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MULTICOMPONENT-TRANSDUCERS: DEFINITION, CONSTRUCTION TYPES AND CALIBRATION CONSIDERATIONS

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Abstract – This paper summarises basic experiences of manufacturing and calibrating multicomponent-transducers (MCTs). Very often a diversity of the "multicomponent" term is found, so at first a definition is given by using the vector item.

Because of the unlimited number of multicomponent applications, a graduation of types is difficult. Moreover there are main differences in construction resulting in different properties. Therefore the main construction principles of MCTs are discussed and an overview is given. Such information may be helpful for the choice of calibration equipment.

Regarding the properties of MCTs a diversity of terms is as often found. Especially the sensitivity to secondary components (sometimes called parasitic components), is often referred to as cross talk and mostly the exact definition is not clear. The terms are discussed and values to be indicated in a calibration certificate are proposed.

The calibrations of multicomponent transducers have been the subject of several considerations. Different methods of the standard equipment are discussed and a procedure is presented based on a force-vector-sensor as a transfer standard.

Keywords: Force, Moment, Multicomponent

1. INTRODUCTION

Multicomponent measurements are getting more and more important. The industry strives to improve products by better quality and lower costs, thus increasing requirements on existing measurement facilities. Therefore, in a lot of applications it is not sufficient to measure forces and moments as a scalar quantity.

In the last years many multicomponent systems including electronic and software of different types were built and it seems that the number of further possible types is unlimited [1]. Today, the multicomponent-traceability is in the state of an early development. A few standard facilities exist for a few numbers of applications only. National Institutes and Calibration Laboratories are thinking about equipment investments to improve the possibilities of calibrating MCTs. But due to the limited experience and the unlimited types of MCTs nowadays an investment decision is very complicated.

Nevertheless the industrial development increases the demand for metrological infrastructure.

2. DEFINITION

In broader sense the term multicomponent in force and moment measurement usually means to measure more than one force or moment. Normally these forces and moments are arranged in different directions. This definition is not generally adequate, e.g. for an application where *one* force should be measured, but the direction, from which the force will act, is not of interest. Such applications are used in ergonomic measurements, where the applied force acting on the human body is the subject of investigation and where the direction is negligible, e.g. in the process of assembling parts. The force can be determined as follows:

$$|F| = \sqrt{F_x^2 + F_y^2 + F_z^2} \qquad (1)$$

Please take note that, while the output of such a system is only *one* force, the internal measurement is a multicomponent measurement.

Moreover a definition of "multicomponent" must distinguish multicomponent measurements from classic force and torque measurements (the term "torque measurement" is avoided later on in this paper, since torque measurement is only a special kind of moment measurement). It is state-of-the-art to measure forces and moments not as vectorial quantities, but as scalar quantities. Research and development over the last few decades has resulted in transducers, standard machines, guidelines and best practices to measure the magnitude of the force or moment vectors with high accuracy. Therefore the uniaxial force and torque transducers and the deployed equipment are well manufactured, adjusted and decoupled. But to measure the magnitude of the vectors is only the tip of the iceberg.

Forces and moments are vectors in space with six degrees of freedom. A force is described by five parameters because of its line volatile characteristic and a moment is described by three parameters because of its space volatile characteristic, of which respectively only one parameter is measured in classic uniaxial measurements. Based on this declaration a general definition of "multicomponent" can be stated as:

Multicomponent measurement means the description of forces and moments with more than one vector-parameter (the magnitude) and it depends on the application, which further parameters have to be described.

Table 1 shows the characterisation and parameters of forces and moments as vectors.

Table 1. Description of Forces and Moments as Vectors.

Vector	Force	Moment
Attribute	Line volatile	Space volatile
Characterisation	5 parameters	3 parameters
Parameters	Magnitude incl. Sign 2 coordinates 2 angles	Magnitude incl. Sign 2 angles

In the special case of (1) the multicomponent character of measurement arises from two points: first the magnitude of force and second the knowledge, that the direction is not decisive. This second point is the difference to the classic uniaxial measurement.

3. CONSTRUCTION TYPES

As previously mentioned, the number of possible multicomponent transducer types seems to be unlimited. However there are main construction principles. Basically the MCTs may be distinguished in monolithic, semi-expanded and expanded types. These three types have different properties regarding the relations of forces and moments, the sensitivity against secondary components (cross talk) and the achievable uncertainty. Table 2 provides a general overview.

In general all types of multicomponent transducers follow these principles, even if a semi-expanded or expanded type is made of one piece [2].

The expressions semi-expanded or expanded in this context also means semi-decoupled or decoupled. Different joint types for decoupling a hexapod-structure are discussed in [3].

Table 2. Construction Types of MCTs with Rough Estimation of Parameters.

System	Monolithic	Semi-expanded	Expanded
Force / Force-Relation	~1:1 … 1:10	~1:1 … 1:10	Any
Moment / Force-Relation	~0,01 … 0,1 N·m/N	> 0,1 N·m/N	Any
"Cross talk"	<~ 3 %	<~ 3 %	<~ 1 %
Achievable Uncertainty	10^{-1} … 10^{-2}	10^{-1} … 10^{-2}	10^{-3}

3.1. Monolithic multicomponent transducers

Monolithic transducers are used in applications, where the acting forces and moments are in closed relationships to one another. Due to the fact that one elastic element of the transducer is the basis to measure the strains of different forces and moments, the sensitivity against the secondary components is usually higher than in expanded transducers. For example it is not possible to measure high forces in one direction and small forces in the others with high accuracy and resolution.

Commonly the components of these transducers are the forces F_x, F_y, F_z and moments M_x, M_y, M_z related to a Cartesian coordinate system. Depending on the application the transducers provide between two and six components.

As in every multicomponent system the point of origin must be defined by the manufacturer. The forces and moments in any point of an application can be calculated by coordinate transformation using digital equipment.

Fig. 1. Multicomponent Transducer of Monolithic Type

3.2. Semi-Expanded Multicomponent-Transducers

In semi-expanded transducers multiple elastic elements are used, for example to support higher moment / force relations than given in Table 2 for monolithic transducers. Each elastic element measures more than one force or moment. A perfect decoupling of these values is also not achievable as described in the previous chapter.

Fig. 2 shows an example of a semi-expanded multi-component transducer including three two-component-transducers measuring two forces each. With each transducer one force is measured in axial direction and one force in tangential direction. These six magnitudes of force, together with the fixed structure geometry describe the complete force vector acting on the system. Compared to monolithic transducers, which mostly provide the forces and moments in Cartesian coordinate system, digital equipment is already used for the calculation of the force vector or the forces and moments in Cartesian coordinate system.

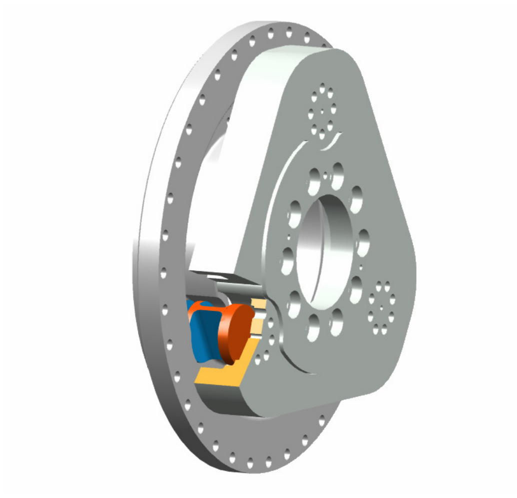

Fig. 2. Semi-Expanded Multicomponent Transducer

3.3. Expanded Multicomponent Transducers

The most flexible systems regarding the relations of forces and moments are expanded systems. Uniaxial force transducer types are arranged together with decoupling elements to measure single components. A good example for the industrial use of these systems is the measurement of very small frictional forces in combination with high loads in test rigs for tyres.

With these systems the lowest uncertainties are achievable, so they are suitable to be used in standard machines and transfer standards [3,4].

Fig. 3 shows a platform including seven uniaxial force transducers. Depending on the requirements such platforms are known with six, seven or even eight uniaxial transducers.

Fig. 3. Expanded Multicomponent Transducer of Platform Type

4. CALIBRATION CONSIDERATIONS

4.1. Calibration Results

In the majority of cases there are more than one sensitivity of interest in applications of MCTs: the sensitivity to the main component of the respective channel and the sensitivities to any secondary force or moment channel. In a calibration procedure the sensitivities may be determined and in a calibration certificate all the sensitivities have to be applied with uncertainties.

In data sheets of MCTs very often a "cross-talk" is given as a relative value. But commonly it's not defined how to calculate this value and an uncertainty of this cross-talk-value is never given. Indeed, the indication of a relative cross-talk-value seems not to be applicable in a calibration certificate, therefore the above mentioned main sensitivities and secondary sensitivities should be used.

Fig. 4 shows the output signal of a MCT. For simple applications of a MCT the declaration of single-value-sensitivities is adequate and it reduces the calibration effort. Therefore the sensitivities c_1 and k_1 have to be declared, for a six-component transducer it is 6 c_1-values and 30 k_1-values. These 36 values sufficiently describe a linear transducer system, this means linear main sensitivities and linear secondary sensitivities in minimum within a third of the calculated uncertainty.

$S_{F_i,M_i} = c_{1,i}\cdot F_i,M_i + \sum_{j=1}^{n} k_{1j}\cdot F_j,M_j$	main sensitivity and secondary sensitivity
$+ c_{2,i}\cdot F_i,M_i^{\,2} + c_{3,i}\cdot F_i,M_i^{\,3}$	Non-linearity of main sensitivity
$+ \sum_{j=1}^{n} k_{2,j}\cdot F_j,M_j^{\,2}$	Non-linearity of secondary sensitivity
$+ \sum m_{i,j}\cdot F_i,M_i\cdot F_j,M_j$ $+ \sum m_{i,j}\cdot F_i,M_i\cdot F_j,M_j^{\,2}$	Mixed influence of secondary sensitivity

Fig. 4. Output of a MCT and Sensitivities *c*, *k* and *m*

In unfavourable conditions the sensitivities may be influenced in higher order or in mixed mode (e.g. F_z x M_z) by load deformation, but a system analysis and a declaration of higher order sensitivities c_2, c_3, k_2, and so on within a calibration seems mostly to be inapplicable. In these cases it is preferable to calibrate the MCT in mixed load and in different working points and to show the deviations of signal S to the reference values of the standard as the calibration result.

4.2. Standard Equipment

As mentioned before it seems impractical for a national institute or a calibration laboratory to provide standard equipment for all MCTs. The unlimited design of MCTs regarding the connection dimensions, the different load of each component and the special requirements of the applications argue against it.

In some applications it seems adequate to use uniaxial standard machines, like dead weight machines, to calibrate the main sensitivities. Thereby problems arise, that the secondary components are not exactly known. But they cannot be disregarded, because elastic deformations both of the standard machine and force introduction elements as well as eccentricities and misalignment generate secondary components, meaning real forces and moments. These could be interpreted as secondary sensitivities, but the secondary components are real. So even in existing dead weight standard machines the calibrations of MCTs are only possible with due attention to the following point: either using adequate extension equipment to avoid any secondary component for sure, or, often easier, to measure the secondary components.

Therefore the use of an expanded MCT as a reference standard is preferable. With such a standard all introduced components can be determined.

4.3. Traceability

Generally the traceability of multicomponent standards must include the calibration of forces and the calibration of the geometry of the structure. An example of the metrological characterisation of an expanded MCT in a hexapod structure is described in [4]. With the described procedure a calculation of the measurement uncertainty is possible. The uncertainty of an expanded MCT is estimated in the dimension of 0.1%. The procedure described in [4] may be named as primary path.

This procedure is recommended when mounting a new multicomponent standard. In case of a recalibration in an existing standard the realisation of this procedure is time and cost intensive, because the structure has to be dismantled. Therefore a secondary path is recommended using a Force Vector Sensor [5]. With a Force Vector Sensor, used as a transfer standard, the multicomponent standards can be calibrated without dismantling.

While calibration the standard will be loaded by means of one or more Force Vector Sensors. One Force Vector Sensor is needed for the application of forces, two sensors in the opposite direction are needed for the application of pure moments. For the calibration of the standard in mixed load more than two Force Vector Sensors are needed. With the Force Vector Sensors the introduced forces and moments are characterised in full, including magnitudes and directions. Fig. 4 shows the principle using four Force Vector Sensors for the calibration of a clockwise and anticlockwise moment.

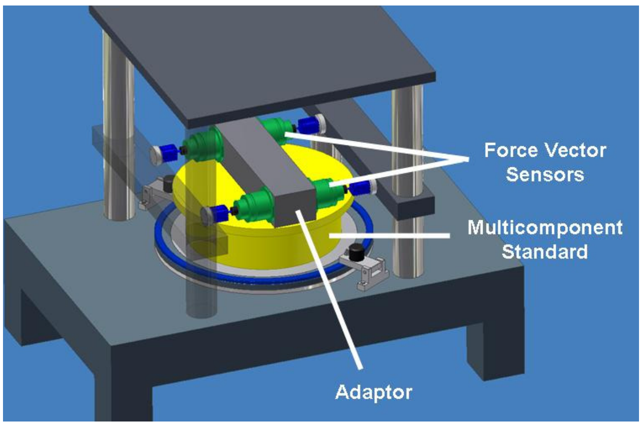

Fig. 4. Calibration Principle

Of course the internal coordinate systems both of the Force Vector Sensors and the multicomponent standard must be well adjusted by using precisely manufactured and stiff adaptors.

To close the traceability chain of multicomponent measurement to the widely used deadweight Force Standard Machines, a Force Vector Sensor itself as a transfer standard must be calibrated in a Force Standard Machine using special artefacts. The detailed procedure has previously been described in [6].

CONCLUSIONS

The industrial force and torque measurement is becoming more and more the measurement of forces and moments as vectors and therefore the metrology infrastructure has to be improved.

Comparing different multicomponent transducer principles, transducers of expanded type provide the lowest uncertainties. It is shown, that they are most suitable for the use as multicomponent standards. With experience, they can be designed and constructed in wide ranges according to very different requirements.

There are two preferable possibilities to present multicomponent calibration results: first the calculation of main and secondary sensitivities with its respective uncertainties, most suitable for linear transducer systems. Second the calculation of indication deviations in different working points with the respective uncertainties, most suitable for nonlinear transducer behaviour or in applications with mixed load.

To trace the multicomponent standards back to the widely used Force Standard Machines on a secondary path, a Force Vector Sensor was previously developed. All necessary equipment for a closed metrological chain from dead weight Force Standard Machines to the industrial use of multicomponent transducers stands by.

The achievable uncertainties in multicomponent calibration of course are greater than in force or torque calibration. But first steps to improve the multicomponent measurement are made in the last decade and GTM works on further steps.

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