PROPOSAL OF A METHOD TO REMOTELY MEASURE MICROTREMORS FOR VIBRATION DIAGNOSES OF RAILWAY STRUCTURES

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ABSTRACT: An accurate method for remotely measuring structure microtremors is proposed by using an improved Laser Doppler Velocimeter. The remote microtremor measurements of an RC rigid-frame structure are presented in order to verify the efficiency of the proposed method. Dynamic structural characteristics, such as the natural frequency and the fundamental mode shape, of a real RC structure are accurately estimated.

Key Words: LDV, remote measurement, microtremor, vibration diagnosis, railway viaduct, AEM

INTRODUCTION

In the field of health monitoring of railway structures, the vibration induced by various sources is used to determine the natural frequency of structures (Nakamura 1996, Nishimura *et al.* 1998). Microtremors are very small vibrations under normal conditions due to natural and artificial sources, such as tidal waves, traffic noise, industrial vibration, and so on. Microtremor measurements are one of the most efficient and safest methods for the purpose of determining structure characteristics because no special vibration sources like a moving car or impact by hitting structures are necessary. By microtremor measurement, the structure dynamic characteristics, such as the natural frequency and mode shape, can be easily obtained (Uehan and Meguro 2003a).

In addition to these advantages, others may be obtained if a method for remotely measuring microtremors is available. For instance, it is possible to improve the measurement work efficiency and safety. In the inspection of railway structures, such as viaducts or bridges, sensors might be installed at dangerously high places. In the case of earthquake damage inspection, inspection engineers are exposed to the risk of secondary disasters due to aftershocks. If a remote measurement method is adopted, there is no need to install and remove sensor and cables from dangerous positions.

In this article, an accurate method for remotely measuring structure microtremors is proposed by using the improved Laser Doppler Velocimeter (LDV). A method to solve the problems related to microtremor measurement using LDV is introduced. The method accuracy is verified with the results of the measurements of an existing reinforced concrete structure.

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DEVELOPMENT OF THE REMOTE MICROTREMOR MEASURING METHOD

Laser Doppler Velocimeter

The authors decided to use the Laser Doppler Velocimeter (LDV) for the remote microtremor measuring method. The LDV (**Figure 2**) is an optical measurement device that is able to detect the velocity of a moving objective by using the difference in frequency between incident and reflected laser beams. **Figure 3** shows the frequency change between incident and reflected laser beams. The frequency of reflected laser beam f_r is shown below.

$$f_r = \frac{\lambda_0 \cdot f_0 + v \cdot \cos\theta}{\lambda_0 \cdot f_0 - v \cdot \cos\theta} \cdot f_0 \qquad (1)$$

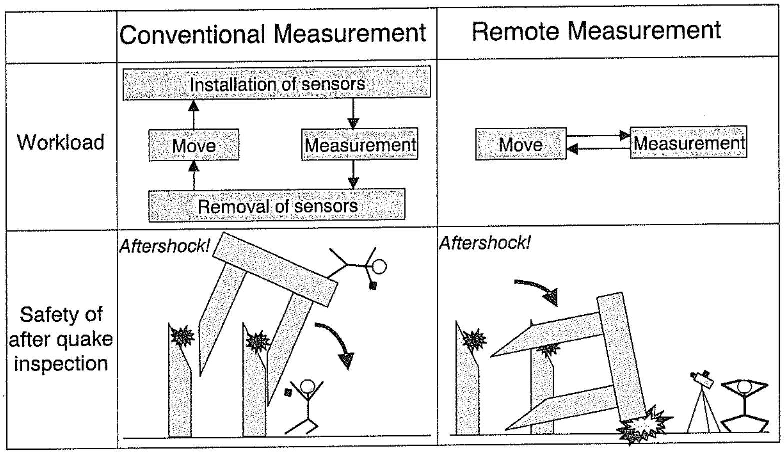

Figure 1. Advantages of remote measurement

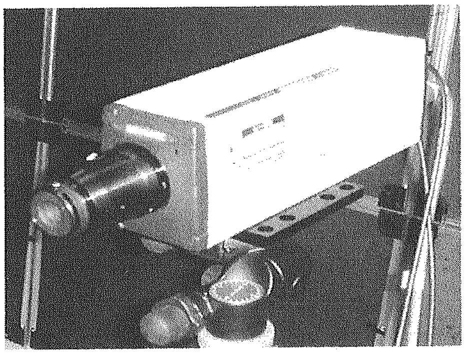

Figure 2. Laser Doppler Velocimeter (Graphtec: AT0023)

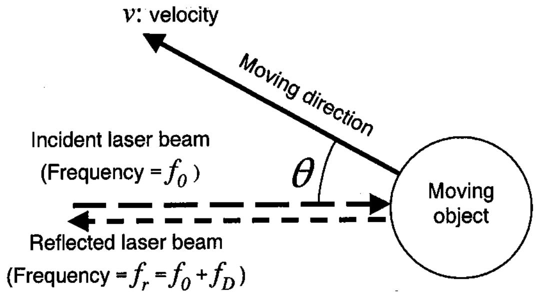

Figure 3. Frequency change between incident and reflected laser beams

where, λ_0 and f_0 are the wavelength and frequency of the incident wave, respectively, v is the velocity of the moving object, θ is the angle between the direction of laser irradiation and movement of the object. The frequency change f_D is shown by the next equation.

$$f_D = |f_0 - f_r| = \left(1 - \frac{\lambda_0 \cdot f_0 + v \cdot \cos\theta}{\lambda_0 \cdot f_0 - v \cdot \cos\theta}\right) \cdot f_0 = \frac{2v \cdot \cos\theta \cdot f_0}{\lambda_0 \cdot f_0 - v \cdot \cos\theta} \tag{2}$$

Because $\lambda_0 \cdot f_0$ is much larger than $v \cdot \cos\theta$, f_D is approximated by the next equation.

$$f_D = \frac{2v \cdot \cos\theta}{\lambda_0} \tag{3}$$

Then, the velocity of the moving object, v, is given by:

$$v = \frac{\lambda_0 \cdot f_D}{2 \cdot \cos\theta_0} \tag{4}$$

Problems of microtremor measurement by using LDV

LDV is a device that detects the relative velocity between LDV itself and the measuring object. Therefore, the vibration of LDV itself has a significant influence on the measurement record, when a very small vibration is measured. In the case of the outdoor microtremor measurement of railway structures, the vibration of the LDV itself, which is caused by various ground vibrations and/or winds, can not be disregarded (**Figure 4**).

The influence of LDV vibration is especially serious in the case of the damage inspection after an earthquake, because it is executed under a high noise condition due to restoration work. Therefore, a method that can remove the influence of LDV vibration is indispensable for highly accurate measurement of structure microtremors.

Method to remove the influence of LDV vibration

The authors developed a method to remove the influence of LDV vibration by using the record of the vibration sensor installed in LDV (**Figure 5**). The velocity $V_L(t)$ of LDV at time t is a relative velocity between the measured point on the structure and the LDV. The $V_S(t)$ is the velocity of LDV recorded by the vibration sensor installed in LDV at time t. Then, the absolute velocity of the measured point $V(t)$ from which the influence of LDV vibration is removed is shown by the next equation.

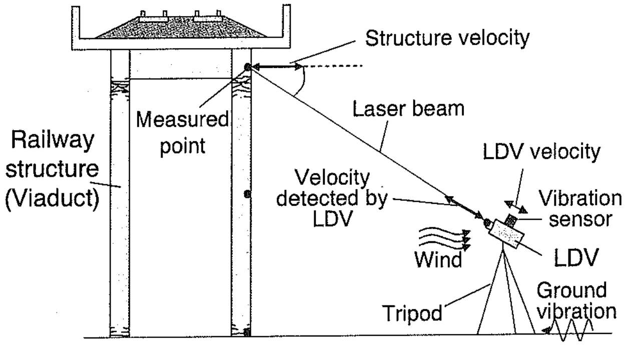

Figure 4. Outline of remote microtremor measurement

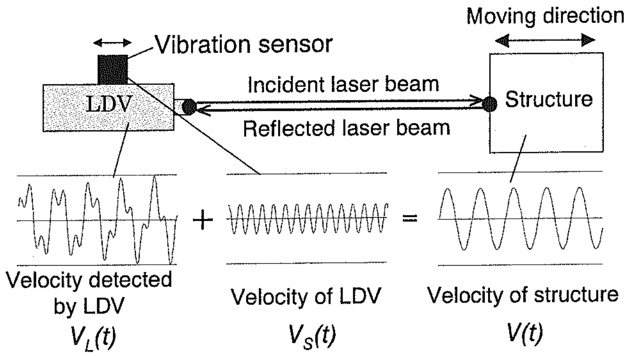

Figure 5. Removal of influence of LDV vibration

$$V(t) = V_L(t) + V_S(t) \tag{5}$$

When the angle between the direction of laser irradiation and structure movement is θ, the absolute velocity of the measured point $V(t)$ is shown by the next equation (Uehan and Meguro 2003b).

$$V(t) = (V_L(t) + V_S(t)) / \cos\theta \tag{6}$$

IDENTIFICATION OF DYNAMIC CHARACTERISTICS OF A REAL RC STRUCTURE

Outline of the measurement

The fundamental frequency and mode shape of the existing RC structure shown in **Figure 6** were identified by using the proposed remote microtremor measuring method. The microtremors of the structure from the point A to E were sequentially measured by an improved LDV that has a vibration sensor and telephoto lens (**Figure 7**) installed 5.2m away from the structure as shown in **Figure 8**. When each point was measured, microtremors at the LDV and the point R of the structure were measured simultaneously.

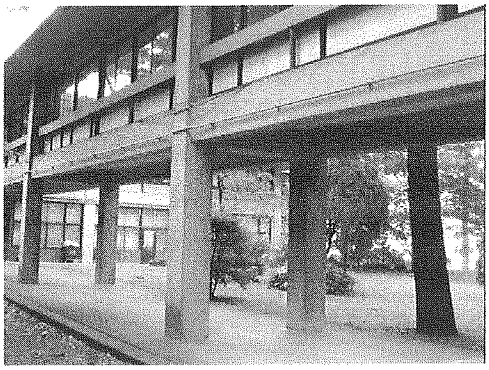

Figure 6. Measured structure (2-story RC rigid-frame structure)

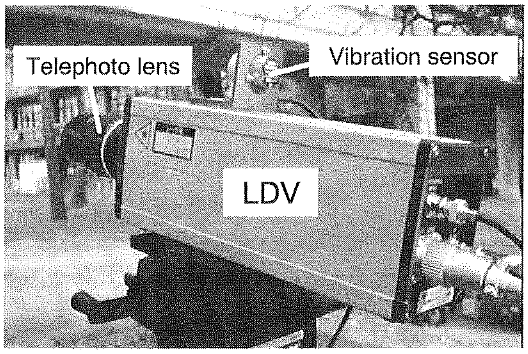

Figure 7. Improved LDV

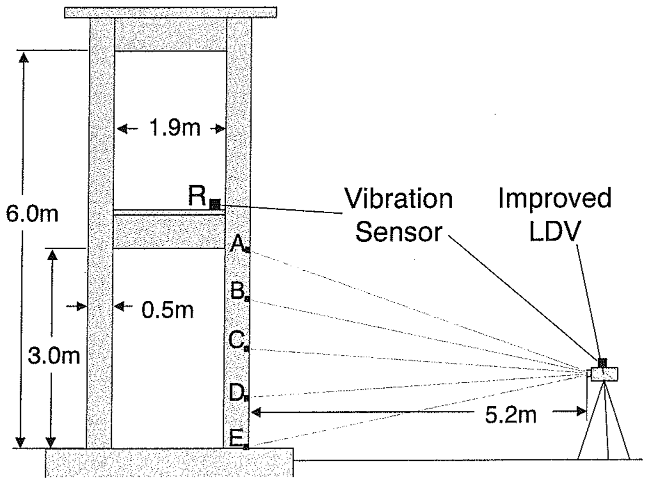

Figure 8. Outline of measurement and measured RC structure

Verification of the method to remove the influence of LDV vibration

Figure 9 shows the record of each sensor obtained when the point A was measured. The vibration of the point A identified by the proposed method is also shown in **Figure 8**. **Figure 9** shows the Fourier spectrum of the waves shown in **Figure 8**.

Although the data recorded by the LDV with no correction was strongly influenced by LDV vibration, the results identified by the proposed method almost correspond to the real structure microtremor recorded at the point R. The natural frequency of the structure (3.6 Hz) was accurately estimated by the proposed method.

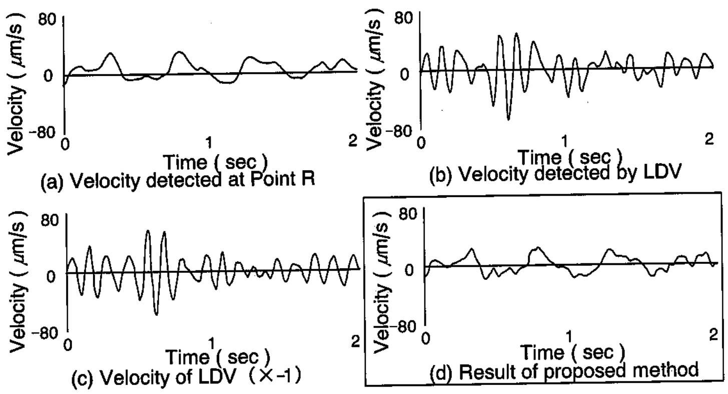

Figure 8. Velocity at measured points

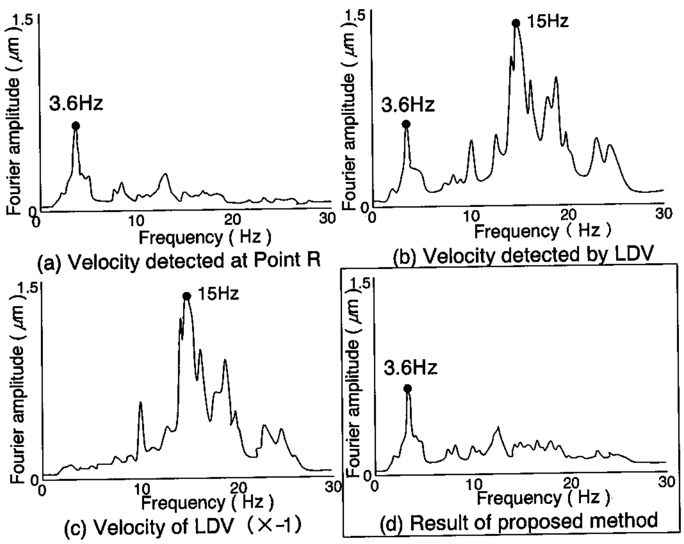

Figure 9. Fourier spectra at measured points

Mode shape identification of the RC structure

Next, the fundamental mode shape of the lower column of the RC structure was estimated. The spectrum amplitude of 3.6Hz at the point A to E was standardized by those obtained by the simultaneous measurement at the point R. The standardized spectrum amplitude is considered to be the mode amplitude of the column. The numerical simulation result of the fundamental mode shape of the structure is shown in **Figure 10**. The Applied Element Method (AEM) (Tagel-Din and Meguro 1997), which has been used in a series of our research works, was used for the simulation. The fundamental mode shape of the structure estimated by the remote microtremor measurement is shown in **Figure 11**. The result estimated by the proposed method corresponds to the mode shape obtained by the numerical analysis.

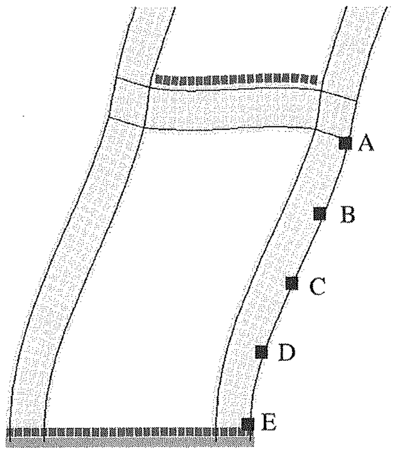

Figure 10. Fundamental mode shape of RC column estimated by the AEM

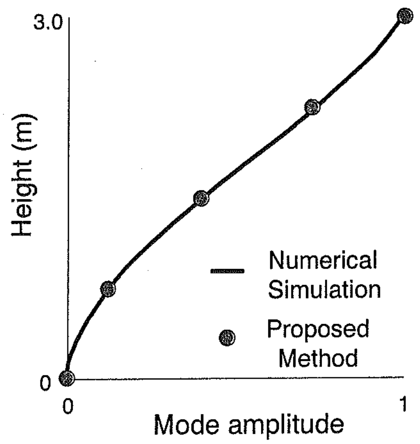

Figure 11. Fundamental mode shape of RC column

CONCLUSION

An accurate method for remotely measuring structure microtremors was proposed by using an improved Laser Doppler Velocimeter that has a vibration sensor and telephoto lens. In the proposed procedure, the absolute vibrations at the measuring point, which influence the LDV vibration, are removed. The remote microtremor measurements of an RC rigid-frame structure were presented in order to verify the method efficiency. Dynamic characteristics, such as the natural frequency and mode shape, of the RC structure were accurately estimated. From the results, the proposed microtremor measuring method is considered a fine and accurate tool for the inspection of railway structures.

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