Contactless Torque Sensor Development

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Abstract: This paper presents the development of a contactless torque sensor, which operates on a new principle. The used method is based on the birefringence effect of optically anisotropic materials. Experiments made are similar to the reflective photoelasticity. Instead of conventional photoelastic coating a Perspex tube of thin wall thickness was used. When torque was applied, stress had arisen in the tube, which could be measured optically. The main goal of this study was to create a torque sensor, which could be used in industry too. The paper deals with the theoretical basics, it gives an overview of the development up to now, presents measurement results, shows possible practical realizations for small and large torques, and also proposes possibilities for further developments.

Keywords: optical torque sensor, photoelasticity, birefringence

1. Introduction

Torque sensors are used in many fields, such as research, testing, production and education. The commonly used force and torque sensors apply indirect measuring principle, which means they measure the deformation of an elastic element due to the applied torque. The most common sensing element is strain gauge. This method has some problems, for example it is difficult to pick the signal from the rotating shaft and the friction loss of the slip rings can result in inaccurate measurement. When small torque is to be measured, due to the small dimensions of the elastic element, there can be 20% strain difference between the two ends of the gauge [10].

There are contactless torque sensors too, which operate on optical or magnetic principle. In the commonly used industrial optical torque sensors there are two plates with radial slots between a detector and a LED. One of the plates is mounted to the input shaft, the other one to the output shaft. Applying torque the shafts rotate relative to each other and the gaps will be overlapped. The overlapping is proportional to the applied torque. These sensors are used in vehicles to aid braking and steering [5]. The sensor described in [8] and several rotary optical sensors and transducers [9] operate with similar principle.

Other possibility is described in [1]. Here polar filters are attached to the two ends of the shaft between a detector and a LED. Applied torque changes the angle of polarization between the filters, which changes the intensity of light entering the receiver.

The operational principle of the developed torque sensor is based on the birefringence effect of optically anisotropic materials.

2. Physical principles

When polarized light beam enters into a birefringent material (like glass or several plastics) it splits into two perpendicular beams. The directions of beams are identical to the ones of principal stresses arising in the material due to loading. Since the birefringent materials have different refractive indexes in the principal directions, the velocity of the two light beams will be different, so one will be delayed. This delay is called retardation [2].

At photoelastic experiments the sample to be tested is placed between two polar filters. Assuming that the birefringent sample's width is *b*, strains in the direction of the principal stresses are ε_{b1} and ε_{b2}, retardation *R* can be written in form of

$$R = bK(\varepsilon_{b1} - \varepsilon_{b2}) \tag{1}$$

where *K* is material specific, strain-optical coefficient.

It is experienced that in case of elastic deformation the optical and the mechanical principal directions are the same, on the other hand the phase shift between the two light beams is proportional to the difference between the principal stresses in the birefringent material. This proportionality can be expressed with stress optical coefficient:

$$\mathrm{R} = \frac{\lambda \mathrm{b}}{S}(\sigma_{b1} - \sigma_{b2}). \tag{2}$$

Sometimes it is more convenient to use relative retardation *m* [2]:

$$m = \frac{\mathrm{b}}{\mathrm{S}}(\sigma_{b1} - \sigma_{b2}) = \frac{\mathrm{bE_b}}{\mathrm{S}}(\varepsilon_{b1} - \varepsilon_{b2}). \tag{3}$$

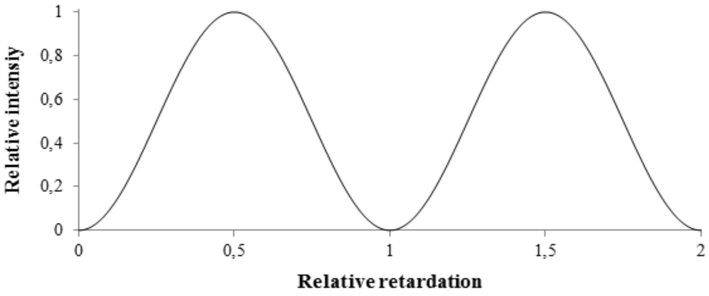

Figure 1. Relative intensity vs. relative retardation

When the birefringent sample is loaded steadily, retardation will change. If this material is examined between perpendicularly polarized polariser and analyser plates, then the image sometimes enlightens, sometimes darkens. The relationship between the relative retardation proportional to the loading and the intensity of light can be expressed with the following equation assuming 45° angle between the plain of polarisation of the polarizer and the first principal optical axis [7] (see in Figure 1).

$$\mathrm{I} = \mathrm{I}_0^2 \sin^2(\mathrm{m}\pi) \tag{4}$$

3. Contactless torque sensor development

3.1. Test equipment and basic calculations

Our test equipment is based on reflective photoelasticity. The shaft to be measured was coated by a photoelastic layer that deformed together with the shaft. When torque was applied to the shaft, stress could be measured by a reflective optical sensor. As photoelastic coating was not available, thin perspex and polyurethane tube was used. Polarizing filters available on the market are too expensive, so the polarizer and the analyzer were taken out of an old calculator display. The sketch of the test equipment is shown in Figure 2.

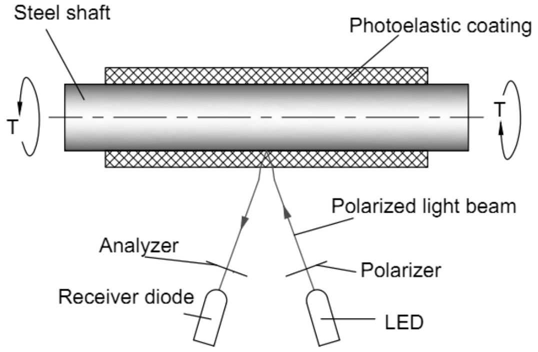

Figure 2. Test equipment

At first the range of measurement of the sensor was calculated using relative retardation. Equation (4) shows how the sample darkens and enlightens due to relative retardation. The function has its maximum at m=0.5, where the first enlightenment occurs.

In case of pure torsion of a shaft of outer radius R, the difference of the principal stresses equals to the diameter of Mohr's circle [4]:

$$\sigma_1 - \sigma_2 = 2\frac{T}{I_p}R \tag{5}$$

The difference of principal strains at the outer radius is [3]:

$$\varepsilon_1 - \varepsilon_2 = 2\frac{T}{I_p E}R \tag{6}$$

The light passes through the coating of width *b* twice, so the relative retardation is:

$$m = \frac{2bE_b}{S}(\varepsilon_{b1} - \varepsilon_{b2}) \tag{7}$$

Assuming that a thin coating does not contribute to torque transmission and adheres perfectly to the shaft, strain at the outer radius of the shaft is equal to that of in the coating. This assumption leads to

$$m = \frac{4bRE_b}{SI_pE}T \tag{8}$$

expression. From equation (8) the maximal torque can be calculated at different relative retardations.

3.2. Test equipment for measuring large scale torque

For measuring large torque Perspex tube as coating was used. The realized test equipment is shown in Figure 3.

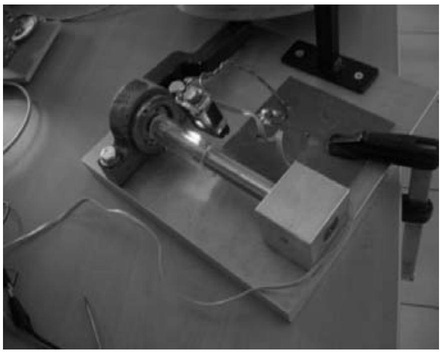

Figure 3. Realized test equipment

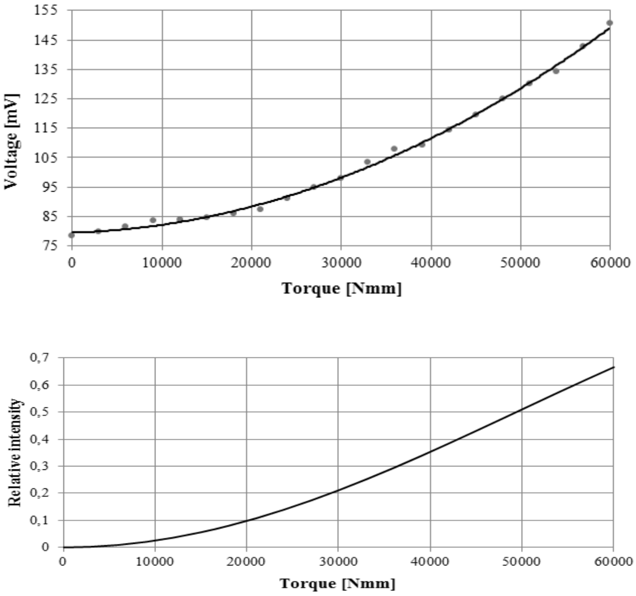

Figure 4: Measured data (up), theoretical diagram (down)

Several experiments were performed. Measured data and the theoretical calculated diagram are shown in Figure 4.

Comparing measured data with the theoretical diagram it can be seen, that the curves are very similar, so the theory was confirmed. Small deviations are due to the disturbing effect of ambient light and the residual stresses in the tube after production.

3.3. Test equipment for measuring small torque

For measuring small torque the metal shaft of high rigidity was omitted and only an elastic tube was used as a measuring and coupling element all in one, as it can be seen in Figure 5 [6].

Several optically active materials were tested. The first experiments were performed with Perspex tube, but it was not suitable for measuring small torque because of its high stress-optical coefficient. Later a Polyurethane tube was used and the experiment proved to be more successful. When torque was changed the output voltage also changed.

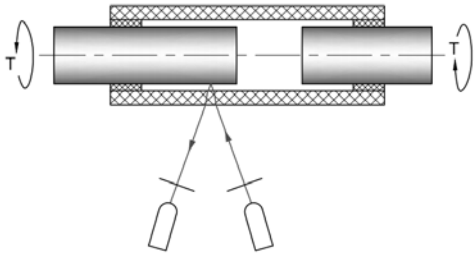

Figure 5. Test equipment for measuring small torque

4. Conclusions and further development

This paper presented a torque sensor operating on a brand new principle based on the birefringence effect of optically anisotropic materials. The experiments confirmed the physical theory and that it can be used for torque measurement. A working test equipment was created. Further investigations are needed to make the sensor more accurate. These developments include using thinner coating, eliminating ambient light with covering or modulation and keeping the optical part in a fixed position with fine mounting. Additionally new experiments are necessary to examine the usability of the principle during high speed rotation and setting a favourable operational point with preload to be able to sense torque direction too.

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