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Design and development of an additive manufactured force transducer

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This paper discusses the design and development of an additive manufactured force transducer for force measurement applications. The force transducer is of square ring shape and dimensions have been evaluated in accordance to available literature. Fused filament fabrication technique has been adopted for fabrication of the force transducer and strain gauges have been applied at defined location in form of a Wheatstone bride. Efforts regarding metrological characterization are underway and successful demonstration of the force transducer will define a new development in the direction of force transducers.

Keywords: Force transducer, Strain gauge, Additive manufacturing, Metrological characterization

1 Introduction

Force transducers have been utilized for numerous applications fulfilling force measurement like electronic weighing machine, aircrafts, thrust measurement of jet or rocket engines, torque measurement, automobile industry etc[1]. There is an immense range of force transducers, ranging from few Newton's to mega Newton's, depending upon the required applications. They have been well equipped with different measuring devices or indicators such as dial gauged, digital dial gauged, strained gauged, hall effect sensor, fibre optics sensor, tuning fork etc for the realization of applied force. Among these, strain gauges have been prominently used for the strain measurement[2,3]. Conventional methods used for fabrication of force transducer have certain drawbacks such as time-consuming, material wastage and lack of manufacturability. Additive manufacturing or 3-D printing technology is prominently used to combat these drawbacks. With the advent of this technology, the force transducer has been utilized in various areas such as robotics, biomedical environment, and meteorological applications etc[4]. 3-D printers can be used to manufacture new, cost effective customized force transducer and it is possible to manufacture transducer with small size and in an economical manner in the field of robotics[5,6]. A brief summary of different types of force transducers is shown in Table 1.

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2 Additive manufacturing

Additive manufacturing also called, as three dimensional (3-D) printing is a flexible technique that develops physical objects from 3-D computer-aided design (CAD) model in a layer by layer manner. 3-D printing technology utilize digital environment of the manufacturing procedure. So, digital files can easily be shared and altered on a distribution basis. Other features include such as lowest amount of material wastage, mass-customized products, manufacturing of complex structures and fast prototyping, shorter time to market etc. Due to major advancements in the additive manufacturing (AM) process, it is possible to fabricate complex structures as well as electronic components like resistor, inductor and capacitor and circuits. Due to the fabrications of electronics on a flexible substrate, for example, plastic films, papers, and fabrics it is possible to produce customized electronic products[23]. 3-D printing provides major sustainability benefits such as redesigning of products, minimal wastage of materials, extended product life, economical products, design freedom and reconfigured value chains[24,25].

2.1 Opportunities and challenges in additive manufacturing

Apart from significant advantages, 3-D printing technology still has some challenges. Table 2 lists the various advantages and challenges.

3 Design and development of force transducer

A force transducer as discussed earlier might be of different shapes and are available commercially

Table 1 — List of available force measurement devices[7-22].

Sl. No.	Force Transducers	Working Principle	Limitation
1	Tuning- fork force transducer[7, 8]	Cantilever deflection is converted into an output voltage.	No theoretical basis for verifying the design
2	Hall – effect force transducer[9]	Output voltage indicates the measurement of displacement	Small force measurement only, bulky construction.
3	Octagonal ring force transducer for force measurement[10]	Wheatstone bridge	low capacity transducer
4.	Force balanced transducer [11]	Electromagnetic force balance lever structure	Ambient conditions effect the output
5.	MEMS force sensor[12]	Micro-machined torsional oscillators	Complex fabrication, small force measurement
6.	Low profile load cell[13]	Wheatstone bridge	Complex circuits of strain gauges
7.	3-D Printed strain gauge type force sensor[14]	Wheatstone bridge	The design needs several improvements.
8.	Static force transducer based on the resonant piezoelectric structure[15,16]	The electrical admittance spectrum determines the magnitude of the applied force.	sensors are susceptible to electrical signals (noise). Expensive sensors.
9	N- shaped force transduce[17]	Wheatstone bridge	No analytical detail is available, complex construction
10.	Diaphragm force transducer[18]	Displacement is accounted as Wheatstone bridge output using strain gauges.	Developed for low force measurement upto 5 kN only.
11.	Solid-state laser force transducer[19]	Measurement is based upon the photoelastic effect in lasers.	The test set up cannot be designed and developed in- house. Expensive and time-consuming setup.
12.	Ring-shaped 3 –axis micro force/torque sensor[20]	Piezoresistive technology using strain gauges is applied for fulfilling the measurement purpose.	Too small sensor design is itself a problematic parameter, to use it appropriately.
13.	Strain gauge sensors for impulse force$_{21}$	Measures dynamic and static forces, both.	Measurement uncertainty is high because of parasitic resonances.
14.	Ring-shaped magneto- elastic force sensor[22]	Magnetic flux generates an output voltage.	No quantitative model is discussed.

Table 2 — Some advantages and challenges in additive manufacturing[25-33].

Sl. No.	Advantages	Challenges
1.	Design for additive manufacturing and assembly (DFAM) process provide to reduce development time, cost, and enhance quality and profit.	Some 3-D printing techniques have limited materials for product manufacturing.
2.	Generation of customized products with no additional tooling.	Poor surface quality and post-processing is often required.
3.	Minimal material wastage, recycling of waste material, weight reduction of products.	Intellectual property issues.
4.	Due to digital nature of design file, it can be shared from one end to another end.	The development of multifunctional and functionally graded materials is in initial stage.
5.	Manufacturing of complex structures due to functional design.	Support structure materials are wasted and cannot be recycled.
6.	On-demand manufacturing and excellent scalability.	Some 3-D printing techniques have some issues with the cost and speed of the manufacturing process
7.	Sustainability benefits: improved resource efficiency, larger product life, product redesign, remanufacturing.	Supports sustainable production but towards industrial purposes, it is unclear.
8.	Manufacturing of stretchable, light weight sensors and electronics sensor. For examples flexible force sensor.	In the electronics industry; conductivity, types of materials, and issues in the printing method.
9.	Using 3-D printing, biomedical implants, tissues, organs, and customized drugs can be printed. The most common material is ceramic.	Some regulatory issues, limited availability of bio materials.
10.	Fused filament fabrication (FFF) and inkjet printing are prominently used in the development of different type of sensors such as force, pressure, strain and electrical and electronics sensors etc.	Other 3-D printing techniques are also used but their uses in the field of sensors have not been found on a large scale.
11.	3-D printing provides health benefits related to human health and safe working environment.	A more development is needed regarding working environment.

through the different manufacturers. Despite of ready to use availability of the force transducers, attempts have been made in past on continuously basis regarding development of simple shaped force transducer. Some of the simple shapes include ring[34], hexagonal[35], elliptical[36], square[37] and octagonal[38] etc. Additive manufacturing enables the fabrication of complex shaped force transducers, simple shaped force transducers are fabricated through the conventional methods. Recently, there has been thrust over the development of 3-D printed force transducers[7,39-41] and some of the force transducers have been developed and reported. In this regard, authors would like to thrust upon the development of simple shaped force transducers developed recently before emphasizing over the complex shaped force transducers. Authors are presenting herewith development of a square ring shaped force transducer with simple design and manufacturing consideration to evaluate the practical viability of the force transducer.

A square ring shaped force transducer has been one of the simple shaped force transducers developed recently for metrological and industrial application. The force transducer as shown in Fig. 1 is square shaped from outside and ring from inside. The force transducer is designed is designed for the nominal capacity of 1 kN (Fig. 1). The material is taken as Acrylonitrile Butadiene Styrene (ABS). ABS has very less density, in the range of 1.05 – 1.20 g/cm^3 with modulus of elasticity in the range of 1.00 – 2.65 GPa.

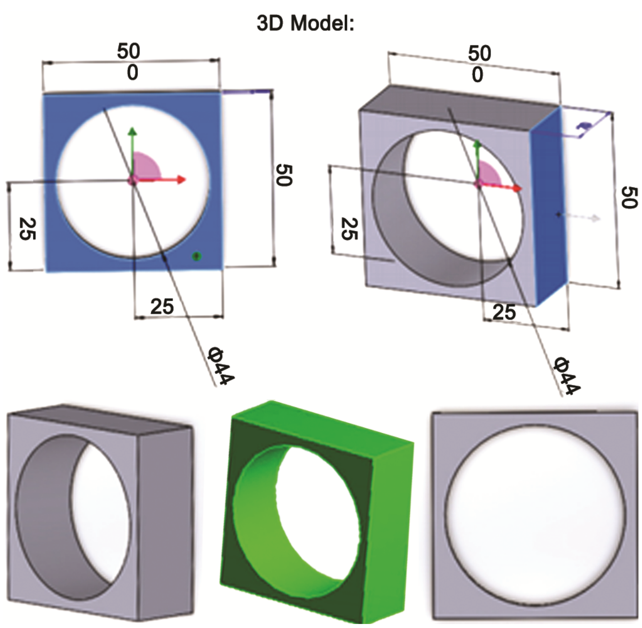

Fig. 1 — Schematic of the force transducer.

The force transducer was fabricated (Fig. 2) using FFF technique of additive manufacturing in-house through CubePro™ FFF printer. The layer thickness was kept 200 µm and the temperature of the nozzle was kept 285 °C with bed temperature 100 °C.

3.1 Strain Gauging of the Force Transducer

In this study, foil-type strain gauges were used. The resistance of all four strain gauges were 350 Ω (R) with a gauge factor (K) equals to 2. A Wheatstone bridge was formed by arranging the strain gauges (Fig. 3). Equation (1) shows the bridge in proper balance conditions with equal strains.

$$\frac{R_1}{R_4} = \frac{R_2}{R_3} \quad \ldots (1)$$

Strain gauges were installed at identified positions, as shown in Fig. 3. No temperature compensation was considered in the present study as the calibrations were done in a controlled environment, as mentioned in the metrological characterization. The force transducer is shown in Fig. 2.

4 Results and Discussion

The force transducers were developed for different applications for several decades. Force transducers are

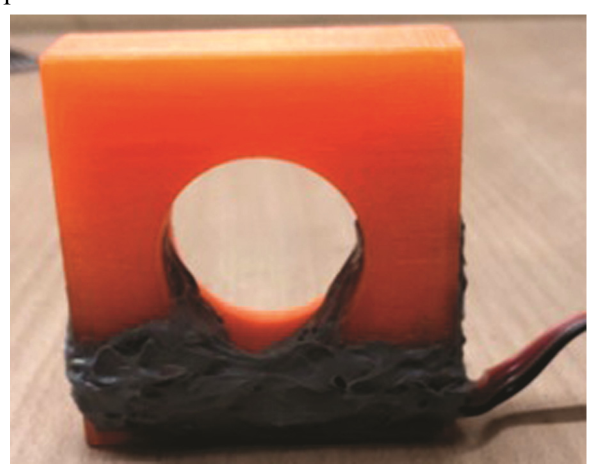
Fig. 2 — Additive manufactured strain gauged force transducer.

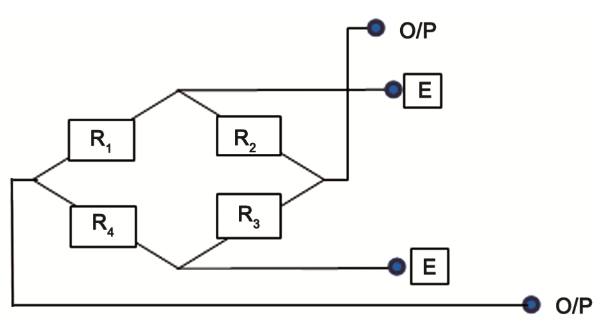

Fig. 3 — Wheatstone bridge circuit.

required for different scientific and industrial applications, e.g. verification of material testing machines, hydraulic presses, building structures etc. With growing need, attempts were made to develop force transducers in lower capacity. The presented study focuses the following objectives:

(i) Ease in the machining of flat contours.
(ii) Applying strain gauges on the flat surface is easy.
(iii) No economic barriers due to ease of design and manufacturing features.
(iv) The transducer can be easily used as a force transfer standard and on-site calibration.
(iv) Minimal material wastage.

A square ring shaped force transducer for nominal capacity of 1 kN was fabricated through additive manufacturing technology. The technique and the shape adopted offered the pre-requisite objectives. L Foil type strain gauges were applied over the outer flat surface at an angle of 90^{o} and a Wheatstone bridge was formed. The metrological characterization of the force transducer in accordance to ISO 376: 2011 is underway in order to prove the practical viability of the force transducer developed.

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