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A NEW CALIBRATION PROCEDURE FOR MULTICOMPONENT TRANSDUCERS

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Abstract: Traceability of multicomponent measurements is still at an underdeveloped stage. Calibration facilities are rare compared with the diversity and number of applications of multicomponent transducers. Public calibration guidelines are not available.

As GTM works step-by-step on the improvement of multicomponent measurements, a new calibration procedure was developed and registered for accreditation at the German Accreditation Body (DAkkS). The procedure yields the complete description of the force vector independent of its direction and magnitude, and the corresponding uncertainty matrix. Thought has been given to uncertainty contributions like mechanical remanence, coordinate transformation and mixed loads.

Keywords: Force, Moment, Vector, Multicomponent Calibration.

1. INTRODUCTION

In industrial testing facilities the number of applications for multicomponent transducers is increasing very fast. Reasons are the demand for higher product quality to achieve a better position against the competitors as well as the development of new methods to reduce costs. The number of possible transducer types seems to be unlimited and the calibration sector seems unmanageable.

Calibration considerations have been previously described [1]. Simple calibrations with the determination of the main and secondary sensitivities were recommended as “one-value” calibrations. Because of cost considerations these are still the most popular calibrations. But in some applications they are indeed not sufficient to fulfil the measurement requirements. An example is the testing of coil springs, where the force vector passes through zero and the mechanical remanence has a noticeable influence. The mechanical properties of coil springs are important for the dimensioning of automotive shock absorbers, and side forces and moments must be minimized by aligning the force vector concentric with the spring axis. For this purpose multicomponent transducer systems of the platform type are used to measure precisely the piercing points of the force vector on the top and on the bottom of the coil spring.

The aim of the developed procedure was to describe the characteristics of multicomponent transducers and the vector of the uncertainty $\vec{U}(\vec{F})$ as a calculation-prescript, to allow the calculation of the corresponding measurement uncertainty for any load situation. Furthermore it should be implementable to any design of multicomponent transducer.

2. CALIBRATION

The calibration was performed on a multicomponent reference standard of the platform type. Figure 1 shows the basic mechanical assembly of the calibration.

A multicomponent transducer (grey) is connected in series to the multi-component reference standard (yellow) and is loaded by an eccentric, inclined force vector $\vec{F}$.

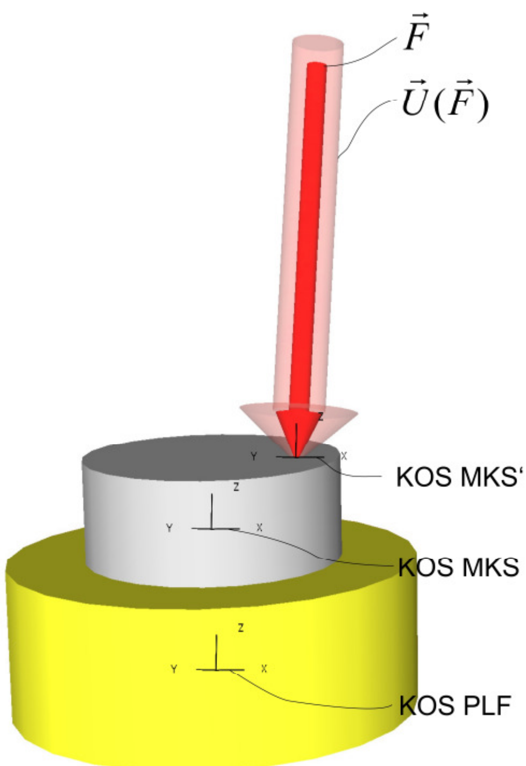

Figure 1: Basic assembly

The force vector is described by the reference standard ("PLF"). The results of the calibration are usually expressed in the coordinate system of the multicomponent transducer under test ("KOS MKS"). However, the results may be interesting at any other point, for example at the force introduction point ("KOS MKS'"). In all cases, the calibration results have to be transformed from the coordinate system of the reference standard ("KOS PLF") to the coordinate system of interest.

In Figure 1 the total expanded uncertainty of the calibration $\vec{U}(\vec{F})$ envelops the arrow representing the force vector. The shape of the envelope is only schematic and does not represent the expected uncertainty.

To determine the uncertainty vector even with loads that pass through zero for the individual components, the start load values were set as low as the traceable reference standard allows. Since force vectors may change their direction in an application, this results in an alternating load for the individual components (e.g. a reversal of the force vector in Figure 1 leads to an alternating force in the x-direction). Thus, basically alternating forces are assumed for all different force directions. An uncertainty contribution due to the remanence (zero point hysteresis) and the strict use of absolute measurement uncertainties in calculations have to be considered.

A separate loading situation was required for every single positive and negative force and moment:

$$\vec{F} = (F_x, F_y, F_z)^T \quad (1)$$

$$\vec{M} = (M_x, M_y, M_z)^T \quad (2)$$

These are twelve different loading situations for a six-component system plus an additional mixed load test for the verification of the superpositionable system properties. Superpositionable means that a superposition of the forces and moments is allowed and the calibration results are valid for any force vector in the field application, even if the same force vector was not applied during the calibration. To demonstrate the applicability to any loading, a superposition criterion was defined which has to be fulfilled.

Preferably the single force loads should be aligned with the axes of the coordinate system to generate small moments. Also the moment introduction should be aligned with the coordinate system.

In each force and moment direction three preloads were applied. To determine the remanence, the zero signals of the decoupled and unloaded multicomponent transducer after the third preload were recorded. Unloaded means that the zero signal of the transducer must not be influenced by any lever arm used for the moment introduction. Identical tare loads for the positive and negative load cases are necessary. Any attachment that could lead to an offset must be removed for the determination of the remanence zero-value.

After the preloading two measurement series of seven load steps with increasing loads were carried out. The steps are chosen according to the range of the multicomponent system in geometric series (2, 4, 8, 16, 32, 64 and 100%). Subsequently to the first upward series a downward series was carried out to determine the reversibility error.

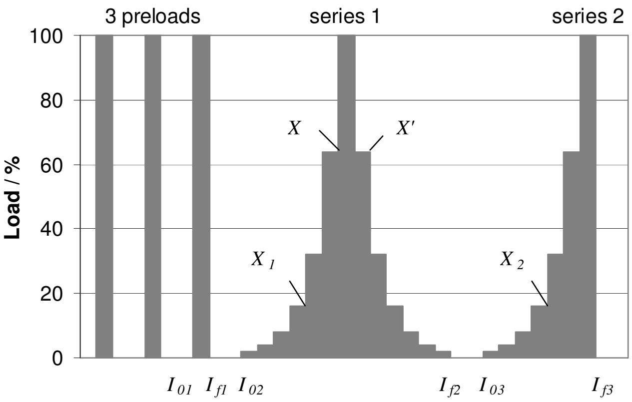

Figure 2: Load diagram

After performing the series in all twelve load cases, a mixed load was applied. Mixed load means that the introduced force is not aligned with an axis of the coordinate system. In a superpositionable system the magnitude of such a 'misaligned' force vector will be comparable to the results of the axis-aligned loads.

For practical considerations the mixed load should preferably correspond to the expected load in the application.

3. EVALUATION

Since the calibration method is a multidimensional reference measurement method, the evaluation and the uncertainty contributions must be calculated with absolute physical units. Relative uncertainty statements in multi-component applications can usually not be clearly defined and may lead to erroneous calculations.

The matrix operations for the evaluation were conveniently carried out in steps. First a geometry matrix describes the mounting orientation of the single transducers to yield the signals orientated with the coordinate system.

The second step is a pre-sensitivity matrix to convert the signals into results with physical units.

Third step is the main sensitivity matrix containing the interpolation. Therefore the main sensitivity matrix is of third order with linear, square and cubic parameters. The main sensitivity matrix thus contains all the elements for the interpolation covering the positive and negative ranges of the single components. The use of a common basis for calculating both the positive and negative range is an important condition for the use at zero point crossings.

The evaluated parameters are zero point deviation, repeatability, hysteresis, remanence, indication deviation and resolution. Furthermore the deviation at mixed loads is evaluated, which must fulfil a defined linearity criterion.

Loadings in different mounting positions to determine the reproducibility are not required. The determination of the repeatability is sufficient, since the applied force vectors are fully described and considered.

The zero point deviation is the maximum difference between the zero of the third preload and of the two measurement series.

$$f_0 = \max\left|I_f - I_0\right| \tag{3}$$

The repeatability is calculated at each loading step from the two series of the respective main component with increasing load.

$$b = \left|X_2 - X_1\right| \tag{4}$$

The hysteresis is calculated at every single load step from the first series.

$$h = \left|X' - X\right| \tag{5}$$

The remanence is the difference between the zero points after the third preloading, with loads applied in the positive and negative direction. Therefore identical tare load situations are indispensable.

$$f_{v0} = \left|I_{f+} - I_{f-}\right| \tag{6}$$

The indication deviation is evaluated by use of the polynomial elements of the sensitivity matrix, based on the mean values of increasing and decreasing load:

$$f_c = \left|\frac{1}{2}\left(\frac{1}{n}\sum_{i=1}^{n} X_{\text{int},i} + \frac{1}{m}\sum_{i=1}^{m} X'_{\text{int},i}\right) - F\right| \tag{7}$$

with

$$F = \{F_x, \ldots, M_z\} \tag{8}$$

The deviation at mixed load is used to confirm the super-positionable system properties, but it is not a contribution to the measurement uncertainty. The difference is calculated from the value displayed at mixed load and the sum of the values determined in uniaxial loading.

$$f_g = \left|X_g - X_{\text{int}}\right| \tag{9}$$

Superpositionable properties are given if the ratio of deviation divided by the measurement uncertainty is less than 0.2. The value 0.2 seems arbitrary, but was chosen to ensure a generous safety margin of 5.

$$\frac{f_g}{U} \leq 0{,}2 \tag{10}$$

4. UNCERTAINTY

The expanded uncertainty of the calibration arises from the uncertainties of the reference standard, the transformation of the coordinate systems and the calibrated multicomponent transducer. The determined uncertainty contributions of the transducer are calculated in conformance to Euramet cg-04 [2] and ISO 376 [3], wherever applicable.

$$U = 2 \cdot \sqrt{U_{cmc}^2 + U_{Trans}^2 + f_0^2 + \frac{1}{3}b^2 + \frac{1}{12}h^2 + f_{v0}^2 + f_c^2 + \frac{1}{6}r^2} \tag{11}$$

For the application, three different cases regarding the hysteresis and remanence are considered:

Case I: It is assured that no alternating load will appear. The uncertainty contribution due to the remanence is negligible and the uncertainty contribution of the hysteresis is taken into account.

Case II: When alternating loads will appear, it can be assured that the load cycles can be run several times and the measured values of the first cycles will be discarded. For the following load cycles the loading direction is known and half of the remanence is taken into account, which also covers the hysteresis.

Case III: When alternating loads will appear and no reliable prediction can be made, the full remanence is considered which also covers the hysteresis.

Table 1: Uncertainty contributions

Quantity	Distribution	Variance $u^2(x_i)$		
		Case I	Case II	Case III
zero point deviation	one value	$u_0^2 = (f_0)^2$		
repeatability	rectangle	$u_b^2 = \frac{1}{3}(b)^2$		
hysteresis	rectangle	$u_v^2 = \frac{1}{3}\left(\frac{h}{2}\right)^2$	not required	not required
remanence	one value	not required	$u_{v0}^2 = \left(\frac{f_{v0}}{2}\right)^2$	$u_{v0}^2 = (f_{v0})^2$
indication deviation	one value	$u_c^2 = (f_c)^2$		
resolution	2 x rectangle	$u_r^2 = \frac{2}{3}\left(\frac{r}{2}\right)^2$		

The calculation of the uncertainty vector is based on the generally formulated mathematical model for a multi-component system:

$$\mathbf{Y} = \mathbf{F}(\mathbf{X}) \tag{12}$$

with

$$\mathbf{Y} = (Y_1, \cdots, Y_m)^T \equiv (F_x, F_y, F_z, M_x, M_y, M_z)^T \tag{13}$$

and

$$\mathbf{X} = (X_1, \cdots, X_n)^T \equiv (Ch_1, \cdots, Ch_n)^T \tag{14}$$

The uncertainty vector is then calculated according [4] and [5] as

$$\mathbf{U_Y} = \mathbf{C_X U_X C_X^T} \tag{15}$$

The sensitivity coefficient matrix $\mathbf{C_x}$ contains the results of the geometry and sensitivity matrices and $\mathbf{U_x}$ contains the discussed uncertainties of the input quantities.

$$\mathbf{C_X} = \begin{bmatrix} \frac{\partial F_1}{\partial X_1} & \cdots & \frac{\partial F_1}{\partial X_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_m}{\partial X_1} & \cdots & \frac{\partial F_m}{\partial X_n} \end{bmatrix} \tag{16}$$

$$\mathbf{U_X} = \begin{bmatrix} u(X_1, X_1) & \cdots & u(X_1, X_n) \\ \vdots & \ddots & \vdots \\ u(X_n, X_1) & \cdots & u(X_n, X_n) \end{bmatrix} \tag{17}$$

In the calibration certificate the uncertainty vectors $\mathbf{U_Y}$ are given in four matrices for the constant, linear, quadratic and cubic parameters. The constants represent the uncertainties of the zero point crossings due to the remanence and for each of the three discussed cases of alternating load a vector $\mathbf{U_Y}$ with the four matrices is shown in the certificate.

Only the main diagonals of the matrices are occupied, the influences of the secondary components are already included in the sensitivity matrices.

U_0		U_{Fx} / N	U_{Fy} / N	U_{Fz} / N	U_{Mx} / N·m	U_{My} / N·m	U_{Mz} / N·m
Fx	1 / N	2,33023E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fy	1 / N	0,00000E+00	3,44194E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fz	1 / N	0,00000E+00	0,00000E+00	4,26215E+00	0,00000E+00	0,00000E+00	0,00000E+00
Mx	1 / N·m	0,00000E+00	0,00000E+00	0,00000E+00	3,13464E-01	0,00000E+00	0,00000E+00
My	1 / N·m	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	4,13488E-01	0,00000E+00
Mz	1 / N·m	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	6,37164E-01

U_1		U_{Fx} / N	U_{Fy} / N	U_{Fz} / N	U_{Mx} / N·m	U_{My} / N·m	U_{Mz} / N·m
Fx	1 / N	1,79812E-03	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fy	1 / N	0,00000E+00	1,49046E-03	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fz	1 / N	0,00000E+00	0,00000E+00	3,31793E-03	0,00000E+00	0,00000E+00	0,00000E+00
Mx	1 / N·m	0,00000E+00	0,00000E+00	0,00000E+00	2,88338E-03	0,00000E+00	0,00000E+00
My	1 / N·m	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	2,57819E-03	0,00000E+00
Mz	1 / N·m	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	9,47183E-04

U_2		U_{Fx} / N	U_{Fy} / N	U_{Fz} / N	U_{Mx} / N·m	U_{My} / N·m	U_{Mz} / N·m
Fx	1 / N^2	1,75968E-06	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fy	1 / N^2	0,00000E+00	2,14125E-06	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fz	1 / N^2	0,00000E+00	0,00000E+00	1,88763E-07	0,00000E+00	0,00000E+00	0,00000E+00
Mx	1 / N·m^2	0,00000E+00	0,00000E+00	0,00000E+00	4,94355E-06	0,00000E+00	0,00000E+00
My	1 / N·m^2	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	4,97982E-06	0,00000E+00
Mz	1 / N·m^2	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	1,86223E-05

U_3		U_{Fx} / N	U_{Fy} / N	U_{Fz} / N	U_{Mx} / N·m	U_{My} / N·m	U_{Mz} / N·m
Fx	1 / N^3	-2,92083E-10	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fy	1 / N^3	0,00000E+00	-5,23839E-10	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00
Fz	1 / N^3	0,00000E+00	0,00000E+00	-5,75085E-12	0,00000E+00	0,00000E+00	0,00000E+00
Mx	1 / N·m^3	0,00000E+00	0,00000E+00	0,00000E+00	-2,74640E-09	0,00000E+00	0,00000E+00
My	1 / N·m^3	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	-2,64701E-09	0,00000E+00
Mz	1 / N·m^3	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	0,00000E+00	-4,12464E-08

$$U_{F_i} = \sum_{k=0}^{3} \sum_{j=1}^{6} \left|F_j\right|^k \cdot (U_k)_{ji} \qquad F_i, F_j = F_x, \cdots, M_z$$

Figure 3: parameter example of one uncertainty vector $\mathbf{U_Y}$

5. CONCLUSIONS

A calibration procedure for multicomponent transducers was developed with the description of the uncertainty as a vector. Particular attention was paid to the remanence, as force vectors may reverse in the different applications. Attention was also paid to the superposition-ability because not every load case can be verified in a calibration.

The procedure appears to be broadly applicable. In a first phase the multicomponent reference transducer of a spring testing machine was successfully calibrated. Due to the involved procedure the calibration takes time and the costs are not negligible. But for high demands it is worth the effort since the information content is very comprehensive.

7. REFERENCES

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