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Investigations on metrological characterization of elliptical shaped force transducers for precision force measurement

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ABSTRACT

Force measurement is very vital in various scientific applications and its precise measurement is very necessary for reliability of the measurement process. There are several types of simple shaped force transducers, which may range from ring shaped force transducers to cantilever type or beam type force transducers. Ring shaped force transducers are one of most commonly used type of force transducers are developed on the basis of theory of thin rings. Till today, some of the modifications of ring shaped force transducers have been reported, the present investigation discusses the development of elliptical shaped force transducer as a modification of ring shaped force transducers and its preliminary investigation on metrological characterization based on the calibration procedures according to standards ISO 376-2011. The force transducer has been developed for the nominal capacity of 20 kN and strain gauges have been applied over the optimum locations to minimize cross sensitivity. The force transducer is developed exclusively for static force measurement related applications to serve as a link in providing the traceability to the user industries and calibration laboratories or serve as force transfer standard. The force transducer has been evaluated for suitability as a precision force transducer with the help of the 50 kN Dead Weight force machine traceable to national standard of force. The elliptical shape force transducers are found to have comparable metrological characteristics as compared to other ring shape force transducers.

Symbols

b width of the cross section of ring (mm)
t thickness of cross section of ring (mm)
R_o mean radius (mm)
P applied force (N)
E young's modulus of elasticity (N/m^2)

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δ deflection of the ring (mm)
σ stress, N/m^2
ε strain (mm/mm)
w_{rep} relative uncertainty due to repeatability (%)
w_{int} relative uncertainty due to interpolation (%)
w_{zer} relative uncertainty due to zero offset (%)
w_{res} relative uncertainty due to hysteresis (%)
w_{rpr} relative uncertainty due to reproducibility (%)
w_{res} relative uncertainty due to resolution (%)
$w_{c\,(tra)}$ relative combined standard uncertainty (%)
$W_{(tra)}$ relative expanded uncertainty (%) at k = 2
W uncertainty of measurement (%)
k coverage factor

1. Introduction

Force measurement is very important for different engineering applications. The applications may be like measurement of cutting forces in different machining processes (milling, turning, drilling etc.), electronic weighing scales, thrust measurement etc. These different applications are served by different types of force transducers, which may have different shape as well as different working principle. The history of modern force transducers started long back in 1927 at National Bureau of Standards, United States of America (now called, National Institute of Standards and Technology, USA), when ring shaped precision force transducers were developed. These force transducers consists of an elastic ring shaped sensing element and a deflection measuring devices like dial gauge, micrometer or vibrating reed. Such force transducers, even are employed nowadays for force measurement (Libii, 2006; Rehman & Rehman 2007).

The ring shaped force transducers have been serving as a base for development of different types of force transducers. Now, with span of time and growing technological requirement, strain gauged force transducers are used on large scale. These force transducers are commonly available by various manufacturers through the globe and have varying performances. Though, some of the commercially available force transducers are ultra precise, but they have complex design and manufacturing issues. Their machining is very complicated as well as strain gauges is very difficult. It is also very difficult to have their design related investigations as their irregular shape may not be analysed by conventional theories. Hence, there is need to have simple shaped force transducers to have simple design and manufacturing considerations. In the recent past years, there has been continuous demand for the measurement of force more precisely and with low uncertainty. The developed force transducers had higher degree of uncertainty and were unable to serve as force transfer standard. Though, tuning fork type force transducers have been developed with improved uncertainty, but for very low capacity like 50 N. Hence, the force transducers, which may be used through a wide range with uncertainty of force realization better than 0.10 % (k = 2) with higher capacity and for precise static force measurement may serve as force transfer standards is the major concern. Such force transducers are precise enough to meet the major industrial needs (Dirk et al. 1995, Hayashi et al. 2008 and Kumar et al. 2011).

Taking the objective of development of simple shaped precision force transducers, some researchers have been reported regarding the development of square ring shaped force transducer, hexagonal ring shaped force transducer and extended octagonal ring shaped force transducer

(O'Dogherty 1996, Kumar and Sharma 2012 a,b, Kumar et al. 2013, 2015). Hence, for better precision and reliability, the present paper attempts to development of elliptical shaped force transducers. Finite element analysis reveals the importance of modern computational tools and their suitability while designing or analysing the force transducers. The strain gauges applications have been greatly affecting by their locations, makes the computational investigations very critical (Chen et. al. 2007; Kumar et al. 2012). The elliptical shaped force transducer has been developed for nominal capacity of 20 kN and has been calibrated in compression mode by the 50 kN dead weight force machine. Though such type of force transducers are available with dial gauge as measuring devices, but up to best of knowledge, no systematic design and development related literature is available. The 50 kN dead weight force machine used for calibration of the force transducer is traceable to national standard of force by precision force transfer standards and uncertainty of force realization is up to 0.015 % (k = 2). The metrological characteristics of the force transducer have been evaluated according to the calibration procedures based on the standard ISO 376-2011. The relative uncertainty due to repeatability, reproducibility, zero offset, resolution, hysteresis and interpolation have taken into account depending upon the procedure used to evaluate the uncertainty of force realization by the force transducers. There is now need to develop such type of force transducers for different nominal capacities for investigating suitability over the wide range of force measurement (ISO 376-2011; Kumar et al. 2013)

2. Analytical study

The ring force transducers have been designed on the basis of theories of thin rings under the action of axial forces and using suitable assumptions. The ring shaped force transducers have been suitably modified into different types of force transducers like octagonal ring, extended octagonal ring, etc. Now, efforts have been made to investigate the consideration of elliptical ring shaped force transducers as a modification of ring shaped force transducer. The elliptical ring shaped force transducer has been presented here with a modification of ring shaped force transducer. The analytical expressions have been developed based on R_o/t ratio (mean radii to thickness ratio) and the ratio is found to be within 0.1 to 0.4. It has been reported that the deflection of the ring shaped force transducers is greatly affected by the R_o/t ratio and it is very instrumental in defining, whether the force transducer falls under thin ring (R_o/t ratio ≤ 0.2) or thick ring (R_o/t ratio ≥ 0.2). The analytical expressions for stress, strain and axial deflection of the ring shaped force transducers are well established and have been developed / validated by experimental observations for the rectangular section of ring shaped force transducers by earlier researchers (Kumar et al. 2011). These expressions have been reported to be very useful by different researchers. The deflection, δ of the force transducer under the action of forces P can be obtained by using Castigliano's Theorem and can be represented by equations,

$$\sigma = 0.7P\,R_0 / E\,b\,t^2, \tag{1}$$

$$\varepsilon = 0.7P\,R_0 \;/ b\,t^2, \tag{2}$$

$$\delta = P\,R_0^3 / E\,b\,t^3. \tag{3}$$

The expressions discussed above hold good for ring shaped force transducers and a number of researchers have used for development of circular, hexagonal, octagonal, extended octagonal and square ring shape force transducers for various applications as reported earlier. The force transducers developed have been used for measurement of dynamic forces like force measurement during cutting processes like milling, drilling, turning etc. and were not meant for static force realization so that they could serve as force transfer standard for maintain traceability of force realization from force standard machines to force calibration machine or verification of material testing machines and had higher uncertainty of force realization. Though some of the modifications of ring shaped force transducers like square ring shaped force transducer and hexagonal ring shaped force transducer have been demonstrated for static force measurement related applications, but their uncertainty of measurement is found up to 0.10 % (k = 2), and these developments are in their preliminary phases too. Their suitability over the wide range of force measurement related applications is still to be justified (Kumar, et al. 2015).

The ring shaped force transducers have been discussed earlier (Kumar et al., 2011) and their metrological investigations have been discussed there also. There has been well documented design procedure for ring shaped force transducers and already, a number of modifications have already been proposed by researchers as on date. The ring shaped force transducers have been calibrated according to the standard procedure like ISO 376 and it is found that uncertainty could be about 0.025 % (excluding relative uncertainty due to hysteresis) and up to 0.10 % (including relative uncertainty due to hysteresis). Suitable discussion pertaining to different metrological characteristics has already been made by researchers (Kumar et. al., 2013).

Up to best of knowledge of authors, no concrete evidence has been found, which discuss the analytical expressions of stress – strain and deflection of elliptical shaped force transducers except as described by Kaushik et al. (2013). Hence, the stress – strain and deflection has not been computed by analytical means, an elliptical shaped force transducer of material EN 24 (due to good elastic properties) has been designed. The material properties and geometrical parameters of the transducer were as follows: Young's modulus = 210 GPa, Poisson's ratio = 0.3, inner radius = 40 mm, parallel side length = 120 mm, thickness = 20 mm and width = 45 mm. A schematic diagram of the considered elliptical shape force transducer has shown in Fig. 1. The effect of end bosses is not taken into account, as it does not impact the findings of analytical and as well as computational investigations significantly (Kaushik, et. al. 2013).

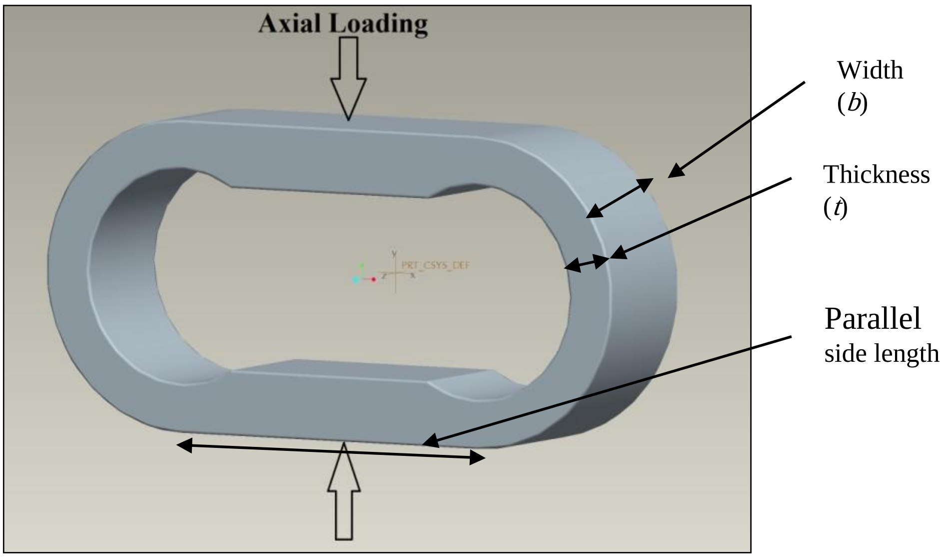

Fig. 1. Elliptical shaped force transducer

3. Design Studies

The software ABAQUS 6.8 standard student edition has been used for the finite element analysis of the elliptical shaped force transducer with the nominal capacity of 20 kN. A three dimensional solid continuum 4-node linear tetrahedron node element with reduced integration is considered and the analysis is of linear type. The mesh size is suitably taken and about 645 elements are present in the elliptical shaped transducer. The material is of isotropic nature and is considered elastic. Elements are selected from the standard library of the software and the maximum deviation factor for curvature control is 0.1. The point force or concentrated force is applied in compression mode using ABAQUS

6.8 for studying the stress–strain pattern of the transducer. The bottom end the force transducer has been fixed, as no rotation is permitted and the other end free, from which the force is applied. The stress – strain are found to be moderate at 90^{o} to the either axis and the strain gauges may be applied over the selected locations suitably (Fig. 2) (Chen et. al., 2007).

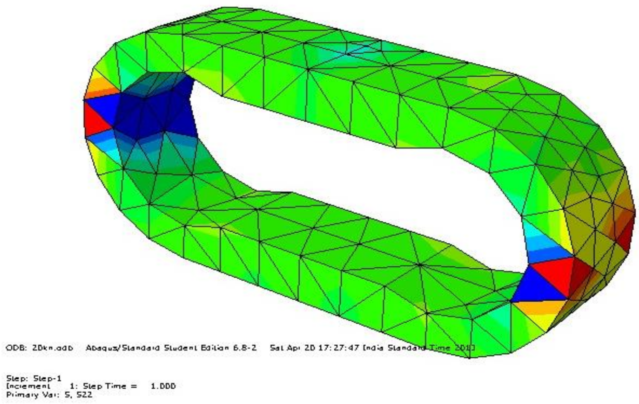

Fig. 2. Stress Distribution for force 20 kN (Kaushik et al., 2013)

The deflection of the elliptical shaped force transducer is found to be 2.461 mm by computational means. The effect of the end bosses has not been taken into account according to the previous investigations as reported earlier (Chen et al. 2011).

4. Fabrication and Metrological Investigations of the Force Transducer

Taking the dimensions and geometry of the force transducer to be developed, the force transducer is fabricated and the force transducer first it is annealed then strain gauges are applied over the suitable locations after finishing the identified locations. The selected locations are maintained with surface roughness within few microns. The metal foil type strain gauges have been used for force transducers. Strain gauges have been applied to the curved surfaces 90° to the vertical axis using a hot curing adhesive (Fig. 3). Proper curing and post curing of the strain gauges has been done and connections are made as per the Wheatstone bridge. A strain gauged elliptical shaped force transducer has been shown in Fig. 4. This Figure outlines the locations of applications of the strain gauges.

For deflection measurement of elliptical shaped force transducer, a high resolution dial indicator of resolution 0.002 mm is used. The deflection is found to be 2.488 mm, which is in well correlation to that obtained by computational means. It means that the findings of the computational means are justified.

The force transducer has been calibrated according to the calibration procedures using the 50 kN dead weight force machines (Chen et al. 2007). The 50 kN dead weight force machine has been calibrated by precision force transfer standards and is traceable to national standard of force through unbroken chain of traceability (Fig. 5). The dead weight force machine is one of the selected facilities in India for precision force realization up to 50 kN by precisely known dead weights. The elliptical shaped force transducer has been calibrated according to the calibration procedures based on the standard ISO 376-2011. A high resolution digital indicator (with 0.00001 mV/V) has been taken for the observations. The environmental conditions during the calibration are maintained to neutralize the thermal effects due to variation of the temperature.

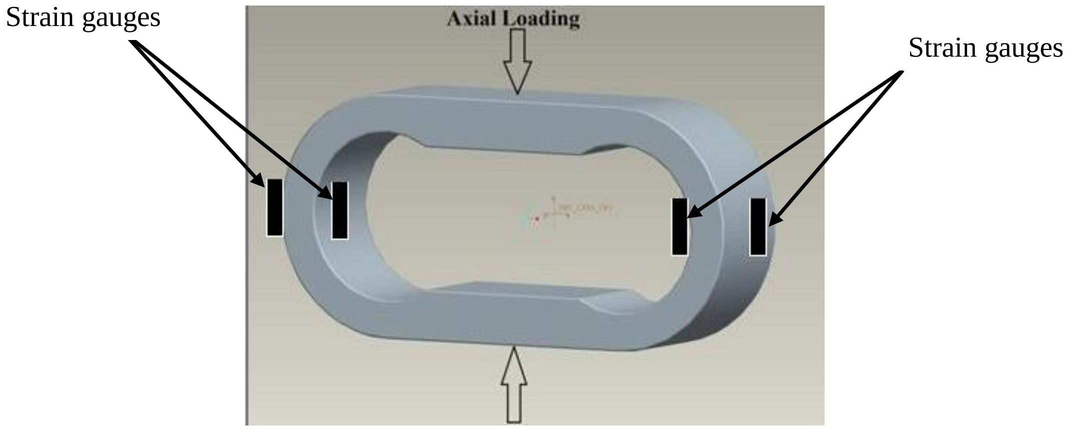

Fig. 3. Locations of the strain gauges applied

Fig. 4. A realistic strain gauged elliptical shaped force transducer

Fig. 5. 50 kN dead weight force machine (Kumar et al., 2015)

4.1 Calibration Procedure

The calibration procedure adopted consists of following series:

- The digital indicator is switched on and kept about 1 hour for stabilization.
- The force transducer is subjected to three preloading for nominal capacity.
- The force transducer is subjected to two series of calibration series in ascending order at the initial position, say 0^o and observations are taken at 10 % incremental forces and waiting time for taking observations is kept 30 seconds.
- The force transducer is rotated to a position 120^o and preloaded once to its nominal capacity. The force transducer is now subjected to a calibration series in ascending and then descending order.
- Again, the force transducer is rotated to a position, 240^o and preloaded once. The force transducer is subjected to a calibration series in ascending and then in descending order.

The different factors pertaining to the uncertainty of measurement of the force transducer are listed below (Kumar et al., 2015). This uncertainty has been computed using Eqs. (4-11). The different factors pertaining to the uncertainty of measurement of the force transducer are listed below. The factors have been mentioned earlier somewhere else (Kumar et al., 2013).

(a) Relative uncertainty due to repeatability
(b) Relative uncertainty due to reproducibility
(c) Relative uncertainty due to zero offset
(d) Relative uncertainty due to resolution
(e) Relative uncertainty due to reversibility
(f) Relative uncertainty due to interpolation
(g) Uncertainty of measurement of force applied

The uncertainty of measurement of the force transducer is evaluated by computing the relative uncertainty due to the factors mentioned above depending upon their applicability to the calibration procedure used, as follow:

$$W_c\left(tra\right) = \sqrt{\left[w^2(rep)+w^2(rpr)+w^2(zer)+w^2(res)+w^2(hys)+w^2(int)\right]}, \quad (4)$$

$$W\left(tra\right) = k.W_c(tra), \quad (5)$$

$$W = \sqrt{\left[W^2(tra)+W^2(cmc)\right]}. \quad (6)$$

The metrological investigations are summarized in form of Figs. (6-8).

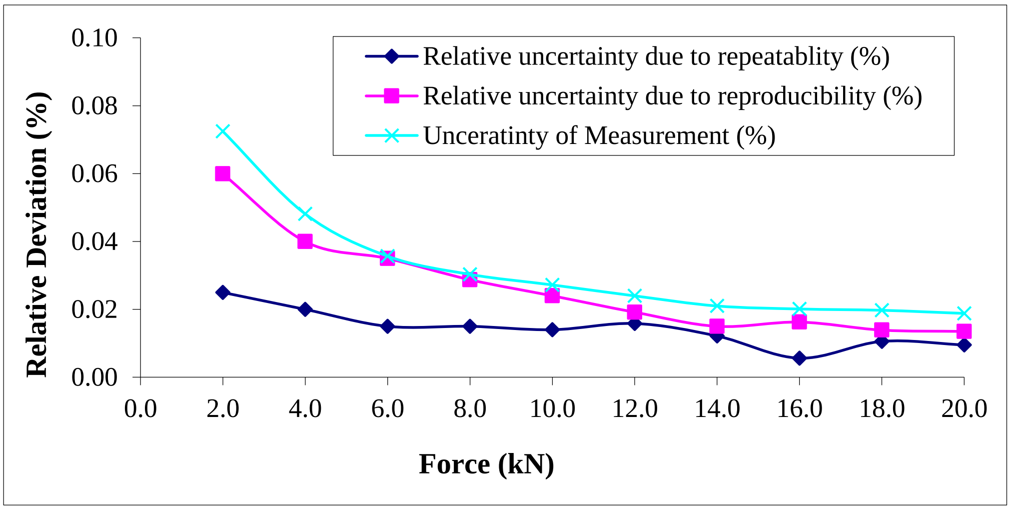

Fig. 6. Metrological characterization of force transducer

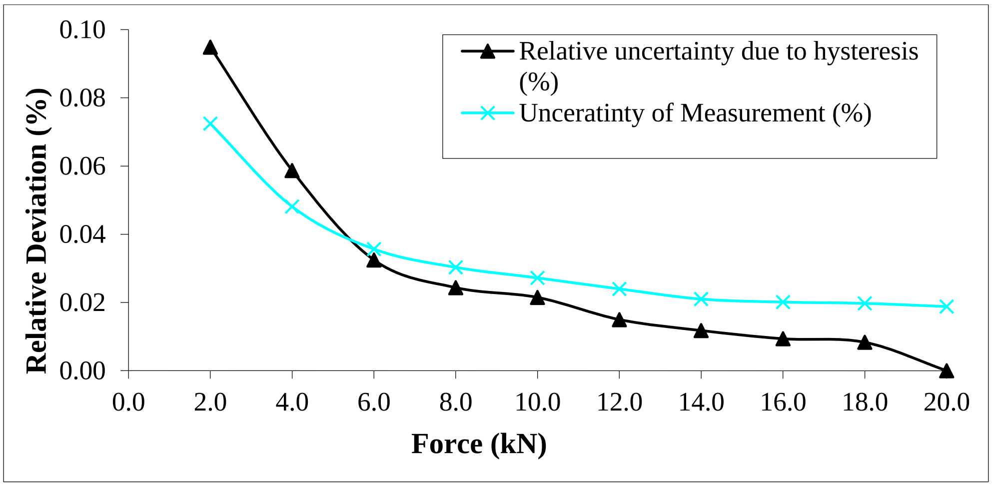

Fig. 7. Uncertainty of measurement of force transducer as a function of relative uncertainty due to hysteresis

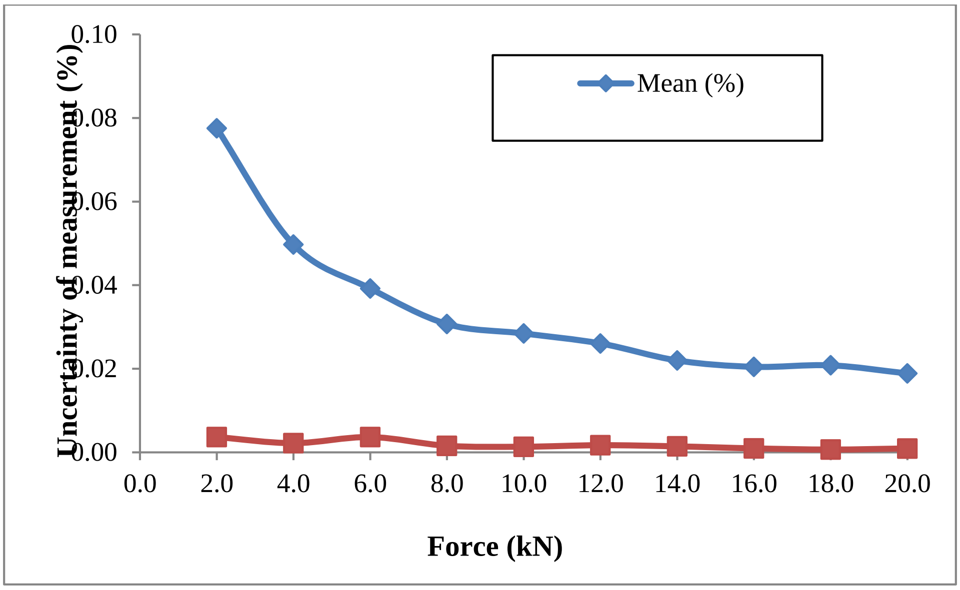

Fig. 8. Mean and standard deviation of uncertainty of measurement of force transducer over 10 series of calibration

5. Results and Discussions

The ring shaped force transducers have been modified to different shapes like square ring, hexagonal ring, octagonal ring and extended octagonal ring for different applications. The static force measurement related applications are very important like verifications of material testing machines, thrust measurement, electronic weighing scales and for dynamic force measurement related application like measurement of cutting forces during different machining processes. There has been little attention given to the development of simple shaped force transducers for static force measurement applications, through commercially manufactured force transducers are available through the globe.

The ring shaped force transducers provide ease of design as well as manufacturing. Hence, the present investigation reports the development of elliptical shaped force transducer as a modification of the ring shaped force transducer. The force transducer has been developed on the basis of thin rings and has been analysed by analytical approach as well as computational approach. The computational investigations are very helpful in identifying suitable locations over the force transducers to apply the strain gauges (Kumar et al. 2012).

The force transducer has been fabricated of material EN-24 steel for capacity 20 kN. The investigation on metrological characterization of the elliptical shaped force transducers has been done using the calibration procedures based on standards ISO 376-2011 using the 50 kN dead weight force machine with uncertainty of force realization 0.015 % (at k = 2). The uncertainty of measurement of the force transducer is a cumulative effect of relative uncertainty due to repeatability, reproducibility, zero offset, interpolation, hysteresis and resolution. Figs. 6 to 8 summarize the different facets of the metrological investigations of the force transducer.

Fig. 6 shows the uncertainty of measurement of force transducer along with relative uncertainty due to repeatability and reproducibility. It has been observed that the uncertainty of measurement is higher at lower range of the force transducer due to higher relative uncertainty due to repeatability and reproducibility. Fig. 7 discusses the uncertainty of measurement of force transducer as a function of the relative uncertainty due to hysteresis. Relative uncertainty due to hysteresis is a very dominant factor and is keeping on reducing along as the nominal force applied keeps on increasing. Fig. 8 discusses the standard deviation and mean of the uncertainty of measurement of force transducer computed over 10 series of calibrations. The mean value of uncertainty of measurement of force transducer is up to 0.08 % for nominal force 2 kN and between the 40 % - 100 % of nominal capacity of force transducer, the uncertainty of measurement computed is up to 0.05 % ($k = 2$), which makes the force transducer suitable for precision measurement related applications.

A more rigorous investigation has been carried out by comparing the metrological characteristics of a dial gauged elliptical shaped force transducer. The dial gauged elliptical shaped force transducers are commonly used for various static force measurement related applications. It has been felt over the long time to replace the dial gauge with a suitable media due to poor stability and resolution of the dial gauge. The dial gauged force transducers are commonly used only for the specific forces according to guidelines of the standards like ISO 376-2011. The dial gauged elliptical force transducer has been calibrated according to ISO 376-2011 and the uncertainty of measurement of the force transducer is evaluated (Fig. 9). It has been found that the uncertainty of measurement of strain gauged force transducer is better and provides the ease of interpolation, which facilitates that application of any force within the range of the force transducer.

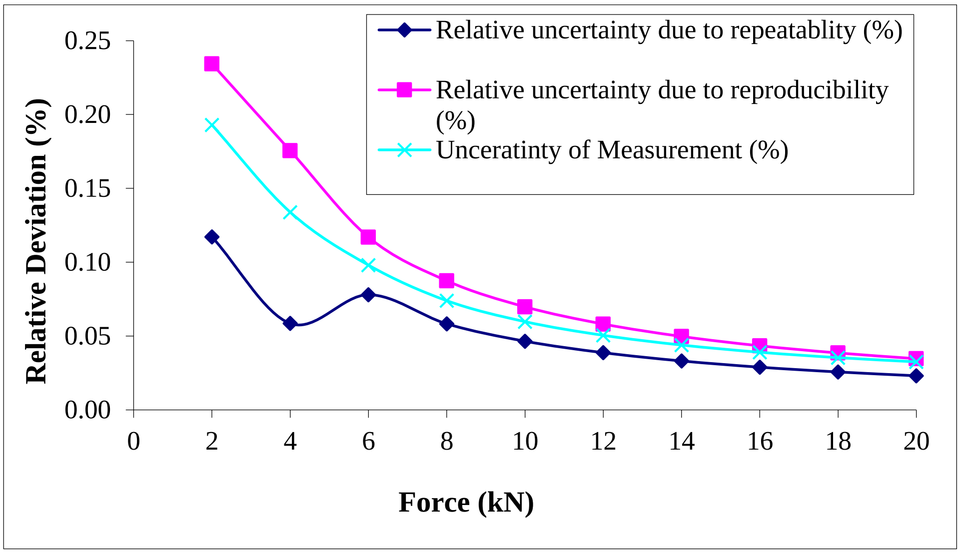

Fig. 9. Metrological characterization of an elliptical dial gauged force transducer.

The elliptical shaped force transducer has been compared to ring shaped force transducers as well as other different modified ring shaped force transducer like hexagonal ring shaped force transducer (Table 1). It has been found that the uncertainty of measurement of the elliptical shaped force transducers as well as hexagonal ring shaped force transducers is up to 0.10 % while taking suitable factors into consideration (Fig. 10). The uncertainty of measurement of elliptical shaped force transducer is found to be either very close or better to the uncertainty of measurement of such force transducers e.g. ring shaped force transducer (Kumar and Sharma 2012 a), hexagonal ring shaped force transducer and square ring shaped force transducer (Kumar et al. 2013) are found to have uncertainty of measurement up to 0.10 (k=2), while the elliptical shaped force transducer is found to have uncertainty up to 0.10 (k=2), while taking suitable factors into account. Square ring shaped force transducer's metrological performance has not been tabulated as it has been developed only for 1 kN nominal capacity. There is need to emphasis over the development of such force transducers over the range of different nominal capacities. Attempts are to be made for lowering the uncertainty of measurement of such force transducers, which will make the elliptical shaped force transducers suitable for precision metrological applications in addition to other force measurement related applications.

Table 1. Comparison of different shaped force transducers

Force (kN)	Uncertainty of measurement (%) of force transducer		
	Ring shaped	Elliptical shaped	Hexagonal ring shaped
2	0.16	0.07	0.09
4	0.15	0.05	0.09
6	0.13	0.04	0.08
8	0.11	0.03	0.07
10	0.09	0.03	0.06
12	0.07	0.02	0.06
14	0.05	0.02	0.05
16	0.03	0.02	0.05
18	0.02	0.02	0.04
20	0.01	0.02	0.04

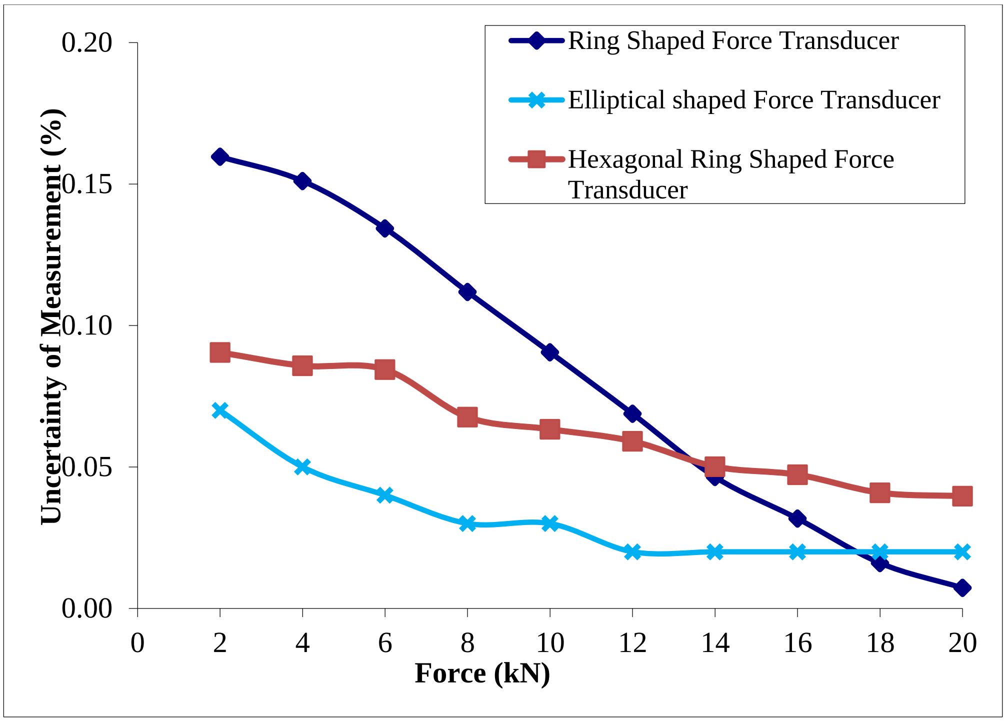

Fig. 10. Comparison of different shaped force transducers

6. Conclusions

The elliptical shaped force transducer of nominal capacity 20 kN is designed and developed as a modification of ring shaped force transducer and has been investigated by analytical and computational approaches. The force transducer has been equipped with strain gauges and a high resolution digital indicator. A 50 kN dead weight force machine has been employed for metrological investigations of the force transducer and the calibration procedure adopted is in line with standard ISO 376-2011. The force transducer has been found to exhibit equivalent or better metrological characteristics to the other simple shaped force transducers like square ring shaped or hexagonal ring shaped force transducer as reported recently. The elliptical shaped force transducer may be well suited for precision force measurement related applications and may be useful for industrial applications due to its economic aspects also. Such type of force transducer need to be developed to promote the force transducers with ease of design and manufacturing. Attempts to be made to develop such force transducers over variety of range from kN to MN to facilitate the utility of such kind force transducers over the wide range.

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