Elastic behaviour of millimetre-scale polymeric triskelion-like flexures

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Abstract

A small study of the non-linear translational spring behaviour in triskelion planar suspensions uses low-cost mm-scale polymeric devices to explore the effect of several design parameters. The paper summarizes the approach and presents illustrative results. The stiffening characteristic is often quite modest and the angles of suspension beams may be useful for fine-tuning to different applications.

1 Introduction

The three-beam planar flexures called triskelions are attracting considerable interest. E.g., some commercial CMM microprobes now exploit micro-fabricated triskelions [1], to provide modest control of stiffness values over μm-scale motions in three translational freedoms. Other applications will benefit from different compromises between potential operational parameters. Nano-force transfer standards [2] are an excellent example, ideally needing very predictable *z*-stiffness in an approximation to single-freedom translation. Taking a triskelion to be a symmetrical thin structure in the *xy* plane, its central hub relatively easily undergoes small *z*-translations and *x*- and *y*-axis rotations by means of bending and torsion of the suspension beams; the other three freedoms are effectively constrained by the much higher stiffnesses on their axes. Overall, it behaves similarly to a reduced-stiffness diaphragm. Intuitively, the three suspension beams relate to the three freedoms, but even an elementary pseudo-kinematic view of published designs indicates a significant over-constraint (mobility well below three); so, e.g., non-linear (stiffening) spring behaviour is expected. The present study therefore asks whether somewhat larger triskelions might be exploitable as guides or reference springs in low-cost instrument systems, seeking practical data on how design parameters might be selected to suit differing applications.

2 mm-scale polymeric triskelions

All published parametric models seem to derive closely from [3], a linear elastic model of symmetrical forms having rigid platforms and rigid inner arms with 60° 'elbow' connections (as in microprobes). More complete models clearly need experimental data for how strongly spring non-linearity and relative axis stiffnesses vary with sizes and angles within the triskelion flexure. Testing micro-devices is challenging and costly, so an easier regime is desired. Making low-cost triskelions suggests injection moulding. For both reasons, this study focusses on acrylic polymer devices at millimetre scales.

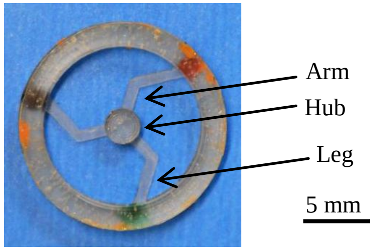

Figure 1: 120° acrylic angle-beam triskelion

As the pilot study needed a few each of several design variants, specimens were hand fabricated using simple open moulds machined into aluminium substrates. The negatives of a relatively deep central hub and outer ring, connected by shallower leg structures, were filled with a commercial acrylic surface replication resin and smoothed off with a microscope slide. Despite the relatively poor control of this manual process, beam thickness (the most critical dimension) repeated to within a spread of 20 µm. Fig. 1 shows a device with 120° elbow angle. For all results given here, the central hub radius was 1.5 mm and all beam sections were 1 mm wide. The 'rigid' arm and hub were both 1 mm deep. In alternate angled beam designs both leg and arm had the same thickness. Having more modes of deflection (freedom), they would be expected, if stable, to be less stiff and more linear than rigid-arm designs.

3 Measuring force-displacement characteristics

Figure 2 schematizes the force-displacement test-rig used. A side-acting inductive gauge (T) carries a 50 mm probe arm (A) to which is clamped a small, hard spherical probe tip and a saturated magnet that forms a force actuator with a solenoid coil (FT). The tip contacts the hub of the specimen (S) held on a fine motion *xyz*-stage. The gauge (Taylor Hobson Talymin) offers a range of 0.2 mm, resolving practically to ~50 nm. The actuator provides a force closely proportional to coil current up to about 1 N that is essentially independent of small variations in magnet position, although there is a small effect from the internal springs of the sensor. A second displacement gauge (H, an optical grating, 1 µm resolution) monitors changes in the z-height of the stage and sample and allows a manual nulling technique. The sample was raised by a set amount and then the force increased to deflect the hub downwards to its previous position (as indicated by T). This provides both larger range and reduced uncertainty from internal springs.

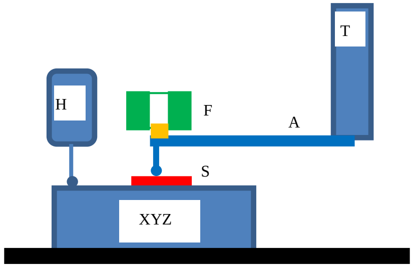

Figure 2: Test-rig schematic

First trials located the tip on the outer ring of specimens, acting rather like a micro-hardness tester. Indentations were just discernible above the noise floor for loads up to 500 mN, providing a low-quality estimate for Young's modulus in the region of 1-5 GPa, reasonable for the polymer. This confirms that sample indentation is negligible for stiffness measurements up to at least several kN m^{-1}.

Summarizing (through limited space) results from rigid arm triskelion designs, centrally loaded devices with suspension beams nominally 0.1-0.2 mm thick and 4 mm long could deflect by over 1 mm without failure. They had slowly stiffening force-displacement curves that could consistently be fitted by a 3rd order polynomial with $R^2 > 0.999$; this is to be further investigated. Typically, stiffness was constant within 1% up to over 200 µm deflection with a 60° elbow, but only to ~100 µm for 90° ones. Dimensions and materials properties were not closely controlled for valid numerical comparisons, but short-range stiffness values were broadly consistent with basic linear models and the patterns observed qualitatively as might be expected from over-constraint on the internal bending and torsion modes.

Figure 3 shows results from a 60° angle beam device of 0.1 mm thickness. The inner arm was 2 mm long, the outer leg 4 mm. The curve is noticeably straighter than from a similar rigid arm design up to 1 mm. Initial stiffness is ~530 N m^{-1}, lower than rigid arm designs by less than might be expected intuitively. The longer leg section dominates the arm, which it still allows some relaxation. The stiffnesses for 90° and 120° elbows were around 1 kN m^{-1} and 700 N m^{-1}. The 120° design was the most non-linear, the 90° one the least. The reduced internal constraint might also reduce torsional stiffness at the hub to make the devices less useful as linear springs. Applying the load at points close to the hub edge (the worst case for a real application) showed that additional twisting reduced the stiffness under the load by a consistent 7% at the reasonable limit for 'linear' behaviour. This suggests that the same internal deflection modes dominate all the out-of-plane motions.

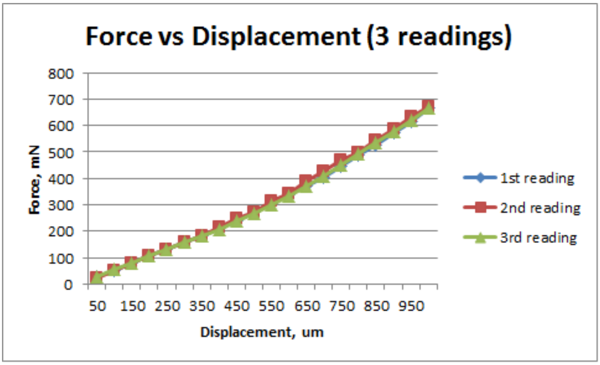

Figure 3: Typical stiffeneing behaviour for a 60 angle-beam triskelion

4 Conclusions

This pilot study encourages further investigations. While numerical comparisons are unwise with current results, consistent patterns show these low-cost polymeric triskelions have useful near-linear ranges within slowly stiffening characteristics. There is clear scope for tuning performance by deviating from the 'classic' design.

References:

[1] e.g. IBS Precision Engineering *ibspe.com/category/triskelion-touch-probes* accessed February 2013

[2] Pril W O 2002 *PhD Thesis*, University of Eindhoven

[3] Jones C W, Chetwynd D G, Singh J and Leach R K 2011 *Proc. 11th eu**spen** Int. Conf.*, **V1** 191-194, Como

Acknowledgment

The authors are grateful to Prof. Richard Leach and Dr Chris Jones at the UK National Physical Laboratory, whose large contributions and support of other work in this field led directly to the present study.