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A COMPLIANT MEASURING SYSTEM FOR REVOLUTE JOINTS WITH CLEARANCE

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ABSTRACT

This paper suggests a simple yet efficient experimental method to record the displacement of the shaft in a revolute joint with clearance. Two light and compliant cantilevers have been mounted on the rocker, each being instrumented with two strain gauges which can measure bending. These cantilevers are mounted in an orthogonal fashion, near the axis of the revolute joint, each touching the shaft at the outermost part. As the mechanism is operated, the shaft oscillates inside the clearance and bends the compliant cantilevers, hence the instant displacement can be obtained by measuring the four strain gauges with an high-speed acquisition device.

KEYWORDS Revolute joint, clearance, vibrations, strain gauges, four-bar linkage.

1 INTRODUCTION

In order to study tribological phenomena caused by clearances in revolute joints, a custom four-bar linkage mechanism has been built (Fig.1). The revolute joint between the rod and the rocker can be easily replaced, so that different degrees of backlash can be tested [1].

In previous works, this experimental test bed has been successfully used to investigate wear of surface pairs. Also, vibrations acquired by means of accelerometers agreed with those provided by our simulation software [2].

The precise and reliable simulation of joints with clearances is a debated topic: since many dissimilar numerical schemes have been proposed in the past [2][3], our experimental test bed aims at providing real data to validate these models.

Numerical simulations showed that, most often, the rod shaft should perform two almost periodical sets of high-frequency oscillations inside the hole with clearance, hence wearing two distinct zones of the contact surface. Under specific circumstances, the shaft/bearing contact may be lost, causing impact events.

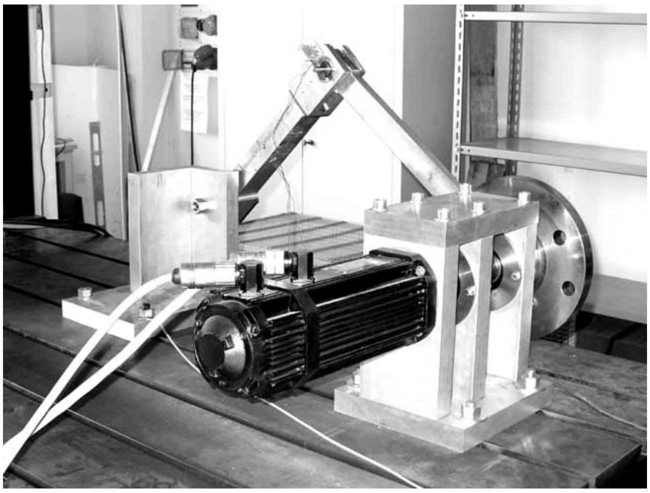

Figure 1: The test bed with the four-bar articulated mechanism

In order to provide an experimental confirmation of these numerical results, this paper suggests a simple yet efficient experimental method to record the displacement of the shaft in the reference system of the revolute joint.

In detail, two small compliant cantilevers have been mounted on both sides of the rocker, each exploiting two strain gauges which can measure bending. These cantilevers are orthogonal, and their ends touch the shaft at the outermost part. As the mechanism is operated, the shaft oscillates inside the clearance and bends the compliant cantilevers. This way, the instant displacement can be obtained by measuring the four strain gauges with an analogic high-speed acquisition device.

By means of proper calibration look-up tables, this acquisition system can output precise graphs in terms of time-dependant displacement, either in polar and cartesian coordinates. Loss of contact between shaft and bearing can be detected and measured. Outcoming data can be used to validate and to complement results coming from other sources, such as numerical simulations, inductive sensors or high-speed films.

2 THE MEASURING SYSTEM

The revolute joint of the four-bar mechanism has been build with special functionalities: for example, worn bearings can be easily replaced, and clearance gap can be effortlessly seen from the side.

For the purposes of this article, a special version of the revolute pair has been machined, where the shaft (which moves with the rod) has two lateral cylinders facing outside the joint, as references. By monitoring the displacement of these cylinders respect to the rocker, which moves with the bearing, one can get the relative position of shaft and bearing. Hence, also one gets also the position of the point of contact in the clearance.

Different methods have been taken into consideration for measuring the X-Y displacement of the cylinders. Most noticeably, the adoption of two orthogonal inductive sensors represented one of the most precise and reliable proposals.

However, the employ of these inductive sensors has been soon impaired by their cost, and by their inability of bearing the very high accelerations affecting the rocker.

Thus, we designed a cheap acquisition method based on the deformation of two small strips of metal, which are in contact with the external part of the shaft. When the shaft performs a pure

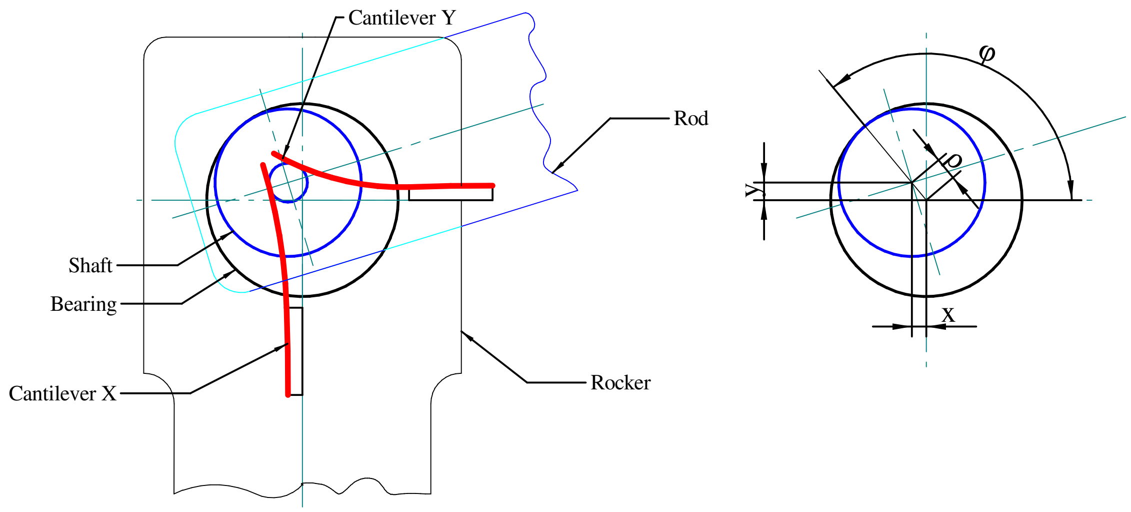

Figure 2: The principle of the measuring device (clearances and displacements are exaggerated)

rotational motion about its axis, the bending of these cantilevers isn't affected. On the other hand, displacements of the shaft axis can be detected by studying the bending of the two cantilevers. This principle is similar to the motion of two orthogonal glyphs, as depicted in the scheme of Figure 2.

The diameter of the cylindrical surfaces for the contact between cantilevers and shaft is small, and surfaces must be carefully machined. In fact, the measured bending of the two plates shouldn't be affected by the rotation of the shaft about its axis: this happens only if the contacts between the plates and the cylinders are really smooth, without roughness and friction which may cause noise.

Cantilevers can been cut from a thin sheet of brass, for example with 0.1 mm of thickness. We experienced that their length should be kept as low as possible, otherwise the mass/stiffness ratio may grow up to causing resonance phenomena; it is wise to keep the natural frequency of the plate as high as possible. Results from our test bed suggest that 0.1mm x 10mm x 20mm brass plates can give satisfactory results even when applied to machinery rotating up to 500rpm.

Also, one must ensure that the cantilevers won't ever loose contact with the shaft: this can be secured if the plates are a bit pre-bent when the shaft is in neutral (centered) position, so that a residual contact force is ensured even when the shaft displacement is opposed to the stiffening direction of the cantilever. Also, when operating the device at high speeds, this precompression effect help avoiding the detachment of the cantilever even if subject to extreme inertial forces.

Figure 3 shows that such a measuring device can be built with few efforts.

3 DATA ACQUISITION

Two strain gauges have been glued to each plate, in a half-bridge configuration, so that the deflection of the plate can be measured with an analogic acquisition system featuring at least two input channels.

To this end, we used a National Instruments SCXI board with four strain gauge channels with conditioning and automatic calibration (Fig.4). As a side note, our SCXI system can also simultaneously acquire four accelerometers and triggering signals too; this additional information has been used to improve our datasets.

Although the acquisition board features a 10Hz filter, this has been removed because we meant to sample the two channels up to 10'000Hz.

Figure 3: The measuring device, mounted on the revolute joint with clearance

Such a high sample rate is mandatory even for average rotating speeds. Most often, each rotation of the flywheel causes the shaft to perform two sets of high-frequency oscillations inside the hole with clearance, sliding on two preferential zones of the bearing many times per revolution. In some circumstances, the shaft-bearing contact may be lost and subsequent impact phenomena may worsen the situation, introducing vibratory effects with very high frequencies.

Despite the limitations, our measuring system was able to perform decent acquisitions for flywheel speeds up to 500rpm, providing meaningful results which capture these high-frequency oscillatory effects.

4 DATA PROCESSING

Signals s_x and s_x coming from the strain gauges are proportional to the deflection of the two cantilevers. These bending measures are roughly proportional to the x and y displacements of the shaft:

$$\begin{Bmatrix} x \\ y \end{Bmatrix} \cong \begin{bmatrix} C_x & 0 \\ 0 & C_y \end{bmatrix} \begin{Bmatrix} s_x \\ s_y \end{Bmatrix} \tag{1}$$

A more precise mapping should take into account the non-linearity effects. In fact it is not exactly true that the motion along axis x does not affect at all the bending of the y cantilever, and vice versa: this side effect is caused by the fact that, for high bending of a plate, its contact plane isn't aligned anymore to its resting direction, as it can be seen in the exaggerated case of Fig.2. These non linear effects, despite negligible in most cases, can be cured with the adoption of correction curves or LUTs (look up tables), hence turning eq.1 into a more complex nonlinear mapping of the type:

$$\begin{Bmatrix} x \\ y \end{Bmatrix} \cong \begin{Bmatrix} f_x(s_x, s_y) \\ f_y(s_x, s_y) \end{Bmatrix} \qquad f_x : \mathsf{R}^2 \to x \in \mathsf{R}, \quad f_y : \mathsf{R}^2 \to y \in \mathsf{R} \tag{2}$$

The acquisition software that we used, based on LabVIEW™, can implement the mappings of Eq.2 via correction curves or LUTs (look up tables), however we experienced that a simple linear mapping as in Eq.1 is enough in most situations.

Figure 4: The acquisition system and the motor control system

After displacements x and y have been obtained, one can get the polar coordinates ρ (radial displacement) and φ (phase) using the following functions:

$$\begin{aligned}\rho &= \sqrt{x^2 + y^2} \\ \varphi &= \mathrm{atan2}\left(\frac{x}{\rho}, \frac{y}{\rho}\right)\end{aligned} \tag{3}$$

Note that we used the atan2( ) function, which can be found in most programming languages, because it can distinguish between the four quadrants, while the tan( ) function cannot.

The information about the phase φ is noteworthy because it also tells where the contact point between shaft and bearing takes place.

5 RESULTS

Measures of displacements and of polar coordinates ρ and φ have been performed for rotating speeds in the range 100rpm-500rpm and with clearances ranging from 0.5mm to 1.5mm. Results are obtained in form of time-dependant plots (see, for an example, Fig.5).

Even if special care must be paid when replacing the bearings, either to avoid damages to the thin cantilevers either because the displacement signals must be zeroed, this measuring system proved to be simple to operate, reliable and tough, and we were able to acquire significant data in all situations.

Results have been compared with computer simulations, showing a good agreement between experimental outcomes and numerical data (Fig.6).

6 CONCLUSION

An experimental four-bar linkage has been built with the purpose of studying the effect of clearances in revolute joints. A simple and efficient measuring device has been built, which is able to record the small motions of the shaft affected by backlash. This approach is based on the bending of small metallic plates, so only few strain gauges are required.

Because of the mechanical approach, this measuring method cannot be used at very high frequencies, nor in cases where moving parts are very light and may be disturbed by the contact with the plates. However it proved to be inexpensive, sturdy, simple to build and mount, and reliable enough for our purposes.

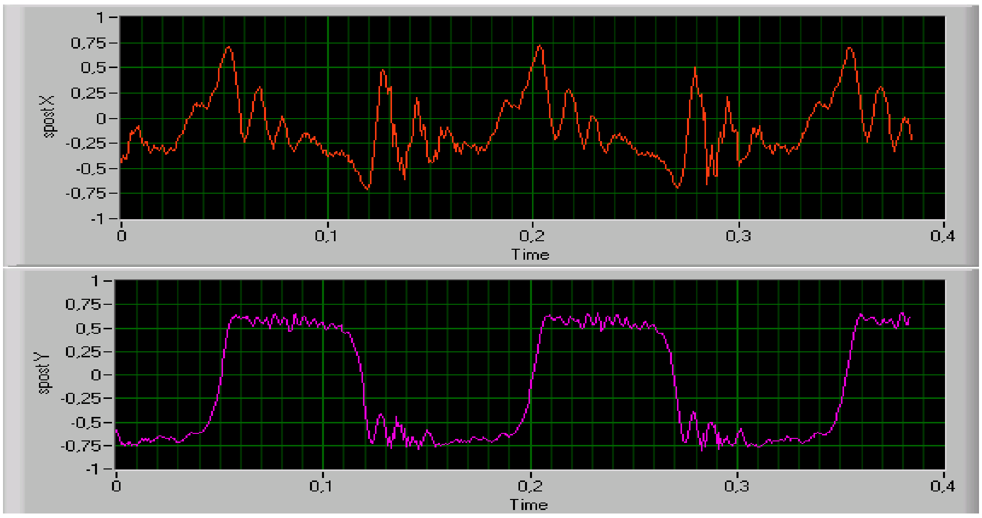

Figure 5: Example of displacements *x* and *y* for case of speed=400rpm and clearance =1mm

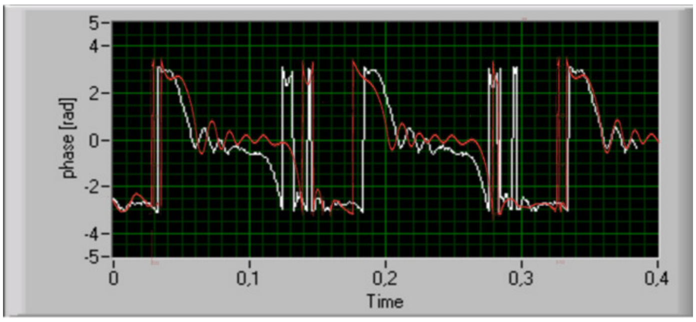

Figure 6: Phase φ (in –π..+π range), comparison between experimental (white) and numerical simulation (red)

Acknowledgments

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