STIFF TORQUE TRANSDUCER WITH HIGH OVERLOAD CAPABILITY AND DIRECT FREQUENCY OUTPUT

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ABSTRACT

A new torque transducer with high overload capability and direct frequency output is reported. It employs the recently developed metallic triple-beam resonators with thick-film printed lead zirconate titanate (PZT) drive and pickup elements. The new torque transducer has been tested in a torque range of up to 20 Nm, resulting in a strain level of 400 microstrain on the measurement shaft surface and giving a large frequency-change output of 800 Hz. The strain level required by the new torque transducer can be much lower (~100 microstrain) than the level (~1800 microstrain) usually required by conventional metallic resistance-strain-gauge-based torque transducers, thus increasing the transducer overload capability by a large factor. Nevertheless, under such a low strain level, the new torque transducer can still output an adequately large frequency change of 200 Hz for measurement. Having a large overload capability is very important in many torque measurement applications where rapid and large overloads can occur.

1. INTRODUCTION

For many years metallic resistance strain gauges have been used as the principal sensors for measuring torque on a shaft. To obtain a measurable output signal (up to about 30 mV before further amplification), surface strain is usually designed to approach the elastic proportional limit (up to about 1800 microstrain) of the sensing structure. For this reason torque transducers based on metallic resistance strain gauges can seldom withstand overloads of more than double the rated full-range torque [1]. In addition to the disadvantage of small signal outputs, the mounting of strain gauges is normally labour intensive.

This paper presents details of a new torque transducer with high overload capability and large frequency-change output, requiring relatively low strains on the sensing structure. The new torque transducer uses the recently developed metallic resonant digital strain gauges. They are double-ended triple-beam tuning fork resonators with thick-film printed lead zirconate titanate (PZT) drive and pickup elements [2-4].

2. METALLIC RESONATOR

Figure 1 shows a photograph of the metallic resonator. The resonator substrate is photochemically etched from 430S17 stainless steel sheet. Thick-film piezoelectric elements are screen-printed onto all of the three tines at each end to achieve a balanced structure, but in this work only the PZT elements on the central tine are used for driving and detecting the tuning fork resonance. The overall length of the device is 40.5 mm, including a mounting pad at each end. The resonator itself is 23.5 mm long, 0.25 mm thick, 2 mm wide for central tine and 1 mm wide for outer tines. When the resonator is subjected to a tensile force, its natural frequencies change. The differential resonance mode of resonator is used for measurement: the central tine oscillates in anti-phase with the outer tines. The resonator can be attached to a sensing structure using adhesives or by spot welding. A new design of the resonator has incorporated a mounting hole at each end to allow mounting by bolts [5].

Figure 2 shows the resonant frequency of the resonator operating in air, measured in an open loop by using a HP 89410A Vector Signal Analyser. The PZT element at one end of the resonator was driven by an AC signal of 1V peak-peak from the Signal Analyser with the tracking generator scanning over a frequency range covering the resonant frequency. The PZT element on the other end of the resonator was connected to a Kistler 5011 Charge Amplifier and the output from the charge amplifier was fed back to the signal analyser for frequency response analysis of the resonator. The Q-factor of the resonator was calculated to be 4100, which is very favourable when compared to the Q-factors of other metallic resonators [6-8]. A high Q-factor implies low losses of the vibration energy from the resonator to the external structure and hence low power requirements for maintaining the resonance. A resonator acts as an electromechanical band-pass filter rejecting both mechanical and electrical noise at frequencies outside its resonant bandwidth. A high Q-factor thus means good stability of operation. A high Q-factor is also important as it allows better identification of the resonant frequency and, results in a high resolution for measurement.

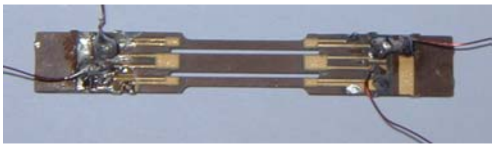

Figure 1: Metallic triple-beam tuning-fork resonator.

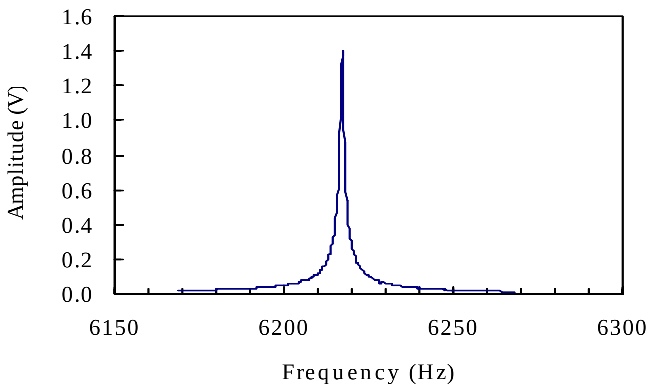

Figure 2: Resonant frequency of resonator.

A feedback closed-loop electronic circuit has been designed to maintain the resonator in resonance while loads are applied, resulting in changes in its resonant frequency. The circuit consists of a phase-locked-loop (PLL) chip, with its signal input from one of the thick-film PZT elements as pickup and its voltage-controlled-oscillator (VCO) output being phase shifted to drive the other thick-film PZT element. The circuit outputs a digital frequency signal for measurement.

3. TORQUE TRANSDUCER DESIGN

Figure 3 shows a photograph of the torque transducer with resonators. The torsion shaft is machined from 17-4PH stainless steel and has an overall length of 131.6 mm. The middle section of the shaft for torque measurement has a diameter of 15 mm; the outer shoulders are 35 mm × 35 mm square with width 12 mm. Two resonators are spot-welded onto the outer shoulders at ±45° relative to the neutral axis of the shaft (one on either side). The resonators are therefore set perpendicular to each other.

When a torque is applied to the shaft the maximum or principal shear stresses exist at 45° to the neutral axis of the shaft. These stresses are compressive in one direction and tensile in the other direction and they have equal values. The resonators are mounted along the tensile direction for the specified torque direction. If the torque is to be measured for both clockwise and anticlockwise directions, the resonators will need to be mounted with pre-tension in one direction, so as to keep the resonators still in tension when the torque is applied from the other direction. The torque transducer presented here measures one directional torque and the resonators have been mounted without pre-tension.

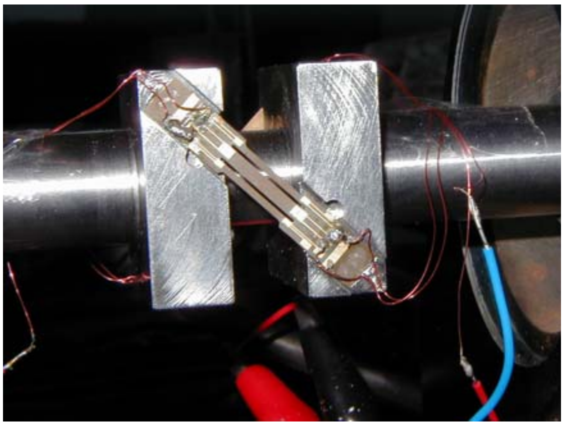

Figure 3: Design of torque transducer.

4. TEST RESULTS

Figure 4 shows the response of the torque transducer from one of the resonators for torques up to 20 Nm. The torque transducer was loaded and unloaded with 2 Nm torque steps for 5 cycles of operation. The sensitivity of one resonator to torque has been measured to be 28 Hz/Nm, and the other resonator showed a sensitivity of 40 Hz/Nm. Table 1 summarises the typical characteristics of the torque transducer from the resonator with highest sensitivity.

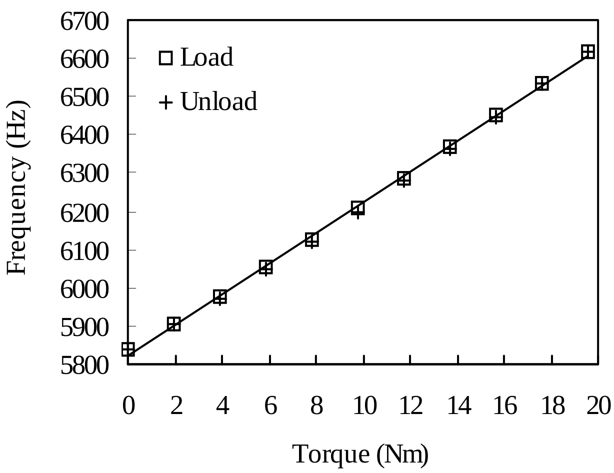

Figure 4: Response of torque transducer.

The strain level calculated on the shaft surface for the measurement section under an applied torque of 20 Nm and without resonators attached is about 400 microstrain. This strain is far less than the level of 1800 microstrain usually required for torque transducers based on metallic resistance strain gauges. Nevertheless, under such a relatively low strain level, the new torque transducer gives a large frequency-change output of 800 Hz, showing a high sensitivity. If the same shaft is subjected to a reduced torque range of 5 Nm, an even lower strain level of 100 microstrain will occur on the shaft surface in the measurement section, and the new torque transducer will still output an adequately large frequency change of 200 Hz. The overload capability of the new torque transducer will be much greater than that of a conventional resistance strain-gauge-based torque transducer by a factor of 18. This is a major advantage for many torque measurement applications where large static and dynamic overload capability is required.

Table 1: Characteristics of experimented torque transducer.

Initial frequency	5837 Hz
Sensitivity	40 Hz/Nm
Applied torque range	0-20 Nm
Stability (at 10 Nm for 30 minutes)	0.03%
Repeatability	0.1%
Hysteresis	1.2%
Non -linearity	2.1%

The temperature coefficients of the resonators mounted in the torque transducer have been evaluated in a limited temperature range from 23 ^{o}C to 29 ^{o}C. The test room was heated up to a temperature of 28.5 ^{o}C, and then cooled down naturally to a temperature of 23.8 ^{o}C. Both frequencies and temperatures were recorded at the same time as the room was cooled down. One resonator showed a temperature coefficient of -2.76 Hz/^{o}C, and the other resonator showed a temperature coefficient of -1.27 Hz/^{o}C.

5. CONCLUSIONS

This paper has presented the use of thick-film PZT printed metallic triple-beam resonators to design a torque transducer with high overload capability and a large frequency-change output. The advantages of this new sensing technology are as follows: resonant frequency output compatible with digital microelectronics; high Q-factor for high stability and high resolution measurement; low strain level requirement for high overload capability applications; high sensitivity and low-cost manufacture. The experimented torque transducer has shown a sensitivity of 40 Hz/Nm in a torque range of up to 20 Nm. The strain level on the surface of the measurement torsion shaft is about 400 microstrain, which is much lower than the level (~1800 microstrain) usually required if using metallic resistance strain gauges. There is a great potential for the new torque transducer to work at even lower strain levels, say 100 microstrain with an increased large overload capability and an adequately large frequency-change output of 200 Hz. The new sensing technology has also been used to design a stiff load cell for potential silo weighing applications [9].

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The new resonant sensors and transducers are the subject of international patent applications invested in a universities' spinout company.

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