A novel constant force compliant precision stage to balance a load in six degrees of freedom

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Abstract

Introduction - In many applications in precision engineering a constant load, such as a gravity force, needs to be positioned with ultra-high accuracy, often situated in a vacuum environment. In order to eliminate backlash, friction and the need for lubrication, compliant mechanisms are often used [1]. However, in a vacuum the associated positive stiffness of the flexible elements results in excessive levels of heat produced by actuators. This positive stiffness can be counteracted using a stiffness compensation mechanism with a negative stiffness, resulting in a statically balanced (i.e. zero stiffness with near zero actuation force) compliant mechanism (SBCM). SBCMs are having a constant potential energy in every position and therefore has zero stiffness [2,3]. In this work we present the novel design of a zero stiffness, 6 degrees of freedom (DoF) compliant precision stage, which is able to balance a gravity force applied on the stage.

Design - In a prior study [4] several concepts for balancing a force along a trajectory are discussed and it has been shown that straight guided bi-stable buckling beams show the best mechanical efficiency for the ratios of compensated force and statically balanced domain to the size of the mechanism. We proposed a novel compliant mechanism to balance 6 DoF, while carrying a load. Static balancing of the out-of-the-horizontal-plane motions (translation along the vertical z-axis (*Tz*), rotations about the horizontal x-axis (*Rx*) and y-axis (*Ry*)) are proposed by cooperative action of three identical statically balanced units, arranged in a triangular configuration (Fig. 1). These units consist of bi-stable buckling beams (with a negative stiffness domain)

and v-shaped beams (with a constant positive stiffness). Balancing the in-the-horizontal-plane motions (translation along the horizontal x-axis (*Tx*), y-axis (*Ty*) and rotation about the vertical z-axis (*Rz*)) is achieved by three flexible rods. Loading these flexible rods near their buckling load results in a near zero stiffness for in-plane motions [5]. An investigation on optimizing the design parameters to minimize the residual actuation force was also performed. A prototype was fabricated (Fig. 1). The bi-stable buckling beams and the v-shaped beams were made of Titanium Grade 5 (Ti6Al4V) (E=113GPa, σ_y=830MPa), and the flexible rods were made out of brass (E=97GPa). Experiments were done to evaluate the concept and compare to the results from simulation (Fig. 2).

Experimental evaluation - Experimental evaluation showed that the design is successful. A gravity force of 34.4N was balanced with a residual stiffness of 1.75N/mm in a domain of 2mm for the out-of-plane translation (Fig. 2). The out-of-plane rotational stiffness was less than 18.5Nm/rad (Fig. 3a). This was caused by parasitic torsion of the bi-stable beams and v-shaped beams. The stiffness for in-plane translations and rotation was 0.4N/mm and 2Nm/rad, respectively (Fig. 3b,c).

Conclusions - The results show that near zero stiffness 6 DoF positioning can be achieved. This novel compliant mechanism is able to cancel out the stiffness due to its monolithic structure, and at the same time position a load in 6 DoF with minimum actuation force. The novel mechanism or the principle may extensively be applied in several applications in precision engineering or in other relevant fields, such as vibration isolation.

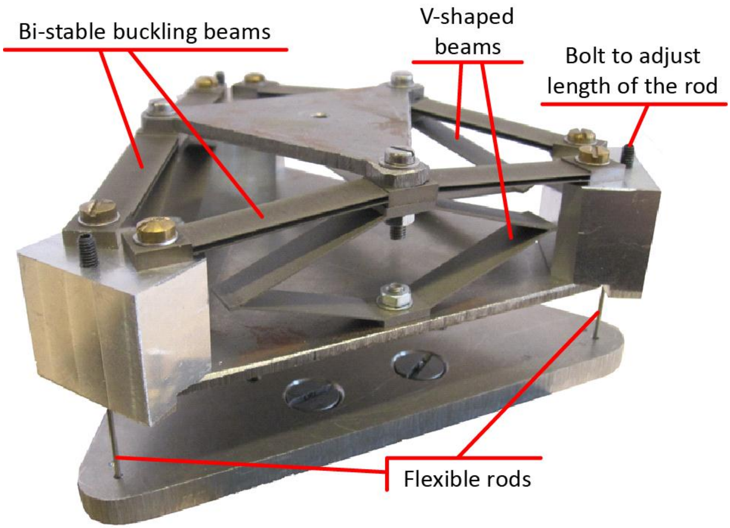


Figure 1: Prototype of zero stiffness six degrees of freedom compliant precision stage and its components: the bi-stable buckling beams and the v-shaped beams for out-of-plane motions, and flexible rods for in-plane motions; the length of the rods can be tuned with the bolts.

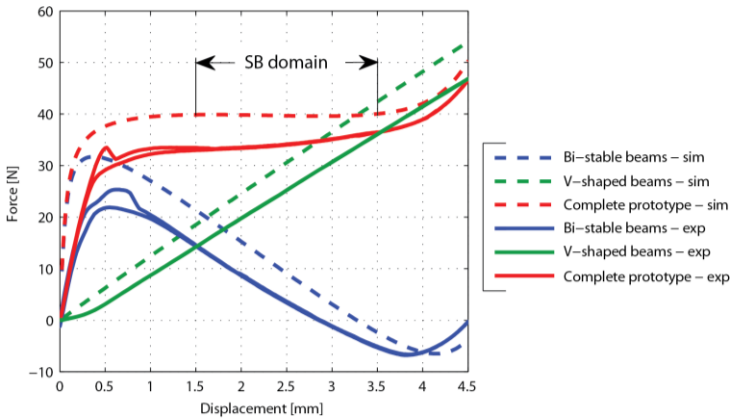
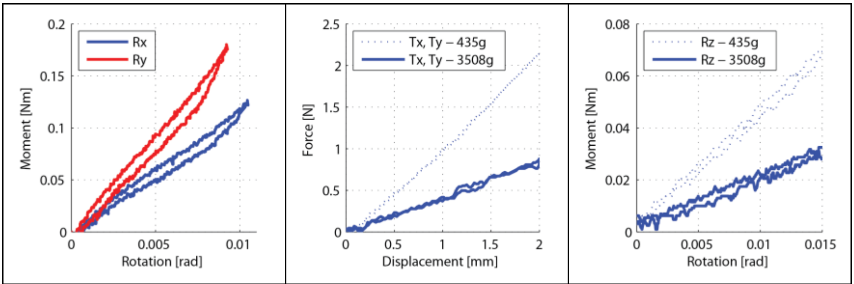


Figure 2: Results of the force-displacement characteristic of the bi-stable buckling beams, v-shaped beams and the complete prototype, for simulations in ANSYS^{TM} (dashed) and experiments (solid) in *Tz* direction. The residual stiffness in the balanced domain of the prototype is 1.75N/mm, from 1.5-3.5mm displacement.



(a) (b) (c)

Figure 3: Results from the measurement for (a) rotational stiffness for out-of-plane motions (K_{Rx}=12Nm/rad, K_{Ry}=18.5Nm/rad), (b) stiffness in *Tx* and *Ty* direction (K_{Tx}=K_{Ty}=0.4N/mm), (c) rotational stiffness in *Rz* direction (K_{Rz}=2Nm/rad).

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