Multi-Component Measurement Technology for Forces and Moments

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Abstract

This paper introduces the requirements and possibilities of simultaneous force and moment measurements in industrial testing. Apart from describing the principal mechanics of force and moment vectors, important implications of ignoring disturbing components are mentioned. This is followed by an overview of practical applications of multicomponent measurements. The main part of the paper describes a new measurement tool for the data acquisition, evaluation and vector analysis. This comprises issues of transducer selection and applicability, details of the electronics used and also addresses the software design. Examples of typical applications of the entire system are given with an emphasis on outlining the mode of operation and ease of adaptation to new problems. Finally, the principles of system calibrations are described.

1. Introduction

The measurement of forces and moments, due to the interactions of the components with each other, tends to be a complex task. Non-ideal loading conditions add further complications. The components to be measured are the magnitudes of the force and moment vectors, as well as the co-ordinates and spatial angles which describe their position in space. Fig. 1 shows this situation with the so-called force-screw as example. The six components describing this case are the magnitudes of force and moment, two spatial angles and the co-ordinates in the x-y-plane: F, M, x, y, Θ, ϕ.

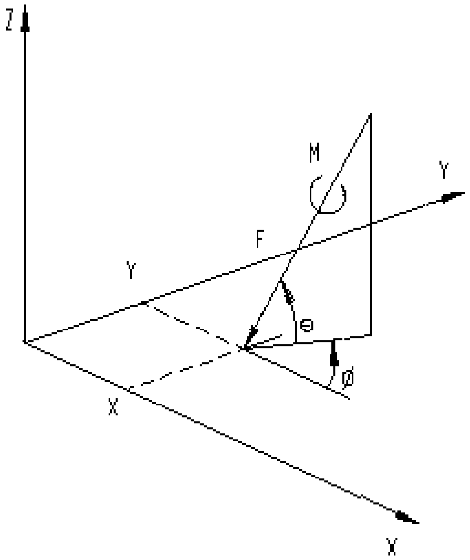


Fig. 1: Components of a "force screw"

Even uni-axial force measurements are falsified by:

- Non-perpendicular force application, described by two unknown angles as disturbing quantities
- Eccentric force introduction, described by two unknown distances as disturbing quantities.

Example: Tensile testing: Specimen diameter 10 mm: An eccentricity of the force of 0.1 mm causes an increase of the surface stress (due to additional bending) by 8 %, exceeding the permissible uncertainty for most applications by far!

In order to evaluate such tasks, GTM has developed the **MultiComponentAnalyzer (MCA)**, a universal tool to measure up to six arbitrarily selectable force-, moment- or position components (co-ordinates and angles).

The **MCA** shown schematically in Fig. 2 consists of the **six-component-transducer**, measuring the three perpendicular forces F_x , F_y and F_z and the three corresponding moments M_x , M_y and M_z, the **measuring electronics** with sensor excitation, signal processing and digitising, and a **computer system with software** for signal analysis and display of the desired quantities in selectable shape, which can be adjusted easily by the user.

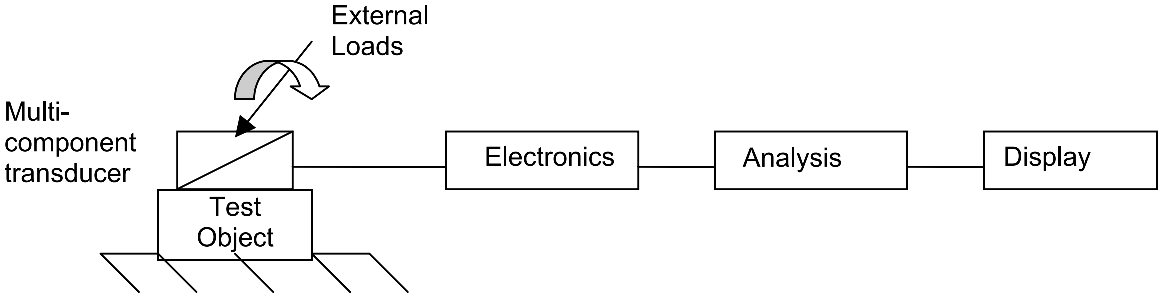


Fig. 2: Components of the MCA system

2. Applications

Principally, the applications for the **MCA** can be divided into measurements of which all components to be measured have considerable importance for the application (n = 6 main components), and measurements that have less than six main components (n < 6), where the remaining (6 – n) secondary components may act as disturbing quantities. The **MCA** offers two possibilities for these cases:

- **Mathematical correction**: Measurement of the disturbing influences and correction of their effects on the main component(s) by calculation. This approach leads to the elimination of the systematic error and to a reduced variance, as a portion of the formerly random errors are now turned into systematic errors.
- **Mechanical elimination**: Measurement of the disturbing influences and their suppression by online control, using a suitable adjustment device.

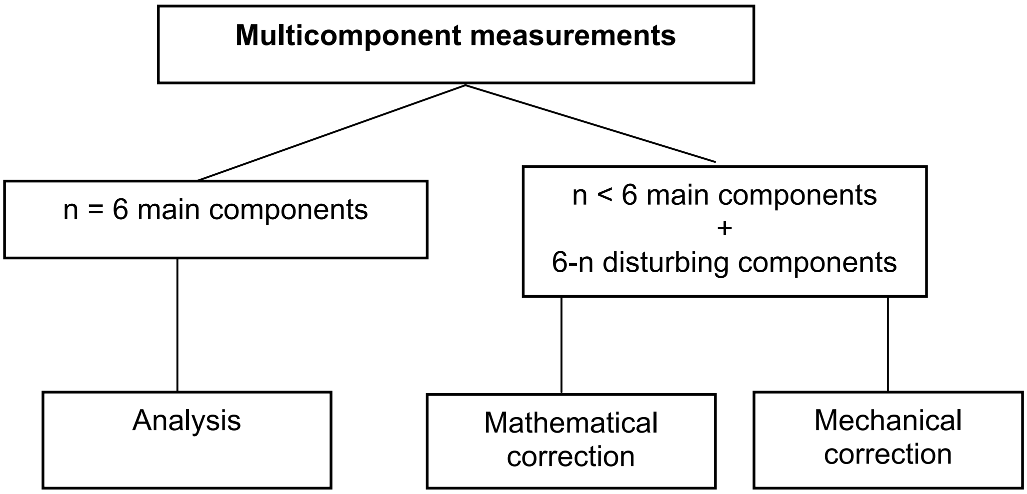


Fig. 3: Tasks and possibilities for applications

Between the extreme cases of $n_{max} = 6$ (e. g. wind tunnel balance) and $n_{min} = 1$ (e. g. tensile tests) there are numerous further applications for the successful use of the MCA.

The transition between the two main areas is not strictly defined, as the example of the development of an artificial knee joint demonstrates.

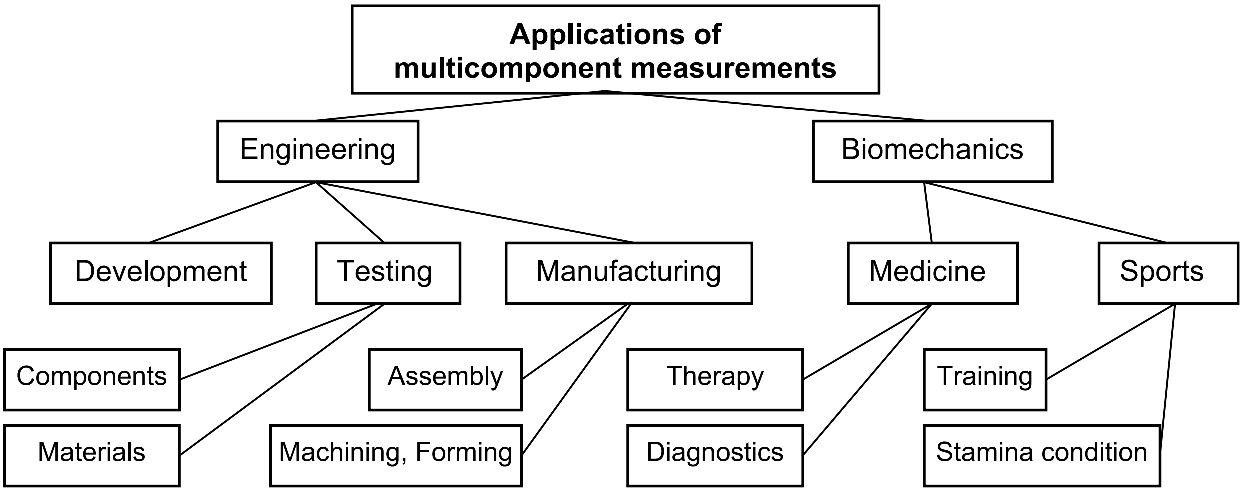


Fig. 4: Areas of application

2.1 Technical applications

Wind tunnel balances

- Aerodynamic measurements on aircraft and cars (scale models and full size)
- High precision required (0.05 % and better), quasi-static measurements
- Large dimensions / high costs are acceptable
- All 6 components, possibility of very large moments

Material testing

- Specially shaped specimens, defined loading cycles
- Often dynamical loading
- Compact transducers required
- Uni-axial with smallest and least disturbing components

Component testing

- E. g. fatigue tests on car suspensions
- Dynamic, medium accuracy sufficient (0.5 %)
- Compact transducers, small moments
- Measuring platforms for large moments
- At least 3, often up to 6 components

Manufacturing

- E. g. cutting force measurement
- Dynamic, high static bias, low to medium accuracy (1 %)
- Compact transducer required
- Often 3 force components, moments possible

Assembly

- Robot technology, screw tightening control
- Defined transducer resilience required for robots (lag time until drive-stop)
- Lower precision sufficient (> 1 %)
- 2 to 6 components, often in-situ-calibration of robot tools

2.2 Biomechanical applications

- Force and moment measurement between a person and the ground
- Analysis of limb movement, detection and measurement of potential anomalies
- For rehabilitation (directed exercises, success checks online)
- Low precision sufficient (5 %)
- 3 to 6 components

3. Description of the MCA system kit

Each measuring chain begins with a sensor which establishes the connection between the physical “external” world and the virtual “internal” world of analogue and digital electronic signals. The real world makes numerous demands on the sensor which determine its design. Once the signal has been acquired, further processing follows mainly standardised paths. Temporal parameters such as filter characteristics, integration time and sampling rate can be realised in a wide range by an electronics system. The type and details of the data analysis in the computer are governed by the desired output, i. e. the purpose of the measurement. Towards this end, the MCA software incorporates every practical scenario such that it can be adapted without special knowledge.

3.1 Multicomponent transducers

In the three-dimensional force system, a maximum of six independent force reactions can occur. The capacities and types of the MCA transducers cover all practical force ranges and combinations from a minimum of two and up to a maximum of six possible components.

Six-component transducers

- For simultaneous occurrence of 3 or more main components
- Sensor body made from one piece, hence low cross talk, low hysteresis
- Capacities: 4 kN to 160 kN, 250 N·m to 8000 N·m
- Medium moment capacity, equivalent to approximately 50 mm eccentricity at full load
- Very stiff, high natural frequency (for dynamic measurements)

Two- and three-component transducers

- For mainly uni-axial loading, or tension-torsion applications
- Sensor body made from one piece, hence low cross talk, low hysteresis
- Capacities: up to 1 MN and above, up to 10 kN·m
- Small moment capacity, equivalent to approximately 10 mm eccentricity at full load
- Very stiff, high natural frequency (for dynamic measurements)
- Available as transfer standard

Measuring platforms

- For arbitrary combinations of components
- Capacities can be varied across large ranges
- For very high moments, only limited by platform size
- Lower stiffness

Fig. 5: Multicomponent transducer MK6

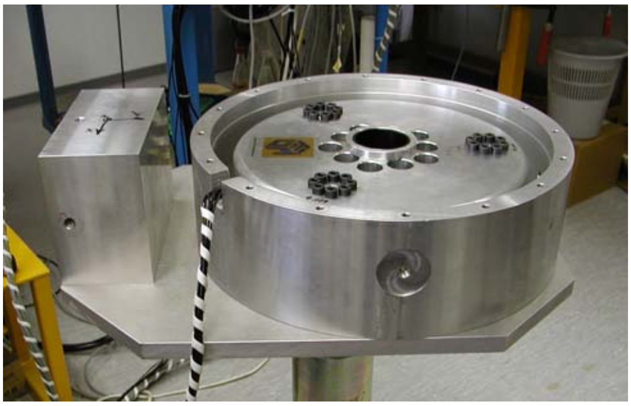


Fig. 6: Measuring platform (measuring wheel)

3.2 Electronics

The electronics are the constant term in the MCA kit, their task is to condition the signals as produced by the sensor and to pass them on to the computer. This is achieved by three dual-channel data acquisition cards of the type PC-DMS in a PC. They produce a stabilised and controlled excitation voltage, and amplify, digitise and filter the measuring signals.

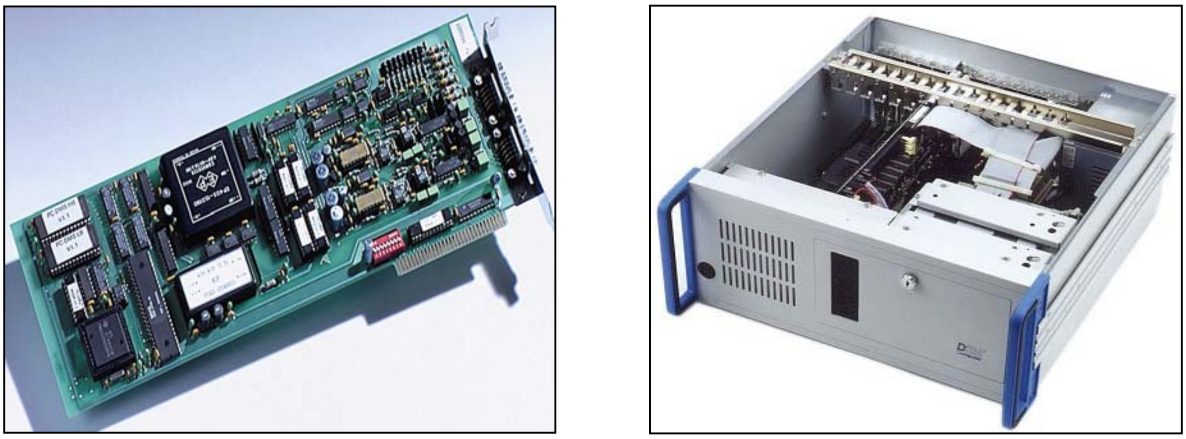


Fig. 7: PC-DMS card and computer with expansion slots

3.2.1 Resolution for static measurements

For static measurements the electronics achieve an effective (reproducible) resolution of 100000 digits with an integration time of 0.5 s, 2 mV/V sensitivity and 20 V excitation. This resolution of 0.001 % relative to full scale output exceeds the achievable sensor accuracy by far and can be used in three ways:

- Utilisation of even very small measuring ranges of about one per cent of the transducer capacity with just one sensor!
- Very high tare loads, e. g. 99% tare still leave 1000 digits for the measuring signal proper.
- Very small changes of the measured value (corresponding to the maximum resolution of 0.001 % can be detected (“magnifier”).

3.2.2 Dynamical characteristics

The parallel design of the signal processing units warrants almost simultaneous data acquisition for all six channels. The time lag between the separate channels amounts to max. 3.2 µs. The maximum sampling rate is 500 samples/s, this enables measurements of dynamic signals containing frequencies of 200 Hz and more, covering the whole technically relevant range. The maximum phase lag for a 200 Hz oscillation is less than 0.25° and thereby negligible.

3.3 Software

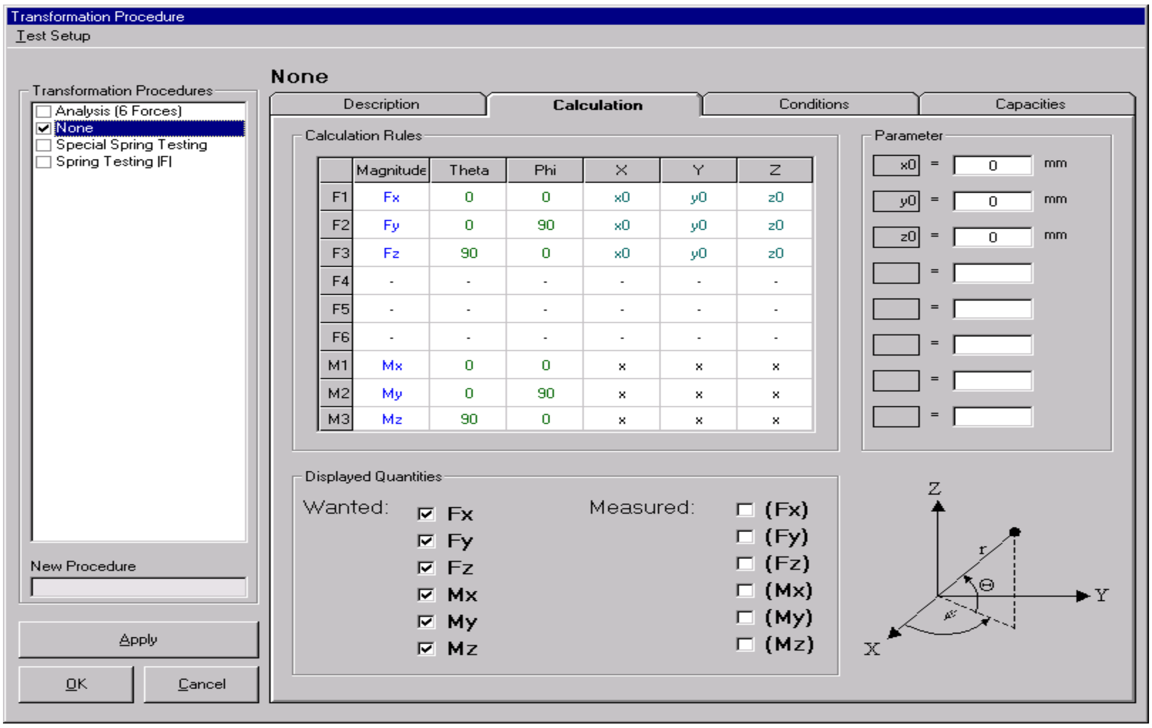
The **software** offers exceedingly simple adaptation to the most varied measurement situations: The user selects from a table of given physical quantities up to a maximum number of six variables and enters the numerical values of the known quantities. This input triggers a pre-installed calculation program which computes and displays the desired components from the readings taken by the sensor. In a second step, these measured values can be analysed further according to the application (determination of characteristic quantities etc.), and processed for a lucid display. This display can be on-line (for control purposes, for monitoring and avoiding of critical conditions etc.) or off-line for an in-depth analysis of dynamic processes (“magnifier effect” in time: monitoring of crack propagation etc.)

Software design and operation:

The input masks allow the selection of up to six wanted physical quantities (output). Depending on the application, these could be for example: The magnitudes of three forces and three moments, or four forces and two moments etc. or up to six individual forces. As a force vector is determined not only by its magnitude but also by its spatial direction and the co-ordinates of its foot point, these quantities may also be selected as output, as long as the maximum number of variables does not exceed six. It should be noted in this context that force vectors can be displaced along their line of action without any change to their effect, and that moment vectors can be moved freely in space without changing their effect as long as their direction is not reversed. The section table has been composed with this in mind: The force direction and position is fully given by two spatial angles φ and Θ, and by any two of the three co-ordinates x, y, z (one **d**egree **o**f **f**reedom). A moment is fully determined by the two angles, the corresponding position fields are blanked (three degrees of freedom).

The completeness of the input table is demonstrated by the following plausibility argument: A maximum of six different forces can be measured, each determined by 5 quantities (6 – 1 dof). Of these 30 values, 24 must be fixed, and 6 are variables.

If a combination of three perpendicular forces through the co-ordinate origin and three moments of the same orientation is used, there will be 3 times 5 values for the forces, and 3 times 3 values for the moments (6 – 3 dof). This makes 24 values, 6 of which are variables. The "missing" six quantities to the total of 30 are implicitly given by the fact that all forces pass through the origin (three parameters x0, y0 and z0) and by the coincidence of moment and force angles (three co-ordinate angles of 90 degrees), Fig. 8.



None

Calculation Rules

	Magnitude	Theta	Phi	X	Y	Z
F1	Fx	0	0	x0	y0	z0
F2	Fy	0	90	x0	y0	z0
F3	Fz	90	0	x0	y0	z0
F4	-	-	-	-	-	-
F5	-	-	-	-	-	-
F6	-	-	-	-	-	-
M1	Mx	0	0	x	x	x
M2	My	0	90	x	x	x
M3	Mz	90	0	x	x	x

Parameter

x0 = 0 mm
y0 = 0 mm
z0 = 0 mm

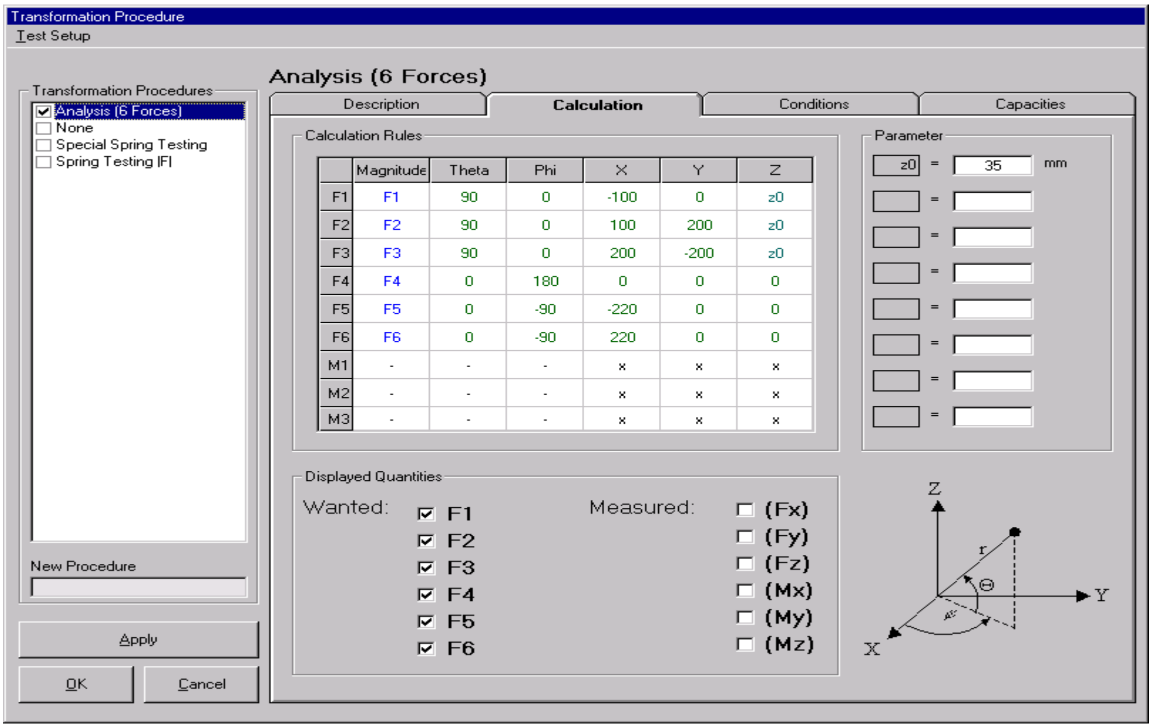
Displayed Quantities

Wanted: ☑ Fx ☑ Fy ☑ Fz ☑ Mx ☑ My ☑ Mz

Measured: ☐ (Fx) ☐ (Fy) ☐ (Fz) ☐ (Mx) ☐ (My) ☐ (Mz)

Fig. 8: Measurement of the magnitudes of 3 forces and 3 moments

Fig. 9 shows the data input for six forces with known angles and foot points.



Analysis (6 Forces)

Calculation Rules

	Magnitude	Theta	Phi	X	Y	Z
F1	F1	90	0	-100	0	z0
F2	F2	90	0	100	200	z0
F3	F3	90	0	200	-200	z0
F4	F4	0	180	0	0	0
F5	F5	0	-90	-220	0	0
F6	F6	0	-90	220	0	0
M1	-	-	-	x	x	x
M2	-	-	-	x	x	x
M3	-	-	-	x	x	x

Parameter

z0 = 35 mm

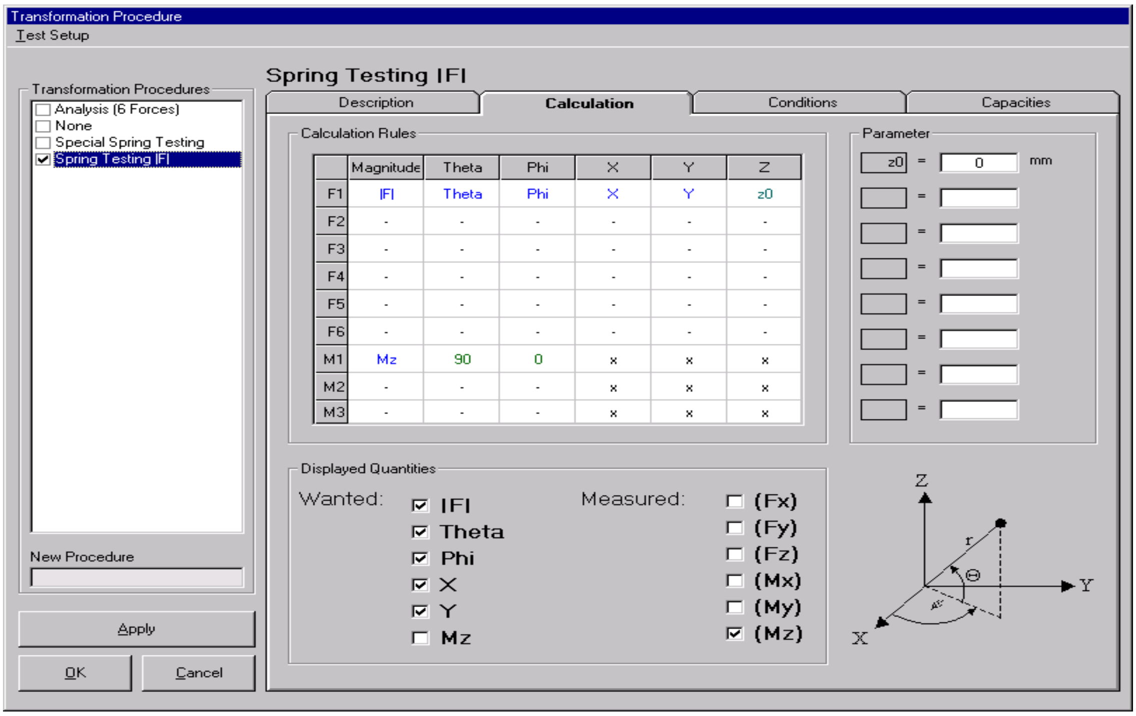
Displayed Quantities

Wanted: ☑ F1 ☑ F2 ☑ F3 ☑ F4 ☑ F5 ☑ F6

Measured: ☐ (Fx) ☐ (Fy) ☐ (Fz) ☐ (Mx) ☐ (My) ☐ (Mz)

Fig. 9: Analysis of six forces

The following example demonstrates the testing of springs as mentioned above. Whereas an ideal compression spring reacts only with an axial force along its central axis proportional to the deformation, real springs also generate lateral forces and a torque around the longitudinal axis due to imperfect force introduction at their ends. These unwanted reactions can in some applications cause disturbing effects, such that their quantitative determination becomes important for spring development and quality control. Hence, Fig. 10 shows as output quantities the magnitude of the force vector F, its spatial directions φ and Θ, its projection point x, y at the lower end and the torque M_z around the central axis.



Transformation Procedures
☐ Analysis (6 Forces)
☐ None
☐ Special Spring Testing
☑ Spring Testing |F|

Spring Testing |F|

Calculation Rules

	Magnitude	Theta	Phi	X	Y	Z
F1	|F|	Theta	Phi	X	Y	z0
F2	-	-	-	-	-	-
F3	-	-	-	-	-	-
F4	-	-	-	-	-	-
F5	-	-	-	-	-	-
F6	-	-	-	-	-	-
M1	Mz	90	0	x	x	x
M2	-	-	-	x	x	x
M3	-	-	-	x	x	x

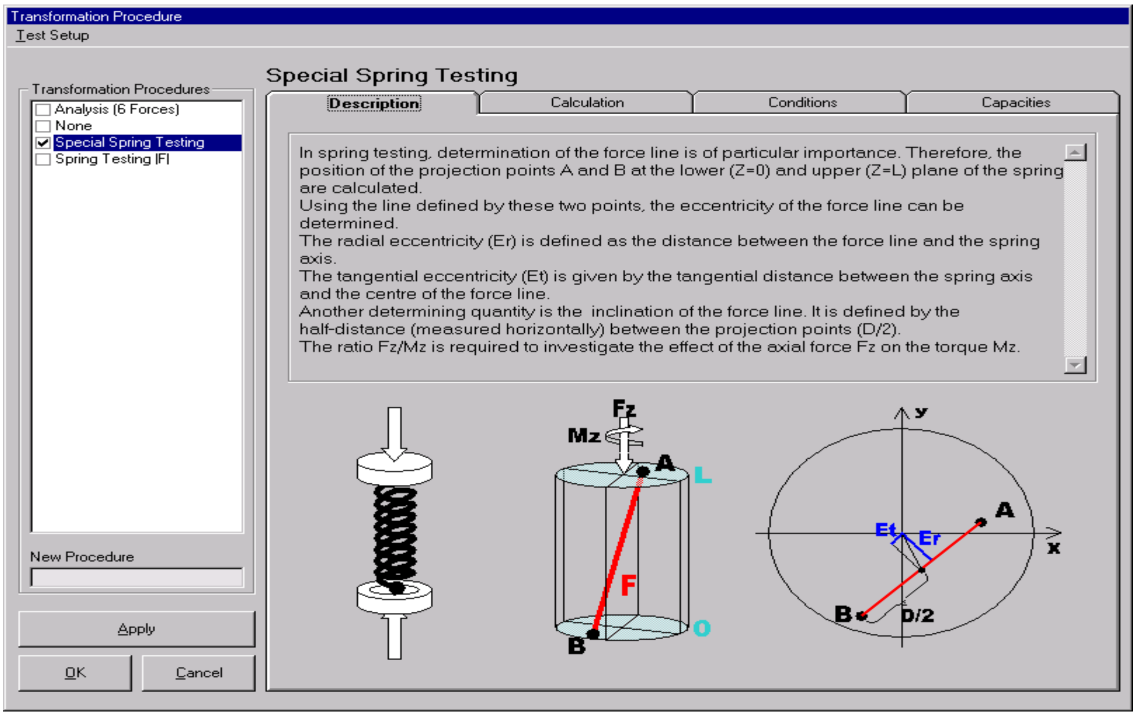
Parameter
z0 = 0 mm

Displayed Quantities

Wanted:	Measured:
☑ |F|	☐ (Fx)
☑ Theta	☐ (Fy)
☑ Phi	☐ (Fz)
☑ X	☐ (Mx)
☑ Y	☐ (My)
☐ Mz	☑ (Mz)

Fig. 10: Spring testing

The given parameter z determines the height position for which the position co-ordinates of the force vector are to be calculated, in the shown case z = 0 at the lower end of the spring.



Transformation Procedures
☐ Analysis (6 Forces)
☐ None
☑ Special Spring Testing
☐ Spring Testing |F|

Special Spring Testing

In spring testing, determination of the force line is of particular importance. Therefore, the position of the projection points A and B at the lower (Z=0) and upper (Z=L) plane of the spring are calculated.
Using the line defined by these two points, the eccentricity of the force line can be determined.
The radial eccentricity (Er) is defined as the distance between the force line and the spring axis.
The tangential eccentricity (Et) is given by the tangential distance between the spring axis and the centre of the force line.
Another determining quantity is the inclination of the force line. It is defined by the half-distance (measured horizontally) between the projection points (D/2).
The ratio Fz/Mz is required to investigate the effect of the axial force Fz on the torque Mz.

Fig. 11: Special evaluation for spring test results

The measured values can be processed further as desired. The description in Fig. 11 is an example for a common evaluation, with the spatial position of the force vector given by its upper and lower projection points and with calculated eccentricities to quantify the off-axis effects.
The examples show the flexibility and simple use of the program. Internal routines prevent the input of undefined or “prohibited” conditions, such as the selection of seven output variables.
Display options are bargraphs for fast overview and response, digital numerical output for precision measurements and a scope function to view processes and signals versus time.

4. Calibration

Calibration, i. e. the quantitative determination of the transfer characteristics of the multicomponent sensor system, is required to convert the measured electronic signals of the various channels into the desired mechanical components. To achieve this, the transducer is loaded in defined ways, the results of which leading to the conversion matrix c_{ij}:

$$\begin{aligned}
F_x &= c_{11}\cdot S_x + c_{12}\cdot S_y + c_{13}\cdot S_z + c_{14}\cdot S_{M_x} + c_{15}\cdot S_{M_y} + c_{16}\cdot S_{M_z}\\
F_y &= c_{21}\cdot S_x + c_{22}\cdot S_y + c_{23}\cdot S_z + c_{24}\cdot S_{M_x} + c_{25}\cdot S_{M_y} + c_{26}\cdot S_{M_z}\\
F_z &= c_{31}\cdot S_x + c_{32}\cdot S_y + c_{33}\cdot S_z + c_{34}\cdot S_{M_x} + c_{35}\cdot S_{M_y} + c_{36}\cdot S_{M_z}\\
M_x &= c_{41}\cdot S_x + c_{42}\cdot S_y + c_{43}\cdot S_z + c_{44}\cdot S_{M_x} + c_{45}\cdot S_{M_y} + c_{46}\cdot S_{M_z}\\
M_y &= c_{51}\cdot S_x + c_{52}\cdot S_y + c_{53}\cdot S_z + c_{54}\cdot S_{M_x} + c_{55}\cdot S_{M_y} + c_{56}\cdot S_{M_z}\\
M_z &= c_{61}\cdot S_x + c_{62}\cdot S_y + c_{63}\cdot S_z + c_{64}\cdot S_{M_x} + c_{65}\cdot S_{M_y} + c_{66}\cdot S_{M_z}
\end{aligned} \qquad \textbf{(1)}$$

In this, F and M are the forces and moments to be measured, respectively, and S are the electronic output signals of the multicomponent transducer. F_x for instance is the force component in the x-direction and S_y is the signal of the y-channel generated by the sensor. The coefficients c are the corresponding calibration factors, c_{11}, c_{22} etc. being sensitivities, all others such as c_{12}, c_{12} etc. are cross-talk coefficients.
For normal accuracy requirements this linear matrix is sufficient. However, for high-precision work second-order terms must be taken into account, and are determined by calibration also.
The calibration is performed corresponding to the requirements of the application prior to shipment of the multicomponent sensor, i. e. the matrix is part of each individual sensor. It should be noted that due to the vector character of the forces and moments, each sensor is calibrated with respect to a defined reference position. If this reference is later altered, such as during a tool change of an assembly robot, the matrix elements must be altered correspondingly. The MCA software can achieve this automatically by using the new position in its calculations.
In applications where the sensors are part of a closed-loop force controller, the calibration can be carried out using a specially developed multicomponent transfer standard. A typical case are the aforementioned industrial robots, which operate with changeable end actuators and require fast tool changes. The robot brings its sensor to be calibrated into contact with the multicomponent transfer standard, upon which it applies loads according to pre-determined requirements. The new matrix follows then from a comparison of the electronic signals of the two sensors.

5. Conclusion

Multi-component measurements form a demanding area of force and moment technology. Current and future applications will contain tasks for these methods, and the necessity and importance of looking beyond uni-axial force measurements will rise with the advances of product and technological development.
To fulfil these expectations, the measurement expert requires powerful aids, since he cannot be relied upon to algebraically resolve the complex simultaneous equation systems according to the rules of technical mechanics. Such aids not only consist of selection tools for and provision of appropriate sensors and electronic systems, but in particular software which enables to

acquire and evaluate results according to a given task without prior expertise. The MultiComponentAnalyzer system achieves this to a particularly high degree.
This new dimension of force measurement technology thus brought within reach enables apart from more precise statements on test results (more accurate judgements of loading conditions) also the nearly complete elimination of disturbing components during such tests, if suitable control systems are available which use the data measured by the MCA.

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