On the design of 2DOF MEMS nano-positioning stages for long stroke and high bandwidth

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***Abstract*—An analysis of the motion of a parallel-kinematics 2DOF nano-positioning stage is described. The relative magnitudes of the stiffnesses in the desired and unwanted directions of motion allow for a stable positioning stage with a large stroke. The large stroke achieved by the device is comparable to larger, non-MEMS devices, and can be operated to its full stroke with actuation voltages of less than 80V. The nanopositioner is designed such that the position of the stage can be estimated from the input voltage with a high degree of confidence. The relative The layout of components has been designed such that unwanted resonance modes are shifted to frequencies far from the operating frequencies. The design consists of a central positioning stage, actuating combs, connecting springs, and the substrate base. Two actuating combs are found at the edges of the device for actuating the device in the x and y directions. These are connected to the substrate with beam springs that are oriented perpendicular to the direction of actuator movement. The central positioning stage is connected to the actuating combs using beam springs which are oriented parallel to the direction of actuation of the comb.**

***Index Terms*—SOIMumps, MEMS, nano-positioner, 2DOF, electrostatic.**

I. Introduction.

In order to minaturise and enable batch production of nano-positioning stages, efforts have been made to create MEMS based devices that replicate the function of larger nano-positioning stages. These nano-positioners have found use in applications such as microscopy and ultrahigh-density data-storage systems.

Various actuation methods used in nano-positioners are well understood ()()(), and coupled with methods for increasing the stroke of actuators (), and methods of position sensing ()(), devices capable of being used for microscopy are able to be created ().

In order to optimise the devices for use in eg. an AFM, an understanding of the relationships between the suspension geometery and the motion in each direction is required.

Here, we present an analysis of the spring suspension used in a parallel-kinematics 2DOF nano-positioner manufactured using the SOIMumps process. The device uses the same parallel-kinematic topology as used in (Yong's Paper), however the mechanical design has been re-engineered for improved stability and die size, with the aim of using the positioner as a scanning stage in an AFM.

The positioner is actuated electrostatically by two large comb-actuators placed orthogonal to each other, which suspend a central positioning stage by an array of beam-springs, and are themselves suspended by a similar array of beam-springs. While the comb-actuators are used for actuation, their capacitances are also measured during operation for simultaneous actuation and sensing using the same components.

The suspension of the nano-positioner stage has been designed such that although the position sensor is placed far from the positioning stage, its output maps accurately to the actual position. Careful selection of the suspension parameters will yeild improvements in the device's stroke, stability, bandwidth and actuation voltage.

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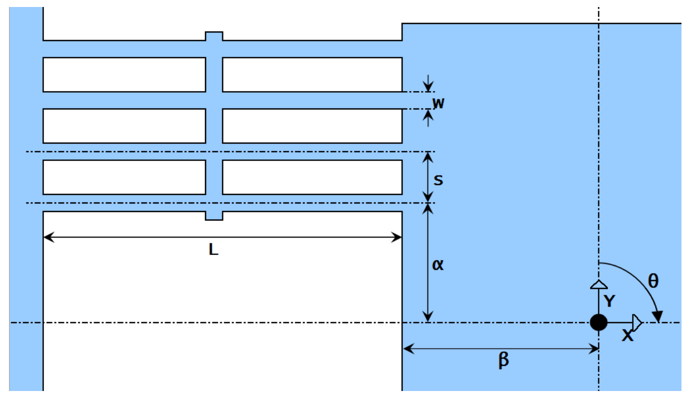

Fig. 1. Simplified flexure suspension diagram.

II. Engineering Analysis.

A. Flexure Suspension.

The nano-positioner is designed such that the position of the stage can be estimated from the input voltage with a high degree of confidence,

The characteristics of motion of a spring-suspended object in both the steady-state and frequency domains is governed in part by the stiffness of the suspension.

The stiffnesses of a suspension system using a multiplicity of beam springs separated into segments by a rigid inter-beam web, as shown in Figure 1, can be expressed as in equations (1)-(4).

$$k_x = nk_{x_0} = nEwT/L \tag{1}$$

$$k_y = nk_{y_0} = nETw^3/L^3 \times q^2 \tag{2}$$

$$k_z = nk_{z_0} = nEwT^3/L^3 \tag{3}$$

$$k_\theta = nk_{y_0}\beta^2 + \sum_{i=0}^{n-1} k_{x_0}(is+\alpha)^2 \tag{4}$$

where E: Youngs modulus
T: Beam thickness
n: Number of beams
q: Number of segments per beam

Note that the second moment of area $I_0 = bh^3/12$ (for a rectangular cross-section), has been expanded for clarity, and that the small displacement theory () has been used in developing these equations. Thus the small, non-linear terms have been neglected.

The directional spring-constants of the suspension can be tuned somewhat independently due to the powers of the terms. It can be seen that increasing the width of the beams, or the addition of a web across them dramatically increases the stiffness of the suspension in the Y direction, with comparatively smaller increases seen in the other directions.

In comparing the magnitudes of the different spring constants ratiometrically, these methods for tuning the system become evident.

$$R_{xy} = k_x/k_y = L^2/(w^2q^2) \tag{5}$$
$$R_{zy} = k_z/k_y = T^2/(w^2q^2) \tag{6}$$
$$R_{xz} = k_x/k_z = L^2/T^2 \tag{7}$$

If R_{xy} and R_{zy} are maximised, as is the case when the width or number of segments in the suspending beams is selected to be small, motion of the suspended body may be restricted to approximately rectilinear motion in only the Y direction. Any external disturbances will then have a much smaller impact on the position of the body in the remaining directions. For a nano-positioner where the position sensors are placed far from the positioning stage, the well defined path of motion is required for good mapping between the sensed and actual position.

Earlier nano-positioner implementations have suffered from low tortional rigidity in both the actuating combs and the positioning stage. This has resulted in low strokes, and uncertainty in the position of the stage.

For nano-positioners actuated with electrostatic comb actuators, large actuating forces and hence long strokes cannot be achieved without high lateral and tortional stiffnesses. When large forces are generated by using comb actuators, potential for the non-linear snap-in effect exists if the combs are allowed to rotate or move laterally.

If high lateral stiffness has been achieved by maximising R_{xy} as above, very high tortional stiffnesses can be obtained by maximising the α term in (4); by placing the beams as close as possible to the extremities of the stage.

For a nano-positioning stage to be used in an AFM, operation at high frequencies is desired.

Something should be added about the maximum deflection of the beam before failure?

The layout of components has been designed such that unwanted resonance modes are shifted to frequencies far from the operating frequencies. The design consists of a central positioning stage, actuating combs, connecting springs, and the substrate base. Two actuating combs are found at the edges of the device for actuating the device in the x and y directions. These are connected to the substrate with beam springs thTch are oriented parallel to the direction of actuation of the comb.

B. *Electrostatic Actuation.*

III. Device layout.

The device is a parallel kinematics 2DOF positioner. The positioning stage is suspended from the actuation combs by use of many thin beam flexures. The actuation combs are in turn suspended from the substrate base with a similar array of beam flexures. The stiffness of the positioning stage suspension will be a series combination of the base-actuator and actuator-stage suspension systems, and will have stiffnesses as shown in (8) - (10).

$$k_X{}^{-1} = 4k_{xA}{}^{-1} + 4k_{yB}{}^{-1} \tag{8}$$
$$k_Y{}^{-1} = 4k_{yA}{}^{-1} + 4k_{xB}{}^{-1} \tag{9}$$
$$k_\Theta{}^{-1} = 4k_{\theta A}{}^{-1} + 4k_{\theta B}{}^{-1} \tag{10}$$

Since the measurement location is far from the positioning stage, a large stiffness in the suspension system is required. By using a layout that uses many thin beam flexures, the stability of the positioner is increased, with the designed device achieving spring constants of:

$$k_X = k_Y = \tag{11}$$
$$k_Z = \tag{12}$$
$$k_\Theta = \tag{13}$$
$$k_\Phi = \tag{14}$$
$$\tag{15}$$

for the device as described with

$$\begin{aligned} n_A &= 9 & n_B &= 5 \\ w_A &= 3\mu m? & w_B &= 3\mu m? \\ L_A &= & L_B &= \\ s_A &= & s_B &= \\ h &= & E &= \end{aligned}$$

A. *Single-Beam, Beam Array Comparison.*

The nano-positioner described uses arrays of many beam springs rather than a few single-beams at the extents of the device. If the device was designed using single beams as is the case in other devices (find references of such), the stroke and frequency characteristics suffer. Show examples and compare numerically.

The 1st resonant frequencies of the positioning stage due to the application of these springs' forces on the positioner in a vacuum can be estimated as:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{16}$$
$$f_\theta = \tag{17}$$
$$\tag{18}$$

Which places the unwanted resonances at frequencies that are much higher than the desired motion, such that they wont be induced during normal operation. Something about the mass of the sample affecting the resonant frequency.

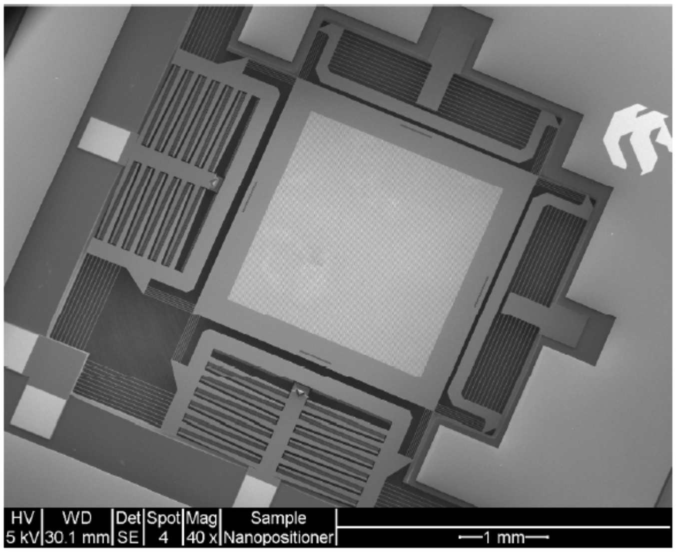

Fig. 2. SEM image of fabricated nano-positioner.

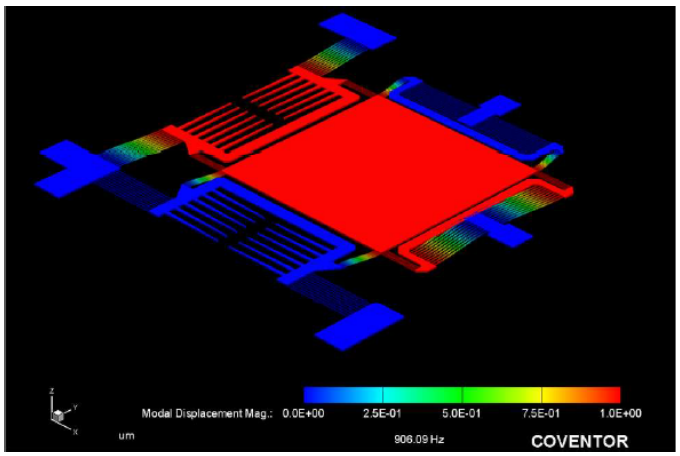

Fig. 3. CoventorWare modal analysis showing first in-plane resonant mode of nanopositioner.

IV. Device Characterisation.

The described device was manufactured using the SOI-Mumps process using a layer thickness of Xμm.

A. DC Characteristics.

The device was operated in open loop with voltages blah, provided this response.

B. AC Characteristics.

Blah blah.

C. Comparison with Modelled Values.

V. Conclusion

The conclusion goes here.

Appendix A
Proof of the First Zonklar Equation

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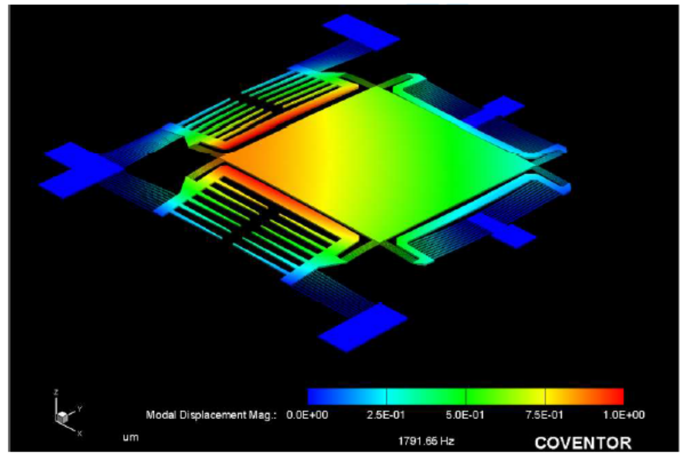

Fig. 4. CoventorWare modal analysis showing higher-order resonant mode of nanopositioner.

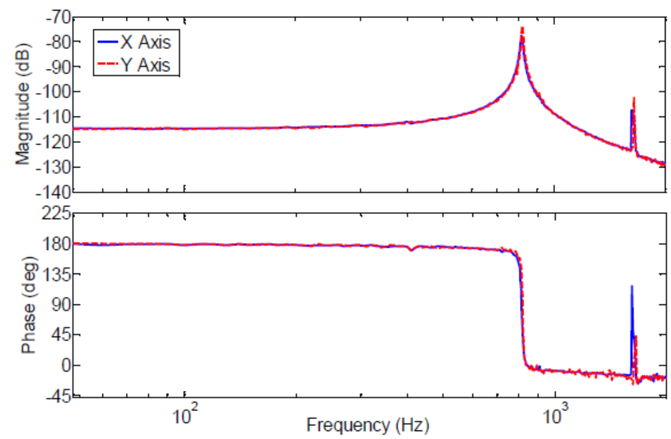

Fig. 5. Actuation Voltage vs Displacement.

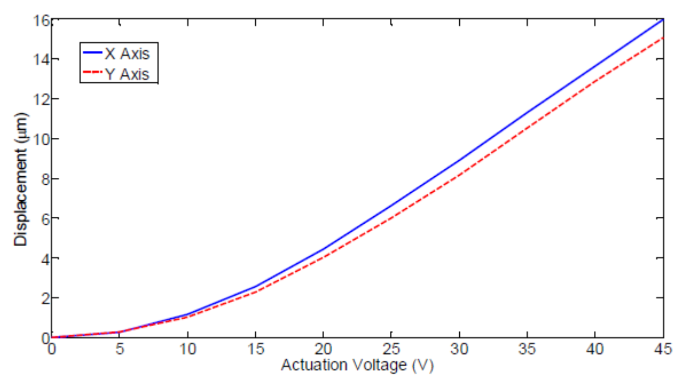

Fig. 6. Frequency Response.

Acknowledgment

The authors would like to thank...

References

[1] H. Kopka and P. W. Daly, *A Guide to LaTeX*, 3rd ed. Harlow, England: Addison-Wesley, 1999.

Aaron Hammond Some text about me