IMEKO 20th TC3, 3rd TC16 and 1st TC22 International Conference
Cultivating metrological knowledge
27th to 30th November, 2007. Merida, Mexico.

A new six-component force vector sensor – first investigations

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Abstract:

Force transfer standards allow high-accuracy measurements of forces to be carried out – but they measure only one component of the force vector. The spatial direction of this component is given by the orientation of the transducer. A new force transducer is now designed to measure additionally the direction of the force vector, i.e. all its three components, as well as additional bending moment components and the torque, with high accuracy. For use as a transfer standard, the force vector sensor has to be traced back to standard machines in national metrological institutes. For calibration in deadweight machines, new methods have to be developed.

Key words: force standard, calibration, traceability.

1. Introduction:

Force and torque transducers of different types of construction and different classes of uncertainty are available on the market nowadays. Most of them are able to measure forces, respectively torques, acting along one axis defined by the transducer's orientation. Thus a scalar quantity is obtained instead of a vector. In many cases it is necessary to know the exact direction of all special components of force and torque. Several transducers are available for multi-component measurements - but often they do not satisfy the accuracy requirements. Other systems, such as the IMGC six-component dynamometer [1], are very precise but they do not meet the customer's requirements regarding size and weight. Therefore, a new compact force vector sensor was developed by the German Gassmann Testing and Metrology GmbH (GTM). This sensor is capable of measuring the axial force by means of a high-precision force transfer standard which is mounted on top of a so-called vector sensor, which is designed to measures the direction of the force and the moment vectors. The new force vector sensor aims towards uncertainty class 00 according to ISO 376. In order to investigate its properties, the sensor will be calibrated in different calibration machines, including the most accurate ones, the deadweight machines of the German metrological institute, PTB. But these machines realize only a force in vertical direction. Therefore new calibration methods are being developed at the PTB.

2. Construction Principle of the Sensor

The new six-component force vector sensor consists of a force transfer standard and a multicomponent sensor. The GTM force transfer standard of KTN-VN type is able to measure the axial force F_z with highest precision. It is placed on top of a multicomponent sensor which on his part is capable of measuring side forces and moments (figure 1). Between upper und lower plates of the multicomponent 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.

Figure 1: Force vector sensor and spherical calibration body mounted into the 100 kN force standard machine

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 multicomponent 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. The development of the sensor was carried out using numerical simulations. Figure 2 shows the strain at different load situations.

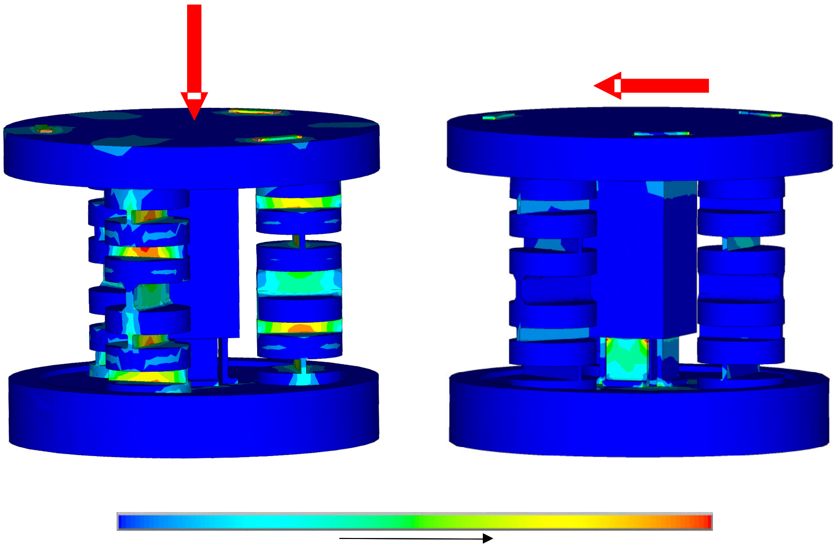

Figure 2: Numerical simulation of the vector sensor at different loads

The interest of the industry focuses especially on a vector sensor with smaller angles between the force vector and F_z, the axis of the transducer. Therefore the first type of the force vector sensor measures axial forces up to 100 kN, side forces up to 10 kN, bending moments up to 500 N·m and torques up to 100 N·m.

The analyzing GTM VN-Digitizer device with the MCA software – the visual surface is shown in figure 3 - 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.

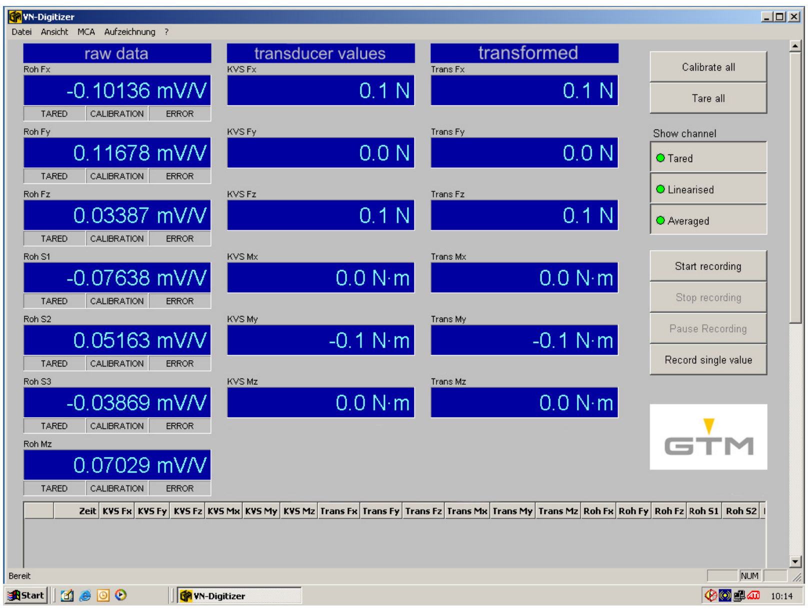

Figure 3: MCA-software of the VN-Digitizer amplifier

3. Calibration

The force vector sensor has to be calibrated in national metrological institutes in deadweight force standard machines (FSM) to realize the uncertainty class aimed at. Force and torque standard machines usually realize only one direction of force or torque. To generate different load directions, new procedures and additional facilities have to be developed. There are three main principles promising success: inclining the force vector sensor, building additional facilities to generate side forces or moments and the use of a multi-component reference-type calibration device [2].

3.1 Inclining the Sensor with a Spherical Calibration Body

The first method is to incline the force vector sensor inside the FSM by a certain angle against the axis of the deadweight machine, i.e. its gravitational force. In this case the sensor will measure only the component acting in the directions of its measuring axis. The inclination can be realized by the help of wedges but the maximum inclination is limited to small angles of a few degrees. For the generation of arbitrary angles the idea of a spherical calibration body came up, where the reference point or the coordinate system of the sensor is placed in the centre of the sphere (figure 4). After the centring of the calibration body in the FSM, the reference point of the sensor will stay on the axis of the machine while the calibration body is turned inside its bearings. In an earlier project, the calibration of a multicomponent strain and stress sensor for the supervision of structures was carried out in a similar way using a wheel-formed calibration body [3]. The first prototype of the vector sensor was optimised to measure smaller angles of the force vector towards the F_z axis. For that reason, the calibration body in figure 4 was optimised to a smaller construction outline – in order to optimise the mounting efforts in the FSM and to reduce production uncertainties – according to the ratio of axial and side forces. This spherical calibration body 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 body, 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 body 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. Figure 1 shows the force vector sensor mounted inside this spherical calibration body.

With this equipment, the force vector sensor can be mounted between the two parallel compression plates of the deadweight machine. The spherical area allows the calibration body with the mounted force vector sensor to be turned by angles of up to 15°. Several problems had to be solved during the design. Numerical simulations were performed to calculate and reduce the influence of the necessary mounting screws inside the calibration body. Local changes in strain should not have any effect on the signals of the sensor. In addition, the manufacturing uncertainties for the surface are a problem. These uncertainties were also estimated in numerical simulations.

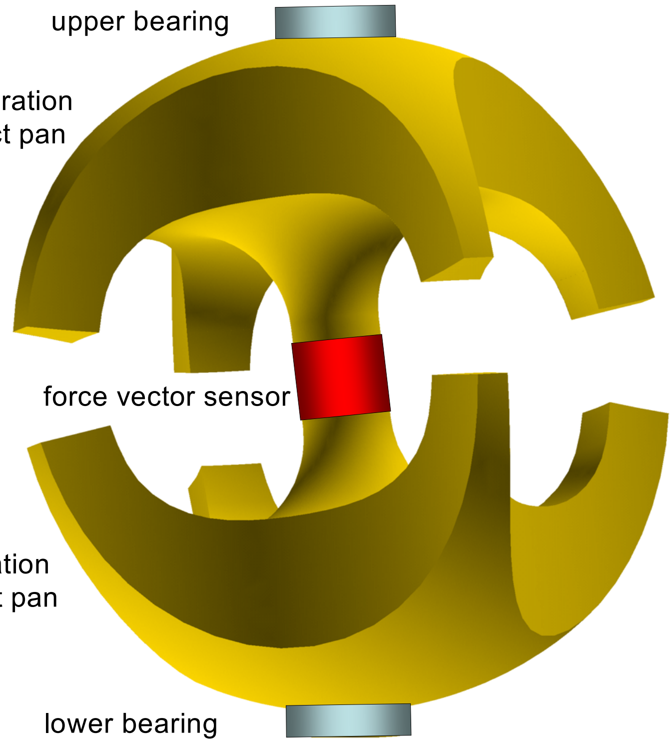

Figure 4: Design of a spherical calibration body

3.2 Additional Facilities to Generate Side Forces

The second method is to build extensions for the deadweight machine. Therefore, a frame is clamped around the crosshead of the force standard machine (figure 5). On this frame, a beam with carriage guides can be moved vertically and fastened in different positions. There are two different carriages moving on the beam horizontally. One of the carriages supports a pulley for an additional mass stack system to generate forces, the other a screw drive (figure 6). The drive is equipped with a high precision force transducer to measure the applied force. The carriage and the beam are moved on the guides by spindle drives for precise alignment. A special cap on the top of the sensor enables the application of side forces using rope and pulley or the spindle drive. The point of application of the force can be moved to different positions on the cap to generate moments. Both carriages can be used at the same time, so moments can be applied while side forces are compensated. While using this equipment for applying side forces, axial force can be applied using the deadweights of the force standard machine for highest precision. During these measurements, the force vector sensor is fastened to the lower crosshead by special means, to prevent movement of the sensor after alignment. All this equipment can be easily removed to use the force standard machine for standard calibration procedures in its original state.

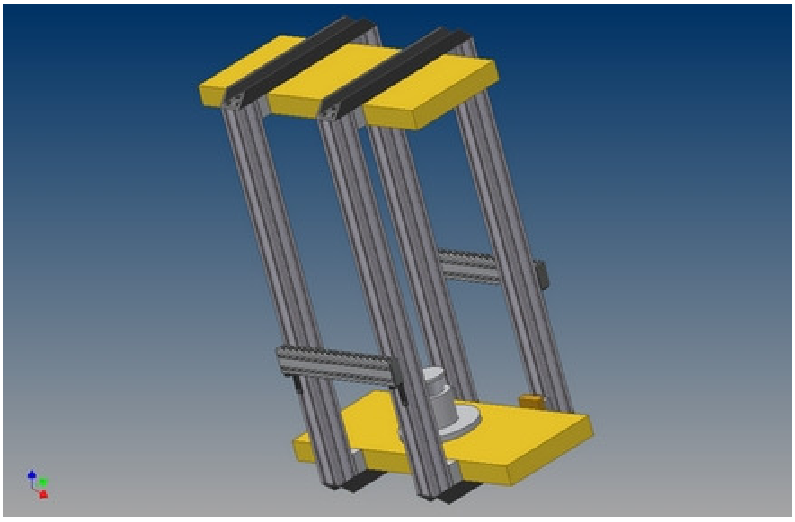

Figure 5: clamped frame for the 100 kN force standard machine

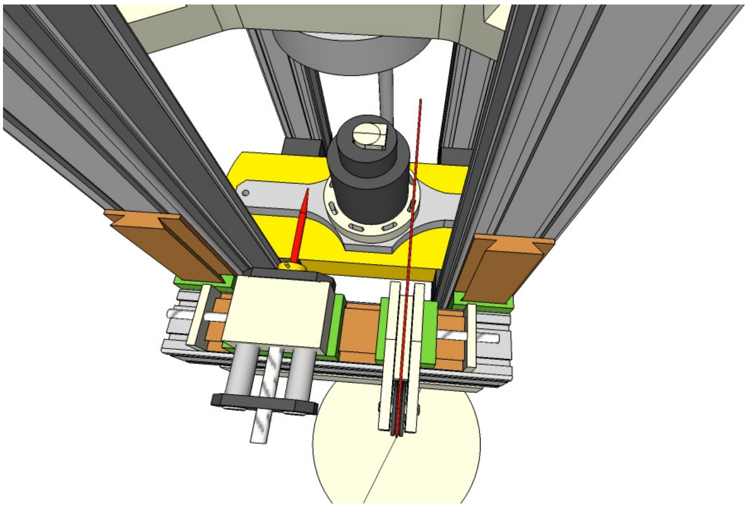

Figure 6: Spindle drive and pulley for generating side forces and bending moments

3.3 Multi-Component Reference Calibration

A multi-component force and moment calibration device of reference type [2] has also been used for examination and calibration. Here, 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 (figure 7). 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.

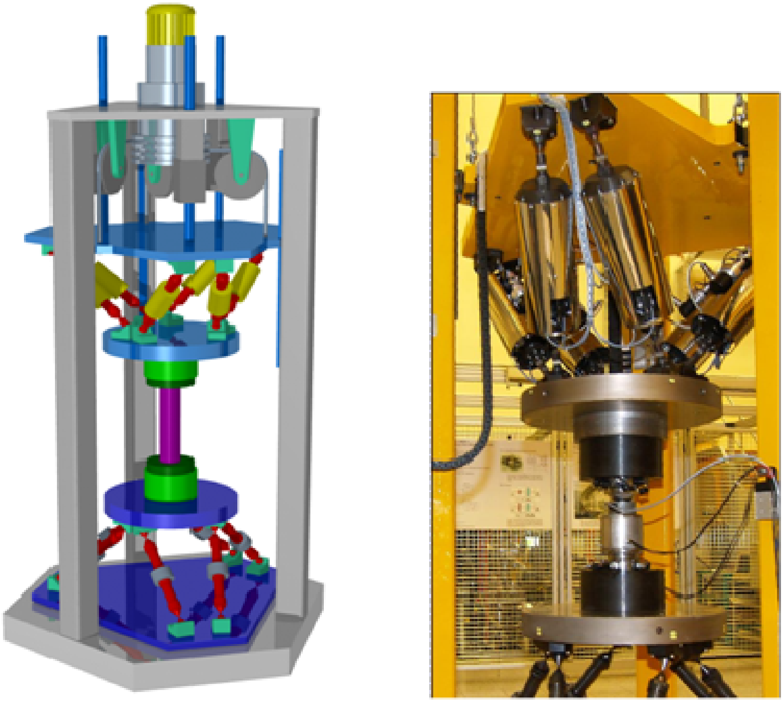

Figure 7 Force Vector sensor mounted into the multi-component reference type calibration device

4. First Investigations

For first investigations, a prototype of the force vector sensor was built. The prototype consists of a force transfer transducer with a capacity of 100 kN and a vector sensor capable of measuring side forces of 10 kN and moments of 1 kN·m.

The design has been accomplished by the help of numerical simulations. The force vector sensor was analysed to verify the decoupling of the different components.

First measurements investigated the influence of the vector part of the sensor for accuracy of the force transfer normal. Therefore, the force vector sensor was placed in the 100 kN force standard machine. Only axial force F_z was applied in steps of 10 kN up to 100 kN. Three upward and downward series were measured. Then the sensor was rotated in steps of 90° and only upward series were measured (figure 8). These rotation measurements were repeated. In a measuring range from 40% to 100% of the rated load the results show an uncertainty of $4 \cdot 10^{-5}$. The other channels were additionally observed in order to determine crosstalk. The standard deviation of values for side forces F_x and F_y is $4 \cdot 10^{-4}$. The results also suggest that these figures describe not only crosstalk but show also parasitic effects of the force standard machine. These effects have to be determined to reduce the uncertainty of the concerned components.

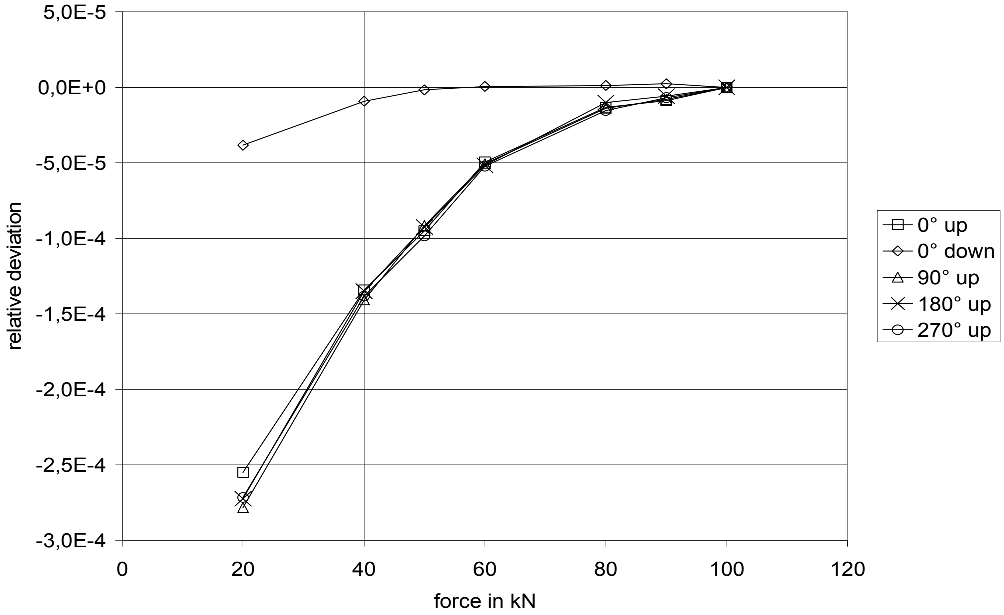

Figure 8: Relative deviation from linearized curve

Further investigations using all three methods are presently going on. The results will be compared to describe the metrological characteristics of the force vector sensor. The work will result in a calibration procedure for this type of force transducer. It is also aimed at a general calibration procedure for different kinds of multi-component force transducers. High precision force vector sensors can be used as transfer standards. They will be used to calibrate multi-component test stands, for example for wheel and tyre testing. Multi-component calibration devices can be traced back directly to force and torque standard machines avoiding the calibration of force transducers and geometry of the structure.

5. Summary

The new force vector sensor has proven that it enables a lower uncertainty than all other existing compact multi-component force and torque transducers. The vector sensor part has no negative influence on the mounted transfer standard. It is the aim to quantify individual contributions to the uncertainty budged on the basis of comparison measurements. The investigation of the calibration procedures and the mathematical description of the uncertainty model are performed in interaction with the development of the sensor as such by the manufacturer. The results constantly enter into the development of new prototypes. The objective is to make an efficient sensor available to the user by the end of 2008 which can be calibrated at PTB as a transfer standard.

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