Effect of load pad shape on the position error of column type strain gauge force transducer

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Abstract. The position error of column type strain gauge force transducer was analysed, and the effect of load pad on the position error was investigated. Six load pads with various spherical radius were designed and fixed on two column type transducers with capacities of 300 kN and 100 kN to measure their position errors and verify the theory analysis. It is shown that the position error formula could be used to illustrate the effect of load pad shape on the position error. The increment of spherical radius of ball or cup caused the increment of side force and additional moment acted on the force transducer, which resulted in larger position error. The radius should be as small as possible under the permission of material strength.

1. Introduction
With the rapid development of technology and industry, the strain gauge force transducer is more and more widely used in force measurement in the fields of highways, high-speed railways, large bridges, huge buildings, metallurgy and aerospace. The strain gauge force transducer is composed of force introduction, including the loading pad, elastic element, strain gauge, Wheatstone bridge and so on. The loading pad play an important role to adapt the loading direction. Because it is impossible to maintain the two working surfaces of Force Standard Machine (FSM) parallel enough to guarantee that the force will be centred on the primary axis of the force transducer. Any slight misalignment could move the contact point off to one edge of the hub, which induces a large moment into the measurement. With the compensation for misalignment of the loading pad, minor misalignments merely shift the contact point slightly off the centreline.

The performance of the loading pad depends on the shape, the contact form and the finishing of the contact surfaces. The load pad is made from hardened tool steel to confirm its strength \cite{1}. The contacting surfaces are better to be ground to a finish of 32 micro inch RMS. A rough finish will result in galling and wear of the loading surfaces \cite{2}. The suitable spherical radius is absolutely necessary to confine the stresses at the contact point within the limits of the materials. Use of too small a radius will cause failure of the material at the contact point or even fracture \cite{3}.

In this study, the model of the load pad was analysed and several load pads with various dimensions were tested to investigate the performance of the load pads.

2. Theory analysis
Figure 1 shows the schematic diagram of force transducer and load pad. Because of the angular misalignment $\alpha$ between the transducer and working surfaces of FSM, the ball would rotate in the cup when the transducer loaded. The force in the primary axis of the transducer is $F_N$, $F_N = F \cos \alpha$, in
which $F$ is force applied on the transducer. A side force $F_t$ and an additional moment $M$ are introduced,

$$F_t = F \sin \alpha, \quad M = e \cdot F_N = e \cdot F \cos \alpha$$

where $e$ is the eccentricity of the load. Because of the geometric analysis, $\alpha + \theta_2 = \theta_1$ and $R \theta_1 = R \theta_2$, from which $\theta_1 = R \alpha / (R_2 - R_1)$ is calculated. Substitute the eccentricity $e = R_2 \sin \theta_2 = R_2 \sin \left[ R \alpha / (R_2 - R_1) \right]$ into equation (1), one can obtain

$$M = F \cdot R_2 \sin \left[ R \alpha / (R_2 - R_1) \right] \cos \alpha$$

Equation (2)

As shown in figure 2 and figure 3, the four strain gauges were attached on elastic element. The angular misalignment, such as $\beta$ and $\gamma$, would exist for the technical limitation of strain gauge attachment. Once the manufacture of transducer finished, $\beta$ and $\gamma$ are fixed. Under the primary load $F_N$ and parasitic component ($F_t$ and $M$), the strains of elastic element where the strain gauge located were calculated with the knowledge of solid mechanics,

$$\varepsilon_i = \frac{1}{E} \left[ \frac{F_N}{S} + \frac{M - F h}{I} R \cos (\theta_1 + \phi) \right],$$

$$\varepsilon_2 = -\frac{\mu}{E} \left[ \frac{F_N}{S} + \frac{M - F h}{I} R \cos (90^\circ + \phi) \right],$$

$$\varepsilon_3 = \frac{1}{E} \left[ \frac{F_N}{S} + \frac{M - F h}{I} R \cos (180^\circ + \beta + \phi) \right],$$

$$\varepsilon_4 = -\frac{\mu}{E} \left[ \frac{F_N}{S} + \frac{M - F h}{I} R \cos (270^\circ + \gamma + \phi) \right]$$

where $S$ is the section area of the elastic element; $\phi$ is the angle in the cylindrical-coordinate system; $R$ is the radius of elastic element section; $E$ is the Young’s modulus; $\mu$ is the Poisson's ratio; $I$ is the inertia moment, $I = \pi R^4 / 4$. The output of Wheatstone bridge circuit, see figure 4,

$$X = \frac{K}{4} (\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4)$$

where $X$ is the output; $K$ is the sensitivity coefficient.

Figure 2. Strain gauge distribution.

Figure 3. Strain gauges attached with angular misalignment.

Figure 4. Wheatstone bridge circuit.
Substitute equation (3) into equation (4),

\[ X = \frac{2K}{4E} \left( \frac{F_s}{S} + \frac{M - F_h R}{I} \right) \left[ \sin \left( \frac{\omega + \beta}{2} \right) \sin \left( \frac{\beta}{2} \right) \right] + \frac{2K \mu}{4E} \left( \frac{F_s}{S} + \frac{M - F_h R}{I} \right) \left[ \sin \left( \frac{\omega + \gamma}{2} \right) \sin \left( \frac{\gamma}{2} \right) \right] \]  

(5)

The position error of the transducer was computed by

\[ b = \frac{X_{\text{max}} - X_{\text{min}}}{X_i} \times 100\% \]  

(6)

where \( b \) is the position error; \( X_{\text{max}} \) and \( X_{\text{min}} \) are the maximum and minimum output of the transducer in different measuring positions, respectively. \( X_i \) is the average output over different testing positions.

According to equation (5), \( \omega \in [0, 2\pi] \), \( X_{\text{max}} \) and \( X_{\text{min}} \) can be determined and substituted into equation (6),

\[ b = \left[ R_s \sin \left( \frac{R \alpha}{R_s - R_i} \right) \cos \alpha - h \sin \alpha \left[ \sin \left( \frac{\beta}{2} \right) + \mu \sin \left( \frac{\gamma}{2} \right) \right] \right] \left[ R(1 + \mu) \cos \alpha \right] \]  

(7)

3. Experiment

In order to investigate the effect of the shape on the position error of column type transducer, six load pads were designed, as shown in Table 1. The load pads were made from hardened 100Gr6. The load pads were fixed on a 300 kN and a 100 kN column type force transducer, which were ground plane parallel, and measured in a 300 kN Dead Weight Force Standard Machine (DWFSM) with a relative expanded uncertainty of 0.005% \((k=2)\). A DMP 41 was used as the amplifier. The platens with angular misalignment of 0.5 degree and 1 degree were placed under the transducer.

| No. | 1   | 2   | 3   | 4   | 5   | 6   |
|-----|-----|-----|-----|-----|-----|-----|
| \( R_1 \) | 150 | 250 | 350 | 60  | 120 | 200 |
| \( R_2 \) | \( \infty \) | \( \infty \) | \( \infty \) | 90  | 180 | 300 |

4. Results and discussion

The position error measurement results of the 300 kN and 100 kN column type force transducers using various load pads are shown in figure 5 and figure 6, respectively. It is found that the position error increase rapidly with the increment of the angular misalignment \( \alpha \), which is caused by the increment of the side force \( F_i \) and additional moment \( M \). Moreover, it would increase more quickly if the spherical radius of ball or cup is larger. Comparing the position errors from the load pads of No. 1, No. 2 and No. 3 with the same cup, the increasing speed of position error is largest using the ball with the radius of 350 mm. Besides that, comparison of the load pads of No. 4, No. 5 and No. 6 with the same spherical radius \( \Delta \) of \( R_1 \) to \( R_2 \), \( \Delta = R_1/R_2 = 2/3 \), shows that increasing speed of No. 4 with \( R_2 = 90 \) mm is lower than No. 6 with \( R_2 = 300 \) mm. It could be illustrated by equation (2), the moment \( M \) is proportional to \( R_2 \) with the same ratio \( \Delta \).

Comparing the measurement result of position error with that calculated by equation (7), as shown in figure 5 and figure 6, it is found that the position error formula of equation (7) can predict and explain the position error of column type strain gauge force transducer. The angular misalignment of strain gauges, \( \beta \) and \( \gamma \), is fixed once the attachment finished. So \( \sin(\beta/2) + \mu \sin(\gamma/2) \) in equation (7) a constant. When \( R_2 = \infty \), the position error increases with the increment of \( R_1 \) with the same \( \alpha \). In such case, the ball radius should be as small as possible under the permission of material strength. With the same spherical ratio \( \Delta \), \( R_2 \) should be small enough to reduce the position error.
5. Conclusion
The theory analysis and experiment result show that the position error formula could be used to illustrate the effect of load pad shape on the position error. The increment of spherical radius of ball or cup would cause the increment of side force and additional moment acted on force transducer, which results in larger position error. The radius should be as small as possible under the permission of material strength.

References
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