DEVELOPMENT OF NON-CONTACT VIBRATION MEASURING SYSTEM FOR INSPECTION OF SEISMIC DAMAGE TO RAILWAY STRUCTURES

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ABSTRACT :
This paper introduces the non-contact vibration measuring system known as U-Doppler that has recently been developed by the RTRI. An effective tool for the quick damage inspection of structures is necessary for promptly restoring an ill-functioned railway system due to an earthquake. In the field of railway structure monitoring, dynamic characteristics estimated by vibration measurements are applied to evaluate structural integrity. Adopting a long-distance remote measurement method with U-Doppler enables improvement of the efficiency and safety of measurement, since it is unnecessary to install sensors and cables at locations high above structures and remove them later. This paper first gives an outline of U-Doppler and its measuring method. It then goes on to verify the accuracy of U-Doppler using the results of laboratory experiments, microtremor measurement of a rigid-frame viaduct, impact vibration measurement of a bridge pier, and deflection measurement of a bridge girder.

KEYWORDS:
U-Doppler, LDV, remote vibration measurement, inspection, railway structure

1. INTRODUCTION

This paper introduces the non-contact vibration measuring system known as U-Doppler that has recently been developed by the RTRI.
An effective tool for the quick damage inspection of structures is necessary for promptly restoring an ill-functioned railway system due to an earthquake. In the field of monitoring of railway structures, the dynamic characteristics estimated by vibration measurements are applicable to evaluate the structural integrity. These techniques make use of the vibration characteristics of structures such as maximum response, natural frequency and mode shape as a structural index of soundness. The vibration induced by sources such as passing trains, shock from weight impact [Nishimura & Tanamura, 1998] and microtremors [Nakamura, 1996] is used to obtain the indices for inspection. For instance, the maximum deflection of bridge girder by moving train, the natural frequency of bridge pier by impact vibration measurement or the natural frequency of viaduct by microtremor measurement is applicable as the index of structural damage.
When measuring vibrations using this method, the installation and removal of sensors is extremely time-consuming, and in many cases work must be performed in dangerous locations such as high places or adjacent to damaged structures or railway tracks.
The author therefore developed U-Doppler (Fig. 1, Table 1), a long-distance non-contact vibration measuring system for diagnosis of railway structures [Uehan, 2007] that offers enhanced safety and efficiency by implementing various improvements to the Laser Doppler Velocimeter (LDV) for use in the field. The U-Doppler sensor is placed on a tripod near the structure to be measured, and the laser is irradiated to the structure. The vibration velocity of the structure can be measured using this approach in the same way as when a sensor is fitted to the structure. It is possible to measure vibrations of a variety of magnitudes from several dozen meters away, from relatively large structural vibrations caused by passing trains to microtremors—microscopic vibrations under normal conditions caused by natural and artificial sources such as tidal waves, wind, traffic noise and industrial vibration. U-Doppler enables considerable time savings, as it does not require sensors to be installed or removed, and eliminates the risks associated with having to work in

dangerous locations.

In this paper, the author first introduces the outline of U-Doppler. Next, the author verified the accuracy of the U-Doppler with the results of laboratory experiments, the microtremor measurement of rigid-frame viaduct, and the deflection measurements of bridge girders. Additionally, the author introduces the retroreflective target marking system for remote vibration measurement.

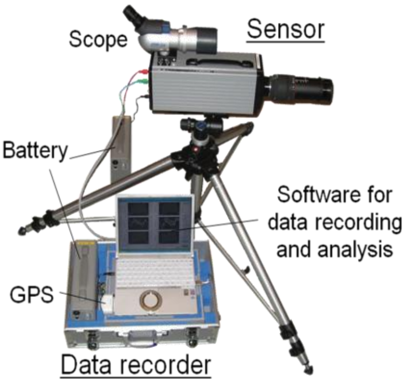

Fig. 1 U-Doppler

Table 1 Specifications of Sensor Unit

Dimensions and weight	113(W)×141(H)×351(D) mm, 5.5 kg
Power supply	Battery（operation time: 8 hours ）or AC adapter
Laser protection class	Eye-safe class II visible He-Ne gas laser
Velocity range	0.2 μm/s to 100 mm/s
Frequency range	DC to 600 Hz
Working distance	1.0 to 100 m（surface dependent）

2. REMOTE VIBRATION MEASURING METHOD OF U-DOPPLER

2.1 Laser Doppler Velocimeter

The author decided to use a Laser Doppler Velocimeter (LDV) for the remote vibration measuring method. The LDV is an optical measurement device capable of detecting the velocity of a moving object using the difference in frequency between incident and reflected laser beams. **Figure 2** shows the frequency change between the incident and reflected beams. The frequency of reflected beam f_r is:

$$f_r = \frac{\lambda_0 \cdot f_0 + v \cdot \cos\theta}{\lambda_0 \cdot f_0 - v \cdot \cos\theta} \cdot f_0 \tag{2.1}$$

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

$$f_D = \left| f_0 - f_r \right| = \left(1 - \frac{\lambda_0 \cdot f_0 + v \cdot \cos\theta}{\lambda_0 \cdot f_0 - v \cdot \cos\theta} \right) \cdot f_0 = \frac{2v \cdot \cos\theta \cdot f_0}{\lambda_0 \cdot f_0 - v \cdot \cos\theta} \tag{2.2}$$

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

$$f_D \approx \frac{2v \cdot \cos\theta}{\lambda_0} \tag{2.3}$$

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

$$v = \frac{\lambda_0 \cdot f_D}{2 \cdot \cos\theta} \tag{2.4}$$

2.2 Problems encountered during on-site remote vibration measurement

The LDV is a device that detects the relative velocity between itself and the object of measurement. The vibration of the LDV itself therefore has a significant influence on the measurement record when very small vibrations are involved. In the case of outdoor microtremor measurements of railway structures, vibration of the LDV caused by various ground vibrations and/or wind cannot be disregarded (**Fig. 3**). Furthermore, the influence of LDV vibration is severe in the case of damage inspection after earthquakes [Uehan & Meguro, 2000] because it is executed under high-noise conditions due to restoration work. A method that can remove the influence of LDV vibration is therefore indispensable for highly accurate measurement of structural vibration.

In addition, when performing measurements on civil engineering structures, in many cases the direction of the structural vibrations and the optical axis of the irradiation laser do not correspond, meaning that the amplitude of

vibration of the object is not measured correctly.
Compensation functions using built-in sensors were therefore applied to U-Doppler.

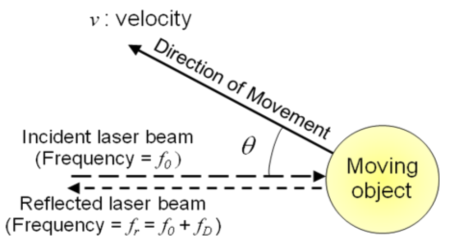

Fig. 2 Frequency change between incident and reflected laser beams

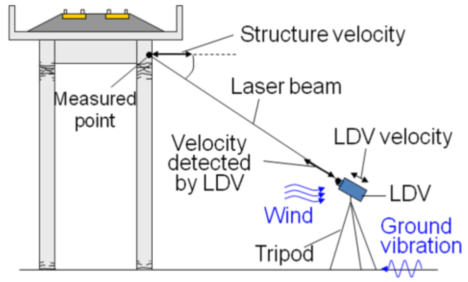

Fig. 3 On-site remote vibration measurement

2.3 Compensation functions of U-Doppler using built-in sensors [Uehan & Meguro, 2003]

The author developed a method to remove the influence of LDV vibration using information from a vibration sensor installed on the LDV unit. In addition to the LDV optical sensor, the U-Doppler sensor unit incorporates a contact vibrometer with the same sensitivity and phase properties as the optical sensor. The influence of U-Doppler sensor vibration is removed using the time-history data recorded by the vibrometer. In **Fig. 4 (a),** the structure is moving in the same direction as the laser irradiation. The velocity $V_L(t)$ recorded by the LDV at time t is the relative velocity between the measured point on the structure and the LDV. $V_S(t)$ is the velocity of the LDV recorded by the vibration sensor installed on the LDV at time t. Then, the absolute velocity of the measured point $V(t)$, from which the influence of the LDV vibration is removed, is:

$$V(t) = V_L(t) + V_S(t) \quad (2.5)$$

The U-Doppler unit is fitted with an internal sensor to measure its inclination and automatically adjust the amplitude measurement data as necessary (**Fig. 4 (b)**). When the angle between the direction of laser irradiation and structural movement reaches θ, the influence of the LDV vibration is removed from $V_L(t)$ by the method outlined in **Eqn. 2.5**. Next, as shown in **Eqn. 2.4**, the influence of the angle is corrected through division by $\cos\theta$. The absolute velocity of measured point $V(t)$ is then:

$$V(t) = (V_L(t) + V_S(t)) \;/\; \cos\theta \quad (2.6)$$

The U-Doppler data recorder displays a variety of information in real time (**Fig. 5**), including the velocity before compensation, the vibration of the sensor unit, the velocity after compensation, spectra for all data, and the sensor inclination. Analysis of data, including spectrum analysis, differentiation, integration and filter processing can be performed at the measurement site.

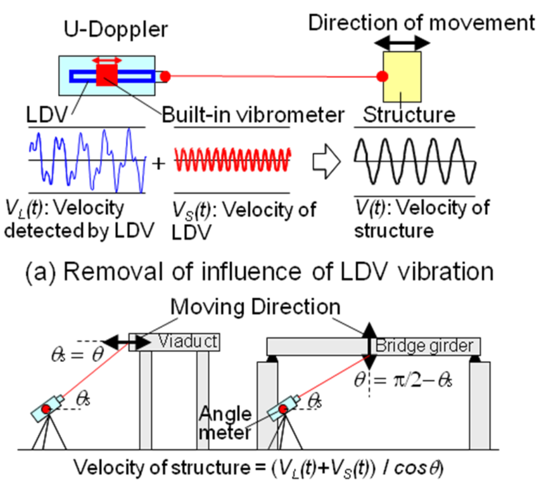

Fig. 4 Correction of detected velocity using built-in sensors

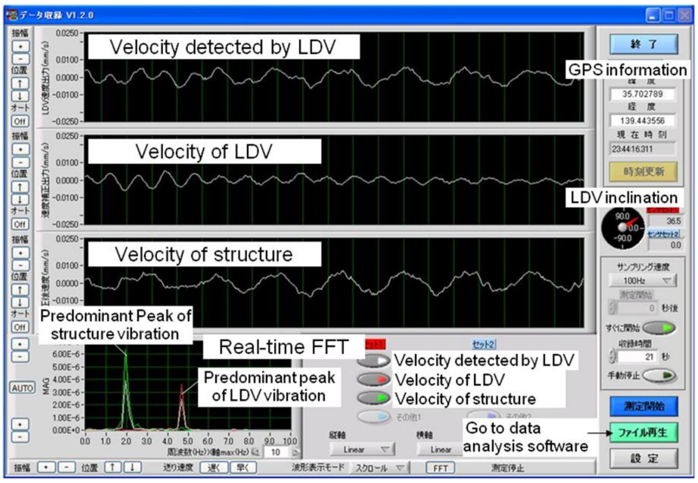

Fig. 5 Display of data recording software

3. EXPERIMENT TO VERIFY THE PROPOSED METHOD

3.1 Microtremor measurement

To verify the accuracy of the proposed remote microtremor measuring method, the fundamental frequency and mode shape of the rigid-frame structure model were identified. Four L-shaped steel columns support the model's top girder as well as additional weights and the sensor.

As shown in **Fig. 6**, the structure microtremor at Point A is simultaneously measured with the LDV (this experiment had been executed before U-Doppler was developed) and Sensor 2. Sensor 1 is also set on the LDV. The angle between the laser beam and the direction of movement of the target structure is zero in this case. Sensors 1 and 2 (velocimeter: Buttan Service CR-4.5 2S) are conventional units for measuring structure microtremors. The horizontal components of microtremors are simultaneously recorded by all sensors every 0.01 sec. **Figure 7** shows the Fourier spectra of the microtremors recorded by each sensor. Spectrum (a) corresponding to Sensor 2 shows the actual vibration characteristics of Point A. A clear peak at 4.6Hz is visible, and corresponds to the model's fundamental frequency. Spectrum (b) associated with Sensor 1 shows the fundamental natural frequency of the LDV on the tripod. Spectrum (c) obtained from the LDV recording with no correction has two predominant peaks. It seems to have been affected by the LDV vibration shown in Spectrum (b). In the case of Spectrum (d) derived according to the proposed method, the influence of the LDV's vibration is removed from Spectrum (c) and the predominant peak is the same as that shown in (a). These results show the validity of the proposed method.

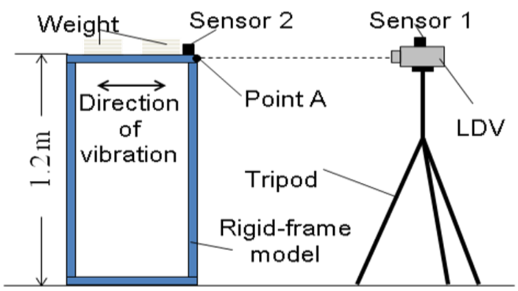

Fig. 6 Setup of experiment for remote microtremor measurement

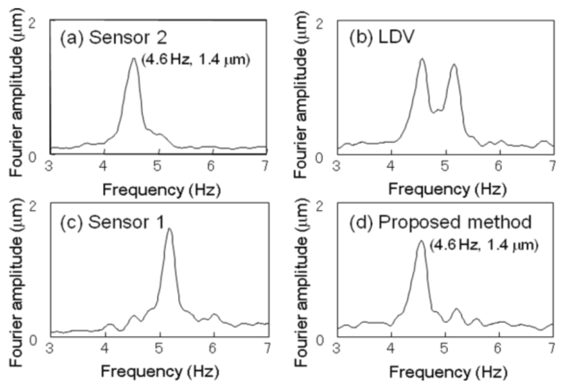

Fig. 7 Spectra obtained by sensors and the proposed method

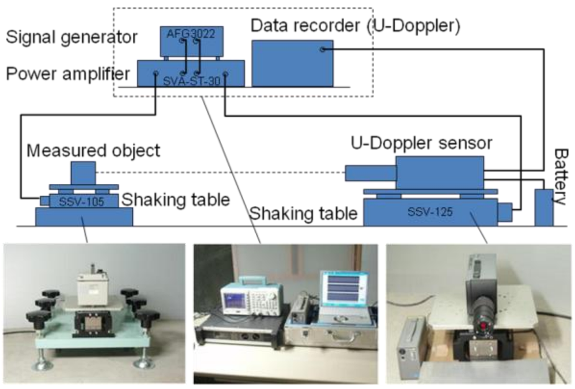

Fig. 8 Experimental apparatus composed of two shaking tables

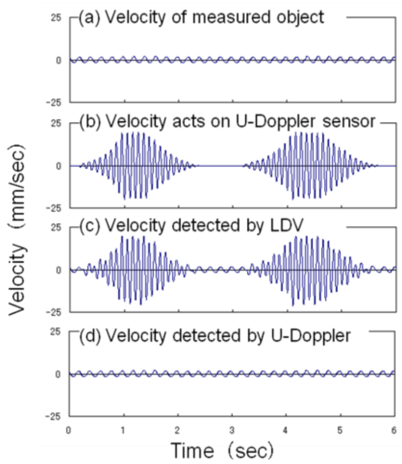

Fig. 9 Experimental results of shaking table test

3.2 Measurement under conditions of high noise

In the case of outdoor measurement, significant vibration might act on the remote measurement sensor as a result of strong wind and/or ground vibration caused by passing vehicles or construction work. To verify the measurement performance of U-Doppler under high-noise conditions, the author executed a laboratory experiment using apparatus composed of two shaking tables (Sanesu SSV-105 and SSV-125) (**Fig. 8**).

Figure 9 shows the experimental results. Waveform (a) is the vibration of the object measured (frequency: 5.0

Hz, maximum amplitude: 2.0mm/sec, sinusoidal), and waveform (b) is the vibration that acts on the U-Doppler sensor (frequency: 10 Hz, maximum amplitude: 20mm/sec, transient). Waveform (c) obtained from the LDV recording with no correction does not correspond to the vibration of the object measured. On the other hand, waveform (d) obtained using U-Doppler with correction does correspond to the vibration of the object measured. The compensation technique using a built-in vibration sensor is therefore effective when significant transitional vibration acts on the U-Doppler sensor.

4. IDENTIFICATION OF THE DYNAMIC CHARACTERITICS OF REAL STRUCTURES

4.1 Natural frequency estimation of a viaduct using microtremor measurement

The author identified the fundamental frequency and mode shape of an existing RC structure using the proposed remote microtremor measurement technique. The microtremors of the structure at Points A to E were sequentially measured with the U-Doppler unit (in the development stage) installed 5.2 m from the structure as shown in **Fig. 10**. When each point was measured, microtremors at the U-Doppler unit and Point R on the structure were measured simultaneously.

Figure 11 shows the microtremor record of each sensor, obtained when the microtremor at Point A was measured. The vibration at Point A identified using the proposed method is also shown in the figure. **Figure 12** shows the Fourier spectrum of the waves illustrated in **Fig. 11**.

Although the uncorrected data recorded by the LDV was strongly influenced by the U-Doppler sensor vibration, the corrected data measured using U-Doppler almost corresponds to the real structure microtremor recorded at Point R. The natural frequency of the structure (3.6 Hz) was accurately estimated from the U-Doppler data.

Next, the first mode shape of the structure's lower column was estimated. The spectrum amplitude of 3.6 Hz at points A to E was standardized by the values obtained using simultaneous measurement at point R. The standardized spectrum amplitude is considered to be a mode amplitude of the column. The estimated mode shape shown in **Fig. 13** corresponds to the mode shape obtained by numerical analysis.

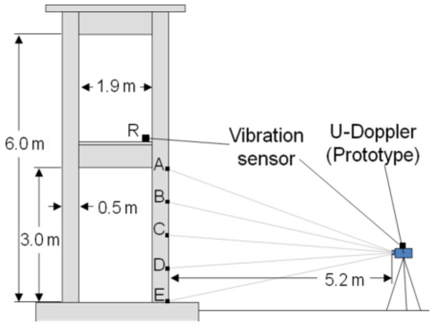

Fig. 10 Measured RC rigid frame viaduct and arrangement of sensors measurement

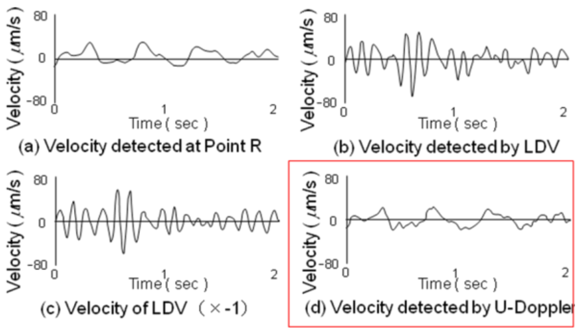

Fig.11 Velocity obtained by conventional sensors and U-Doppler

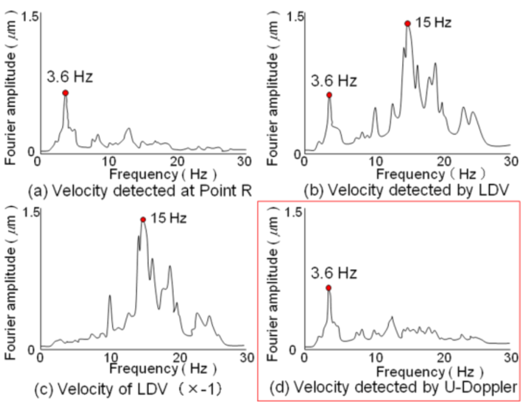

Fig. 12 Fourier spectra obtained by conventional sensors and U-Doppler

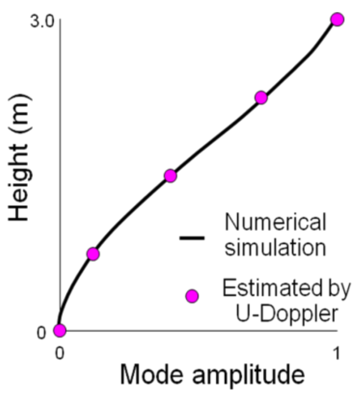

Fig. 13 Fundamental mode shape of RC Column

4.2 Natural frequency estimation of a bridge pier by impact vibration measurement

The inspection method known as impact vibration testing was introduced to judge bridge pier soundness. In this method, impact is applied to the top of the pier using a weight of approximately 30 kg, and the response wave is measured using a sensor installed on the pier. The structure's soundness is judged from its natural frequency estimated by the predominant peak of the response wave's Fourier spectrum.

The author verified the applicability of U-Doppler to the sensor for impact vibration testing. The response at the top of the pier as a result of weight impact was measured using a U-Doppler unit installed on the riverside (**Fig. 14**) at a sampling frequency of 500 Hz. In this case, the distance from the U-Doppler sensor to the measured pier was approximately 40 m, and the angle between the direction of the pier vibration and the optical axis of the irradiation laser was approximately 50 degrees. Reflective paint was applied to improve the laser reflective quality of the measured point. **Figure 15** shows (a) the waveform and (b) the spectra of impact vibration measured using U-Doppler and the conventional sensor installed at the top of the pier. The results of both sensors correspond closely. This result suggests that U-Doppler is applicable as a sensor for impact vibration testing of bridge piers.

The author confirmed that U-Doppler is capable of measuring microtremors on the bridge pier from a distant riverside location. However, the development of a pier inspection method using remote microtremor measurement is a task for the future, because in some cases the natural frequency estimated by microtremor measurement was not steady.

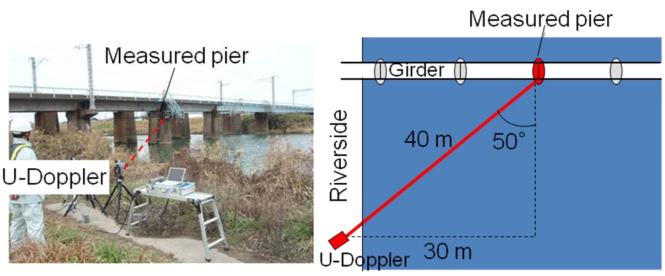

Fig. 14 Measurement of bridge pier vibration by U-Doppler

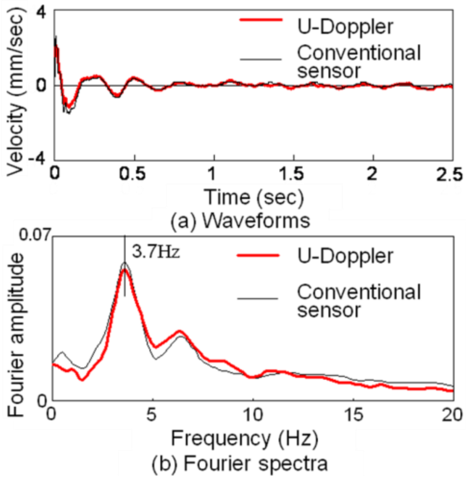

Fig. 15 Waveforms and Fourier spectra detected by conventional sensor and U-Doppler

4.3 Deflection measurement of bridge girders

Deflection measurement of bridge girders is executed whenever necessary, as they influence passengers' ride comfort and the running quality of trains. However, the execution of the conventional deflection measurement method using piano wire and a displacement gauge is difficult when a river or road is present under the girder. The author therefore decided to apply U-Doppler to dynamic deflection measurement of a bridge girder (**Fig. 16**).

Dynamic deflection measurement of a deck plate girder with a span length of 21 m was executed (**Fig. 17**). The deflection at the center of the span was measured by installing U-Doppler sensors in two places ((a): directly under the measured point, (b): in the vicinity of the pier). Simultaneous measurement using the conventional method was executed for comparison. The velocity response of the girder to a passing train was recorded (sampling frequency: 200 Hz, HPF setting: DC) and integrated using the author's proposed technique.

Figure 18 shows the dynamic deflection of the girder when a train (local train, 10 cars, 94 km/h) passed. In this case, a reflective seal was stuck on the measurement point to improve the laser reflective quality. The maximum values of deflection obtained using the conventional method and two U-Doppler sensors were correspondingly sufficient at a practical level. This result suggests that U-Doppler is applicable as a sensor for dynamic deflection measurement of railway bridge girders.

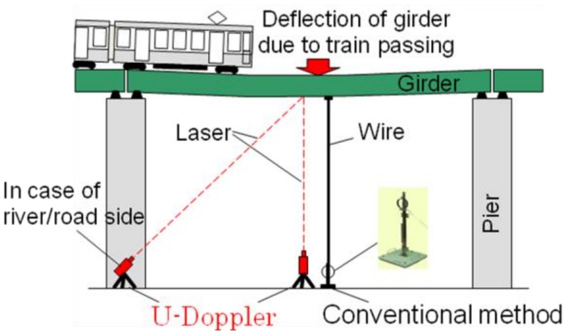

Fig. 16 Measurement method of dynamic deflection of bridge girder

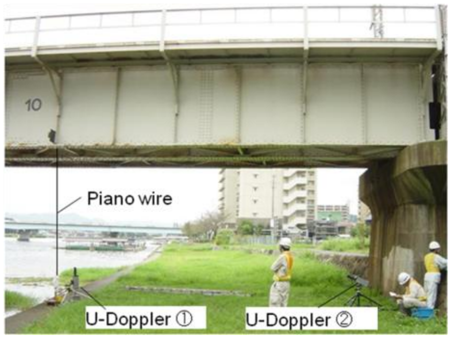

Fig. 17 Measured girder and arrangement of sensors

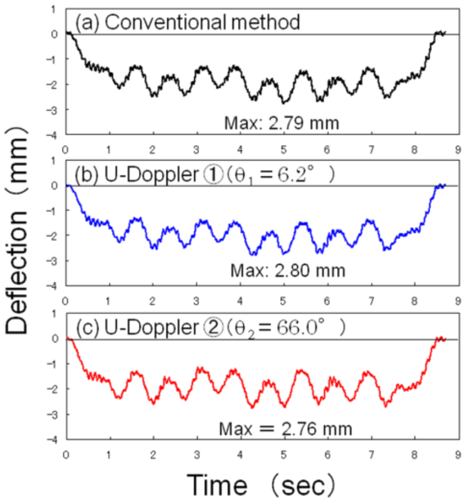

Fig. 18 Comparison of detected girder deflections

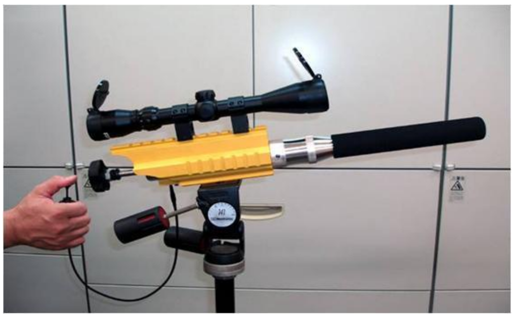

Fig. 19 Paintball launcher

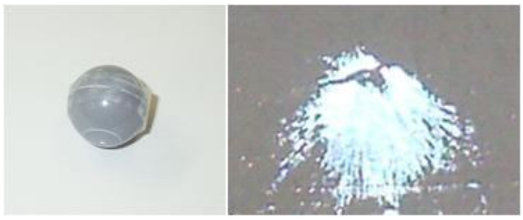

Fig. 20 Paintball and retroreflective target

Fig. 21 Field test scenery

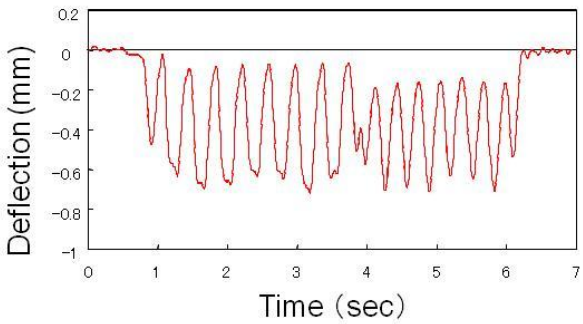

Fig. 22 Example of measured deflection

5. DEVELOPMENT OF RETROREFLECTIVE TARGET MARKING SYSTEM

The authors developed a reflective target marking system as intended to improve the safety and efficiency of remote measurement works.

In many occasions, it is inevitable to improve the retroreflectivity of measured points where the structural vibration measured with the LDV. The installation of the retroreflective target decreases the safety and efficiency of remote measurement work at unsafe locations such as high places or those adjacent to damaged structures.

The developed reflective target marking system is composed of the Launcher (**Fig.19**) and the retroreflective paint ball as apparent in **Fig.20**. The launcher is a custom-designed air powered gun, and its shooting range is approximately 30 to 50-m (shooting environment dependent). The paint ball is as filled with the retroreflective paint containing a number of minute glass beads. Each glass bead is covered with an aluminum reflective layer on half of its surface. The paint ball is shot from the launcher to the measurement point on a structure. As the paint ball hit the structure, its frangible plastic shell breaks on impact and the retroreflective paint adhere to the structure surface. Then, the retroreflective target with approximately 10 cm diameter is formed.
Figure 21 shows the field test scenery of the marking system and **Fig. 22** shows a result of dynamic deflection of the bridge girder. The marking system could form the retroreflective target from the ground to the bridge girder of 12 m in height, and the dynamic deflection measurement was successful.

6. CONCLUSION

The author proposed an accurate method of remotely measuring structure vibration, and developed the practical U-Doppler non-contact vibration measuring system for vibration diagnosis of railway structures. The accuracy of U-Doppler was verified by the results of laboratory experiments, microtremor measurement of a rigid-frame viaduct, impact vibration measurement of a bridge pier, and deflection measurement of a bridge girder. The results of the experiments and field measurements indicate that U-Doppler can be considered a sensitive and accurate measuring system for the vibration diagnosis work on railway structures such as viaducts, bridge girders, and bridge piers.
U-Doppler can contribute to considerable savings in labor hours and eliminate the risks associated with having to work in unsafe locations. The author plans to develop further application techniques for U-Doppler in the diagnosis of various railway structures.

REFERENCES

Nishimura, A. and Tanamura, S. (1998). A Study on Integrity Assessment of Railway Bridge Foundations. *RTRI Report*, **Vol. 3, No. 8**, 41-49 (in Japanese).
Nakamura, Y. (1996). Real-time information systems for seismic hazards mitigation UrEDAS, HERAS and PIC. *Quarterly Report of RTRI*, **Vol. 37, No. 3**, 112-127.
Uehan, F. (2007). Development of “U-Doppler” Non-Contact Vibration Measuring System for Diagnosis of Railway Structures. *RTRI Report*, **Vol. 21, No. 12**, 17-22 (in Japanese).
Uehan, F. and Meguro, K. (2000). Quick Inspection Method for Earthquake-damaged RC Structures by Non-linear Numerical Simulation. *JSCE Journal of Applied Mechanics*, **Vol. 3**, 621-628 (in Japanese).
Uehan, F. and Meguro, K. (2003), Development of Non-contact Microtremor Measuring Method for Vibration Diagnosis of Railway Structures. *JSCE Journal of Earthquake Engineering*, **Vol. 27** (CD-ROM)(in Japanese).