L Tz^2/4L^2S$
Ry (yaw)	$\beta Tz/S - 3\alpha Tz^2/4SL$

Table 1: Angular errors of flexure stage due to construction parameters [2]

the length of the flexure's stroke, ΔL is the difference in flexure lengths, L is the average flexure length, ΔS is the difference of the span lengths between the top and bottom of the flexures, S is the average span length, α is the angle between the neutral axes of the flexures, and β is the angle between the principal axes of inertia of the flexures. [2] Using these expressions the designer can determine what the best aspect ratios are for the spans and flexure lengths and determine appropriate tolerances for the manufacturing of the flexure. This level of tolerancing may be necessary for the design of an appropriate transducer system for use in especially sensitive optical devices, such as interferometers.

CONCLUSION

The transducer Hatheway presents offers the optomechanical engineer an interesting and advantageous class of positioners to use for highly repeatable precision motion control. The transducer has few moving parts, is intrinsically athermal for applied displacements, and offers good stiffness provided the flexure system is designed appropriately. The device is limited by its small range of travel, angular sensitivity to the flexure's motion, and small thermal error introduced by the steel micrometer's asymmetry in CTE. Overall, this is an exceptionally straight-forward inexpensive way to achieve one angstrom positioning using simple principles of elastic mechanical behavior.

References

[1] Hatheway, Alson E. An instrument for generation and control of sub-micron motion. Proc. of SPIE Vol. 1167, Precision Engineering and Optomechanics, ed. D Vukobratovich (Nov 1989)

[2] Hatheway, Alson E. An instrument for generation and control of sub-micron motion. Proc. of SPIE Vol. 1167, Optomechanical and Precision Instrument Design, ed. A E Hatheway (Sep 1995)