

A contemporary investigation of force transducers: Past and present scenario

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In this paper, retrospective investigation of different types of force transducers, used in different applications (metrological, industrial, scientific etc.) for force measurement, has been done. The paper discusses the complete classification of force transducers based on shape, display and applications. Various types of force transducer have been discussed in the paper including symmetrical, unsymmetrical and alteration types. An attempt has been made to provide a comprehensive investigation related to metrological aspects of force transducer.

Keywords: Force transducer, Force measurement, Types of force transducer

1 Introduction

Force transducers, since many decades, have been used for force measurement and used to maintain traceability of force from standard machines to the functional areas, where it is required. Measurement of force using force transducers is required in numerous industrial applications like thrust force measurement in rocket engine or jet engine or gas turbine, electronic weighing scales, torque measurement on engines, or pumps and gearboxes, verification of material testing machine, measurement of cutting forces in different machining process like turning, drilling, milling, morphological study, rolling mills, high capacity hydraulic press machines, weighing of aircrafts, automobile industry calibration of hardness blocks for different scales such as Rockwell, Brinell and Vickers, micro hardness atomic force microscopy, etc. In addition, mechanical force measurement also plays an important part for design optimization of machining process such that improvement can be done in regard with the tool breakages and chatter control. Further, prediction of chip loading and accuracy of machined surface also rely on mechanical force measurement. Hence, the use of apt force transducers for variety of force measurements related to both industrial, metrological and scientific application's is very important.

Force transducers, used in variety of engineering applications are of varying complexity depending

upon the shape, material and applications etc., thus insisting accurate and precession measurement of force. It is also desirable to understand characteristics and basic operation of transducers before designing or identifying force measurement requirements for any application. For example, in case of metrological applications, high precision transducers are required¹. Further in biomedical fields, where transducers are used in human as well as veterinary tendons, the physical principle of force transducers are used plays a major role². In case of structural concrete testing, where transducers are used in reinforced concrete for bending moment, axial, shear force measurement and different force transducers are developed to find the reaction force of the external columns of reinforced concrete three bay. Further in the field of industrial transducer, where the transducers are used in design and development of a low capacity precision⁴. In case of manufacturing application, where the force transducers are used, where the critical force measurements are strictly needed⁵. Further for the measuring dynamic force, correction method for measuring dynamic force applied to force transducer is required. Levitation mass method⁶ is usually used for correcting the force measured by force transducer in a dynamic system. Further in the field of steel spring material, where transducers are used, effect of microstructure on the hysteresis performance of force transducer play a very vital role⁷. In case of biomechanics field, where the transducer are used in measure the functional grip forces through novel force

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transducer⁸. Further in the field of retrospective investigation of force transducer, where the force transducers are used force measurement for dead weight force machine⁹.

It can be seen from above discussion that, there are many ways force transducers can be classified. In the present paper, a brief review of the various types of force transducers used in different applications is presented. A brief discussion of the present trend and future development is also been made in the present paper.

2 Classification of Force Transducer

Force transducers can be classified in many ways for example, based on display, shape, type of application etc. In this section detail review of various force transducers classified under different categories are presented.

2.1 On the basis of indicating device

On the basis of the indicating devices, the force transducers may be classified as shown in Fig. 1. The force transducer may broadly be classified into analog type or digital type on the basis of indicating device.

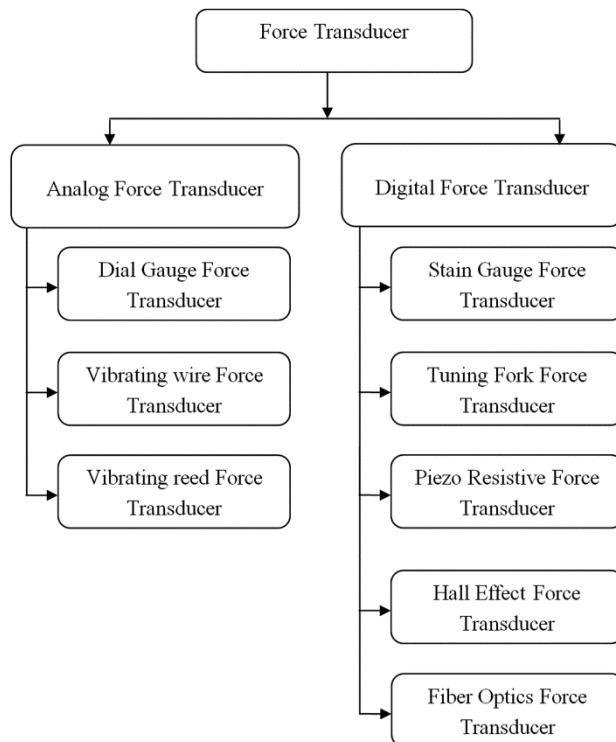


Fig. 1 – Classification of force transducers on the basis of indicating device.

2.1.1 Analogue force transducer

Analog force transducers consist of the force transducers using analogue devices like micro meter or vibrating reed, dial gauge as representing device for force measured by the sensing element of the force transducer. Deflection of sensing elements is sensed by the dial gauge and the amount of deflection gives the measure of applied external force. These types of transducers majorly face problems like restricted resolutions for the display of dial gauges and very poor uncertainty of measurement. Though many applications use this practice, but up to best of knowledge of authors, such practice are not recommended by any of standard⁹. On the better side, dial gauge force transducers are very easy to design and have easy manufacturing consideration. This type of force transducers are majorly used in the application areas where only the final value of force applied is needed and intermediate steps are not required.

(i) Dial gauged force transducer

Dial gauge force transducer proving instrument have been used to measure as per ISO 376, standard the force in terms of the reading given by dial gauge (deflection, variation, etc.) and additional traceability of force. The force is may be applied in two modes one is compression and other is tension. The force is applied on the sensing elements via end bosses it deflects and the deflection is measured by wall. The value of deflection given by dial gauge is used as a reference value to measure the applied force. Some investigations are presented in past regarding such force transducers stability and reliability.

(ii) Vibrating reed force transducer

Vibrating wire force transducer: These types of transducers basically use a slender like structure, e.g. wires, tube etc, which vibrates at its natural frequency. The value of the natural frequency depends upon the force or load applied and is then measured to give the input value of the measurand. These types of transducers are used where loading and unloading is in variable condition. It is also used in other various applications like, tensometer for monitoring concrete structures, monitoring water levels at high stable and sensitive means. These type of force transducers are very complex in shape and structure and strongly connected with mechanical assembly of the measurement system comprising an electromagnetic excitation and a piano wire¹⁰ (Fig. 2).

Vibrating reed force transducer works on natural frequency and plays a vital role in a different application areas like sensors, determination of elastic property of material, mechanical resonator and instrumentation. Xiang *et al.*¹¹ Studied and developed the new vibrating reed machine and they are using a helical RF resonator type as the capacitive transducer. Vibrating reed magnetometer constructed with high sensitivity. The vibrating reed magneto- meter method makes use of the force which is exerted on a sample with a magnetic dipole moment in a gradient field¹². Gamboa *et al.*¹³ calculated the process of equipment for future application thin films comprising for different layer of fabrication. Natural frequency and damping factor of various fabricated films of different layers were measured. Simulations were also performed using FEM methodology to predict the natural frequency and damping factor of films and were then compared with the experimental results of three layered films. A schematic force transducer of this type has been shown in Fig. 2.

2.1.2 Digital force transducers

Digital force transducers consist of the force transducers using digital display, like fiber optics force transducer, strain gauged force transducer, piezo-resistive (MEMS) force transducer, frequency based (tuning fork) force transducer, and Hall Effect based force transducer, as representing device for the measured force of the sensing element of the force transducer principles. Development of such force transducer started in 1950's and as on date, most prominently used for precision force measurement, dominated by strain gauged force transducer. These transducers are more advanced as compared to analog force transducer because the computer compatibility of digital system is very good¹⁴. These force transducers were developed in 1950's and were made

commercially, still strain gauged force transducer are more prominent. On the basis of working principles some of the types of digital force transducer are given as below.

(i) Strain gauge transducers

These force transducers were developed in 1950's and are used for very consistent force measurement as on date. The use of force measurement system is often analyzed using numerical data to understand the effect of varying load conditions and the predicted value should be equal to the true value in the ideal case generally force. In given transducers stain gauge in of foil type is used on larger scale⁹. Some new strain gauged transducers are developed for biomechanics applications and to measure functional grip forces. This device is also used to measure radial forces divided into six different components and can measure force up to a range of 250 N each segment with accuracy of 1% which can provide precious contribution data for biomedical models⁸. One of the physical parameter, i.e., torque plays a very important role in several applications for power, agriculture, aviation and automobile industry. It measures mechanical type torque having higher uncertainty. It has been studied and developed 5 N m capacity of torque transducer using strain gauge and also analyzed metrological characteristics' against standard torque machine (bmc = 0.05 % at $k = 2$) to measure the uncertainty of torque transducer¹⁵ is 0.06 % (at $k = 2$). To measure forces on medically used mitral valve annuloplasty devices, a new annular force transducer is developed. These transducers are X- shaped and are designed to optimally measure the simultaneous in and out of plane forces. It also reduces the unon-uniformity of the forces in the mitral annular segments and in the MV plane¹⁶. Strain gauged force transducers (Fig. 3) offers to measure

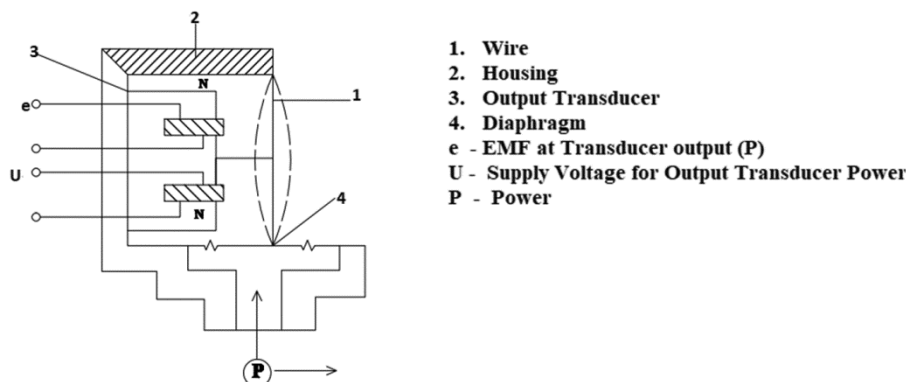


Fig. 2 – Schematic diagram¹⁰ of VWFT.

the force in terms of electrical form like voltage as output of Wheatstone bridge, according to that the strain gauge based force transducer are arranged¹. Considering one of the most important parameter in a competitive situation, traceability plays a very important role globally. Kumar evaluated the uncertainty of 1 MN force calibration machine¹⁷. Further, provided an innovative design to accommodate parasitic force and bending moment components. They also suggested that transducers specific calibration can also reduce the parasitic components. They also suggested that transducers specific calibration can also reduce the parasitic components. A typical process for measurement of force consisting of intermediate steps has been outlined in Fig. 3.

(ii) Tuning fork type force transducer

Tuning fork type force transducer has got low power consumptions, high precision and high stability and is basically uses for frequency measurement. In 1960's, spring based or mechanically operated pendulums were replaced in large quantity by crystal watches, which uses advanced technology for satisfactorily stable for regular uses. Friedt and Carry¹⁹ discussed about the quartz tuning fork used in application requiring accurate time reference. They also showed that the quality factor can be changed by injecting energy in phase or out of phase. A design and fabrication strategy was presented by Xu *et al.*²⁰ for a quartz tuning fork temperature sensor. The vibratory modes were analyzing and the sensor structures are optimized using FEM analysis. Hayashi *et al.*²¹ developed the 50 N capacity tuning fork type

force transducer having enough high precision force measurement, durability and stability for experimental use. It has compared two type of tuning fork transducer with three different type of high quality strain gauge force transducer. Main advantages of these types of transducers are long term stability, repeatability, reproducibility, creep, hysteresis, and temperature coefficient as compared to strain gauge type force transducer.

(iii) Piezo-resistive force transducer

These sensors are working on the principle of piezo resistive effect. They use the cantilever force sensors made-up with screen printed method based on the sacrificial layer development. They are made up using design from the sacrificial layer process and thick film technology. The beam is strained by the applied functional force which is measured by the electrical sensor located on beam surface. Material which constitutes the piezo-resistance defines the gauge factors of these kinds of transducer²². Further the use of titanium dioxide (TiO_2), diamond-like carbon (DLC), and thin films sputtered silicon carbide (SiC) have been discussed. These types of materials are used for high temperature application and the piezo-resistive transducer sensors are produced using RF magnetron sputtering of these materials²³. It is also used for lower range of force measurement, in sub Newton or micro Newton range. Search *et al.*²⁴ performed studies for optimized doping condition and characterization for the fabrication of such devices.

(iv) Hall effect based force transducer

Hall Effect based force transducer works on the principal of varying its output voltage in response to a

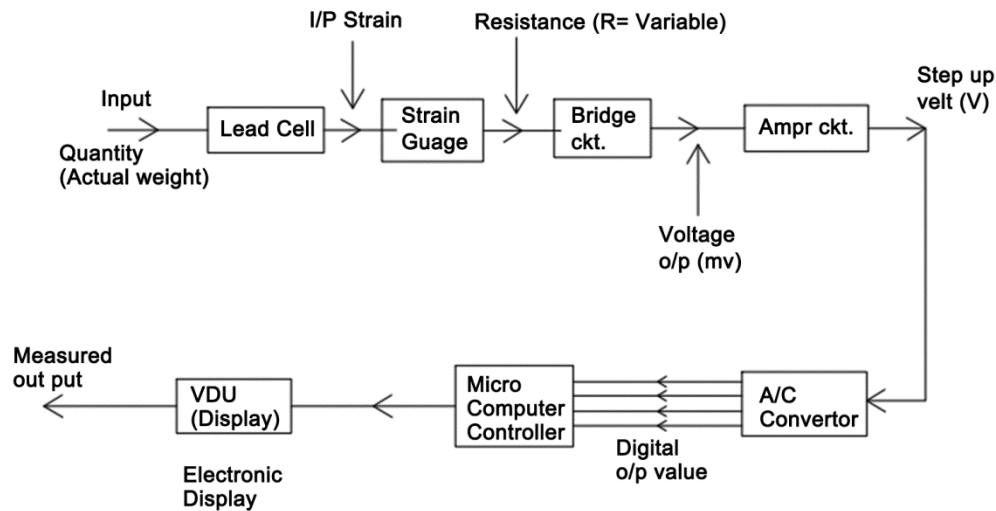


Fig. 3 – Various step of force measurement sequence¹⁰.

magnetic field. There are various applications, where these transducers are used. For example, current sensing and positioning of the pneumatic or hydraulic cylinders speed, speed detection, measurements in speedometers, proximity switching, frequency meters, tachometers, and magnetic levitation, etc. Hall Effect transducers are very sensitive type transducers hence; choice of material plays a very important part in maintaining the sensitivity. The materials used are the Graphene, Indium antimonide (InSb), Indium phosphide (InP), Gallium arsenide (GaAs), Garshelis and Indium arsenide (InAs). Garshelis *et al.*²⁵ found that stress-caused difference in leakage flux may be of sufficient quantity and can show little sufficient non-linearity and hysteresis a useful measure of an applied force and the simple design leads to its use in the construction of small, low-cost force transducers. Kyberdt *et al.*²⁶ developed a hall effect based transducer which are using in automatic manipulation for four degree of freedom. These transducers have lot of features including capability to find slip vibrations, sensitivity and changes in forces with movement through a sensor matrix. Jezny *et al.*²⁷ found out hall effect based force transducer are normally used in time the speed of wheels and shafts, such as for IC engine ignition scheduling, anti-lock braking systems and tachometers. Constant efficiency is maintained in brushless DC electric motors so that actual location of the permanent magnet can be identified. To select a proper sensing technology effectiveness and efficiency needs to be determined based on some critical parameters such as, travel distance, operating cost, precision and resolution.

(v) Fiber optics force transducer

Force transducers based on fiber optics are used in various applications like welding application, moisture monitoring, strength of bridge monitoring, telecom cable and crack monitoring in structure, to measure temperature and also used for stress and strain measurement. One of the most important fields where the fiber optics force transducer is used, is biomedical²⁸. Arata *et al.*²⁹ studied the application of optical transducer in minimal invasive surgery (MIS) where the force information is sent to the surgeon when direct vision is not possible during surgery. Further a Fiber Bragg Grating (FBG) sensor based back-born sensor structure prototype model was developed and presented for medical purposes. In a FBG sensor based transducer the structure of fiber optics plays a vital role that is, it should be able to

transform the bending motion to development or compression motion so as to perfectly determine the force. The developed medical force sensor transducer has been very compact, lightweight and bio compatible with a capability for temperature compensation and amplification of output. Zhu *et al.*³⁰ studied about the perfect investigational study of landslides based on combined optical fiber transducer and various types of windbag holes and find out the two types of bore holes, inclined and vertical constructed using landslide experiment model.

2.2 On the basis of electrical phenomenon

The force transducers classified on the basis of the electrical phenomenon have been shown in Fig. 4. There are mainly three electrical phenomenon line resistance, inductance and capacitance.

2.2.1 Resistive force transducer

One of the most general techniques to measure force relies on the principle of sensing resistance. The main advantages these types of force transducers are their low, maintenance-free technology, reliability, simple structure and variable resolution. Further, it is easy to measure electrical resistance over a broader range, as the cost associated with electrical property measurement is very modest. Based on these features resistive type force transducers are majorly preferred in majority applications areas¹⁰. Jafer *et al.*³¹ developed a wireless system for monitoring of multi-sensors. Their aim was to build an effective telemetry system for temperature signals and water pressure. Two novel ideas had been presented by Marcellis *et al.*³² for fully-analog and automatic Wheatstone bridge-based circuit readouts and extended the operating gap of the long-established bridge. They also established that, in the initial interface the reading of the output signal and the use

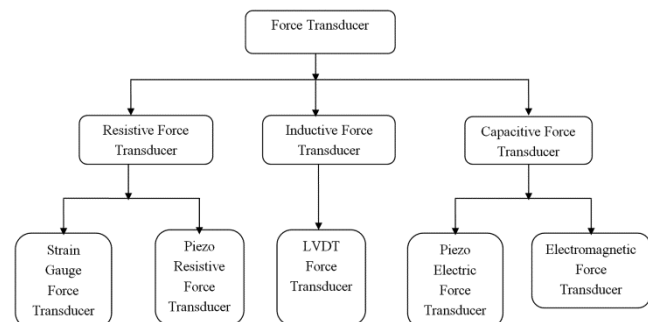


Fig. 4 – Classification of force transducers on the basis of electrical phenomenon.

of a fully-analog four quadrant multiplier as voltage controlled resistor (VCR) is enough to easily approximation wide resistive sensor variations.

An integrated Readout Interfacing Circuit (ROIC) was studied by Fauzi *et al.*³³ for resistive transducer using SILTERRA CMOS 0.13 μm which changes the voltage based on the reading of shift in resistance. The aim of their project was to use Wheatstone bridge to build an integrated interfacing circuit with higher sensitivity. They were able to growth sensitivity, when compared to the conventional bridge, by 4 % using the technology discussed above. Zainuddin *et al.*³⁴ verified the function of an active bridge circuit as the ROIC for a tactile sensor. They applied the tactile sensor to a 3D prosthetic finger, to exhibit the sensitivity of the active bridge circuit for more than one gestures depending. They found that sensitivity of active bridge circuit was more when compared to conventional bridge, similar to studied earlier³³.

2.2.2 Inductive force transducer

These type transducers are based on the changes observed in a single coil self-inductance or in a two coil mutual inductance when applied to an external field. The applied external fields could be a force, pressure, torque, linear or rotary displacement, vibration velocity and acceleration. The change in inductance is because of the movement of concentric magnetic core due to applied external field³⁴.

2.2.3 Capacitive force transducer

Capacitive force transducers are very accurate when compared with other electric transducers, and are mostly used for their tremendously high robustness, stability, resolution, drift-free measurement capability, large bandwidth and sensitivity. It can also be used for harsh environments like high temperature, radiation, and magnetic fields, as well as in different non-contact or noninvasive applications. Impedance of capacitive force transducer is very good. Carr *et al.*³⁵ investigated the behavior of capacitive force transducer through the various experiments and they found that resonant frequency is dependent on the thickness of membrane. They also found that random and grooved back plates have given the better results. Liu *et al.*³⁶ analyzed the limitation and capability of multi-user MEMS processes (MUMPs) process for capacitive micro machined ultrasonic transducers (cMUTs) fabrication. Further found that MUMPs cMUTs have potentially comparable performance with cMUTs from other

processes. Sato *et al.*³⁷ proposed designed thick member structured transducer and analyzed the sensitivity and verified it using finite element analysis (FEA). They found that sensitivity increased by three times, when compared with the conventional design, by reducing the mass of the thick membrane by 70% for same resonance frequency of the membrane. Emadi *et al.*³⁸ developed a novel transducer cell configuration used which can be used for very high performance transducer at low megahertz range. Two vibrating cell membranes were used in its cell structure for these types of transducers. It works on MEMS sacrificial technique. Transducer output is also measure in axial direction. Maity *et al.*³⁹ analyzed characterizes a 2-D CMUT array element using FEM simulation in open air and found good results. Capacitive Micro machined Ultrasonic Transducers (CMUTs) are used in veracious application like nondestructive evaluation and medical imaging.

2.3 On the basis of output parameter

On the basis of the output parameters, the force transducers classified are shown in Fig. 5. Generally, the output parameter is voltage, deflection and frequency.

2.3.1 Deflection force transducer

Kumar *et al.*⁴⁰ studied the circular ring shaped force transducer, usually used for force measurement. They performed experiments and FEM analysis of circular ring transducer under axial load condition for high precision and accuracy. Further, the results computed by FEM analysis for the axial deflection varied up to a maximum of 3% when compared to experimental values. The above results are representing the deviation between the value examined by computational using finite elements method and experimentally. The finding pared the way for conversion of analog force transducer to digital force transducer using strain gauges.

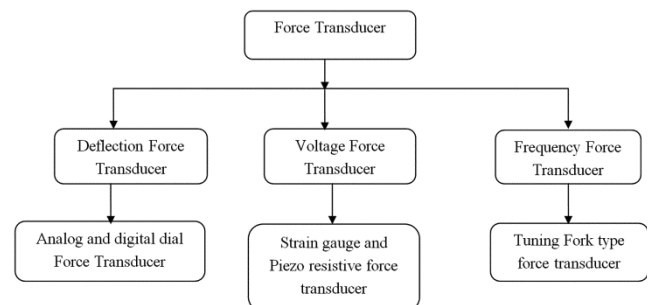


Fig. 5 – Classification of force transducers on the basis of output parameter.

2.3.2 Voltage force transducer

These types of transducers are classified based on the output parameter. Normally, voltage serves as the output parameter for the strain gauge and piezoresistive force transducers. Jenkins *et al.*⁴¹ studied about usage of strain gauge to measure bone fracture healing. They showed that, real time tracking is possible with the help of voltage type output transducer and showed the utility of strain gauge to measure the very critical parameters during the bone fracture healing operations. The details of strain gauge force transducers are discussed earlier. Such force transducers are most commonly used for metrological and industrial application.

2.3.3 Frequency force transducer

The frequency force transducers are categorized based on the resonance frequency as output parameter. Generally, the tuning fork type force transducers are providing the output results in terms of frequency. A tuning type force transducer was designed by Hayashi *et al.*²¹ which had the operating capacity up to 50 N. The facility was examined using force standard machine at the National Metrology Institute of Japan (NMIJ). Jun *et al.*²⁰ used the comprehensive thermal characterization of the XY-cut quartz tuning fork resonator to study a less power and high precision temperature sensor.

2.4 On the Basis of Shape

On the basis of shape, the force transducers are classified in Fig. 6. The force transducer may be either simple shaped or complex shaped and they may be further categorized into different shapes.

2.4.1 Column shaped force transducer

To monitor the health of structures, machine tool and controlling of robot with precise accuracy, moment transducers, which can measure the multi-component force system, are required. Now a day's infrastructure is playing a vital role to growth of our country. In this regard to maintain the accuracy, precision and load distribution of structure column shaped force transducers are required. A multi element force/moment sensor with a column type structure was designed by Kim *et al.*⁴² and the ratio of length and diameter ($\frac{L}{D}$) for the sensing of part. Studies were conducted experimentally and using finite element analysis software, using decoupling method with adding and subtraction process with

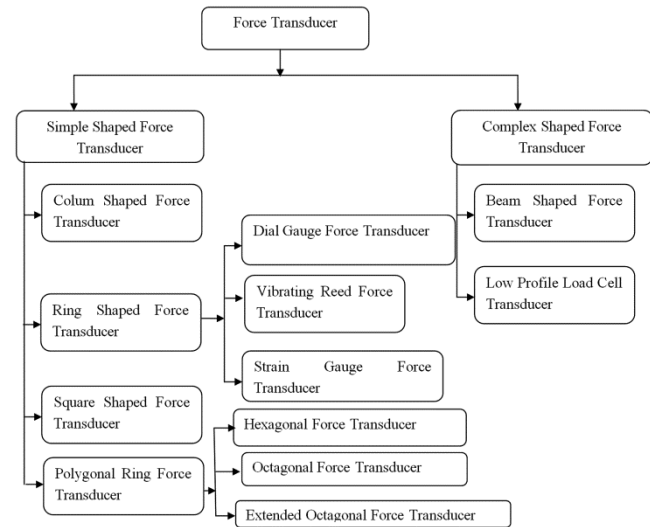


Fig. 6 – Classification of force transducers on the basis of shape.

single strain gauge. It was found that efficient and economical use of column type force transducer is essential for measuring the force or moment component of building structures. A column type force-moment transducer was studied by Park *et al.*⁴³ which had very high stiffness and different frequency range when compared to binocular type force transducer. Further dynamic evaluation was carried out and resonance frequency for the multi component force-moment transducer was compared to that of theoretical approximation.

2.4.2 Ring shaped force transducer

This type of force transducer is also known as proving ring shaped force transducer. These transducers were designed by National Institute of Standards and Technology, USA. These transducers are available in different capacities ranging from Newton to mega Newton depending upon the applications. Due to the simple design and easy manufacturing associated with ring shaped transducers, these transducers had served as force transfer standards for long time. For deflection measurement, they normally employ dial gauges. After performing large number of investigations, it was found that deflection could be linear up to some extent and can deviate from the linearity up to some extent⁹. Sudhir *et al.*⁴⁴ developed a thin elastic ring force transducers of 100 N suitable for static force measurement. Ring shaped force transducers have ability to segregate the tangential and normal components of applied force makes it the most used force transducer. For a 100 N transducer, using

various calibration processes based on ISO 376 and IS 4169, measurement uncertainty was found to be 0.2 % ($k = 2$). Kumar *et al.*⁴⁵ investigated the ring shaped force transducer of capacity 20 to 50 kN in both the tension and compression mode using various calibration process based on ISO 376 and IS 4169. The uncertainty in measurement was found to be 0.025 % ($k = 2$) for 50 kN as per ISO 376. Further studies stress strain and deflection analysis using FEM software as well as analytical study has been completed and found force transducers have been found to show encouraging metrological results.

2.4.3 Square ring shaped force transducer

It is a modification of ring shaped force transducer and outer side looks like basically a square and inner side like a ring. The square shape of the outer surface of the force transducer offers suitability for application of strain gauge due to flat surface. Kumar *et al.*⁴⁶ developed and studied the behavior of a square ring shaped transducer analytically, computationally and experimentally. 1 kN square shaped ring transducer has been developed and calibrated in both the modes in compression as well as tension in accordance to ISO 376. The transducer has been investigated in terms of their metrological performance. Uncertainty has been also measured for the transducer and found up to 0.10 % ($k = 2$) from 10 % -100 % of their rated capacity.

2.4.4 Polygonal ring shaped force transducers

These types of transducers are basically modified version of ring shaped transducers. Different shaped polygonal transducers are designed by many researchers depending upon the application area and usage of the transducer. Some of the common shapes of these transducers are hexagonal, octagonal etc. These transducers are used in various application like turning, milling, drilling and boring etc.

Kumar *et al.*⁴⁷ designed and developed hexagonal shaped force transducer. Further investigated them analytically, experimentally and computationally to enhance the design. The beauty of these force transducers is prepared with strain gauge and as well as dial gauge. They developed a 20 kN capacity hexagonal shaped force transducer and also carried out the metrological investigation in accordance with the standard calibration method based on ISO 376 and found the uncertainty of measurement in the transducer up to 0.01 % ($k = 2$). They also found out

that relative error in the measurement because of reversibility is also very important while calculating the uncertainty of the transducers, especially in the lower range. An uncertainty of 0.125 % for 2 kN was found due to reversibility which is in accordance with the guidelines of the standard ISO 376, making it suitable for metrological application. The outstanding feature of hexagonal shaped ring transducers that it offers application in the area of where force applied is over flat side surfaces. Gianfranco *et al.*⁴⁸ designed hexapod –shaped multi-component force transducer on the basis of specific request from railway industries, requiring the measurement of two force component like axial force and transversal force for performances of coil spring in railway carriage suspensions. They found that relative expanded uncertainty of about 0.2 % for both cases axial force as well as transversal force.

Soliman⁴⁹ developed octagonal ring force transducer as a sensing component for measuring the mechanical forces. The further investigated strain distribution along the different faces and regions of the ring use the programming and simulation software MATLAB. They also used L₉ orthogonal array of finite element simulation software for their performance measurements and design parameters. They found that from simulation a considerable variation in strain along ring face and average strain was practical to measure than maximum strain.

Kumar *et al.*⁵⁰ used an octagonal shaped ring transducers in a dynamometer. This shape was used by them to obtain better stability when it is mounted and to obtain zero rotation on the top side of ring section. It also isolated the transverse and vertical force components, making it suitable for applications involving dynamic conditions, where torque measurement is also required. They also investigated the uncertainty and which was found to be 0.10 % better than strain gauge transducers.

An extended octagonal shaped ring transducer was developed by Godwin⁵¹ for a specific application tillage studies. The main purpose to design extended octagonal ring transducer is to measure a different components of forces and moment in a two force plane from the soil reaction to simple times. They found that for extended octagonal ring transducer the output varies linearly and does not depend on the load positions on the tine. In case of maximum tillage

studies with two dimensional force systems have very less hysteresis and cross sensitivity and meets as per necessities.

Afzalnia *et al.*⁵² designed and developed an extended octagonal ring transducer to find forces in various directions inside a large square baler compression chamber. The extended octagonal ring transducer exhibited excellent linearity and low cross sensitivities. They found that when strain gauges installed on the plunger arms, force measurement in the *x*-direction inside the bale compression chamber were nearby to the analytical results for maximum force inside the compression chamber of the baler.

2.4.5 Complex shaped force transducer

Complex shaped force transducers are not easy to fabricate simply because of manufacturing of complex shape⁵³. Bending beam shaped force transducers generally use the strain gauge. To monitor the strain of the elastic element of various size, shape, and design depends on the applied forces, i.e., bending forces. There are various bending beam shapes force transducer are available for different applications. These force transducers are available in various ranges from low to high capacity. One of very popular transducer in use is S shaped. S-type load cell series offers a compact design for a variety of weighing and test and measurements applications.

3 Present Scenario

In current scenario various type of force transducers are available commercially for different applications, whether it may be scientific, industrial or metrological in the range from sub-Newton to mega Newton force. Despite of several types of force transducers (based on principle), strain gauged force transducers are dominant in most of the functional applications.

3.1 Commercial availability of force transducer in range of sub-Newton to mega Newton

Now a days, different types of commercial force transducers are available in the range mentioned above with varying metrological characteristics depending upon their principle and applications. There are force transducers with uncertainty of measurement as low as 0.005% or up to 1% for industrial applications. Simple shaped force transducers are designed and developed for particular

applications in-house and there are limited examples in this regard.

3.2 Complex shape and design considerations

The most important of aspect of force transducer is design complexity due to which the manufacturing associated with it can become costly and difficult. Hence it became really important to consider the design for any industrial application of force transducer. Such constraints are responsible for limiting the development of complex shaped force transducers for in-house applications.

3.3 Trade barrier

Trading plays an important part in the force transducers availability in the market. Presently only few big manufactures are present in India as well as across the globe. The procurement process for end user is very difficult because of the involvement of various modalities between manufacturing unit and customers. Therefore, the cost of the transducer raises because of handling charges, transportation charges etc. Apart from it there is a possibility of damage because of various handling procedure involved. Hence, it becomes difficult for the customer to order a precise force transducer because of its cost. Ecommerce has its own disadvantage, as only general type force transducer is available on ecommerce websites and these cannot be used everywhere. To overcome this problem there is a need to develop simple shaped force transducer with simple manufacturing techniques such that, even small scale industries can manufacture it with low cost and high precision. Recently, Kumar *et al.*^{45,46} has developed ring shaped and square ring shaped force transducer using strain gauge with high accuracy and precision. The design is very simple and load capacity is also variable. Hence, there is a need to develop more similar type of simple force transducer.

3.4 Simple shaped force transducers

These have been developed over past years through the globe for different applications, their practical viability is yet to be established over a larger range (i.e. N to MN). A simple shape force transducer offers the ease of installation of strain gauge because of its geometry and shape. There is nod of continuous efforts of development of such force transducers for their practical viability and versatility for different applications.

4 Metrological Aspects

Force transducers are metrologically characterized by globally on the basis of guidelines of ISO 376 and ASTM E-74, though most widely, ISO 376 is used. ISO 376 (present version 2014) provides the guidelines for calibration procedure to be adopted and different factors pertaining to uncertainty of measurement leading to its evaluation. Figure 7 provides the details of ISO 376 in order to consider different factors like relative zero offset, relative resolution, relative repeatability, relative reproducibility, relative reversibility, and relative creep etc. to be considered as the case may be of analogue force transducer or the digital force transducer. Table 1 gives guidelines regarding contribution of the factors mentioned above while computing the uncertainty of measurement of the force transducer. Each factor mentioned above has already been discussed earlier by researchers^{46,47} and in ISO⁵⁴ 376. Different components pertaining to uncertainty of measurements have been summarized in Fig. 7. Table 1 mentions the limits of the different

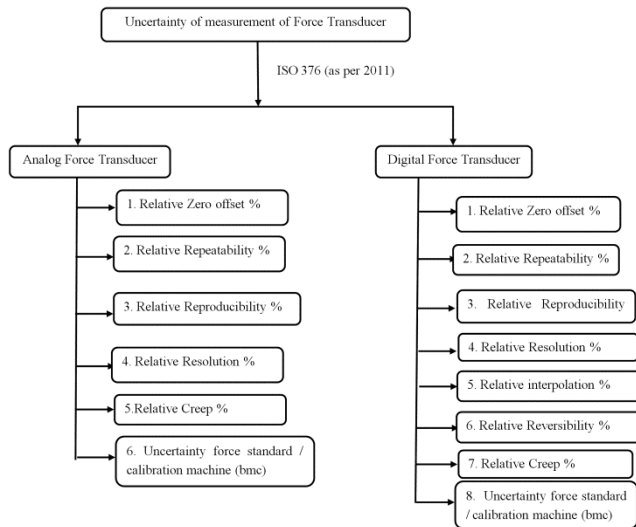


Fig. 7 – A scheme of different factors contributing to uncertainty of measurement of force transducer as per ISO 376 as the case may be.

uncertainty of measurement contributing factors as per ISO 376.

5 Conclusions

Following conclusions are by the authors from their cross sectional investigation pertaining to different aspects of the force transducers:

- (i) Different types of force transducer like analog force transducer (dial gauge, vibrating reed, vibrating wired), digital force transducer (proving ring, Hall effect based, tuning fork, fiber optics, strain gauge based force transducer), resistive force transducer (Piezo resistive and strain gauge base), inductive force transducer (LVDT force transducer), capacitive force transducer (piezo electric and electromagnetic force transducer) deflection, voltage and frequency force transducer discussed and summarized. Also discussed simple shaped (column shaped, ring shaped, square ring shaped, polygonal ring) and complex shaped force transducer (beam shaped and low profile load cell force transducer).
- (ii) Modern force transducers are based on measurement of the strain proportional resistance of metallic foils (also known as strain gauges) fixed on elastic elements and are being widely used for force measurement. The change in strain gauge resistance is measured using normally four strain gauges placed suitably on elastic element and connected in a Wheatstone bridge powered by an external excitation voltage. The difference voltage generated in the bridge is monitored by a digital indicator.
- (iii) Various characteristics related to the force measuring instruments have been reviewed and discussed related to metrological characterization of force transducers.
- (iv) Authors would like to thrust upon the need of simple, but precision force transducers which can be cost effective and can be used of various

Table 1 – 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 | | | | | | |
|-------|---|---|-------------------------------------|-------------------------|------------------------------------|-------------------------|------------------------------------|
| | % of Reproducibility (<i>b</i>) | % of Repeatability (<i>b</i> ²) | % of Interpolation (<i>fc</i>) | % of Zero (<i>fo</i>) | % of Reversibility (<i>v</i>) | % of Creep (<i>c</i>) | % 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 |

load capacity for different metrological and industrial applications.

- (v) In concluding remark it can be said that, still a lot of work needs to be done to expand the application areas of the modern day force transducers.

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