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ЛАБОРАТОРНАЯ ТЕХНИКА

EXTENDED OCTAGONAL RING TRANSDUCERS FOR MEASUREMENT OF TRACTOR-IMPLEMENT FORCES

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The extended octagonal ring transducers are popular devices for force and moment measurements in agricultural engineering research due to its capability in measuring forces independently in two dimensions and resultant moment in one dimension. In this study design, construction and calibration of extended octagonal ring transducers are discussed. The transducers were designed to measure the two force components of the soil reaction with minimum cross-sensitivity. Strain distributions in the extended octagonal rings were analyzed using finite element method to locate optimal strain gauge positions to minimize cross-sensitivity between the two force components. A Data acquisition system consisted of a programmable DT800 data logger with 12 differential voltage and 16 frequency channels, and a PC for storing the data for further graphing and analysis. The system was tested for its sensitivity, cross-sensitivity, linearity and repeatability. The results of the calibration tests revealed that the system was well working for a range of draught and vertical forces up to 25 kN. The results showed a high degree of linearity between bridge output voltage and force applied. The minimum coefficient of determination, R^2, was found to be 0.99. The interactions of the applied forces on the orthogonal force bridges were less than one percent. The system could best be used for the measurement of draught (horizontal) and vertical forces where medium size equipment is attached with a tractor.

1. INTRODUCTION

Many researchers have used various transducers in order to measure forces between the tractor and agricultural equipments. Extended octagonal ring (EOR) transducers seem to be appropriate to measure force and torque in agricultural engineering research area. The high ratio of sensitivity to hardness, appropriate size and easy installation features the extended EOR. Also this type of transducers have the capability to measure both horizontal and vertical components of acting forces and also the resultant bending moment which have created because of the mentioned forces on ring.

Principles governing the EOR transducers are such, that when perpendicular forces (horizontal and vertical) are applied on the transducer, some strain nodes are created on transducer, which is capable of independent measurements of the horizontal and vertical force components. Installation of the strain gauges in the correct horizontal and vertical strain nodes could achieve the minimum interaction between horizontal and vertical forces [1]. In [2–4] general formulas for the strain and displacement of the EOR were introduced using analysis of plain extended ring. By using photoelastic method, nodal points of strain confirmed the general formulas [2, 4]. These formulas were used in [5–8] for construction of the EOR transducers.

In this study, the design and construction of EOR transducers, which are able to measure the forces between tractor and implements as parts of three-point hitch dynamometer, is presented. Strain distributions in the EOR were analyzed using finite element method (FEM).

2. MATERIALS AND METHODS

2.1. Design of extended octagonal rings transducer

After determining the maximum horizontal, vertical and lateral design loads between the tractor and implements, extended octagonal ring (EOR) transducers were designed. The material selected for the design of the EOR transducers was mild steel 1015 AISI having yield stress of 235 MPa and modulus of elasticity of 207 GPa, which gave high strength and compactness to the transducer.

One of the most common and most efficient methods for designing this type of transducers is the way, which is presented in [8]. In this method, design and construction of EOR transducer is done with the maximum external torque that is applied on the transducer during operations and considering the coefficient of transducer hardness of 1.6, which causes moment sensitivity of 0.4 on transducer [9]. The formulas that have been presented by for designing EOR transducers are [8]:

$$K = \frac{L}{r}, \tag{1}$$

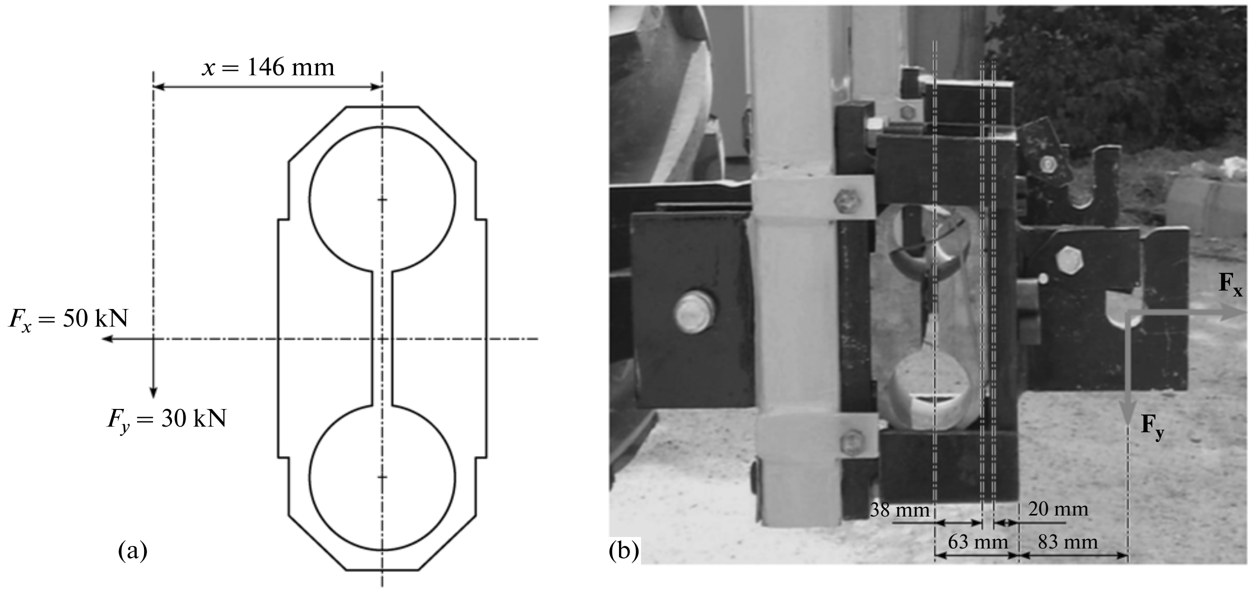

Fig. 1. (a) Forces on extended octagonal ring transducer, and (b) Distance of the acting point of forces to the middle part of the transducer.

$$M_s = \frac{\varepsilon E b t^2}{M_0}, \quad (2)$$

where K is the coefficient of hardness of transducer, $2L$ is the distance between ring centers (mm), r is mean radius of ring (mm), M_s is moment sensitivity (kN · m), M_0 is external moment which is applied on the transducer, ε is strain at ring surfaces, E is Young's modulus of ring material (GPa), b is the width of transducer (mm), and t is the thickness of ring (mm).

Considering the above relations for the design of EOR transducers, the maximum external moment (M_0) should be determined first which is applied on transducer. Also, it is essential that the EOR transducers should only be affected by the vertical and horizontal forces. Thus, side forces on transducers existing at lower hitch point connections should be restrained.

Figure 1a shows the free body diagram of EOR transducers during operations. The amount of each horizontal, vertical and side forces at lower connection points of tractor was calculated to be 25, 15 and 10 kN, respectively. Also in order to ensure the design strength of the transducers against the forces and impacts during operations, confidence coefficient was set at 1.5.

Regarding to the three-point hitch dynamometer design, the distance of the acting point of the horizontal and vertical forces to the middle part of the transducer (x) was considered 146 mm (Fig. 1b). Hence, the maximum external moment is calculated as:

$$M_0 = F_y x = 23.17\ (\text{kN}) \times \\ \times 0.146\ (m) = 3.384\ \text{kN} \cdot \text{m}. \quad (3)$$

Precise observation of parameters for appropriate designing of the EOR transducers is essential. These include the width of transducer b and the diameter of the holes φ (Fig. 2a). In this study, the width of transducer was selected as 90 mm. Also, in order to increase the sensitivity of the EOR transducer, the diameter of holes was selected as 60 mm. Considering that the distance of the acting point of the forces to the middle part of the transducer x of 146 mm and also the maximum amount of vertical force of 23.17 kN on the transducer, the amount of external moment applied on the transducer was calculated 3.384 kN · m (Eq. 3). The other parameters, provided b = 90 mm, M_0 = = 3.384 kN · m and S_y (AISI 1015) = 235 MPa, were calculated based on the following equations [5]:

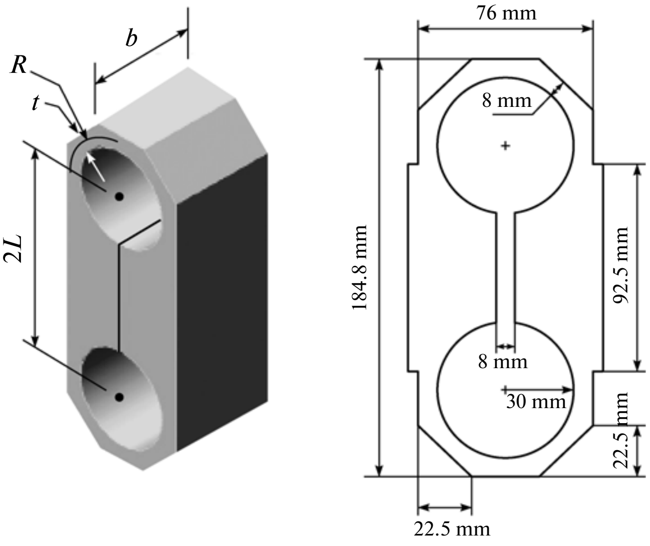

Fig. 2. (a) Some important design parameters in the extended octagonal ring transducer; (b) the final dimension of the designed EOR transducer.

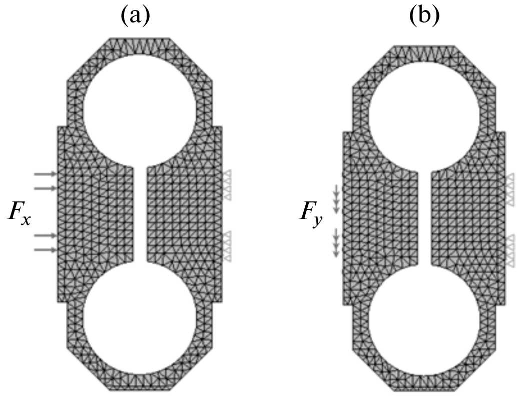

Fig. 3. Model used for the finite element analysis of the EOR: (a) horizontal load, F_x application and boundary condition of displacement; (b) vertical load, F_y application and boundary condition of displacement.

$$\sigma = \varepsilon E, \tag{4}$$

$$M_s = \frac{\varepsilon E b t^2}{M_0} = 0.4. \tag{5}$$

Consequently, according to the above relations, the value of M_s will be 0.4 and then the value of ring thickness was calculated to be equal to 8 mm. Also the radius of ring holes was considered 30 mm:

$$\frac{S_y b t^2}{M_0} = 0.4, \tag{6}$$

$$t^2 = \frac{0.4 M_0}{S_y b}. \tag{7}$$

Figure 2b shows the final dimension of the designed EOR transducer.

2.2. Design of data acquisition system

In order to collect the horizontal and vertical forces data, which is created between the tractor and agricultural mounted equipments, three EOR transducers have been used. After the mechanical design of EOR transducer, we attempted to specify the location of strain gauges installation on each transducer. On each EOR transducer, eight strain gauges were installed to measure the horizontal and vertical forces.

2.2.1. Determination of the strain nodes on the EOR transducer. To specify the location of strain gauges on each transducer, strain energy theory and also the design formulas which have been developed in [1, 8, 9] were used. A computer program was written in MATLAB software to specify nodal points:

$$M_\varphi = \frac{F_x R}{2}\left(\frac{2}{\pi} - \sin\varphi\right) + \frac{F_y R}{2}\cos\varphi - \frac{M_0\left\{\left(2 + \frac{\pi R}{2l}\right) - \left[\left(\frac{2R}{l} + \pi\right)\sin\varphi\right]\right\}}{\left(8 + \frac{\pi R}{l} + \frac{2l\pi}{R}\right)} \Rightarrow \text{for} \quad 0 < \varphi \le \pi, \tag{13}$$

$$M_\varphi = \frac{F_x R}{2}\left(\frac{2}{\pi} + \sin\varphi\right) - \frac{F_y R}{2}\cos\varphi + \frac{M_0\left\{\left(2 + \frac{\pi R}{2l}\right) + \left[\left(\frac{2R}{l} + \pi\right)\sin\varphi\right]\right\}}{\left(8 + \frac{\pi R}{l} + \frac{2l\pi}{R}\right)} \Rightarrow \text{for} \quad \pi < \varphi \le 2\pi, \tag{14}$$

$$\varepsilon_\varphi = \frac{6 M_\varphi}{E b t^2}. \tag{15}$$

The above formulas present the bending moment values M_φ in different angles φ on EOR transducers, when the two perpendicular forces i.e. F_x and F_y and the external moment M_0 are acting on the transducer. Regarding to this point that the EOR transducer designed and constructed as a measurement part of three-point hitch dynamometer, the acting point of the forces considered as the external moment on the EOR transducer, only affected by F_y and the other force (F_x) has not any effect on M_0. The internal moment is functions of both F_x and F_y. Using the ob-

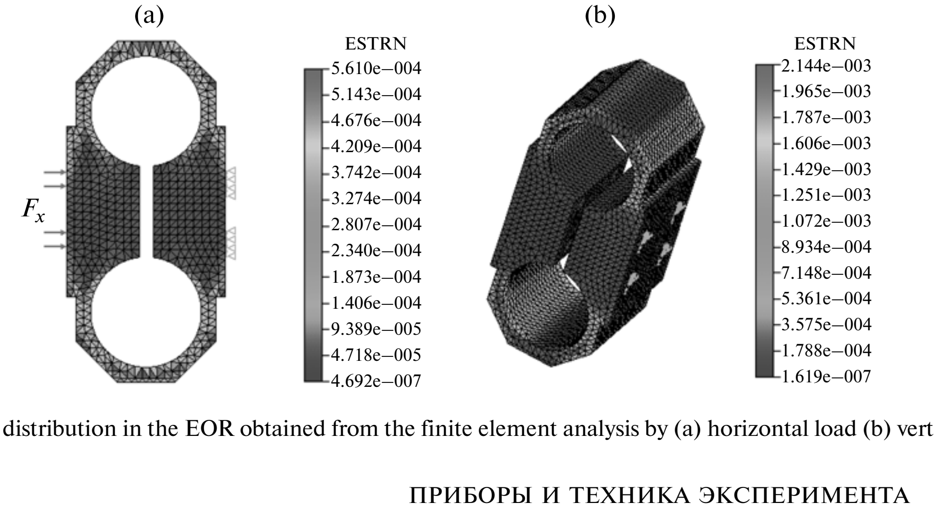

Fig. 4. Strain distribution in the EOR obtained from the finite element analysis by (a) horizontal load (b) vertical load.

tained M_φ data, the tangential strain could be calculated from $\varepsilon_\varphi = \frac{6M_\varphi}{Ebt^2}$. Therefore, based on the data obtained from the MATLAB program and finite element method (Fig. 3), the strain nodal points for specification of the location of strain gauges on the EOR transducer were determined. Strain gauge were installed at the angle of 90° and 39.54° for independent measurement of F_x and F_y, respectively.

2.2.2. Element type, boundary conditions and load application. Linear elastic finite element analysis was used to calculate the strain distribution in the EOR transducer to identify optimal strain gauge locations. The SolidWorks software was used to generate a mesh of solid mesh type elements for the EOR (Fig. 3). The Solid mesh element has quadratic displacement behavior and is well suited to modeling irregular meshes. There were a total of 89715 nodes in the meshed transducer. In the horizontal and vertical directions, the loads, $F_x = 25$ kN (Fig. 3a) and $F_y = 15$ kN (Fig. 3b), were applied separately to the transducer. The moment was ignored in the finite element analysis. Fig. 4 shows strain distribution, which is created by the horizontal and vertical loads.

2.2.3. Electrical resistance strain gauges. For the strain gauges the TML FLA-3-11-1L type was selected with gauge resistance of 120 Ω and gauge factor of 2.1. Installation points of Wheatstone bridge resistance strain gauges and their configurations are shown in Fig. 5. The Wheatstone bridges on each transducer transfer the voltage changes due to variation in vertical and horizontal forces on the transducer to the input channels of data logger and then the collected data are transferred to a portable computer for data analysis and post processing. In this study, for collecting and storing of the EOR transducers data and also the S-type load cells data in calibration system, a programmable Data taker DT800 model data logger with 12 analog channels and 16 digital channels was used.

2.2.4. Calibration. In order to calibrate the EOR transducers, a system that is able to apply an equivalent force of 20 kN to the transducer, was designed in the University of Mohaghegh Ardabili. The system includes a chassis which contains special bracket bases and also a 2-way power screw and S-type load cells to apply vertical and horizontal forces. The chassis was fixed by bolts to a concrete foundation.

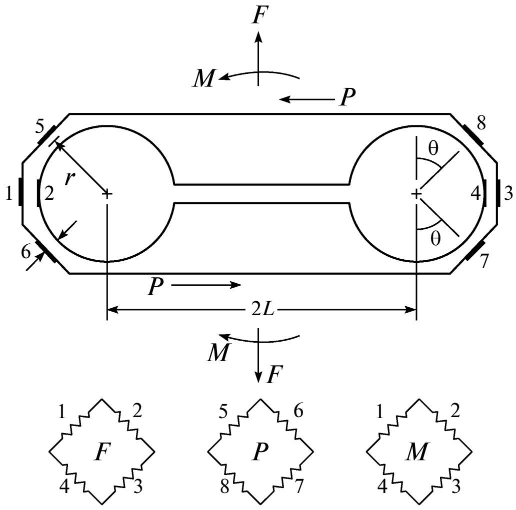

Fig. 5. Electrical resistance strain gauges configuration for measurement of applied moment and forces on the EOR transducer.

3. RESULTS AND DISCUSSION

Static calibration tests to obtain calibration coefficients, sensitivity, cross-sensitivity, linearity and repeatability for each transducer, was performed. Table shows the calibration parameters of the EOR transducers. The EOR transducers calibration test's results indicate that the coefficient of calibration equation for transducers No. 2 and No. 3 are different from transducer No. 1 because of the different maximum loads which were used to calibrate them. The test results for repeatability showed negligible difference for all of three transducers. Considering the obtained results, the transducers have suitable sensitivity for measuring the forces.

A high degree of linearity between the applied vertical and horizontal forces and bridge outputs were found (Fig. 6 and 7).

The cross-sensitivity for all of the transducers was very small. The observed cross-sensitivities of the EOR transducer No. 1 were 0.99% and 0.92%, respectively, for horizontal and vertical forces, while for the transducer No. 2 were 0.99% and 0.93% and for the transducer No. 3 was 0.97% and 0.96%, respectively, for

Calibration parameters of the EOR transducers

No. transducer	Coefficient of calibration equation		Zero offset of calibration equation		Coefficient of correlation	
	F_x	F_y	F_x	F_y	F_x	F_y
№ 1	33.27	39.47	–33.01	–265.96	0.99	1
№ 2	28.19	34.89	371.41	350.71	0.99	0.98
№ 3	27.35	33.28	348.65	–103.51	0.99	0.96

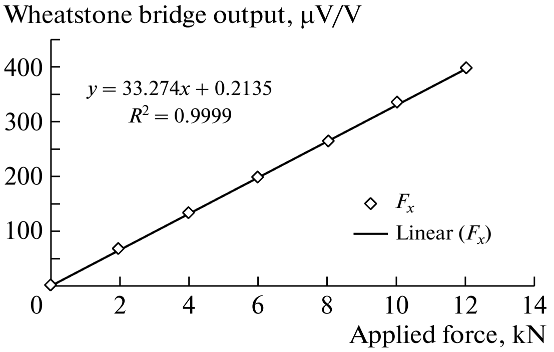

Fig. 6. Calibration curve for horizontal force of the EOR transducer № 3.

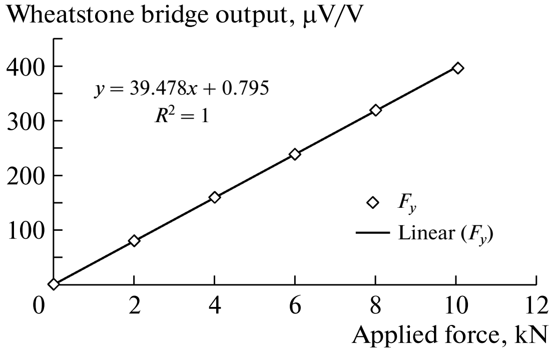

Fig. 7. Calibration curve for vertical force of the EOR transducer № 3.

horizontal and vertical force measurement. In [4] cross-sensitivities were of 1.1% and 2.1% for draft and vertical force, respectively, when the vertical force gauges were mounted at 34° and the loading fixture was confined to central part of the base section. Kheiralla et al. reported the cross-sensitivities of one of the EOR transducers which is used as a measurement part of a three-point hitch dynamometer, were 1.2% and 2.0%, respectively, for horizontal and vertical force, while for the other EOR transducer were 1.6% and 0.8%, respectively, for horizontal and vertical force when the vertical force strain gauges were mounted at 39° on each transducer [6].

4. CONCLUSIONS

In this study, design, construction and calibration of three extended octagonal ring transducers were presented and discussed. These transducers could measure tractor-implement forces in two directions. These force components need to be measured with minimum cross-sensitivity. Strain distributions in the extended octagonal rings were analyzed using a MATLAB program and finite element method to specify the optimal strain gage positions to minimize cross-sensitivity between two force components. Strain gauges were installed at the angle of 90° and 39.54° for independent measurement of horizontal and vertical forces, respectively. The results showed a high degree of linearity between bridge output voltage and force applied. The cross-sensitivity of the applied forces on the orthogonal force bridges were less than one percent. The system could best be used for the measurement of tractor-implement forces where medium type equipment is attached to the tractor.

5. ACKNOWLEDGMENTS

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