

STATIC AND DYNAMIC IDENTIFICATION OF MULTI-COMPONENT FORCE AND TORQUE SENSORS

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Abstract: An experimental setup for characterizing the dynamic and static behavior of multi-component force and torque sensors is presented. In this setup, a 6-DoF force and torque sensor based on the principle of electromagnetic force compensation (EMFC) is used to apply static and dynamic force and torque vectors to a sensor to be identified. Several characteristics of the sensor under test, such as linearity and dynamic behavior can be evaluated. The system presented here can generate forces and torques with up to 7 N and 0,35 N·m and has resolutions of 10 μ N and 0,3 μ N·m respectively.

Keywords: force measurement, torque measurement, multi component, sensor identification

1. INTRODUCTION

The characterization of the behavior of force and torque sensors is a requirement for the accurate measurement of forces and torques. In the literature, there are several measuring principles [1] for these quantities available, with corresponding implementations and prototypes. Two examples are the measurement of deformations in compliant mechanisms with strain gauges and the electromagnetic force compensation (EMFC). The performance of these systems has been extensively evaluated regarding aspects such as the linearity and dynamic response. There are well-known methods for consistently analyzing one-component force measurement systems [2-4], however, when considering multi-component force and torque sensors, more attention should be taken [5]. With the additional measuring components, new requirements for adjusting the position and orientation of the sensor are introduced. Furthermore, the coupling between the different measuring components must be considered and, for the torque components, the center of the measuring axes, which can differ from the geometrical center of the sensor because of manufacturing tolerances, must be identified. The identification of multi-component force sensors has been addressed in the literature and several technics have been presented. For instance, the use of deadweights and automated load changers are principles applied to one component sensors that were successfully adapted to multi-component force measuring systems [5-8]. Other calibration technics, such as the Shape from Motion method, are dedicated to multi-component sensors [9,10]. In this work, an experimental setup for identifying multi-component force and torque sensors is presented and used for

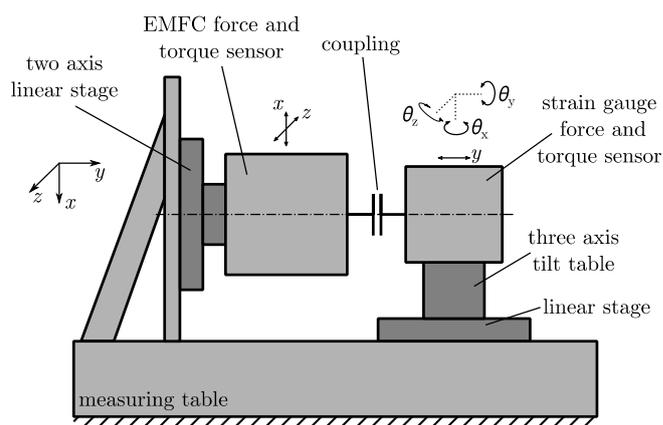


Figure 1: Experimental setup.

characterizing the dynamic and static behavior of a test sensor. The system adopted for the tests is a force and torque sensor based on strain gauges, which is capable of measuring forces and torques in three orthogonal directions simultaneously [6]. The presented experimental setup was designed with the objective to identify the static and dynamic behavior of force and torque sensors with a measurement range of up to 7 N and 0,35 N·m. The system can generate forces and torques with a resolution of 10 μ N and 0,3 μ N·m respectively. A further objective of this setup is to verify numerical simulations used for describing the dynamic and static behavior of the test sensor.

2. EXPERIMENTAL SETUP

The experimental setup used for the identification tasks is presented in figure 1. The EMFC force and torque sensor is the main component of the system. It is a multi-component force and torque sensor based on the principle of electromagnetic force compensation [11]. The sensing element is a levitating body whose position and angles are controlled by six voice-coil actuators. This sensor can be used to generate force and torque vectors with arbitrary magnitude, direction and time behaviour. The line of action of the forces generated can be changed as well and, in this way, the forces can be applied directly to the centre of the sensor under test without generating a torque in the coordinate system of this sensor. The sensor to be tested is coupled to the EMFC system by a rigid coupling. The relative position and angle between the systems can be adjusted in six degrees of freedom with a single-axis linear stage, a two-axis linear stage and a three-

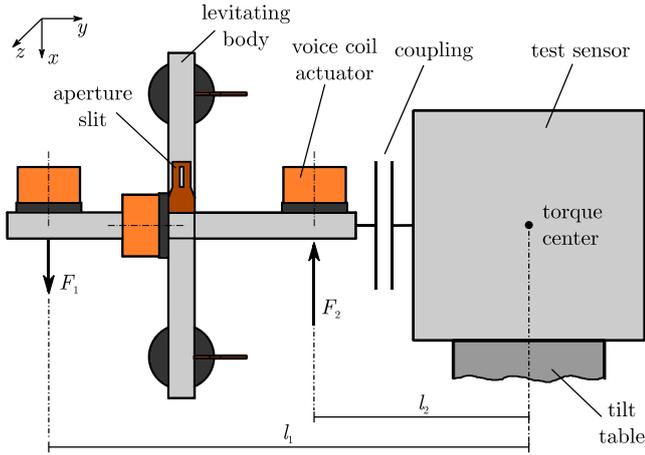


Figure 2: Levitating element and test sensor.

axis tilt table. These adjustment directions are shown in figure 1. While this system was used only with one type of test sensor, it can be adapted to any multi-component force and torque sensor that has a similar measuring range.

The levitating body of the EMFC force and torque sensor is shown in figure 2. The voice coil actuators are used to generate the dynamic and static forces for the identification process. These actuators are also responsible for generating an offset force to compensate the weight of the levitating body. As an example, a pair of forces F_1 and F_2 is shown in figure 2. With these forces it is possible to generate a force in the x direction with the magnitude

$$F_x = F_1 - F_2, \quad (1)$$

and a torque in the z direction with the magnitude

$$T_z = F_1 \cdot l_1 - F_2 \cdot l_2. \quad (2)$$

The torque component is calculated for the torque center of the test sensor. In case the parameters l_1 and l_2 are unknown, they can be identified by generating linearly independent combinations of F_1 and F_2 and measuring the output torque T_z of the test sensor. In this way, the following linear system of equations is obtained:

$$\begin{bmatrix} T_z^1 \\ T_z^2 \\ \vdots \\ T_z^n \end{bmatrix} = \begin{bmatrix} F_1^1 & -F_2^1 \\ F_1^2 & -F_2^2 \\ \vdots & \vdots \\ F_1^n & -F_2^n \end{bmatrix} \begin{bmatrix} l_1 \\ l_2 \end{bmatrix}, \quad (3)$$

where n represents the amount of measurements and combinations for the forces F_1 and F_2 . This overdetermined system of equations can be solved by using the ordinary least squares method. The solution is given by the following expression:

$$\mathbf{l} = (\mathbf{F}^T \mathbf{F})^{-1} \mathbf{F}^T \mathbf{T} \quad (4)$$

In this equation $\mathbf{l} \in \mathbb{R}^2$ represents the vector containing the parameters l_1 and l_2 , $\mathbf{F} \in \mathbb{R}^{n \times 2}$ is the matrix with the combinations of forces and $\mathbf{T} \in \mathbb{R}^n$ is the vector with the measured torques.

With this system it is possible to generate arbitrary test signals, such as the chirp signal, the maximum length binary sequence (MBLS) and signal patterns given by calibration guidelines for force sensors, like the DAkkS-DKD-R 3-3, published by the national accreditation body for the Federal

Republic of Germany [12]. The forces and torques are generated and measured simultaneously by using a real-time controller equipped with eighteen analog-to-digital converter (ADC) input channels and six digital-to-analog converter (DAC) output channels. Six ADC channels are used for measuring the electrical output signals of the test sensor which are proportional to the applied forces and torques, six ADC channels are used for measuring the electrical signals related to the position and angles of the levitating element and six ADC channels are used for measuring the current flowing in the voice coil actuators with the help of measurement resistors. These current signals are used to determine the forces and torques generated by the EMFC sensor. The reference signals for the forces and torques are generated by the six DAC channels. Since the six output signals from the test sensor are measured simultaneously, it is possible to identify interferences and cross-talk between the components. The force and torque vectors generated by the EMFC sensor are resulted from the sum of the forces and torques generated by the six voice coil actuators, in a way that it is possible to freely change the direction of the forces and torques actuating in the test sensor. An additional feature of the presented system is the possibility to measure the linear and rotational stiffness of the test sensor by using the position and angle signals provided by the six aperture slit displacement sensors together with applied forces and torques.

4. SIMULATION MODEL

Force and torque sensors are used in several branches of science, industry and commerce. Depending on the specific application, additional elements have to be attached to the sensor to perform the measurement task. For example, in the Lorentz force velocimetry [13,14], permanent magnets have to be mounted in the sensing element in order to measure the interaction forces between a liquid metal flow and the static magnetic field generated by the permanent magnet. Depending on the mass of the element attached, the eigenfrequency of the system can suffer a significant change and, when measuring dynamic forces, it is fundamental to track these changes to determine the frequency response of the sensor. In order to easily predict these changes, a simulation model of the sensor can be used. The experimental setup presented here can be applied not only for the identification of force and torque sensors, but also for validating numerical models that describe these systems.

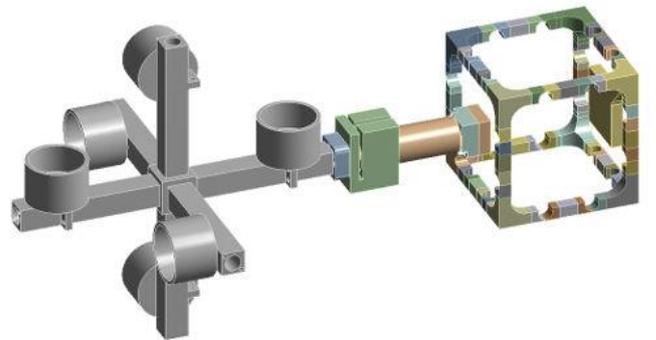


Figure 3: Model used for the FEM simulations.

With a consistent numerical model it is possible to identify how design changes and measurement conditions influence the static and dynamic behaviour the sensor. This is important not only for the application of force and torque sensors, but also for the design of new systems.

By using a finite element analysis software, a model for the current experimental setup considering both EMFC and test sensors was implemented (figure 3). This model was used to perform a harmonic analysis and identify the frequency response of the test sensor with the EMFC sensor coupled to it, while generating dynamic forces and torques. The model of the test sensor could be verified by comparing results from both simulations and measurements.

5. RESULTS

The measurement setup presented here was used to identify the frequency response of the multi-component test sensor. Figure 4 shows the measured frequency response for the linear and angular directions, representing the sensor's dynamic response for the force and torque measurement

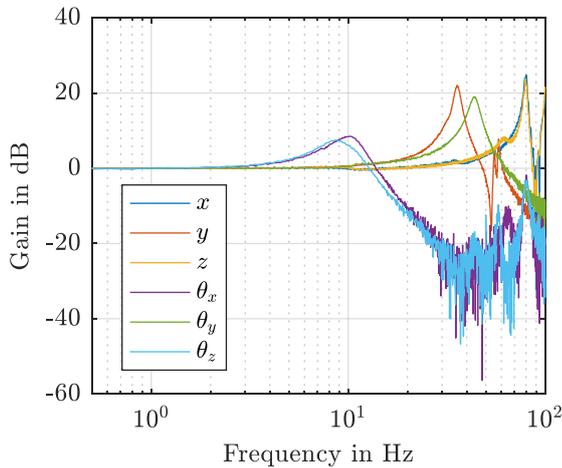


Figure 4: Frequency response of the test sensor for the six degrees of freedom.

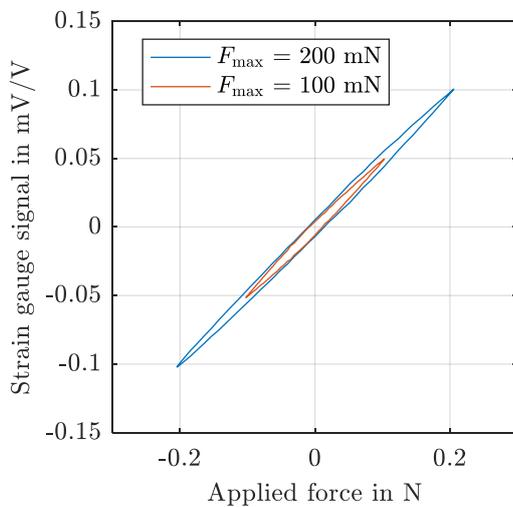


Figure 5: Hysteresis measured in the strain gauge force sensor. Representation of the hysteresis effect on the x-axis exaggerated by factor 20.

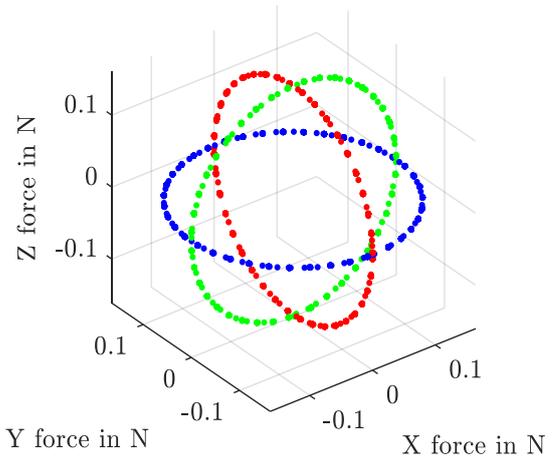


Figure 6: Results for the shape from motion measurement.

respectively. Some characteristics of the system, such as eigenfrequency and damping, can be evaluated through this figure. These measurements were performed with chirp test signals for the forces and torques, and the frequency responses shown here were determined by using the output force/torque signals of the test sensor and the forces and torques generated by the EMFC sensor. Additionally, the linearity of the static behaviour of the test sensor was investigated. Figure 5 contains the measurement results of the sensor's hysteresis for the x direction. In order to perform this measurement, static force levels were applied to the sensor in a way to generate cycles of loading and unloading. Two measurements with maximal forces of 100 mN and 200 mN were performed. For these measurements, the hysteresis was responsible for an maximal relative error of about 0,3 %. For the axis y and z , a similar hysteresis effect was observed in the test sensor. The stiffness of this sensor could also be measured for the y axis and a value of 12,8 kN/m was obtained. Simulations were performed with the objective to determine the stiffness for the same direction and a value of 11,1 kN/m was obtained.

Since the direction of the forces and torques generated by the EMFC sensor can be freely changed, it is possible to execute an identification procedure similar to the shape-from-motion calibration [9,10]. The main difference between the original method and the procedure executed in this work is that, instead of rotating the sensor to change the direction of the acting force, which is the gravitational force, the test sensor is maintained in a static position and the identification force is generated in different directions. In this way the moving mechanism for rotating the test sensor is not required. Figure 6 shows a measurement result for this identification method, where forces with magnitude of 0,1 N were generated in different directions. In this figure three circles over the planes xy (blue), xz (green) and yz (red) are shown, that were produced by rotating the identification force around the axis z , y and x respectively. These circles indicate if the test sensor exhibits any sort of deviation when combined forces from different components are generated.

The results obtained with the simulation model could be verified by comparing them with measurement results.

Table 1 contains the eigenfrequencies of the test sensor obtained from both measurements and simulations. The magnitude of the error between the results is also shown in this table and a maximal error of 1,9 Hz was observed. The results shown here are for the first mode of vibration.

Table 1: Eigenfrequencies for the measurements and simulations.

Direction	Measurement	Simulation	Error magnitude
x	79,8 Hz	79,5 Hz	0,3 Hz
y	35,9 Hz	37,8 Hz	1,9 Hz
z	79,9 Hz	79,5 Hz	0,4 Hz
θ_x	10,2 Hz	10,0 Hz	0,2 Hz
θ_y	43,8 Hz	45,1 Hz	1,3 Hz
θ_z	8,7 Hz	10,1 Hz	1,4 Hz

6. CONCLUSIONS

With the proposed experimental setup, the dynamic behaviour and hysteresis effect present in a multi-component force and torque sensor could be evaluated, and a numerical model of the sensor could be verified experimentally. The stiffness and the center of the sensor coordinate system could be evaluated as well. Although the results presented here were obtained by performing measurements with only one test sensor, the experimental setup shown can be used to characterize other force and torque sensors, precision mechanics like compliant mechanisms and to measure position and angle dependent characteristics of actuators.

7. ACKNOWLEDGMENTS

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