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Development and Testing of Ring Shaped Force Transducers

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The present paper discusses the development of ring shaped force transducers. The force transducers developed have been designed on the basis of thin rings. The force transducers are developed for the nominal capacity of 100 N and in this range the ring shaped force transducers are generally not available. Hence, effort has been done for developing precision force transducers of ring shape due to simplicity of shape and ease of manufacturing. The force transducers have been calibrated according to the calibration procedure based on IS 4169-1988 (reaffirmed 2003). The uncertainty of measurement for the force transducers developed has been evaluated while taking the uncertainty components due to relative repeatability, relative interpolation, and relative zero offset etc. The results have been reported here. The approach adopted may further be extended to develop the force transducers of similar shape for lower capacity like 10N, 20 N & 50 N for future research work.

Keywords: force transducer, deflection, castigliano's theorem, curved bars

Introduction

The force transducers are commonly used in various engineering applications. The applications may be like weighing scales, verification of material testing machines, thrust measurement of rockets etc. Wide ranges of force transducers are available in the capacities ranging form newtons to mega newtons depending upon the suitability. The force transducers were first developed in 1927 at National Bureau of Standards (NBS), USA (now called as National Institute of Standards and Technology, NIST). It consists of an elastic ring and a deflection measuring device like micrometer / vibrating reed or dial gauge. It uses to be called as proving ring commonly. Such types of instruments are still used, but with the development of strain gauges, in 1960s, strain gauged force transducers are developed and now dominating the arena. Though a number of different type and shapes of force transducers are developed, but ring shaped force transducers are very common due to ease in manufacturing and design. A number of researchers have worked in past for design and development related issues of ring shaped force transducers and fewer have even suggested and developed suitable modified ring shaped force transducers, though they might be suitable to certain limited applications as described and may have poor accuracy[1,2,3].

The aim of the present research has been to develop force transducers of 100 N and suitable for static force measurement and may be used as force transfer standard. Hence, due to very low capacity of force transducer, thin ring shaped force transducers have been selected and suitable assumptions have been made during the design studies. The dimensions have been determined suitably for the force transducer and it has been studied metrologically on the basis of calibration procedure according to standard IS 4169-1988 (reaffirmed 2003). The uncertainty of measurement of force transducer includes the uncertainty components due to relative repeatability, relative zero offset and relative interpolation etc.[4, 5].

Symbols

b	Width of the cross section of ring (mm)
t	Thickness of cross section of ring (mm)
R	Mean radius (mm)
F	Applied force (N)
E	Young's modulus of elasticity (N/m^2)
I	Moment of area (m^4)
M	Moment due to force at any position, say x (N.m)
θ	Angle of segment of ring (radian)
δ	Deflection of the ring (mm)
σ	Stress (N/m^2)
h	Shape factor for curved bars
W	Overall uncertainty of measurement of force transducer

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Analytical Study

The force transducer has been idealized as a ring as earlier researchers have done and the effect of end bosses has not been taken into account for the present investigations. Though a number of researchers earlier have already discussed the design issues of ring shaped force transducers, but no attention has been given to the low capacity ring shaped force transducers. The ring shaped force transducers developed so far lies in the range of kN to MN, but no effort has been done regarding applying the similar methodology for development of force transducers of capacity < 500N. The *t / R* ratio plays a vital role while designing ring shaped force transducers and for present investigations, the *t / R* ratio has been taken < 0.1 for improved sensitivity of the force transducer. A quarter of the ring of selected for analytical study and suitable assumptions have been taken according to the Castigliano's theorem (Fig. 1). Suitable analytical expressions have been taken from earlier researcher's work and available literature for computation of stress - strain and axial deflection[4, 6].

$$\delta = \left(FR^3 / EI\right)\left(\pi/4 - 2/\pi\right) \quad \ldots (1)$$

$$\sigma = \frac{1.07\,FR}{bt^2} \quad \ldots (2)$$

Using, the theory for bending of curved bars[4],
Moment M, at any section of the quarter of the ring may be,

$$M = \frac{FR}{2}\left[\left(\frac{R^2}{R^2+h^2}\right)\left(\frac{2}{\pi}\right) - \sin\theta\right] \quad \ldots (3)$$

Deflection of the ring,

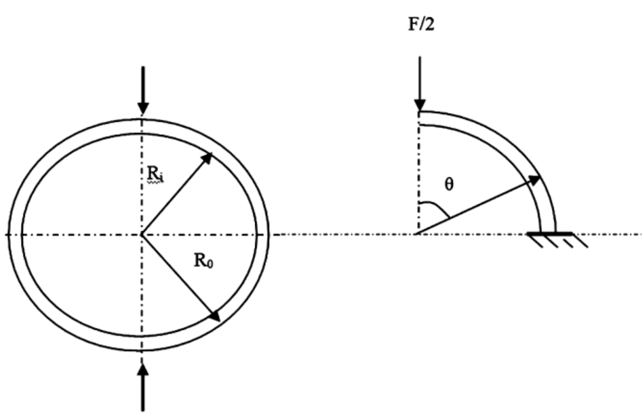

Fig. 1—A Idealized Ring Shaped Force Transducer

$$\delta = \frac{FR^3}{EI}\left[\frac{\pi}{4} - \frac{2}{\pi}\left(\frac{R^2}{\left(R^2+h^2\right)}\right)\right] \quad \ldots (4)$$

Where, for rectangular cross section,

$$h^2 = \frac{R^3}{t}\log_e\left(\frac{2R+t}{2R-t}\right) - R^2 \quad \ldots (5)$$

Equation (2) represents the deflection of the ring shaped force transducer under action of axial forces. A study has revealed that the deflections obtained by the methods discussed above are in close proximity for thin rings. The force transducer has been designed and fabricated on the basis of theory of thin elastic rings and the stress – strain computed are found within safer limits.

Fabrication and Metrological Investigations of Force Transducers

The ring serving as the elastic element for force measurement has been subjected to heat treatment to obtain the requisite hardness. The strain gauges are implanted over the predefined locations of the ring. The surface is suitably flattened and surface roughness is restricted as minimum as possible so that strain gauges may be implanted smoothly. Suitable care is taken to the strain gauging during and after their implantation. The strain gauges are arranged according to Wheatstone bridge as discussed earlier by the researchers. The output of the Wheatstone bridge is a measure of the force applied to the force transducer. The output, which is essentially an electrical signal, may be recorded by suitable digital indicator in form of mV/V or divisions.

The force transducers have been subjected to the metrological performance evaluation on the basis of calibration procedure according to the standard IS 4169-1988 (reaffirmed 2003). The force transducers have been calibrated from 10% - 100% of the rated capacity and uncertainty of measurement of the force transducers have been computed. A high resolution digital indicator has been used to take the observations. The calibration procedure is as follow[7, 8]:

a. Digital indicator is switched on for 30 min to warm up and stabilization.
b. Before start of calibration, no load output is noted. It is tared.
c. Calibration of force transducer has been done in tension mode.

d. Before application of first series of calibration forces, force transducer is preloaded thrice to its rated capacity and is kept at full load for about 90 seconds.

e. Calibration is carried out by applying one series of calibration forces in ascending order. The steps may be taken from 10 % - 100 % in incremental steps of 10 % of the full capacity of force transducer. Every time a position is changed, the force transducer is preloaded once upto full capacity for about 90 seconds.

f. Uncertainty of measurement of force transducer involves uncertainty due to factors including relative zero offset, relative repeatability, relative resolution and relative interpolation. The overall uncertainty of measurement of force transducer, W is determined by considering the best measurement capability (bmc) of the force calibration machine.

g. The relative repeatability is computed from the 3 calibration series taken at different angular positions (Fig. 2).

h. The uncertainty of measurement of the force transducers is evaluated as discussed earlier by the researchers[8] (Fig. 3).

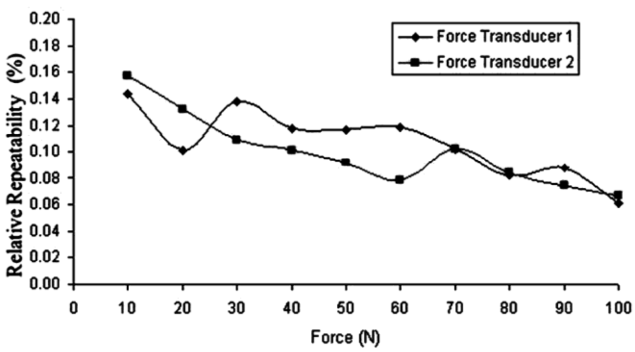

Fig. 2—Relative Repeatability (%) of Force Transducers

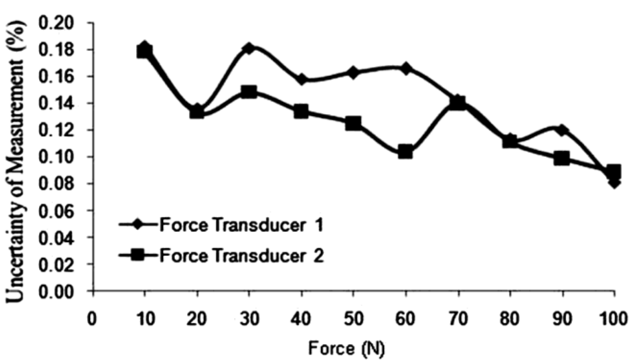

Fig. 3—Uncertainty of Measurement (%) of Force Transducers

Results and Discussions

The force transducers have been designed and developed on the basis of thin elastic rings and on the basis of proven research work of the past researchers. The force transducers developed in past are in range of kN to MN. With growing industrial requirements, thrust has been felt for precision measurement of force in range < 500 N. Though, there are commercial force transducers available in the range < 500 N, but they are of very complex shapes and their fabrication or strain gauging is a very difficult task. The present paper attempts to discuss the development of ring shaped force transducer of nominal capacity 100 N, which is of very simple shape with simple design / manufacturing considerations and may provide stable metrological performance.

The force transducers have been developed for nominal capacity of 100 N and a suitable elastic material has been selected to have good results. The force transducers have been metrologically studied as per standard IS 4169-1988 (reaffirmed 2003) and have yielded satisfactorily results. The relative repeatability of the force transducers has been investigated. The relative repeatability of the force transducers in found to upto 0.20 % (Fig. 2) and lie within the permissible limits as specified the standard discussed. The overall uncertainty of measurement of the force transducer, while taking into uncertainty components due to relative repeatability, relative resolution, relative zero offset and uncertainty of force measurement of force calibration machine into account is upto 0.20 %, which is well within limits as permitted by the standard IS 4169-1988 (reaffirmed 2003) (Fig. 3). The force transducers may further be studied further for improvement in metrological results and for the development of ring shape force transducers of capacity like 10 N, 20 N or 50 N etc. to fill the gap and to meet the growing industrial need for force measurement in this particular range.

Conclusion

The ring shaped force transducers have been developed for nominal capacity of 100 N on the basis of thin elastic rings. The force transducers have been found to have uncertainty of measurement better than ± 0.20 % ($k = 2$) while taking relative uncertainty due to factors like repeatability, zero offset, interpolation, resolution etc. Though ring shaped force transducers have been developed for higher capacities by various researchers, but with the growing requirements for measurement of low forces, thrust are required for development of low capacity force transducers. Hence, necessary efforts must be undertaken to develop force transducers for capacities like 1 N, 10 N, 50 N etc. and in the sub-newton range. Further, efforts are required to improve the uncertainty of force transducers in lower range.

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