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COMPENSATION OF LEVER ARM DISTORTION OF FORCE STANDARD MACHINES

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Abstract: The demand for lower uncertainties in force measurement is increasing. Deadweight force standard machines are known to yield the lowest measurement uncertainty in force realization. However, their capacities cannot be extended indefinitely as they become too large in size and prohibitively expensive. Lever amplification of a deadweight force is an option for higher capacities in force realization. This paper describes a new method (patent pending) for automatic compensation of lever arm distortion in order to keep the amplification ratio constant.

Keywords: Force, Lever Arm, Calibration

1. INTRODUCTION

GTM's force standard machines for higher loads use a lever system to amplify forces with high accuracy, by having strain controlled support of the lever. On each force introduction point of the lever, the bending moments are measured by means of strain gauges which are bonded to elastic hinges. Force introduction points are the connection point of the masses, the support of the lever at its fulcrum and the connection point on the loaded side of the lever, see Fig. 1.

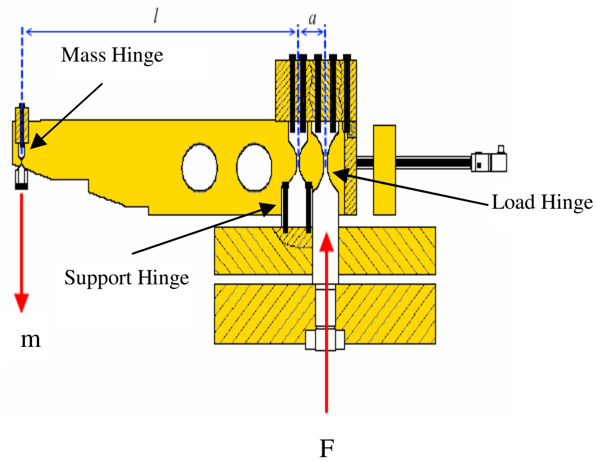

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Fig. 1: GTM Lever Amplification System

The sum of the bending moments is the feedback value for a closed loop control system of the drive of the lever-side crosshead, which is always in active mode while amplifying the force, with a setpoint of zero.

2. DESCRIPTION

A FSM with lever amplification has been designed and developed by GTM Gassmann Testing and Metrology, Germany, and has been installed at National Physical Laboratory, India in 2010. The machine consists of a deadweight part with 100 kN capacity, a lever part with 1 MN capacity, and a lever with a ratio of 1:10 supported by strain controlled hinges, see Fig. 2. The main construction principles of the 100 kN / 1 MN FSM of lever type with strain controlled hinges were previously described in [1] and the performance of the NPL-India machine was published in [2]. A load-depending compensation of the lever arm distortion was realized with special strain controlled hinges.

Fig. 2: 100 kN / 1 MN FSM of NPL India

3. COMPENSATION OF LEVER ARM DISTORTION

It is known that a lever arm will deform when loads are applied to its ends. This distortion reduces the effective lever length especially on the long side of the lever see Fig. 3. The lever arm length directly influences the lever amplification ratio. As the generated force at the lever side of the machine is a result of the deadweight force multiplied by the amplification ratio a systematic error in measurement results from any distortion of the lever arm which is not taken into consideration. In order to reduce this systematic error it is known from practise that some degree of mechanical compensation can be applied. However, great effort, usually by trial and error, is necessary for this.

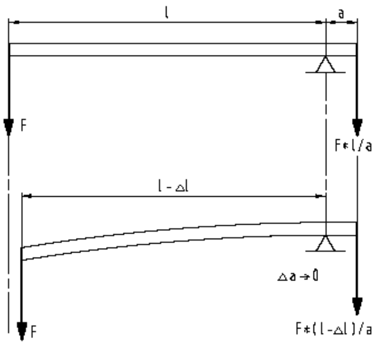

Fig. 3. Lever arm reduction by distortion

To improve this situation GTM has designed an automatic system to compensate the lever arm distortion, using special strain controlled hinges. The lever bearings with elastic hinges are completely free of friction and wear and define the pivot and load introduction points of the lever with the best possible precision, including long term. The ratio can be set exactly through the adjustment of the long lever arm length.

The special strain controlled hinges are equipped with measuring circuits for bending moments and additional measuring circuits for axial loads. Here GTM benefits from the experience in manufacturing high precision sensors.

The measurement of axial loads can be achieved relatively easily since it is not necessary to measure the axial force with extreme precision as only a small part of the axial measurement signal is used for the compensation.

The different strain controlled hinges must however have their sensitivity exactly adjusted. With the help of these special strain controlled hinges in this type of machine the systematic effect of the lever ratio reduction caused by distortion can be compensated.

The load-dependent distortion of the lever arm is compensated by the evaluation and sensitivity adjustment of the measured bending moments and axial forces. A fraction of the measured axial force signal is added to the sum signal of the bending moments. This is the corrected feedback value for the closed loop control system of the drive of the lever-side crosshead. As the corrected feedback value is generated in real time and automatically during operation of the machine no additional time and effort for calibration tasks is necessary.

4. DESCRPTION OF COMPENSATION

Equations (1) and (2) describe the balanced system. In the balanced system the sum of all moments is zero

$$\sum M = 0 = m \cdot g \cdot \left(1 - \frac{\rho_a}{\rho_m}\right) \cdot l + F \cdot a + M_b - \Delta F \cdot a \tag{1}$$

The force on lever side is:

$$\rightarrow \quad -F = m \cdot g \cdot \left(1 - \frac{\rho_a}{\rho_m}\right) \cdot \frac{l}{a} + \frac{M_b}{a} - \Delta F \tag{2}$$

With

F:	force on lever side [N]
m:	mass on deadweight side [kg]
g:	local acceleration of gravity [m/s²]
ρ_a:	density of air [kg/m³]
ρ_m:	density of mass [kg/m³]
l:	long lever arm [m]
a:	short lever arm [m]
M_b:	sum of bending moments of lever support [N·m]
ΔF:	systematic force error of F due to distortion [N]

The conventional method was that the closed loop control system of the drive of the lever-side crosshead moves the crosshead in such a way that the sum signal of all bending signals of the elastic hinges is zero. The systematic force error out of the lever arm distortion had to be minimized by other mechanical means.

For the new GTM electronic method for the compensation of lever arm distortion a correction force F_{corr} is determined from the axial load signal and added to the sum of the bending signals. This is done in such a way that a modified sum of the bending moments M'_b includes the correction moment M_{corr} which is generated by F_{corr} .

$$M_{corr} = F_{corr} \cdot a \tag{3}$$

The modified sum of the bending moments M'_b is

$$M'_b = M_b + M_{corr} = M_b + F_{corr} \cdot a \tag{4}$$

The correction force F_{corr} has to be determined in such a way that it is nearly equal to the systematic force error ΔF . In that case the modified sum of the bending moments M'_b compensates the systematic force error ΔF .

$$-F = m \cdot g \cdot \left(1 - \frac{\rho_a}{\rho_m}\right) \cdot \frac{l}{a} + \frac{M'_b}{a} - \Delta F \tag{5}$$

From a practical point of view a small deliberate deflection of the hinges is used to achieve the compensation. The force which is needed for the deflection of the hinges is equal to the systematic force error. This compensation method can only be used with strain controlled hinges and not with knife edge bearing designs.

The necessary correction force F_{corr} can be described by a polynomial function and can be calculated from the measured axial force of the elastic hinge. The measurement error of the axial force has a negligible effect on the measurement uncertainty of the force standard machine.

In order to determine the dependency between load and correction force F_{corr} a self-calibration of the force standard machine can be carried out. For this purpose several force transfer standards of similar type can be calibrated with smallest measurement uncertainty in the deadweight part of the force standard machine. Afterwards measurements with these calibrated force transfer standards can be done in the lever amplification part of the force standard machine. The measurements can be performed with single transducers and with build-up-systems of these force transfer standards.

4. LINEARITY OF LEVER FORCES

The linearity error of lever force of a 1000kN Force standard machine with and without lever arm compensation is shown in Fig. 4.

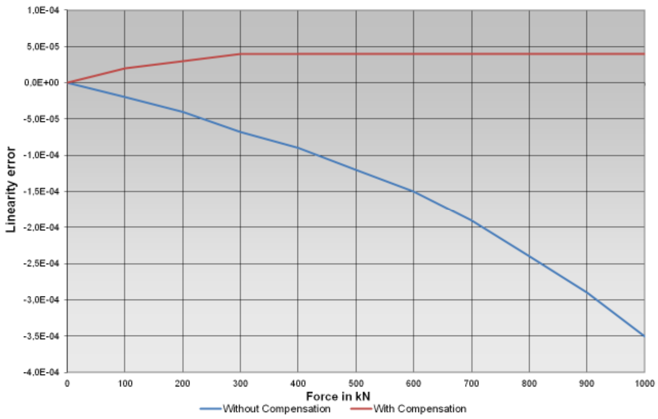

Fig. 4: Linearity error of Lever Force

Without any lever arm compensation the linearity error increases up to more than $3x10^{-4}$ at 1000kN. In case the electronic lever arm distortion compensation is used the linearity error is nearly constant and less than $5x10^{-5}$ across the whole measuring range. The electronic compensation of lever arm distortion reduces the linearity error significantly.

The detailed uncertainty contributions for this force standard machine with lever amplification have been discussed in Measurement No. 45 [2].

5. CONCLUSIONS

The load-dependent compensation of the lever arm distortion can be achieved with special strain controlled hinges. This compensation reduces the measuring uncertainty of lever force standard machines with strain controlled hinges. Machines with this type of compensation of lever arm distortion can achieve relative expanded uncertainties of less than $9 \cdot 10^{-5}$ on the lever side [2].

6. REFERENCES

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