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INVESTIGATION AND CALIBRATION OF A FORCE VECTOR SENSOR WITH A CALIBRATION ARTEFACT

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Abstract – This paper deals with the investigation of a new type of force vector sensor developed by Gassmann Testing and Metrology (GTM). The measurements were performed in the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig. The new force vector sensor is capable of measuring the main axial force and six secondary components: two side forces perpendicular to the main axis, three axial forces arranged in a triangle parallel to the main axis and furthermore a moment with the main axis of the sensor as axis of rotation. With these components one can describe the force as a vector giving the amplitude of the force vector, its direction and the force application point.

Keywords: multi-component measurement

1. INTRODUCTION AND PRINCIPLE OF THE SENSOR

There are many force sensors available on the market as single-component transducers, measuring only forces with a given direction but with very small uncertainties. Multi-component force sensors produce higher uncertainties, suffer sometimes from large dimensions or are heavy build-up systems of several high-precision single-component transducers. For the use as a transfer standard for calibration and investigation of force machines or test stands a compact sensor was needed. Therefore the force vector sensor was developed by GTM.

For the use as transfer standard the force vector sensor has to be calibrated and traced back to the national standards. So the sensor was investigated and a calibration method was developed at PTB.

The complete six component transducer consists of two parts: a precise force transducer for axial load and a multi-component sensor for the two sideway force directions and the three moment components. In the investigated case, a GTM force transfer standard KTN-VN measures the axial force F_z. It is mounted on top of the multi-component sensor which is capable of measuring sideway forces and moments (figure 1). Between upper und lower plates of the multi-component sensor, three bending spring elements are placed in an equilateral triangle around the axis of the sensor. Each spring is designed to reduce the crosstalk of the other force or moment components. From these three signals the bending moments M_{bx} und M_{by} are calculated by the analysing MCA-software of the GTM VN-Digitizer measuring amplifier. A column is placed in the middle of the multi-component sensor with four leaf springs measuring the side forces F_x , F_y and the torque M_z. The four leaf springs are connected to the upper plate of the sensor by a membrane which is flexible against axial forces to minimize crosstalk to the three spring-bodies for the measurement of bending moments [1]. The final crosstalk is lower than 1% between the two sideway force components and lower than 0,1% for all other components.

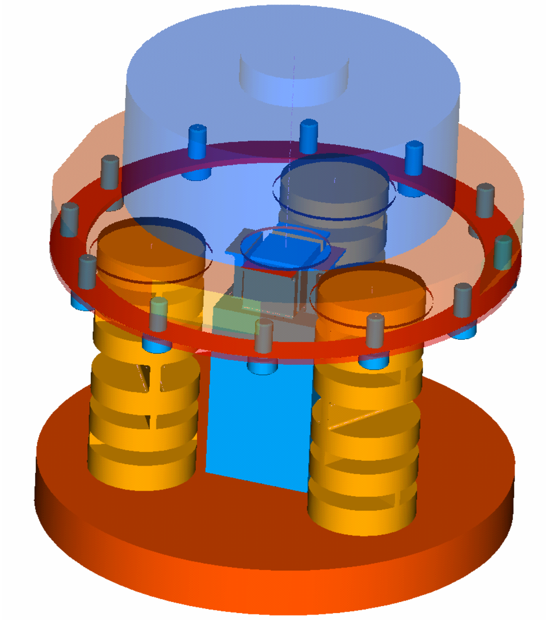

Fig. 1. Construction principle of the force vector sensor consisting of a high precision force transducer and a multi-component sensor.

The analyzing GTM VN-Digitizer device with the MCA software is used to calculate the results in arbitrary form, for example three forces and three moments or value and direction of the resulting force vector. The results can be transformed to different coordinate systems.

2. INVESTIGATION OF THE FORCE VECTOR SENSOR

Today's calibration facilities are normally able to realize force and torque very precisely – but only one component in one axis. To investigate and calibrate the new force vector sensor, it was the aim to realize as much different load components as possible. Finally, the force vector sensor was investigated with three different methods to realize different load components and the results were compared to develop a calibration method for the sensor. The tested prototype is capable of measuring axial forces of up to 100 kN, side forces of up to 10 kN and bending moments of up to 500 N·m.

Force standard machines (FSM) of deadweight type provide the forces with smallest uncertainties in the direction given by gravity. The force vector sensor was mounted with special facilities inside the FSM by a certain angle against the axis of the deadweight machine, i.e. its gravitational force.

These facilities can be simple wedges – useable in first investigations – or the sensor is mounted in the FSM on a special spherical calibration artefact for the generation of arbitrary angles by rotation in the bearings, so different force vectors can be applied. Figure 2 shows the Force Vector Sensor mounted on the spherical calibration artefact.

Figure 2. Force vector sensor mounted on the spherical calibration artefact

This spherical calibration artefact consists of two main parts, the lower mounting part and the upper force application parts. With the help of alignment fixtures, the force vector sensor is mounted on top of the calibration artefact, whose bottom area is a sphere. The centre of this sphere lies at the coordinate system's reference point inside the sensor. Sensor and calibration artefact are placed on a cone bearing. A cap mounted on top of the force vector sensor is also furnished with a sphere sized to fit its centre to the point of application. After the centring of the calibration artefact in the FSM, the reference point of the sensor will stay on the axis of the machine while the calibration artefact is turned inside its bearings. In an earlier project, the calibration of a multi-component strain and stress sensor for the supervision of structures was carried out in a similar way using a wheel-formed calibration artefact [2].

In the second calibration procedure, a load frame with different systems for lateral force and moment generation is mounted around the standard measuring machine. The design of both procedures is novel as regards the required small uncertainties. First tests show hopeful prospects and abet the results of the other two investigated calibration procedures, but still further investigations will be done especially with this type of multi-component load facility.

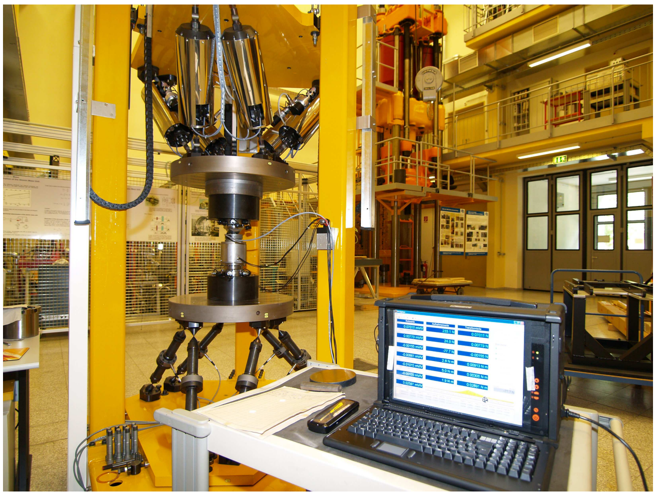

Figure 3. Force vector sensor in multi-component calibration machine

The prototype of the force vector sensor was also investigated on a multi-component calibration machine of hexapod structure as shown in figure 3. This machine applied axial and side forces to the force vector sensor of up to 10 kN. The force vector sensor is mounted between two parallel plates. The upper plate can be moved in lateral and angular directions using six electrical drives arranged in a hexapodal structure in order to generate arbitrarily directed force or moment vectors in combination. The lower plate is supported on a hexapodal structure of links. Each of the six links consists of a calibrated force transducer and special joints transmitting only one direction of force. From the signals of these reference transducers the load applied to the sensor under test can be computed using the calibrated geometry of the machine. The load values generated by the facility are then compared with the values measured by the force vector sensor. Since this machine uses reference transducers, its uncertainty cannot compete with that of the best deadweight machines. Additionally, this calibration device is able to generate maximum forces of only 10 kN, whereas a nominal force of 100 kN is needed for the force vector sensor. But the advantage of the multi-component machine is its ability to apply combined forces and moments without changing the transducer's mounting or the load application.

3. CALIBRATION AND UNCERTAINTY OF THE FORCE VECTOR SENSOR

For calibration of the force vector sensor the spherical calibration artefact method was chosen because of the low uncertainty achievable by using dead weight force standard machines. The sensitivity coefficients a_{ij} are calculated as in (1) with F_x and F_y being side forces, F_z axial force, f_x and f_x output signals for side forces and f_z output signal for axial forces.

$$f_i = \sum_{j=x}^{z} a_{ij} F_j \,, \; i = x; y; z \; \text{ and } \; (a_{ij}) = A \qquad (1)$$

For solving this linear system at least nine independent sets of data from nine different loading conditions covering the whole range of nominal load are required. Therefore the sensor is rotated around each single sideway force axis x and y for applying only one component of sideway forces and around both axes at a time for applying both components F_x and F_y. So different directions of force vectors are applied giving independent sets of data. From this data the matrix A in (2) describing the response characteristics of the sensor (with F in kN and f in mV/V) was calculated for the prototype.

$$A = \begin{pmatrix} 0{,}34 & 5{,}2\cdot 10^{-3} & 1{,}0\cdot 10^{-4} \\ 3{,}7\cdot 10^{-3} & -0{,}34 & -1{,}2\cdot 10^{-4} \\ -2{,}4\cdot 10^{-5} & -2{,}1\cdot 10^{-5} & 2{,}0\cdot 10^{-2} \end{pmatrix} \qquad (2)$$

From these characteristics also crosstalk can be derived. For nominal load of 10 kN for sideway forces and 100 kN for axial force crosstalk of side force to axial force is at 0,5‰, between side forces at 1% and of axial force to side force below 1‰. For the use of the force vector sensor for measurements another matrix is needed to calculate the load from output data (3). For linear transfer models the transformation matrix is the inverse matrix of A. Equation (4) shows the coefficients for the transformation of output signals into components of the force vector.

$$F_i = \sum_{j=x}^{z} b_{ij} f_j \,, \; i = x; y; z \; \text{ and } \; A^{-1} = (b_{ij}) \qquad (3)$$

$$A^{-1} = \begin{pmatrix} 3{,}0 & 4{,}6\cdot 10^{-2} & -1{,}5\cdot 10^{-2} \\ 3{,}2\cdot 10^{-2} & -3{,}0 & -1{,}8\cdot 10^{-2} \\ 3{,}5\cdot 10^{-3} & -3{,}0\cdot 10^{-3} & 49{,}9 \end{pmatrix} \qquad (4)$$

For calibration also uncertainty needs to be regarded. The components of uncertainty for the calibration of the force vector sensor with the spherical calibration artefact are listed in table 1.

Table 1. Components of Uncertainty, regarding side forces F_x *and* F_y and axial force F_z

component	$u_i \rightarrow (F_x, F_y)$	$u_i \rightarrow (F_z)$
alignment	$7 \cdot 10^{-4}$ mV/V	$4 \cdot 10^{-4}$ mV/V
digitizer	$5{,}2 \cdot 10^{-5}$ mV/V	
hysteresis	$6 \cdot 10^{-3}$ mV/V	$5 \cdot 10^{-5}$ mV/V
creep	$4 \cdot 10^{-5}$ mV/V	
inclination sensor	$4 \cdot 10^{-2}$°	
response matrix	$8 \cdot 10^{-4}$ mV/V	$4 \cdot 10^{-8}$ mV/V

From these data the combined uncertainty can be calculated using the uncertainty model in figure 4. The uncertainty budget for the force vector sensor and the resulting combined uncertainty are given in table 2.

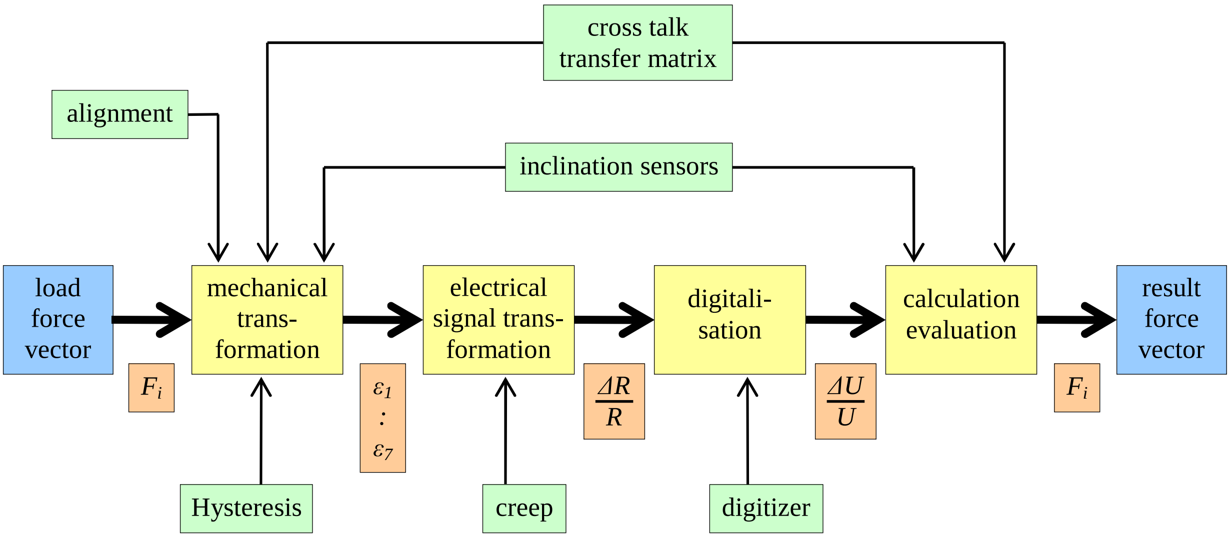

Figure 4. Uncertainty model for force vector sensor

Table 2. Relative uncertainty budget for side forces and axial force

component	→ (F_x, F_y)	→ (F_z)
alignment	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
digitizer	$1{,}5 \cdot 10^{-5}$	$2{,}6 \cdot 10^{-5}$
hysteresis	$1{,}8 \cdot 10^{-3}$	$1{,}5 \cdot 10^{-5}$
creep	$1{,}2 \cdot 10^{-5}$	$2 \cdot 10^{-5}$
inclination sensor	$7{,}2 \cdot 10^{-3}$	$8 \cdot 10^{-6}$
response matrix	$2{,}4 \cdot 10^{-4}$	$9{,}9 \cdot 10^{-7}$
combined uncertainty	**$7{,}4 \cdot 10^{-3}$ kN**	**$1{,}1 \cdot 10^{-4}$ kN**

The budget shows very low uncertainty in axial component of the force vector. The uncertainty budget for the side components show that the inclination sensors add the biggest part. By changing this sensors the uncertainty can be decreased to lower uncertainty for the side forces.

5. CONCLUSIONS

The results of investigation show that the new force vector sensor achieves lower uncertainties in multi-component force measurement. This will allow to use the sensor in precision measurements for instance as transfer standard for calibrating multi-component force measuring stands and for investigating parasitic effects in high precision force standard machines. As the sensor is also capable of measuring moments analogue methods for calibration will be developed so all six components of a force and moment vector can be measured with lower uncertainty.

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