Experimental investigation of the stiffness of planar ball guides

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Abstract

One important aim of precision planar ball guides design is a high stiffness. A mathematical appropriate design allows the deployment of three balls only. In order to fulfil the load and stiffness requirements of the guide a much higher number of balls is used. In this overconstrained situation the stiffness is reduced by an unknown value compared to the calculated theoretical result due to manufacturing deviations. The following contribution presents an experimental investigation of planar guides concerning their stiffness.

1 Motivation

The majority of high precision planar positioning systems are based on the use of aerostatic guides. A growing number of applications require the operation under vacuum conditions thus demanding space consuming complex air extraction systems. Stacked assemblies of linear ball guides are still cumbersome and offer a low 1st natural frequency. Planar ball guides are an attractive compact alternative solution. They are applicable under atmospheric pressure as well as under technical vacuum conditions without any additional technical effort.

A planar ball guide consists of two flat surfaces and balls arranged in a flat cage in between [1]. In order to safely avoid overloads more than the theoretical number of three balls has to be used. This unavoidably results in an overconstrained situation caused by residual manufacturing deviations of the balls, the stage and the runner. The number of carrying balls varies during the movement thus derating the overall stiffness and load capacity in comparison to the theoretically expected values. Therefore stiffness can be taken as a measure for the number of carrying balls at a certain position. A survey of the literature showed that there is no investigation of planar ball guides available yet.

A theoretical model for dimensioning of planar ball guides for use in high precision positioning systems is under development at our Institute. One of the most important design parameters is stiffness. Since analytical stiffness calculations do not take into account manufacturing deviations experimental investigations are necessary to verify and to improve the model with regard to a more precise estimation of stiffness.

2 Measurement setup

The chosen measurement setup (Fig. 1) allows precise vertical load variation. Deadweights are applied to the runner causing a vertical displacement of the runner in the micrometre range due to elastic deformations of the balls, the guide and the runner itself [2]. Thus, a laser interferometer is the only possible solution for quantifying the vertical movement of the runner.

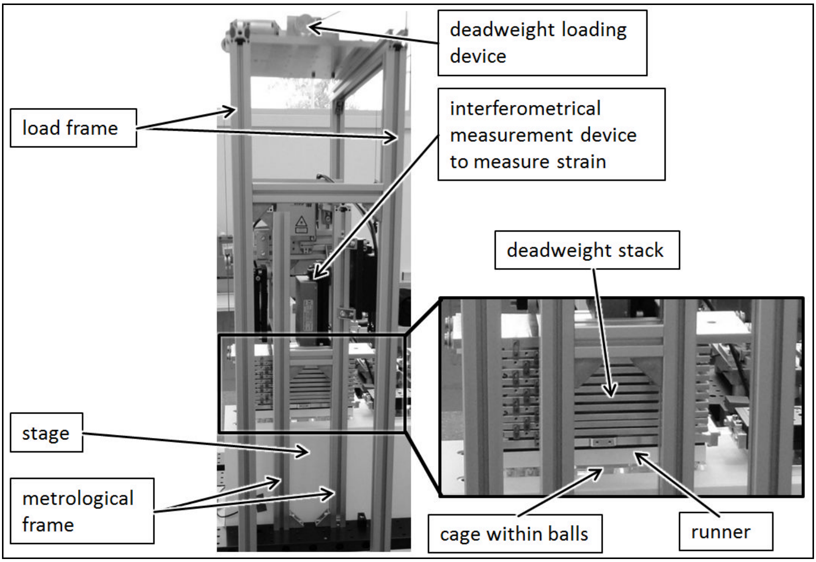

Figure 1: Measurement setup

To minimize parasitic influences there are two separated frames, the metrological frame to carry the measuring devices and the load frame to carry the loading device. Deadweights are placed stepwise atop the runner to vary the load.

3 Measurement results

Experiments were conducted with lapped planar plates made of high-tech aluminium oxide ceramic with overall geometrical deviations of less than 4 µm (flatness, waviness, roughness) and steel balls of class G5 (DIN 5401) with a diameter of 13/32 inch and form deviations in the sub-micrometre range.

Stiffness values (Fig 3) are determined with just the mass of the runner and loaded stepwise with ten weights. The stiffness values were calculated by the displacement of the runner and the differential load. The uncertainty of the stiffness values account for up to 2.6 N/µm (k=2) and a maximal standard deviation of 0.057 N/µm.

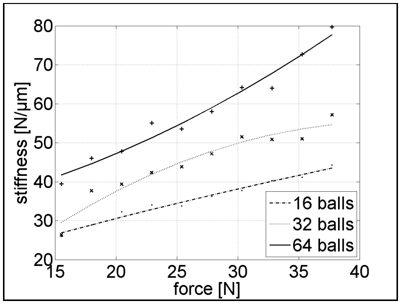

Figure 2: Stiffness in dependence of load and ball number

Fig. 2 shows polynomial fitting curves for these stiffness values. It can be recognized, that the stiffness increases with the number of balls and with the load. The slope of the polynomial fitting curves varies with the number of balls.

The comparison of the measured stiffness c_m with the maximum theoretical stiffness c_{theo} is given by the stiffness ratio k_c (1)

$$k_c = \frac{c_m}{c_{theo}} = \frac{c_m}{\frac{n}{2}\cdot k_{cor}\cdot c_{Hertz}} = \frac{c_m}{\frac{n}{2}\cdot k_{cor}\cdot \sqrt[3]{3\cdot F\cdot d\cdot\left(\frac{1-\nu_1^{\,2}}{E_1}+\frac{1-\nu_2^{\,2}}{E_2}\right)^{-2}}} \tag{1}$$

where n is the total number of balls, F is the load per ball, d is the ball diameter, E_1 and E_2 are the Young's moduli and ν_1 and ν_2 are the Poisson's ratios for each element respectively. The correction constant k_{cor} considers the difference between the real ball-plane-contact stiffness and the Hertzian stiffness c_{Hertz} to account for some simplifications in the Hertzian theory. The reference stiffness c_{ref} (Fig. 3) is measured with three balls (the mathematically appropriate design) and defines the correction constant k_{cor} in this case to 0.91.

To achieve the requested high level stiffness the load atop the runner is required to be as high as possible. The allowable load, however, is limited by the elastic range of the used materials.

With growing ball number the influence on the stiffness ratio decreases (Fig. 4).

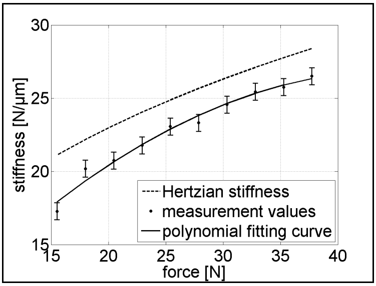

Figure 3: Reference stiffness c_{ref}

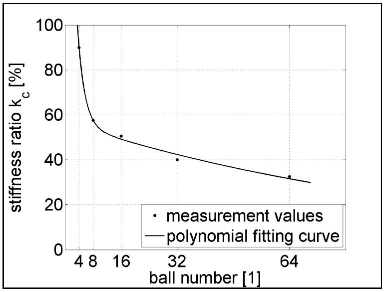

Figure 4: Stiffness ratio k_c

4 Conclusions and Outlook

This study shows the significant dependence of a planar ball guide's stiffness on ball number and load. Furthermore it is shown that the stiffness ratio decreases with increasing ball number. The measurement setup was proven to show high reproducible results.

These investigations are an initial step for a verification of the theoretical model for planar ball guide design. The measurements have to be continued to separate influences factors on the resulting stiffness more precisely. In a next step the weights will be applied in different positions to simulate the movement of the runner.

Acknowledgements

These results were achieved in a sub-project of the Collaborative Research Centre 622 at the Ilmenau University of Technology, which is funded by the German Research Foundation (DFG).

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