Magnification Ratio of Mechanical Displacement Amplifier in Sensing Device

Jia Jiuhong *, *Liao Zuoyu*, *Hu Xiaoyin*, *Tu Shandong*

Key Laboratory of Pressure Systems and Safety of Ministry of Education, School of Mechanical and Power Engineering,
East China University of Science and Technology, Shanghai 200237, P. R. China

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Abstract: In order to monitor deformation of high temperature components for a long time, a sensing device integrating a bridge-shaped mechanical displacement amplifier has been designed. This sensing device has higher resolution and accuracy than conventional extensometers. However, the relation between the magnification ratio and the structure size of the displacement amplifier is a bottleneck of sensing device design. Addressing this, the magnification ratio of a mechanical displacement amplifier is analytically derived based on its geometry structure. Six prototypes of the displacement amplifier made in propathene are manufactured, and an experimental system is set up to validate the accuracy of the established magnification ratio equation. Theoretical magnification ratios and experimental magnification ratios are compared and agree well, which verifies that the proposed equation is reliable. This analytical equation provides an effective design method for bridge-shaped mechanical displacement amplifiers with an expected magnification ratio.

Key words: design method; magnification ratio; bridge-shaped amplifier; sensing device

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0 Introduction

Many industries, including pressure vessels and pipes of petroleum, chemical industry, electric power, and metallurgy, often involve high temperatures and corrosion environments for a long terms, and therefore cause inevitably unrecoverable deformations, like disintegration in mechanical properties and physical damages in materials, which seriously threatens the entire industry[1-2]. How to determine accurate deformations of test pieces is crucial to studies on high temperature material damages because those materials of test pieces will be applied to practical industries[3-4]. Therefore, it has attracted broad attentions to monitor the deformation, in order to ensure security of devices and to avoid unnecessary shutdown of plants.

The main challenges in monitoring high temperature deformation come from harsh working environment and extremely small deformation of components. It is impossible for traditional deformation measuring sensors to on-site monitor strain under a temperature over 500℃ for a long time[5]. High temperature strain gage, which is commercially available, can work under high temperature only for a short period of time[6]. In order to solve this problem, Tu et al. developed a local deformation measuring technique using optical fiber marking and remote monitoring for high temperature creep testing[1]. Morris et al. presented ARCMAC strain measurement system using image analysis[7-8]. However, these two optical methods are restricted by the resolution of tele-microscope and image processing accuracy. Thereby, extension-based sensing device was designed and verified in order to satisfy on-site monitoring requirements[9-10]. Nevertheless, the accuracy of those resolutions are not sufficient yet

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* Corresponding author, E-mail address: jhjia@ecust. edu. cn.

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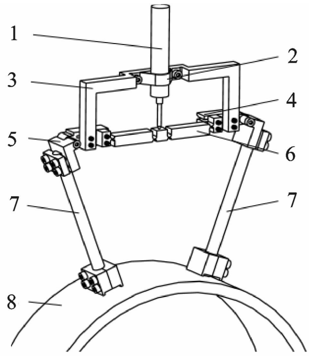
for the very small strain measurement of in-service high temperature components. Therefore, a mechanical displacement amplifier was proposed to be integrated into a sensing device to accurately on-line monitor small deformation of high temperature component[11]. This device is composed of two parts: One is an extension mechanism, and the other is a displacement amplifier. This mechanical amplifier is only sensitive to input displacement while not to interference signal. This is an advantage over the conventional circuit amplification for electrical equipments.

The mechanical amplifier is a kind of displacement compliant mechanism, which is widely used in MEMS, precision instruments and so on[12-14]. Therefore many investigations have been conducted on the displacement compliant mechanism. Xu et al. studied the flexibility, accuracy, and stress-considerations of flexure hinges for piezoactuator deformation magnifying mechanisms[12]. Ryu et al. analyzed the machining error of a monolithic flexure hinge mechanism[15]. Pedersen et al. discussed a topology optimization method for the design of large displacement compliant mechanisms[16]. Rubio et al. considered the thermal effect compensation in the design of compliant mechanisms[17]. Gerson et al. studied the overall structural displacement transfer of amplifiers[18]. Liu et al. investigated the design of a large-range amplifier mechanism[19]. However, the relation between magnification ratio and structure size of displacement amplifier has not been reported. Since physical magnification is a decisive parameter for output precision of sensing devices, magnification ratio of an amplifier should be focused on for a reliable design method.

1 Working Principle of Sensing device

In order to on-site monitor deformation of high temperature components for a long time, a sensing device integrating a mechanical displacement amplifier is designed. This sensing device is exclusively self-supporting, and can easily be fixed on any part of a component to measure the strain. A schematic of the sensing device mounted on a pipe specimen is shown in Fig. 1. It is composed of two extension bars, a sensor and a mechanical displacement amplifier.



1:Sensor; 2:Clamp; 3:Bracket; 4:Connecting peice; 5.Mounting block 6:Amplifier; 7:Extension bar; 8:Test peice

Fig. 1 Structure of the sensing device

The extension bars are mounted on the measured surface of the specimen by binding or welding. The angle between the connecting piece and mounting block can be adjusted within the ranges of >0 and ⩽90°, so as to install on test pieces with different surface shapes, such as a plane, a curved surface and so on. The amplifier is assembled between two connecting pieces. The connecting pieces and mounting blocks are mounted on same straight line which is parallel to another straight line where the top ends of the two extension bars are located, so that the deformation of a test piece is delivered equally to the amplifier. The midpoint of the amplifier acts as an output end. The sensor is mounted on the sensor bracket, and perpendicular to the amplifier mechanism. The sensor used in this kind of sensing device can be a LVDT displacement sensor, a laser displacement sensor, an eddy current sensor or the same as those. The bracket should be designed specially according to the sensor. The detailed introduction of this sensing device can be found in an approved American patent [11].

The mechanical displacement amplifier is the critical part of the sensing device. Therefore, design of the magnification mechanism is very important. There are usually three basic magnifying elements: Simple lever, bridge-shaped and four-bar linkage magnification. Benefiting from the the symmetrical structure, the bridge-shaped deformation magnifying mechanism has a high gain and linear output motion which can be used for precisely oriented applications. Therefore, a bridge-shaped structure is selected to be integrated into the sensing device. The structure of the displacement amplifier is depicted in Fig. 2.

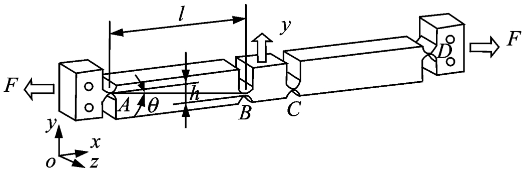


Fig. 2 Structure of the mechanical displacement amplifier

The deformation of the tested piece is transmitted by extension bar, mounting block and connecter to the amplifier. The transmitting error can be neglected because of the rigidly connectinons among extension bar, mounting block, connecter and amplifier. The output value of the amplifier can be sensed by the test terminal.

2 Analytical Model of Mechanical Displacement Amplifier

The physical magnification ratio of the amplifier is a decisive parameter of the sensing device′s precision. Therefore, a precisely analytical magnification ratio model is very important. It will benefit researchers not only in the design period but also in optimization phases of the amplifier.

In order to derive a theoretical magnification model, the structure of the mechanical displacement amplifier is analyzed. The amplifier is a symmetrical structure, as shown in Fig. 2. It consists of rigid arms and corner-filleted flexure hinges. The corner-filleted flexure hinges are denoted by A, B, C and D. The horizontal distance and the vertical distance of AB are l and h, respectively. When the driving force F is imposed on two ends of the structure in x direction, the output displacement of the mechanism comes out vertically in y direction.

Since the structure of the amplifier is symmetrical, half of the amplifier is analyzed, as shown in Fig. 3. The inclination angle of rigid arm AB is θ. When giving a horizontal input x to the amplifier, it produces a vertical output y. And the inclination angle change of AB is θ. At this moment, the velocity of points A and B are

$$v_A = \frac{\partial x}{\partial t}$$

$$v_B = \frac{\partial y}{\partial t} \tag{1}$$

The deformation magnifying ratio can be calculated according to the instant velocity of points A and B. There may be some information, which can not be included in Fig. 3, because the movements of the flexure hinges are complex. Therefore, a correction factor K is introduced in the magnification ratio equation. Then the displacement magnification ratio can be expressed as

$$R_{\text{amp}} = K \cdot \frac{\partial y}{\partial x} = K \cdot \frac{\dfrac{\partial y}{\partial t}}{\dfrac{\partial x}{\partial t}} = K \cdot \frac{v_B}{v_A} \tag{2}$$

The instantaneous center of the rigid body AB rotation is point O. The instantaneous angular velocity of the rigid AB is ω. The instantaneous velocities of points A and B are given as follows

$$v_A = \omega \cdot |AB| \sin\theta$$

$$v_B = \omega \cdot |AB| \cos\theta \tag{3}$$

According to Eqs. (2), (3), the magnification ratio can be calculated as

$$R_{\text{amp}} = K \cdot \frac{v_B}{v_A} = K \cdot \frac{\omega \cdot |AB| \cos\theta}{\omega \cdot |AB| \sin\theta} = K \cdot \cot\theta \tag{4}$$

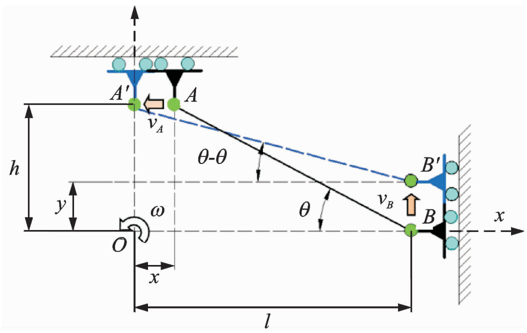


Fig. 3 Motion sketch map of the half amplifier

The above analysis, demonstrate that the magnifying ratio of the amplifier depends on the inclination angel θ. This angle θ can be defined according to the expected magnification ratio during the design period of the amplifier.

3 Experiment of Magnification Ratio Equation

In order to validate the reliability of the established magnification ratio equation, six prototypes of the mechanical displacement amplifier made in propathene are manufactured, as shown in Fig. 4. The parameters of the prototypes are listed in Table 1. And an experimental system is set up as shown in Fig. 5. In the present research, the mounting blocks and the sensor bracket are simplified as shown in Fig. 5, because tests are performed on the vibration isolation table, which is horizontal. The material of extension bar is selected as corundum. The amplifiers are mounted on the end of the two extension bars by mounting blocks. The other two ends of the extension bars are fixed separately on an amount and a micro displacement worktable, both of which are fixed on the vibration isolation table. The micro displacement worktable works as a displacement input device. When loading, one of the extension bars of the sensing device is driven by the micro displacement worktable. The displacement of the micro displacement worktable is delivered by the extension bars to the amplifier. The input displacement of the amplifier is magnified mechanically. The magnified output displacement is measured by the sensor. The chosen sensor is an eddy current sensor, and a mask of this sensor is mounted on the middle of the amplifier. The signal of the sensor is processed by the converter and data acquisition, and recorded in the computer.

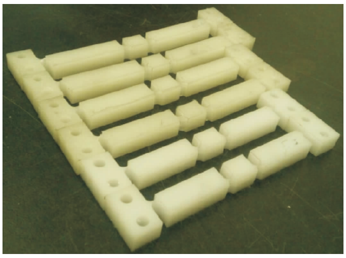
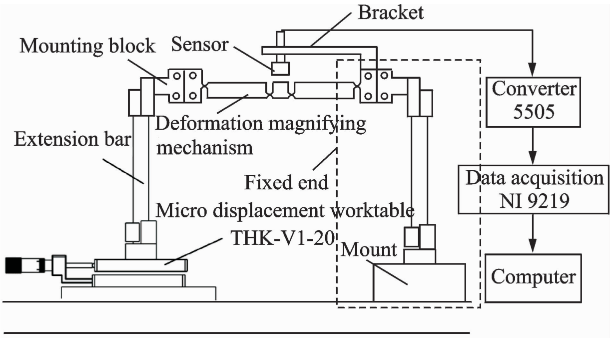


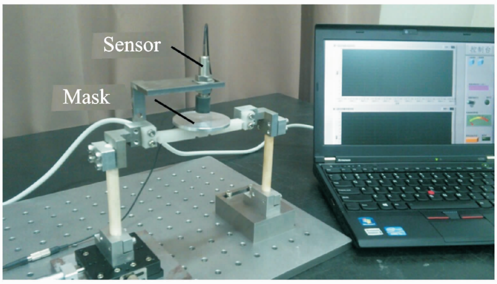
Fig. 4 Amplifier prototypes made in propathene

Table 1 Key parameters of amplifiers

Prototype	l/mm	h/mm
Prototype 1	40	5
Prototype 2	35	5
Prototype 3	30	5
Prototype 4	45	4
Prototype 5	35	4
Prototype 6	30	4



(a) Schematic of experimental principle



(b) Photo of the experimental equipment

Fig. 5 Magnification ratio verifying experimental system

In the process of testing, 100 μm input displacement is horizontally loaded each time until the input displacement reach 1 mm. Each specimen of the deformation amplifier is tested repeatedly three times, and the recorded values are the averaged value of these tests. The ratios of the output values and the input displacements are the experimental magnification ratio.

The theoretical magnification ratio can be calculated by Eq. (4) using parameters in Table 1. The correction factor K is decided by the test, which is 0.617. The theoretical magnification ratios and the experimental magnification ratios are compared in Fig. 6. It can be seen that experimental results well match the theoretical results, which proves that the theoretical magnification ratio equation is dependable.

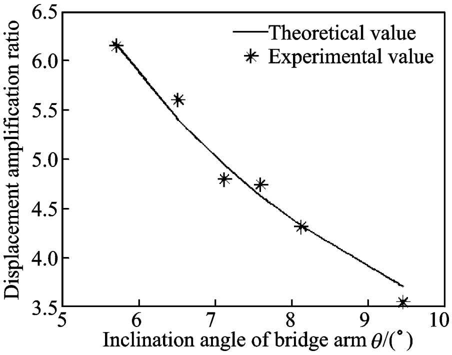


Fig. 6 Comparison of the theoretical and experimental magnification ratios

4 Conclusions

In the present research, a sensing device integrating a bridge-shaped mechanical displacement amplifier is depicted. The mechanical magnification ratio of the amplifier is analytically derived based on its geometry structure. Some prototypes of the amplifiers are manufactured, and an experimental system is set up to verify the analytically derived magnification ratio equation. The magnification ratios of the amplifier are calculated by both the analytically equation and the experimental input and output displacements. Theoretical value and experimental value are compared, which match well. Therefore, the analytical magnification ratio equation is verified. This analytical magnification ratio equation can be used to design a bridge-shaped amplifier according to the expected magnification ratio.

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Prof. **JIA Jiuhong** received the Ph. D. degree from the School of Mechanical Design and Theory , Shanghai Jiaotong University, Shanghai, China, in 2008. She joined the School of Mechanical and Power Engineering, East China University of Science and Technology in 2008. Her research focuses on high temperature structural safety monitoring technology.

Mr. **Liao Zuoyu** is a graduate student of East China University of Science and Technology. His research focuses on structural health monitoring.

Dr. **Hu Xiaoyin** received the Ph. D. degree in power engineering and engineering thermophysics from East China University of Science and Technology in 2013. His research focuses on structural health monitoring.

Prof. **Tu Shandong** received the Ph. D. degree in chemical machinery from Nanjing College of Chemical Technology in 1988. He worked as a Guest Scientist in Royal Institute of Technology (KTH) from 1990 to 1993. He was invited to serve as a visit professor in South Korea's Central University in 1998. He has been a Distinguished Professor of Yangtze River of East China University of Science and Technology since 2001. His research focuses on high temperature structural integrity.

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