Synopsis of "Design of quasi-kinematic couplings" by Martin L. Culpepper[1]

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Overview

Culpepper presents the details and concepts of quasi-kinematic coupling (QKC) for use in assemblies and manufacturing where nanometer-micron range repeatability is desired and cost is of major concern. He presents experimental data confirming the accuracy and repeatability of this type of coupling. He also derives a theoretical model for his concepts accompanied by a MathCAD design tool for development of QKC devices.

Introduction

A coupling in general is a method for attaching two or more parts of an assembly. A typical coupling in traditional manufacturing is the pinned joint, which is formed by pressing a pin into mating holes in two parts. This is a very common low cost approach, but cannot practically be used for micron-level and sub-micron level accuracy without inhibitive cost. To achieve this kind of performance there has been considerable use of kinematic coupling, which uses six points of contact with very small contact area to exactly constrain two parts. Kinematic coupling (KC) designs achieve very good accuracy and repeatability yet suffer from high manufacturing cost and also from high Hertzian contact stresses at the contact regions.[2] In a world driven by the need for high performance and low cost, Culpepper presents QKC, which promises to achieve near KC performance at a fraction of the cost as shown in Culpepper's Fig. 2.

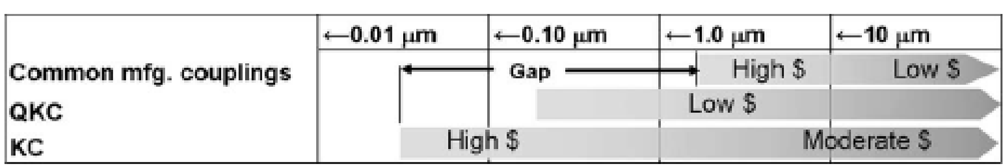

Fig. 2. Cost and precision of common couplings.

Instead of point contact found in KC, QKC uses line contact that distributes the loading while maintaining near kinematic performance. Culpepper's Fig. 1 shows the geometric similarities between the two methods. In the KC example shown in Culpepper's Fig. 1B, three balls mate with three radial v-grooves and establish six contact points. Typically the v-grooves require high tolerances and special heat-treating that makes them expensive. The QKC example shown in Culpepper's Fig. 1A has similar geometry but the balls and relieved grooves form arc contact. This creates a slightly over constrained coupling that simulate a KC. An additional advantage of the elements of this QKC is their ease of manufacturability, and thus low cost.

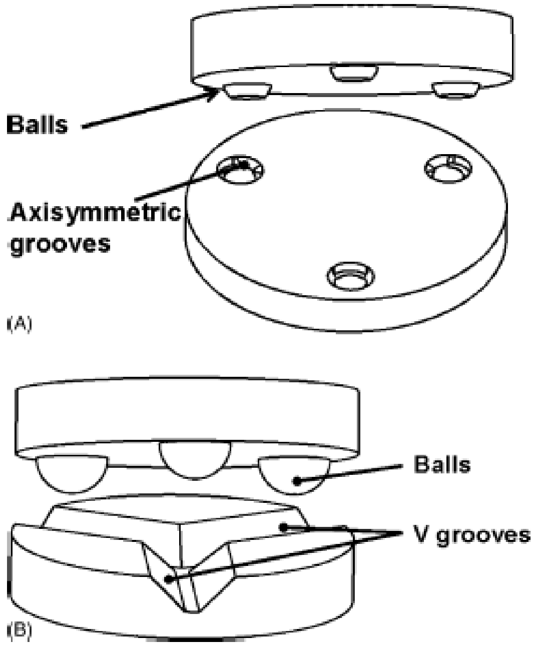

Fig. 1. Quasi-kinematic (A) and kinematic (B) couplings.

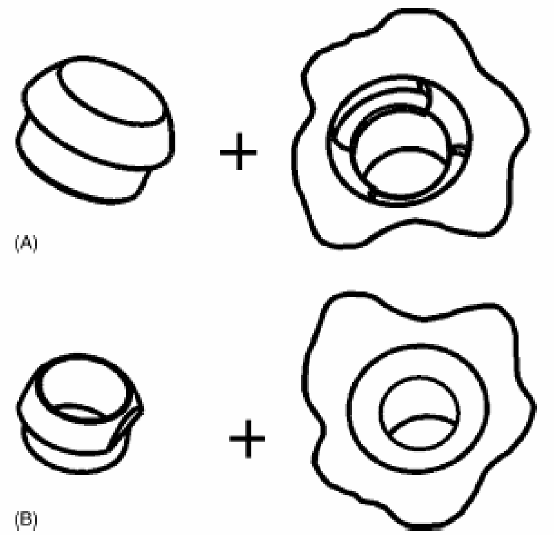

Fig. 3. Relieved groove (A) and relieved ball (B) QKC joint designs.

QKC low cost requirement
Culpepper states that in order to satisfy low-cost requirements for QKC, several guidelines must followed:

1. Good surface finish of elements: QKC balls can be made of low-cost, polished steel spheres. Burnishing the softer grooves with the harder steel balls can give the desired surface finish for good performance.[2]
2. Easily made geometry of groove features: The geometry of the alignment features shown in Culpepper's Fig. 3 is axisymmetric and therefore can be easily made with common machining practices.
3. Practically achieved sealed interfaces: By designing compliance into the mating elements of QKC, the two joined parts can be closely aligned and a sealed interface can be achieved.

Quasi-kinematic coupling theory
Culpepper outlines how the modeling of the stiffness of QKC differs from that of KC. In KC, the contact elements provide stiffness normal to the ball-groove contact. The contact is modeled as Hertzian "spring like" stiffness. In contrast, the arc contact found in QKC provides stiffness in the radial direction as well as in the normal direction. Culpepper defines a constraint metric, CM_i, that is used to quantify the relationship between the stiffness parallel to the bisector (radial direction) and the stiffness perpendicular to the groove (normal direction). The two stiffness values are a function of the contact angle of the QKC. This angle can be seen illustrated in Culpepper's Fig. 5. The equation used for the constraint metric is a simple ratio as defined below (Culpepper's eq. 1):

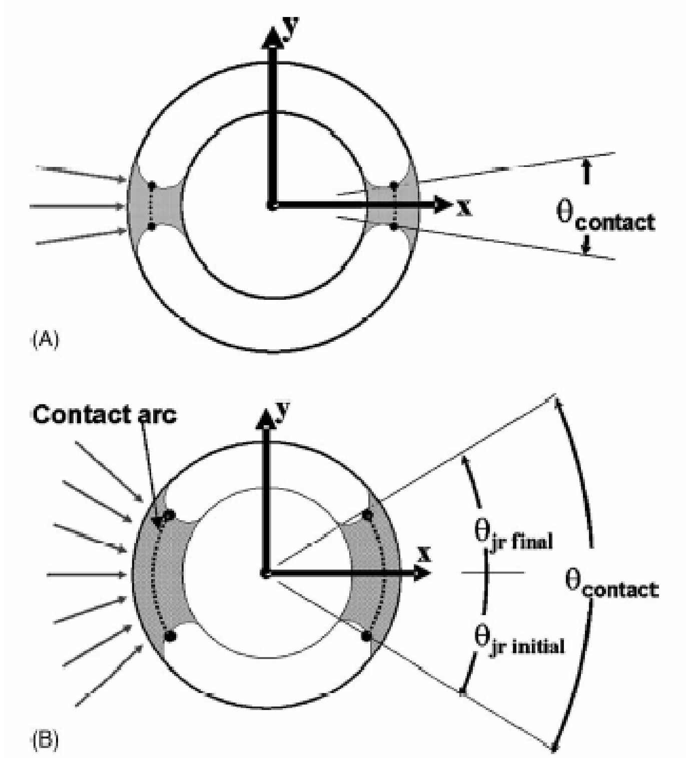

Fig. 5. The link between $\theta_{contact}$ and over constraint in QKCs with (A) small $\theta_{contact}$ and (B) large $\theta_{contact}$.

$$\mathrm{CM}_i = \frac{\text{Stiffness parallel to bisector}}{\text{Stiffness perpendicular to bisector}} = \frac{k_{i\,\|\mathrm{Bisector}}}{k_{i\,\perp\mathrm{Bisector}}} \quad (1)$$

This constraint metric is expected to vary from unity for $\theta_{contact} = 180°$ and approach zero as $\theta_{contact} \rightarrow 0°$. As the amount of relief increases and the arc contact length decreases the QKC approaches a theoretical KC. Culpepper presents a radial plot of the stiffness as a function of the two dimensional direction to illustrate the result of his theoretical calculations. Theoretical stiffness calculations are used to illustrate the effect of contact angle on CM and on the maximum stiffness. The constraint metric is used primarily to prevent excessive overconstraint while preserving the required stiffness in QKC design.

MathCAD model

Not without benefit to practical application of this theory, Culpepper presents a MathCAD model (also available for download at httpo://psdam.mit.edu) for use as a QKC design tool. Sanity-checks are conducted on the model for agreement by subjecting it to unidirectional forces and moments and by checking resulting reaction forces.

Experimental Results

In addition to the MathCAD model based on the theoretical derivations, Culpepper presents some experimental results of an automotive assembly application of QKC

(Culpepper's Fig. 11B). Due to very high stiffness requirements for this example, the QKC was more overconstrained and as a result only illustrated to some extent the capability of a truly optimized QKC. The experiment shows that after an initial wear-in period the location repeats to within 0.25 μm. Culpepper, in other writings, points out that when a wear in period is not allowable, a preload can be used to plastically deform the contact regions between the balls and grooves.[3] Without the wear-in period these experimental results compare favorably to the 0.10 μm kinematic coupling results of Slocum and Donmez.[4]

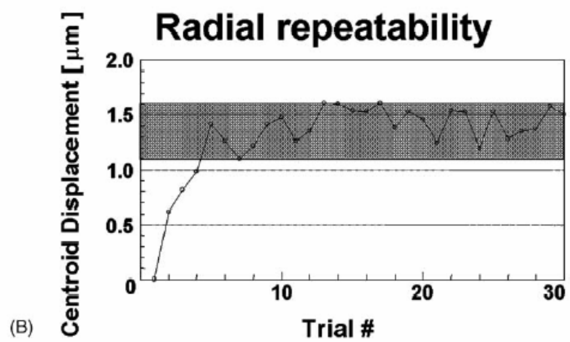

Fig. 11. QKC (A) test setup and (B) repeatability results for $\theta_c = 32°$; $\theta_{contact} = 60°$; K (N/μm$^{2.07}$) $= 1 \times 10^{-2}$; $b = 1.07$; $R_c = 0.66$ cm; 25 N preload.

Conclusions

Culpepper presents a theory-based model and constraint metric for use in the design of QKC, and backs up his theory with experimental results. His approach facilitates the cost effective design of QKC that is weakly over constraining while retaining stiffness performance that is superior to classical KC.

References

1. Culpepper, M.L., "Design of quasi-kinematic couplings," Precision Engineering 2004; 28:338-357.
2. Slocum, A.H., "Design of three-groove kinematic couplings," Precision Engineering 1992; 14:67-73.
3. Culpepper, M.L., "Design and application of compliant quasi-kinematic couplings," Ph.D. Thesis, MIT, Cambridge, MA, 2000; p.89-108.
4. Slocum, A.H. and Donmez, A., "Kinematic couplings for precision fixturing – Part 2. Experimental determination of repeatability and stiffness," Precision Engineering 1988; 10:115-122.