LOW-COST OPTICAL NEURAL-NET TORQUE TRANSDUCER

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ABSTRACT

Torque signals are used today across a broad range of automation applications such as dynomometer test stands and web process lines. Some of the drawbacks to using commercial torque transducers include their cost, reliability, and mechanical stiffness. It is possible to utilize an artificial neural network coupled with the photoelastic effect of many polymers to provide a small, low-cost torque sensor. The availability of low-cost torque sensing opens up many new applications that previously did not cost justify the investment in a commercial torque sensor. The sensor material has a high bandwidth which enables sampling high-frequency torque signals. High frequency torque signals are particularly useful for investigating machinery dynamics and for machinery health assessment.

INTRODUCTION

Torque sensing today is typically done by installing a torque transducer in-line between the prime mover (motor) and driven equipment using conventional couplings at each end. This device, typically costing between $4,000 (USD) and $10,000 (USD), provides a torque signal which is filtered and linearized through a torque transducer amplifier. The resulting torque signal may then be displayed or as typically done, the data is then input to an industrial automation system for closed loop control or used in a laboratory setting as testing instrumentation. These devices are generally not used unless the application specifically requires torque sensing such as for torque feedback control. The deficiencies in conventional torque transducers include the following:

1. High cost
2. Reliability and high-repair costs (typically due to excessive torque applied)
3. Size and space required (transducer size and extra couplings required)
4. Limited bandwidth (generally rated for 500Hz. At best 300Hz typically available)
5. Control system performance (due to inherent torsional compliance of the torque transducer)

Alternative techniques include strain gauges, magneto-strictive devices, and torque calculation from motor current. Issues such as cost, reliability, packaging, complexity, and accuracy limit the usefulness of these alternative torque sensing technologies although developments are occurring in various labs which are directed at eliminating these deficiencies.

The following describes a non-contact, neural net-based, optical torque transducer. This sensor is based on polymeric photo-elastic materials which exhibit a characteristic change in index of refraction as a function of the material strain. When viewed with polarizing filters, birefringence pattern is produced. The birefringence pattern is a function of the material strain, wavelength of light, material thickness, and material strain-optic coefficient. The resultant strain (or micro-strain) and may be determined by using a trained artificial neural network. The trained neural net is

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implemented on a small single board computer integrated with the optics.

This sensor provides low cost torque data, may be embedded in machinery or incorporated in an intelligent coupling, provides high bandwidth (>50kHz), and provides for self-validating operation.

The cost and bandwidth of this device enables it to be deployed in many industrial applications as an effective diagnostic tool. For example, mechanical problems with gear boxes or centrifugal pumps connected to a motor exhibit a high frequency (higher than 300 Hz) torque fluctuation. We may interrogate the frequency spectrum of the torque signal at characteristic frequencies to determine the health of such connected equipment or motor bearings.

DEVICE PRINCIPLE

As a beam of polarized light enters the photo-elastic material the incoming beam is resolved into two orthogonal circularly polarized components. Each component travels through the material with a different velocity. When the beams exit the material the phase-retarded beams are passed through a polarizer (analyzer) to generate a two-dimensional intensity pattern[1]. The intensity pattern represents the relative phase shift between the two beams as shown in Figure 1.

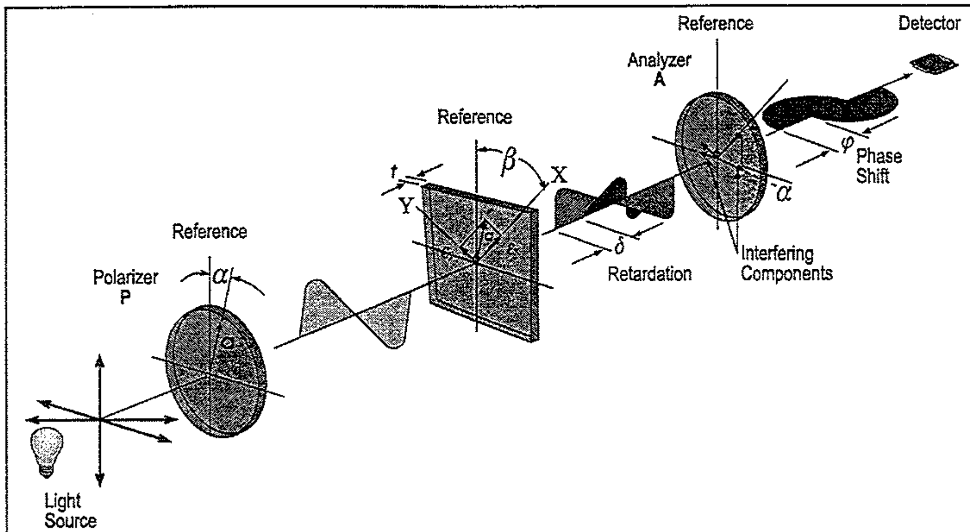

Figure 1
Phase Retardation of a Beam Passing Through a Photoelastic Part

According to Brewster's Law, the relative change in index of refraction is a function of the strain-optic coefficient of the material. The amount of phase shift is a function of the wavelength of light, material thickness, t, strain-optic coefficient, E, and the difference in principal strains, $(\varepsilon_1-\varepsilon_2)$, as shown in Equation 1. The photoelastic effect is typically used in transmission as shown in Figure 1 or in reflection. The relative phase retardation of the beam exiting the photoelastic material is given by δ in Equation 1.

(1) $$\delta = t(n_1-n_2) = tE(\varepsilon_1-\varepsilon_2)$$

Using this relation, the intensity of light, I, exiting the analyzer is given by Equation 2.

[1] Drawing details and demonstration samples provided courtesy of Measurements Group, Inc., Raleigh, NC., USA

(2) $$I = a^2 \sin^2(\pi\delta\lambda)$$

where λ is the optical wavelength. This principle was first observed in the 19th century and has been used for many years to provide a qualitative analysis of the deformation or residual strain in manufactured components. The polymeric material may be cast, machined, extruded, or even sprayed on a part. The interpretation of the fringe pattern typically is done by an expert. Areas of narrow, grouped fringes represent areas of strain concentration. Some of the tools which may help in this analysis include a Polariscope and a hand-held, fringe matching-correlator called a calibrator. These tools may be used to provide a point-wise evaluation of the direction of principal strains or the difference in principal strains.

Since the resulting two-dimensional fringe pattern is quantifiable and reproducible this problem may viewed as a general, 2-dimensional pattern classification problem. Rather than fit the computational model to this geometry and algorithmically compute the part strain we use an artificial neural network as pattern classifier. The computational model requires a ray-tracing technique coupled with a point-wise interpretation of the phase retardation. We have found the artificial neural network to be fast, efficient, and accurate for this pattern matching problem.

We have looked at several supervised learning algorithms and have found the QuickProp[1] to be superior for this application.

SENSOR DESIGN

The sensor design is based on reflection photoelasticity. A polarized light beam is projected onto the surface of the photoelastic component. The reflected beam is then passed through another polarizer and imaged onto a detector (Figure 2). The sampled image intensity values are then input to a neural network where the resulting torque value is computed and either displayed locally or transmitted in digital (RS232) or analog (4-20 ma) form (Figure 3).

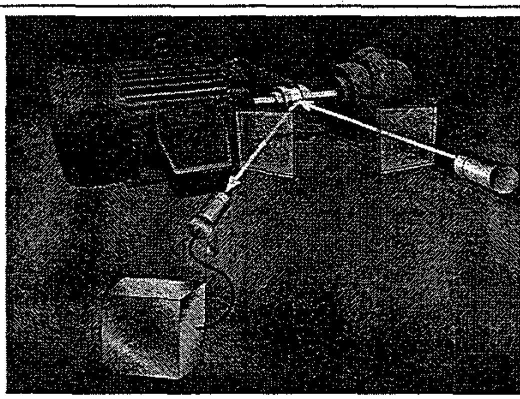

Figure 2
Optical Torque Sensor Integrated with a Motor and Load

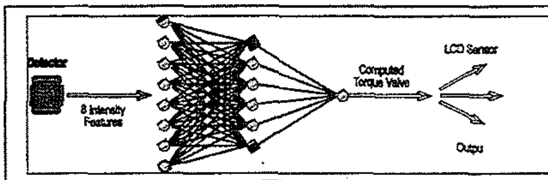

Fig 3
Neural Net Processing to Compute Torque

Fig 4
Torque Sensing Couplings and Fringe Pattern

The designs include a sleeve or collar that skips over the shaft of machinery or a coupling insert that provides speed and torque information. The inside, reflective surface is coated with an aluminum-

[1] S. E. Fahlman, *Faster Learning Variations on Back Propagation: An Empirical Study*, Proceedings of the 1988 Connectionist Models Summer School, San Mateo, CA, USA, Morgan Kaurmann Publishers, 1988

filled epoxy. The reflected light beam is imaged onto a linear detector array and the results from the A/D process is input to an artificial neural network. The QuickPropagation technique for supervised learning was used for this sensor since it provided good accuracy and a short training time[1]. The neural net processor is implemented on a single board computer and is integrated with optics, power supply, local display, and communications as shown in Figure 5.

The sensor design and neural net processing scheme provides for both steady-state torque computation as well as for high-speed, dynamic torque calculation. At present the image acquisition is synchronized with shaft position using a single bit trigger. An axi-symmetric sleeve or coupling will permit the random and high frequency sampling of fringe patterns.

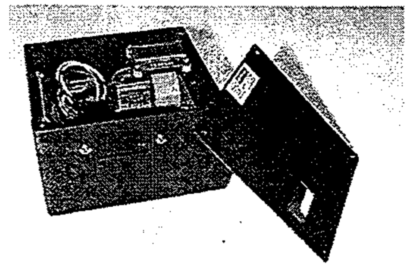

Figure 5
Integrated Neural Net, Optics, Display, and Communications

DEVICE APPLICATION AND BENEFITS

The optical neural net torque sensor provides a capability for torque feedback control for applications which are not pursued today. The specific advantages that make this device well suited for control applications include low cost, transducer stiffness (e.g. as a sleeve-mounted device), and reliability. These benefits are summarized in Table I below. We anticipate this device will provide equal or enhanced capability over conventional torque transducers at less than 1/10 the cost. Both the optical neural net torque transducer and conventional torque transducer are shown in Figure 6 (left side and right side respectively). As seen from this figure the proposed sensor requires a smaller footprint and eliminates a coupling. In addition, the compact size of the transducer permits mounting in the bell housing of a gear box or a pump to provide real-time information on input power. This capability is presently not available with commercial torque transducers today.

TABLE I

Summary of Sensor Benefits

- Low Cost (10-100x lower)
- Reliable
- Non-contact
- High Bandwidth (>10x)
- Small size
- Eliminates coupling
- Embeddable in products

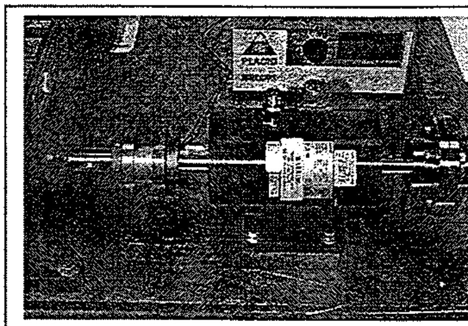

Figure 6
Commercial Torque Transducer and Neural Net Torque Sensing Coupling

CONCLUSIONS

Embedded intelligence coupled with photoelastic material properties, has enabled an optical neural net torque transducer which provides unprecedented capabilities for low cost, non-intrusive, high-bandwidth torque sensing. These capabilities provide new opportunities for torque sensing for control and machinery diagnostics. In addition, the foundation elements of this device which include embedded intelligence, material properties, adaptive pattern matching, and integrated optics are applicable across a broad range of sensors and intelligent actuators. These fundamental building blocks are expected to be the cornerstone of many future intelligent and self-validating sensors.

[1] D. Chung, F. L. Merat, F. M. Discenzo, J. S. Harris, Neural net based torque sensor using birefringent materials, Sensors and Actuators, A 70, 1998, pp. 243-249

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