AN AMPLIFIER DESIGN FOR AN EXTENSOMETER IN HIGH TEMPERATURE DEFORMATION MONITORING

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In this paper a displacement amplifier is designed in order to integrate an amplifier into an extensometer, so that the precision and resolution of the extensometer can be improved for strain monitoring of high temperature components. At the first, the displacement amplifiers are investigated and the requirements for displacement amplifiers applied for high temperature deformation monitoring is summarized. At the second, a lever-type mechanical displacement amplifier for the extensometer is designed and the amplification ratio is derived. At last, feasibility of the designed displacement amplifier is analyzed from three items using FEA. They are loading force, amplification ratio and environmental temperature, which is ineluctable when the extensometer working in harsh environment for online strain monitoring. Analyzed results show that the loading force coming from the torque moment of the flexure hinge can be forced by the extensometer rods, amplification ratio equation is proved correct, and the thermal effect on accuracy can be corrected in data processing.

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ABSTRACT: In this paper a displacement amplifier is designed in order to integrate an amplifier into an extensometer, so that the precision and resolution of the extensometer can be improved for strain monitoring of high temperature components. At the first, the displacement amplifiers are investigated and the requirements for displacement amplifiers applied for high temperature deformation monitoring is summarized. At the second, a lever-type mechanical displacement amplifier for the extensometer is designed and the amplification ratio is derived. At last, feasibility of the designed displacement amplifier is analyzed from three items using FEA. They are loading force, amplification ratio and environmental temperature, which is ineluctable when the extensometer working in harsh environment for online strain monitoring. Analyzed results show that the loading force coming from the torque moment of the flexure hinge can be forced by the extensometer rods, amplification ratio equation is proved correct, and the thermal effect on accuracy can be corrected in data processing.

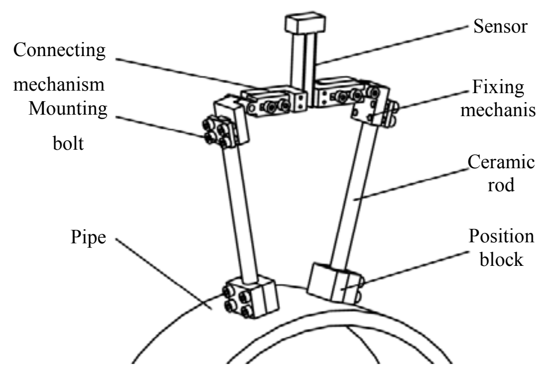
1. GENERAL INSTRUCTIONS

High temperature components are widely used in aviation, power generation, petroleum and chemical industry. Aero engine blade, main steam pipes in power plants, heating elements of heating furnaces in petrochemical plants are all typical high temperature components that play an important role in devices. Their service lives are always shortened by many factors including creep, thermal fatigue, corrosion, et al [1]. To ensure the safety of devices over a long period, life monitoring is a promising potential method. Deformation can be well correlated with creep and fatigue life in many cases, so deformation measurement has been the most straightforward and reliable method for life monitoring [2-4].

The main challenges in monitoring of high temperature deformation come from harsh working environment and micro deformation of components. Usually traditional deformation sensors are impossible to work under high temperature. And as the most reliable sensor for deformation measuring, high temperature strain gage cannot work under extreme environment for a long period. To solve this problem, extensometer-based sensing device was designed and verified [5]. Research results showed that the designed device can be used under high temperature. Nevertheless, the recognition ability of micro deformation of some components is not satisfied. Therefore, the measurement resolution of the sensing device still needs improvement.

The mechanical displacement amplifier has been successfully and widely applied in MEMS, precision instruments and so on [6-11]. Thus the mechanical amplification method will be introduced in the extensometer-based measurement method in this paper. And the displacement amplifier for the extensometer is designed.

2. DESCRIPTION OF THE DESIGNED EXTENSOMETER



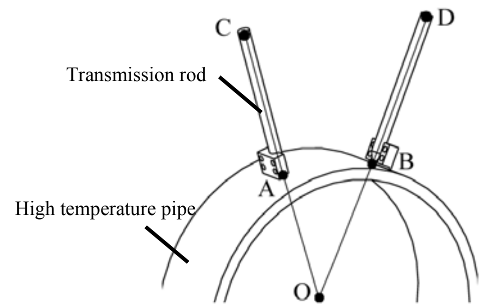


Figure.1 Designed Sensing Device. Figure 2. Transmission mechanism of the sensing device.

Especially for the deformation measurement of the main steam pipe, an extensometer for deformation monitoring is designed. The extensometer is comprised of two connecting mechanisms, two fixed mechanisms, two ceramic rods, two position blocks, one sensor and some mounting bolts. The sensor used in this extensometer is a strain gage transducer in the DTC-A series, which is developed for measurement relating to crack opening in the materials. The sensor is mounted between two connecting mechanisms. The connecting mechanisms are mounted on the ceramic rods by the fixed mechanisms, and the ceramic rods are fixed on the tested pipe by the position blocks which are inside the insulating layers. The connecting mechanisms, the fixed mechanisms and the sensor are all outside of the insulating layers.

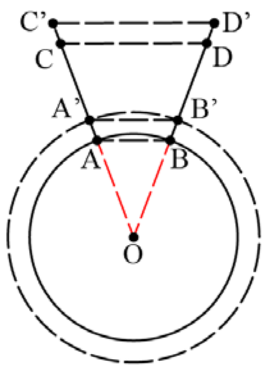
The deformation transmission mechanism of the designed extensometer is shown in Fig.2. When the component has an expansion deformation, the points A and B move to A' and B' respectively, and points C and D move to C' and D' respectively as shown in fig.3. The line segment $|AB|$ is the measuring range of the sensing device. The line segment AC equaling to h is the length of the transmission rod, and the angle included by line AC and line CD equaling to θ are known.

Therefore,

$$|CD| = |AB| + 2h\cos\theta \quad (1)$$

$$|C'D'| = |A'B'| + 2h\cos\theta \quad (2)$$

The change in line AB is ($|A'B'| - |AB|$), and the change in line CD is ($|C'D'| - |CD|$). It's obvious that they are in equivalency according to equation (1) and equation (2).



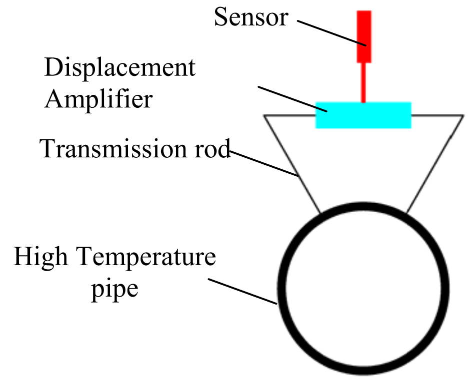


Figure. 3 Principle of measurement. Figure.4

The location of the displacement amplifier.

3. INVESTIGATION OF DISPLACEMENT AMPLIFICATION

As described in section 2, the horizontal change of segment $|CD|$ reflects the real deformation of the component. Therefore, in order to amplify the measured deformation, the displacement amplifier could be located at the ends of transmission rods, depicted as fig 2. Once the component deforms, $|CD|$ changes to $|C'D'|$, the amplifier can be actuated in horizontal and produces an amplified displacement in vertical. The amplified displacement can be identified by the sensor, shown as fig.4.

Due to the different characteristic of the actuators and application situations, the displacement amplifiers applied in extensometer are quite different from the existing in the following three aspects:

(1) Loading Force:

The existing amplifiers always couple with the PZT actuators, which are capable of producing low strain and high-force output. The actuator usually can deliver a maximum driving force of 800 *N* [12]. However, the driving force of the amplifiers applied in extensometer is passed by the transmission rods from the test components. Because some heat-resistant materials, such as zirconia ceramics materials, usually bear weak bending strengths, the driving force provided by the transmission rods can't be as large as the PZT actuators and may be only one-tenth. That is to say, the amplifier will have a much smaller input stiffness than the existing amplifiers [13].

(2) Input Displacement

The PZT actuator has a typical maximum output displacement of about 15μm [14], but the high temperature components always have a much larger deformation value in their service lives. Take the main steam pipes as an example, the design outer diameter is 350 mm, the deformation may reach 1mm in diameter in their service period. This is a much larger input displacement in structure than the existing amplifiers. The design formula of amplification ratio, which is the most important to an amplifier, needs verification in the whole range of input displacement.

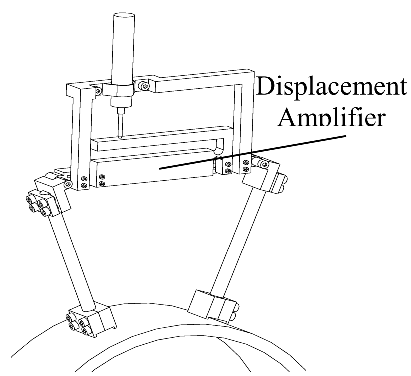
(3) Environmental Temperature

The mechanical displacement amplifier applied in MEMS, precision instruments and so on are commonly used in room temperature. Therefore, there is no need to take the temperature variation into account. However, the amplifiers in the extensometer for high temperature strain measurement are different. The extensometer designed for the main steam pipes are expected to use more than one year. In this condition, the displacement amplifier will experience a temperature difference of at least 40℃. Moreover, the amplifiers are mostly produced by aluminium alloy, which material is sensitive to the operating temperature to a certain extent. Therefore, it's necessary to consider the thermal effect in design of the amplifier for the extensometer.

4. DESIGN OF DISPLACEMENT AMPLIFIER

According to the key factors mentioned above, research of the mechanical displacement amplifier for strain monitoring of high temperature components should be redone based on the design theory and the experiment method of the existing amplifiers. Therefore, a lever-type mechanical displacement amplifier is designed, as shown in Fig. 5. The lever-type mechanical displacement amplifier is the most widely used amplifier, which can achieve large amplification ratio in a comparably smart size. Assume that the flexure hinge in the amplifier has a 1-DOF (Degree of Freedom) rotational compliance which arises from the rotational deformation, and the other elements are rigid bodies. The model of designed amplifier is depicted in fig.6. When the distance between measurement points C and D (denoted in fig.3) increases, the point F moves to F'. At this time, a horizontal displacement input ΔX is loaded to the amplifier. Due to the structural features of the amplifier, an amplified output displacement ΔY can be attained in the vertical direction. The amplification ratio can be expressed:

$$r = {\Delta Y}/{\Delta X} \tag{3}$$



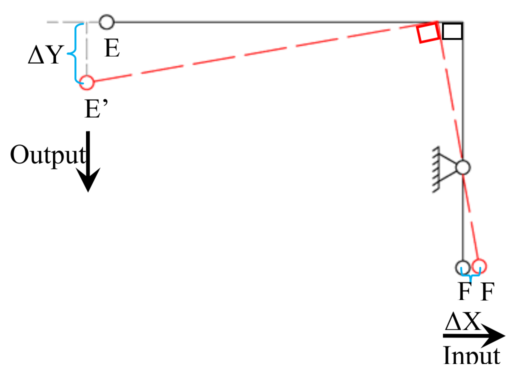
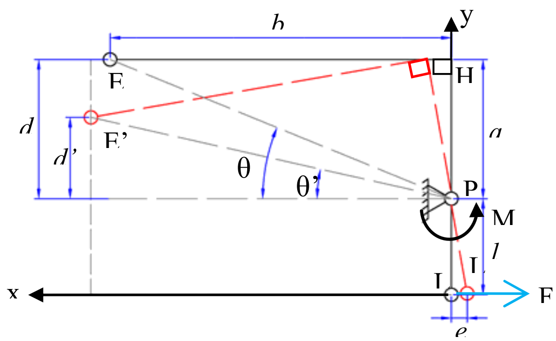


Figure.5 The sensing device with a displacement amplifier. Figure.6 Working principle of displacement amplifier.



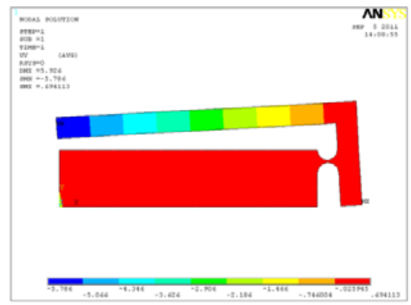


Figure.7 Analysis of amplification ratio.

Figure.8 FEA of the amplifier.

The operational principle can be described as Fig. 7. The flexure hinge is simplified as a rotation joint P. Point L and E denote the input and output ends respectively. Line EH is vertical to LH. The initial inclination angle of EP is θ. The horizontal input displacement ΔX produces a vertical output displacement ΔY, which reduces the incline angle of EP from θ to θ'. According to the geometrical relation of the model, the following relations can be obtained:

$$\Delta X = e = l * \sin(\theta - \theta') = l * \Delta\theta \quad (4)$$

$$\Delta Y = d - d' \quad (5)$$

$$d = a \quad (6)$$

$$d' = \sqrt{a^2 + b^2} * \sin\theta' \quad (7)$$

where *a, b, l* denote the length of |HP|, |EH| and |LP| respectively. And *e* is the input displacement.

Substituting Eqs. (6), (7) into Eq. (5), an expression of ΔY is obtained. And then the amplification ratio can be solved by ΔX and ΔY:

$$r = \frac{a}{e} - \sqrt{a^2 + b^2}\,\frac{\sin(a/b - e/l)}{l} \quad (8)$$

5. FEASIBILITY OF THE DESIGNED DISPLACEMENT AMPLIFIER

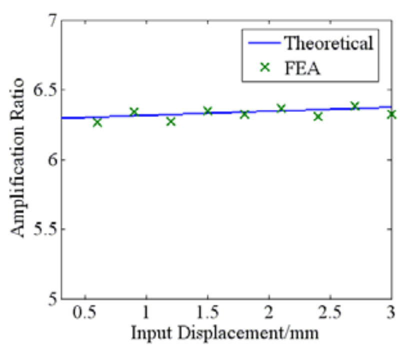
For the amplifier, shown in Fig.5, the point L is the input end in the process of loading. According to its mechanical analysis, the following equation can be attained:

$$M = F * l = \Delta\theta * K_\theta \quad (9)$$

where K_θ is the rotational stiffness of the flexure hinge. Different from the existing displacement amplifiers driven by tension, the designed amplifier is actuated by a torque moment. To flexure hinges, the tension stiffness is much larger than the rotational stiffness. Therefore, the amplifier can be easily actuated by the transmission rods.

To verify the amplification ratio in the whole input displacement range, finite element analysis method is applied. The parameters of the analyzed amplifier are a=17.5mm, b=110mm, l=17.5mm. The FEA model is shown as in fig.8, and the comparison of results from FEA and theoretical deduction by Eq. (8) is depicted in fig.9. It can be found that the amplification increases with the input displacement. The ratio from the design formula has a minimum of 6.28 while the maximum is 6.37 with the difference of 1.4%. Take the FEA results as the benchmark, the maximum error of design formula appearing at the input displacement of 2.3mm is 0.7% which verifies the accuracy of the design formula.

Moreover, the effect of temperature to the output displacement is also calibrated by FEA. To express the thermal displacement clearly, the output displacement at 0℃ is treated as the reference and the difference at 10□, 20□, 30□, 40□ is plot in fig.10. It is obviously that the output has an even 20μm drift when the environmental temperature changed from 0□ to 40□, which proves the necessity to consider the thermal effect when design a displacement amplifier for a extensometer and the accuracy of the amplifier can be corrected in the data processing.



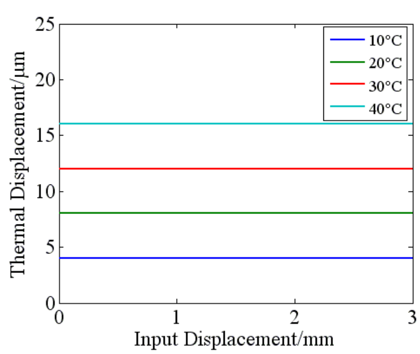


Figure.9 Theoretical and FEA of the amplification ratio. Figure.10 Output displacement under different temperature

6. CONCLUSION

In order to improve the precision and resolution for strain monitoring of high temperature components, a displacement amplifier is integrated into an extensometer in this paper. The requirements for displacement amplifiers applied for high temperature deformation measuring is summarized after the analysis at first. And then a lever-type mechanical displacement amplifier for the extensometer is designed and the design formula of the amplification ratio is derived. At last, loading force, amplification ratio and effect of temperature variation on output value of the amplifier are analyzed, and the results show that the driving force passed by the transmission rods can easily actuate the designed displacement amplifier, amplification ratio equation is proved correct, and the thermal effect on accuracy can be corrected in data processing.

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