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Design, Development and Metrological Investigation of a Trapezoidal-shaped Force Transducer

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This paper demonstrates the design and development of a trapezoidal-shaped force transducer with simple assembly to accommodate easy strain gauging on flat surfaces. Finite element analysis has been performed for computational studies. The design is validated based on experimental results. Force metrology has been discussed in detail following the standard procedures as per ISO 376: 2011. Metrological investigation for category D (includes reversibility and interpolation) shows that the proposed design of the force transducer, achieved class 0.5 standards of force transducers with uncertainty in the measurement of only up to 0.10 % or better throughout at a nominal capacity of 15 kN (tensile load). The methodology proposed here paves way for future efforts to develop miniaturized strain gauged force transducer for a wide range of micromachining and similar other precision engineering industrial applications. Force measurement is an integral part of various industrial applications that require installation of force transducers. Sometimes, these transducers are required for on-site calibration of large testing machines. So, the current research work discusses and describes the designing of dial-gauge as well as strain-gauge arrangements of measuring of applied force.

Keywords: Calibration, force transducer, ISO 376: 2011, strain gauge, trapezoid, uncertainty of measurement

1 Introduction

The capability of precise force measurement is at the heart of many applications such as evaluation of the strength of an engineering component, the factor of safety estimation to design a component, thrust or drag measurement of an aircraft, transmission systems in automobiles, hardness measurement, and estimation of cutting forces for assessment of cutting tool life to name a few. While some applications involve measurement of static forces such as self-load other applications may involve dynamic force measurement. In the series of efforts to estimate the force in both conditions, a variety of force sensors or force transducers are developed in the past. These include diaphragm force transducer, N-shaped force transducer, Hall Effect transducers, Load cell, MEMS force sensor, Tuning fork sensors, and simply shaped force transducers. Kim *et al.*[1] developed a column-type force and moment sensor equipped with strain gauges as a measuring device. This force sensor is limited in use by interference error of force components and complexity of fabrication. Kumar *et al.*[2] suggested the concept of diaphragm force transducers with easy fabrication in which force measurement is accomplished with strain gauges. However, the uncertainty of measurement is found up to 0.06 % in the case of steel and 0.22 % for silicon diaphragm force transducers, which is again on the higher side. A general comparison of the various force transducers/sensors proposed in the literature is summarized and shown in Table 1[3-24]. Most of these devices have limitations in terms of capacity, ease of fabrication, and uncertainty of measurement. Also, the analysis on the economic aspects of the strain gauged force transducers with comparable metrological features shows that force transducers in the nominal capacity range of 5 kN – 50 kN are available in the price range of $ 400 to $1000 [25-27]. The current limitations and the high costs involved necessitated the development of an affordable and economic force transducer with robust capacities and ease of fabrication. This became the key motivation behind the present investigation.

This research discusses the development of a new measurement system for static tensile force measurement by a low-cost force transducer with simple design and assembly. The mechanical member

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Table 1 — Review of force transducers developed in the past[3-24].

S. No.	Force transducer / sensor	Concept / Working Parameter	Limitation
1.	Diaphragm force transducer[3]	Displacement is accounted as Wheatstone bridge output using strain gauges.	Developed for low force measurement of up to 5 kN only.
2.	N- shaped force transducer[4]	Wheatstone bridge output using strain gauges	Difficult construction and strain gauging.
3.	Hall – effect Force transducer[5]	Controlled current and position of Hall generator produced output voltage that indicates the measurement of displacement of order of ± 1.5 mm	Small force measurement, Large size and weight of permanent magnets, multipart connections of the closed-loop transducer.
4.	Force sensor based on Quartz tuning fork[6]	Cantilever deflection is converted into an output voltage.	Attainment of required operating temperature range and vacuum, Large size, inferior time resolution.
5.	MEMS force sensor[7]	Small forces measurement using micro-machined torsional oscillators.	Complex fabrication, a lot of analytical calculations are involved, measurement of very small forces only.
6.	Octagonal ring force transducer for 2 axis force measurement[8]	Strain gauges are used for the measurement of force. Elastic sensing element induces deflection	Low capacity transducer, inner geometry is circular that hampers the application of strain gauges on the inner surface.
7.	Low profile load cell[9]	Wheatstone bridge output using strain gauges	Complex circuits of strain gauges
8.	Commercially available force transducer[10]	Some of them imply strain gauges	High costs, complex configuration, No computational analysis exists in the public domain.
9.	Force balanced transducer[11]	Electromagnetic force balance lever structure for measuring static loads.	The output is greatly influenced by the air gap, temperature
10.	Vision-based force measurement[12]	Based on the linear elastic theory which is applied on a contour of an elastic object. Force is measured by preparing a force template matching algorithm.	In house manufacturing is far too difficult.
11.	Static force transducer based on resonant piezoelectric structure[13,14]	Electrical admittance spectrum determines the magnitude of applied force.	Frequency response of the given vibration mode degrades while measuring higher forces. Measuring range limits up to 1500 N only. In the case of static force measurement, the charge generated by the piezoelectric sensor speedily declines to zero. These sensors are susceptible to electrical signals (noise). Expensive sensors.
12.	Silicon-based shear force sensor[15]	Change in resistance determines the applied unknown force, experimenting with different angles.	It can only be used for low force measurement.
13.	Paper-based MEMS sensor[16]	Piezoresistive effect produced by conductive materials patterned on a paper substrate.	Useful for measuring mN forces with limited usage.
14.	Polymer based Capacitive sensor[17]	Capacitive change is measured on the application of 3 axial loads.	No theoretical analysis is available. It can be used only for the measurement of low force in the range of kN.
15.	Wireless thin layer force sensor based on magneto strictive composite materials[18]	Magneto- mechanical response gives the output. The maximum load that can be applied to the sensor is 1.5 MPa.	On the application of load, material properties of the sensor change. In house design & development is difficult. May not serve the purpose of on-site force calibration.
16.	Extended orthogonal ring transducer [19-21]	The orthogonal shaped sensor is designed with a strain gauge circuit to get an output in the form of change in EMF. It is designed to be used in force measurement in tillage studies.	Inner geometry is circular, so sticking of strain gauges, internally is difficult.
17.	3 D Printed Strain Gauge type force sensor[22]	It is developed using digital list processing printing. Strain gauges are printed using inkjet technology.	Repeatability error is very high (6.7%) with long response time. The design needs several improvements.
18.	3-layer circular piezoelectric transducer[23]	Analytical model is developed using the electromechanical properties of the proposed geometry and it is verified using FEM. Transducer deflection is proportional to the applied voltage.	Design lacks experimental evidence
19.	Ring-shaped magneto-elastic force sensor[24]	Ring shaped magnetic core is the primary sensing member. The force is applied in the direction of the diameter of the core.	Application -oriented design

developed here for force sensing is trapezoid-shaped. Dial gauge and strain gauges are used for the measurement of the applied force. The proposed design is validated by analyzing the concept by two techniques, *i.e.* finite element method, and experimental method. The proposed force transducer bears a fabrication cost not exceeding $150. There might be force transducers which are cheaper but may not be able to offer comparable metrological features. Moreover, the projected design of force transducer is developed in-house, and efforts may be made continuously to improve the metrological features further with the view to miniaturization to make it widely applicable in precision measurements.

2 Transducer Design: Computational Method

The trapezoidal-shaped force transducer Fig. 1 is an addition to the concept of simple shaped force transducers for precision industrial and metrological measurements/applications. In the proposed design, the shape of the sensing member is trapezoid as opposed to circular, thereby making it symmetrical to the vertical axis. As shown in Fig. 2, the inner length of the transducer is kept at least 160 mm for accommodating dial gauge arrangement to measure deflection precisely. The thickness of the sensing member is kept as 10 mm throughout. The length of the parallel sides is considered in coherence with the width (35 mm) of the sensing element. Table 2 shows the design parameters and their nominal values. The proposed trapezoid geometry offers the following advantages:

a. Ease in the machining of flat contours.

b. Adhering to the flat surface is easy and feasible (either on the inner or outer surface).

c. No economic barriers due to its simple design and manufacturing features.

Fig. 1 — 3-D view of the force-sensing element of the transducer

d. The transducer can be easily used as a force transfer standard and on-site calibration.

e. The nominal capacity of the proposed force transducer is 15 kN and has comparable sensitivity in the range of 1 N or better.

2.1 Computational solution to obtain the deflection

The computational analysis is conducted using Hypermesh v 13 software. Fig. 3 shows the flow chart of the various design steps involved in the computational analysis. Assuming EN 31 steel material properties and tensile loading conditions of 15 kN nominal force, the results from the numerical analysis are discussed in the later sections. The end bosses are neglected for analyzing a vertically symmetrical continuous configuration only. Approximation analysis has been completed using the Optistruct solver taking into consideration of mid-side nodes. Tetra meshing is done, by creating trias in the 3-D trapezoid section. The number of elements involved in finding maximum values of stress/strain is

Table 2 — Dimensions of the trapezoid element

S.No.	Parameter	Magnitude
1	Outer length	180 mm
2	Inner length	160 mm
3	Width	35 mm
4	End boss diameter	30 mm
5	End boss height	35 mm
6	Modulus of elasticity	210 GPa

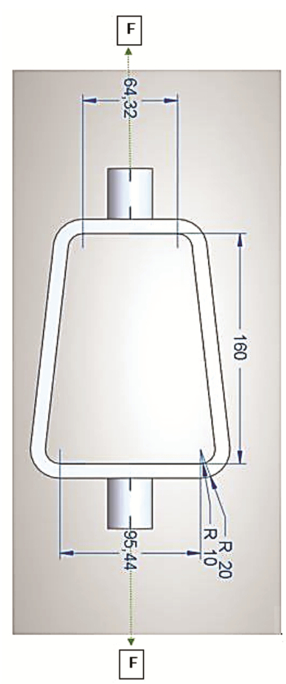


Fig. 2 — Dimensions of sensing element of the transducer

31407 and the minimum values of stress/strain are obtained with 47929 elements. The maximum and minimum deflection is obtained with 2954 grids and 54 grids, respectively[28].

2.2.1 Tensile stress and strain

The peak stress in the trapezoid is about 739.2 MPa (corresponding to the peak strain of 3.051×10^{-3}) at the point of application of force, as shown in Fig. 4 (a-b). This analysis helps in identifying suitable locations for applying strain gauges while making the Wheatstone bridge.

2.2.2 Deformation under tensile load

The maximum deflection of the sensing member is observed to be about 0.641 mm at the top of the beam as shown in Fig. 5 (a-b) marked by the red region. The trapezoid's deformation is studied and evaluated, for establishing the relationship between the deflection and the applied force. As per the Castigliano's findings, the partial derivative of the total strain energy with respect to the deflection at any point will be equal to the force applied at that point, in the direction corresponding to the deflection[29].

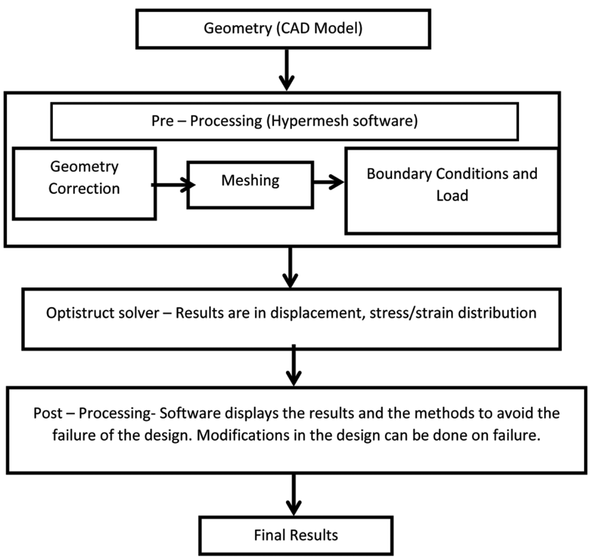
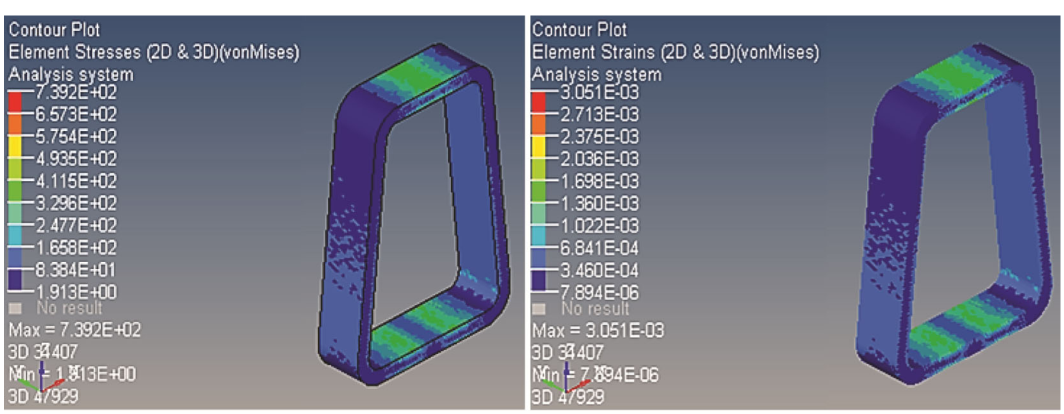


Fig. 3 — Overview of the transducer computational analysis procedure

3 Fabrication of Sensing Element of Force Transducer with Application of Dial Gauge & Strain Gauge

With the help of the computational study and as per the dimensions shown in table 2, the fabrication of EN 31 steel transducer Fig. 6 (a) is done on a vertical milling machine. Finishing operation is performed for adhering strain gauges. The permissible limit of surface roughness is up to 5 µm required for applying strain gauges. A high-resolution dial gauge indicator is fixed with the trapezoidal frame as shown in Fig. 6 (a) with a resolution of 0.1 µm. As shown in Fig 6 (b), the strain gauges are fixed on both sides at outer surfaces at 90˚ to connect in a Wheatstone bridge. The bridge is balanced and gives a null output when there is no force. An electrical output (mV/V) is obtained on the application of the external force.

The maximum stress/ strain points are at the top and bottom ends of the trapezoid geometry as shown earlier. Ideally, these points should be selected for strain gauging. However, the strain gauges are adhered to the outer surfaces at 90˚, because of two reasons: (i) The precision of the strain transducer with strain gauges at the selected locations (right and left) is better than the precision of the strain sensor with strain gauges at the top and bottom locations[30]. (ii) Secondly, the presence of the end bosses at the two ends causes difficulty in mounting of gauges on these locations. A high-resolution digital indicator (resolution 0.00001 mV/V) has been used for taking observation for undergoing the metrological characterization of



(a) Stress analysis **(b) Strain analysis**

Fig. 4 − FEA of trapezoid member for 15 kN tensile load

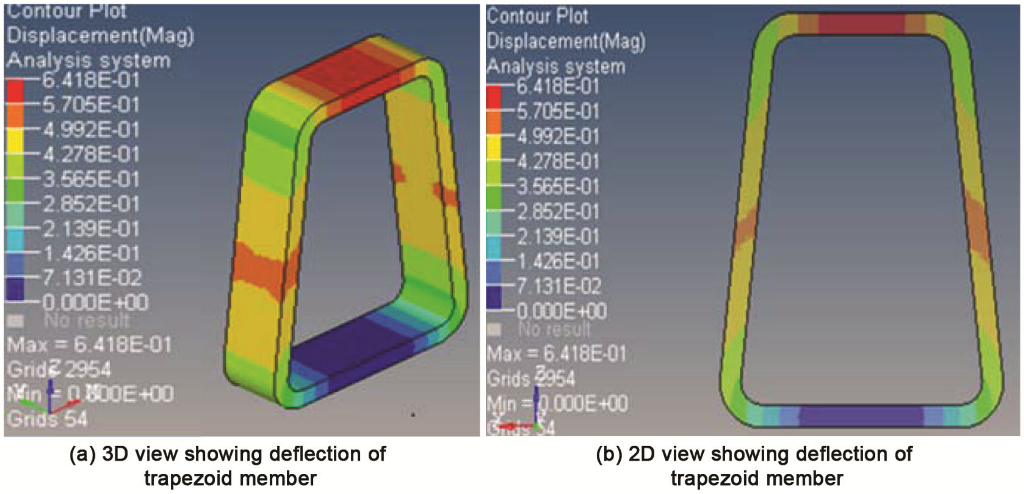


Fig. 5 − Deflection of trapezoid member for 15 kN tensile load

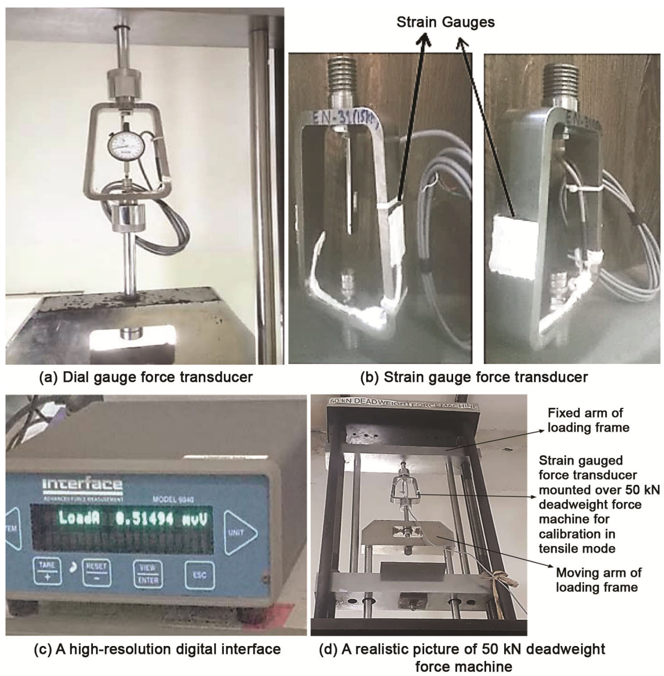


Fig. 6 − Hardware involved in calibration

the transducer Fig. 6 (c) over the 50 kN dead-weight force machine Fig. 6 (d).

4 Calibration Procedures

For rigorous metrological evaluation, the force transducer is calibrated using the 50 kN capacity deadweight force machine (DWFM) (uncertainty of measurement 0.015 % (k = 2) under a controlled environment (Temperature 23 ± 1^{o}C and Relative Humidity 50 ± 10 %). Transducer calibration on DWFM is a convenient method of application of precisely known static forces (dead weights) directly on the specimen (transducer)[31]. Following the calibration steps, as shown in Fig. 7, the deflection is measured using a high-resolution dial gauge and the electrical output using the digital indicator in the case of SGFT.

Other researchers have performed the calibration based on the standard ISO 376: 2011 for evaluating the performance of the force transducer[32]. Also, it is recommended to calibrate the instrument by increasing the force slowly and reading the same value for three series of measurements[33-34].

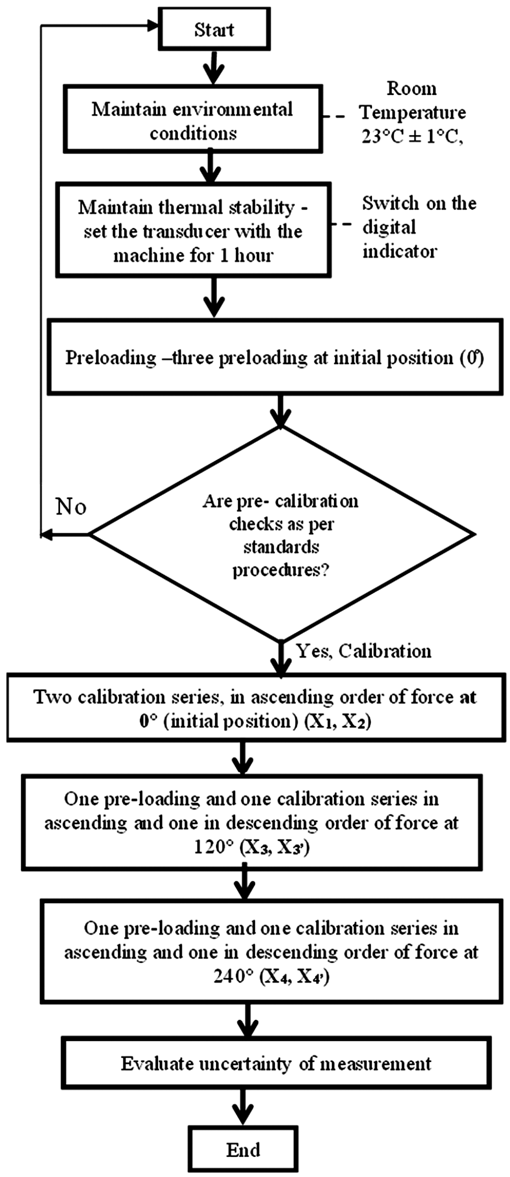


Fig. 7 − Flow chart of calibration procedure

4.1 Deflection comparative study: Computational (CD), and Experimental (ED)

The validation of computational deflection is made by calculating the deflection by the experimental method using a precision dial gauge of resolution 0.1 µm. A comparison of the two values and a graphical representation of the data is shown in table 3 and Fig. 8, respectively. In general, numerical values obtained by FEA showed proximity to the experimental values.

4.2 Metrological characterization of strain gauged force transducer (SGFT)

SGFT is studied for its metrological characteristics as per standard procedures and its performance evaluation is done by finding statistical dispersion

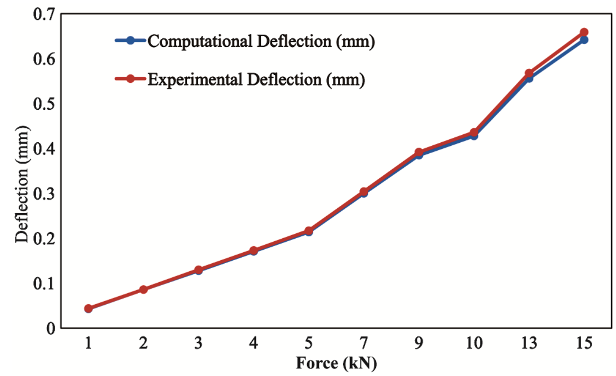


Fig. 8 − Comparative line graph of deflection

Table 3 — Deflection of the force transducer measured experimentally and compared to FEA simulation values

Force (kN)	Computational Deflection (mm)	Experimental Deflection (mm)	Deviation (%)
1	0.043	0.044	2.75
2	0.086	0.086	0.49
3	0.128	0.130	1.25
4	0.171	0.173	1.06
5	0.214	0.217	1.41
7	0.300	0.304	1.47
9	0.385	0.392	1.76
10	0.428	0.436	1.86
13	0.556	0.568	2.07
15	0.642	0.659	2.60

around the true value. It can be better understood in terms of the uncertainty of measurement of the force transducer. The uncertainty of measurement is related to the measurement and calibration process under defined environmental conditions. The factors considered to estimate the uncertainty of measurement is as per the ISO 376: 2011. The calculation of uncertainty of measurement is an effort to set reasonable constraints for the measurement result according to specified metrological standards[35-36]. Various factors that contribute to the calculation of the uncertainty of measurement are described in table 4.

The relative uncertainty of measurement is evaluated as follows:

$$w_{ct} = \left(w_{rep}^2 + w_{rpr}^2 + w_{res}^2 + w_{zer}^2 + w_{int}^2 + w_{rev}^2\right)^{0.5} \quad \text{... (1)}$$

Combined standard uncertainty of measurement is given by:

$$W = k.w_{ct} \quad \text{... (2)}$$

The overall expanded uncertainty of measurement is computed as follows:

Table 4 — List of factors that contribute to the uncertainty of force measurement in a force transducer

Factor (% relative error due to)	Brief description	Computation (*100) (2a)	Type of error	Probability Distribution	Factor of division (a/factor)
zero offset (zer)	Ideal value is zero but the measuring instrument gives generally a non-zero value reading, which leads to zero offset.	$\frac{\{\max(\text{X1 full load: X4 full load}\}}{\text{average at full load}(\text{X1, X2, X3, X4}}$	Rectangular	Type B	√3
Resolution (res)	Occurs due to instrument resolution.	$\frac{\text{resolution}}{\{\text{average}(\text{X1, X2, X3, X4})\}}$	Triangular	Type B	√6
Repeatability (rep)	Deviation of observations under the similar conditions e.g. same position	$\frac{\{\max(\text{X1: X2}) - \min(\text{X1: X2})\}}{\{\text{average (X1, X2)}\}}$	Rectangular	Type B	√3
reproducibility (rpr)	Deviation of observations under dissimilar conditions e.g. different position	$\frac{\max(\text{X1: X3: X4}) - \min(\text{X1: X3: X4}}{\text{average (X1, X3, X4)}}$	Triangular	Type B	√6
interpolation (int)	Least square polynomial fitting curve (Xa). Generally, degree of polynomial is 2 or 3.	$\frac{\{\text{average (X1, X3, X4)} - \text{Xa}\}}{\{\text{average (X1, X3, X4)}\}}$	U shaped	Type B	√2
Reversibility (rev)	Difference between two consecutive calibration series (X3 and X3')	$\frac{\{\text{X3}' - \text{X3}\}}{\text{X3}}$	Rectangular	Type B	√3
Uncertainty of measurement of applied force (cmc)	It is uncertainty of measurement of the force calibration machine	--	Normal	Type A	1

$$U = \left((W^2) + (w_{cmc}{}^2)\right)^{0.5} \quad \text{... (3)}$$

The metrology results are summarized in Fig. 9 and details are shown in detail in Appendix-1. Metrological characterization revealed encouraging results with the uncertainty of measurement up to 0.10 % and the relative error due to repeatability is much lower than the MEMS silicon diaphragm force transducer[37]. The factors as per class D instruments of ISO 376: 2011 have been considered and the force transducer is found suitable for reversibility and interpolation related measurements also.

The calculations for the uncertainty of measurement are validated through the excel sheet developed by the National Research Council (NRC), Canada based on the guide of the uncertainty of measurement[38]. The actual measurements made in the form of an excel sheet are shown in table 5. In this excel sheet, half of the relative deviations of the uncertainty contributing factor (a) are to be filled after dividing its (2a) value by 2 and the type of distribution of uncertainty contributing factor should be selected. The value has been checked for all the nominal forces, though for illustration purposes, calculations are made at 7 kN.

5 Results and Discussions

The proposed trapezoidal-shaped design proved efficient in fulfilling force measurement requirements

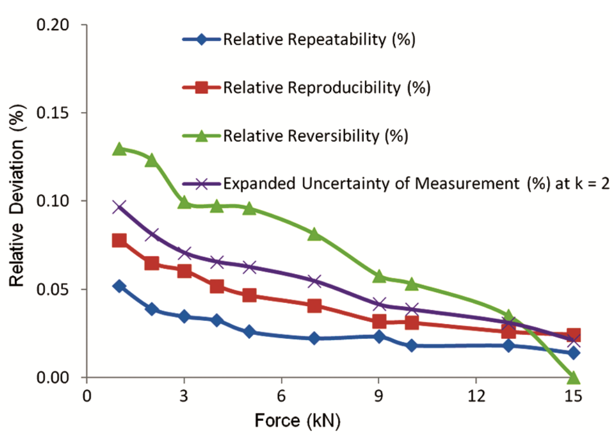


Fig. 9 – Uncertainty of measurement of SGFT

with established measurement uncertainty. According to EURAMET classification for force measurement, this trapezoid design of force transducer lies in class 0.5 category of force measuring instruments, for the full working range. The category is of class 00, upon considering the transducer's working range from 50 % to 100 %[39].

5.1 Design attributes

The design offers advantages in terms of design and manufacturing feasibilities along with economic considerations (fabrication cost is only about $150). The detailed expense has been described in table 6.

Table 6 — Fabrication cost

Description	Estimate ($)
Raw material cost	$ 20
Machining cost	$ 20
Heat treatment cost	$ 10
Surface finishing operation cost	$ 10
Strain gauging cost	$ 30
Dial gauge assembling cost	$ 20

*Estimate has not included the cost of calibration

The trapezoidal-shaped force transducer has flat inner surface unlike previously developed simple shaped force transducers. Simple ring/rectangular shaped force transducers have circular inner geometry. Hexagonal-shaped and octagonal-shaped force transducers have also developed by the researchers for fulfilling the force measurement related applications. These transducers have circular inner geometries. The symmetry and circularity of inner sections has to be monitored while machining and fabrication. The measurement of force has performed using analog and digital measurement instruments. The force is applied to the transducer, axially. So, the importance of correct symmetry and circularity plays a vital role in force measurement by analog (dial-gauge) instruments. On the other hand, strain gauges have to be mounted over the surface of the transducer for measuring the applied force, digitally. The sticking of strain gauges on the circular surface is another limitation of circular geometry. Trapezoidal-shaped force transducer has flat inner and outer geometries. Flatness offers easy machining and fabrication as well as application of strain gauges or other devices for strain/ deflection measurement. However, in this work, the strain gauges are assembled at the outer surface. In future, a handy sensor may be developed with strain gauges on the inner surfaces to evaluate the metrological performance.

This is an uncomplicated design that can be designed and developed in-house. There are force sensors/transducers/ load cells developed by the researchers with complex strain gauge assembly using 20+ strain gauges[40]. An optimized design of S-type load cell has developed by researchers for the maximum load capacity of 2500 N. The maximum stress, strain and displacement of the structural member are 203 MPa, 974 and 53.3 μm. S-type load cells are used in applications that require low force measurement. Also, the output of the design is not verified based on mechanical metrology[41]. Trapezoidal-shaped sensor is designed for a nominal capacity of 15 kN. Structural analysis shows 739.2 MPa maximum stress at 15 kN. So, the proposed force transducer is able to measure higher forces. The repeatability error of a load cell developed using additive manufacturing is 0.3 mV for 100 gm weight[42]. In the proposed trapezoidal-shaped force transducer, relative uncertainty due to repeatability error is 0.004 % at 15 kN force.

5.2 Target applications

With the achieved uncertainty of measurement in the present investigation, the force transducer finds the application in the following areas:

- Verification of uniaxial testing machines, where the uncertainty of force applied can be up to 0.2 %[43]. The trapezoid force transducer belongs to 0.5 class of accuracy and can be applied to calibrate tension/ compression testing machines. Also, it can be used as a transfer standard needed for the calibration of testing machines[44].
- Calibration of hardness blocks, where the permissible uncertainty of measurement of force transducer is upto 0.1 %[45].
- Calibration of force proving instruments which are used for applications where the uncertainty of measurement up to 0.1 % or higher is acceptable.

5.3 Practical Viability

Further trials were done to establish the measurement repeatability and for the verification of metrological characteristics in terms of the uncertainty of measurement of the force transducer. These results are shown in Appendix 2. The same calibration procedure was adopted and 10 runs were conducted over 2 months to judge its stability. It was established that the uncertainty of measurement was up to 0.10 %, making the proposed force transducer practically viable. Efforts are to be made for further improvements in the uncertainty of measurement of force transducer up to 0.05 % or better to have their practical viability on a larger scale to take advantage of simple design and manufacturing features of the force transducer reported.

6 Conclusion

The proposed trapezoidal-shaped DGFT and SGFT offer easy installation and operation in force measurement applications. The metrological characterization shows that the relative uncertainty error due to repeatability, reproducibility, and reversibility are not significant, as compared to other available force transducers. So, the proposed design is able to cater the applications that require measurement of force upto 20 kN, for example determination of cutting forces in machining, determination and application of force in the assembly of engine hydromount in automotive industry, on-site calibration of large testing machines, etc.

NOMENCLATURE

rep	relative repeatability (%)
rpr	relative reproducibility (%)
zer	relative zero offset (%)
rev	relative reversibility (%)
res	relative resolution (%)
int	relative interpolation (%)
w_{ct}	relative uncertainty of measurement (%)
cmc	calibration and measurement capability of force
W	combined standard uncertainty of measurement (%)
U	overall expanded uncertainty of measurement (%)
DGFT	Dial gauge force transducer
SGFT	Strain gauge force transducer

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ANNEXURE 1: Uncertainty of measurement of SGFT with contributing factors

Force (kN)	Mean Value of observations (mV/V)	Relative deviation due to (%) (2a)							Relative contribution to the combined standard uncertainty of measurement (%) (a/factor of division from table 4)							Relative uncertainty of Measurement wct(%)	w (%) at k=1	W (%) at k = 2
		re (%)	rpr (%)	zer (%)	res (%)	rev (%)	int (%)	cmc (%)	re (%)	rpr (%)	zer (%)	res (%)	rev (%)	int (%)	cmc (%)			
1.0	0.03850	0.052	0.078	0.010	0.026	0.130	0.053	0.015	0.015	0.016	0.003	0.005	0.038	0.019	0.008	0.048	0.048	0.097
2.0	0.07705	0.039	0.065	0.010	0.013	0.123	0.007	0.015	0.011	0.013	0.003	0.003	0.036	0.003	0.008	0.040	0.041	0.081
3.0	0.11557	0.035	0.061	0.010	0.009	0.100	-0.028	0.015	0.010	0.012	0.003	0.002	0.029	-0.010	0.008	0.034	0.035	0.071
4.0	0.15413	0.032	0.052	0.010	0.006	0.097	-0.012	0.015	0.009	0.011	0.003	0.001	0.028	-0.004	0.008	0.032	0.033	0.066
5.0	0.19268	0.026	0.047	0.010	0.005	0.096	0.000	0.015	0.007	0.010	0.003	0.001	0.028	0.000	0.008	0.030	0.031	0.063
7.0	0.26977	0.022	0.042	0.010	0.004	0.082	0.013	0.015	0.006	0.009	0.003	0.001	0.024	0.004	0.008	0.027	0.028	0.055
9.0	0.34681	0.023	0.032	0.010	0.003	0.058	0.004	0.015	0.007	0.006	0.003	0.001	0.017	0.001	0.008	0.019	0.021	0.042
10.0	0.38536	0.018	0.031	0.010	0.003	0.053	0.007	0.015	0.005	0.006	0.003	0.001	0.015	0.002	0.008	0.018	0.019	0.039
13.0	0.50092	0.018	0.026	0.010	0.002	0.035	-0.012	0.015	0.005	0.005	0.003	0.000	0.010	-0.004	0.008	0.014	0.015	0.031
15.0	0.57817	0.014	0.024	0.010	0.002	0.000	0.006	0.015	0.004	0.005	0.003	0.000	0.000	0.002	0.008	0.007	0.011	0.021

ANNEXURE 2: Repetitive measurements of the force transducers and uncertainty of measurement (%)

Force (kN)	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10	Average	Std. Dev.
1.0	0.096	0.094	0.094	0.098	0.095	0.096	0.095	0.096	0.098	0.095	0.096	0.001
2.0	0.081	0.082	0.080	0.083	0.080	0.081	0.080	0.081	0.083	0.082	0.081	0.001
3.0	0.069	0.071	0.070	0.070	0.072	0.070	0.070	0.069	0.069	0.071	0.070	0.001
4.0	0.063	0.063	0.064	0.063	0.063	0.064	0.064	0.066	0.063	0.064	0.064	0.001
5.0	0.062	0.061	0.061	0.060	0.062	0.062	0.062	0.061	0.064	0.062	0.062	0.001
7.0	0.056	0.056	0.053	0.053	0.053	0.054	0.055	0.053	0.054	0.053	0.054	0.001
9.0	0.041	0.042	0.041	0.041	0.042	0.042	0.042	0.043	0.041	0.040	0.042	0.001
10.0	0.039	0.040	0.038	0.039	0.040	0.040	0.041	0.042	0.042	0.041	0.040	0.001
13.0	0.030	0.030	0.032	0.032	0.031	0.031	0.032	0.033	0.033	0.031	0.032	0.001
15.0	0.022	0.022	0.021	0.021	0.020	0.021	0.022	0.023	0.020	0.021	0.021	0.001