Design of a Low-cost CMM with Nanometer Uncertainty

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Abstract

A novel ultra precision coordinate measuring machine (CMM) using three linear encoders and three vacuum preloaded (VPL) porous air bearings is designed and critical components are tested. The functional axes of the linear encoders intersect at a single point that coincides with the center of the probe tip. In this configuration the CMM complies with the Abbe principle over its whole range, which greatly decreases the influence of guideway deviations.

1 Operating principle

Several ultra precision coordinate measuring machines have been developed. Applications include the measuring of aspheric lenses, micro components and calibration artifacts. These machines include the NMM by Sios [1], UP CMM by Ruijl [2], F25 by Zeiss [3] and NanoCMM by van Seggelen [4]. The measurement principle of these CMM's is either based on laser interferometers combined with a zerodur workpiece table [1,2] or on linear encoders combined with a kinematic intermediate body [3,4]. As a result these CMM's are the state-of-the-art in precision 3D metrology.

These machines target nanometer precision over a large range and are expensive as a result. Therefore the TriNano, a novel ultra precision CMM, is designed that uses a highly symmetric design, simple kinematics and linear encoders. This design reduces cost while achieving nanometer precision in a reduced measurement range, as schematically shown in figure 1.

The TriNano uses three zerodur encoder scales, each mounted on a 1D translation stage and aligned to the center of the stationary probe tip. The encoder head remains

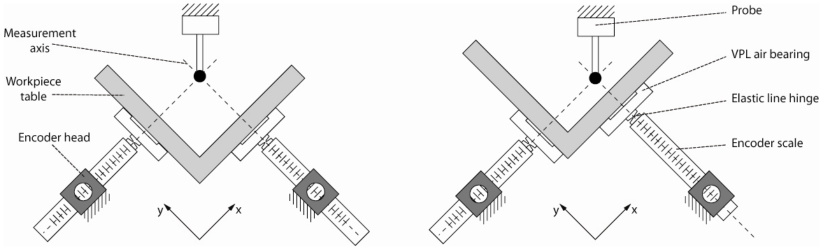

Figure 1: Operating principle of the TriNano CMM, schematic 2D representation of the 3D configuration.

stationary. In figure 1 it can be seen that when the right 1D translation stage moves, the workpiece table is translated in the same direction guided by the vacuum preloaded (VPL) air bearing mounted on the left 1D translation stage.

The design thus consists of three identical, relatively simple 1D translation stages, as displayed in figure 2. The use of an elastic line hinge between the VPL air bearing and the translation stage prevents over-constrained positioning of the workpiece table. The result is a highly symmetrical, kinematic design. The parallel operation of the stages results in favourable dynamics.

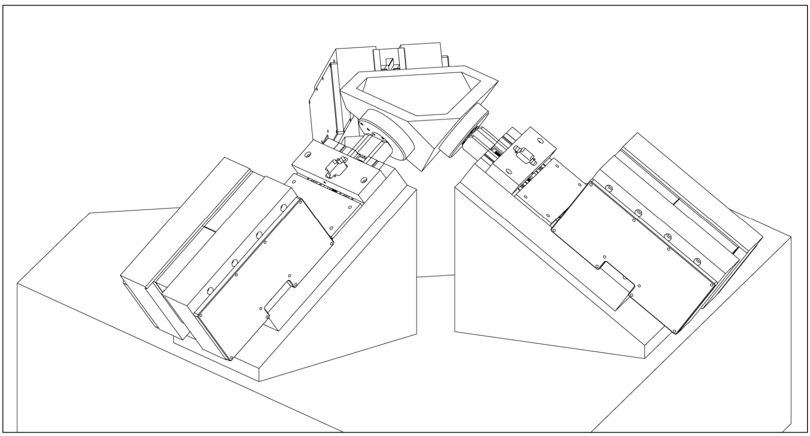

Figure 2: Drawing of the positioning system of the TriNano. The probe, probe frame and covers are removed.

As can be seen from figures 1 and 2, the air film of the VPL air bearing is part of the metrology loop. It is therefore critical that variations of the height of the air film are small. Furthermore, the dynamics of the air film are the limiting factor in the dynamic behaviour of the TriNano. For these reasons an experimental characterization of a VPL air bearing was performed.

2 Vacuum preloaded air bearing experimental characterization

Since VPL air bearings are internally preloaded, the test setup remains simple, as shown in figure 3. The VPL air bearing is mounted inside a ring, on which three capacitive sensors are mounted and is attached to a granite surface plate via three elastic rods. Air and vacuum are supplied through standard regulators.

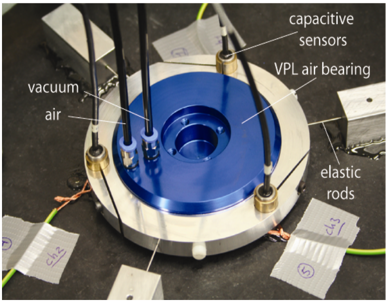

Figure 3 VPL air bearing test setup

Figure 4 shows the variation of the height of the air film measured over a period of 10 minutes. From this figure, background noise of ±4 nm and a total variation of ±8 nm can be observed. The cyclic variation of the gap height is most likely caused by variations in the air and vacuum pressure supplies, improvements are expected by using better vacuum and pressure control.

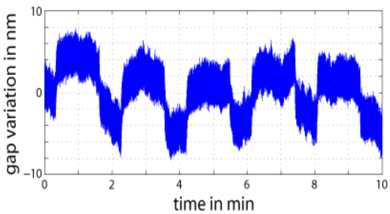

Figure 4 Air gap variation

The stiffness of the air film is a determining factor in the overall dynamic performance of the TriNano. To measure the dynamic stiffness of the VPL air bearing, an electrodynamic exciter was placed on top of the setup in figure 3. To determine the axial dynamic stiffness the shaker was placed in the centre of the VPL air bearing. By placing the exciter off-centre the then excited angular modes can be observed. Results of these measurements are shown in figure 5.

An axial eigenmode (figure 5, left) is observed around 1000 Hz. From the angular dynamic measurements on the right of figure 5 the first angular eigenmode is observed around 600 Hz. The static stiffness is determined by extrapolating to 0 Hz and amounts to 2.8e7 N/m. From the weighted difference of the sensors response and the offset of the exciter, the static angular stiffness can be determined and amounts to 2.1e4 Nm/rad. The dynamic response remains flat up to 400 Hz. With these stiffnesses the first natural frequency of the TriNano is estimated to be about 150 Hz.

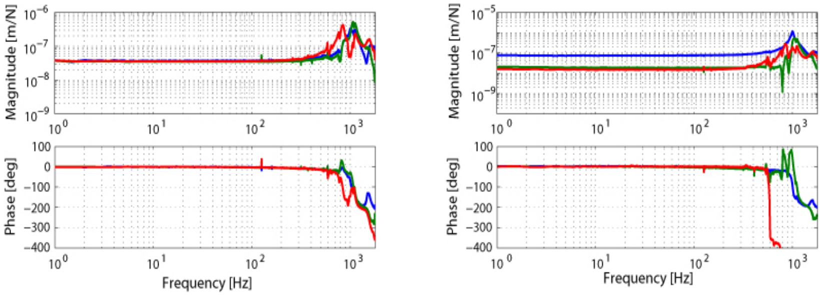

Figure 5 Dynamic measurements VPL air bearing, axial dynamic (left) compliance and angular dynamic compliance (right).

3 Conclusion/Summary

A novel ultra precision coordinate measuring machine (CMM) using three linear encoders and three vacuum preloaded (VPL) porous air bearings is proposed. The stability of the air film height of the VPL air bearing is ±8 nm over a period of 10 minutes. These deviations are small enough to use the VPL air bearing in the metrology loop of the TriNano. It is not expected that the dynamics due to the VPL air bearing are a limiting factor in the performance of the TriNano CMM.

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