

FLEXURE-BASED MESO-LEVEL STAGE DRIVEN BY LINEAR PIEZO MOTORS

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ABSTRACT

This paper presents the design and experiments of a one-axis flexural stage with a range of ± 0.75 mm. The flexural stage uses a monolithic design based on flexures to eliminate stiction in combination with a piezo linear motor to avoid backlash. Closed position feedback control is achieved with a non-contact optical encoder with a resolution of 50 nanometers. The flexure element can typically be modeled as a spring element. Therefore, it ideally has a linear relation between force and deflection. But actually, the results from the experiments on this flexure stage show that it tends to have a linear relation between force and deflection at small deflections (less than 400 microns). At deflections larger than 400 microns, the relation becomes nonlinear. The experimental results on the nonlinear property of the flexure element are presented in this paper. The flexural stage is driven directly by linear piezo motors whose working principle is based on resonance of piezo-electric elements that drive the friction plate which is attached to the moving frame. The fact that the motors are based on friction has an appealing feature: When the stage reaches the target position, the motors can be turned off and hold the position by the static friction between the friction shoes and the friction plates. Hence, it can completely avoid the servo noise and also limit the heat generated from the motors. The experiments prove that this static friction is enough to hold the stage and are also provided in this paper.

INTRODUCTION

The emerging of meso-level machining creates increasing demand on developing linear stages with travels ranging from zero to a few millimeters. The short travel creates a problem for most conventional stages which tend to be based on ball screws and rolling element bearings. For short travels, the hydrodynamic lubrication layer necessary to prevent fretting of the rolling elements cannot always be formed, which can significantly reduce the life of the ball screw and bearings [1]. Flexure based stages, on the other hand, don't use rolling element

bearings, thereby avoiding this issue. However, commercially available flexure stages tend to be driven by piezo-stack actuators, whose limited strain tends to limit the travel of such stages to a few hundreds of microns.

This paper presents a new type of linear stage that combines the advantages of conventional stages with those of flexure-based systems [2]. The moving part of the stage is supported by flexures and is driven directly by linear piezo motors whose working principle is based on resonance of piezo-electric elements that create very small steps on the order of nanometers at very high frequencies. This oscillation is then transferred to a friction plate, thereby generating linear motion. As such, the travel of these stages is limited by the range of the flexures but not by the motors.

As is well known, flexural bearings create extremely straight motion and if designed properly, provide tremendous stiffness in all directions except the direction of motion. They furthermore exhibit neither friction nor stiction, which is a critical feature in ultra-precision motion control where the reversal of an axis' motion typically causes a tracking error due to the change from kinetic to static friction.

The fact that the motors are based on friction has a very interesting side effect: Once the slide has reached its target position, no servo control is required to hold this position. Hence, the motors can be turned off, which not only completely avoids any kind of servo noise but also limits the amount of heat generated in the system. This, however, is only true for external forces that do not exceed the frictional force between the motor and the friction plate. There is a difficulty, though; linear piezo motors tend to exhibit a significant non-linearity in the motor velocity response versus the command voltage. The resulting dead-band where the motor creates no velocity despite a non-zero command voltage needs to be accounted for in the control system in order to minimize servo errors during a move. Also of concern is the motor mount. The

motors must be preloaded against the friction plate in order to generate a thrust force. In order to maintain preload and to account for changing distances between the motor and friction plate, a compliant mount is needed. However, to avoid backlash, the mount also needs to be very rigid.

DESIGN AND CONTROL SYSTEM

The flexural stage in Figure 1 has been designed to provide a travel of ± 0.75 mm. The stage is a monolithic design where the inner frame (moving frame) is supported by four flexure beams.

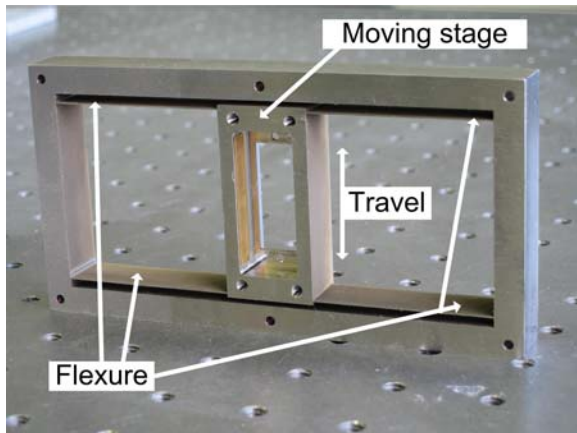


FIGURE 1. Monolithic flexural stage

The stage is driven directly by two linear piezo motors (HR4-1-S-3, Nanomotion Ltd) which sit on the back plate. As a result, the flexural stage provides extremely straight motion with no backlash. The friction shoes of the motors with a proper preload force push against the friction plates that are attached to the inner frame. As can be seen in Figure 2, the two HR4 motors fit inside the cavities created by the flexure beams of the moving stage and drive the moving stage from opposite sides. This requires the direction of one of the motors to be opposite from the other. Because both HR4 motors are driven by the same AB5 amplifier, a special y-connector is required where one of the motor connectors has the forward and reverse signals reversed.

The friction strips come with a sticky tape attached to the back and for typical applications, this is the recommended means of securing the strip. In this case, however, the length of the strips is rather short and the sticky tape proved to be too compliant. As a result, the moving frame drifted over time. Replacing the sticky tape with epoxy solved this issue.

The digital encoder (RGH 24, Renishaw) is fixed to the center of the back plate and read the

position of the moving frame by scanning the encoder the strip that is attached to the moving frame.

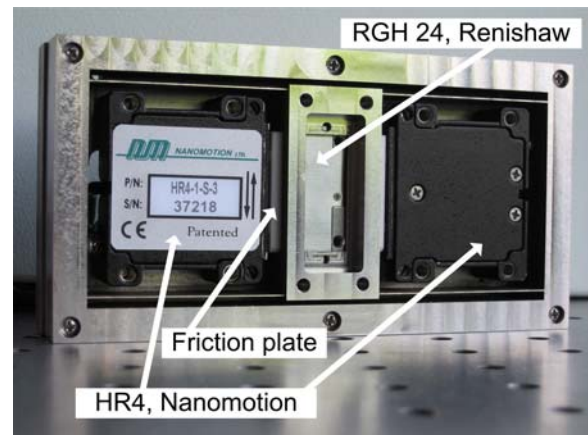


FIGURE 2. Flexural stage with linear piezo motors and non-contact digital encoder (full assembly)

The flexural stage is controlled in a closed-loop by a PID controller at a rate of 62.5 microseconds (PXI-7354, National Instruments). The position feedback from the encoder that is sent to the PID controller is a digital signal with a resolution of 50 nanometers. The motor driver (AB5, Nanomotion Ltd) used to drive the motors receives the command voltage from the PID controller and transforms it to a high frequency signal sent to the motors in order to create movement of the friction shoes.

EXPERIMENTS AND RESULTS

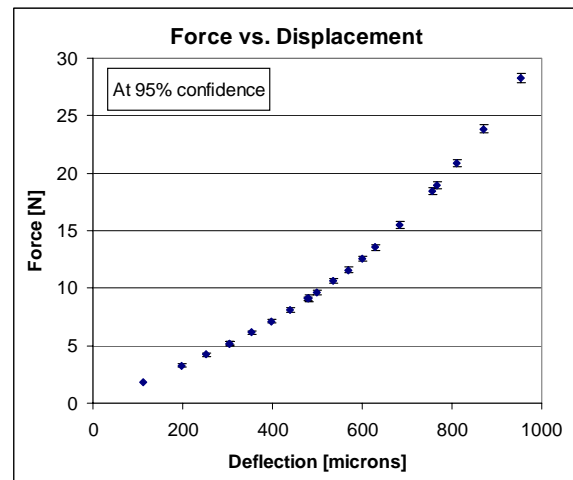


FIGURE 3. The relation of force and deflection of the flexural stage

The force vs. deflection experiment has been setup by attaching the inner frame of the flexure

stage with a set of deadweights. By increasing the weight and measuring the position from the encoder, the relation between force and deflection from the center of the flexure stage can be determined as shown in Figure 3.

From Figure 3, the results show that the flexure stage tends to have an almost linear relationship when the deflection is less than 400 microns and develops a non-linear relationship at deflections larger than 400 microns. The linear range of 400 microns is quite small when compared with the 40 mm length of the flexure beam. There are not only bending stresses applied to the beam but also an axial stress due to the symmetry constraint of this design. This axial stress limits the linearity range to less than a normal flexure system. But this design has some advantages: each flexure uses only a single beam element which reduces the chance of twisting the beams. As a result, it can hold a larger weight in the vertical direction, and it has a very compact stage size which makes it easy to manufacture. Also, the symmetry of the flexures, while limiting the axial travel, prevents any parasitic motion of the stage, thereby creating an extremely straight motion of the moving stage.

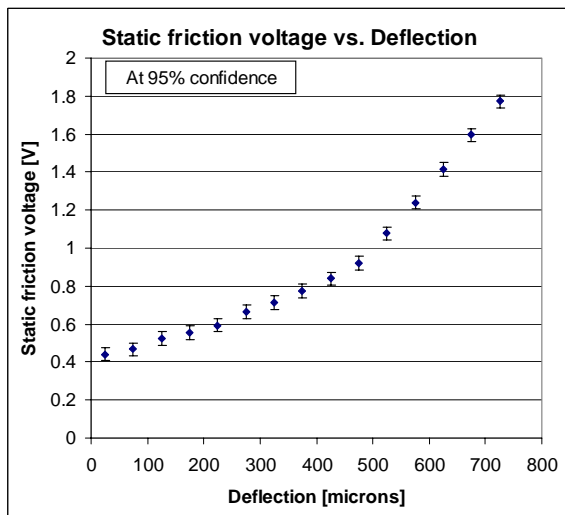


FIGURE 4. The relation of static friction voltage and deflection of the flexural stage

The static friction voltage is the minimum command voltage that is required to start the moving of the stage. This voltage offset is a result of the inherent friction in the drive system. As such, as the stage is commanded to move, the servo voltage will start at this offset rather than at zero Volts. This dramatically increases the controllability of linear piezo motors.

In the case of a flexure based system which ideally has no friction, the static friction voltage is the voltage needed to overcome the spring force of the flexure which is related with its deflection in addition to the friction of the motor. As shown in Figure 4, the static friction voltage increases linearly versus deflection for the first 400 microns from the center position. After this point of 400 microns, the relation becomes non-linear. These results agree with the results from Figure 3. In the neutral position of the stage at a deflection of 0 microns, the static friction voltage is about 0.4 V which means that the magnitude of the dead-band of these motors is 0.4 V. To improve the dynamic positioning control of the flexure stage, the static compensation voltage, which typically is a static value, may be dynamically updated according to Figure 4 to compensate for the non-linear effect.

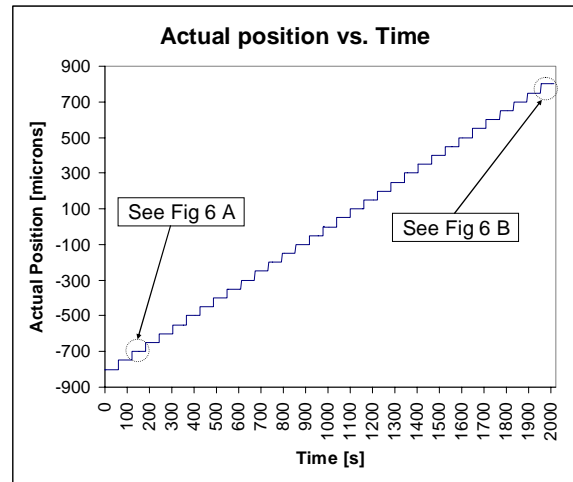


FIGURE 5. The actual position of the flexural stage vs. time (the motors are turned off at the beginning of each step and hold for 1 minute before moving to the next position)

Most servo systems, after having reached the target position, maintain this location through active servo control, meaning the drive system remains under power. As such, the system is subject to servo noise which causes small amounts of motions that induce errors.

Drive systems based on linear piezo motors can make use of the inherent friction of the drive system and allow the motors to be turned off completely once the target position has been reached. This also eliminates heat generation from the motors, thereby increasing the thermal stability of the system.

Therefore, to hold the position of the flexural stage, the static friction between the friction

shoe and friction plate is an important factor in resisting the spring force of the flexure and any applied external force as well. Figure 5 presents the results of an experiment that shows the travel of the stage over its entire range. The stage was positioned in 50 micron increments and held in place by turning off the motors at the end of each step.

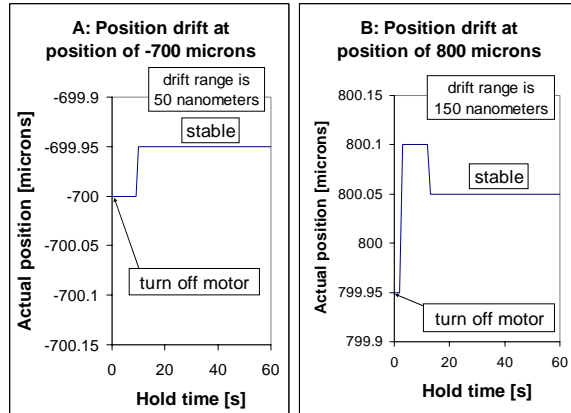


FIGURE 6. The position drift vs. time at hold position of -700 and 800 microns. The motors are turned off at the beginning of each control position and hold the position for one minute before moving to the next position.

Figure 6 shows the position of the stage as a function of time in more detail. As can be seen, the position of the stage drifts after the motors are turned off but the drift is limited to a maximum of 50 nanometers for Figure 6A and 150 nanometers for Figure 6B.

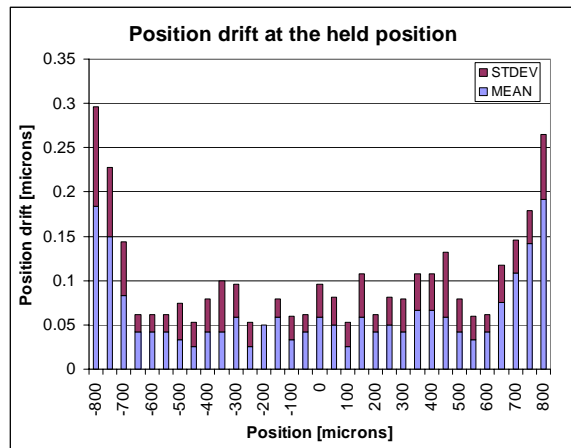


FIGURE 7. The mean and standard deviation (STDEV) of the position drift from 6 experiments (after waiting 1 minute at each brake position)

Figure 7 shows the mean values and the standard deviations from 6 experiments of the position drift after a holding time of 1 minute at

each position with the motors turned off. The results show that the positions that are further away from the center tend to exhibit larger position drifts. The position drift from all experiments is less than 0.4 micron which is acceptable for most applications in meso-level machining.

CONCLUSIONS

We have shown a new type of linear stage with greatly increased travel compared to standard nanopositioning stages. The stage is a monolithic flexure-based design that in combination with two linear piezo motors exhibits no detectable backlash or error motion.

The flexure based system ideally has no friction; the major force that the motors need to overcome is the spring force from the flexure as well as any external force applied to the stage, which is predictable.

The static friction between the motor and the friction strips is sufficient to hold the stage at any position over the entire length. This allows the motors to be turned off at each position, thereby eliminating heat generation from the motors. As a result, thermal drift of the system is all but eliminated.

The quality of the mounting of the friction plates to the frame is very important. The standard sticky tape is too compliant owing to the short length of the friction strips. Replacing the tape with epoxy dramatically increases the performance of such a drive system.

FUTURE WORK

The non-linear behavior of the flexure affects the static friction voltage, which no longer is a static value but increases as the flexures are moved away from their neutral positions. For increased positioning accuracy and even better dynamic performance, a control algorithm that allows this offset voltage to be updated dynamically will be developed.

REFERENCES

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- [2] E. Bamberg, S. Heamawatanachai, J.D. Jorgensen, "Flexural micro-EDM head for increased productivity of micro-holes", ASPE Proc. 2005, pp. 82-85.