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Strain visualization sticker using moiré fringe for remote sensing

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ABSTRACT: Evaluation of the strain on a bridge's members is required to maintain its safety. To meet this requirement, we propose a strain visualization sticker that can display numeric characters and fringes corresponding to the magnitude of strain without the use of electronic elements such as amplifiers, strain gauges and wires. We focus on the slight displacement produced by the strain, and visually magnify and display its displacement with a moiré fringe pattern. The sticker is simply attached to the bridge's members, and it provides strain information by displaying characters that can be read with the naked eye. An accurate numerical value of the strain can be obtained from an image of the sticker through image processing. The structure of the sticker is simple, and its fabrication is inexpensive. We assume that a slight displacement is generated by the strain, and results show that the sticker provides displacement information in the form of readable characters, giving accurate numerical value of displacement of less than 1 μm using image processing.

1 INSTRUCTIONS

Evaluation of the strain on a bridge's members is required to maintain its safety (Chang, S.J. et al. 2010) (Ni, Y. Q. et al. 2010) (Uchino, M. et al. 2010), and a large amount of research has been carried out by measuring such strain using electrical sensors, such as strain gauges. When such sensors are attached to measurement points, it is necessary to supply electrical power to these points. This implies that external power must be supplied via wiring or that an internal electrical power source must be fitted into the sensor. Furthermore, wired or wireless methods are needed to transmit the measurement data from the sensor. This tends to make the overall systems larger and more expensive.

To solve this problem, measurement techniques that do not require electrical power to be supplied to measurement points have been developed, utilizing optical elements or ultrasound, for example. In an earlier paper, we proposed a mechanism that utilizes moiré fringe patterns to visualize a physical force without the need for an electrical power supply at the measurement point (Takaki, T. et al. 2008, 2010).

In this study, we propose a strain visualization sticker that can display characters and fringe patterns that correspond to the magnitude of strain without the use of electronic elements, such as amplifiers, strain gauges and wires. We focus on the slight displacement produced by the strain and visually magnify and display its displacement with a moiré fringe. Figure 1 shows the concept of how to use the sticker. The sticker is simply attached to the bridge's members, and it provides strain information by displaying characters which can be seen with the naked eye. An accurate numerical value of the strain can be obtained from the image of the sticker through image processing. When using a telescopic lens, this value can be remotely measured. The structure of the sticker is simple, and its fabrication is inexpensive; therefore, our proposed measurement method using the sticker can be employed for multipoint measurement.

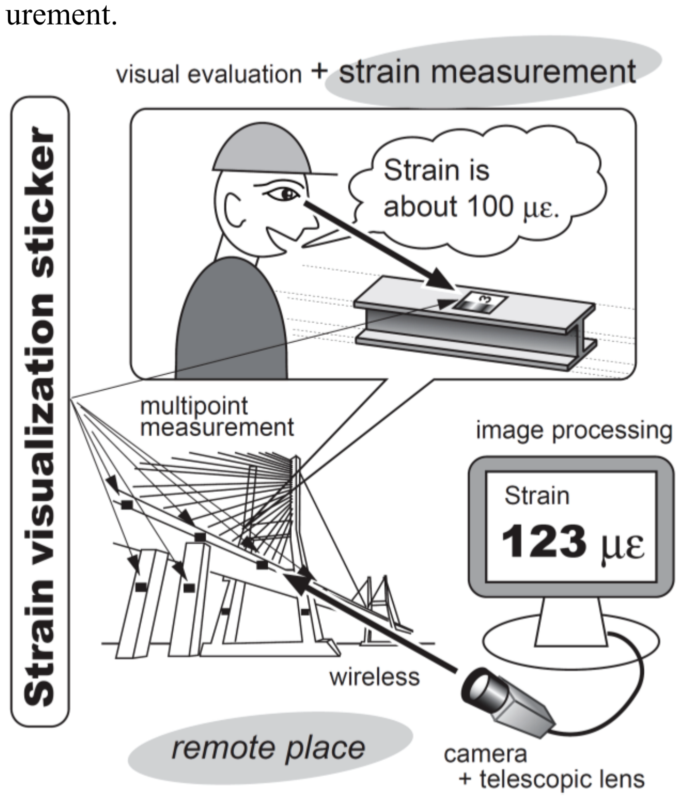

Figure 1. Concept of a proposed strain visualization sticker

This paper is organized as follows. Section 2 presents the principle of the strain visualization sticker. Section 3 describes a moiré fringe pattern that achieves both high magnification and clarity, without using expensive printing technology. Section 4 describes the method for acquiring strain data using a captured image of the sticker, and Section 5 describes the developed strain visualization sticker. In Section 6, we assume that a slight displacement is generated by the strain, and we experimentally verify that characters corresponding to the magnitude of the displacement are accurately displayed. We verify that the developed sticker can measure even a slight displacement of less than 1 μm using the captured image of the sticker. Section 7 concludes the paper.

2 STRAIN VISUALIZATION STICKER

2.1 *Moiré fringe*

Let us first explain moiré fringes (Kobayashi, A. S. 1987). As shown in Fig. 2 (i), by superimposing line grating 1 of pitch p on line grating 2 with pitch $p + \Delta p$ $(\Delta p \ll p)$, a fringe known as a moiré fringe appears with pitch W. Pitch W is larger than the pitch of line gratings 1 and 2. Their relationship is given by

$$W = \frac{p+\Delta p}{\Delta p} p. \tag{1}$$

As shown in Fig. 2 (ii), when line grating 1 at pitch p is moved in direction (A), the moiré fringe at pitch W moves in direction (A). Therefore, the displacement x can be displayed visually at a magnification M of $(p + \Delta p)/\Delta p$. When the relative displacement of the line gratings is x, the displacement of the moiré fringe x_m can be described by the following equation:

$$x_m = Mx. \tag{2}$$

2.2 *Structure of the strain visualization sticker*

Figure 3 shows the structure of a proposed strain visualization sticker. The sticker is composed of two transparent films. The line grating is printed on the back of the upper film and on the front of the lower film. To obtain a clear moiré fringe, the back of the lower film is painted with white color. To prevent the two films from separating, the region between the two films is filled with oil. When the ends of the films are bonded to an object as shown in Fig. 3, the slight displacement x produced by the strain ε on an object is displayed by the moiré fringe at a magnification of M. Therefore, the strain ε can be confirmed visually. L is the distance from the bonded positions of the upper film to the bonded positions of the lower film. The relationship between a slight displacement x and stain ε is given by

$$\varepsilon = \frac{x}{L}. \tag{3}$$

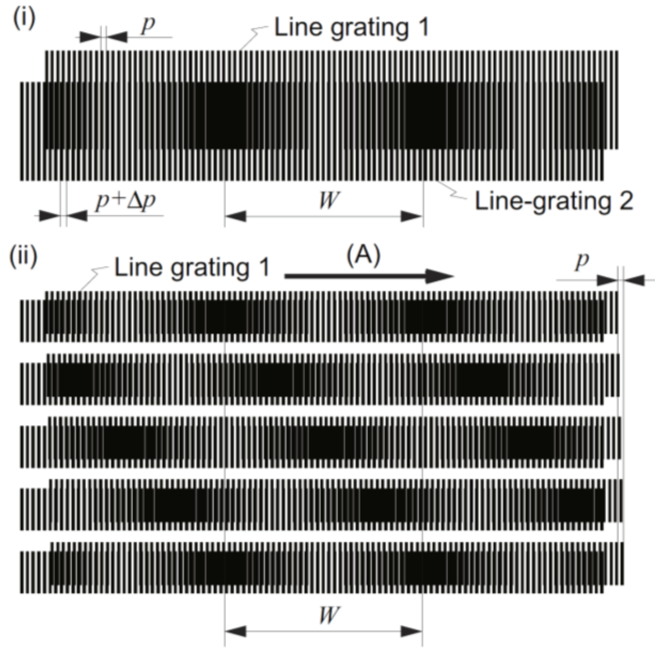

Figure 2. Example of a Moiré fringe.

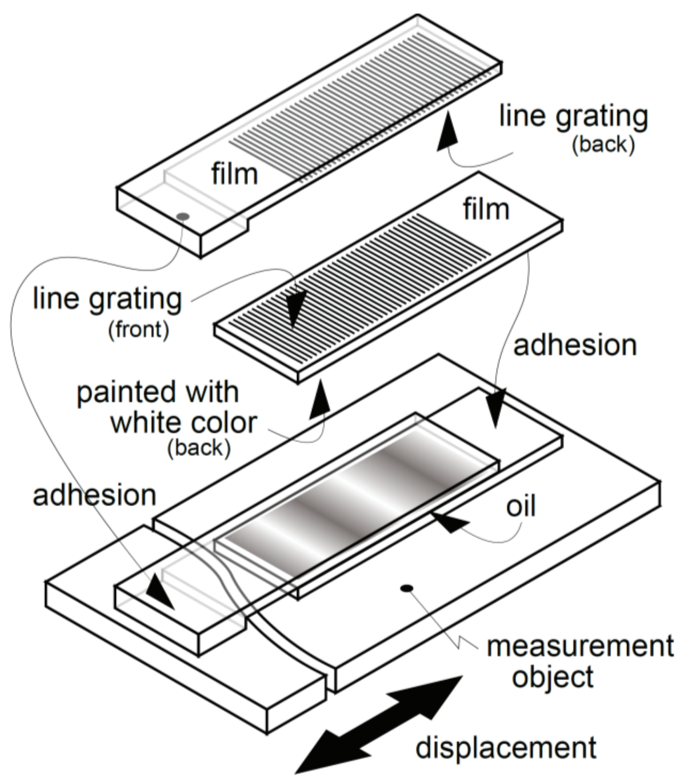

Figure 3. Structure of the strain visualization sticker.

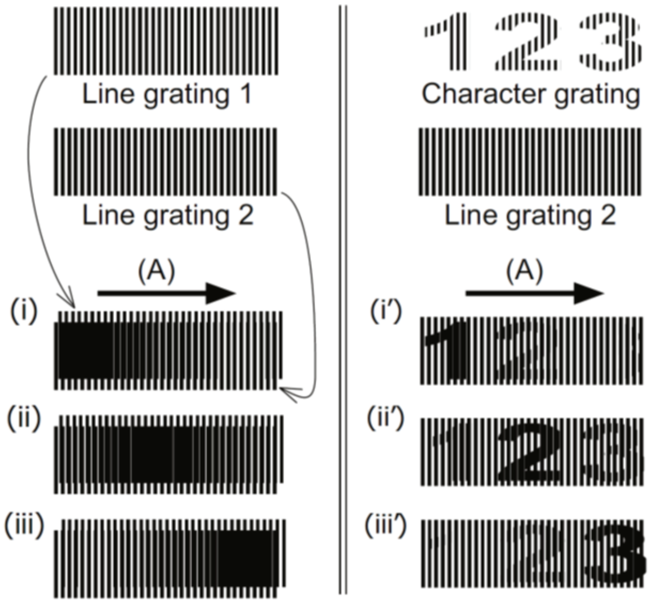

Figure 4. A moiré fringe with characters.

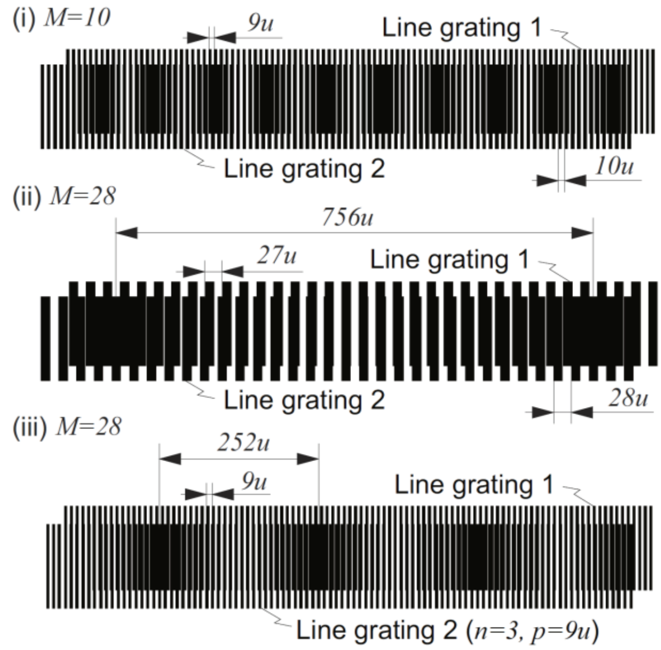

Figure 5. Moiré fringe and magnification M.

3 IMPROVING VISIBILITY OF THE MOIRÉ FRINGE

3.1 *Displaying characters with the moiré fringe*

The moiré fringe shown in Fig. 2 is a simple fringe pattern, and its visibility is not necessarily adequate. To improve the visibility, in this section, a method is proposed to display characters with the moiré fringe. The movement of the moiré fringe is shown on the left in Fig. 4. Similar to Fig. 2, if line gratings 1 and 2 are superimposed and line grating 1 is moved in direction (A), the moiré fringe moves, as in Fig. 4 (i)-(iii).

We propose a method to display characters with a moiré fringe, as shown on the right in Fig. 4. In place of line grating 1, we propose the use of gratings in the shape of characters, which we refer to as character gratings. If this character grating and line grating 2 are superimposed and the character grating is moved in direction (A), characters are displayed in the order shown in Fig. 4 (i')-(iii').

3.2 *Highly magnified, legible moiré fringe and printing technology*

The moiré fringe in the sticker should have high magnification and be sufficiently legible. Moreover, for this method to be practically feasible, fabrication should be possible with inexpensive printing technology. In this section, a method is presented to show a highly magnified, clear moiré fringe, even with a grating fabricated using inexpensive printing technology. First, we describe the printing technology and magnification, and then, the clarity of the moiré fringe pattern. Next, we propose a grating pattern that produces a clear moiré fringe, using inexpensive printing technology.

3.2.1 *Printing technology and magnification*

Assuming that the fabrication of a fringe involves the use of a printer, we discuss the resolution of the printer at magnification M. For example, if a printer has a resolution of 600 dpi, the finest lines that can be printed are 1/600 th of an inch. The unit of width corresponding to finest lines that can be printed is defined as u. From Eq. (1), to obtain a high magnification M, the Δp should be small. However, considering that printing technology is used, the minimum Δp is u. Thus, henceforth, Δp is defined as u. For example, to obtain a magnification M of 10, the pitches p and $p+\Delta p$ must be $9u$ and $10u$, respectively, for line gratings 1 and 2 according to Eq. (1). Similarly, to obtain a magnification M of 28, they need to be $27u$ and $28u$, respectively. These moiré fringes are shown in Figs. 5 (i) and (ii).

3.2.2 *Clarity of moiré fringes*

The moiré fringes produced with this sticker should be clear. When the grating lines are too fine to see, the moiré fringe can be clearly observed. Conversely, when the grating lines are thick, the grating is visually more discernible than the moiré fringe, and the fringe cannot be clearly observed. Thus, the moiré fringe in Fig. 5 (i) is clear because the line grating is fine, and the moiré fringe in Fig. 5 (ii) is less clear, because the grating is thicker.

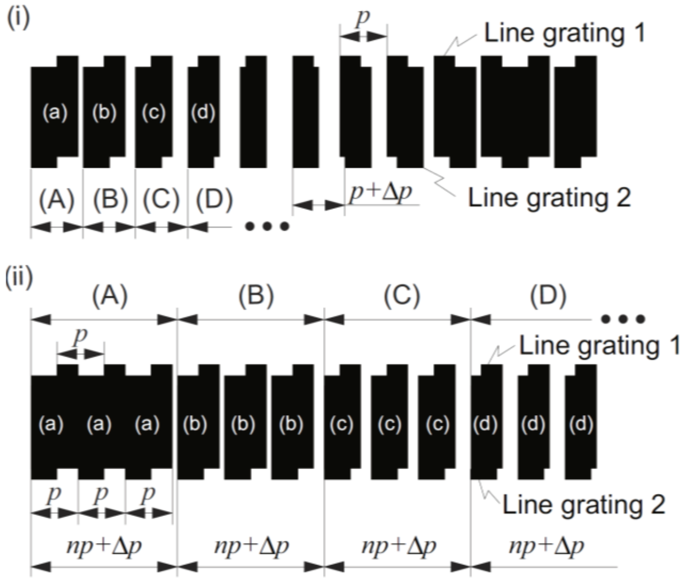

Figure 6. Moiré fringe and magnification M.

3.2.3 *Magnification and clarity*

The magnification M of the moiré fringe in Fig. 5 (i), which is clear, is small at M =10. M in Fig. 5 (ii), which is not clear, is large at M =28. Thus, there is a tradeoff between clarity and magnification in moiré fringes. In this grating pattern, to achieve both high magnification M and clarity, u must be small. However, to make u small, a more expensive printing technology that can print very fine lines is necessary, which is undesirable because it leads to higher costs.

3.2.4 *Proposed grating pattern*

To obtain clear and highly magnified moiré fringes without the use of expensive printing technology, we propose a line grating pattern. Figure 6 (i) shows a magnified figure of one pitch of the moiré fringe in Fig. 5 (i). The dark areas where the lines of gratings 1 and 2 are superimposed are defined, in order, as (a), (b), (c), and (d). We propose a configuration of line grating 2 in which the dark areas are repeated as (a)(a)(a)..., (b)(b)(b)..., (c)(c)(c)..., and (d)(d)(d)..., as shown in Fig. 6 (ii). In this pattern, the fringe of pitch p repeated n times (in the figure, $n = 3$) is placed every $np + \Delta p$. Pitch W of the moiré fringe in Fig. 6 (ii) is

$$W = \frac{np+\Delta p}{\Delta p}\, p, \tag{4}$$

and the magnification M is $(np+\Delta p)/\Delta p$. The moiré fringe, when p=9u and n=3, is shown in Fig. 5 (iii). From Eq. (2), its magnification M is 28 and the magnification M in Fig. 5 (ii) is also 28. However, the pitch of the line grating is finer in Fig. 5 (iii). Therefore the moiré fringe in Fig. 5 (iii) is clearer than that in Fig. 5 (ii). If line gratings are configured in this way, an expensive printing technology that can print small u, is not necessary; a clear moiré fringe with high magnification M can be obtained with inexpensive printing technology.

Here, we explain why pitch W of the moiré fringe differs although the magnification is the same (M =28) in Figs. 5 (ii) and (iii). The relationship between the pitch p of line grating 1, pitch W of the moiré fringe, and the magnification M is obtained as $W = Mp$ from Eqs. (1) and (4). Therefore, even with the same magnification M, when the pitch p of line grating 1 differs, pitch W of the moiré fringe also differs correspondingly. In the cases of Fig. 5 (ii) and (iii), the values of the pitch p of line grating 1 are $27u$ and $9u$, respectively; therefore, the values of the pitch W of the moiré fringe are $756u$ and $252u$.

4 METHOD OF EXTRACTING STRAIN VALUE BY IMAGE PROCESSING

4.1 *Fitted sine curve*

The image of a moiré fringe is trimmed from an original image taken by a camera, and the x- and y-axes are defined as shown in Fig. 7 (i). The size of the trimmed image is (X, Y), and the brightness value of the pixel at (x, y) is defined as $I(x, y)$. $f(x)$ is the average of the brightness value along the y-axis. $f(x)$ can be written as

$$f(x) = \frac{\sum_{k=0}^{Y-1} I(x, y)}{\mathrm{Y}}. \tag{5}$$

$g(\mathrm{x})$ is a sine curve fitted to $f(\mathrm{x})$. In the image, when a unit length corresponds to l pixels, $g(x)$ can be written as follows:

$$g(x) = A \sin(\frac{2\pi}{lW} x + \theta) + B. \tag{6}$$

Figure 7 (ii) shows the difference between $f(x)$ and $g(x)$ in an example case. A, B, and θ are the amplitude of the brightness value, offset of the brightness value, and phase of the moiré fringe in the trimmed image, respectively. A, B, and θ can be obtained using the least squares method.

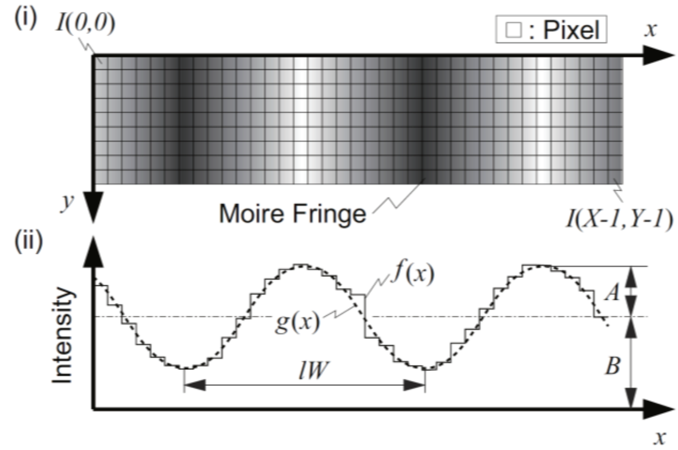

Figure 7. Intensity of a moiré fringe and corresponding fitted curve.

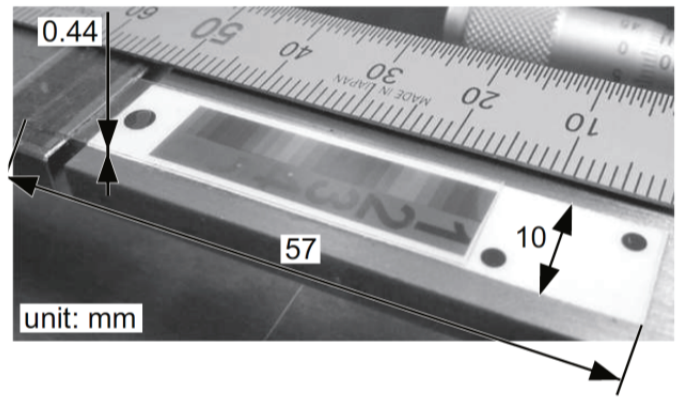

Figure 9. The developed strain visualization sticker.

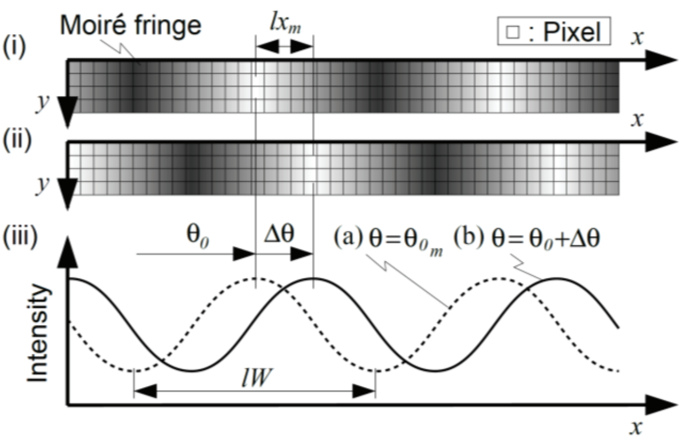

Figure 8. Phase of a moiré fringe.

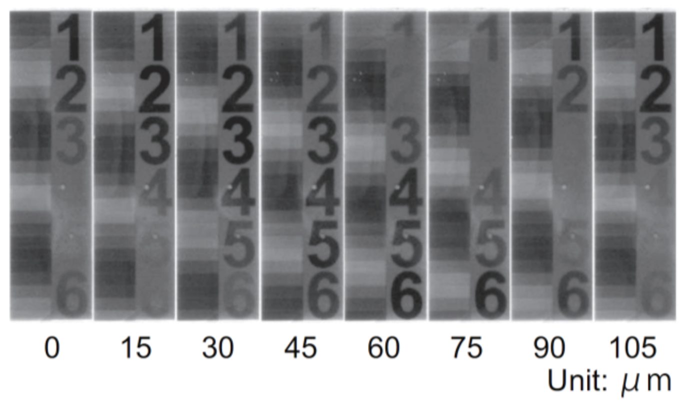

Figure 10. The developed strain visualization sticker under a range of displacement.

4.2 *Phase of fitted sine curve and displacement of moiré fringe*

Figure 8 (i) shows the image of a moiré fringe when the measured object has no strain. The brightness value of this moiré fringe is fitted to $g(x)$, and the phase in this state is assumed to be θ_0, as indicated by (a) in Fig. 8 (iii). When a strain ε occurs on the object, a displacement of x occurs, and the moiré fringe moves by x_m, which can be calculated from Eq. (2). In the image, when the moiré fringe moves by lx_m, as shown in Fig. 8 (ii), the phase θ shifts by $\Delta\theta$, as indicated by (b) in Fig. 8 (iii). The relationship between these two terms is given by

$$lx_m = \frac{lW}{2\pi}\Delta\theta. \quad (7)$$

From Eqs. (2) and (7), the displacement x is given by

$$x = \frac{p}{2\pi}\Delta\theta. \quad (8)$$

From Eqs. (3) and (8), the stain ε is given by

$$\varepsilon = \frac{p}{2\pi L}\Delta\theta. \quad (9)$$

5 THE DEVELOPED STRAIN VISUALIZATION STICKER

Figure 9 shows the developed strain visualization sticker. The length, width, and thickness of the sticker are 57 mm, 10 mm, and 0.44 mm, respectively. The material of the film is polyester. The line gratings are printed on the film using a photomask technique. The finest line produced with this technique is 0.01 mm. The left side of the sticker displays a simple moirés fringe pattern for image processing; the right side displays characters using moiré fringes to allow reading of the measured strain with the naked eye. The magnification M of the simple moiré fringe is 121, and its pitch p, Δp and the pitch repetition number n are 0.1 mm, 0.01 mm and 12, respectively. The magnification M of the character fringe is 501, and its p, Δp, and n are 0.1 mm, 0.01 and 50, respectively.

6 EXPRIMENT

6.1 *Measurement by naked eye*

Figure 10 shows photographs of the sticker for 15 μm increments of the displacement. As shown, the developed sticker can display the character corresponding to the displacement.

6.2 *Measurement using image processing*

We assume that a slight displacement is generated by the strain and experimentally verify that the proposed sticker and algorithm can detect less than 1 μm displacement. Figure 11 shows the experimental setup. We use a micro-translation stage to generate a micron-scale displacement, and this displacement is visualized by the proposed sticker. An image of the sticker is taken with a CMOS camera (Micro Vision Co., Ltd. VC-4302) from a distance of 420 mm. The size and frame rate of the image are 640×480 pixels and 8.2 fps, respectively. The focal length of the lens is 35 mm. For comparison, we also measure the displacement using a laser displacement sensor. The sampling time of the laser displacement sensor is 20 ns, and a moving average of 10000 points is used as a filter to eliminate noise.

Figure 12 shows the experimentally measured displacements where the translation stage generates displacement steps of less than 1 μm. The displacements are measured by the proposed method and the laser displacement sensor. These two values are very consistent. When the two films of the sticker are bonded to an object to be measured and the distance between the bonded points is $L = 50$ mm, a displacement of 1 μm corresponds to a strain of 20 $\times10^{-6}$. In this case, our proposed sticker can measure a strain of less than 20×10^{-6}.

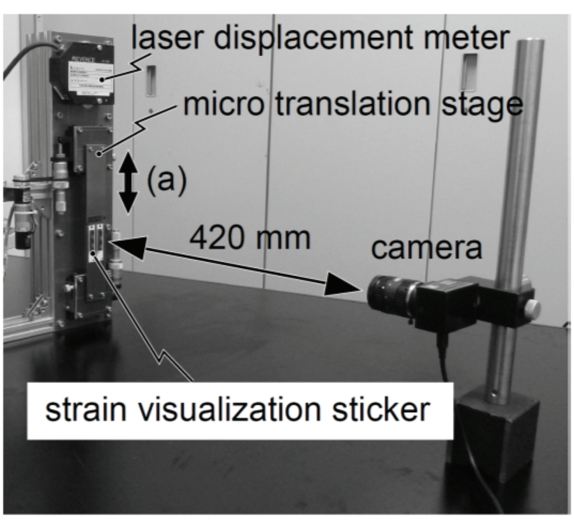

Figure 11. Experimental setup.

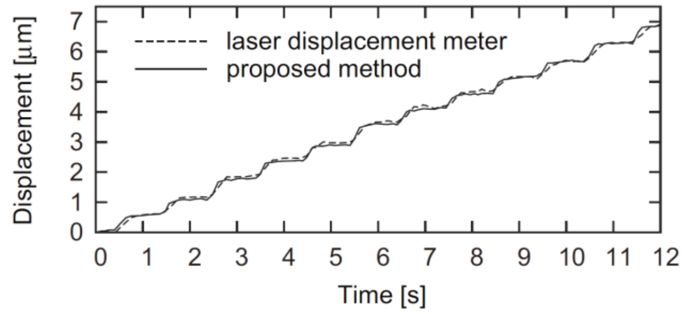

Figure 12. Experimental result.

7 CONCLUSION

A method was proposed to display fringes or numeric characters that correspond to a measured strain without the use of electronic elements by a novel application of moiré fringe patterns. We assume that a slight displacement is generated by the strain, and we have confirmed experimentally that numbers corresponding to this displacement can be visually represented. Using captured images of the sticker, we have verified that the developed sticker can provide measurements of slight displacements of less than 1 μm.

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