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# PROPOSAL AND INVESTIGATION OF A NEW METHOD FOR CALIBRATION OF STRAIN CYLINDERS USING LASER INTERFEROMETRY

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**Abstract:** This research is to investigate the possibility of calibrating a strain cylinders using laser interferometry, thus to provide a new type of transducer that can provide both force and deformation indications. This new method for calibration of strain cylinders is based on application of a double channel laser interferometer in a force standard machine. Experimental results show that the deformation of a strain cylinder has a definite and stable relationship with the force applied, and can be calibrated and directly traced to the wavelength of laser.

**Keywords:** strain cylinder; laser interferometry; calibration; deformation; compression testing machine.

## 1. INTRODUCTION

A strain cylinder, also named strain gauged column, is a kind of force transducer with four channel outputs. It is often used for alignment verification of compression testing machines. Specifications of strain cylinders and proving procedure for verification of compression testing machines are specified in international and national standards [1-2]. The calibration of stain cylinders can be done in a force standard machine according to international standard ISO 376 [3].

Methods and tools in precision engineering are frequently introduced into the field of force metrology in recent years. For example, laser interferometry has been used in measurement of deformation or displacement of key parts [4, 5], dynamic calibration [6-8], and so on. Coordinate measuring technique has been used in on-machine or off-machine measurement of key dimensional parameters [9, 10]. These methods and tools show great capability and advantages in solving some certain problems.

In this paper, a new method for calibration of strain cylinders using laser interferometry is proposed and investigated. The new method is based on the application of a double channel laser interferometer in a force standard machine, and shows advantages and provides more information.

## 2. BASIC CONCEPT

The idea of the new method for calibration of strain cylinders is to introduce laser interferometer in a force standard machine and obtain deformation information when calibration forces are applied, and calibrate the relationship between force, deformation and strain in parallel. In this way, a new standard that can provide both force and deformation indication is provided, and can be used for both alignment verification and indication verification of compression testing machines is proved. Also this research illustrates the possibility of providing a new deformation-type force transducer using a non-gauged steel cylinder together with a multi-channel laser interferometer. This new force transducer is much simpler in structure and usage not requiring the complicated manufacturing and assembling process of strain gauges.

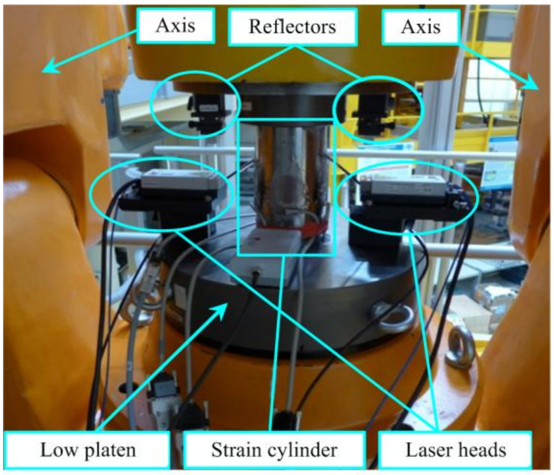
This idea is applicable on the condition that the deformation of a strain cylinder has a definite and stable relationship with the force applied, and can be calibrated using a laser interferometer in a force standard machine with good repeatability and reproducibility. This will be proved through experiments and assessment of this new type of transducer in following sections.

## 3. EXPERIMENTAL SETUP AND CALIBRATION PROCEDURE

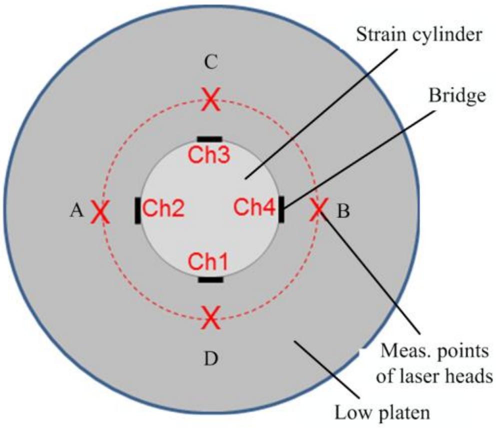
### 3.1 Experimental setup

The experimental setup is shown in Fig. 1. The experiments are carried out in a 5 MN force standard machine. The maximum force applied on the cylinder is 2 MN. The strain cylinder, laser heads and reflectors of the laser interferometer are assembled between the upper platen and lower platen of the machine, and the strain cylinder is centrally assembled on the lower platen.

The strain cylinder is 100 mm in diameter and 200 mm in height. It conforms to requirements about material and dimensional tolerances in Ref. [1]. Four full bridges of strain gauges, numbered as Channel 1 to Channel 4, are assembled at fours ends of a pair of orthogonal diameters half-way up the cylinder. Each bridge consists of two elements measuring the axial strain and two elements measuring the circumferential strain. The outputs of four bridges are recorded by dedicated strain measuring equipment DMP41.




a)




b)

Fig. 1 Experimental setup in the 5MN force standard machine. a) Experimental setup. b) Top view of strain cylinder with 4 bridges and 4 corresponding measurement points

A MI-5000 double channel laser interferometer from SIOS Meßtechnik GmbH is used. The relative length measurement accuracy of it is up to $1\times10^{-6}$, so the length measurement error introduced is negligible during experiments, showing great advantage of a tool from the field of precision engineering. For each channel, interferometric optics excluding the measuring reflector are assembled together as a laser head. Laser is transmitted to each of the two laser heads through a length of optical fiber. Corresponding to orientations of four bridges on the strain cylinder, there are four corresponding measurement points for laser heads on the lower platen, which are at fours ends of a pair of corresponding orthogonal diameters of a circle and designated as “A”, “B”, “C” and “D” in Fig. 1 b). In such a way, the strain cylinder together with the laser heads work as a new type of transducer with four “deformation sensing elements”. The four “deformation sensing elements” are uniformly distributed over 360° and numbered as Channel 1 to Channel 4 too.

### 3.2 Calibration procedure

Procedure of calibrating a strain cylinder using a double channel laser interferometer is proposed with reference to ISO 376. The cylinder is rotated around its axis to four uniformly distributed positions over 360°. Deformation and strain data at the four rotation positions are averaged to eliminate the influence of non-uniform force distribution characteristics of the force standard machine. A series of increasing calibration forces and then a series of decreasing calibration forces are applied at each rotation position. Because stain cylinders are only used for compression test, data corresponding to deceasing calibration forces are not used for interpolation, but only used for assessment of relative reversibility error. The two laser heads are first assembled at Point “A” and Point “B”, and the strain cylinder is calibrated at four rotation positions. Then the two laser heads are re-assembled to Point “C” and Point “D”, and the strain cylinder is calibrated at another four rotation positions. In such a way, outputs of four channel “deformation sensing elements” of the new type of transducer can be obtained at each rotation position.

Data recorded by DMP41 are designated as $X_{chi,j}$ and $X_{chi,j}'$ in the following sections, where $i$ is the channel number of strain bridges and $i$ = 1, 2, 3 or 4, $j$ is the rotation position of the strain cylinder and $j$ = 0, 90, 180 or 270, $X_{chi,j}$ is corresponding to increasing calibration forces and $X_{chi,j}'$ is corresponding to decreasing calibration forces. Similarly, data recorded by the laser interferometer are designated as $Y_{chi,j}$ and $Y_{chi,j}'$, where $i$ is the channel number of “deformation sensing elements”.

## 4. DATA PROCESSING AND EXPERIMENTAL RESULTS

### 4.1 Data processing results

The abundance of data continuously sampled at a sampling rate of 10Hz are pre-processed first, so to obtain values of deformation and strain corresponding to 11 calibration forces during each incremental force loading and decremental force loading.

Through data pre-processing, four channel values of deformation and strain corresponding to 11 calibration forces at each rotation position, either increasing or decreasing, are obtained. The interpolation curves are determined from average values of deformation and strain at four rotation positions. As mentioned before, data corresponding to decreasing calibration forces not used for interpolation. Three-degree polynomial fitting are carried out to obtain third degree equations about relationship between force, deformation and strain.

#### 4.1.1 Polynomial fitting results of force vs. deformation

Equations giving the relationship between the calibration force and deformation are calculated as follows:

$$\begin{cases} F = -2.013*10^{-6}*Y_{ch1}{}^{3} + 0.002064*Y_{ch1}{}^{2} + 4.272*Y_{ch1} - 0.4283 \\ F = -1.748*10^{-6}*Y_{ch2}{}^{3} + 0.001859*Y_{ch2}{}^{2} + 4.337*Y_{ch2} + 0.3774 \\ F = -2.263*10^{-6}*Y_{ch3}{}^{3} + 0.002216*Y_{ch3}{}^{2} + 4.270*Y_{ch3} + 0.06657 \\ F = -2.356*10^{-6}*Y_{ch4}{}^{3} + 0.002293*Y_{ch4}{}^{2} + 4.226*Y_{ch4} - 0.7880 \end{cases} \quad (1)$$

$$F = -2.096*10^{-6}*\bar{Y}^{3} + 0.0021083*\bar{Y}^{2} + 4.276*\bar{Y} - 0.2008 \quad (2)$$

where $F$ is the calibration force in unit of kN, $Y_{chi}$ is the deformation of Channel $i$ in unit of μm, $i$ = 1, 2, 3 or 4, $\bar{Y}$ is the average deformation of the four channels.

Curves of the four three-degree equations are shown in Fig. 2. It can be seen that the 4 channels of the strain cylinder have very good consistency. It can be concluded that the deformation of a strain cylinder has a definite and stable relationship with the force applied by the force standard machine.

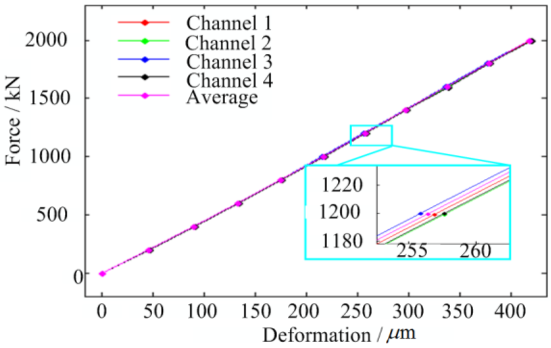



Fig. 2 Curves of relationship of force vs. deformation

#### 4.1.2 Polynomial fitting results of deformation vs. strain and force vs. strain

Equations giving the deformation as a function of strain are calculated as follows:

$$\begin{cases} Y_{ch1} = 8.584 * X_{ch1}^{3} - 31.77 * X_{ch1}^{2} + 283.3 * X_{ch1} + 0.2128 \\ Y_{ch2} = 3.058 * X_{ch2}^{3} - 15.29 * X_{ch2}^{2} + 268.0 * X_{ch2} - 0.5468 \\ Y_{ch3} = 7.588 * X_{ch3}^{3} - 28.62 * X_{ch3}^{2} + 279.4 * X_{ch3} + 0.03244 \\ Y_{ch4} = 13.35 * X_{ch4}^{3} - 45.43 X_{ch4}^{2} + 294.3 * X_{ch4} + 1.062 \end{cases} \quad (3)$$

$$\bar{Y} = 8.102 * \bar{X}^{3} - 30.22 \bar{X}^{2} + 281.3 * \bar{X} + 0.1592 \quad (4)$$

where $X_{chi}$ is the strain indication of Channel $i$ in unit of mV/V, $i$ = 1, 2, 3 or 4, $\bar{X}$ is the average strain of the four channels.

Curves of the four three-degree equations are shown in Fig. 3. Since the four strain bridges are well matched and thermally and electrically balanced, so these four curves have good consistency too.

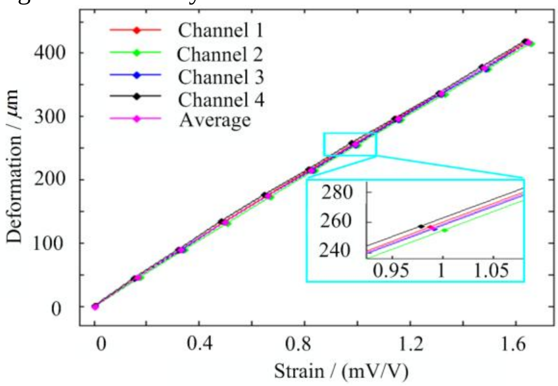



Fig. 3 Curves of relationship of deformation vs. strain

Equations giving the calibration force as a function of stain can be similarly calculated as follows:

$$\begin{cases} F = 3.942 * X_{ch1}^{3} - 9.654 * X_{ch1}^{2} + 1221 * X_{ch1} + 0.04842 \\ F = -15.24 * X_{ch2}^{3} + 48.81 * X_{ch2}^{2} + 1168 * X_{ch2} - 2.339 \\ F = -3.916 * X_{ch3}^{3} + 12.59 * X_{ch3}^{2} + 1204 * X_{ch3} - 0.2183 \\ F = 19.09 * X_{ch4}^{3} - 55.75 * X_{ch4}^{2} + 1261 * X_{ch4} + 3.191 \end{cases} \quad (5)$$

$$F = 0.8159 * \bar{X}^{3} - 0.7826 * \bar{X}^{2} + 1214 * \bar{X} + 0.06329 \quad (6)$$

During real applications, either average signal or non-averaged signals of four channel strain bridges can be used. The average signal represents the amplitude of the force applied on the strain cylinder, while the non-averaged values of four channels illustrates the force distribution applied on the strain cylinder.

With Equations (3) ~ (6), a new type of transducer which provides both force indication and deformation indications is provided. This new type of transducer can be used as a standard for both alignment verification and indication verification of compression testing machines.

### 4.2 Assessment of deformation calibration results

The calibration results of deformation $Y$ are assessed with reference to ISO 376.

#### 4.2.1 Relative reproducibility error

The relative reproducibility errors of deformation value $Y$ are shown in Fig. 4. The maximum relative reproducibility error $b_{max}$ happens when the calibration force is 200 kN, $b_{max}$ = 6.4. It has been found that the reproducibility error is mostly resulted by the non-uniform force distribution characteristics of the force standard machine. The indication variation of deformation at different rotation positions and the relative reproducibility error can be significantly reduced if the force distribution is more uniform.

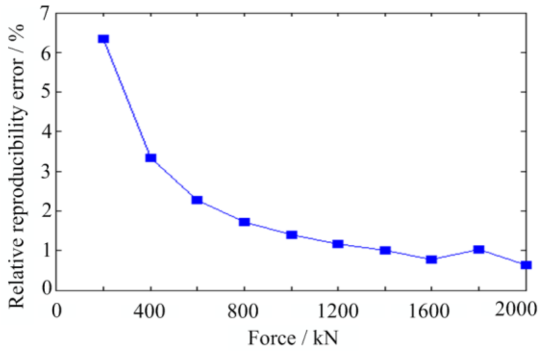



Fig. 4 Relative reproducibility errors in %

#### 4.2.2 Relative interpolation error

The relative interpolation errors of Channel 1 to Channel 4 are shown in Fig. 5. The maximum relative interpolation error $|fc|_{max}$ happens in Channel 4 when the calibration force is 200 kN, $|fc|_{max}$ = 0.84. The relative interpolation error can be averaged if the averaged deformation of the four channels is used.

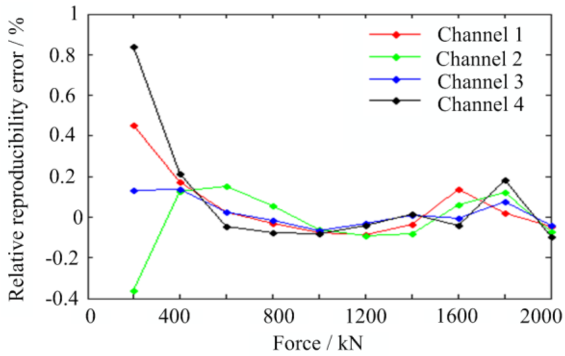



Fig. 5 Relative interpolation errors of 4 channels

#### 4.2.3 Relative zero error

The relative zero errors of Channel 1 to Channel 4 are shown in Fig. 6. The maximum relative zero error $fo_{max}$

happens in Channel 3 when the cylinder is at 270° rotation position, $fo_{max}$ = -3.5.

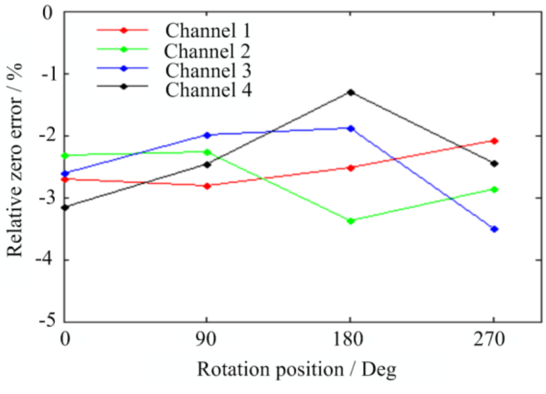



Fig. 6 Relative zero errors of 4 channels

#### 4.2.4 Relative reversibility error

The relative reversibility errors of Channel 1 to Channel 4 are shown in Fig. 7. The maximum relative reversibility error $v_{max}$ happens in Channel 4 when the calibration force is 200 kN, $v_{max}$ = 13. The reversibility error is mostly resulted by the hysteresis between incremental and decremental force loading. Since strain cylinders are only used for compression test, this does not prove to be a problem.

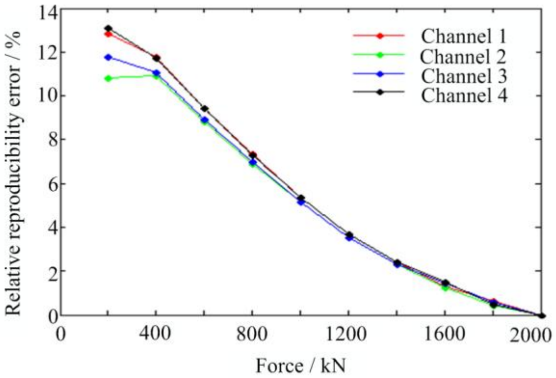



Fig. 7 Relative reversibility errors of 4 channels

#### 4.2.5 Relative creep error

Average calculation of 25 s data which works as a 0.04 Hz low pass filter is used. The experimental results of relative creep error test are shown in Fig. 8. The maximum relative creep error $c_{max}$ = 0.091.

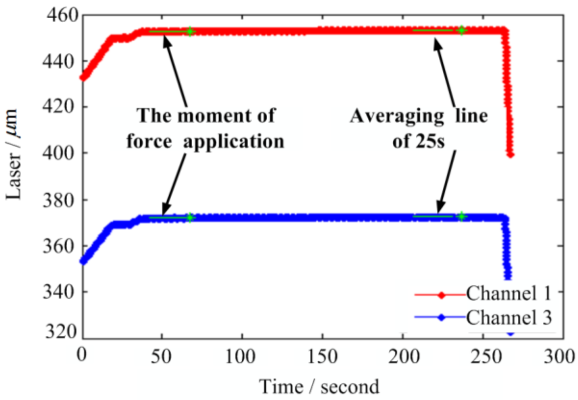



Fig. 8 Experimental results of relative creep error test

## 5. CONCLUSION

A new method for calibration of strain cylinders using laser interferometry is proposed and investigated. This new method is illustrated through calibrating a strain cylinder with a SIOS double channel laser interferometer in a 5 MN force standard machine at PTB. Calibrated procedure, data processing method and assessment of calibration results are designed with reference to ISO 376. Experimental results show that the deformation of a strain cylinder has a definite and stable relationship with the force applied, and can be calibrated and directly traced to the wavelength of laser.

Therefore, a new type of transducer that can provide both force and deformation indications is proved, and can be used for both alignment verification and indication verification of compression testing machines and other uniaxial testing machines. This method can also be applied to non-gauged standard cylinders, thus to provide a new deformation-type force transducer using a non-gauged steel cylinder together with a multi-channel laser interferometer.

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