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NEW METHOD FOR ONLINE COMPENSATION OF PARASITIC EFFECTS IN FORCE MEASUREMENT

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Abstract: The proper evaluation and classification of force realizing machines requires transfer force transducers providing measurement results that ensure reproducibility and minimum measurement uncertainty even with changing mounting conditions. This article is to introduce a transfer force transducer which - due to its mechanical and electrical structure - ensures a reduced mounting-position dependent measurement uncertainty. By using a multi-channel measuring amplifier system and applying a compensating algorithm for the axial force signal, a further significant increase in reproducibility can be achieved.

Keywords: force transfer standard, reproducibility, bending moment analysis

1. INTRODUCTION

The following factors have determining effects on the uncertainties of the force measurements in force realizing machines:

- parasitic, static force components (eccentric force introduction, deformation of the force transducer, deformation of the loading mechanism, rotation effect, overlapping effect [1])
- parasitic, dynamic force components (pendulum motion of the weights [2], foundation vibrations, vibrations due to adjacent machinery)
- ambient (temperature, humidity, air pressure, etc.)

Thus, when comparing force measuring mechanisms by means of transfer force standards the requirements to be met by the design of the transfer transducer and the actual measurement procedure are very demanding. Common strategies mainly aim at preventing parasitic influences from affecting the standard force signal. Here, analysing the mechanical system "force transducer" results in two major perceptions:

- The force transducer construction must be symmetrical to parasitic influences to achieve a minimum parasitic interference.
- To design the force transducer independent of parasitic force quantities, it must additionally be of large dimensions (St. Venant), to ensure homogeneous force distribution even in the case of local parasitic influences (threaded joint, contacting surfaces).

The transfer force transducer design introduced here, has additional features:

- Measurement and online evaluation of parasitic force components (bending moments)
- Reduced measurement uncertainty due to software correction of the axial force signal
- Transducer-specific calibration ensuring process tolerances of the individual force transducers to be taken into consideration precisely.

2. FORCE-TRANSDUCER DESIGN

The force transducer enables usage for compressive or tensile forces. With compressive loading, the spherically grinded upper surface of the centric thread is used for force introduction. The pedestal adapter fastened with screws permits both fastening via an internal thread and force extroduction via an even supporting surface.

The force transducer's deformation body has been designed as an axisymmetrical multi bending beam. The 16 bending beams have been arranged on two planes thus augmenting the transverse force stability. During the dimensionating phase special importance was attached to design the areas of strain as symmetrically as possible thus enabling transverse forces, bending moments and temperature effects (adiabatic creep) to be compensated to a large extent in the axial force bridge circuit.

Due to the fact that the transducer geometry has been especially designed to fit the pedestal adapter, relative motions in the contacting plane are prevented, thus, avoiding hysteresis effects due to friction.
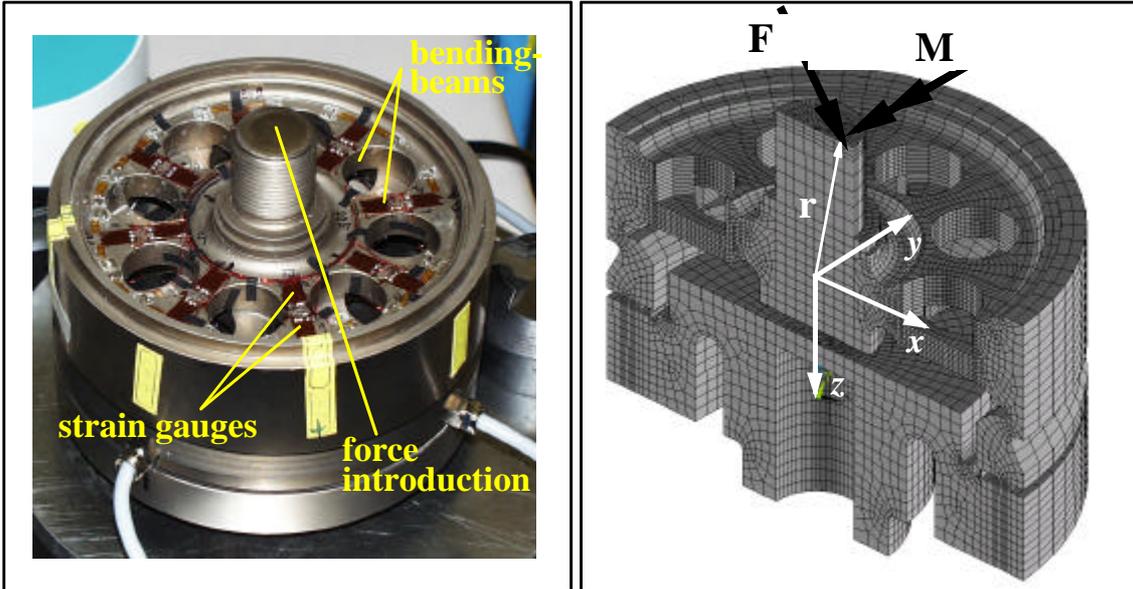

Figure 1.   Force transducer and finite element mesh with forces and moments

A total of 24 strain gauges is used to measure the strains. Here, two full bridges are used to determine the bending moments M_{Bx}, M_{By} effective in the x-y plane. The reasons for reducing the effective forces and moments to the standard force F_z and the bending moments M_{Bx} and M_{By} are given below:

In general, the force **F** with the components F_x, F_y, F_z and the momentum vector **M** with the components M_x, M_y, M_z are effective on the transducer at the force introduction point (position vector **r**) (figure 1). Transfering this system to the origin of co-ordinates on the measurement plane results in a system consisting of the components **F'** and **M'**.

$$\mathbf{F'}=\begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}; \quad \mathbf{M'}=\begin{pmatrix} M_{Bx} \\ M_{By} \\ M_T \end{pmatrix}=\begin{pmatrix} r_y F_z - r_z F_y + M_x \\ -r_x F_z + r_z F_x + M_y \\ r_x F_y - r_y F_x + M_z \end{pmatrix}$$

(1)

In a single bending beam, the components F_x, F_y generate strains in the same direction; due to the symmetrical dimensioning, these parasitic influences are compensated in each bending beam. With force standard machines and axially aligned transducers the following applies:

$$r_x, r_y << r_z; \quad F_x, F_y << F_z$$

(2)

If the force is introduced via a spherical cap, the axial torsion moment M_T against the bending moments M_{Bx}, M_{By} may be omitted, since the small contacting surface enables only very small moments to be transmitted. This means that reducing the forces and moments to the axial force signal u_{Fz} and the bending moment signals u_{Mbx}, u_{Mby} represents a sensible compromise between expenditure and measurement precision. The MGCplus multi-channel amplifier system with 3 ML38 amplifier modules is used for evaluation, the catman® measurement software for online data conditioning. Figure 2 shows the evaluation of the standard force and the bending-moment signals for the 100 kN force step.
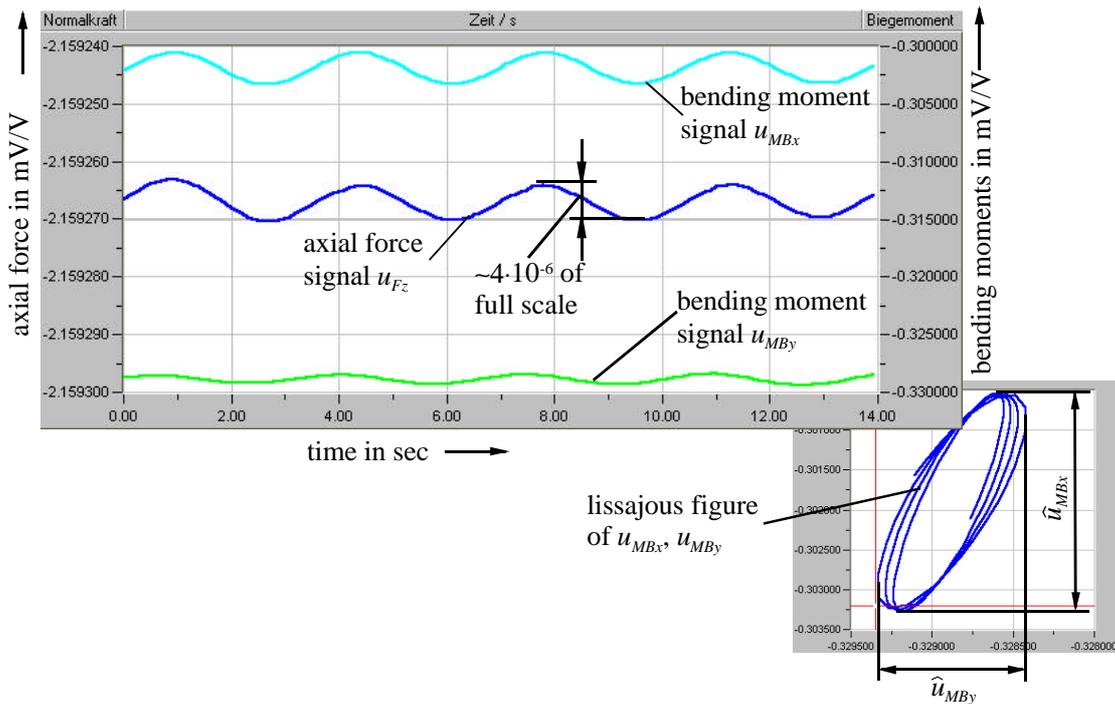
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Figure 2.   Measurement of axial force and bending moments in a 100 kN dead weight machine

The figure distinctly shows the standard force machine's pendulum motion [4]. The Lissajous representation enables the phase relationship between the bending-moment channels to be analysed.

This figure makes explicit the excellent compensation of the axial force bridge: the pendulum effect on the axial force signal is approx. $4 \cdot 10^{-6}$ of full scale.

3.   CALIBRATION AND ONLINE COMPENSATION OF THE FORCE TRANSDUCER

However, the additional bending-moment channels do not only offer the possibility to determine the effective parasitic force and bending moment components and to assess the quality of the measurement mechanism. The bending-moment signals also enable a correction of the axial force signal to be made in order to reduce the measurement uncertainty, especially under unfavourable conditions of force introduction. Thus, the reproducibility of the force measurement in different standard loading machines is considerably improved.

For calibrating the transfer transducer, a defined moment is introduced into the transducer first and then the bridge signals are measured. If the transducer is rotated during this measurement, this will result in a sinusoidal dependency of the bridge signals from the angle of rotation   . A defined moment could be generated e.g. with an eccentric force or a transverse force. The eccentric force was realized using a wedge of 0.2 degree, resulting in a constant eccentricity of 0.5 mm. If the transducer is loaded, a defined moment dependant on the eccentricity and the chosen force step is generated. The force transducer was measured in 6 positions, before mounting and measuring it was axially rotated about 60 degree.

The second calibration method is introducing a defined transverse force into the force transducer. In this case the transducer is mounted horizontally and is loaded with a defined force via coupled weights. Again the force transducer is rotated and axial force and bending moments are measured in 8 different positions.

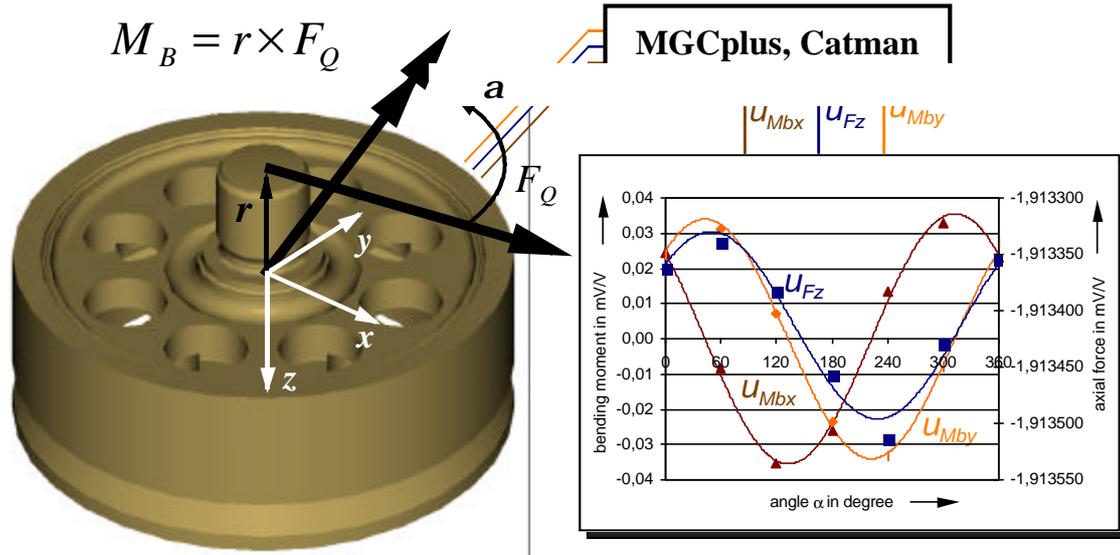Figure 3 shows the results obtained from a transverse force test.

Figure 3.   Calibration of the force transducer with eccentric or transverse forces

The functional interrelationships can be approximated from the measurement data:

$$u_{Fz}(M_B, a) = A_0 + A_1 \cdot M_B \cdot \cos(a + A_2) \tag{3}$$

$$u_{Mbx}(M_B, a) = B_0 + B_1 \cdot M_B \cdot \cos(a + B_2) \tag{4}$$

$$u_{Mby}(M_B, a) = C_0 + C_1 \cdot M_B \cdot \cos(a + C_2) \tag{5}$$

The signal's amplitude and phase relationships depend on the geometry, the arrangement of the strain gauges, and the respective process and application tolerances. However, the amplitude and phase relationships are invariable for each individual transducer. The coefficients A_i, B_i, and C_i determined during calibration are used as transducer-specific constants in the compensation algorithm for computing the axial force signal correction. The bending moment signals u_{Mbx}, u_{MBy} which are independent of each other are put into equations (4),(5) to determine the bending moment M_B and the angle   . Then, equation (3) is used to compute the corrected measured value u_{Fz}'. Due to the fact that it will never be possible to realize the bending moment bridges fully symmetrical, it is not possible to prevent an axial force from affecting the bending moment signals. However, this interference of the axial force onto the bending moment channels is also determined during calibration and is compensated by an additional correction factor. It could be shown, that both calibration methods (transverse force and eccentric force) will deliver comparable results.

4. EXPERIMENTAL RESULTS

The calibration and evaluation of the transfer force transducer and the evaluation methods have been conducted on the 240 kN deadweight force calibration machine at HBM in Darmstadt and on the 100 kN deadweight force standard machine at PTB in Braunschweig. For the tests, force steps according to DIN EN 10002-3 have been chosen, i.e., two upward series was measured in the 0° initial position, the next two upward and downward series were determined in the 120° and 240° positions.

Figure 2 shows pendulum motions occurring in a deadweight force calibration machine. Normally, these are not fully suppressed in the axial force signal. Compensation results in an effective suppression of the pendulum frequencies (Figure 4).
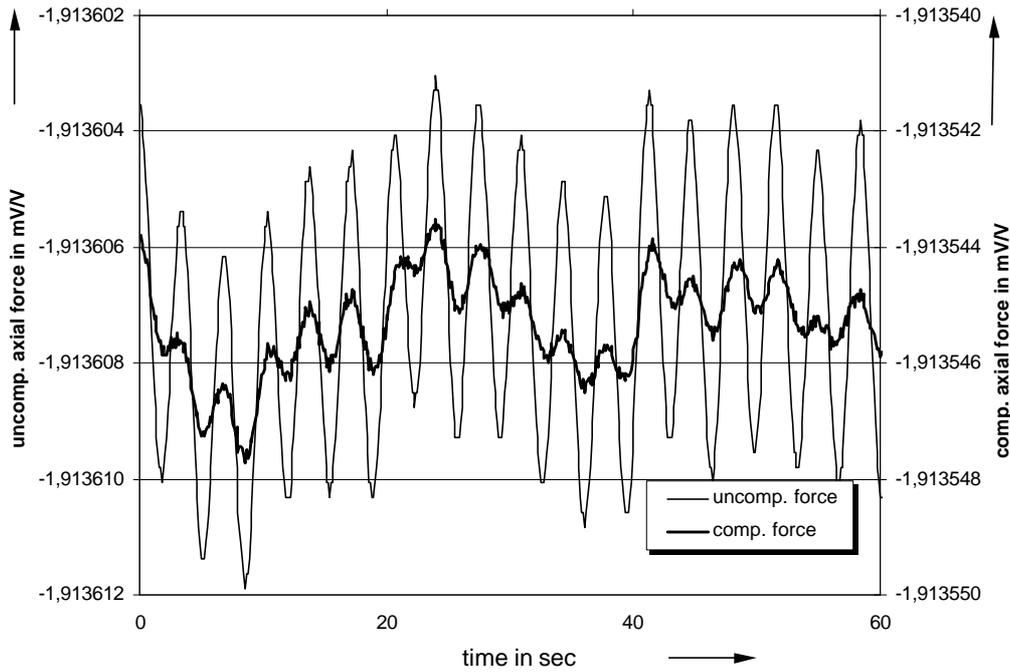
Figure 4.   Suppression of the influence of pendulum motion to the standard force signal

Filtering the axial force signal could also reduce the influence of parasitic dynamic force components. Due to the fact that the pendulum frequencies are in the range below 0.5 Hz, long settling times are required. The benefit offered by the compensation by means of an evaluation of bending moments becomes quite obvious especially with static parasitic force or eccentric force introduction. The results obtained from the rotational measurement series show that the measurement series span is reduced markedly (Figure 5).
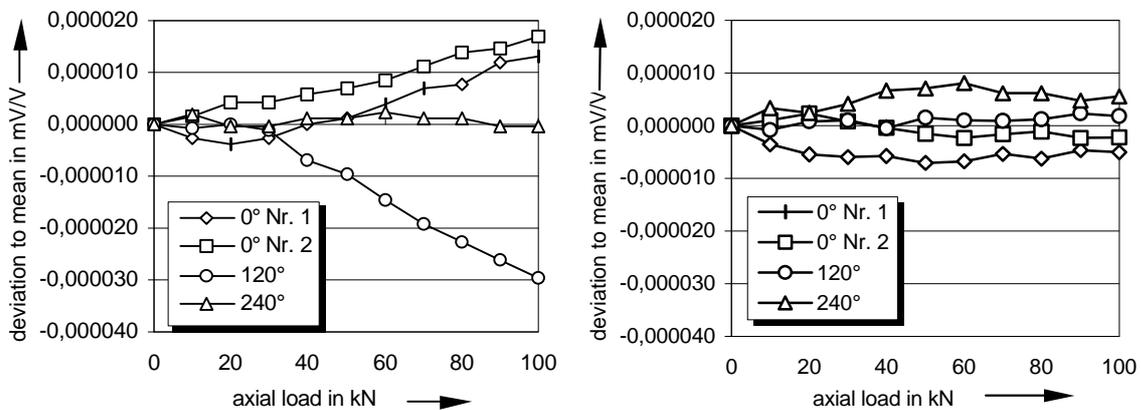

Figure 5.   Reproducibility of uncompensated a) and compensated b) force signals

Due to the fact that the parasitic forces with high force steps are more important, the compensation effect observed will also be more significant. The maximum rotation-dependent rel. deviations amount to a total of $<1 \cdot 10^{-5}$.

The compensation of the axial force signal will only be successful, if stability and reproducibility of the axial force and bending moment bridge signals are guaranteed. Therefor, a lot of efforts were made to reduce creep to <0,003% (Figure 6) and keep reversibility to less than 0,002%.
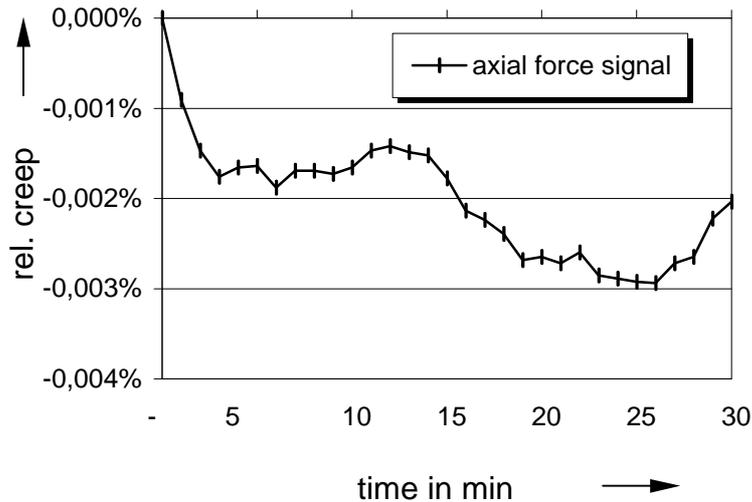
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Figure 6.   Relative creep of axial force signal

5. CONCLUSION

   The innovative force transducer enables tensile and compressive forces to be measured very precisely. Due to the symmetrical design, parasitic force components and ambient influences such as temperature variations etc. are efficiently suppressed. Applying the bending-moment compensation results in a further enhanced reproducibility even with larger parasitic force components being effective. The user benefits from evaluating the bending-moment bridges which enables the force transducer's mounting position and the loading mechanism's function to be checked.

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