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An analytical, numerical and experimental study of an octagonal ring force transducer for a 2-axis force measurement

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Abstract. A reliable force transducer is urgently required in engineering design, optimization, monitoring systems, and mechatronic fields. In this paper, characteristic of an octagonal ring as force transducer is studied. This transducer utilized strain gauge which is designed to able measure the external force in 2-axis both vertical and horizontal simultaneously. Strain distribution analysis on the transducer were done to get the accurate position of the strain gauge bonded using theoretical and numerical approaches. In the end, an octagonal ring force transducer is manufactured and the calibration test is conducted. The experimental results show a good performance of sensitivity, linearity, repeatability and low cross coupling error. The result found that developed force transducer is suitable and reliable to measure static and dynamic forces.

1. Introduction

Force measurement is an important task in engineering fields to obtain the information related to mechanical system in various applications. In the past before the 20th century, various methods have been used for measuring forces based on mechanic, pneumatic and hydraulic devices [1]. These nonelectric force measuring methods which not have sensitivity to electric signal as required in the current measurement system to be integrated with control and automation systems. Therefore, force transducer is a key component in the force measurement system which can converting an applied force into a material strain or deformation [2]. This deformation is then can be sensed by resistive, capacitive, inductive and piezoelectric sensors to given the output reading in electrical signals [3].

The force transducer structure have elastic element that can occurs stresses and displacements when external force applied on it. These stresses can be determined by using measurable parameters, such as strain, that vary in response to loading. Strain gauge in one of more strain sensors which is simple, low cost and easy to use. Strain gauges were arranged in the form of a Wheatstone bridge, a means accurately detecting very small changes in resistance of strain gauge during imposed by external force on the transducer structure. The output of the bridge is a measure of the applied force that expressed in the form of an electrical output, like voltage (V) [4].

Recently, many types and various geometrical shape of strain gauge based force transducers have been developed for measuring force. Ștefănescu [1] have classified ten types of force transducers which can be measured force in range 200 N to 50 MN. Ring shaped type force transducer is still populer area of research although many years of research. Typically circular [5], square [4], hexagonal [6] and octagonal [7] shaped rings are approved as the basic geometric structures of a force transducer. Some



studies in the past have applied the octagonal ring as dynamometer in turning process [8], milling process [9, 10] and also drilling process [11]. However, the octagonal ring force transducer is multi-purpose 2-axis force transducer that can use in many applications. In previous study, there are still rare studies of strain analysis that compare analytical, numerical and experimental. In addition, an octagonal ring force transducer application as a 2-axis force plate for biomechanics study of human motion is still very rare. Therefore, in this study will focus on design, construction and characterization an octagonal force transducer for two-axis forces measurement that is normal and tangential forces.

2. Design Analysis

An octagonal ring force transducer was designed in this study. The transducer is expected to detect external forces in two directions that are vertical and horizontal forces, or normal and tangential forces. The good model of transducer can be indicated by high sensitivity and low interference error between two directions of external force. An octagonal ring with two force exerted on the top of its structure was shown in Figure 1. The transducer is designed for maximum capability of 750 N, and the other geometries are selected about 15 mm of width (b) and 12.5 mm of radius (r). The maximum stress and strain on the octagonal ring surface due to external force was set as the point to be placed the strain gauge.

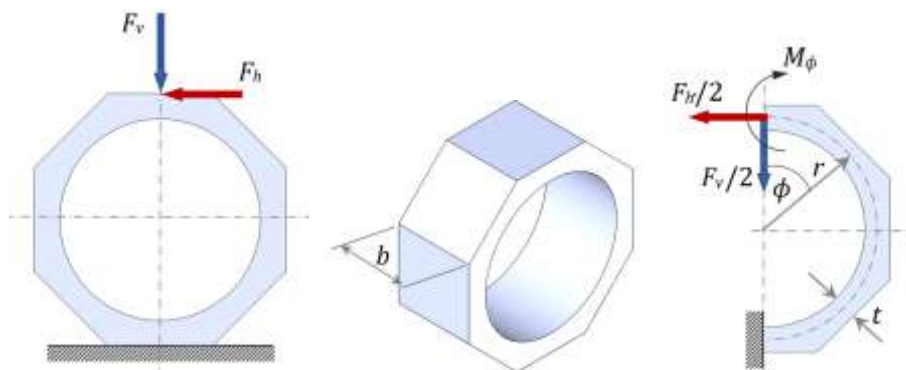


Figure 1. The octagonal ring force transducer model

2.1. Analytical Study

Analytical study was employed to estimate strain and stress of the octagonal ring. Figure 1 shows the octagonal ring is subjected to the vertical or normal force (F_v) and the horizontal or tangential force (F_h). When the bottom of the structure was fixed on the base and the external forces acting on the top of the ring would cause a moment to occur which varied with the angular position (ϕ). Elastic strains ε_{F_v} and ε_{F_h} due to forces F_v and F_h are calculated according to ring theory by using the following equations [10].

$$\varepsilon_{F_v} = \pm \frac{1.09 F_v r}{E b t^2} \quad (1)$$

$$\varepsilon_{F_h} = \pm \frac{2.18 F_h r}{E b t^2} \quad (2)$$

Since the material structure is stainless steel 304, with yield strength of 215 MPa, then in order to avoid structural failure due to overload, the maximum stress on the transducer must be below the yield strength (S_y) of the structural material. By taking into account the safety factor (sf) of 1.3, the maximum allowable stress can be obtained through the following:

$$\sigma_{max} = \frac{S_y}{sf} \quad (3)$$

then

$$\sigma_{max} = \frac{215}{1.3} = 165.4 \text{ MPa} \quad (4)$$

Therefore, by taking account the allowable maximum stress 165.4 MPa to equations (8) and (9), it can be obtained the range of allowable thickness of load cell structure that are:

$$t_{max} = \sqrt{\frac{2.32 F_t r}{\sigma_{max} b}} = \sqrt{\frac{2.18 (750)(12.5)}{(165.4)(15)}} = 2.87 \text{ mm} \quad (5)$$

$$t_{min} = \sqrt{\frac{1.09 F_n r}{\sigma_{max} b}} = \sqrt{\frac{1.09 (750)(12.5)}{(165.4)(15)}} = 2.02 \text{ mm} \quad (6)$$

The allowable thickness of structure is obtained in range 2 mm up to 3 mm, then it is selected with maximum thickness is 3 mm. If the actual force is exerted to the structure with thickness of beam about 3 mm in vertical and horizontal directions, so we obtained the actual stress are:

$$\sigma_{F_h} = \frac{2.18 (750)(12.5)}{(15)(3)^2} = 151.38 \text{ MPa} \quad (7)$$

$$\sigma_{F_v} = \frac{1.09 (750)(12.5)}{(15)(3)^2} = 75.69 \text{ MPa} \quad (8)$$

2.2. Numerical Study

Finite element (FE) analysis of the octagonal ring force transducer have been done to validate the analytical method. In the previously, FE method as an effective computational tool was used to identified the optimum location of strain gauge on the cross beam transducer [12, 13]. The octagonal ring has been modelled in three dimensional forms with the dimensions as follows: outer diameter 28 mm, inner diameter 22 mm and width 15 mm. Stainless steel 304 was used for structure material with Young's modulus of elasticity is 200 GPa and Poisson ratio 0.29. The boundary conditions as can be seen in Figure 1, the bottom end of the octagonal ring shaped transducer has been fixed and the top of ring is kept free which the force is applied in vertical and horizontal directions. The external forces are given from 10 N up to 100 N in each direction.

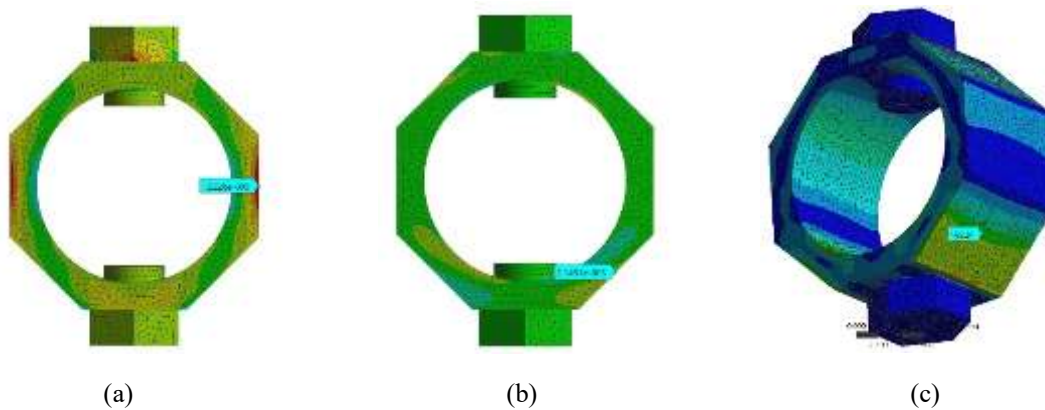


Figure 2. Strain distribution on the octagonal surface: (a) when vertical force, F_v was given; (b) when horizontal force, F_h acting on the top; (c) stress occurred at angle 39.5° from the bottom point.

Figure 2(a) shows strain occurred due to vertical force (F_v) acting on the top of the ring. It can be observed that the maximum strain occurred at an angle 90° about $12 \mu\epsilon$ or 1.2×10^{-5} mm/mm when the external force is 50 N. While the horizontal force was given on the top of the ring, the maximum strain appears at a 39.5° is about $21.5 \mu\epsilon$ or 2.15×10^{-5} mm/mm as shown in Figure 2(b).

Figure 2(c) shows stress occurred due to horizontal force (F_h). It can be seen that stress occurred at an angle 39.5° is 165.24 MPa. When this result is compared to the mathematical analysis, it can be found that the result is closely match to each other. The error of stress occurred between analytical and FE is not exceeding 9 % which it can be reasonably acceptable in engineering design study.

2.3. Experimental Study

The point of maximum stress and strain of octagonal ring force transducer was set as mounting of strain gauge. In order to measure strain due to the vertical force, a strain gauge has been mounted at an angle 90° from vertical axis. While, to detect the strain as result of horizontal force, another strain gauge has been mounted at an angle 39.5° from vertical axis as shown in Figure 3(a). A linear strain gauge with the nominal resistance about 350Ω was used for each channel of the transducer. Its dimension was 3 mm of length, 3.2 mm of width and gauge factor about 2. Before fixing the strain gauge, the surface of structure was polished with sandpaper and cleaned it with acetone. A quarter Wheatstone bridge was used for each channel by utilizing NI-9945 for balancing the circuit. Then, NI-9237 has been used for signal conditioning and data acquisition. The display and data recording program was developed in house using LabVIEW software.

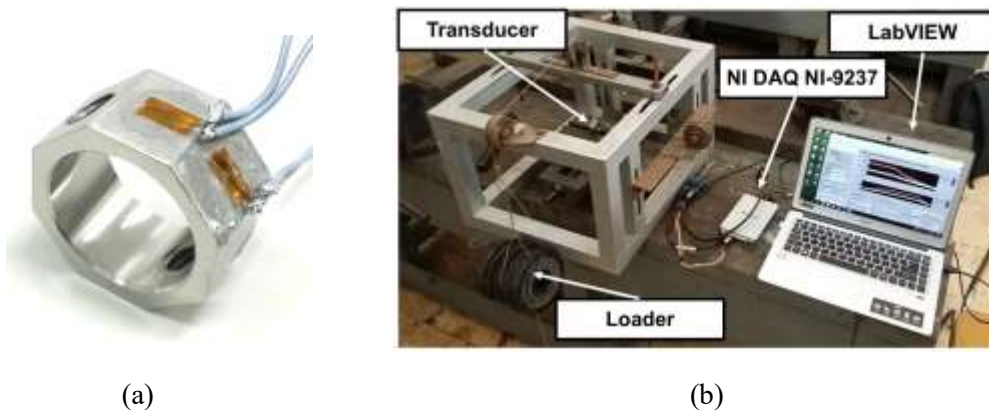


Figure 3. (a) Strain gauge location on the transducer; (b) experimental setup for static calibration.

The experimental test was performed using a developed calibration frame to determine the relationship between the input load and output of the voltage as shown in Figure 3(b). It is also to investigate the performance and sensitivity of force transducer after design and construction. The calibration was made in two directions or coordinates for F_v (vertical) and F_h (horizontal) for an applied load of up to 100 N, with incremental steps of 10 N. The calibration tests were repeated three times to ensure the consistency, and the average values were recorded.

3. Result and Discussion

Figure 4 shows the output signal of strain gauge during calibration test. It can be seen that the signal increase due to external load is linear calibration curves for normal and tangential force measurements. From the calibration curve we can observed the sensitivities of the octagonal ring force transducer were obtained in vertical force direction is $5.3 \times 10^{-4} \mu\text{V/N}$, and horizontal force direction is $9.1 \times 10^{-4} \mu\text{V/N}$. In addition to the curves, their found that the average interference error in vertical direction was 2.9%.

Whereas the transducer was subjected to horizontal force, the interference error was 4.3%. These results are consistent with those of other studies that their found the error about less than 5% [14].

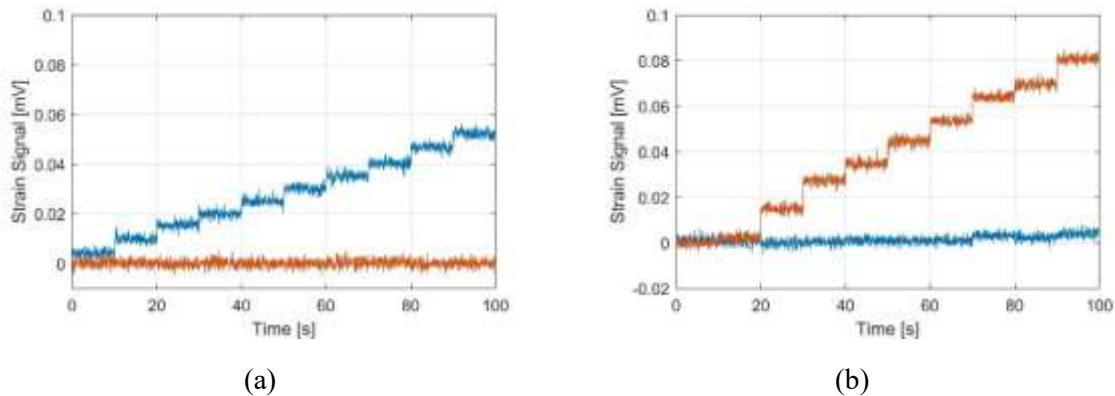


Figure 4. (a) Strain signal when external force on vertical direction; (b) Strain signal when external force on horizontal direction.

In order to convert the output value in voltage signal (mV) to the strain in theoretical analysis the equation is as follows [13]:

$$\frac{V_o}{V_i} = \frac{1}{4} GF \cdot \varepsilon \quad (9)$$

where V_i is the input voltage of the Wheatstone bridge, V_o is the output voltage, GF is the gauge factor, and ε is the strain. Figure 5 shows the result obtained from analytical, numerical and experimental analysis of strain occurred on the octagonal force transducer. It can be evidenced from the curve that analytical and numerical predictions closely match to each other. The error in vertical and horizontal directions between analytical and numerical is 3.3% and 15%. The present findings seem to be consistent with the results reported earlier regarding the numerical studies of hexagonal ring-shaped force transducer, though the extent of relative deviation is much less between the analytical method and experimental [6, 7]. However, when we observed the experimental result, indicated that the strain measurement on the octagonal ring is successful in following the rising trend of strain values when analysed in mathematical and numerical analysis. Although the value of the strain slightly deviated from the analytical a numerical due to several factors, that are the installation of strain gauge, calibration frame and the environmental condition.

In order to evaluate the performance of the developed octagonal ring force transducer, an experimental test was performed to detect the horizontal force which was conducted in four times. The aim of this test is evaluating the repeatability or consistency of transducer in detecting the fluctuation force during applications. A fixed force 30 N was subjected in the horizontal direction of transducer, but in vertical direction was not given any load.

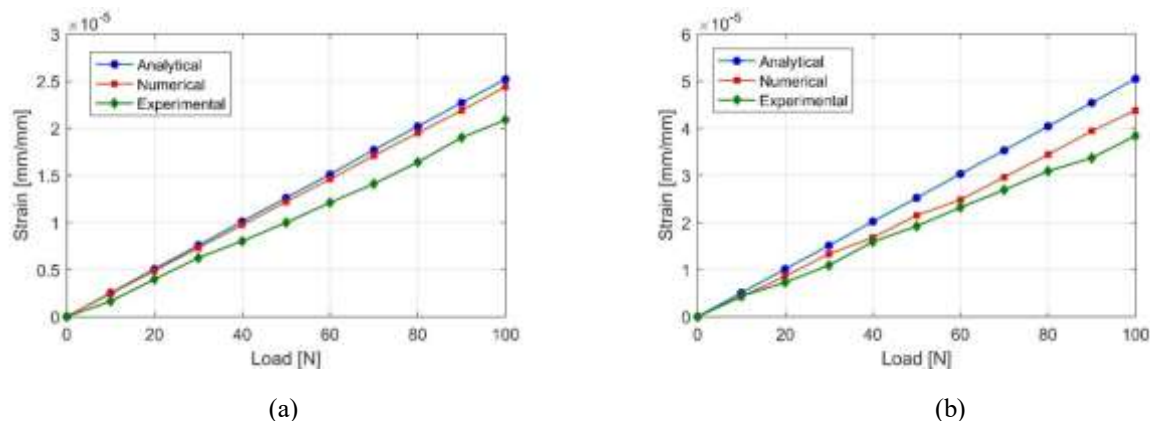


Figure 5. Comparison strain from analytical, numerical and experimental on the octagonal ring when loading up to 100 N (a) vertical direction; (b) horizontal direction.

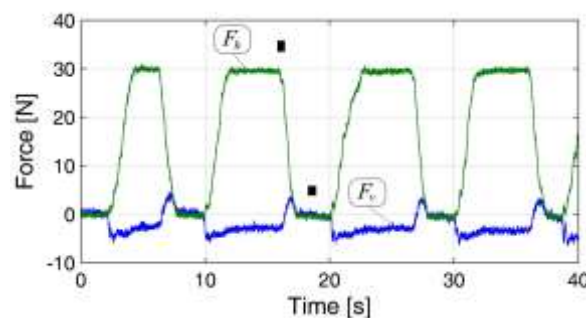


Figure 6. Result of measurement test of developed load cell.

Figure 6 shows the force signal reading in four times loadings. It can be observed that the load cell can be detected horizontal force (F_h) accurately. However, it found any error or disturbance in the vertical direction, but it was not exceed 9% from maximum scale output of developed octagonal ring.

4. Conclusion

An analytical, numerical and experimental study of a transducer for vertical and horizontal force measurements has been presented. The sensor system is developed based on an octagonal type structure which is utilized by strain gauge. The maximum measurement of the external force is designed up to 750 N. The results of calibration and measurement tests showed that its sensitivity was approximately in the range $5.3 \times 10^{-4} - 9.1 \times 10^{-4} \mu\text{V/N}$ and it has cross-sensitivity error of below 4.5%. The differences result between theoretical and experimental analysis were found in range 3.3 – 15%. The developed system gave a satisfactory performance and it has the potential to be used as sensor system in two axis force measurement such as in tribometer and applications.

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