An Improved Strain Gauge-Based Dynamic Torque Measurement Method

M. Hilal Muftah, S. Mohamed Haris, K. Petroczki and E. Awad Khidir

***Abstract*—**Torque transducers, which use strain gauges to respond to stresses in torsion bars, due to applied torque are widely used to measure a wide range of torques in numerous applications. Moreover torque measurement is a very complicated measurement so it requires a special solution for each case; in this case it must be built into a hammer grinder machine's structure. A new torque determination method using a new shape of the strain gauge is used in this research. The aim of this paper is to measure the torque value into a rotating shaft. During the design of the strain gauge torque transducer, one strain gauge is used, considered and experimentally investigated. The lateral dead-weights are used through the calibration which was carried out with (0.5m) long lever three times for both clockwise and anticlockwise directions. The dead-weights (0.5 to 4.5Kg) are used for a hammer grinder machine shaft. Lastly the testing the transducer during operation in real conditions has also been done three times using (4Kg) and the value of the maximum applied torque is approximately (8Nm). Also measurement of the acting mechanical power is about (3200W) for the period of rotating speed (3800rpm). The whole measuring system together with strain gauge sensor, the amplifier up to the notebook is accomplished measuring with high dynamics.

***Keywords*—**Dead weights; measurement; rotating shaft; sensor; strain gauge; torque transducer.

I. Introduction

THE torque transducer or sensor is a device that measures the torque on a rotating system, for example a rotor, hammer grinder machine, transmission, or turbine. Generally, torque measurements can be classified into two categories: static and dynamic torque measurements. In a static measurement system, the measured torque is the moment that twists the stationary object.

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On the other hand, in a dynamic measuring system, the object is rotated or turned by the applied torque [1].

Torque measurement in a static system is easier than in a dynamic system. This is because for the latter, there is some difficulty in the transmission of the measurement signal between the stationary and rotating parts. The torque magnitude can be obtained by measuring force and displacement, angle of twist, shear stress or power [3].

There are two main reasons for measuring torque. Firstly, for industrial purposes, it is necessary in controlling mechanical power. The other reason is to improve load values in deflection analysis [2]. These values help in the design of rotating systems to ensure appropriate and acceptable capacity so as to avoid failure under shear stresses emanating from applied torque [5].

The main goal of the work presented in this paper is to propose a new and improved strain gauge based torque transducer for measuring dynamic loading on a rotating shaft. This new transducer has high load ability and provides direct frequency output signal, for transmitting in-operation torque measurement.

A. The Definition of Torque

Torque is a very important physical parameter that plays a significant role in determining the quality of goods. Referring to Figure 1, torque can be roughly defined as a measure of the force that acts to rotate a body, C [2].

The body rotates around an axis, which is called the pivot point, O when subjected to a force, F. The distance, r from the pivot point to the point where the force acts is called the moment arm [8]. Note that r is also a vector, and points from the axis of rotation to the point where the force acts. The torque magnitude can be calculated using Eq. (1), where measurement unit of torque is Nm, which is equal to the torque that is produced by a force of 1N acting on a point at a radius of 1m from the pivot [4].

This definition is applicable to both static and dynamic torque measurements.

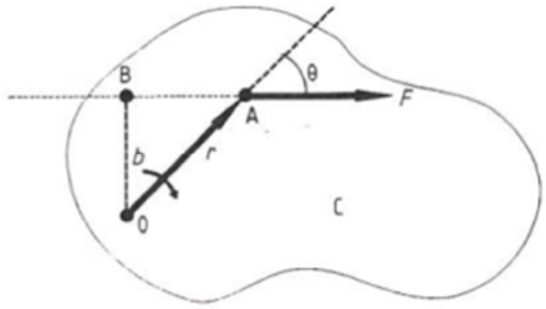


Fig. 1 the definition of the torque [2]

More generally, the torque can be defined as:

$$\vec{T} = \vec{r} \times \vec{F} \quad (1)$$

In the one dimensional case:

$$\vec{T} = \vec{r} \times \vec{F} \times \sin(\theta) \quad (2)$$

where θ is the angle between the position vector, *r* and the force vector, *F*.

In the case of a shaft rotating with angular velocity *ω* and power *P*, torque can also be calculated from:

$$T = \frac{P}{\omega} \quad (3)$$

B. Strain Gauge Transducers

The working principle of the metallic strain gauge torque transducer is to measure the strain in a flexible section of the shaft. In this case, four strain gauges are attached into the rotating shaft as a Wheatstone bridge circuit. The first two strain gauges are fixed at ±45° on one side of the shaft axis and the other two strain gauges are also prepared at the same way on the other side of the shaft as shown in Fig. 2.

In this case, shear strain occurs when the torque is applied to the shaft. Therefore tensile strain, which is measured by one pair of gauges, will increase the circuit resistance which, on the other hand, will be decreased by the other pair due to compression strain [16]. Formerly the measured torque can be read from a measuring device as output voltage.

As well, strain gauge for shaft torque measurement is the most commonly method used for torque measurement before twenty years ago. This is because there is not any friction torque presented in this method. In addition, it can be used in a various change of temperatures [2] and is also insensitive to twisting or axial stresses [3].

Furthermore, it is a very difficult to connect the bridge to its power supply and display devices [3]. Slip rings can be set for power and/or data transformation technique as some solution, but it cannot be reliable while worked in an unclean condition [2]. The noise level in difference of connection resistance may be the similar to the signal itself. The strain gauges accurate setting into the shaft axis is very difficult to accomplish and creates this transducer quite expensive [5].

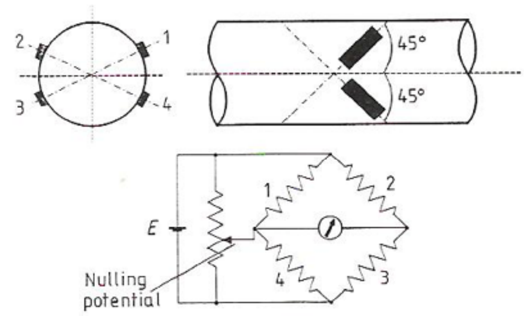


Fig. 2 using strain gauges in torque measurement for a shaft [2]

Harish in 2011 has designed a torque transducer, which has been made of high strength aluminum alloy due to low ability of only 5Nm. The principle of this method is by means of analytical method and proved using the finite element analysis, too. Figure 3 shows the kind of the sensing element is a solid square element, undergoes elastic deformation when the torque is applied and the deformation is detected by the strain gauges that were fixed over it [10].

Moreover, in this study the strain gauges were used to determine the strain and stress that are made in torque transducer. They are fixed at angle of 45° to the axis of the sensing element. The calculated shear strain and shear stress are approximately equal to the measured values [10]. Also, the metrological descriptions of the torque transducer produced good results. However, in this method a solid square element was used instead of a solid circular element as the sensing element.

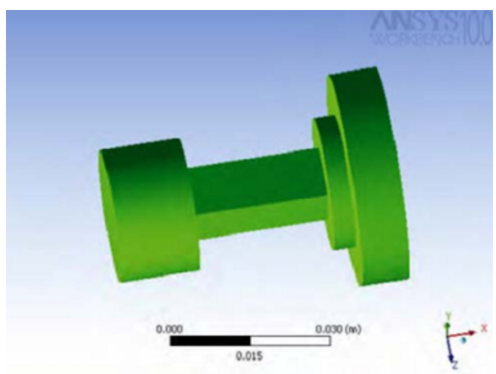


Fig. 3 a solid square element model of the torque sensor [10]

Through these methods and strategies, the problem at this stage is to improve an appropriate method to convert the resistance variations in the component of the gauge into a more obvious amount.

In view, resistance quantity performs to be a direct process. It is a basically electrical consideration and Ohm meters that are used for its quantity are generally electronic devices [11]-[12]. In this general case though, the determination and precision required for the strain quantity at manufacturing planes is greater than the abilities of all but the most advanced of these devices.

Lastly, different electric circuit and wiring measures have been established to straight and exactly change the resistance variations to relational voltage variations [12].

Basically, the equation for the resistance of a wire, R can be presented by

$$R = \rho . \frac{L}{A}, \tag{4}$$

where A is the cross-sectional area, ρ is the resistivity and L is the length of the wire. Also, the sensitivity of the material can be expressed as the Gauge Factor:

$$GF = \frac{dR/R}{\varepsilon}, \tag{5}$$

where dR/R is the change of resistance and ε is the applied strain.

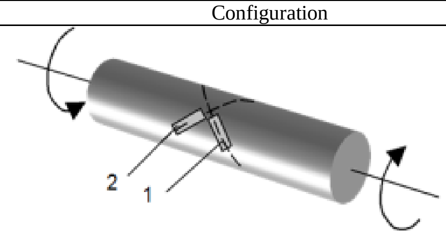
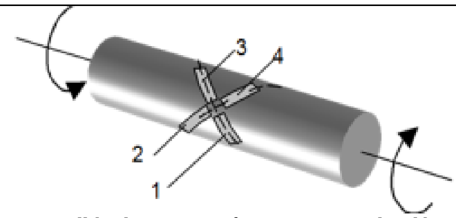
II. Detecting Twisting Strains into a Shaft

Generally, twisting presents an exciting experiment this is for the reason that the main stress is a shear stress, and hence it is commonly required to measure the causing shear strain [9]. Formerly, as known that strain gauges sense simply an additional strain, a rosette shape is used to measure the quantity of strain at a point and to conclude any element of specific (2D) strain.

Furthermore, it is needed to put on at least three gauges in a rosette shape to conclude the (2D) strain quantity. Conversely, it is typically possible to put on less than three gauges if selected materials are previously recognized [9].

In this case while detecting the twisting strain into a shaft that is circular in shape, where the major strain directions are recognized in development to be at (±45°) to the axial of the shaft direction. In all, two-part (T-shape) or (90°) rosette is fixed such that the two singular gauges are ranged directly in the major directions of the strain. Table 1 shows a number of the possible structures.

Table 1 a number of the possible structures for twisting shaft [9]

No.	K	Configuration
T-1	2	 Half Bridge: Gauge at ±45 to centreline sense principal strains which are equal and opposite for pure torsion; bending or axial force induces equal to strains and is rejected; arms are temperature compensated.
T-2	4	 Best: Full-bridge version of T-1; rejects axial and bending strain and is temperature compensated.

In the past, the change in angular displacement between the two ends of a twisting shaft was used to determine either a stage difference measurement such as (photo electrically, electromagnetically or inductively) or a variable lighting measurement [8]. Even though the undoubted achievement of torque measurement that uses cultured devices, strain gauges are still frequently used in the field of industries. This is because it is a very simple to use and it is not expensive. Strain gauges also give a high precision when a torque is applied [5]. Opposing to the most last kinds of extensometers the strain gauge provides the relative quantity strain, ε as an output signal related to the input.

The main function of metallic strain gauges is mostly a strain result on the resistance of electrical conductors [6]. A shaft weighed down with twisting is focus to a biaxial stress case. The major standard stresses frequently occur at an angle of $\pm 45^0$ to the cylindrical shafts. The strain gauges can be used to measure strains made by the standard stresses [7]. In this research the V-shape with the measuring grid axes at $\pm 45^0$ to the axis of symmetry, the measuring axes must relate to the main stress directions. Accurate result will only be set by an accurate measurement. The axes of the measuring grids must relate to the main stress directions.

Overall, this kind of the strain gauge is small in size and form, not expensive, easy to attach, and the sensitive is high to sense the strain but insensitive to ambient or process temperature variations. Figure 4 shows a metallic strain gauge as V-shape with the measuring grid axes at ±45° to the axis of the symmetry. The strain gauge length is 2mm, its factor is 2.05 and the resistance of the gauge is 120Ω [13].

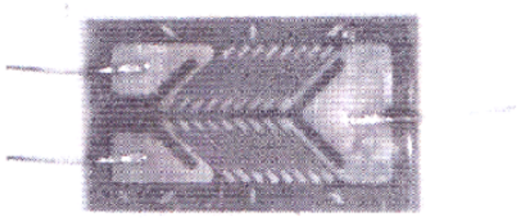


Fig. 4 V-shaped metallic strain gauge

III. Torque Transducer Design

A torque transducer or torque sensor is a device to measure the torque on a rotational structure, such as an engine, crankshaft, gearbox, transmission, rotor, or a bicycle crank. Otherwise, torque transducers or torque sensors are devices transforming an applied torque into an electrical output signal [18]. They are made up of assessing body and an instrument [17]. The configuration of each torque transducer can be different in the system of signal transmission and measuring body design [9].

Transducer of torque buildings are regular and characteristically factory-made from steel (SAE4140 or 4340). There are some types of evaluating body forms. Public shapes are solid, hollow, square-section, shafts and cages as shown in (*Fig. 5*). Essentially, their shells where strain occurs due to torque must be smooth for mounting sensors [9].

In torque transducers the measurement signal is primarily generated on the rotor. The strain gauge circuits are passive measuring systems and must therefore be supplied with an excitation voltage of several volts. The output signal corresponding to the measured quantity is in the order of several (mV). There are two possible ways of transmitting the measurement signals and supply voltage between the rotor and the stator. They are: transmission via slip rings and contactless transmission [9].

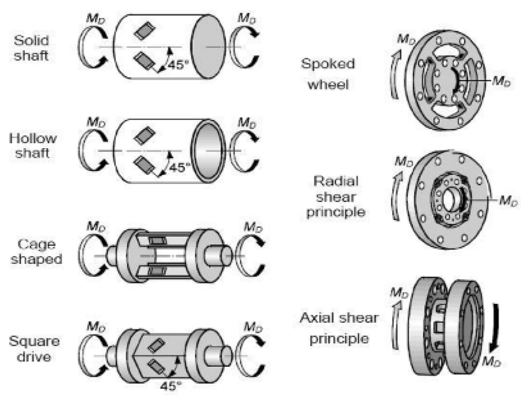


Fig. 5 commonly used measuring body forms [9]

Figure 6 shows a photo of the torque transducer using strain gauge. The middle part of the shaft has a diameter of 28 mm that is for the measurement of the torque. One strain gauge V in shape is mounted into the shaft at ±45° comparative to the axis of the shaft (on one side) [13]. In this case, the determined shear stresses will occur at ±45° to the axis of the shaft if a torque is applied [13]-[14].

These shear stresses are two important parameters, one of them is the tension that occurs in one direction and the other is the compression, which occurs in the opposite direction. Additionally, they have the same magnitudes. As a result, with a bar under tension, the positive longitudinal stain occurs in the active direction of the force, i.e. the longitudinal direction; in the transverse direction the negative transverse strain, i.e. transverse contraction occurs. With a bar under compression, the longitudinal strain is negative and the transverse strain is positive. The strain gauge is mounted on the shaft for the exact torque direction.

Fig. 6 V-shaped strain gauge mounted on a shaft

In this research the shaft of a hammer grinder machine was used. A full bridge circuit has been also used with four active strain gauges. A Slip ring device was chosen to transfer the bridge supply voltage and measurement signals.

Also this kind of equipment is the slipping assemblies for suitable rotating shafts of various sizes with two sets of brushes for separate mounting. The set contains five slip rings; four for joining of the strain gauges and the fifth in case a ground joining with the rotating shaft to avoid noise [13].

For a full bridge circuit, the following formula can be used to determine the indicated strain, ε_i, measured in micro strains.

$$\varepsilon_i = \frac{2M_t}{G \cdot S_p}, \quad (6)$$

where the torsion moment M_t is in Nm, the polar section modulus, S_p is in m^3, and can be determined from Equation (8),

$$S_p = \frac{\pi d^3}{16}. \quad (7)$$

Here, *d* is the diameter of the shaft in mm. The shear modulus, G measured in N/m^2 and can be calculated using Equation (8) [2].

$$G = \frac{E}{2(1+\nu)}, \quad (8)$$

where E is the Young's modulus for steel in kN/mm^2 and ν is the Poison's ratio.

All in all SK5 and SK6 are slip ring assemblies from HBM. They have special features such as low noise, high transmission, low thermal induced voltages and very low change in contact resistance. In this research, a digital tachometer was used to read the speed during operation it sends a ray directly to small piece is mounted on the bearing to receive the reading of the speed [13]. Also the SK6 has been used to transfer the signal from rotor to stator as shown in Fig. 7 and Figure 8 shows the mechanical outline of the slip ring SK6 which is used in the experiment.

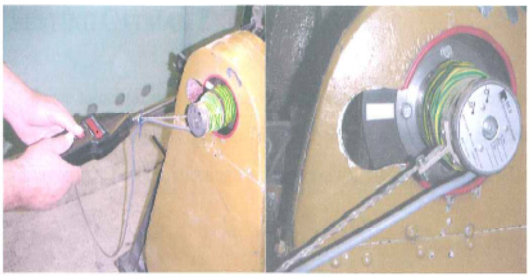


Fig. 7 measurement with digital tachometer and SK6 is mounted in the end of the shaft

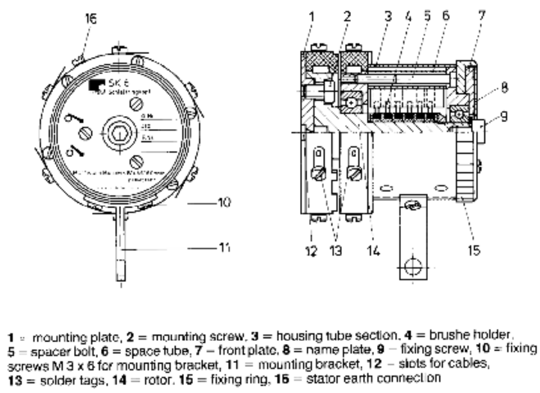


Fig. 8 the mechanical outline of the slip ring SK6

Moreover, Equation (6) in this case can be used to calculate the indicated strain value and the following facts have been used, these facts are: Young's modulus is 202kN/mm2 for steel and Poison's ratio is 0.28 from references. Also 22.07 Nm of torsion moment and 28 mm of shaft diameter have been used, hence the indicated strain value was found to be equal to 127 micro strains.

IV. Results and Discussion

To measure the strain, first and foremost the strain gauge, which is used in this research, has to be measured. To do this measuring, some weights are converted to forces to be required. In this experiment forces from (5 to 45N) have been used.

Next, the torque transducer has to be calibrated with using deadweights (5 to 45N) to measure torque for three cycles of operation and then the total average for these three cycles has to be measured as shown in Fig 9.

Fig. 9 torque transducer calibration using deadweights

Table 2 calibration of the torque transducer readings, series 1

W (K)	F (N)	M (Nm)	Uorup(mV/V)	Uordown (mV/V)	Average of Readings (mV/V)	Strain (µS)
0.0	0.000	0.0000	0.0000	0.0000	0.00000	0.0000
0.5	4.905	2.4525	0.0073	0.0073	0.00730	14.141
1.0	9.810	4.9050	0.0148	0.0148	0.01480	28.283
1.5	14.71	7.3575	0.0222	0.0222	0.02220	42.425
2.0	19.62	9.8100	0.0296	0.0296	0.02960	56.567
2.5	24.52	12.262	0.0370	0.0370	0.03700	70.709
3.0	29.43	14.715	0.0444	0.0444	0.04440	84.851
3.5	34.33	17.167	0.0518	0.0518	0.05180	98.993
4.0	39.24	19.620	0.0592	0.0592	0.05920	113.13
4.5	44.14	22.072	0.0666	0.0666	0.06660	127.27

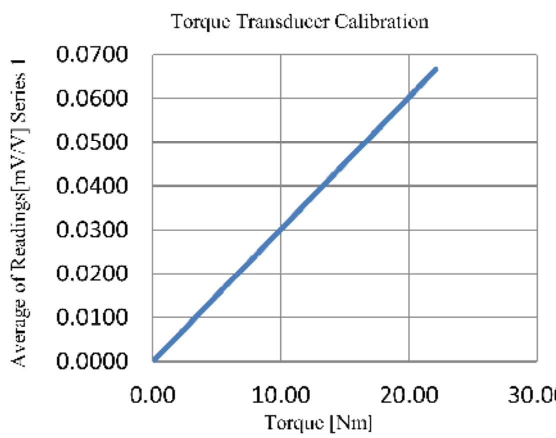


Fig. 10 diagram of the torque transducer calibration related to the series 1

Table 3 calibration of the torque transducer readings, series 2

W (Kg)	F (N)	M (Nm)	Uorup (mV/V)	Uordown (mV/V)	Average of Readings (mV/V)	Strain (µS)
0.0	0.000	0.000	0.0000	0.0000	0.00000	0.0000
0.5	4.905	2.452	0.0073	0.0073	0.00730	14.141
1.0	9.810	4.905	0.0149	0.0148	0.01485	28.283
1.5	14.715	7.357	0.0224	0.0222	0.02228	42.425
2.0	19.62	9.810	0.0298	0.0296	0.02970	56.567
2.5	24.52	12.262	0.0373	0.0370	0.03713	70.709
3.0	29.43	14.715	0.0447	0.0444	0.04455	84.851
3.5	34.33	17.167	0.0522	0.0518	0.05198	98.993
4.0	39.24	19.620	0.0596	0.0592	0.05940	113.13
4.5	44.14	22.072	0.0671	0.0666	0.06683	127.27

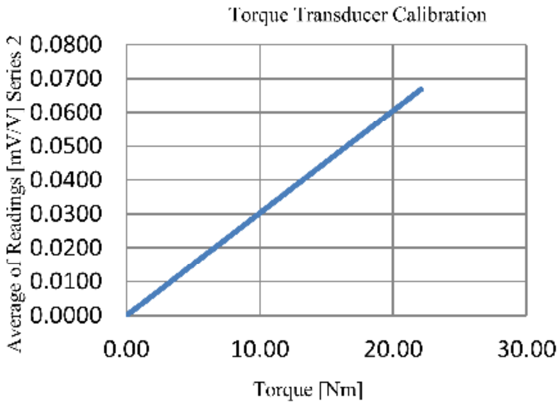


Fig.11 diagram of the torque transducer calibration related to the series 2

Table 4 calibration of the torque transducer readings, series 3

W (Kg)	F (N)	M (Nm)	Uorup (mV/V)	Uordown (mV/V)	Average of Readings (mV/V)	Strain (µS)
0.0	0.0000	0.0000	0.0000	0.0000	0.00000	0.0000
0.5	4.9050	2.4525	0.0073	0.0073	0.00730	14.1419
1.0	9.8100	4.9050	0.0147	0.0147	0.01470	28.2838
1.5	14.7150	7.3575	0.0221	0.0221	0.02205	42.4257
2.0	19.6200	9.8100	0.0294	0.0294	0.02940	56.5676
2.5	24.5250	12.2625	0.0368	0.0368	0.03675	70.7095
3.0	29.4300	14.7150	0.0441	0.0441	0.04410	84.8514
3.5	34.3350	17.1675	0.0515	0.0515	0.05145	98.9933
4.0	39.2400	19.6200	0.0588	0.0588	0.05880	113.135
4.5	44.1450	22.0725	0.0662	0.0662	0.06615	127.277

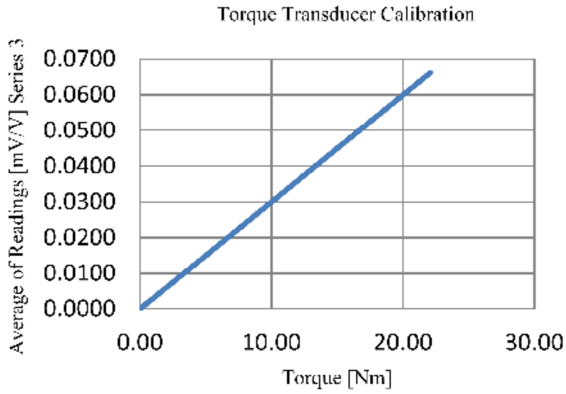


Fig.12 diagram of the torque transducer calibration related to the series 3

The strain value was determined into the shaft when a torque is applied of (22.07Nm) within strain gauge is mounted is about 0.06653 mV/V, which is equal to 132 micro strains.

Table 5 the total average for three cycles

W(Kg)	F(N)	T(Nm)	Average(mV/V)
0.0	0.0000	0.0000	0.00000
0.5	4.9050	2.4525	0.00730
1.0	9.8100	4.9050	0.01478
1.5	14.7150	7.3575	0.02218
2.0	19.6200	9.8100	0.02957
2.5	24.5250	12.2625	0.03696
3.0	29.4300	14.7150	0.04435
3.5	34.3350	17.1675	0.05174
4.0	39.2400	19.6200	0.05913
4.5	44.1450	22.0725	0.06653

Figure 13 shows the correlation between torque and the average reading for three cycles of the output given increasing or decreasing excitation. The torque in the diagram is measured in Nm.

In constant, there has been a stable increase in torque values over approximately all the readings of the average of the output excitation. That means there is no drop in the readings of torque.

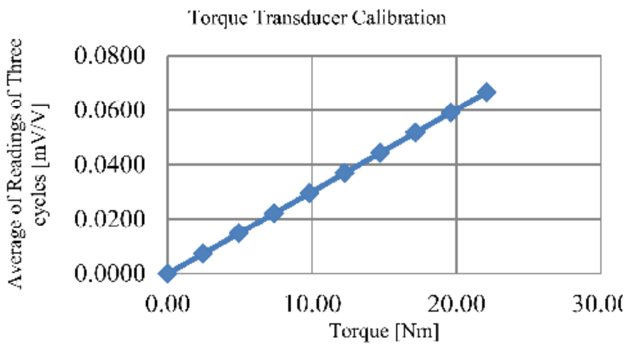


Fig. 13 strain gauge readings versus torque

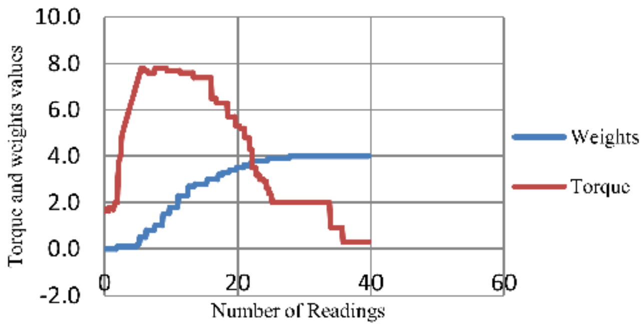


Fig. 14 the diagram of the torque and the weights during process within loads

This process has been done during process within loads four kilograms of corn in actual situations, first to measure the rotational speed, n and the electrical power, P, then to measure the torque, T value. In this research the Catman Express software was used to obtain all of them [15]. More than 400 reading were taken, so only representative values are shown. Table 3 shows these readings.

Table 6 short readings of the measuring during processes

HBM_CATMAN_DATAFILE_31			
CHANNELS: 3			
SEPARATOR: 9			
MAXLINES: 400			
_CH1_ldo	_CH2_Torque	_CH3_Weight	Electrical power
S	Nm	Kg	W
dt =1 ms	dt =100 ms	dt =100ms	
0	1.6	0.0	640.9
0.1	1.6	0.0	640.9
0.2	1.7	0.0	640.9
0.3	1.7	0.0	640.9
0.4	1.7	0.0	678.6
0.5	1.7	0.0	678.6
0.6	1.6	0.0	678.6
0.7	1.8	0.0	640.9
0.8	1.8	0.0	640.9
0.9	1.8	0.0	640.9

Figure14 shows the reaction of the torque transducer using one of the strain gauge for torque value is approximately 8 Nm within loads of 4 Kg. The torque and the increase of the output material were measured versus time with 10 Hz sampling frequency.

When the voltage between two phases is 410V, the line current is 10A, the electrical power is 4100W, and the speed was 3788 rpm which was measured with tachometer.

To calculate the acting mechanical power Equation (4) can be used, with

$$\omega = 2\pi \frac{n}{60} \qquad (9)$$

The rotational speed, *n* was 3788 rpm and the torque, *T* was 8 Nm, then the acting mechanical power, P was3171.82 W.

V. Conclusion

The strain gauge torque transducer, which measures the strain in an elastic element built into the rotating shaft, is the most common torque transducer and widely used in many laboratories and in industry. In this paper, the use of a V-shaped strain gauge for torque measurements to measure dynamical load for the period of rotating shaft has been presented. As a result, the calibration was accomplished with a 0.5 m long lever and dead weights in 0.5 kg steps up to 4.5 kg. The linearity error and the hysteresis errors were very low, less than 0.5%. Furthermore, the torque and the increase of the output material were measured versus time with 10 Hz sampling frequency in a value of torque up to 8Nm.

The strain value into the measurement twisting shaft surface during calibration process was about 132 micro strains. Additionally, the calculated value of the strain was around 127 micro strains, hence, the difference between the calculated and the measured (during operation in real conditions) strain value was 1.5%. This is smaller than 3.5%, which means essentially to be good result. The sensitivity of the transducer 0.06653 mV/V is below the standard torque transducer, which is 2.0mV/V because we don't need to modify the stress-strain properties of the original hammer grinder very much. The rotational speed was measured by a digital tachometer and was found to be 3788 rpm.

Electrical power was measured with a portable electrical power meter and was found to be equal to 4000 W. The real mechanical power was calculated after test and it is found equal to be around 3200W. The strain gauge precise setting into the shaft axis was very easy to complete and makes this transducer inexpensive. The grinder in the laboratory supplied with this up-to-date measuring system gives the better possibility for analyzing the whole mechanical process. Although, the output signal of the transducer is better than before, but it is still relatively low because there is a difficulty in the signal transmitted between the stationary and rotating part in the dynamic system.

For good analysis of the machine, the sensitivity of the torque transducer must be increased in future. To do this, a new transducer construction must be developed. To increase the sensitivity, the form of the species must be changed. The suitable X shape twisting resistant measuring body with strain gauges is necessary. But this transducer must be put into two bearings. There are many technological problems with this solution, but they can be solved.

A new shaft speed sensor and electric engine speed sensor must be built into the machine. The new measuring system is suitable very much for measuring torque dynamically and exactly on the rotating shaft of the hammer grinder machine.

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