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Zero-force rectilinear flexure-based translation stage: Experimental validations

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Abstract

Compliant mechanisms can advantageously be preloaded by buckled beams in order to reduce their motion stiffness, and therefore also their actuation forces. However, preloading compliant mechanisms has the side-effect of modifying the deformation of their flexural elements, thus resulting in altered motion trajectories. In this paper, the case of a flexure-based translation stage is treated taking into account both issues at the same time, leading to a design benefiting from a preloaded buckled beam simultaneously for stiffness reduction and motion rectilinearity improvement. The studied mechanism is a compliant planar four-bar rectilinear stage based on four Remote Center of Compliance (RCC) pivots, called *4-RCC*, manufactured in aluminum alloy by Electrical Discharge Machining (EDM), equipped with a buckled beam made of hardened spring steel. The mechanism is dimensioned based on analytical and finite element models to obtain simultaneously a near-zero stiffness and a quasi-rectilinear translation. Experimental results show that the buckled beam reduces the translational stiffness of the stage more than 98%, while decreasing the parasitic shift of the stage by more than 85%. In absolute terms, over a total translation stroke of 8 mm, a parasitic shift below 0.95 µm and a restoring force below 0.1 N were measured. This study validates the proposed design approach and paves the way for the use of such *4-RCC* mechanism for precision positioning applications requiring high-straightness motion and low-power actuation.

Flexures, Rectilinear mechanisms, Stiffness compensation, Parasitic shift, Zero-force, Beam buckling, Electrical discharge machining

1. Introduction

Preloading compliant mechanisms, e.g., to reduce stiffness, may alter their motion trajectories [1,2]. In prior work, we described and modeled a novel flexure-based translation stage based on four Remote Center Compliance (RCC) pivots, called *4-RCC,* presenting near-zero parasitic shift properties [1]. Thanks to the integration of a buckled beam in parallel to the stage, the translation stiffness is drastically reduced while simultaneously improving its motion straightness. In the present paper, a mesoscale prototype of the *4-RCC* mechanism is dimensioned, fabricated and tested experimentally. Measurements are carried out to demonstrate that the buckled beam indeed reduces the stiffness of the stage as well as its parasitic shift.

2. Design

The *4-RCC* planar rectilinear flexure translation stage is based on a parallelogram linkage with four identical RCC pivots R, S, T and U (Fig. 1a). When a fixed-guided buckled beam is integrated within the mechanism, forces P and V are applied to the moving block (Fig. 1b). These forces respectively modify the parasitic translation shift Δy and reduce the natural stiffness F/x of the stage. For specific dimensions of the buckled beam, both the parasitic shift and the stiffness can be significantly reduced [1].

A mesoscale prototype of the mechanism is dimensioned using the analytical model derived in [1], with the aim of both minimizing Δy and F. The obtained parameter values are given in table 1. The *4-RCC* stage is fabricated monolithically in aluminum alloy (EN AW-7022) using Electrical Discharge Machining (EDM). The buckled beam is made of a spring strip (steel 1.1274) with length L, width b and thickness h. These materials are selected for their high yield stress over Young's modulus ratios, $\sigma_{y,0}/E_0$ and σ_y/E. The motion range of the stage along the x-axis is limited to ±4 mm such that the von Mises stress (obtained from simulations, see Sec. 3) remains below the fatigue strength of the materials (estimated as 50% of $\sigma_{y,0}$ and σ_y). A preloading displacement $\Delta l = 0.6$ mm is applied to ensure that the buckled beam is preloaded in second mode branch over the full stroke [1,3].

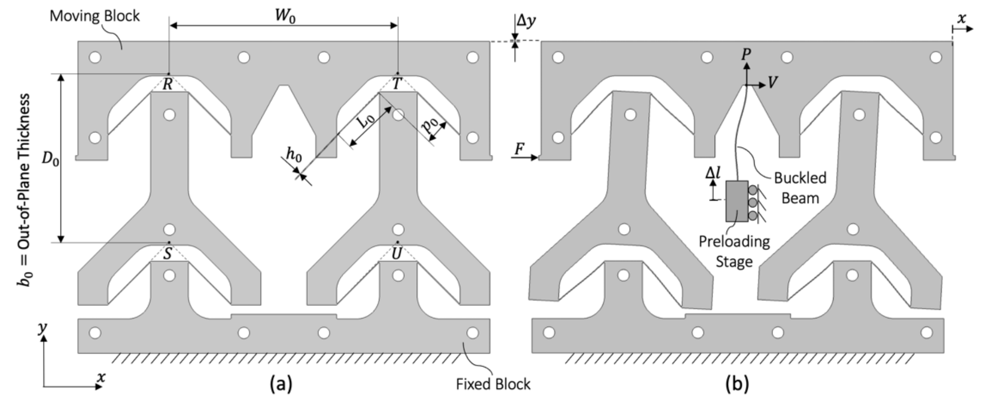

Figure 1. *4-RCC* mechanism (a) as-fabricated and (b) in deformed position and preloaded by a buckled beam

Table 1. Design parameters of the *4-RCC* mechanism (see Fig. 1)

Structure Part		Parameter	Value
4-RCC Stage	Material (EN AW-7022)	E_0	72 GPa
		$\sigma_{y,0}$	460 MPa
	Stage	D_0	73.4 mm
		W_0	100 mm
		b_0	10 mm
	Pivots	h_0	0.3 mm
		L_0	25.5 mm
		p_0	12 mm
Buckled Beam	Material (Spring Steel 1.1274)	E	210 GPa
		σ_y	1600 MPa
	Beam	h	0.3 mm
		L	45 mm
		b	6 mm

3. FEM simulations

A 2D static Finite Element Method (FEM) study is performed on Comsol Multiphysics 6.1 to evaluate the parasitic motions and the force-displacement characteristics of the prototype. Each beam is meshed with quadrilateral shells having 4 and 200 elements along their thickness and length, respectively.

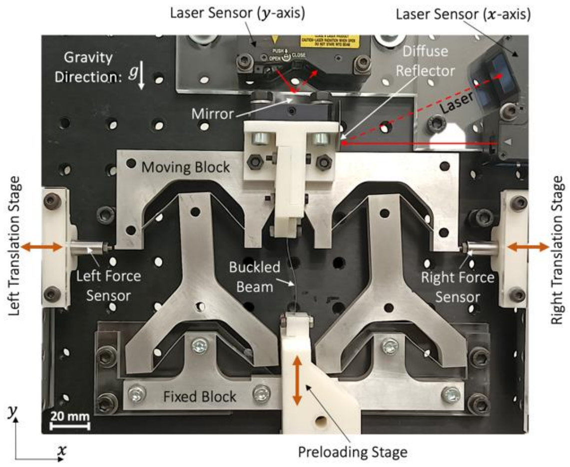

Figure 2. Testbench used to characterize the *4-RCC* prototype

4. Experimental results

A dedicated testbench is provided to characterize the parasitic lateral translation and the primary stiffness of the mesoscale prototype (Fig. 2). Two manual translation stages and respective force sensors (Kistler 9207) are used to displace the moving block in both directions along x while measuring the actuation force F. The end-shortening Δl of the buckled beam is controlled by an additional manual translation stage moving along the y-axis. The parasitic shift Δy is measured using a specular-reflection laser sensor (Keyence LC-2420) and a $\lambda/20$ flat mirror (Edmund Optics 43-412-522) mounted on the moving block and properly aligned with the y-axis. A diffuse-reflection laser sensor (Keyence LK-H082) is employed to measure the stage displacement x. Static measurements are performed with and without the integration of the buckled beam, for comparison purposes, and are averaged over five measurement repetitions for sensor noise mitigation. Gravity is orientated along y to avoid applying out-of-plane loads to the mechanism. Note that in-plane gravity effects are however neglected in the analytical and FEM models. Indeed, the weight of the mechanism (including the mirror system, see Fig. 2) acting along y is lower than 4 N, which is assumed negligible with respect to the buckled beam load $P = 55$ N (value obtained from [1, Eq. (9)]).

Figure 3 shows that the parasitic shift and the natural stiffness are greatly reduced when the fixed-guided buckled beam is added. Indeed, the maximum magnitude of Δy is decreased from 6.4 µm to 0.95 µm and the maximum magnitude of F is reduced from 5.1 N to 0.1 N, considering the total stage stroke of 8 mm. Standard deviations of the measurement repetition (not shown on the graphs) are bounded within 0.3 µm and 0.02 N for Δy and F, respectively. Analytical and FEM results are also plotted in Fig. 3, showing good agreement with the experimental data, and validating thus the established models. Note that the stage has also an in-plane parasitic rotation θ_z, primarily due to the reaction moment applied by the buckled beam to the moving block. However, FEM models show that the magnitude of θ_z does not exceed 17 µrad over the whole motion range.

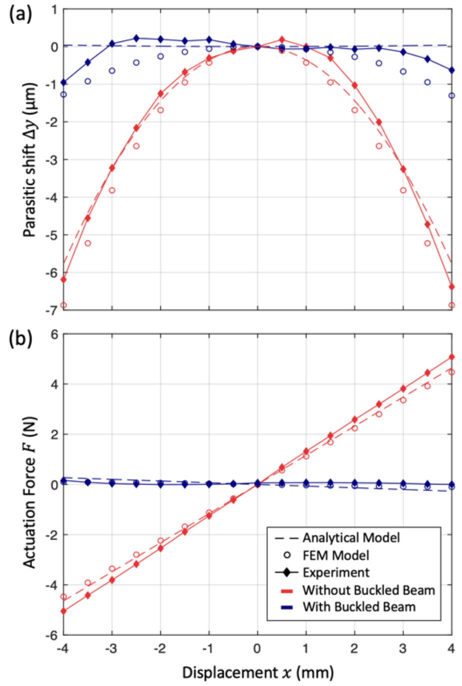

Figure 3. Characteristics of the *4-RCC* mechanism: (a) parasitic shift and (b) actuation force as a function of the stage displacement

5. Conclusion

In this paper, we experimentally validate the parasitic shift and stiffness compensation concept of a *4-RCC* rectilinear translation stage preloaded by a fixed-guided buckled beam. A mesoscale prototype (external volume of 182 x 136 x 10 mm³) is designed and fabricated. Experimental results show that, the straightness error and the actuation force are respectively reduced by 85% and 98% when the buckled beam is added, validating the compensation principle. With a parasitic shift below 0.95 µm and an actuation force below 0.1 N for a translation stroke of 8 mm, the designed rectilinear stage can be used in applications requiring high-precision motion and low-power actuation.

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