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THE INFLUENCE OF THE FORCE FEED-IN SYSTEM ON HIGH-ACCURACY LOW FORCE MEASUREMENT

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Abstract – Forces are vectorial values which can be detected only by measuring their effects. Thus, a force sensitive element for the conversion into another measurable value is needed. If a force in a definite direction is to be detected, a force feed-in system is necessary. Its task is to separate forces from other directions. In the case of low force measurement the feed-in system has a significant influence on the accuracy of the whole force measuring system. This paper analyses the requirements for the force feed-in system depending on the properties of the force sensitive element. The results are shown for three different force sensor types.

Keywords: low force measurement, force feed in system, force sensitive element

1. INTRODUCTION

The measurement of forces can only be realised by measuring their effects. Therefore a primary transducer is necessary to convert the force into another measurable value. Because of the vectorial characteristics of forces we need a force conversion system for the components whereas each transducer unit has to be sensitive for only one component. Those 3D-force transducers are used for instance in robots.

If you want to measure a force in a definite direction a force feed-in system is necessary. Its task is to separate the force to be measured from forces in other directions. In case of low force measurement the force feed-in system has an important influence on the accuracy of the whole force measuring system.

In weighing cells the force feed-in system is used to avoid corner load errors. The stiffness of the feed-in system has to be small in measuring direction and high in perpendicular direction. Difficulties occur when the force sensitive element itself has a high spring constant and its shear force sensitivity is not negligible. In most of these cases the transverse stiffness of the force feed-in system is not high enough for precision force measurement.

2. FORCE CONVERSION SYSTEMS

Figure 1 shows the force conversion system of a load sensor. The scalar value M is a function of the force vector. It can be calculated according to equation (1):

$$M = k_y \cdot \left(\frac{c_{FSEy}}{c_{FFISy} + c_{FSEy}}\right) \cdot F_y + k_x \cdot \left(\frac{c_{FSEx}}{c_{FFISx} + c_{FSEx}}\right) \cdot F_x \tag{1}$$

The goal is to measure the load component F_y. To avoid in case of existing sensitivity k_x any influence of the transversal force F_x on M, a force feed-in system with a much higher stiffness c_{FFISx} than the stiffness c_{FSEx} of the force sensitive element is to be used.

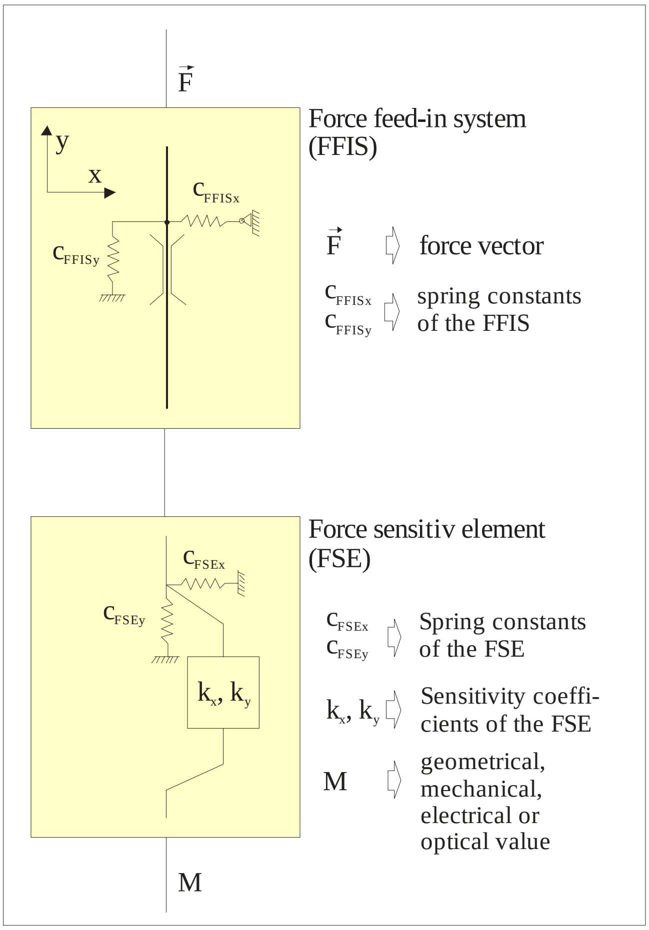

Fig. 1. Force conversion system consisting of a force feed-in system and a force sensitive element

It can be a problem, especially when the stiffness c_{FSEx} of the force sensitive element is very high itself. Furthermore the parasitic stiffness c_{FFISy} of the force feed-in system has to be as small as possible.

The paper will show these relations for three kinds of load cells. There will be analysed an electromagnetic force compensation system, a photo-elastic force sensor [1] and an interference-optical load cell.

3. ELECTROMAGNETIC FORCE COMPENSATION

The electromagnetic force compensation is a very suitable measurement principle for load cells or electronic scales in the highest accuracy class [4]. With this principle the load to be measured is compensated by an electromagnetically generated force (Fig. 2). A compensation coil is inserted in a permanent magnetic field. By means of an optoelectronic position sensor the coil position is controlled. When the load changes a closed loop current control system keeps the coil in zero position. The current is directly proportional to the load. Its value is digitalized and sent to a digital signal processing unit.

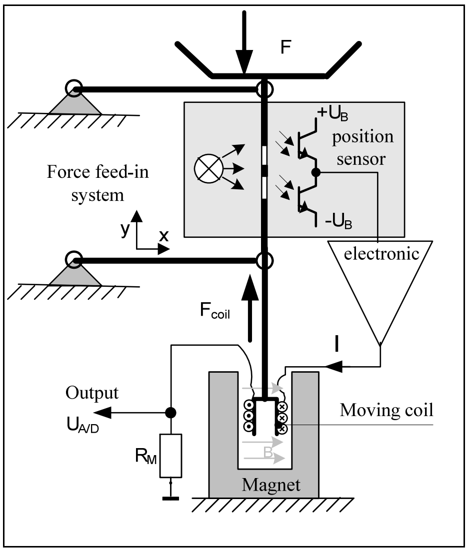

Fig. 2. electromagnetic force compensation

The relation between the force and the current is based on the Lorentz force law:

$$\vec{F} = q\vec{E} + q(\vec{v} \times \vec{B}) \qquad (2)$$

In this equation the first summand describes the electric force. In electromagnetic force compensation systems the second part gives the magnetic force. When a wire carrying an electrical current is placed in a magnetic field, each of the moving charges, which comprise the current, experiences the magnetic Lorentz force, and together they can create a macroscopic force on the wire. In case of a curved wire (coil) in a constant magnetic field the magnetic Lorentz force is given by equation (3):

$$\vec{F} = I \oint d\vec{l} \times \vec{B} \qquad (3)$$

If the path of integration (coil wire) does not change its length, the force is directly proportional to the current. That means that cross motions of the coil have no influence on the current-force conversion. Regarding to equation (1) the cross spring constant c_{FSEx} of the force sensitive element (coil-magnetsystem) and the sensitivity coefficient k_x are theoretically zero. That's why the requirements regarding to the cross stiffness c_{FFISx} of the force feed-in system are not so critical. On the other hand the spring constant c_{FSEy} and the sensitivity coefficient k_y of the force sensitive element in measurement direction are very high, they depend on the closed-loop gain of the control system. That means that the parasitic spring constant c_{FFISy} of the force feed-in system is in most cases negligible. These are reasons for the high accuracy of electromagnetic force compensated load cells or balances.

4. PHOTO-ELASTIC FORCE SENSOR

Mechanical forces can be sensed over a very broad input range (10 nN up to 100 kN) with high resolution and linearity by applying the photo-elastic effect in small solid-state lasers (diode-pumped Nd:YAG crystals) [1].

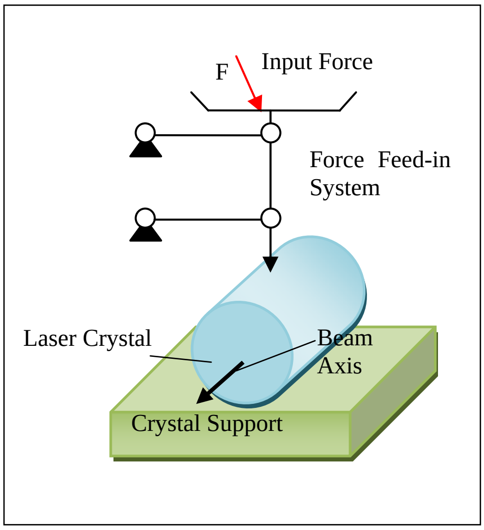

Fig. 3. Minimal configuration of the laser force sensor [1]

The input force vector modulates the optical frequency of the laser crystal (Fig. 3, Fig. 4). For an elastic, mechanically homogeneous laser crystal, the birefringence induced by a radial force F_{sy}, leads to a change of the optical difference frequency $\Delta\nu$ between the two polarized modes given by:

$$\Delta\nu = \nu_1 - \nu_2 = K_a \frac{C \cdot F_{sy}}{\lambda \cdot l \cdot d} \qquad (4)$$

Where l is the length of the crystal and d its diameter, λ the laser wavelength and C is the optical stress coefficient that characterizes the photo elastic crystal K_a is a coefficient, which depends on the shape of the crystal and the geometrical alignment.

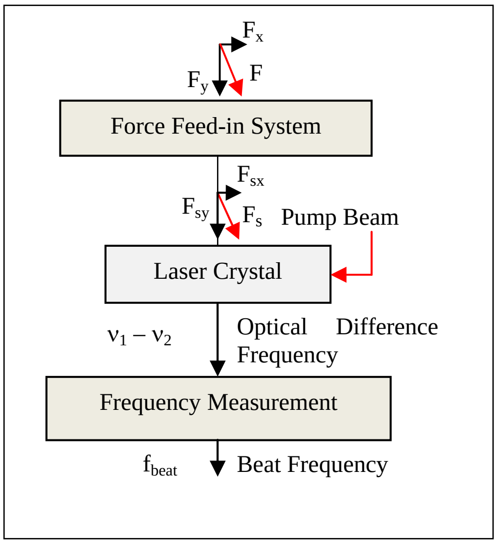

Fig. 4. Signal conversion of the laser force sensor

In praxis we have to consider the influence of tangential forces F_{sx} too. The reason is a not ideal force feed-in system that avoids tangential forces. The tangential force F_{sx} acting on the laser crystal is given according to equation (1):

$$F_{sx} = \left(\frac{c_{FSEx}}{c_{FFISx} + c_{FSEx}}\right) \cdot F_x \tag{5}$$

This force causes sheer stress in the laser crystal which also results into a change of the optical difference frequency. The tangential force F_{sx} can only made small if the spring constant c_{FFISx} of the force feed-in system is much higher than the spring constant c_{FSEx} of the laser crystal. In praxis it's very difficult because of the stiffness of the crystal is very high itself. Using this sensor as a balance a sub scale pan as force feed-in system is necessary. It ensures avoiding tangential forces on the laser crystal.

5. INTERFERENCE-OPTICAL LOAD CELL

The interference-optical load cell (Fig.5) is able to solve this measuring problem by combining a quartz glass deformation body as force feed-in system and force sensitive element with a high-resolution laser interferometer, [2], [3]. The force to be measured induces a deflection of the parallel quartz spring system. The deflection is measured by the interferometer. The laser illumination is realised by means of monomode fibre optics. So we have the force feed-in system and the sensitive element in one element and no separate spring constants. The spring constant c_{FSEx} is much higher than the spring constant c_{FSEy}.
The deflection y_f in measurement direction is given by:

$$y_f = \frac{F_y \cdot l^3}{2 \cdot E \cdot b \cdot h^3} \tag{6}$$

In equation (6) E represents the Young's modulus of the quartz material, b is the width, h is the thickness and l the length of the quartz leaf springs.
The deflexion in x direction due to F_y can be calculated as follows:

$$x_f = \frac{3 \cdot F_y^2 \cdot l^5}{20 \cdot E^2 \cdot b^2 \cdot h^6} \tag{7}$$

The deflection in x-direction leads to nonlinearity in the spring characteristic which was in the realised sensor less than 10^{-5}.

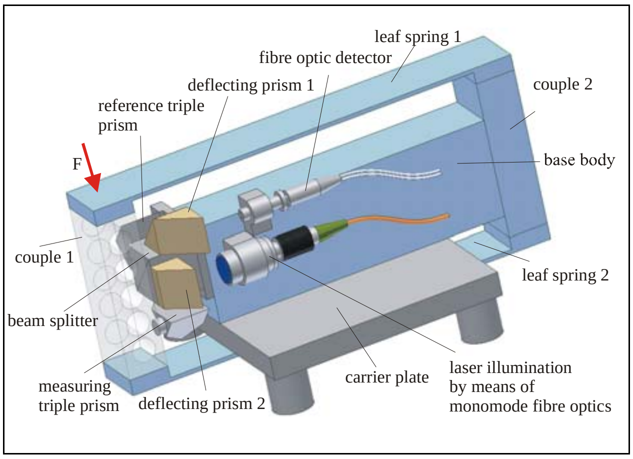

Fig. 5. Interference optical load cell

The laser interferometer is only sensitive in measurement direction. That's why deflections of the parallel spring in x-direction don't directly result in changes of the measurement value M. But there appears a cross coupling effect in case of existing forces F_y and F_x. If the sensor is used for weighing tasks this effect is negligible because of the high stiffness of the parallel spring in x-direction.

The advantage of the interference-optical sensor for force measuring tasks is the possibility of measuring forces in any kind of direction. Cross coupling effects of the gravity force are to be considered in a correction.

The test results obtained with the optical interference weighing cell have shown that it is possible to achieve error limits < 1mg (the corner load error was less than 0.5 mg) by load ranges up to 10 g and measuring times below 0.6 s by applying a well thought-out primary transducer design in combination with a powerful miniature interferometer and an optimized signal processing.

6. CONCLUSIONS

When measuring small forces with low measuring uncertainty it is very important to consider the force feed-in system and the force sensitive element as a complete system. Its metrological properties depend significantly on the several stiffness constants and the quality of the elastic characteristics of the system. The paper shows these relations for three kinds of load cells. The electromagnetic force compensation is able to measure small forces with high accuracy especially in vertical direction. The photo-elastic force sensor has a wide measurement range with high resolution and very good dynamic characteristics. Its problem is the force feed-in system which can be solved by means of a sub scale pan. The interference-optical load cell can measure small forces in any kind of directions with error limits < 1mg (0,01 mN) over a measurement range up to 10g (100 mN). Its measuring time is below 0.6 s.

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