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Disciplines
Agriculture | Bioresource and Agricultural Engineering

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The following article is from Journal of Agricultural Engineering Research 17 (1972): 231–235, doi:10.1016/S0021-8634(72)80026-X.

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A Strain-gauge, Brushless Torque Meter*

ALI R. MAHMOUD; W. F. BUCHELE; JAMES F. ANDREW†

A universal, brushless strain-gauge torque meter employing a force-balance system was designed and developed. Full scale reading of recording systems at any given torque range was secured by use of changeable conical seat inserts and semi-conductor strain gauges.

1. Introduction

Torque measurement instruments are used extensively on agricultural machinery. Most of the commercial1 torque meters have limited application because they are designed to work in a specific range for the required precision and usually are quite expensive. There is a need for an economical, universal, continuous-range, precision torque meter. Buchele2, 3 designed a continuous-range, hydraulic, torque meter. This unit has been modified and redesigned to provide a high precision, universal, brushless, strain-gauge, torque meter, to operate over the range of 0–50 hp at 540 rev/min. Instead of sensing the twist on a small shaft and transmitting the electrical signal through brushes as done with conventional strain-gauge torque meters,4, 5 the brushless torque meter detailed in Fig. 1 uses steel balls and conical shaped seat inserts to produce tension in a stationary steel shell. Strain gauges measure the tension in the shell when torque is applied.

The range and/or sensitivity is altered by replacing the set of conical inserts, shown in Fig. 2, by another set with the appropriate seat angle for the required working range. The larger the included seat angle, the lower the range of the torque meter.

2. Principle of Operation

The torque meter is equipped with two almost identical input-output 2-in diam, hollow-keyed female shafts. Adaptor brushings are used to fit the hollow shafts to the male shafts of the power source and machine. When the torque meter is placed in a power line shaft, it may actually occupy no space. The power lines must be spread apart for inserting the torque meter on to the power line shafts.

Each hollow shaft is equipped with a circular flange whose face is perpendicular to the centre line of the shafts. Each flange has 6 equally spaced cylindrical recesses machined into the inside faces to hold the conical inserts as shown in Fig. 2. The balls contained by the conical inserts,

*Journal Paper No. J-7007 of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa. Project No. 1486
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as shown in the cross-sectional view in Fig. 1, transmit the rotational movement from the input to the output shaft. When applying the force to cause movement, the balls encounter torsional resistance. This causes the balls to tend to roll up the ramps of the conical seat inserts and separate the two flanges. The force transmitted through the balls causes rotation to the output shaft and produces tension to the stationary transducer shell indicated in Figs 1 and 2.

The stationary shell is instrumented with semiconductor strain gauges. The bridge circuit is shown in Fig. 3. The tension produces alike sign strains on gauges R1 and R2 located on the shell,
and unbalances the bridge in proportion to the sum of the resistance changes. If the shell has any tendency to bend, however, gauges $R_1$ and $R_3$ would be strained equally in opposite directions, and the resulting resistance changes would not affect the state of bridge balance. $R_2$ and $R_4$ are in Poisson arrangement for temperature compensation and slightly increased output signal.

3. Theory

In transmitting torque, the balls continue to move axially until their axial force component on the input shaft is balanced by the opposite component of the output shaft. There are 3 types of forces on the balls: first, the tangential force, which is the torque transmitted by the shaft; second, the axial force, which is directly proportional to the torque transmitted; and third, the centrifugal force due to rotation of the shaft. The axial force induces tension in the strain-gauged transducer shell proportional to torque.

With reference to Fig. 4, the following analysis is obtained.

Let: $N_1 = N_2 =$ Equilibrium normal force acting on balls

$\alpha = 30^\circ$, angle the normal force makes with horizontal; (Parallel to shaft centre line), i.e., complementary to half the included angle of conical seat (120°)

$F_1 = F_2 = F_A =$ Axial force

$R =$ Ball pitch radius = 2.375 in

$T_1 = T_2 = T =$ Torque transmitted

$F_T = \frac{T_1}{R} = \frac{T_2}{R} = \frac{T}{R} =$ Tangential force

![Fig. 4. Schematic diagram of the force balance system of the brushless torque meter](image-url)
then:

\[ \frac{F_T}{F_N} = \sin \alpha \]  \quad \ldots (1)

\[ \frac{F_A}{F_N} = \cos \alpha \]  \quad \ldots (2)

therefore:

\[ F_T = F_A \tan \alpha \]  \quad \ldots (3)

\[ T = R \cdot F_A \tan \alpha \]  \quad \ldots (4)

But for each conical insert, \( R \tan \alpha = \text{constant} = K \) therefore:

\[ T = X \cdot F_A \]  \quad \ldots (5)

or torque transmitted is directly proportional to the axial force. The centrifugal force is prevented from influencing the magnitude of the reading by the steel retaining ring (Fig. 2) that prevents movement in a radial direction.

4. Design of the Stressed Element

Transmission of 50 hp at 540 rev/min produces a torque of 486 lb-ft in the mechanical system. Using Eqn (4), the maximum transducer separating force \( (F_A) \) (which is exactly equal to the tension in the shell) is 4250 lb. To avoid machining difficulties, the transducer shell was designed with a thickness of 0.0325 in; it has a tension area of 0.65 in\(^2\). The stress in the 0.0325 in thick shell at 50 hp is 6550 lb/in\(^2\). This is considerably below the ultimate tensile strength of mild steel; it is also rather low stress to produce a detectable signal from foil strain gauges. Semiconductor gauges, which have a gauge factor of 120 and provide 50 times the sensitivity of the regular foil strain gauges\(^5\) were applied to the transducer shell to increase the level of signal.

The maximum strain permitted in the semiconductor strain gauges Type SNB-16-35-59 is \( 2220 \times 10^{-6} \) in/in in tension. When Young's modulus is assumed to be \( 30 \times 10^6 \) lb/in\(^2\), the maximum working stress in the strain gauge is 66,000 lb/in\(^2\). The work stress of the transducer shell was well below this stress.

The high factor of safety (approximately 10) in the design of the transducer shell and availability of additional magnification from the recording system may practically obviate the need to interchange conical seat inserts for different working ranges. The inserts, however, must be changed whenever precision within a given range of torque is required.

5. Features and Operational Characteristics

The brushless torque meter is easily adaptable for any kind of shafts. Dust, moisture, and atmospheric conditions do not affect the electrical signal. The torque meter is constructed with 2 high-thrust ball bearings and 2 heavy-duty ball bearings. The torque meter must be partly disassembled to change the conical inserts. This can be accomplished while the torque meter is located in a line shaft.

The linear curve obtained by calibrating the instrument at amplification setting of 100, with static loading is reproduced in Fig. 5. The equipment used in calibration was a Honeywell Visicorder Model 906C and DANA, d.c. amplifier.

In dynamic use on agricultural machines, the level of noise may be rather high. A low-pass filter, shown in Fig. 3, reduced the noise considerably without affecting the sensitivity. A careful selection of the filter constants \( L \) and \( C \) is essential; the impedance of the filter circuit must be carefully matched with connecting circuitry of the recording system.\(^6\) It is believed that the noise level may be reduced by refining the design and machining process.
Fig. 5. Static calibration curve

REFERENCES

1 Lebow Catalog 200D. Torque and force transducers. 1969. Lebow Assoc., Inc., Oak Park, Michigan