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A novel approach for a coordinate measuring machine probing head with a levitating probe integrating the Kibble-balance principle and a Maxwell-clamp-like mounting concept

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Abstract
In order to enable coordinate measuring machines (CMMs) to achieve measurement accuracy in the nanometre range and a higher dynamic, an innovative probing head has been developed. Conventional CMM probing heads operate either as simple through-trigger head or with elastomechanical deflections of parallel leaf-spring guides as passive system or active system, with additional electromechanical actuators. All of these systems have limitations regarding probing force calibration and metrological traceability. In this paper, a novel design of traceable, active, force- and torque-measuring CMM probing head with a levitating probe is presented. The probe and carrier plate are levitated by six voice coil actuators (VCA) in hexapod-like arrangement without any leaf-springs. This parallel kinematic is controlled in position and orientation using the measuring signals of three 2D position sensors. The arrangement allows the forces of the actuators to be calibrated according to the Kibble-balance principle. A strict separation of the force/torque and position/orientation measuring loops, as well as the special design of the connection between the two loops using a Maxwell-clamp-like mounting, enables the combination of lightweight and rigid materials for the force and torque measuring loop with materials with low thermal expansion for the position and orientation measuring loops. Subsequently, finite element simulations were performed to determine how temperature changes affect the position of the measuring result.

Keywords: CMM, probing head, Kibble-balance, Maxwell-clamp

1. Introduction

Coordinate measuring machines (CMMs) play an important role in the field of advanced manufacturing and precision engineering. In the last decades, an increasing demand for dynamic probing and measurement with nanometre-level accuracy are observed [1]. A probing result is typically influenced by the force/torque that the probing head applies to the stylus, and the interaction between the stylus and workpiece. Therefore, the achievable dimensional measurement accuracy is strongly influenced by the probing force. In conventional probing head concepts, the applied forces/torques are generated and calibrated indirectly, which leads to limited metrological traceability [2].

This article presents a novel approach for a CMM probing head that applies the Kibble-balance principle for traceable force/torque measurements and simultaneous control of the position and orientation of the probing head. Previous work at the Technische Universität Ilmenau has successfully applied the Kibble-balance principle to traceable mass measurements using voice coil actuators (VCAs) based on gravitational force measurements [3,4]. Although the probing heads of CMMs measure the dimensions or surfaces of workpieces fundamentally by measuring forces and torques, the Kibble-balance principle has not been applied to any probing head yet.

In the following section, the concept of the proposed probing head is introduced. First, a traceability-driven actuation concept using voice coil actuators (VCAs) with a hexpod-like arrangement is described, with consideration of their thermal implications. Subsequently, the separation of the force/torque and position/orientation measuring loops is presented. Finally, a finite element simulation (FEM-simulation) was performed to predict the expected thermal behavior of the probing head constructures.

2. Traceable probing head concept

Conventional CMMs probing heads face complex and indirect force calibration procedures and an increasing demand for improvement in measurement accuracy. After the redefinition of the SI unit of kilogram in 2019, traceable force measurements based on electromagnetic force generation using VCAs have become an established concept in precision metrology. To overcome the challenges, which were mentioned ahead, VCAs were used in this study as both actuators and force sensors. This will make in-situ calibration of probing forces possible by implementing different working modes as in mentioned in [4].

However, a single coil actuator allows multiple degrees of freedom (DOFs), which means, the coil and pot magnet can perform lateral and rotative movements with respect to each other. The arrangement of individual VCAs along the coordinate axes should be avoided. Therefore, a hexapod-like arrangement is adopted in this concept, so that all actors carry part of the weight of the flotor. As shown in the Figure 1, six VCAs are arranged in three opposing pairs, and symmetrically distributed at angles of 120°. This configuration allows the flotor to move in six DOFs and therefore enables not only the measurement of the probing forces, but also the measurement of torques on the stylus and flotor.

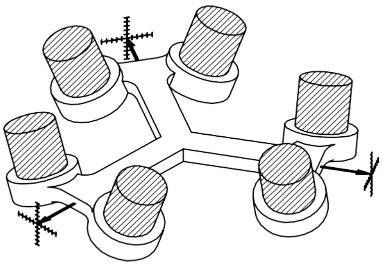

Figure 1. Schematic illustration of hexapod-like arrangement of VCAs

In addition to force sensors, position sensors are required to control the position and orientation of the flotor. Thus, a type of optical 2D-position sensors are assigned to each actuator pair. As the VCAs are in working status, they generate not only heat but also force/torque and vibration to the system. The separation of force/torque loops and position/orientation measuring loops helps to avoid the influence of these factors on the position and orientation measurement with the 2D-position sensor. In this way, better control of position and orientation can be provided. As shown in Figure 2, an extra structural frame was designed to decouple the position sensors from the VCAs. The interface between both loops uses three leaf-spring guides and is distributed similarly to the arrangement of actuator pairs, thereby forming Maxwell-clamp-like mountings. This mounting concept improves the assembly repeatability and positioning accuracy [5].

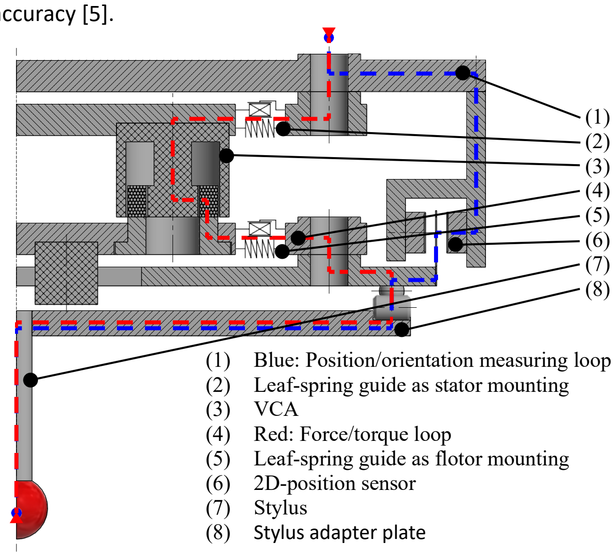

Figure 2. Schematic illustration of the separation of the force/torque loops and position/orientation measuring loops.

3. Expected thermal behaviour

As shown in Figure 2, both the force/torque loops and the position/orientation measuring loops share a common base plate for mounting the probing head to the ram. In practice, they exhibit different thermal behaviors and, therefore, different thermal expansions. Considering the heat generated by the VCAs, a flexible construction for the stator plate and mounting of the pot magnet was designed. During the measurement, the leaf-spring guides act as springs and reduce the stresses at the fastening point resulting from different thermal expansion.

After completing the structural design, FEM simulations were performed to determine the influence of the thermal expansion of the stator plate of the probing head, as shown in Figure 3. The FEM simulation result shows that the thermal expansion of the stator plate is more than 10 µm in the radial direction for a temperature increase of 10 K. However, the center of the stator plate remains at the same position. The same principle was appled for the flotor plate for the mounting of the actor coils. The displacement of the stylus, which is attached at the centre of the flotor, due to the thermal expansion of the stator plate and flotor plate is effectively reduced.

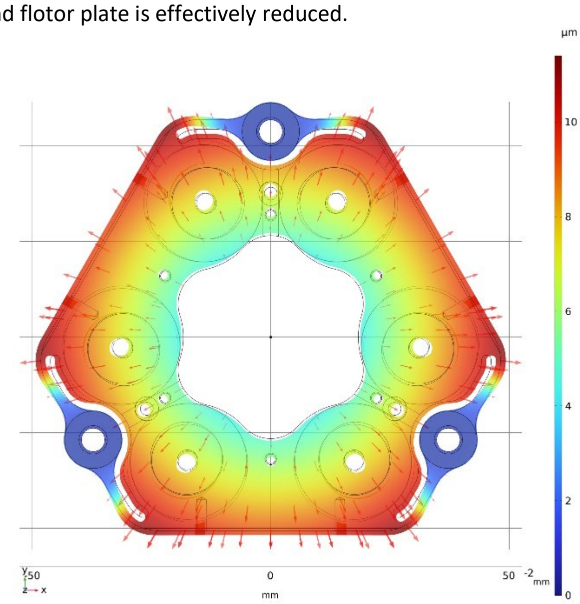

Figure 3. FEM simulation result of stator plate of a temperature increase of 10 K.

4. Conclusion and outlook

In this article, a novel probing head concept for CMMs has been presented with the aim to provide a traceable force and torque measurement with potential of in-situ calibration. By using VCAs as both actuators and force sensors. This concept applies the Kibble-balance principle to CMM probing. Six VCAs are arranged in a hexapod-like geometry, which allow this probing system to move in all six DOFs and therefore enable the measurement of both probing force and torque. This presented design provides a combination of traceability, thermal stability and high measurement accuracy in one probing head.

However, the probing head exists as prototype and has not been operated in probing measurements yet. It will be focus on the implementation of measuring signal processing system and poseture controlling of the probing head in future works, followed by experimental validation of the functionality.

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