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Original Article

VIBRATION DISPLACEMENT MEASUREMENT TECHNOLOGY FOR CYLINDRICAL STRUCTURES USING CAMERA IMAGES

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ABSTRACT

Acceleration sensors are usually used to measure the vibration of a structure. Although this is the most accurate method, it cannot be used remotely because these are contact-type sensors. This makes measurement difficult in areas that cannot be easily approached by surveyors, such as structures located in high or dangerous areas. Therefore, a method that can measure the structural vibration without installing sensors is required for the vibration measurement of structures located in these areas. Many conventional studies have been carried out on non–contact-type vibration measurement methods using cameras. However, they have been applied to structures with relatively large vibration displacements such as buildings or bridges, and since most of them use targets, people still have to approach the structure to install the targets. Therefore, a new method is required to supplement the weaknesses of the conventional methods. In this paper, a method is proposed to measure vibration displacements remotely using a camera without having to approach the structure. Furthermore, an estimation method for the measurement resolution and measurement error is proposed for the vibration displacement of a cylindrical structure measured using the proposed measurement method. The proposed methods are described, along with experimental results that verify their accuracy.

1. Introduction

Contact-type acceleration sensors are usually used for vibration measurement of structures. However, because contact-type sensors need to be directly attached to the structure, approaching the structure is necessary, and consequently, much time and expense are required when measuring a structure that is difficult to approach or located in a dangerous area such as a high-temperature/high-pressure structure and high radiation area in nuclear power plants. Therefore, a remote measurement method is required for measuring the vibration of structures in areas that are difficult to approach.

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Accordingly, along with the rapid advancement of camera hardware, many studies have been carried out on vibration measurement using cameras in recent years [1–6]. Although the measurement resolutions and sampling speeds of methods using cameras are lower than those of sensor measurement methods, they have the great advantage that remote and simultaneous multipoint measurements are possible. Therefore, many studies have been conducted on relatively large structures that have low frequencies and large vibration displacements such as bridges and buildings. However, most of the conventional methods use targets, and in general, the measurement resolution is constrained by the camera resolution. Furthermore, these methods have a disadvantage, where measurement is impossible, when the structure is difficult to approach by surveyors because these methods require the installation of targets such as contact sensors on the object being measured. Recently, a vibration measurement method using the edges of a structure was proposed, but the error range of the measurement signals and the measurement resolutions could not be accurately determined, and the measurement environment had an influence on the image noise [6].

In this paper, a remote vibration displacement measurement method is proposed that uses an improved edge detection method and a camera. The proposed method uses the second derivative of an image and has a measurement resolution equal to the pixel resolution, or higher. This method has the advantage that multipoint measurement is possible. In addition, we propose a method for estimating the measurement resolution and error range when measuring the vibration displacement of a cylindrical structure.

2. Vibration displacement measurement method using cameras

The single pixel value of a grayscale image is determined by the brightness value (0~255), which depends on the amount of light received by the image sensor. This value can be defined as the brightness value of a two-dimensional area transmitted from the photographed area of the subject to the image sensor through the optical lens. Measuring the vibration displacement of a subject begins with the movement detection of a specific point on the subject. The measurement point can be a mark specified by a user or an edge of the subject. Conventional image processing methods for edge detection include Laplacian, Sobel, and Canny edge detectors [7]. These methods determine the edge pixel as the pixel having a strong edge component in the image using the first or second derivatives. Conventional vibration measurement methods using cameras detect the edge and monitor its variation rate using one of these image processing methods. However, the edge coordinates determined through the image processing technique introduced earlier are approximated integer-type pixel coordinate values. Therefore, if a regular image processing technique is used to measure the vibration displacement, a large error will be inherent. To obtain the coordinates of the actual edges of the vibration-displacement measurement subject, they should be expressed as real number-type coordinate values instead of approximated integer-type coordinate values. Therefore, instead of conventional image processing techniques, an improved real-number-type edge detection method is required.

2.1. *Basic theory*

In an image, the boundary between the subject and background is not perfectly distinguished, as in reality. In most cases, the brightness value of the edge area, which is the boundary between the subject and background in the image, does not change radically, but changes gradually. This is because of image resolution problems and blurring.

After acquiring continuous images of the vibrating structure, Fig. 1 shows the influence of the vibration on the brightness changes and brightness variation rates in the edge area. As shown in Fig. 1A, a vibration measurement point (edge area) with a size of 9×9 was selected from the whole image S ($m \times n$ size). Here, the edge is in the horizontal direction, whereas the subject vibrates in the vertical direction. In Fig. 1B, nine pixels in the vertical direction are selected arbitrarily, and the brightness changes in the time domain are shown in Fig. 1C. The brightness value changes of each pixel from pixel P0 to P8, which correspond to the edge area, were due to the vibration of the subject, and the changes appeared clearly at the boundary between the background and subject. Fig. 1D shows the brightness values of P0~P8 from the 38^{th} and 70^{th} frame images, which correspond to the vibration P-P. The vibration of the structure affected the images, and it can be seen that the brightness values in the edge area changed as a result of the vibration.

Fig. 2 shows the first and second derivative results in the edge area using a regular image processing technique. Most of the regular image processing techniques for determining the edge in an image use the first or second derivative.

The first derivative of an image determines the gradient between pixels by obtaining the differences in neighboring pixel values, as shown in Eq. (1). The conventional image processing techniques for detecting the edge using the first derivative include the Sobel, Prewitt, and Roberts methods [7].

$$G(x) = f(x-1, y) - f(x+1, y) \quad (1)$$

$$G(y) = f(x, y-1) - f(x, y+1)$$

where x is a vertical axis coordinate value of the image, y is the horizontal axis coordinate value, f is an input image, and g is a first derivative for f. In general, the edge detection method using the first derivative determines the integer-type pixel coordinate having the maximum derivative value as the edge. A method has been proposed whereby these values are expressed in the form of a Gaussian distribution, and by regarding it as a probability distribution and obtaining the center of mass value, the real number-type edge is determined [6]. However, it is difficult to accurately determine the edge area used in the calculation, and measurement error occurs if the calculation area is incorrectly determined.

The conventional methods for detecting edges using the second derivative, which reacts more sensitively to the edge, include the Laplacian and Laplacian of Gaussian [7,8].

Nucl Eng Technol 47 (2015) 488–499

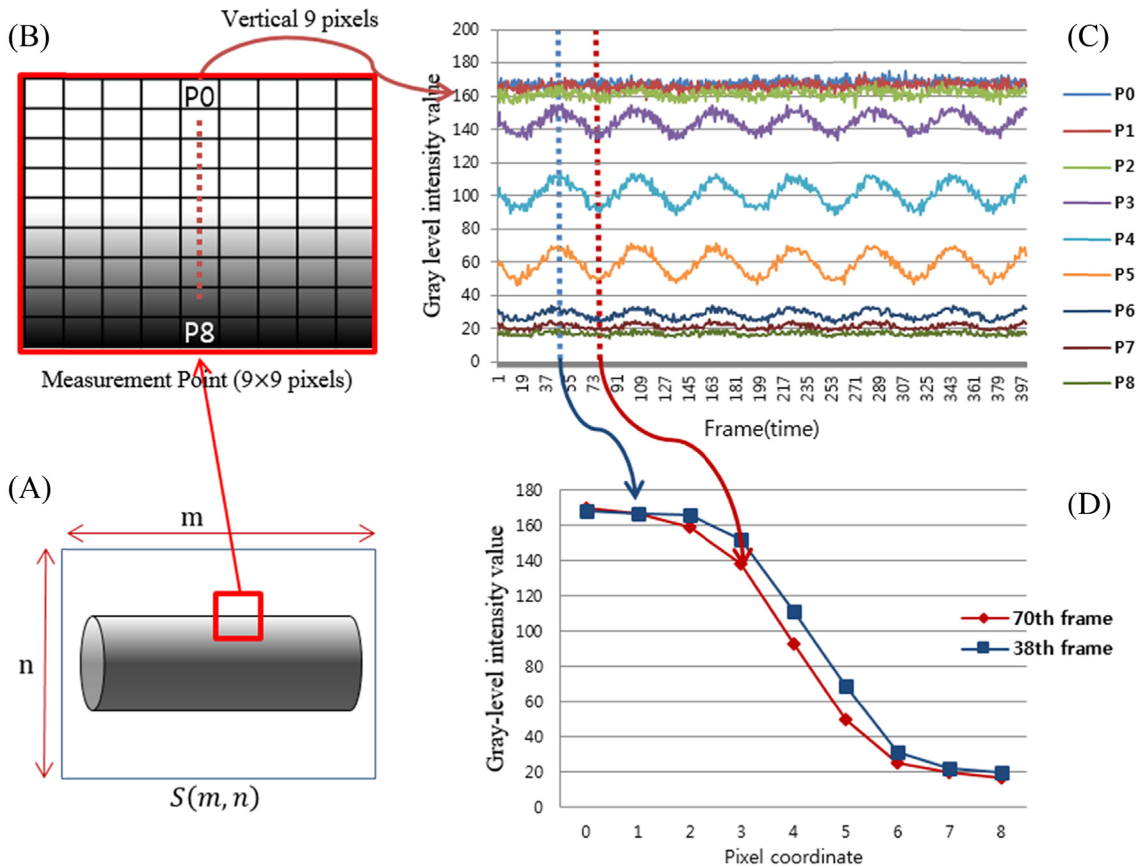


Fig. 1 – Trend of brightness change of nine pixel values corresponding to edge area in image acquired for 2 seconds at 200 frame/s for a subject with a periodic vibration of 1.3 Hz.

The Laplacian differential operator that defines the second derivative in the image is defined as $\nabla^2 f$, which is the sum of the second derivative in the x direction of the image $\partial^2 f/\partial x^2$ and the second derivative in the y direction $\partial^2 f/\partial y^2$, as shown below.

$$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \tag{2}$$

$$\frac{\partial^2 f}{\partial x^2} = f(x+1, y) + f(x-1, y) - 2f(x, y)$$

$$\frac{\partial^2 f}{\partial y^2} = f(x, y+1) + f(x, y-1) - 2f(x, y)$$

The Laplacian operator that defines the second derivative in the image determines the closest integer-type coordinate to the zero-crossing point as an edge using a one-interval second derivative. However, the Laplacian operator is known to be very sensitive to noise. Therefore, the Laplacian of Gaussian method is usually used, which removes the noise through Gaussian smoothing. Gaussian smoothing is a method of changing the value of a reference pixel to remove the noise component using information about the pixels in the vicinity. However, this method cannot completely classify the noises [8]. For vibration measurement, because the information about even one pixel is very important, it is crucial not to change the original pixel information for the purpose of removing noises.

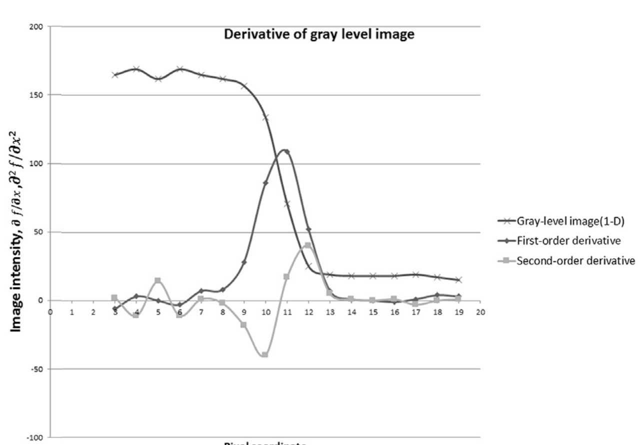


Fig. 2 – First derivative and second derivative results in edge area using a regular image processing technique.

In this paper, as shown in Fig. 3, the mean of the multi-interval second-order derivative method is used to determine the real-number coordinate of the zero-crossing point as an edge. The interval of the proposed method means the differential interval, and the noise effect in the edge area is minimized using the average value obtained by changing the differential intervals. The interval of the Laplacian operator, which is a conventional edge detection method, can be said to be 1, and it reacts to noises very sensitively. Therefore, in the proposed method, one interval is not used. Since the Laplacian operator is a common edge detection method, one interval of the second derivative is efficient, but in the case of an image acquired for vibration displacement measurement, like in this study, the accurate separation of the subject and background is most important.

The mean of the multi-interval second-order derivative method can be defined as follows for a one-dimensional image S.

$$S''(i) = \frac{1}{(T-1)}\sum_{n=2}^{T}[2S(i) - \{S(i+n) + S(i-n)\}] \quad T \geq 10 \tag{3}$$

where i is the coordinate value of the image, n is the second derivative interval, and $S''(i)$ is the mean of the multi-interval second-order derivative for the image S. In the proposed method, n is increased to 2~T. As introduced earlier, since one interval is very sensitive to noises, it is not used. Furthermore, most edge areas are included in ten intervals, and as shown in Fig. 3, since n, which is larger than the edge area, does not affect the zero-crossing point result, T is an integer ≥10.

To find the zero-crossing point, the integer coordinate value closest to zero between the maximum and minimum values is obtained in $S''(i)$. The coordinate value closest to zero in the second derivative can be found using the first derivative value. The first derivative value is shown in the form of a Gaussian distribution, and here, the maximum value is closest to the zero-crossing point of the second derivative. Suppose the coordinates having the maximum value of the first derivative and the next largest value are P_0, P_1. Then, the two points $(S''(P_0), P_0)$ and $(S''(P_1), P_1)$ that cross the zero point can be known. Therefore, the equation for a straight line that goes through two points is

$$(y - P_0)(S''(P_1) - S''(P_0)) = (P_1 - P_0)(x - S''(P_0))$$

It can be rewritten as

$$y - P_0 = \frac{P_1 - P_0}{S''(P_1) - S''(P_0)} \times (x - S''(P_0)).$$

In the above linear equation, when $x = 0$, y is a zero-crossing point.

Therefore, the equation for finding the zero-crossing point y can be redefined as

$$y = \frac{-S''(P_0) \times (P_1 - P_0)}{S''(P_1) - S''(P_0)} + P_0. \tag{4}$$

y is a real number-type edge coordinate value and the pixel unit vibration displacement value.

2.2. *Proposed method of vibration displacement measurement using the edge of a structure*

To measure the vibration displacement of a subject, after acquiring the image data of the subject structure using a camera, the coordinates corresponding to the edge area of the structure are set as measurement areas A and B, as shown in Fig. 4. Through the proposed edge detection method, the real number type edge values of areas A and B are calculated. Using the actual measured diameter value of the subject, the pixel unit displacement value can be converted to mm/pixel units. It is possible to convert the value of measurement area A or B into the actual displacement. The vibration displacement measurement and unit conversion method are as follows.

To utilize the coordinates of the pixels in measurement areas A and B in the equation, the coordinate values increasing in the vertical direction from $(NC_A + n)$ to $(NC_A + \upsilon - n)$ are called i_a, and the coordinate values increasing from $(NC_B + n)$ to $(NC_B + \upsilon - n)$ are called i_b. Here, n means the differential interval, and j is a value increasing from 0 to h-1 as a horizontal coordinate of the measurement area.

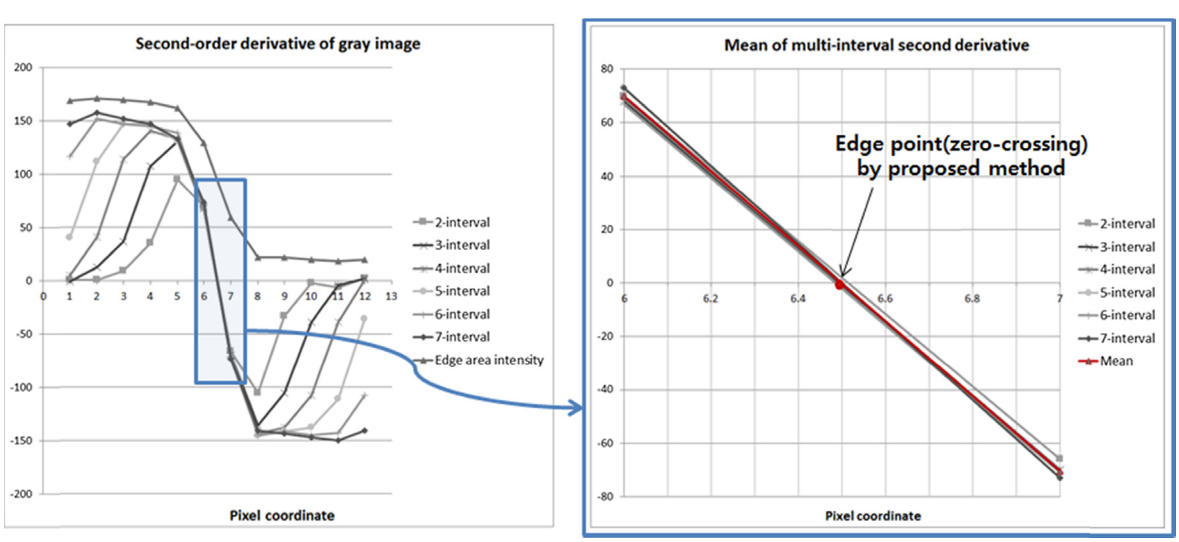


Fig. 3 – Mean of multi-interval second-order derivative of edge area in the camera image using the proposed method.

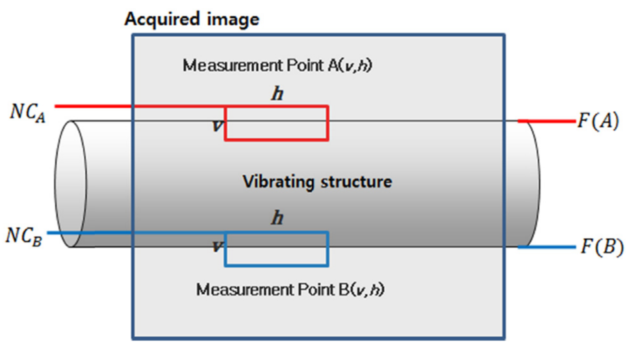


Fig. 4 – Setup of measurement area A based on reference coordinate NC_A and measurement area B based on reference coordinate NC_B in subject image for vibration measurement. The image of each measurement area has vertical axis length *v* and horizontal axis length *h*. The edge values of the two measurement areas found through the proposed edge detection method are *F(A)*and *F(B)*.

Suppose the first derivatives of measurement areas A and B are A' and B', respectively. Then,

$$A'(i_a,j) = |\,A(i_a+1,j) - A(i_a-1,j)\,| \tag{5}$$

$$B'(i_b,j) = |\,B(i_b+1,j) - B(i_b-1,j)\,|$$

and suppose the mean of the multi-interval second-order derivatives of measurement areas A and B are A'' and B'', respectively. Then,

$$A''(i_a,j) = \frac{1}{9}\sum_{n=2}^{10}[2A(i_a,j) - \{A(i_a+n,j) + A(i_a-n,j)\}] \tag{6}$$

$$B''(i_b,j) = \frac{1}{9}\sum_{n=2}^{10}[2B(i_b,j) - \{B(i_b+n,j) + B(i_b-n,j)\}]$$

Suppose Pa_{j0} and Pa_{j1} are the coordinates having the maximum value and next largest value in A'_j, and Pb_{j0} and Pb_{j1} are the coordinates having the maximum value and next largest value in B'_j. Then, the real number-type edge values of measurement areas A and B are defined as follows.

$$F(A) = \frac{1}{h}\sum_{j=0}^{h-1}\left[\frac{-A''(Pa_{j0},j)\times(Pa_{j1}-Pa_{j0})}{\{A''(Pa_{j1},j) - A''(Pa_{j0},j)\}} + Pa_{j0}\right] \tag{7}$$

$$F(B) = \frac{1}{h}\sum_{j=0}^{h-1}\left[\frac{-B''(Pa_{j0},j)\times(Pb_{j1}-Pb_{j0})}{\{B''(Pb_{j1},j) - B''(Pb_{j0},j)\}} + Pb_{j0}\right]$$

Here, the displacement size between F(A) and F(B) can be expressed as the pixel unit diameter of structure $P_d = |F(A) - F(B)|$. The size of a unit pixel can be determined by dividing the actual diameter of the structure by the pixel unit diameter, as follows:

$$P_{size} = D_{real}/P_d \tag{8}$$

By repeatedly applying the processes of Eqs. (5)–(7) to the acquired continuous images, the vibration displacement can be acquired.

3. Error estimation

In the vibration displacement measurement of a cylindrical structure, the errors included in the data measured through the proposed method are classified as diameter measurement error, vibration displacement measurement error, error due to the environment, and error due to the measurement resolution. The errors can be estimated using the following method. Here, the factors having the largest influence on the measurement errors are the measurement errors caused by the measurement resolution and environment due to the characteristics of the camera.

3.1. *Diameter measurement error of a cylindrical structure*

When the measurement subject is a cylinder close to the epicenter, the measurement has an error of $D - D'$, as shown in Fig. 5.

Suppose the actual diameter of a cylindrical structure is D, and the diameter measured using the camera is D'; then, the measurement error is

$$\text{Error} = D - D'$$

If the radius of a cylindrical structure is R, then $D = 2R$. When the distance between the camera and the center of the cylindrical structure is l, since angle θ can be known,

$$\cos\theta = \frac{R}{l} \qquad \theta = \cos^{-1}\left(\frac{R}{l}\right)$$

If θ is used, then it can be known that $D' = 2\times R\sin\theta$. Therefore, the measurement error is defined as follows:

$$\text{Error} = 2R - \left\{2\times R\sin\left(\cos^{-1}\frac{R}{l}\right)\right\} \tag{9}$$

Fig. 6 shows the measurement error ratios when examined using the distance against the diameter of the structure.

It was found that the diameter measurement error using a camera is inversely proportional to the measuring distance. However, if the camera is placed further from the structure to reduce the error, the measurement resolution becomes

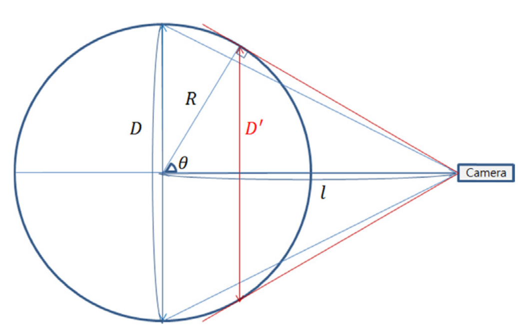


Fig. 5 – Error occurring when diameter of structure is used to determine unit pixel size in proposed vibration displacement measurement method. It shows that when the measurement structure is cylindrical, there is an error of D – D′ due to the distance *l* from the camera to the center of the structure.

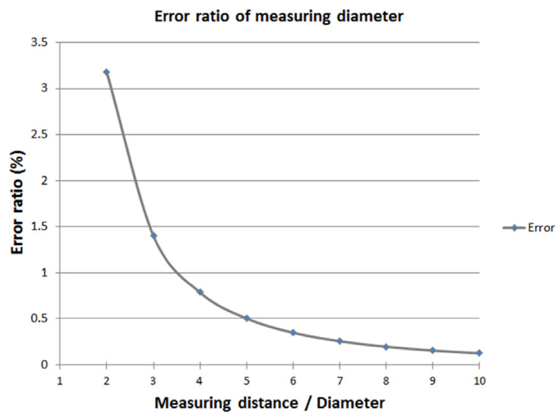


Fig. 6 – Diameter measurement error ratios at different distances between the camera and cylindrical structure.

relatively worse because the size of a unit pixel increases. Therefore, to increase the measurement resolution and reduce the diameter measurement error, it is necessary to use an optical zoom lens from a long distance.

3.2. *Vibration displacement measurement error of a cylindrical structure*

The vibration measurement error of the vibration displacement data measured at the upper part of a structure using a camera is as follows when the cylindrical structure close to the epicenter moves to above the center of the camera image sensor by a displacement of $+\Delta v$, as shown in Fig. 7.

If the cylindrical structure moves to the upper side by $+\Delta v$, the value actually measured should be $R + \Delta v$. However, since the structure is cylindrical, h is measured, the equation to find h is developed as follows:

$$h = h_1 + h_2$$

$$h_1 = R \cdot \sin \theta_1$$

$$h_2 = \Delta v$$

where R is the radius of the cylindrical structure. When the displacement size is $+\Delta v$, and the distance from the camera to the center of the cylindrical structure is l, $\theta_1 + \theta_2$ can be found. Therefore,

$$\cos \theta_2 = \frac{l}{\sqrt{\Delta v^2 + l^2}}$$

$$\cos(\theta_1 + \theta_2) = \frac{R}{\sqrt{\Delta v^2 + l^2}}$$

$$\theta_2 = \cos^{-1}\frac{l}{\sqrt{\Delta v^2 + l^2}}$$

$$\theta_1 + \theta_2 = \cos^{-1}\frac{R}{\sqrt{\Delta v^2 + l^2}}$$

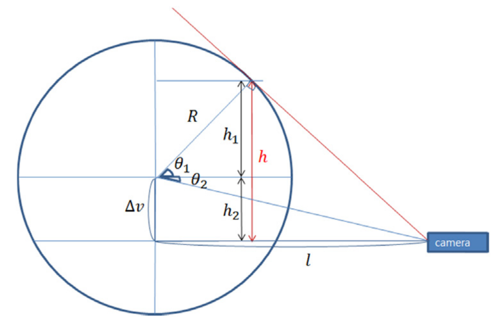


Fig. 7 – Measurement error when a cylindrical structure has displacement of $+\Delta v$ above the center of camera focus.

$$\theta_1 = \cos^{-1}\frac{R}{\sqrt{\Delta v^2 + l^2}} - \cos^{-1}\frac{l}{\sqrt{\Delta v^2 + l^2}}$$

The value measured by the camera is

$$h = R \cdot \sin\left(\cos^{-1}\frac{R}{\sqrt{\Delta v^2 + l^2}} - \cos^{-1}\frac{l}{\sqrt{\Delta v^2 + l^2}}\right) + \Delta v$$

Therefore, the measurement error is

$$Error = (R + \Delta v) - h \tag{10}$$

Fig. 8 shows the measurement error found using the diameter of the structure against the measuring distance.

Furthermore, when the cylindrical structure moves to below the center of the camera image sensor by a displacement of $-\Delta v$, the measurement error of the vibration displacement measured at the upper part of the structure is as shown in Fig. 9.

If the structure moves downward by $-\Delta v$ under the condition that the center of the cylindrical structure and the center of the camera are horizontal, then the value actually measured should be $R - \Delta v$. However, since the structure is cylindrical, h is measured as follows:

$$h = h_1 - h_2$$

$$h_1 = R \cdot \sin \theta_1$$

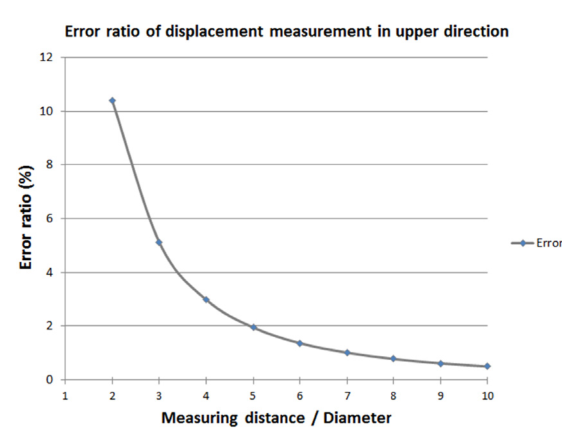


Fig. 8 – Error ratios of vibration displacement measurement using a camera when the structure is vibrating in the upper direction.

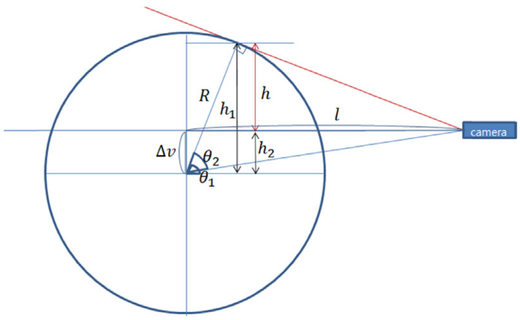


Fig. 9 – Measurement error when a cylindrical structure has displacement of Δv below the center line of the camera.

$$h_2 = \Delta v$$

where R is the diameter of the cylindrical structure. When the displacement size is $+\Delta v$, and the distance from the camera to the center of the cylindrical structure is l, $\theta_1 - \theta_2$ can be found. Therefore,

$$\cos(\theta_1 - \theta_2) = \frac{l}{\sqrt{\Delta v^2 - l^2}}$$

$$\cos\theta_2 = \frac{R}{\sqrt{\Delta v^2 - l^2}}$$

$$\theta_1 - \theta_2 = \cos^{-1}\frac{l}{\sqrt{\Delta v^2 - l^2}}$$

$$\theta_2 = \cos^{-1}\frac{R}{\sqrt{\Delta v^2 - l^2}}$$

$$\theta_1 = \cos^{-1}\frac{R}{\sqrt{\Delta v^2 - l^2}} + \cos^{-1}\frac{l}{\sqrt{\Delta v^2 - l^2}}$$

The value measured by the camera is

$$h = R\cdot\sin\left(\cos^{-1}\frac{R}{\sqrt{\Delta v^2 - l^2}} + \cos^{-1}\frac{l}{\sqrt{\Delta v^2 - l^2}}\right) - \Delta v$$

Therefore, the measurement error is

$$Error = (R - \Delta v) - h \tag{11}$$

Fig. 10 shows the measurement error for the diameter of the structure against the measuring distance.

Figs. 8 and 10 show the results of using the data measured at the upper part of the structure in the measurement method using a camera, which contrast with the errors in the data measured at the lower part of structure. If the multipoint measurement is used, which is an advantage of vibration measurement using a camera, the error can be reduced by measuring the vibrations in the upper and lower parts of a structure simultaneously.

3.3. *Measurement resolution*

The resolution of the proposed vibration displacement measurement method is estimated using the gradient of the zero-crossing section of the second derivative, as shown below.

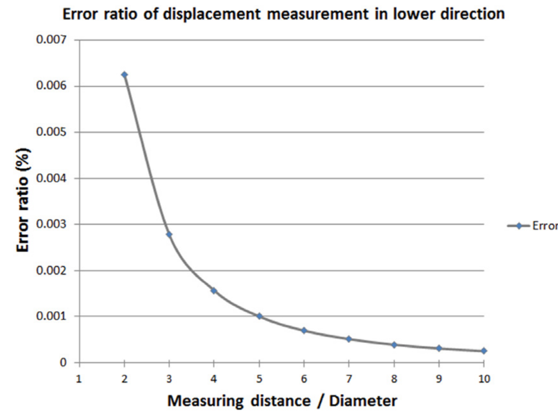


Fig. 10 – Error for vibration displacement measurement of a cylindrical structure using a camera when structure vibrates in the lower direction.

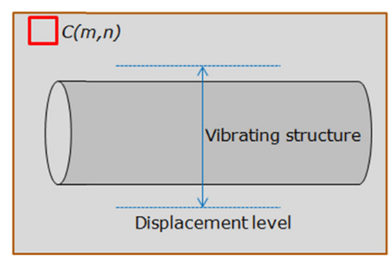


Fig. 11 – Estimation of measurement error caused by sensing noise using image area C(*m*, *n*), which is not affected by vibration when measuring vibration displacement using camera.

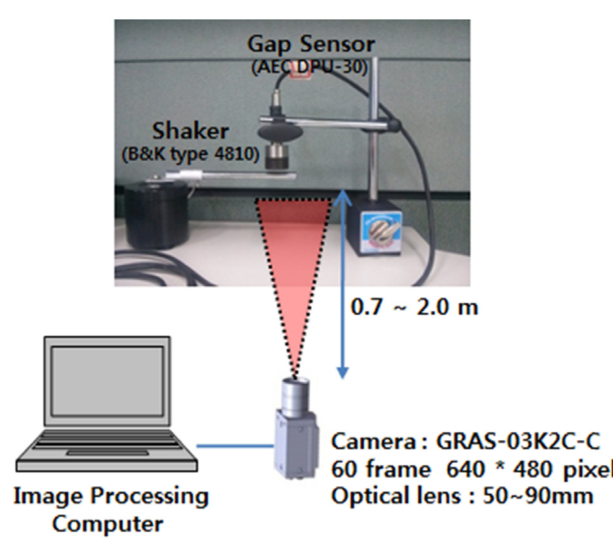


Fig. 12 – Experimental setup for measuring vibration displacement.

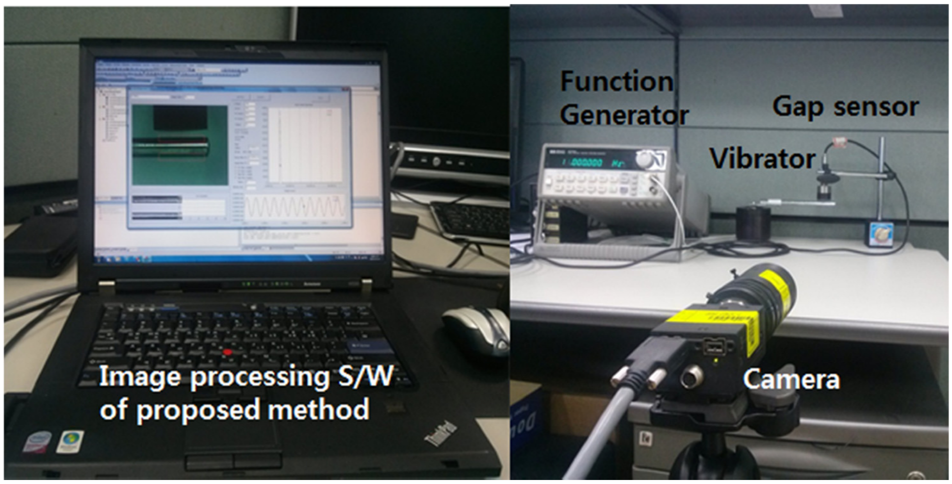


Fig. 13 – The experimental setup.

$$Estimation\ \ resolution \cong \frac{1}{|S''(P_1) - S''(P_0)| \times (T-1)} \quad (12)$$

The gradient of the proposed method acts as a resolution for calculating the real number-type coordinate, which is the zero-crossing between two integer coordinates. In the proposed method, the same gradient can be applied for all the continuous image data acquired in the same environment. Therefore, the resolution of the acquired signal can be estimated using the gradient. The estimated resolution has the largest influence among the errors included in the vibration displacement measurement because it is proportional to the resolution of the camera image used in the measurement, and low compared with the measurement resolution of a contact-type sensor.

3.4. *Error caused by measurement environment*

When acquiring the image data, various sensing noises are included, depending on the measurement environment. Many noises are included in the image sensor as the light energy is converted into electric energy and then digitalized. The noises

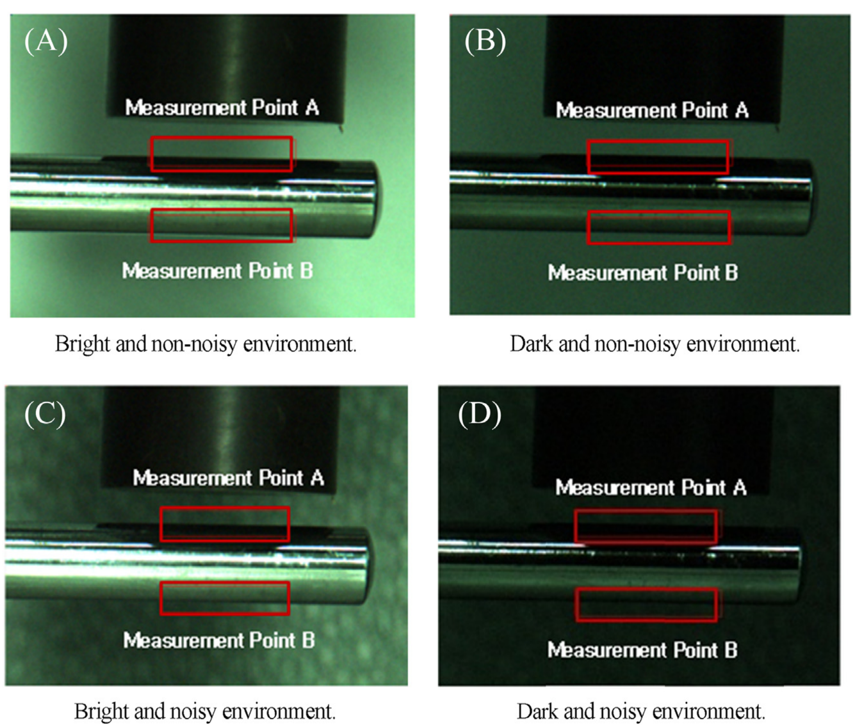


Fig. 14 – Images acquired by a camera at 0.7 m measuring distance among 12 experiments. (A) Bright and non-noisy environment. (B) Dark and non-noisy environment. (C) Bright and noisy environment. (D) Dark and noisy environment.

have the second largest influence on the measurement error, following the measurement resolution. As shown in Fig. 11, when the area of the image not affected by the vibration of the structure in the continuous data is $C(m,n)$, the amount of variation in the average value of the area in the time domain can be viewed as an error caused by the sensing noise, and the following estimation is possible.

$$G(C_t) = \left[\left\{ \frac{1}{m \times n} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} C_t(i,j) \right\} - \left\{ \frac{1}{m \times n} \sum_{i=0}^{m-1} \sum_{j=0}^{n-1} C_{t-1}(i,j) \right\} \right] \Big/ 255 \quad (13)$$

$$\textit{Estimation error of environment} \cong \pm \max[G(C_t)]$$

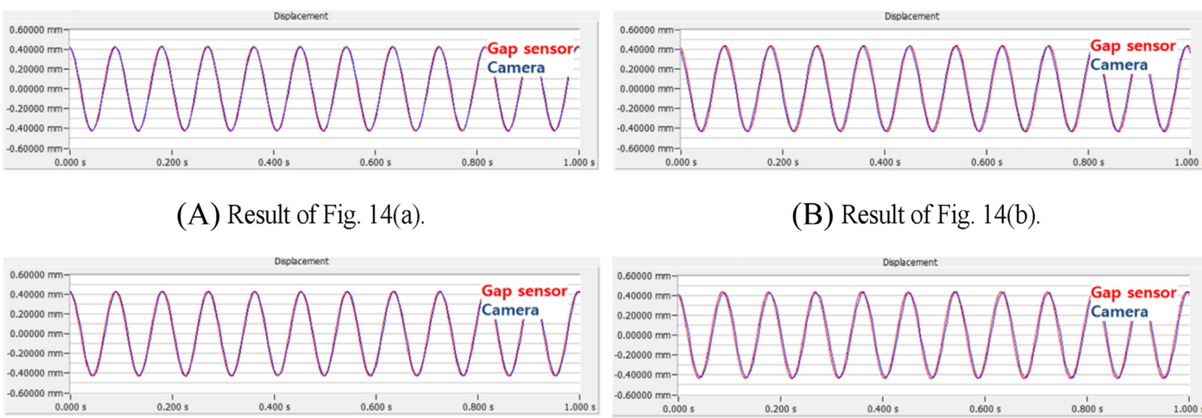
where $C(m,n)$ is the area of the image with size $m \times n$ that is not affected by the vibration in the image acquired to measure the vibration displacement, t is the time, $G(C_t)$ shows the amount of change in the average energy of area C in the arbitrary time, and $\pm\max[G(C_t)]$ represents P-P in the continuous data $G(C_t)$. The noise caused by the environment can be expressed as the amount of change in the energy in the time domain of the area not affected by the vibration. Such noise is shown as measurement error because it is included in the image of the vibration measurement target structure.

4. Verification of proposed method through experiment

To verify the proposed method, an experiment was conducted to evaluate the vibration measurement performance of the proposed method using a shaker and cylindrical structure.

4.1. *Experiment equipment and environment*

As shown in Figs. 12 and 13, the cylindrical structure was attached to the shaker and vibrated, and the vibration was measured using an industrial CCD camera. A total of 200 frames of image data were acquired with a resolution of 640 × 480 using the camera, with constant illumination. The



(A) Result of Fig. 14(a).

(B) Result of Fig. 14(b).

(C) Result of Fig. 14(c).

(D) Result of Fig. 14(d).

Fig. 15 – Comparison of vibration displacements measured by gap sensor and proposed method using experiment images shown in Fig. 14. (A) Result of Fig. 14(A). (B) Result of Fig. 14(B). (C) Result of Fig. 14(C). (D) Result of Fig. 14(D).

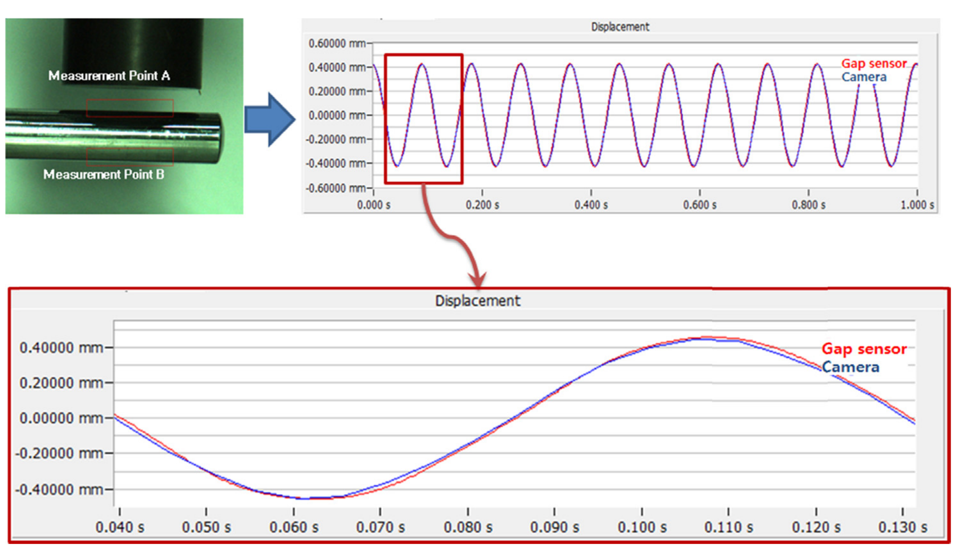


Fig. 16 – Enlarged graph of one-cycle signals of Fig. 15A.

proposed image processing method was developed using Visual Studio C++. The proposed method is experimentally evaluated in comparison with a conventional gap sensor. The gap sensor measuring range is 0~15 mm.

4.2. *Experiment using experimental equipment*

The camera was installed 0.7~2.0 m away from the target object, and images were captured using a 50-mm optical lens. Gap sensor data were simultaneously acquired to assess the measurement errors of the proposed method. The gap sensor data were acquired with a 24 bit resolution and 4,096 Hz sample rate. The performance of the proposed method was evaluated using a relatively inexpensive low-resolution camera to show the applicability in the field at a low cost. The vibration displacement measurement experiments were conducted in various environments. A cylindrical structure with a diameter of 10 mm was vibrated using the shaker. The diameter measurement errors at a measuring distance of 0.7~2.0 m for the cylindrical structure with a 10-mm diameter were 0.2~0.032 μm, which means that their influence on the measurement result would be very small. The experiments were carried out in bright and dark environments, with and without noise, using short- and long-distance measurements, and large and small vibrations. Fig. 14 shows four sample images acquired in various environments.

Fig. 15 shows comparison graphs of the vibration displacement signals measured using the proposed method and the signals acquired from the gap sensor for each experiment image shown in Fig. 14.

Fig. 16 shows a graph of the enlarged one-cycle signals of Fig. 15A. Because the signals were not completely synchronized, there were some time differences, but overall they matched well.

Using the experimental results gained from 12 environments, the results listed in Table 1 were derived by averaging the P-P values of 10 points, and the error range of the signals measured with the proposed method was confirmed to be in the estimated error range. On average, the measurement errors increased with a noisy background. Since the edge detection uses the brightness difference between the target structure and the background, the noise of the background makes the edge detection difficult. The state of illumination showed good results in the bright environment but did not have much influence. As the camera distance from the measurement target structure increased, the measurement error also increased because the size of the unit pixel became larger. The measurement error due to the measuring distance could be reduced using the optical zoom lens.

5. Field test

As shown in Fig. 17, the experiment was conducted using a pipe in the field. The diameter of the pipe was 19.0 mm. The distance between the test target and the camera was 1.5 m, and a 75-mm optical lens was used. The images were acquired under the conditions of a 640 × 480 resolution and 200 frames/s.

Table 1 – Comparison of results of proposed method and gap sensor.

No.	Measuring environment			mm/pixel	Gap sensor (mm)	Proposed method (mm)	Error (mm)	Error ratio	Estimation resolution (mm)	Estimation error (mm)	Total estimation error ratio
	Background	Lighting	Distance (m)								
1	Non-noise	Bright	0.7	0.082	0.852	0.851	0.001	0.12%	0.002	0.001	0.35%
2			2	0.199	0.852	0.858	0.006	0.70%	0.005	0.004	1.06%
3			1	0.118	0.201	0.205	0.004	1.99%	0.002	0.002	1.99%
4		Dark	0.7	0.08	0.852	0.849	0.003	0.35%	0.002	0.001	0.35%
5			2	0.197	0.852	0.846	0.006	0.70%	0.006	0.001	0.82%
6			1	0.115	0.201	0.205	0.004	1.99%	0.001	0.003	1.99%
7	Noise	Bright	0.7	0.081	0.852	0.856	0.004	0.47%	0.003	0.001	0.47%
8			2	0.214	0.852	0.866	0.014	1.64%	0.013	0.001	1.64%
9			1	0.111	0.201	0.204	0.003	1.49%	0.002	0.002	1.99%
10		Dark	0.7	0.081	0.852	0.861	0.005	0.59%	0.007	0.001	0.94%
11			2	0.201	0.852	0.833	0.019	2.23%	0.031	0.001	3.76%
12			1	0.112	0.201	0.198	0.003	1.49%	0.003	0.001	1.99%

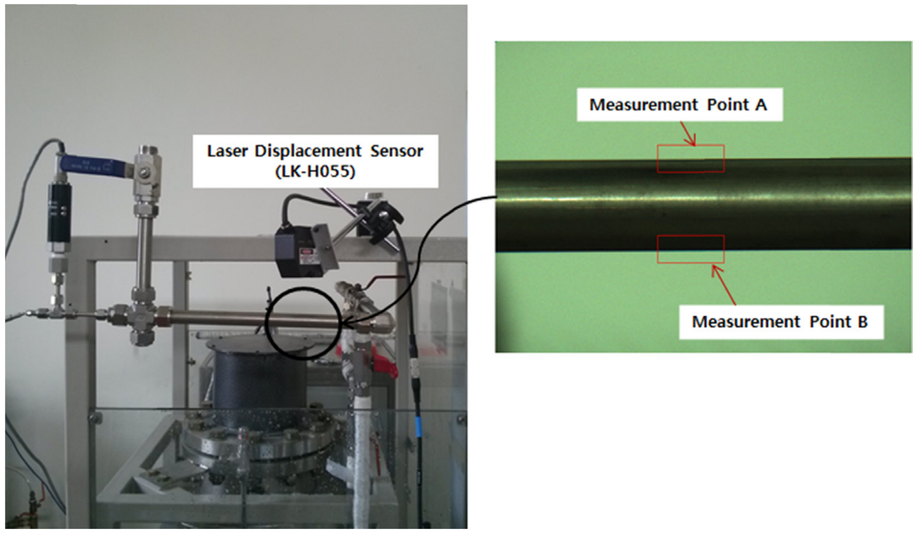


Fig. 17 – Experimental setup for field measurements of vibration displacement.

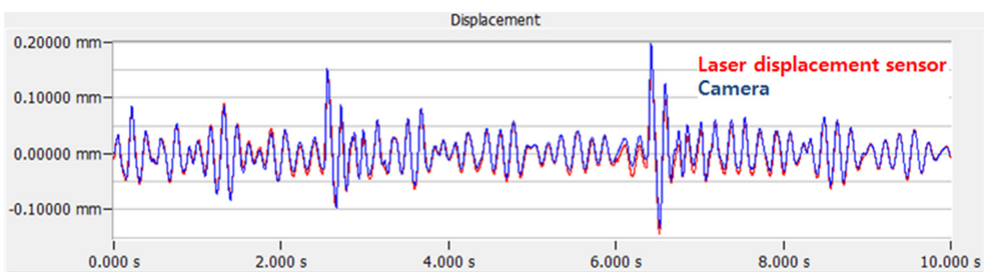


Fig. 18 – Comparison of field measurements of vibration displacements using a laser displacement sensor and the proposed image processing method.

Fig. 18 compares 10 s of data from the laser displacement sensor signals and the signals obtained using the proposed method. The maximum P-P of the signals was 0.309 mm. The RMS value with the proposed method was 0.03327 mm, and the RMS of the laser displacement sensor signals was 0.03284 mm. The RMS difference between the two signals was 0.00043 mm, showing a 1.3% error rate. The single pixel size using the proposed diameter measurement method was 0.106 mm/pixel, and the estimated error for the single pixel size was 0.005 μm/pixel, which could be ignored. The proposed measurement resolution estimation value was 0.00098 mm, and the estimated error caused by the environment was 0.00006 mm, showing the sum of the errors to be 0.00114 mm. Therefore, the error of the measured RMS, 0.00043 mm, was confirmed to be within the estimated errors.

Fig. 19 shows the auto power spectra of the signals shown in Fig. 18. The dominant frequencies were both 6 Hz and showed the same level. The magnitude of dominant frequency is 0.000208 by using the proposed method, and it is 0.000213 by using a laser displacement sensor. Therefore, it seems that the signals of the proposed method and laser displacement sensor matched well.

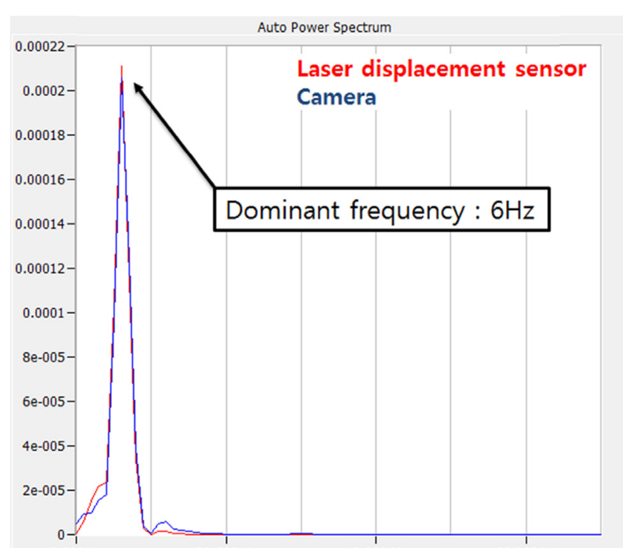


Fig. 19 – Auto power spectrum of proposed method (in field measurements).

6. Conclusion

In this paper, we proposed a remote vibration displacement measurement method for a cylindrical structure and an estimation method for the error of the vibration displacement data measured using the proposed method. Furthermore, the errors that could be included when the vibration displacement of a cylindrical structure was measured using a camera were confirmed. We verified the proposed method using various experiments and estimated the range of errors caused by the environment and the resolution that had the largest influence on the measurement data. We confirmed that the vibration displacement data measured using the proposed method showed errors within the estimated error range. It is expected that the proposed method will make it possible to measure the vibration displacement from a remote distance in dangerous areas or irradiated areas in nuclear facilities where surveyors cannot easily approach a structure. The proposed technique is expected to be able to perform real-time vibration monitoring at long distances when using a network camera. It is much simpler than the configuration of existing vibration monitoring systems. Therefore, we expect to be able to reduce system installation and maintenance costs when using the proposed technique.

Conflicts of interest

None.

Acknowledgments

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