Optimized high-precision flexural hinge shapes

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Abstract

Results of a strength-based optimisation of flexural hinge shapes are given. Both pre-defined and freeform parametric shapes are considered. By employing non-linear parametric optimisation algorithms, shapes that are best suited for the desired applications are determined.

1 Introduction

Compliant mechanisms, given their marked advantages, are widely used in precision engineering and in the micro and nanotechnologies. The mechanical design of the hence employed devices is often based on flexural hinges (Fig. 1) [1-2]. Up to recently, the choice of hinges' notch shapes was determined by the available production technologies and thus limited to circular shapes. The advent of ultra-high precision and MEMS manufacturing technologies has allowed these limitations to be overcome. Various notch shapes have thus been considered with the aim of increasing flexures' compliance [1]. However, due to the presence of stress concentration effects, the extension of the deflection range of the hinges can be achieved only by considering their shape optimisation in terms of strength maximisation. Given the resulting large deflections, the parasitic shifts of the optimised hinges in the geometrically non-linear field must also be considered.

The aim of this work is the optimisation of pre-defined and freeform hinge shapes in terms of their strength. Compliance and parasitic shift values of the thus obtained optima are compared with conventional shapes so as to provide general guidelines on the shapes to be used depending on the desired application.

2 Considered shapes and calculation methods

To compare the different shapes, a constant hinge aspect ratio (Fig. 1) $\gamma = L/h_{\min} = 25$ is assumed. Such a value is chosen so as to emphasize the effect of the fillet region and the parasitic shifts, while minimising shear and meeting the manufacturing technological limits. The limit cases of a prismatic beam without stress concentrations (P shape) and of a conventional right circular (RC) notch are taken as reference. Intermediate shapes obtained via stress minimization criteria for shoulder fillets (parabolic and ‘streamline’ fillet shapes [3] – based on the authors indicated as the Grodzinski (G), Baud (B) and Thum & Bautz (TB) shape) are also considered (Fig. 2). These shapes are compared with: a circular strength optimised hinge with varying prismatic section length (indicated as the optimised circular (OC) shape), the elliptic hinge with $L_p = 0$ (optimised pure elliptical (OPE) shape), the elliptic shape where $r_y = h_{\min}/\pi$ (OEB shape), and a freeform shape (FFO).

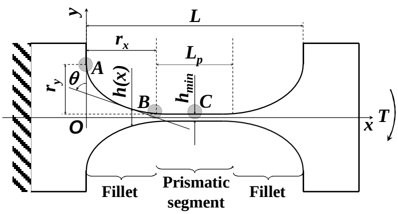

Figure 1: Hinge geometry

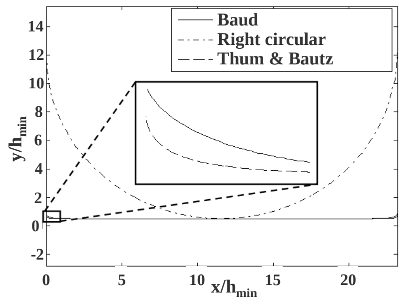

Figure 2: Some of the considered shapes

The case of hinges loaded with a pure couple T at the free end is considered. Preliminary calculations taking into account the shape variation have been performed following the classical Euler-Bernoulli beam model. The presence of sharp cross section variations (with resulting stress concentrations) induces the need to use the finite element method (FEM), which is absolutely necessary when geometric non-linearities are to be considered. The optimisation problem with constrains can then be performed according to the recently developed non-linear parametric optimisation algorithms [4]. On the thus obtained shapes the calculation of the resulting hinge compliances as well as a geometrically non-linear FEM determination of the values of the

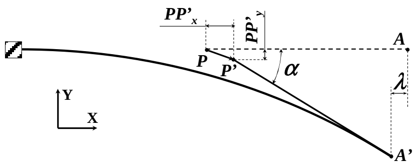

Figure 3: Hinge parasitic shifts

parasitic shifts *PP'* (Fig. 3) is performed. In fact, for slender hinges the hinge point moves as the beam deflects, inducing deviations from ideal pivot kinematics.

3 Results and discussion

The optimisation of conventional shapes by using the outlined procedure has given as optima: the OC shape with r = 1.38 $h_{\min}$, the OPE shape with r_y/r_x = 0.0314, and the OEB shape with r_x = 0.058 L.

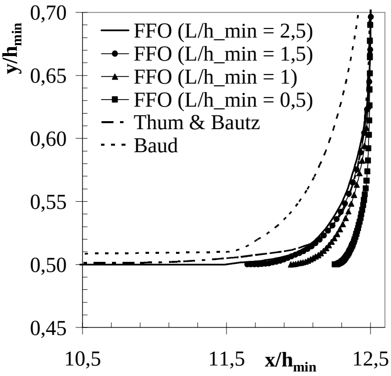

Figure 4: FFO, B and TB shapes

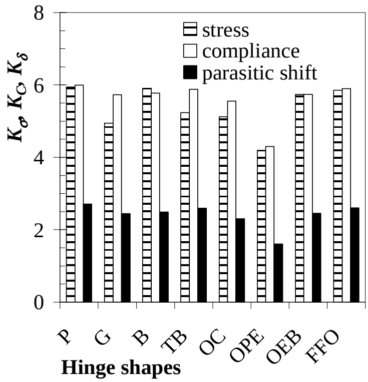

Figure 5: K_σ, K_C, K_δ vs. hinge shape

The FFO shape for the assumed hinge aspect ratio γ = 25 (Fig. 4) is very similar to the TB shape obtained empirically for bulky axisymmetric shoulder fillets. It was established that for γ > 2.5 the FFO shape does not depend on γ, i.e. the hinge shapes for any larger hinge lengths are obtained simply by adding a prismatic section; the determined fillet shape is in this regard an 'absolute optimum'! On the other hand, by reducing the value of γ below 2.5 limits greatly compliance, which conflicts with the objective of increasing the working range of the hinge.

Indicating then with b the constant beam width, with h the beam thickness, with E the modulus of elasticity, with α the hinge deflection and with $\sigma_{\max}$ the maximum stress occurring in the hinge, the parameters which are used to compare the various shapes are the normalised stresses, compliances and parasitic shifts, defined as: $\sigma_n = \sigma_{max}/(E\alpha)$ [rad^{-1}], $C_\alpha = TL/(Ebh^3\alpha)$ [rad^{-1}], $\delta_n = PP'/L$. Comparing the thus obtained values with the values obtained for the RC hinge, the respective ratios defined as (with i indicating the various fillets) $K_\sigma = \sigma_n^{RC} / \sigma_n^i$, $K_C = C_\alpha^i / C_\alpha^{RC}$,

$K_\delta = \delta_n^i / \delta_n^{RC}$ are shown in Fig. 5. The following conclusions can be drawn:

- the FFO shape provides in terms of strength and compliance results which are equivalent to those of an idealised leaf spring with no stress concentrations and presents thus virtually no room for further improvement;
- in terms of decreasing strength, the shapes can be ordered as: FFO, B, OEB, TB, OC, G, OPE;
- in terms of compliances, the “ranking” would be: B, FFO, OEB, TB, OC, G, OPE;
- the relationship between K_σ and K_C gives a direct indication of stress concentration;
- given the relatively large γ value, the δ_n vs. α relation is basically the same for all but the RC shapes, and equal to that of the P shape;
- considering the dependence of δ_n on the normalised load $TL/(Ebh^3)$, and calculating δ_n for the load which for the RC shape produces a certain α (in Fig. 5 are shown values for $\alpha = 10°$ - corresponding to a deflection of almost 60° for the most compliant shapes), for larger α angles the improvement in strength and compliance is inversely proportional to the parasitic shift so that, in terms of decreasing K_δ, the shapes can be ordered as: FFO, TB, B, OEB, G, OC, OPE.

The optimal shape will thus depend on a trade-off between the possibility to increase the strength and the compliance of the notch on one hand, and the parasitic shift on the other. Depending on the foreseen application, the FFO shape will then be the preferred choice if the main concern is stress minimisation and compliance maximisation, followed in this regard by the ‘streamline’ (B, TB) and OEB shapes. On the other hand, the OPE and OC shapes provide a good compromise if aiming at a parasitic shift minimisation with still far smaller stresses than for the RC hinge.

In any case, the optimisation of the hinge shape permits a strong improvement of its behaviour, and should thus be adopted as a standard design procedure for compliant devices based on flexures.

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