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A critical assessment of simple shaped force transducers: Design and metrological considerations

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The paper attempts to investigate the simple shaped force transducers of various types and their considerations pertaining to manufacturing and design. Effort has been made to discuss the metrological issues in order to have their applications regarding industrial and scientific purposes. Efforts regarding critical assessment of different simple shaped force transducers regarding their practical viability have been made. Limitations of the past and present research have been discussed herewith in the report.

Keywords: Force transducer, Metrological characteristics, ISO 376, ASTM E 74

1 Introduction

Force transducers are widely used for various applications in the nominal range from sub-Newton to mega Newton in different arenas. The force transducers are of different types and are of different shape in accordance to the desired application[1]. A force transducer is a sensing element equipped with a measuring device, *e.g.*, either analogue or digital depending upon the principle employed. In past, ring shaped force transducers (with dial gauge and may be mentioned as force proving instrument) have been widely used with wide spectrum of applications. The spectrum of applications may vary with uncertainty of measurement in the range of 0.025 % to 1 % or higher. Such force transducers (or, force proving instruments) suffer from mechanical issues and are unable to provide the features of interpolation, reversibility and digital output along with remote application features, those may be offered by the digital force transducers[2,3]. For precision applications and to ease out the limitations of analogue force transducers, strain gauged force transducers are employed commonly. Though, strain gauged force transducers developed in 1950s, still they have been more dominant for precision and industrial applications over the large scale through the globe. Such force transducers have uncertainty of measurement in the range of 0.025 % to 0.20 %, which is widely accepted for most of the precision and industrial applications. Strain gauged force transducer provide digital output, interpolation of intermediate forces, ease of reversibility and remote application facility[4,5].

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1.1 Design and manufacturing considerations of force transducers

Though there are different commercial force transducers available through the globe, with varying capacity and metrological characteristics, there have been continuous ongoing efforts regarding in-house development of force transducers either customized or may be with difficulties faced with the commercially available solutions. As the commercial force transducers available are of complex shape and they have intricate instrumentation system, their in-house development is difficult due to manufacturing and design considerations. Yet the commercial force transducers offers the superior metrological characteristics with uncertainty of measurement up to 0.02 % (k = 2). Commercial force transducers though offer most practical viable solutions; still their analysis is practically not viable due to complex geometry.

There has been need to make efforts for in-house research and development pertaining to indigenous force transducers despite of availability of commercial force transducers through the globe including several Indian manufactures too. Simple shaped force transducers are critical in implicating design and manufacturing considerations and promoting in-house design and development. The present discussion is pertaining to the different simple shaped force transducers developed recently and their implications regarding design and metrological capabilities.

In this article, an assessment is presented regarding the simple shaped force transducers, generally analogue or digital (mainly strain gauge type); a brief discussion has been made regarding the MEMS force transducer to make the readers aware regarding the present development going through the globe.

1.2 Ring shaped force proving instruments and force transducer

Conventionally, ring shaped force transducers (or, force proving instruments) have been employed since 1927, developed in NBS, USA (now, NIST) through the globe, as shown in Fig. 1. Ring shaped force proving instruments have been employed with dial gauge indicator, micrometer, vibrating reed or digital dial gauge indicator (as the case may be)[6].

Ring shaped force proving instruments are generally calibrated in accordance to the standard procedures based on the guidelines of the standard ISO 376 (current applicable version 2011) and E 74 (current version applicable 13a). The metrological characterization process involves different calibration series and relative uncertainty due to different factors contributing to the force transducer's uncertainty of measurement. The calibration procedure and methodology to evaluate uncertainty of measurement based on standard ISO 376 and E-74 have already been discussed somewhere else in detail[7,8].

It is evident from the Tables 1 and 2 that the deflection is much linear up to an extent and differential deflection is almost alike. Limitation of the dial gauge is the approximation to be done by dividing the observation to tenth place as shown in Table 1 and no reversibility. Table 2 summarizes the average deflection obtained to the same force proving instrument using digital dial gauge instead of dial gauge indicator.

Fig. 1 — A dial gauged force transducer (or, force proving instrument)[2].

If a critical assessment of the Table 1 and 2 is made, it is evident that such force proving instruments suffers from poor resolution, stability of observations, no provision for intermediate force evaluation and reversibility. In order to limit the approximation of the dial gauge, digital dial gauge has been used, but its resolution is limited (0.001 mm), which is best possible available. These issues have raised the concern regarding digitization of the ring shaped force proving instruments to overcome the limitations of the dial gauged force transducers.

Ring shaped force transducers are an upgraded version of force proving instruments by limiting its inherent shortcomings. Such force proving

Table 1 — Deflection of the force proving instrument for different forces of nominal capacity 50 kN (using dial gauge with resolution 0. 1 division, 1 division = 0.002 mm).

Force applied (kN)	Average deflection (Division)	Differential deflection (Division)
5	43.1	43.1
10	86.3	43.2
15	129.5	43.2
20	172.6	43.1
25	215.9	43.3
30	260.2	43.3
35	303.7	43.5
40	347.1	43.4
45	390.4	43.3
50	430.8	43.4

Table 2 — Deflection of the force proving instrument for different forces of nominal capacity 50 kN (using digital dial gauge with resolution 0.001 mm).

Force applied (kN)	Average deflection (mm)	Differential deflection (mm)
5	0.087	0.087
10	0.173	0.086
15	0.258	0.085
20	0.345	0.087
25	0.431	0.086
30	0.517	0.086
35	0.603	0.086
40	0.690	0.087
45	0.777	0.087
50	0.863	0.086

instruments have been digitized suitably by critical investigation regarding design features and computational techniques have been able to identify suitable locations for strain gauges in order to accommodate the strain gauges in Wheatstone bridge form. Output of the bridge after application of force is the indication of the force applied.

1.3 Metrological characterization of the force proving instruments and force transducers

ISO 376 (current applicable version 2011) provides the most acceptable procedure for metrological characterization of the force proving instruments and force transducers globally[7] and up to an extent for some specific applications; ASTM E-74 has been adopted[8]. The metrological characterization includes evaluation of different components for determining the uncertainty of measurement. A brief procedure adopted in accordance to ISO 376 has been summarized below with the components/factors involved. Tables 3 and 4 discuss different factors and their limits contributing to uncertainty of measurement of force transducer in accordance to ISO 376.

Though the previous results have been reported somewhere else[6] the force transducer has been recalibrated for its metrological capabilities in accordance to ISO 376 and results have been summarized in Table 5.

The factors as mentioned above and their evaluation has already been discussed somewhere else by researchers[9].

It may be well concluded from the Table 5 that major component of the uncertainty of measurement is relative uncertainty due to reversibility apart from relative uncertainty due to reproducibility, though other factors including relative uncertainty due to repeatability, resolution, zero offset and interpolation have limited impact over uncertainty of measurement. The conclusion drawn is well within of findings discussed in past research. In this context, authors would like to thrust that the strain gauged force transducers offer the most reliable form of force transducers for force measurement.

In present scenario in developing nations including India, force proving instruments have been used on

Table 3 — Different factors contributing to the uncertainty of measurement of the force transducer as per ISO 376.

S. No.	Factor contributing to relative uncertainty of measurement of force transducer	Force Proving Instrument	Force Transducer	Type of Distribution, Error and Factor of Division
1	Zero offset	Yes	Yes	Rectangular, Type B, √3
2	Resolution	Yes	Yes	Rectangular, Type B, √3
3	Repeatability	Yes	Yes	Rectangular, Type B, √3
4	Reproducibility	Yes	Yes	U shaped, Type B, √2
5	Creep	Yes	Optional	Rectangular, Type B, √3
6	Reversibility	No	Yes	Rectangular, Type B, √3
7	Interpolation	No	Yes	Triangular, Type B, √6
8	Applied force	Yes	Yes	Normal, Type B, 1

Table 4 — Limits of different factors contributing to uncertainty of measurement of force in accordance to ISO 376 for different classes.

Class	Relative error (%) of force proving instruments						
	Reproducibility	Repeatability	Interpolation	Zero	Reversibility	Creep	Uncertainty of force realization
00	0.05	0.025	0.025	0.012	0.07	0.025	0.01
0.5	0.10	0.05	0.05	0.025	0.15	0.05	0.02
1	0.20	0.10	0.10	0.050	0.30	0.10	0.05
2	0.50	0.20	0.20	0.10	0.50	0.20	0.10

Table 5 — Metrological characteristics of the ring shaped force transducer of 50 kN nominal capacity.

Force (kN)	Relative uncertainty contribution (%) due to							Uncertainty of measurement (k = 2)
	Zero offset	Resolution	Repeatability	Reproducibility	Interpolation	Reversibility	Applied force	
5	0.006	0.005	0.032	0.074	0.044	0.245	0.015	0.15
10	0.005	0.002	0.021	0.060	0.060	0.156	0.015	0.10
15	0.005	0.002	0.020	0.052	0.011	0.126	0.015	0.08
20	0.005	0.001	0.017	0.043	0.012	0.114	0.015	0.07
25	0.005	0.001	0.014	0.042	0.005	0.083	0.015	0.06
30	0.005	0.001	0.013	0.035	0.003	0.079	0.015	0.05
35	0.005	0.001	0.013	0.030	0.001	0.068	0.015	0.05
40	0.005	0.001	0.012	0.031	0.003	0.060	0.015	0.04
45	0.005	0.001	0.012	0.031	0.002	0.057	0.015	0.04
50	0.005	0.000	0.012	0.028	0.001	0.000	0.015	0.04

larger level in most of the industrial applications. In addition, there are elliptical shaped force proving instruments and sometimes force proving instruments are equipped with vibrating reed and micrometer, though they are limited in number. According to past reports, it has been found that in India, more than 50% measurement pertaining to force measurement for different applications (particularly in industries) still employing dial gauged force proving instruments. The force proving instruments may wisely be digitized as mentioned above so that they may be able to check the limitations of the conventional force proving instruments.

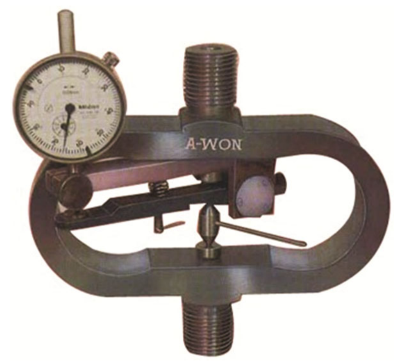

Fig. 2 — A dial gauged elliptical force proving instrument; (Courtesy of Real Scientific Engineering Corp., New Delhi).

2 Advances in the Development of Simple Shaped Force Transducers

The development of simple shaped force transducers has been emphasized on account of following reasons:

(i) Commercially available force transducers are ultra-precise but complex in design and manufacturing with economical constraints. Strain gauging is a difficult task for such force transducers. The output result is greatly affected by the location of the strain gauges. Complex and irregular shape gives challenges in their engineering analysis with conventional theories.

(ii) Demand for measurement of force with low uncertainty and greater precision gives chance to the development of more simple shaped transducers.

(iii) Simple shaped force transducers provide better precision, more reliable to work, improved uncertainty and due to their basic geometrical shapes, it is possible to analyze the behavior using conventional concepts.

The present section attempts to discuss the recent advances reported by different researchers regarding development of different simple shaped force transducers, for different applications either scientific or industrial. Force transducers reported are of different nominal capacities, different shape or may be intended for specific application. An attempt has been made to discuss different salient aspects of the force transducers under investigation.

2.1 Elliptical shaped force proving instrument and force transducer

Elliptical shaped force proving instruments commonly used for force measurement are equipped with a dial gauge or digital dial gauge (Fig. 2). Such force proving instruments are used over the large scale for force measurement in industrial applications. Such force proving instruments uses a fulcrum pin to amplify the deflection of the force proving instrument and dial gauge indicator is used to take the observations accordingly. Table 6 brief summarizes the average deflection of 50 kN elliptical shaped force proving instrument as in case of force proving instrument[10] mentioned in Table 2.

Such force proving instruments offer similar capabilities as in case of force proving instruments and have been in use for past few decades. They are conventionally equipped with dial gauge indicator or digital dial gauge and deflection is the measurement of the external force applied. Such force proving instruments may be digitized, which will be able to limit their inherent shortcomings as in the case of ring shaped force proving instruments.

Recently an elliptical shaped force transducer (with strain gauges) for nominal capacity of 20 kN is developed through critical assessment of design considerations (applicability of conventional theories and finite computational analysis) and discussed its design considerations with the help of conventional theories available and finite element analysis to optimize the locations for application of strain gauges. The analytical expressions are developed based on the mean radius to thickness ratio and the range of this ratio is taken as 0.1 to 0.4. Dimensions and other details are presented in Table 7.

Table 6 — Deflection of a 50 kN capacity elliptical force proving instrument for different forces (using digital dial gauge with resolution 0.01 mm).

Force applied (kN)	Average deflection (Division)	Differential deflection (Division)
5	103.1	103.1
10	206.4	103.3
15	309.8	103.4
20	412.8	103.0
25	515.8	103.0
30	618.8	103.0
35	721.5	102.7
40	824.5	103.0
45	927.3	102.8
50	1030.4	103.1

Details of the elliptical shaped force transducer are as followed for the material EN 24 grade of steel. The computational investigations are done using the ABAQUS 6.8 software. For analyzing the practical scenario, the bottom end of the force transducer is fixed, while the other end is kept free for the application of load. It is also noted that stress – strain conditions are moderate at 90° to the either axis. The deflection of the elliptical shape transducer is found to be 2.46 mm by computational means. The finite element analysis is able to help in identifying suitable locations for applying the strain gauges. The strain gauges are arranged to form a Wheatstone bridge. A digital indicator is used to take the observations. The calibration is done by 50 kN dead weight force machine. The metrological characteristics of the transducer were evaluated using ISO 376 and are summarized in Table 8 after re-calibration.

Salient features of the findings regarding elliptical shaped force proving instrument and force transducer are as follows:

I. Metrological capabilities reveal that the force transducer's uncertainty of measurement is high in lower range due to higher relative uncertainty due to repeatability and reproducibility.
II. Reversibility is another dominant parameter which greatly affects uncertainty of measurement, especially in lower range.

Table 7 — Details of 20 kN elliptical shaped force transducer.

S. No.	Parameter	Unit	Value
1	Length (parallel side)	mm	120
2	Width	mm	45
3	Inner radius	mm	40
4	Young's modulus of elasticity	GPa	210
5	Poisson ratio	--	0.3
6	Deflection (computational)	mm	2.46

Table 8 — Metrological characteristics of the elliptical shaped force transducer of nominal capacity 20 kN.

Force (kN)	Relative uncertainty contribution (%) due to							Uncertainty of measurement ($k = 2$)
	Zero offset	Resolution	Repeatability	Reproducibility	Interpolation	Reversibility	Applied force	
2	0.030	0.008	0.038	0.053	0.028	0.133	0.015	0.09
4	0.030	0.004	0.038	0.053	0.018	0.138	0.015	0.09
6	0.030	0.003	0.030	0.048	0.004	0.115	0.015	0.08
8	0.030	0.002	0.032	0.047	0.014	0.099	0.015	0.07
10	0.030	0.002	0.029	0.042	0.015	0.101	0.015	0.07
12	0.030	0.001	0.030	0.039	0.013	0.088	0.015	0.06
14	0.030	0.001	0.036	0.039	0.009	0.082	0.015	0.06
16	0.030	0.001	0.035	0.041	0.002	0.072	0.015	0.06
18	0.030	0.001	0.034	0.040	0.008	0.077	0.015	0.06
20	0.030	0.001	0.041	0.046	0.009	0.000	0.015	0.05

III. It is found that the mean value of the uncertainty of measurement is up to 0.10 % for nominal force 2 kN.

IV. The force transducer is found suitable for precision measurement applications with uncertainty of measurement in range of up to 0.10 % throughout the range of the force transducer.

V. Results show that the strain gauged force transducer's uncertainty of measurement is better than the dial gauged force transducer.

2.2 Square ring shaped force transducer

Ring shaped force transducers have proven to be better in terms of design, accuracy of measurement, feasibility of design studies using conventional theorems and cost. For better metrological characteristics and more certain force measurement, researchers are working to develop new shapes of primary sensing elements. As discussed earlier, ring shaped and elliptical shaped force proving instrument (and/or, force transducer) possess complex manufacturing considerations. Curved surfaces offer the difficulties in application of strain gauges[11].

Force transducer of square ring shape has been designed recently (Fig. 3) as a modified ring shaped force transducer and developed with the aim to get better measurement and metrological results. It is square in shape from outside and circular in shape from inside. The force transducer is developed for the capacity of 1 kN. The design is analytically examined using Castigliano's Theorem. As per the previous findings, stress - strain is maximum at the point of application of the force and the deflection calculated is the diametric deflection. Deflection through analytical mean is found to be 0.245 mm. Finite element analysis has been carried out using ABAQUS standard student edition with applicable load and boundary conditions according to analytical assumptions. Deflection through computational mean is 0.271 mm.

The force transducer has been investigated as per ISO 376 for relative uncertainty contribution due to reproducibility, repeatability, zero offset, resolution, reversibility and interpolation to evaluate the uncertainty of measurement. The uncertainty of measurement is up to 0.10 % (k = 2). Table 9 summarizes the metrological characteristics of the force transducer of square ring shape after re-calibration.

Salient features of the findings regarding square ring shaped force proving instrument and force transducer as are follows:

I. Force transducer of square ring shape offers comparable metrological characteristics.

II. The force transducer is found to offer its suitability with uncertainty of measurement up to 0.10 %.

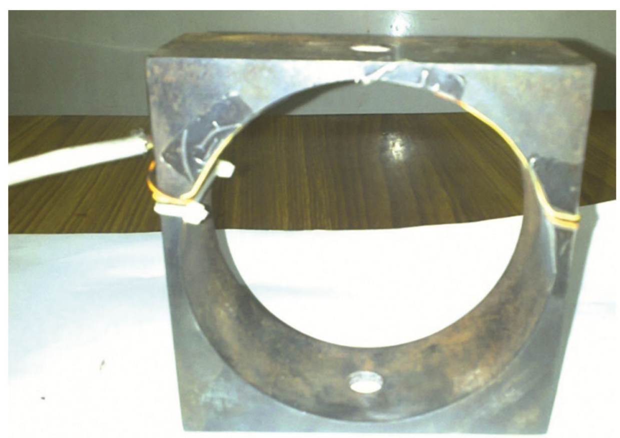

Fig. 3 — A strain gauged square ring shaped force transducer.

Table 9 — Metrological characteristics of a square ring shaped force transducer for nominal capacity of 1 kN.

Force (kN)	Relative uncertainty contribution (%) due to							Uncertainty of measurement (k = 2)
	Zero offset	Resolution	Repeatability	Reproducibility	Interpolation	Reversibility	Applied force	
0.1	0.024	0.020	0.060	0.100	0.016	0.080	0.015	0.09
0.2	0.024	0.010	0.050	0.060	0.021	0.095	0.015	0.08
0.3	0.024	0.007	0.040	0.060	0.034	0.060	0.015	0.06
0.4	0.024	0.005	0.030	0.055	0.017	0.060	0.015	0.06
0.5	0.024	0.004	0.028	0.052	0.012	0.062	0.015	0.06
0.6	0.024	0.003	0.027	0.033	0.002	0.058	0.015	0.05
0.7	0.024	0.003	0.020	0.026	0.004	0.048	0.015	0.04
0.8	0.024	0.002	0.022	0.037	0.009	0.032	0.015	0.04
0.9	0.024	0.002	0.027	0.031	0.000	0.031	0.015	0.04
1.0	0.024	0.002	0.024	0.026	0.009	0.000	0.015	0.03

III. The flat surface offers ease of strain gauging with simple design and manufacturing features.

2.3 Hexagonal shaped force transducer

This is another modified ring shaped force transducer (Fig. 4) for force measurement. It is developed for capacity of 20 kN. Outer surface is hexagonal and inner surface is circular in shape. The analysis of the proposed design is done using analytical expressions and computational analysis. A quarter of the ring is analyzed by finite element analysis and deflection is measured. Deflection is recorded as 1.92 mm at the nominal capacity of 20 kN using dial gauge indicator. The values for stress, strain and deflection for 20 kN applied force are 364 N/mm^2, 1.73×10^{-3} mm/mm and 2.05 mm, respectively, using finite element analysis, which indicates coherence of analytical and finite element analysis[12].

The force transducer developed is found to affirm Class 0.5 in accordance to ISO 376, and is suitable for metrological applications. Table 10 summarizes the force transducer's metrological characteristics after re-calibration.

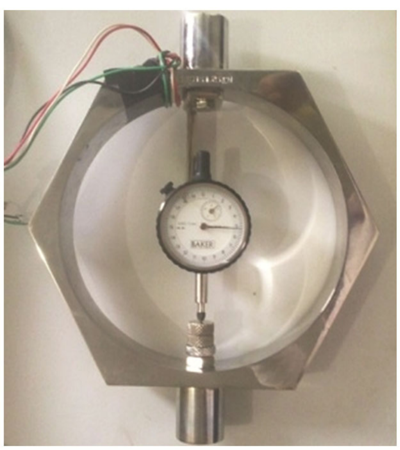

Fig. 4 — A dial gauged and strain gauged hexagonal ring shaped force transducer.

Salient features of the findings regarding hexagonal ring shaped force proving instrument and force transducer are as follows:

I. Force transducer of hexagonal ring shape offers comparable metrological characteristics.
II. Relative uncertainty due to reversibility is higher, especially in lower range.
III. The force transducer is suitable for industrial and metrological measurement related applications.
IV. The flat surface of the sensing element of the force transducer is suitable for application of strain gauges.

2.4 Octagonal ring shaped force proving instruments and force transducer

Force proving instrument and force transducer of octagonal ring shape (Fig. 5) is a modification of ring shaped force transducer. It is designed and developed for 25 kN capacity. It is an octagon from external surface and a circular ring from inner surface. This design facilitates the use of the force transducer for precision static force measurement related applications[13].

The study of force transducer of octagonal ring shape is conducted using dial gauge and strain gauges and has good metrological results according to ISO 376. The external octagonal shape of the transducer facilitates the positioning of strain gauges easily as compared to circular shape. The design is suitably analyzed using conventional theories and computational analysis is done using finite element method. Finite element method helps in determination of suitable locations of strain gauges. The uncertainty

Table 10 — Metrological characteristics of a hexagonal ring shaped force transducer for nominal capacity of 20 kN.

Force (kN)	Relative uncertainty contribution (%) due to							Uncertainty of measurement (k = 2)
	Zero offset	Resolution	Repeatability	Reproducibility	Interpolation	Reversibility	Applied force	
2	0.061	0.008	0.038	0.061	0.021	0.095	0.015	0.08
4	0.061	0.004	0.038	0.061	0.026	0.062	0.015	0.07
6	0.061	0.003	0.020	0.048	0.008	0.030	0.015	0.06
8	0.061	0.002	0.030	0.044	0.015	0.022	0.015	0.05
10	0.061	0.002	0.026	0.044	0.018	0.016	0.015	0.05
12	0.061	0.001	0.030	0.044	0.015	0.011	0.015	0.05
14	0.061	0.001	0.028	0.045	0.009	0.008	0.015	0.05
16	0.061	0.001	0.031	0.047	0.003	0.004	0.015	0.05
18	0.061	0.001	0.028	0.047	0.006	0.004	0.015	0.05
20	0.061	0.001	0.022	0.049	0.012	0.000	0.015	0.05

Fig. 5 — A dial gauged and strain gauged octagonal ring shaped force transducer.

Table 11 — Metrological characteristics of an octagonal ring shaped force transducer for nominal capacity of 25 kN.

Force (kN)	Relative uncertainty contribution (%) due to							Uncertainty of measurement (k = 2)
	Zero offset	Resolution	Repeatability	Reproducibility	Interpolation	Reversibility	Applied force	
2.5	0.007	0.005	0.030	0.050	0.018	0.097	0.015	0.07
5.0	0.005	0.002	0.020	0.037	0.006	0.055	0.015	0.04
7.5	0.005	0.002	0.018	0.033	0.002	0.036	0.015	0.03
10.0	0.005	0.001	0.016	0.027	0.002	0.022	0.015	0.03
12.5	0.005	0.001	0.013	0.018	0.005	0.018	0.015	0.02
15.0	0.005	0.001	0.008	0.015	0.005	0.005	0.015	0.01
17.5	0.005	0.001	0.010	0.014	0.000	0.003	0.015	0.01
20.0	0.005	0.001	0.012	0.014	0.000	-0.001	0.015	0.01
22.5	0.005	0.001	0.011	0.012	0.000	0.006	0.015	0.01
25.0	0.005	0.000	0.010	0.014	0.002	0.000	0.015	0.01

of measurement is up to 0.10 % (k = 2) for dial gauged force transducer of octagonal ring shape and 0.05 % (k = 2) for strain gauged force transducer of octagonal ring shape. Table 11 summarizes the metrological characteristics of the force transducer of octagonal ring shape after recalibration.

Salient features of the findings regarding octagonal ring shaped force proving instrument and force transducer are as follows:

I. Force transducer of octagonal ring shape offers comparable metrological characteristics in terms of uncertainty of measurement.
II. The force transducer offers its suitability for force measurement related applications with uncertainty of measurement up to 0.10 %.
III. The flat surface offers suitability of strain gauging with simple design and manufacturing features.

2.5 Axis symmetrical elastic elements for very large force transducers

As of now, developments have been reported for force measurement in the range up to kN and the developed force transducers have not been attempted for practical viability in the range of several MN. Efforts are been made to develop simple shaped force transducers for meeting industrial requirements like ship building, aerospace, civil engineering in the range up to few MN. Report of development of a strain gauged force transducer is made for forces in the range of 1 MN to 7 MN. The force transducer is designed by 2- dimensional axis symmetric finite element method with ease in design and manufacturing. Design specifications of reported work are as follows:

a) Capacity: 1 MN and 7 MN, overload capacity: 200 %

b) Average strain at nominal capacity: 1000 µm/m to 1500 µm/m
c) Maximum displacement at nominal capacity: < 0.4 mm
d) Height to diameter ratio: as low as possible

Among various flexible structures, following are capable of measuring mega Newton of force like compressed column type, shearing structures, membrane, compressed torus or sphere and other axis symmetrical shapes. The maximum strain gauge sensitivity has been assured by loading in shearing or bending. Different axis symmetric elements like square, hexagonal, rhomboid, triangular, N shaped, rectangular, circular, toroid, parallelogram (rotated as a truncated cone) can be used for serving the purpose. These types of transducers are able to measure large forces but their design structures are very complex. Their analytical estimation is also not possible because of the complexity in studying mono block structures behaviour[14].

2.6 N shaped axis-symmetric elastic elements for strain gauged force transducers

Researchers developed strain gauged force transducer of N shape for measurement of forces up to 10 MN. There are two cylindrical tubes of different diameters, concentrically telescoping one another with a conical tube interconnecting their opposite ends. It is an intricate elastic structure so analytical analysis is not possible. Researchers are working on the design for force measurement based on their understanding. Computational analysis is done using FEM. There is a mixed positioning of the strain gauges: two longitudinal and two tangential connected in Wheatstone bridge[15].

N shaped axis symmetrical design has following advantages over other flexible structures:

a) Ease of design and manufacturing
b) Balanced strain values
c) Used in on site calibration

2.7 Diaphragm shape

In this design, a strain gauged force transducer with simple design has been developed. Metrological performance is characterized as per ISO 376 standards. It is developed for 5 kN and made of EN 24 grade of steel. The diaphragm has 120 mm diameter and 30 mm thickness.

A hardened steel ball is used to apply force over a hemisphere at the center of diaphragm. Stress and displacement are simulated for forces 0 to 5000 N. Based on the findings of FEM, the strain gauges are applied at 90°, 180°, 270° and 360° on the outer flat surface of the transducer. The uncertainty of force measurement is up to 0.10 % (k = 2) which is suitable for industrial applications[16].

Recently, a realistic design, development cum experimental investigations of MEMS silicon diaphragm based force transducer have been presented for measurement of force in lower range (up to 50 N). A unique combination of a thin single crystal silicon diaphragm has been made as a mechanical sensing element in the presented design. The force sensor consists of four piezo-resistors in a Wheatstone bridge as in case of strain gauged force transducers. The force transducer has been characterized for its metrological features. The relative error due to repeatability is found to be < 1%, while the sensitivity has been found to be in order of 0.35–0.40 mV/V/N in the range of 10 N – 50 N forces[17].

3 Present Scenario

The force transducers are available by different commercial manufacturers through the globe, of different capacity, metrological capabilities, shapes etc. depending upon the applications. The nominal capacity of the force transducers may vary from sub-Newton to mega Newton and their classes as per ISO 376 may be from 00 to 2 or even not in scope of classification as per ISO 376.

Different researchers through the globe in past and present, have been working regarding the development of force transducers, though the quantum of reporting of research in this regard may be limited due to practical constraints. A number of force transducers have been developed and some of them have been briefly discussed in the presented manuscript, which are used for scientific and industrial applications including metrological applications.

It has been observed that simple shaped force transducers though developed and offers comparable metrological characteristics to the commercial force transducers. Such force transducers offers ease of manufacturing and design with economical advantages. Such force transducers have been reported for their nominal capacity in the range of kN only, though some designs and developments have been presented for their practical viability in higher range (say MN). In this regard, it is felt that there is need to develop simple shaped force transducers in higher capacity to make critical assessment for their practical viability for higher capacity too.

In addition, authors would like to emphasize over the development of novel simple shaped force transducers in order to keep on continuing the research and development pertaining to simple shaped force transducers for scientific and industrial applications.

4 Conclusions

Following conclusions are drawn from the presented investigation:

(i) A summarized report has been presented regarding different aspects of force transducers and their applications.

(ii) An effort has been made to discuss the analogue types of force proving instruments or transducers with their inherent shortcomings and issues, need to be addressed.

(iii) Discussion has been made regarding development of simple shaped force transducers (employing strain gauges) to improve the inherent limitations of analogue force transducers.

(iv) Brief discussion has been made regarding design, manufacturing and metrological considerations of simple shaped force transducers.

(v) Authors further raise the concern that there is a need to develop high capacity force transducers as limited development has been reported in past to address the raised concerns.

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