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Design studies and testing of a torque transducer

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Torque being a very important physical parameter, plays a very vital role in various applications like aviation, automobile, power and agriculture industries. Torque is, generally, measured by mechanical type torque meters/torque wrenches, having higher uncertainty. These mechanical type torque meters/torque wrenches need to be calibrated using strain gauged torque transducers. Hence, there is acute thrust over development of precise and reliable strain gauge based torque transducers. In the present work, a torque transducer of capacity 5 Nm has been studied. The torque transducer has been metrologically characterized against the standard torque machine (bmc = ±0.05% at k = 2) using the standard calibration procedure based on standard BS 7882:2008. The uncertainty of measurement of the torque transducer is ± 0.06% (at k = 2).

Keywords: Torque transducer, Strain gauges, Finite element analysis

1 Introduction

In the recent few years, there has been continuous increasing demand for measurement of torque more precisely with low uncertainty. Some efforts have been made to develop more precise and reliable torque transducers which may reproduce results with stability[1-3]. Design studies of torque transducers under influence of external torque is very important in optimization of their design for various engineering applications. Generally, some assumptions and approximations are made for deriving analytical expressions measurement of shear stress/strain under influence of external torque. For a more rigorous validation of analytical method, finite element analysis needs to be used. A torque transducer of capacity 5 Nm has been designed using analytical and finite element analysis. The torque transducer has been characterized metrologically according to the standard calibration procedure based on BS 7882: 2008. The torque transducer is found to have a relative repeatability, relative reproducibility, relative interpolation error and relative zero error have been found to be ±0.02%, ±0.04%, ±0.02% and ±0.01%, respectively. The expanded uncertainty associated with the torque transducer is found to be ± 0.06% (at k=2), taking into account the cmc of the standard torque machine ±0.05% (k=2) in controlled atmosphere having temperature (23±1)°C and relative humidity[4-7] (50±10) %.

2 Design Studies

The torque transducers, generally, made of steel alloy, are manufactured by machining of given element. But, in the present study, the torque transducer has been made of high strength aluminium alloy due to low capacity of the torque transducer. The sensing element, a solid square element, undergoes elastic deformation under influence of external torque and the deformation is sensed by the strain gauges mounted in preset manner over it. The following analytical derived expression (according to St. Venant's investigation) gives the relationship between the torque and the shear stress induced for the rectangular cross-section[8].

$$T = x^2 y^2 \tau / (3y + 1.8\,x) \qquad \ldots (1)$$

where τ is the shear stress induced due to the applied torque, T, x and y are longer and smaller side of the rectangular cross-section, respectively, for a square section, $x = y$

$$T = 0.208\,x^3 \tau \qquad \ldots (2)$$

Design of torque sensing element involves determining the dimensions of the sensing element and checking for the shear stress induced due to applied torque. The maximum value of the shear stress occurs at the middle point of a side.

Analytically, shear stress induced in the torque transducer is 24.04 MPa, whereas the shear strain induced is 58.65×10^{-4} due to 5 Nm torque applied.

3 Finite Element Model and Analysis

The torque transducers are designed on the basis of certain theories and assumptions to derive expressions for measurement of stress/strain under external torque. But, analytical expressions may not be consistent with the experimental observations. Hence, for more rigorous validation of analytical derived expressions, finite element analysis may be used. A three dimensional model of the torque transducer has been generated using Pro-E wildfire software 2.0 (Fig. 1) and exported to Ansys workbench 10.0 software. Suitable boundary conditions, constraints have been applied and procedure for finite element analysis of the torque transducer has been adopted. The finite element analysis has been done using the Ansys workbench 10.0 software.

The finite element analysis has elaborated the following facts:

- The Stress distribution under external torque indicates that the shear stress is maximum at the middle point of any side of the sensing element and it tends to decrease as move in either direction (Fig. 2). The shear stress values are within the limits and safe for application of torque desired. The shear stress induced due to 5 Nm torque applied is found to be 25.84 MPa using finite element analysis.
- The strain distribution follows the similar trend to the shear stress distribution (Fig. 3). The shear strain induced due to 5 Nm torque applied is found to be 63.04×10^{-4} using finite element analysis.

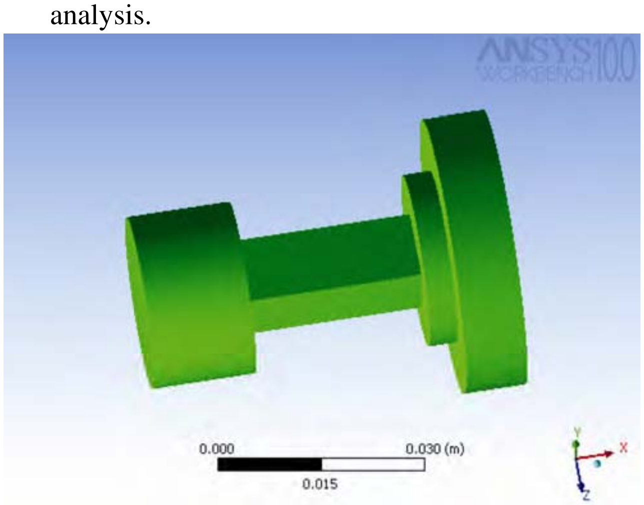

Fig. 1 — Dimensional model of torque sensor

The shear stress/strain distribution studies results the location of high stress/strain zones, suitable for fixing the strain gauges.

4 Strain Gauges Implantation

The strain gauges have been used to measure the stress/strain induced in the torque transducer, when the external torque is applied. The machined element is normalized by applying the maximum torque to the torque transducer. The surface is properly cleaned and has to be dirt free for effective fixing of the strain gauge. Strain gauges are fixed using a suitably curing adhesive at an angle of 45° as is evident from finite element analysis of the torque transducer from the horizontal axis of the sensing element. Proper curing and post curing of the strain gauges have been done. The connections are made according to the Wheatstone bridge configuration to nullify/compensate the temperature effect cased by sensing element.

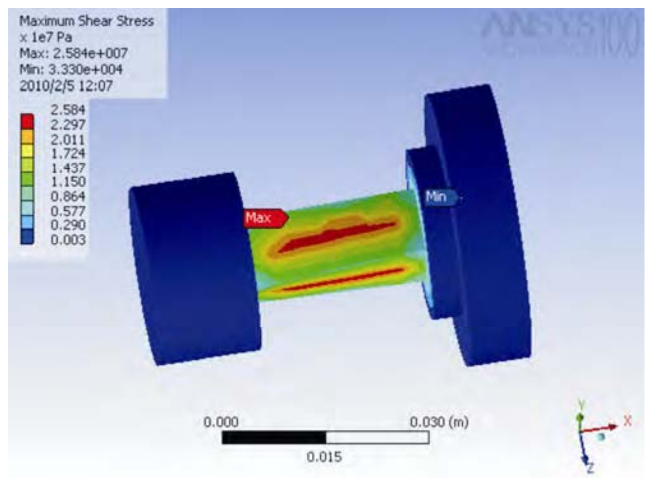

Fig. 2 — Shear stress distribution

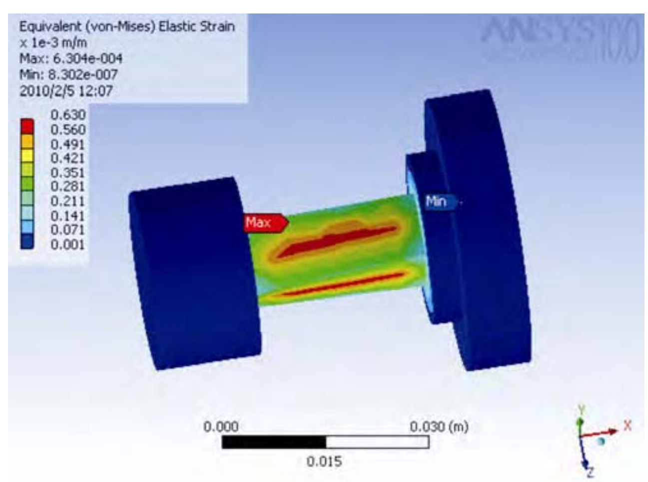

Fig. 3 — Shear strain distribution

However, any change in the torque would cause an unbalance in the Wheatstone bridge circuit which is proportional to the applied torque[9]. The ratio of output voltage (e_0) to input voltage (E_1) can be expressed as:

$$E_0/E_1 = (K/4)*(\varepsilon_1-\varepsilon_2+\varepsilon_3-\varepsilon_4)$$

where K is the gauge factor and it depends upon the strain gauge used and ε is the strain.

5 Metrological Characterization

The torque transducer has been metrologically characterized against the standard torque machine according to a calibration procedure based on the standard BS 7882:2008 under the controlled atmosphere having temperature (23±1)°C and relative humidity (50±.10)%. The calibration procedure is as follows:

- Preload the torque transducer three times to the maximum torque applied torque. Maintain each preload for a period of about 90s.
- Apply two series of increasing torques to the torque transducer without change of the mounting position. The indicator reading may be tarred to zero at the beginning of each measurement.
- Record the readings of the indicator with zero torque applied to the torque transducer before and after each series of torque application. having temperature (23±1)°C and relative humidity (50±.10)%
- The torque transducer is calibrated at two different mounting positions at least 90° apart like 90°/180°/270° etc. The torque transducer should be preloaded once at each different mounting position before recording the indicator readings for series of increasing torque.
- Relative repeatability $(R_1) = (d_1 - d_2)\times100/d_{m1}$
  where d_{m1} is the mean reading for a given torque and d_1, d_2 are the readings in series 1 and 2, respectively.
- Relative reproducibility $(R_2) = (d_{max} - d_{min})\times100/d_{m2}$
  where d_{max} and d_{min} are the maximum and minimum reading of all series, respectively and d_{m2} is the mean of all series.
- Relative error of interpolation (E_{it}) should be calculated in cases where the reading is not measured in units of torque. It should be computed using best fit for first/second/third order polynomial equation.
- Relative zero error $(R_0) = d_{0max}\times100/d_{R2max}$
  d_{0max} is the maximum zero error and d_{R2max} is the mean reading at the maximum applied torque.

The over all uncertainty associated with the torque transducer is calculated considering the relative repeatability, relative reproducibility, relative interpolation error, relative resolution error and relative zero error, combining with the uncertainty of the applied torque u_1 (cmc of the torque machine) of ± 0.05% (k=2) (Table 1).

The overall estimated uncertainty associated with the torque transducer is found to be ± 0.06% (at k=2) (Fig. 4).

Table1 — Different factors contributing to uncertainty of torque transducer

Quantity X_i	Estimates x_i %	Limits Δx_i±%	Probability distribution Type A (or) B Factor	Sensitivity coefficient c_i	Uncertainty contribution $u_i(y)$ %	Degrees of freedom
f_o	6.7×10^{-3}	3.35×10^{-3}	Rectangular Type B 1.732	1	1.934 × 10^{-3}	∞
b	2.23× 10^{-2}	1.115×10^{-2}	Rectangular Type B 1.732	1	6.437 ×10^{-3}	∞
c	4.46×10^{-2}	2.23x10^{-2}	U Type B 1.414	1	1.577×10^{-2}	∞
f_r	1.12× 10^{-2}	5.60×10^{-3}	Rectangular Type B 1.732	1	3.223×10^{-3}	∞
f_c	1.59× 10^{-2}	7.95×10^{-3}	Triangular Type B 2.45	1	3.244×10^{-3}	∞
w_{bmc}	5.0×10^{-2}	2.5×10^{-2}	Normal Type B 2	1	1.25×10^{-2}	∞
Combined Uncertainty u_c					0.03%	∞
Effective Degrees of freedom						∞
Expanded Uncertainty at k=2					0.06%	

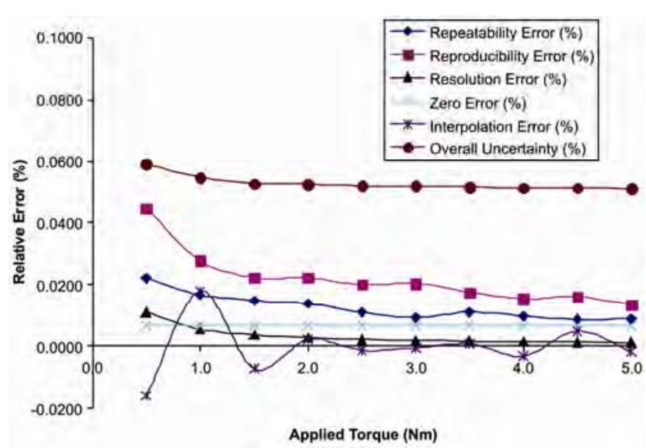

Fig. 4 — Metrological characterization of torque transducer

6 Results and Discussion

The torque transducer made of high strength aluminium alloy for capacity 5 Nm has been designed using analytical method and verified using the finite element analysis also. The values of shear stress/strain computed using analytical method and the finite element analysis are found to be close. The metrological characterization of the torque transducer has been done using the standard calibration procedure based on standard BS 7882:2008, using the standard torque machine with cmc of ±0.05% (at k=2) and the expanded uncertainty is found to be ±0.06% (at k=2) including the relative error due to repeatability, reproducibility, interpolation, resolution and zero error.

7 Conclusions

The present work signifies the design studies of torque transducer of capacity up to 5 Nm and role of finite element analysis in the design of the torque transducers. Values of the shear stress and shear strain are found to be closer as computed from analytical expressions as well as in the case of the finite element analysis. The finite element analysis also locates the locations for fixing the strain gauges. The metrological characterization of the torque transducer has yielded good results in terms of its uncertainty, which is ± 0.06% (at k = 2). Further work is in progress to develop the torque transducers of other nominal capacities and will be reported soon.

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