Concept and Modelling of a Novel Active Triskelion Low Force Transfer Artefact

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Abstract

Although many instruments in nanotechnology and microsystems can measure forces to high resolution, there is currently no traceable way to determine their accuracy. We present a traceable low force transfer artefact concept to meet this need in the UK.

1 Introduction

The application of recent advances in micro- and nanofabrication techniques in fields such as microthrusters for aerospace, dosage systems for pharmaceuticals and atomic force microscopy has created an urgent requirement for traceable micro- to nanonewton force metrology. The UK's National Physical Laboratory (NPL) is developing a chain of traceability to meet UK industry's needs in these fields [1]. The NPL Low Force Balance (LFB) realises traceable forces in the 1 nN to 30 µN range with low nanonewton uncertainties, as the primary standard. NPL has developed a transfer artefact concept to facilitate the cost-effective calibration or characterisation of various force producers or receivers in varied environments. This concept offers usability advantages over complementary solutions [2] at other National Metrology Institutes (NMIs) in terms of speed of use and sensitivity to contact alignment.

2 Concept

The proposed concept for a multi-purpose low force artefact consists of a three-leg or 'triskelion' flexure with piezoelectric sensing and actuation, of the form shown in figure 1. Each leg contains a 'rigid' inner section and compliant outer beam section; the latter deforms under a central external load, and internal piezoelectric sensors sense the resultant strain. The rotational symmetry of the triskelion flexure arrangement offers a significant advantage over conventional cantilever type artefacts. With nominal contact at the device centre, its vertical spring constant shows a plateau with respect to lateral position (figure 2), making alignment less critical. In contrast, the spring constant for a simple cantiver is always highly position-dependent.

The rectangular geometry of the compliant outer beams greatly simplifies modelling, leading to development cost savings. The flexure design is highly tuneable, variations in dimensions being used to select optimum size, stiffness and force range. The concept can be scaled from the millimetre scale, millinewton force regime down to the sub-micrometre scale, nanonewton force regime, and possibly further.

The piezoelectric instrumentation used in this concept was selected for its wide bandwidth of operation and ability to generate strain (actuate) and detect strain (sense). Depending on the selected flexure dimensions, it is possible to operate the device as a calibrated strain sensor, a calibrated strain producer and, with appropriate feedback control, a null-deflection force artefact. This flexibility of use renders the concept suitable for a variety of applications and minimises the need for external displacement metrology to allow traceability.

Standard piezoelectric sensors are typically used for dynamic sensors, performing well at high frequency but with poor DC or quasistatic stability. Bespoke signal processing electronics are being optimised to capture and store the charge produced by the device sensors during a displacement. Appropriate choice of instrumentation amplifier and input bias current compensation should enable the drift-free storage of charge for sufficient time to allow a force measurement to proceed.

The device's processed outputs can be easily incorporated into a larger measurement system. The six sensors allow for redundancy and mathematical reduction of

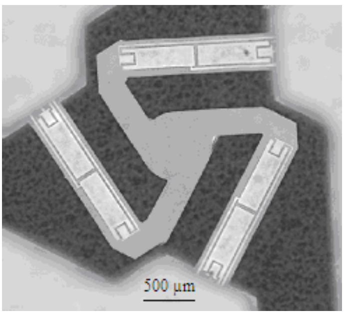

Figure 1: an NPL triskelion device

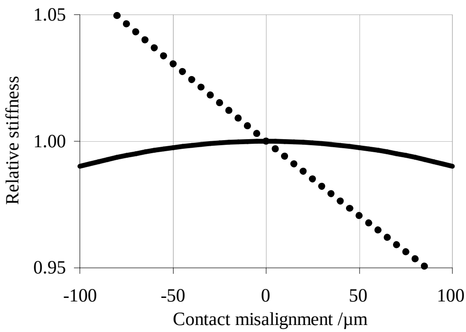

Figure 2: Stiffness sensitivity of similar size & stiffness triskelion (solid line, arbitrary misalignment axis) and cantilever (dashed line, axial axis).

uncertainties. In addition, it is possible to detect, and hence correct, significant contact misalignment from the centre of the device as a difference in response between sensor data from respective legs.

This novel piezoelectric triskelion concept was initially developed at NPL as a component of a probe for traceable micro-coordinate metrology. Traceable low force metrology would support a standard definition for contact between arbitrary surfaces, which at the nanoscale are poorly defined.

3 Modelling

Key to reducing device unit cost is the elimination of unnecessary prototyping steps. However, the range of application requiring traceable force metrology requires the triskelion concept to be scaled to fit a wide range of stiffness and dimensions. Accurate modelling is essential to meet these conflicting demands.

The use and suitability of both first-order analytical and finite-element models were explored to describe and predict the mechanical behaviour of the triskelion flexure system. Provided underlying assumptions can be justified, first order analytical models can describe a flexure system in a manner that facilitates intuitive understanding of mechanical behaviour and simplifies parameter optimisation toward a particular design goal. Finite element analysis approximates second-order motion and kinematic overconstraint in the device and can provide more accurate results but optimisation is computationally intensive and relies on expensive software packages. Assumptions required for first-order treatments in the analytical model include uniform dimensions and material properties and rigidity approximations.

The triskelion model was modelled as three double-ended rectangular cross-section cantilevers with outer ends fixed in six degrees of freedom (6DOF) and inner ends fixed in a common, movable plane, the latter representing the nominally rigid inner legs and hub. An input displacement in 6DOF generates a reaction force from which a vector of stiffness may be derived. The highly parameterised implementation of this model permits additional legs and optimisation of the various parameters (beam size, inner leg length, knee angle) to tune stiffness and resonance to a given application. The model is being extended to second-order to investigate issues such as non-linear effects of large rotations of the flexure.

Artefact	Analytical	FEA	Experimental
A	1	1	1.00 ± 0.10
B	2.87	2.36	2.45 ± 0.12
E	0.85	0.76	0.82 ± 0.04

Table 1: Stiffness ratios A:B:E for three example artefacts obtained by two independent modelling techniques, and experimentally using the LFB.

To verify the principle of the analytical model and test the validity of the underlying assumptions, the stiffness of identically dimensioned and material-specified model geometries were derived using the analytical model and finite-element analysis (Solidworks). Stiffness ratios of three examples are given in table 1. Artefacts A and B have a 1:1.5 thickness ratio; artefacts B and E a 1:1.5 beam length ratio.

The analytical results show good agreement for all artefacts, but thicker examples such as artefact B show a larger discrepancy as the linearity assumptions in linear beam theory begin to break down.

4 Devices

Prototype devices were developed in partnership with Cranfield University. A nickel flexure system is supplemented with a PZT thin film layer selectively poled to create sensors and actuators. The isotropic nature of the nickel permits an arbitrary flexure shape that anisotropic silicon, for example, would not.

The devices have been found to be rugged and more accommodating of over-strain than equivalents. An example device is shown in figure 1. The NPL LFB and a commercial nanopositioning system were used to calibrate the stiffness of the artefacts. The ratios of experimentally observed stiffnesses were found to fall within the range defined by the modelling results, adding confidence to the models.

5 Conclusions

A concept for a piezoelectric triskelion low force transfer artefact is presented. Experimental results suggest that the derived linear flexure model can usefully predict future device behaviour.

References:

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