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COMPLIANT MECHANISMS FOR HIGH-PRECISION POSITIONING

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Abstract: *Given their marked advantages, compliant mechanisms based on spring-strips and flexural hinges constitute a preferred choice in designing high-precision instrument and equipment. In high-precision applications the need to consider the non-linear parasitic displacements makes, however, necessary a careful analytical treatise as well as an experimental validation based on optical techniques.*
Key words: *high-precision, compliant mechanisms, spring-strips, flexural hinges*

1. INTRODUCTION

Today are evident two major tendencies in manufacturing engineering: a tendency towards automation and a tendency towards high-precision. Precision engineering has thus gained in the last years an increasing importance in sectors such as electronics, innovative optics, sensors and actuators, medicine, aeronautics or robotics (Bhushan, 2004). The lack of precision positioning systems due to the presence of inherently stochastic mechanical non-linearities such as friction, backlash and wear in conventional sliding and rolling positioning devices constitutes, in fact, the limit of applicability of tools dedicated to handling and assembly of micro-parts, to the production of micro-electro-mechanical systems (MEMS), of metrological devices, of IT peripheral devices, of high precision machining tools, of scientific instrumentation (STM, AFM, …), …

Increasing attention is thus being dedicated to compliant mechanisms (Howell, 2001) where the absence of the mentioned non-linearities allows to design high-precision positioning devices by which the introduced errors are systematic and can hence be compensated via simple control typologies resulting in reliable designs of limited cost. The analytical treatise of the compliant mechanisms, commonly based on spring-strips or flexural hinges, is, however, generally difficult, since in high-precision application not only the main degree of freedom has to be characterised, but due attention must be dedicated also to non-linear parasitic displacements.

2. COMPLIANT MECHANISMS BASED ON SPRING-STRIPS

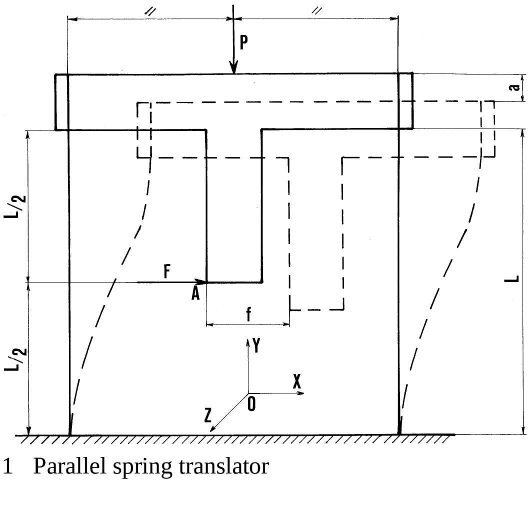

Fig. 1 Parallel spring translator

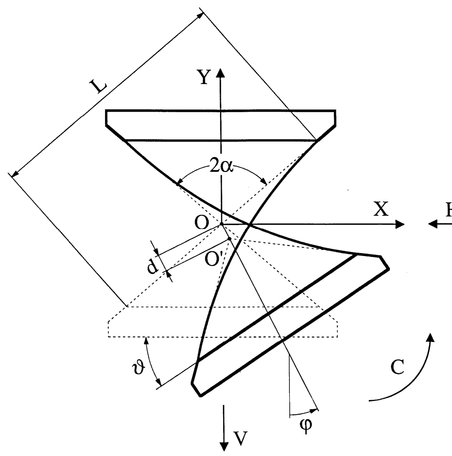

Fig. 2 Cross-spring pivot

The parasitic displacement of a parallel spring translator is constituted by a translation *a* orthogonal to the main degree of freedom *f* (Fig. 1). On the other hand, in the case of a cross-spring pivots (Fig. 2), the parasitic displacement to be characterised is the shift OO' (having amplitude *d* and phase φ) of the geometric centre O of the pivot.

In both cases the analytical treatise reduces to the general problem of cantilever beams loaded at the free end with forces and moments (Fig. 3). This problem can be addressed following analytical approaches of different degrees of approximation. In fact, the "Elastica" method in which the exact expression for beam curvature in the range of geometrically non-linear deflections is used, has recently been extended to the general loading case being considered (De Bona & Zelenika, 1997). In this case, however, due to the presence of elliptic integrals in the final equations, the calculation is computationally complex.

For these reasons, the classical approximated curvature expression, in which the influence of the axial load on the flexural behaviour of the beam is taken into account, but the square of the derivative in the curvature formula is neglected, is often used.

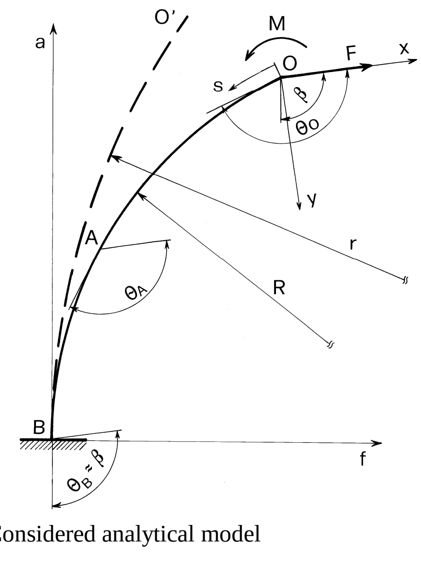

Fig. 3 Considered analytical model

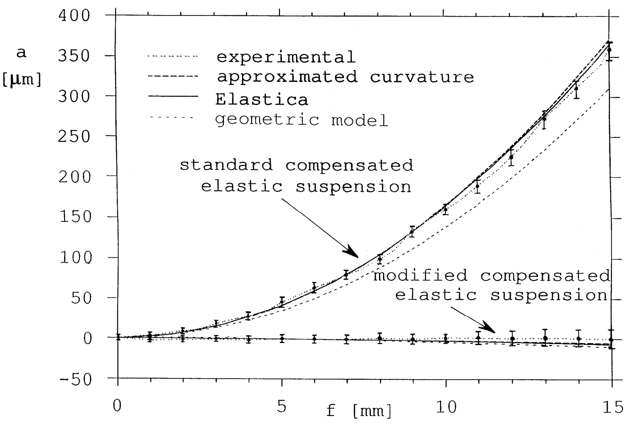

Fig. 4 Results obtained by using the proposed design methods to minimise the parasitic displacements of ultra-high precision positioning devices based on spring-strips

In a first approximation, the considered devices can also be modelled via simple geometrical considerations as rigid pinned quadrilaterals where both the bending of the beams and the influence of the axial loads are neglected.

An experimental validation based on the usage of non-contact optical measurement techniques employing laser interferometry characterised by resolutions and accuracies in the nanometric range was adopted to assess the limits of applicability of the considered analytical approaches (Zelenika & De Bona, 2002; De Bona & Zelenika, 1993). This procedure has allowed the range of approximation of the approximate curvature and geometrical methods to be clearly established, but has also allowed the design parameters of the considered mechanisms to be adapted to the needed requirements, thus obtaining ultra-high precision devices in which the parasitic displacements have been reduced to negligible levels (Fig. 4).

3. COMPLIANT MECHANISMS BASED ON FLEXURAL HINGES

In the case of high-precision devices based on flexural hinges the problem reduces to the minimisation of the stress levels (i.e. maximisation of the fatigue lifetime) of a hinge for a given deflection. Given the new manufacturing possibilities opened up by the introduction of high-precision milling or wire electro-discharge machining (EDM), as well as other micro- and meso-manufacturing technologies (e.g. deep X-ray lithography), this task can be dealt with via the optimisation of the notch shapes (Fig. 5).

A trial to determine the optimal shape of the transition between the bulk material and the hinge ('fillet' region) was thus performed. The analytically and numerically calculated stress-strain behaviour of the two limit cases (prismatic beam and conventional right circular hinge) was therefore compared with that of intermediate shapes based on optimised circular and elliptical fillets, as well as those obtained in classical mechanics via stress minimisation criteria for shoulder fillets (i.e. with the 'streamline fillets' (Peterson, 1953) – Fig. 6).

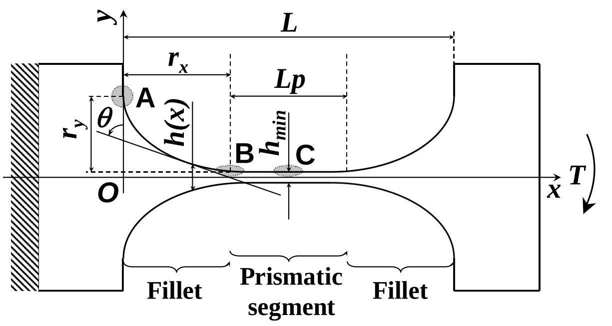

Fig. 5 General geometrical configuration of a flexural hinge

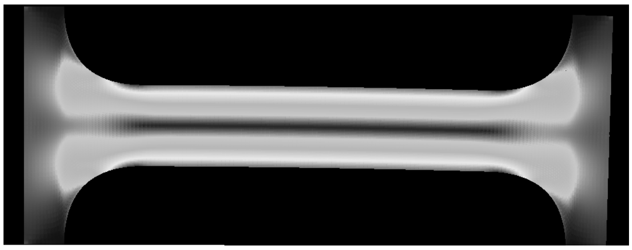

Fig. 6 FEM model of a streamline fillet

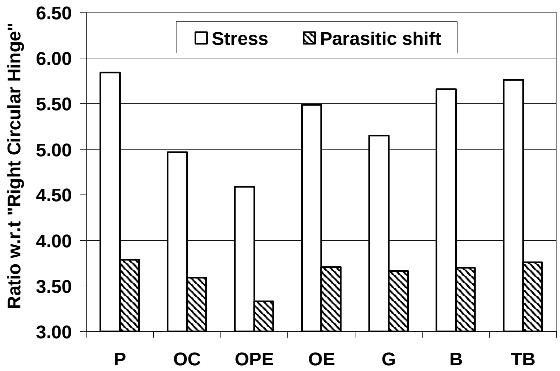

Fig. 7 Ratio of the normalized stress of the right circular (RC) hinge vs. that of the other hinges (white bars) and ratio of the parasitic shift of the various hinges vs. that of the RC hinge (hachured bars). P - prismatic beam hinge, OC - optimised circular hinge, OPE, OE - optimised elliptical hinges, G, B, TB – streamline hinges

It could hence be proven (Zelenika et al., 2004) that, in terms of stresses, the streamline fillets allow a far lower stress for a given rotation (or a far larger displacement range before reaching the fatigue lifetime) than that of the conventional circular hinges to be achieved, presenting very little room for further improvement. This compliance increase is, however, reached at the expense of a parasitic shift increase (Fig. 7).

In fact, the optimal geometrical configuration of the flexural hinges will depend on the specific application. Streamline fillet shapes will thus be used if the main concern will be stress minimisation, while the optimised circular and optimised elliptical shapes provide a good compromise if aiming at a parasitic shift minimisation with still smaller stresses than those of conventional circular hinges.

To validate the theoretical results of Fig. 7, an extensive fatigue test campaign on wire EDM produced hinges is planned in the near future.

4. REFERENCES

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