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CAPACITIVE SENSOR FOR TORQUE MEASUREMENT

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Abstract: Based on acapacitive angle/angular speed sensor a sensor measuring the torque on a rotating shaft has been developed. The torsion resulting from the torque on the shaft is measured by two rotatable electro desplaced between two sensor plates. The relative angle between the two rotors is calculated from measurements of the capacitive coupling between different transmitting stator segments. A prototype of this sensor has been developed with a range of the torque of ±2 Nm with a measurement error of 0.04 Nm and a resolution of 0.02 Nm.
Keywords: capacitive torque sensor, relative angle measurement

1 INTRODUCTION

Measuring the torque on rotating shafts is important for controlling rotating mechanical systems. A common method for torque measurement is measuring the torsion with a strain gauge bridge. A recently developed sensor type is a contactless magnetoelastic torque sensor. Our prototype uses the capacitive angle/angular speed sensor principle described in [BRA92], [BRA93] [FAB97] and [FAB98]. The principles of capacitive measurement and ratiometric calculation provide the advantage of robustness towards environmental influences.

2 WORKING PRINCIPLE

In order to measure the torsion angle resulting from the torque transmitted by a rotating shaft, we have modified the capacitive angle/angular speed sensor by mounting two asymmetric rotors on two concentric shafts between the sensor stators. Both grounded rotors realise a single effective rotor with a variable geometry, depending on the relative angle between the rotating shafts. These modifications extend the abilities of the sensor to measure the absolute angle (360°-range) and the angular velocity of the effective rotor with the ability to measure the difference–angle between the two rotors. Figure 1 shows a typical mechanical construction for converting the torsion on as haft in to an angle between The two rotors. The torsion shaft carrying one rotor is mounted concentrically in a hollow and stiff shaft Carrying the second rotor. From the measured torsion angle and the length and the G-modulus of the shaft the transmitted torque is calculated using Hooke's Law.

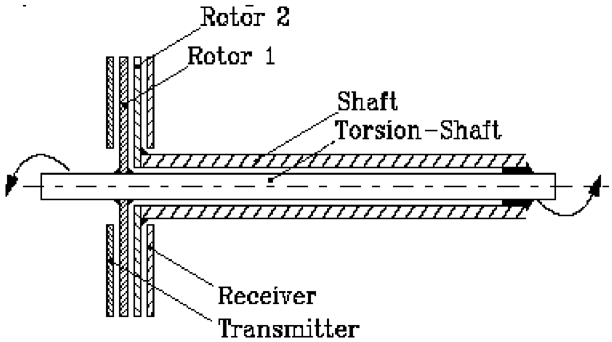
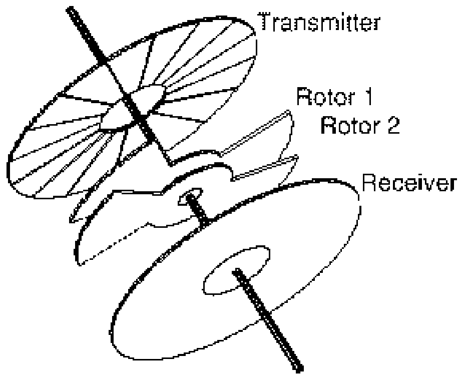


Figure 1. Mechanical construction for applying the torsion to the Rotors of the relative angle sensor

Figure 2 shows the electrode structure of the capacitive sensor. One stator plate is used as transmitter with 16 transmitting segments with centre angles of 22.5°, the other stator contains the receiving ring electrode. Two rotors with a symmetrically arranged blades with a centre angle of 60°

(Figure 2) are mounted mirror-symmetrically on two concentric shafts as shown in Figure 1. The shafts electrically connect the conductive rotors to ground potential. The zero position of the relative angle is defined for overlapping rotors building two blades with centre angles of 75° and 105°. From this asymmetrical geometry results the ability to determine the direction of the torsion or the sign of the torque, respectively, and the maximum range of the difference angle of ±15°. As the applied torque changes the angle between the rotors, the electrical effective size of the rotor blades is changed. These changes influence the capacitive coupling between the transmitting segments and the receiving electrode. In one measurement cycle a pulse sequence is applied to each segment. Depending on the rotor position and the effective size of the rotor the received signals change for each segment. By applying a ratiometric algorithm to the received signals, the signed relative angle between the rotors is calculated.



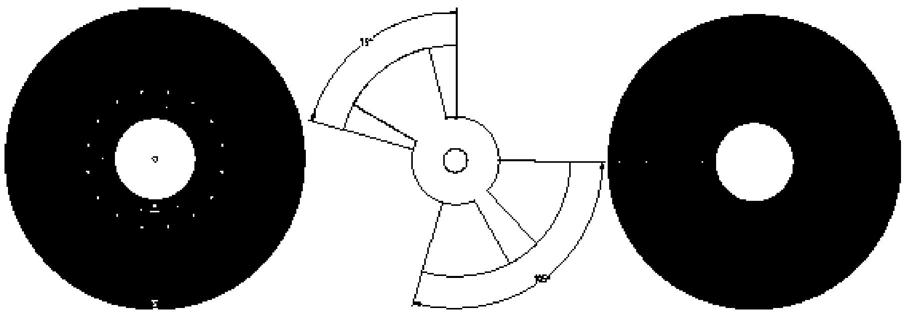


Figure 2. Sensor topology of a capacitive relative angle sensor, transmitter plate with 16 segments, two mirror-symmetrical rotors, receiving electrode.

3 ELECTRICAL CIRCUIT AND SIGNAL CONDITIONING

Figure 3 shows a block diagram of the sensor electronic. A segment driver applies the pulse sequence with a carrier frequency of 15 MHz to the transmitter segments. The receiver electronic consists of an input resonant circuit with a resonance frequency tuned to the carrier frequency as a low noise bandfilter, followed by two amplifier, bandfilter and a electric rectifier unit. The conditioned DC-signal is fed into the analogue digital converter of the microprocessor over a low pass filter. Each measurement cycle results in an array of 16 segment values (SV). Further details to the signal conditioning circuits are given in [WAN99].

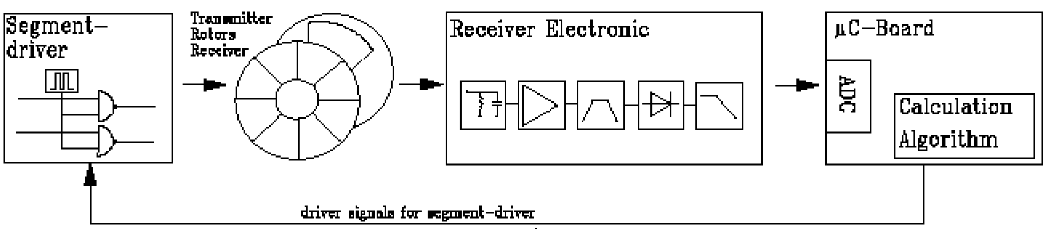


Figure 3. Blockdiagram of the torque sensor electronic.

4 ALGORITHM FOR THE RELATIVE ANGLE MEASUREMENT

Figure 4 shows the schematic geometry of the electrode-rotor configuration for a symmetric configuration of the rotors. The grounded effective rotor blades shadow the signals from the transmitting electrodes above them from the receiver electrode. A torsion applied to the shaft results in an enlargement of the rotor-shadow RS1 and a reduction of the rotor-shadow RS2, respectively, depending on the direction of the torsion. According to these changes the sum of the segment values SV1 to SV8 decreases and the sum of SV9 to SV16 increases proportional to the relative angle, respectively. The segment values of completely shadowed and completely free segments are not influenced by the rotordisplacement, which is a necessary condition to apply the ratiometric algorithm. The relative angle between the rotors is calculated by evaluating the expression

$$relative\ angle = \frac{\sum_{i=1}^{8}(SV_i) + \sum_{i=9}^{16}(SV_i) +}{2\cdot(SV_1+SV_8+SV_9+SV_{16}) - 2\cdot(SV_4+SV_5+SV_{12}+SV_{13})}\cdot 180°$$

In practice the reference value, i.e. the difference-term in the denominator expression, is not constant and a calibration is necessary, therefore, which is effective after a full turn of the resulting rotor. The middle position of the effective rotor is not influenced by the relative displacement x_{rel} (Fig. 4).

To determine the direction of the torsion an asymmetry in the rotor geometry is introduced, as shown in Fig. 2. This asymmetry does not change the evaluation principle. To calculate the relative angle from the expression shown above it is necessary to know the absolute position of the resulting rotor, to choose the right segment values for calculating the relative angle. Therefore a second algorithm is used to roughly determine the absolute position of the rotor with a resolution of one segment width (22.5° for a 16 segment transmitter). This rough positioning algorithm calculates the convolution of the measured segment values with a set of values defined as the zero-position. The maximum of the result gives the offset of the actual rotor position to the defined zero-position.

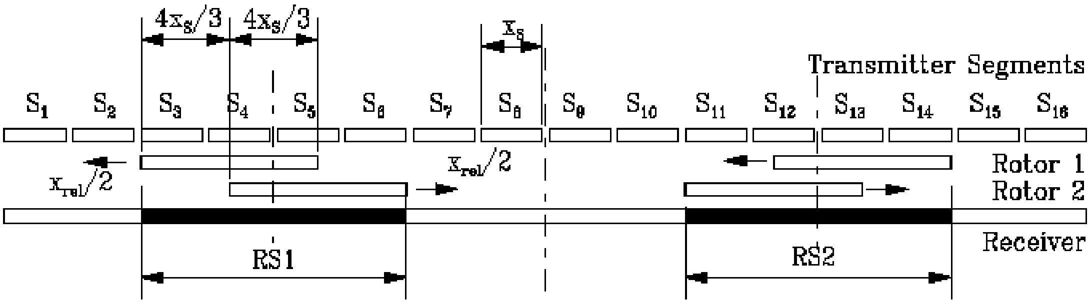


Figure 4. Schematic geometry of the sensor.

5 EXPERIMENTAL RESULTS

Several sensor prototypes using the described topology and two further topologies have been built. The sensors have been evaluated using a test rig with a driving stepper motor with an optical reference angle sensor on one shaft. The second shaft was rotated with respect to the first one by an angular positioning unit with a resolution of (1/60)°, to simulate a torsion of the shaft. The stepper motor was actuated in microstep-mode. A personal computer controlled the stepper motor and processed the signals of the sensor prototypes and the reference sensor.

First measurement showed, that the described rotor structure is very sensible to radial displacements of the rotor. Therefore we introduced a 180°-symmetry, and reduced the measurement range of the absolute angle to 180° and the range of the relative angle to ± 7.5°. The new structure uses 32 transmitting segments with centre angles of 11.25° and rotors with four blades with centre angles of 30°. Each segment is electrically connected to its mirror segment producing 16 segment values for each measurement cycle. Using this new topology almost eliminates the problem of radial offset, as discussed in [ZDIA99].

The third topology we have tested is a mechanical negation of the topology explained before, and is called „inverse topology“. In this inverse topology covered and free segments changes, means that now the shadow area is constant, whereas the free segment area is proportional to the torsion applied to the rotors.

For the prototype with inverse topology we measured the relative angle between the two shafts in the range of ±5° with an error of ±0.1° after calibration. Because of the new topology only a half rotation (180°) of the resulting rotor is necessary to get good calibration results.

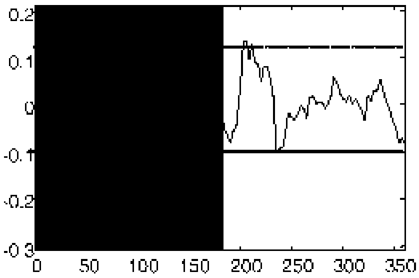


Figure 5. relative angle error versus absolute position

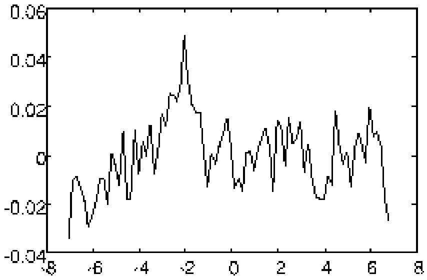


Figure 6. relative angle error versus relative angle range

Figure 5 shows the measurement error of the relative angle versus the absolute rotation angle. The first 180° are used to calibrate the sensor (shaded area in Fig. 5), the resulting error of the calibrated sensor is ±0.1°. Figure 6 shows the error of the relative angle versus the relative angle.

Depending on the torsion shaft used for the torque-measurement the relative angle range can be transformed in a torque range. When using a normal steel shaft, with a shear modulus of 80.000 N/mm^2, an effective length of 200mm and a diameter of 5mm the torque range is ±2 Nm. This is approximately the range of torque needed for automotive power steering.

6 CONCLUSION

The developed prototype is a contactless torque sensors for rotating shafts, measuring the torque in mechanical systems in harsh environments, using the advantages of capacitive measurement. Future developments will concentrate in increasing the resolution of the torque measurement. The dynamical performance of the sensor will be evaluated.

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