Design of a calibration setup for the dynamic analysis of multi-component force and moment sensors

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Abstract. For the dynamic calibration of multi-component force and moment sensors, different requirements need to be considered. We describe the mechanical design process for a calibration setup of such sensors with special focus on the generation of uniaxial force and moment components in different axes, with minimized secondary loads. The design is analysed using FEM simulations and experiments.

1. Introduction
The dynamic behaviour of mechanical systems follows different rules to the static behaviour of such systems. This well-known fact also applies to force sensors and their calibration. While static calibration is a well-established process, dynamic calibration is still a challenge and subject to research around the world [1-6]. The same applies to the use and calibration of multi-component force and moment sensors, which are able to measure multiple components of the force and moment vectors. Different approaches exist for the static characterization and calibration of such sensors [7,8], but many questions and problems are still unsolved.

As a result, the combination of dynamic calibration and multi-component force and moment sensors gives a large number of possible research topics, new approaches and development opportunities. In the following sections, we will describe the design of a calibration setup for the periodic calibration of a six-component force and moment sensor. The focus will be set on the generation of single force and moment loads with as few secondary loads as possible. The design proposal is analysed using the finite element method (FEM) and verified experimentally.

2. Dynamic force calibration
The dynamic calibration of force and moment sensors is a trending topic at different national metrology institutes (NMIs) [1-6]. The calibration methods used can be divided into two groups, continuous or sinusoidal and impact excitation. Continuous excitation is typically performed using electrodynamic shaker systems [9], impact excitation can include impact hammers [10] or accelerated impact masses [2].

In both cases, the reference force used to calibrate the sensor is calculated using Newton’s second law \( F = m \cdot a \). Therefore, the load mass and the relative acceleration between the mass and sensor are needed. Laser interferometry is a well-established method for acceleration measurement [2-4]. One dynamic test stand for force sensor calibration at PTB is equipped with a laser scanning vibrometer, which is capable of measuring the acceleration at different positions in the setup. From those acceleration values, information about rocking modes of the sensor or the load mass can be derived. In
addition, conventional accelerometers can be used as a second source for acceleration measurements, e.g. at positions which are not visible to the scanning vibrometer.

While the described setups are well suited and characterized for the dynamic calibration of uniaxial force sensors, the calibration of multi-component force and moment sensors is still a challenge. Very few publications on that topic are known to the authors [11-14].

3. Setup for dynamic multi-component force and moment calibration

Different aspects need to be taken into account for the design of a calibration setup for the dynamic calibration of multi-component force and moment sensors. To minimize the influence of secondary loads during the calibration of the single axis of a sensor, a special design of the load mass and adapting elements is necessary. A complete reduction of secondary loads cannot be reached, it can however be minimized by the following design proposals.

In [13], a cylindrical load mass combined with an air bearing is used for the calibration of the axial force of the sensor under test, while cubic load masses are used for transverse force, bending moment and torque components. Those cubic mass artefacts are mounted on one side of the sensor using different adapting elements and lever arms. While the use of a cylindrical load mass for axial force is a good choice in this setup, the additional setups show a superposition of transverse force, bending moments, torque and axial force.

As shown in [8], secondary loads can show a significant influence on the sensor signal. The separation of the different influencing factors is difficult. To reduce those influencing factors, a new load mass was designed in this investigation. The design criterion was to move the centre of gravity as close as possible to the origin of the coordinate system of the sensor. In this way, the same load mass can be used for the calibration of axial force and transverse force, while bending and twisting moments are reduced. In addition, the influence of the assembly of different adapting elements for different setups is reduced.

The mounting adapters for excitation in axial and transverse forces consist of three parts: one adapting element that stays mounted on the sensor for both setups, one adapter for axial, and one for transverse forces. This setup has the disadvantage of an additional bolted connection which acts as an additional spring-damper system, but again the influence of the mounting on the sensor is reduced. An additional design criterion for the adapting elements is the position of the centre of gravity of the whole setup. To reduce the bending moments and resulting loads on the bearing of the shaker, the centre of gravity should be centred over the axis of the shaker. Figure 1 shows the load mass and adapting elements in the setup for axial forces. Figure 2 shows the setup for transverse forces. The mounted system of the load mass, sensor and connecting adapter can be rotated in steps of 90 degrees around the horizontal axis to activate forces in the x- and y-directions.
In contrast to the setup for force stimulation, the different moment components cannot be generated without a superimposed force component. The typical methods to reduce force influence, like counter bearings or force couples, do not work for the periodic excitation used in this setup. However, the superposition of only two components is possible by a special design as shown in Figure 3. The centre of gravity of the adapting element including the load mass lies in the x-y-plane of the sensor, the mass element can be moved to different distances from the origin of the coordinate system. This results in a superposition of the transverse force and twisting moment. Using the adapter for axial force, a superposition of the axial force and bending moments can be achieved.

Another important point is the acceleration measurement in a multi-component calibration setup. As the sensor is sensitive to forces and moments in all three spatial directions, a reference force, and therefore an acceleration measurement, are required in three directions. Accelerometers are capable of measuring the acceleration in different directions, but only at one point, while the laser scanning vibrometer can measure at different positions but only registers acceleration in the direction of the laser beam.

As an addition to the existing methods of acceleration measurement, the calibration setup was equipped with a three-dimensional photogrammetric measurement system [15]. In comparison to the laser vibrometer, the photogrammetric system has a reduced spatial and temporal resolution, but provides full 3D displacement information in the observed area. This information can be combined with precise synchronization to the scanning vibrometer and expand the knowledge about the movement of the sensor-mass system.

4. Analysis of the setup
An analysis of the dynamic behaviour of the presented setup was performed using Ansys FEM software. The results of the FEM analysis were verified by experiments in the described shaker setup using periodic chirp excitation.

Different modes of the setup were analysed by means of modal analysis using Ansys FEM software. Figure 4 shows a selection of rocking and longitudinal modes for the axial and transversal version of the force setup. The main resonances are identified at 1078 Hz and 342 Hz for the axial setup and at 360 Hz and 450 Hz for the transversal setup. Figure 5 and Figure 6 show the measured acceleration at the load mass over the excitation frequency for a periodic chirp excitation for axial and transverse force. From the acceleration values, resonance frequencies are identified at 1194 Hz and 420 Hz for axial and at 325 Hz and 506 Hz for transversal excitation. An experimental analysis of the moment setup has not yet been performed, as the adapting elements are still to be manufactured.
5. Conclusion

We presented the design of a calibration setup for dynamic multi-component force and moment calibration. The aim of the setup is the generation of force and moment components with as few side loads as possible. To reach that aim, a specially designed load mass was developed. The centre of gravity of that load mass lies in the origin of the sensor coordinate system. In this way, force components can be generated in all three axes with minimized side moment components. For the generation of moment components, a special adapting element was designed, which allows the generation of bending and torsional moments with the superposition of only one axial or transversal force.

The dynamic behaviour of the setup was analysed using FEM simulation. Resonance frequencies were identified at 1078 Hz and 342 Hz for axial force and at 360 Hz and 450 Hz for transversal force. Experiments confirm the results of the simulation. The remaining deviation of up to 20% of the resonance frequencies can be explained by missing screw elements in the simulation due to performance reasons.

This setup serves as a basis for the future analysis of calibration procedures for dynamic multi-component calibrations and the uncertainty analysis of calibration results.

Acknowledgments

The authors gratefully acknowledge the funding of this work by the Deutsche Forschungsgemeinschaft (DFG) under grants Tu 135/24 and Ku 3367/1.

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