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INTERFERENCE-OPTICAL FORCE SENSOR FOR SMALL FORCES

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Abstract – Force measurement at a resolution in the micronewton range is advantageously performed by means of electromagnetic force compensation. So far, weighing systems of this kind have been working only in a horizontal position. Although resistance strain gauge force sensors are suited to various force directions, they cannot be used for precision measurements in the micronewton range.
In this paper, an interference-optical force (IOF) sensor is described which can be used both for horizontal and vertical force measurement. The force measuring range of a specially designed force sensor amounts to 100 mN (10 g), resolution to 0.01 mN, and the extended measuring uncertainty to 0.008 mN for k = 2. The structure, the operating principle and the signal processing of the force sensor are described and, furthermore, a uncertainty of measurement analysis of the entire system is made. The successful application of the interference-optical force sensor is finally demonstrated by means of the example of the calibration of applanation tonometers.

Keywords: force measurement, laser interferometer, horizontal force measurement

1. INTRODUCTION

At present, the measurement of small forces up to 0.1 N at measurement uncertainties of < 1‰, with the forces acting either horizontally or at an angle, cannot be realized with sufficient accuracy using conventional force sensors. Thus, a position-robust force feed-in system is necessary for solving this problem. Here, it seems to be advantageous to integrate the force feed-in system and the force measuring element as it is the case, for example, in a parallel spring guide. However, this solution can fulfil the great demands made on the measurement resolution and uncertainty only if, on the one hand, the spring guide presents a strictly linear characteristic and negligible elastic creep-effects and, on the other, a sufficiently exact measuring technique for the non-reactive recording of the spring deformation is employed. Conventional strain gauge force sensors having particular deformation bodies are not able to fulfil these requirements. In the force range up to 0.1 N, the applied foil strain gauges still present retroaction. When the forces are small, measurement uncertainties of < 1‰ cannot be reached.

By combining a silica deformation body and a high-resolution miniature laser interferometer, the authors were able to solve the measuring problem [1], [2].
In this paper, a special sensor design is presented which is characterized by a compact, symmetrical structure allowing also horizontal force measurements to be made.

2. SENSOR DESIGN

The sensor principle is shown in Fig. 1: A parallel spring arrangement consisting of a basic body (1) with bending springs (2) and a coupling element (3) attached there to is deflected when an external force F acts upon it. This deflection is then recorded by means of an interferometer, which consists of a modified beam splitter (4) and the corner cube reflectors (5) [3]. Illumination is provided using laser light via an optical fiber (6) and an illumination optics system (7). The interference pattern is scanned by a sensor head (8) and two optical fibers (9). A signal processing unit then converts the optical scanning signal into two electrical sinusoidal signals presenting a phase shift of 90 ° before it is sent to a counting unit via a counting direction discriminator. The counts are then evaluated by a signal processor, which also performs the digital signal filtering, the signal conditioning and any necessary correction algorithms. Furthermore, the signal processing unit realizes the interface to a superordinate computer with the corresponding interface protocol.
The spring force is calculated as follows:

$$F = c \cdot y_{IOK}$$

$$F = c \cdot \frac{N \cdot \lambda_0}{e \cdot i \cdot n} \qquad (1)$$

with

y_{IOK}	-	interference-optically measured spring deflection
c	-	spring constand
N	-	count pulses
λ_0	-	vacuum wavelength
e	-	elektronic interpolation factor
i	-	interferometer factor
n	-	refractive index of air.

From this results the resolvable change in force:

$$\Delta F = c \cdot \frac{\lambda_0}{e \cdot i \cdot n} \qquad (2)$$

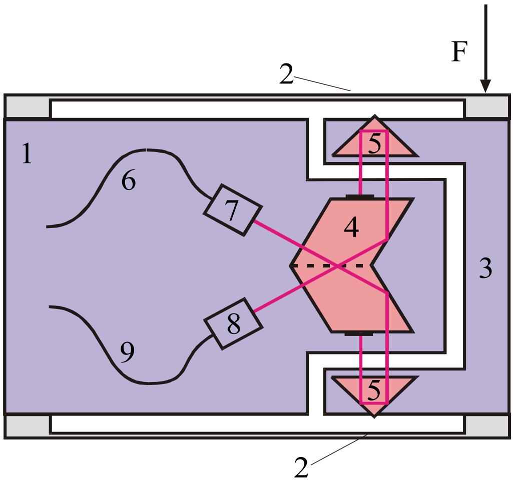

Fig. 1: Interference-optical force sensor (IOF)

The traceability to national standards can be achieved by calibrating the force sensor with a balance weight. Due to the fact that the deformation of the silica glass springs used is temperature-dependent, this calibration is only valid for a well-defined calibration temperature. As the application temperature can differ from the calibration temperature, a temperature correction must be effected.

3. UNCERTAINTY OF MEASUREMENT ANALYSIS

The spring constant c in Eq. (1) is determined by calibration using a 5g-balance weight and saved in the signal processing unit as scaling factor. Thus, this calibration is automatically considered in the uncertainty of measurement analysis.
For the interference-optical force sensor, the following model equation can be applied:

$$F = y_{IOK} \cdot \frac{m_G \cdot g}{y_G} \cdot (1 + e_T \cdot \Delta T) + e_d \qquad (3)$$

with
- F - measuring force
- y_{IOK} - interference-optically measured spring deflection
- m_G - mass of the calibration balance weight
- g - acceleration due to gravity
- y_G - spring deflection during calibration
- e_T - temperature coefficient of deformation
- ΔT - deviation from calibration temperature
- e_d - digitalisation error of the display

The model equation (3) constitutes the basis for the following uncertainty analysis:

Determination of the standard uncertainty of m_G:

The weight m_G is assigned the following uncertainty portions (Table 1):
- uncertainty of the balance weight itself (class F1)
- corner load uncertainty of the IOF
- uncertainty due to the inclination of the IOF during calibration

Table 1: Calibration error limits

Error limits of the calibration balance weight (class F1)	**Limit values of the corner load impact**	**Limit values of the inclination impact**
Standard	Experimental experience	Angle of inclination $< 5'$
$\pm 3{,}6 * 10^{-5}$	$\pm 1 * 10^{-5}$	$\pm 1 * 10^{-6}$

By using an angle vial, angles of inclination of > 5' can be avoided.
The relative standard uncertainty of m_G can be calculated from Table 1 in case of equipartition:

$$w_1 = 2{,}1 \cdot 10^{-5} \qquad (4)$$

Determination of the standard uncertainty of the acceleration due to gravity g:

On condition that the exact local acceleration due to gravity is taken into account when calibrating the test equipment, the relative standard uncertainty of the acceleration due to gravity can be estimated using the following equation:

$$w_2 = 6 \cdot 10^{-7} \qquad (5)$$

Determination of the standard uncertainty of the interferometrically measured spring deflections y_G und y_{IOK}:

The error limits of distance measurement of the interferometer used are < 2.5 nm for a differential measurement. In case of a spring deflection of 0.25 mm when using a 5g-balance weight, the relative standard uncertainty of distance measurement, with equipartition being assumed, amounts to:

$$w_3 = 6 \cdot 10^{-6} \qquad (6)$$

The relative standard uncertainty of the interferometrically measured spring deflection y_{IOK} depends on the distance and, thus, on the measuring force F. From the sensitivity of the force-displacement conversion of 5 mm/N and from the interferometer error limits of 2.5 nm, the relative standard uncertainty of y_{IOK} can be calculated using the following equation:

$$w_4 = \frac{3 \cdot 10^{-4} mN}{F} \quad (7)$$

with F being given in mN.

Uncertainty of the correction of the temperature-dependence of the spring deformation

The temperature dependence e_T of the spring deformation amounts to 2 * 10^{-4}/Kelvin.
The temperature is exactly measured to 0.1 Kelvin. Thus, an uncorrected portion of < 2 * 10^{-5} remains. Hence, in case of equipartition, the uncertainty of correction amounts to:

$$w_5 = 1{,}2 \cdot 10^{-5} \quad (8)$$

Uncertainty of the digital display

The digital resolution of the display amounts to 0.01 mN. With the equipartition of the digitalisation error being assumed, the following relative standard uncertainty of the digital display is obtained:

$$w_6 = \frac{0{,}003 mN}{F} \quad (9).$$

Resulting standard uncertainty of the force sensor

When being divided by F , the total differential of model equation (3) is obtained by means of the following relation, with the correction portion e_T*ΔT of the deformation being permissibly neglected:

$$\frac{dF}{F} = \frac{dy_{IOK}}{y_{IOK}} + \frac{dm_G}{m_G} + \frac{dg}{g} - \frac{dy_G}{y_G} + e_T \cdot d\Delta T + \frac{de_d}{F} \quad (10)$$

For the term e_T*dΔT, the relative uncertainty portion of the correction (8) can be used for calculating the uncertainty of the output quantity F .
Using the uncertainty budget from Tables 2 and 3, the relative combined standard uncertainty for the force F can be given on the basis of Eq. (10):

$$w(F) = \sqrt{\sum_{i=1}^{6} w_i^2} \quad (11)$$

The extended combined standard uncertainty W(F) is obtained using the following relation, with k = 2:

$$W(F) = 2 \cdot w(F) \quad (12)$$

Table 2: Combined standard uncertainty of the force sensor for 10 mN (1g)

Input quantity	Standard uncertainty
m_G	w_1 = 2,1*10^{-5}
g	w_2 = 6 *10^{-7}
y_G	w_3 = 6 *10^{-6}
y_{IOK}	w_4 = 3 *10^{-5}
e_T*ΔT	w_5 = 1,2*10^{-5}
e_d	w_6 = 3 *10^{-4}
Output quantity F	w(F) = 3 *10^{-4} u(F) = 3 µN
Extented combined standard uncertainty (k=2)	W(F) = 6 *10^{-4} für k=2 U(F) = 6 µN

Table 3: Combined standard uncertainty of the force sensor for 100 mN (10g)

Input quantity	Standard uncertainty
m_G	w_1 = 2,1*10^{-5}
g	w_2 = 6 *10^{-7}
y_G	w_3 = 6 *10^{-6}
y_{IOK}	w_4 = 3 *10^{-6}
e_T*ΔT	w_5 = 1,2*10^{-5}
e_d	w_6 = 3 *10^{-5}
Output quantity F	w(F) = 4 *10^{-5} u(F) = 4 µN
Extended combined standard uncertainty (k=2)	W(F) = 8 *10^{-5} für k=2 U(F) = 8 µN

4. APPLICATION

In the field of ophthalmology, the measurement of the intraocular pressure is of great diagnostic importance. Here, according to the international standard DIN EN ISO 8612, the tonometers used are subject to strict pattern approval and, furthermore, must be checked at regular intervals. For the calibration of the widespread and most exact tonometers, the applanation tonometers, a mechanical cross-beam balance is used at present. This highly time-consuming measuring equipment, which offers only a limited measuring accuracy, no longer fulfils the great demands made on an objective metrological quality control. The application of the above-described interference-optical force sensor for checking applanation tonometers has resulted in an efficient testing facility with automated test sequence (Fig.2).
For the check equipment, the following characteristic features and parameters can be stated:

- position-independent force measurement in the whole measuring range , with the error limits being observed
- automated measuring sequence according to check specification for applanation tonometers (force values in the middle of the mobility range, hysteresis)

- additional determination of the entire tonometer characteristic
- protocol output into a file
- traceability to national standards by calibrating with normal weights
- testing time including set-up time: approximately 5 minutes
- no warm-up time
- the check equipment is transportable and can thus be employed on the spot (hospitals, eye specialists' practices)
- measuring range: 100 mN
- resolution: 0.01 mN
- extended measuring uncertainty of the force sensor for k = 2: 0.008 mN
- testing time: < 5 min

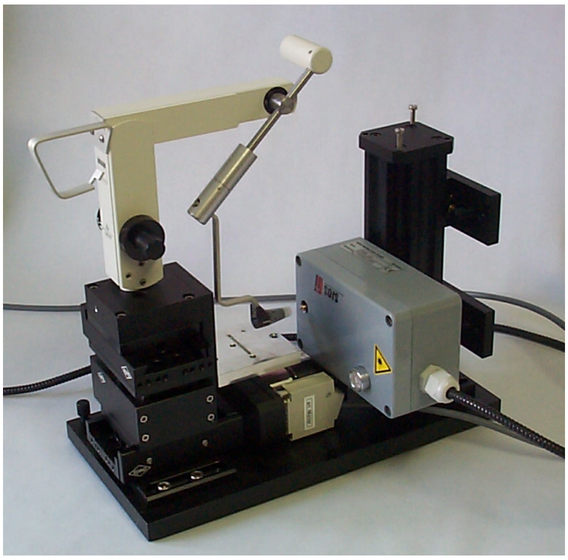

Fig. 2: Interference-optical check equipment for tonometers

5. SUMMARY

The sensor design presented in this paper permits position-independent force measurements to be carried out in the range up to 0.1 N at a resolution of 10 µN and an extended measuring uncertainty of < 10 µN. For measuring horizontal forces, a force resolution of far below 1 µN can be achieved with a suitable dimensioning of the springs subjected to bending.

Literature:

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