Identification of Modal Characteristics of Shinkansen RC Viaducts using Laser Doppler Vibrometers

---

Jaime Hernandez Jr.[1], Takeshi Miyashita[2], Hironori Ishii[3], Phouthaphone Vorabouth[4] and Yozo Fujino[5]

ABSTRACT:

In this paper, a new measurement system using Laser Doppler Vibrometers (LDV) for monitoring Shinkansen RC viaducts will be presented. The LDV with its high accuracy, frequency resolution, and scanning capability, is an ideal non-contact tool for monitoring large structures by ambient vibration measurement. However, the large stiffness of the viaducts cause small ambient vibrations compared with surrounding noise, requiring the need for data compensation. This is accomplished by deducting noise measured by a velocimeter attached to the LDV from the measured ambient vibration data. Additionally, in order to determine the local mode shapes of the columns an impact load using a wooden hammer was used to excite the local vibration modes.

The processing of the data to determine the modal characteristics of viaducts will also be discussed. The processing includes noise and angle compensation, synchronization of measured vibrations, and the determination of natural frequencies and mode shapes using the peak-picking method. Analysis of ambient vibration data along the transverse direction result in global mode natural frequencies of 2.83 Hz, 2.93 Hz and 3.03 Hz. It was also observed that these global mode shapes derived from modal analysis are not pure torsional and lateral modes but a combination of the two. These results suggest the presence of dynamic interaction between adjoining viaducts because of the continuity of the rail tracks connecting the individual viaducts. On the other hand, column natural frequencies of 62 Hz and 153 Hz were determined for the first and second local column modes, respectively. The local mode shapes of a regular column compared with a retrofitted column will also be presented.

INTRODUCTION

The Shinkansen RC viaducts, shown in Figure1, are simple frame structures which support the railway and other electrical equipment needed by the Shinkansen during operation. Because the Shinkansen has proven to be a safe and reliable form of transportation for over 40 years now, there are several thousands of these RC viaducts across Japan, connecting major cities and prefectures. Thus, the Shinkansen transport system is very important to the socio-economic life of the country.

However, the Shinkansen RC viaducts are deteriorating due to age and are subjected to increased service loads. Also, these viaducts have been repeatedly subjected to strong earthquakes that initiate minor damage or increase existing damage.

[1,4,5] Dept of Civil Eng, Univ. of Tokyo, jaime@bridge.t.u-tokyo.ac.jp, phouthaphone@geot.t.u-tokyo.ac.jp, fujino@civil.t.u-tokyo.ac.jp; [2] Nagaoka Univ. of Technology, mtakeshi@vos.nagaokaut.ac.jp:
[3] Yokogawa Bridge Corp. h.ishii@yokogawa-bridge.co.jp

Furthermore, due to lack of technical knowledge in the past, the columns lack the shear reinforcement needed for ductile behavior during severe earthquake loading.

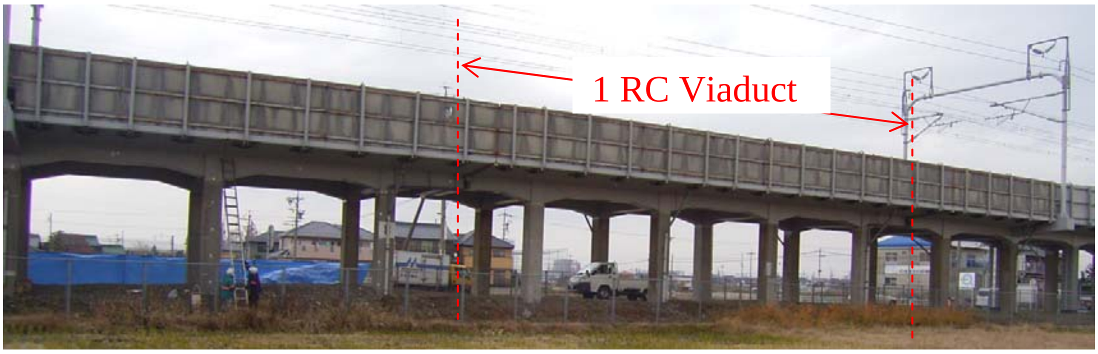


Figure 1: Series of RC Viaducts

Thus, it is imperative that these structures be retrofitted. But because of the number of these viaducts, retrofitting all will require a substantial amount of investment. Therefore, a scheme for identifying which viaducts should be prioritized for retrofit, including a continuous monitoring procedure must be developed.

At present, Japan Railways (JR) uses the natural frequencies (local & global) of its viaducts as an index to evaluate their present condition. The idea being that any changes in the natural frequency of the viaduct results from possible damage that occurred. This is true, theoretically. However, recent research show that changes in the natural frequency is not very sensitive to minor or medium scale damage on a localized level. Neither does it allow locating the position of possible damage. For field measurements, JR uses the Impact Test to determine the natural frequencies of the viaduct. The impact test involves the lateral excitation of the structure by impact hammer to identify the natural frequencies of the viaduct. It is unsafe because workers are required to be lifted several meters above ground in order to hit the structure with a 30 kg mass and cause it to vibrate. This implies the use of heavy machinery during field investigations which may cause injury during an aftershock after a damaging earthquake, aside from the possibility of injury from falling. It is also time-consuming with the amount of work that it entails from preparation, mobilization, setting up and execution of the method. Finally, it is costly and inefficient because of the heavy machinery needed and the number of workers necessary to do the job. Thus, there is a need for a safer, fast and affordable method that can replace the impact test.

Recent SHM techniques use changes in mode shapes of structures in detecting and locating damage because it is more sensitive to damage compared to natural frequency and/or damping. Depending on the spatial distribution of measurement points during experiment, research have shown that changes in mode shapes and its derivatives can locate damage in a structural member, e.g. Kim and Stubbs [2] developed a damage identification method using strain-energy of beams based from derivatives of the mode shapes of undamaged and damaged beams. However, before any SHM technique utilizing changes in mode shapes can be developed for the Shinkansen RC viaduct, it is important to investigate their actual dynamic behavior in the field.

In this paper, a new measurement system using Laser Doppler Vibrometers (LDV) for monitoring RC viaducts will be presented. The LDV with its high accuracy, frequency resolution, and scanning capability, is an ideal non-contact tool for monitoring large structures by ambient vibration measurement. However, the large stiffness of the viaducts cause small ambient vibrations compared with surrounding noise, requiring the need for data compensation. The surrounding low-frequency noise causes the tripod (with the LDV) to vibrate, masking the true ambient vibrations of the viaduct. The compensation is accomplished by deducting noise measured by a velocimeter attached to the LDV from the measured ambient vibration data. Additionally, in order to determine the local mode shapes of the columns, an impact load using a wooden hammer was used to excite the local vibration modes. From the analysis, it was determined that the ambient and train loads are not sufficient to excite the local column modes. The complete system is superior to the impact test not only in terms of advanced technology used but also for safety and efficiency.

The data processing includes noise and angle compensation, synchronization of measured vibrations, and the determination of natural frequencies and mode shapes using the peak-picking method. Analysis of ambient vibration data along the transverse direction result in global mode natural frequencies of 2.83 Hz, 2.93 Hz and 3.03 Hz. It was also observed that these global mode shapes derived from modal analysis are not pure torsional and lateral modes but a combination of the two. These results suggest the presence of dynamic interaction between adjoining viaducts because of the continuity of the rail tracks connecting the individual viaducts. On the other hand, column natural frequencies of 62 Hz and 153 Hz were determined for the first and second local column modes, respectively. The local mode shapes of a regular column compared with a retrofitted column will also be presented. The retrofitting uses steel jackets in order to improve the ductile behavior of the columns during severe earthquake loading.

MEASUREMENT SYSTEM

Laser Doppler Vibrometer (LDV)

Laser Doppler Vibrometers (LDV) are optical vibration measurement devices which make use of the Doppler effect in detecting the frequency change between a reference laser and a measurement laser. The measurement laser is aimed at the vibrating surface and is reflected back to the LDV where the Doppler shift is determined after comparing with the reference laser. Using the Doppler frequency shift the velocity of the vibrating surface is determined.

In this research, two types of LDVs were used during measurement, shown in Figure 2. The first type is a single-point LDV which was used to measure vibration at a reference point, referred to as RLDV. The second type is a scanning LDV which measures the vibration at all the predetermined measurement points, referred to as SLDV. A scanning LDV is equipped with two movable mirrors in the sensor head making it possible to control the direction of the measurement laser. The first mirror is used for horizontal angular control and the second mirror for vertical angular control. The table below shows the general specifications of the SLDV used in this research.

Frequency Bandwidth	0 – 35 kHz
Velocity Range	1,5,25,125 mm/s/V
Working Distance	100 m
Laser Wavelength	633 nm (red)
Laser Protection Class	Class IIIa He-Ne
Angular Resolution	±0.01°

Table 1. Scanning LDV

Velocimeter

The velocimeter component of the measurement system is used to compensate for noise vibrations on the LDV record due to the vibration of the tripod. The servo-velocimeter used is the VSE-15D having the following general specifications:

Detectable Velocity	±0.1 m/s
Measurement Range	0.1, 1 V/mm/s
Velocity Resolution	1.5 µm/s
Frequency Bandwidth	0.07 – 100Hz

Table 2. VSE-15D Specifications

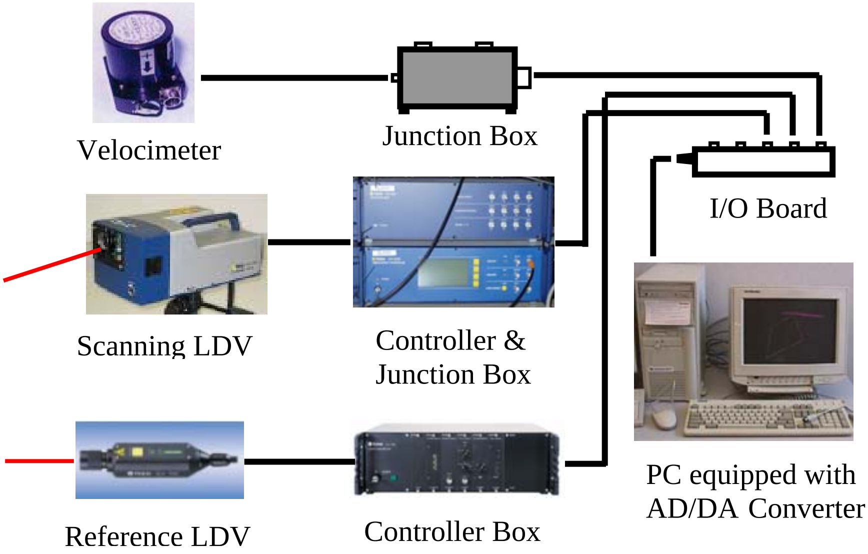


Figure 2: Measurement System Components

DATA PROCESSING

Angle Compensation

The LDV is designed to measure vibrations perpendicular to the surface of the moving object. Thus, when measuring vibrations at an angle with respect to the surface of the structure, the results are inaccurate and compensation is needed.

The Doppler frequency shift f_D is defined to be the difference between the frequencies of the incident laser f_0 and the reflected laser f_r, expressed in terms of the speed of light c and the velocity of the vibrating surface v (inclined at an angle θ from the direction of the source) as,

$$f_r = \frac{c + v\cos\theta}{c - v\cos\theta} f_0 \tag{1}$$

Thus,

$$f_D = \left| f_0 - f_r \right| = \frac{2v}{\lambda_0}\cos\theta \quad \text{and so} \quad v = \frac{\lambda_0 f_D}{2}\sec\theta \tag{2}$$

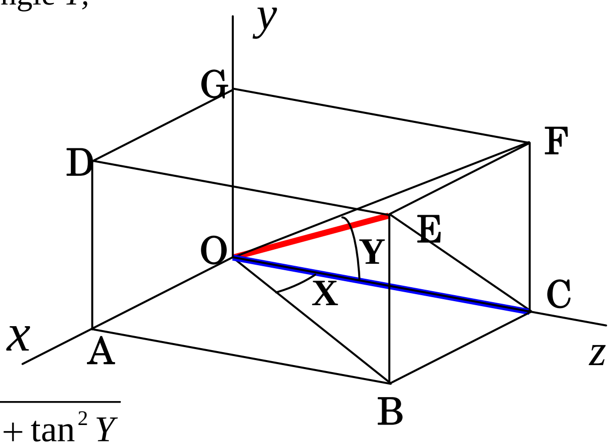
where $c = \lambda_0 f_0$ was used in the derivation, and λ_0 is the wavelength of the incident laser. If the velocity of vibration is perpendicular to the surface of the object, i.e. parallel to the direction of the source, then θ is zero. But for the general case when θ is not zero, we need to compensate by multiplying the measured velocity by *sec* θ.

For the SLDV, owing to the two movable mirrors in the sensor head, we can control the angle of the laser along the horizontal and vertical directions. Thus knowing the horizontal angle X and the vertical angle Y,

$$\Delta OCB: \quad \overline{CB} = \overline{OC}\tan X$$

$$\Delta OCF: \quad \overline{CF} = \overline{OC}\tan Y$$

$$\begin{aligned}\overline{OE}^2 &= \overline{EC}^2 + \overline{OC}^2 \\ &= \overline{OC}^2 + \overline{CF}^2 + \overline{CB}^2 \\ &= \overline{OC}^2(1+\tan^2 X + \tan^2 Y)\end{aligned}$$



$$\frac{\overline{OE}}{\overline{OC}} = \sec\theta = \frac{1}{\cos\theta} = \sqrt{1+\tan^2 X + \tan^2 Y}$$

Noise Compensation

Due to the high stiffness of the Shinkansen RC Viaducts, ambient vibrations are very small so that low-frequency noise from the environment dominate the recorded vibration data. The LDV measurements are affected through the vibrations induced on the supporting tripod. Thus, it is necessary to reduce and/or eliminate these noise vibrations.

In this research, we compensate for the noise vibrations affecting the tripod by attaching a velocimeter to the LDV. The velocimeter measures the vibration of the tripod induced by surrounding noise in the direction of measurement, which is also recorded in the LDV data. Because the velocimeter is directly attached to the LDV, one can directly deduct the measurement of the velocimeter from the LDV record. This procedure is done during pre-processing of the data.

Data Synchronization

The SLDV measures vibration at preselected measurement points consecutively requiring the need to synchronize recorded vibration data before modal identification procedures can be made. This is accomplished using the reference data obtained by the RLDV. The derivation of the equations for the synchronization procedure can be found in Siringoringo [4].

Based on the derivations in [4], the cross spectrum of a consecutive measurement differs from the base measurement by a factor α expressed as,

$$\alpha = \frac{P_{u_{Rij}}}{P_{u_{R0}}} \equiv \frac{\text{auto spectrum of reference laser at time } t_j}{\text{auto spectrum of reference laser at time } t_0} \qquad (3)$$

Thus, to transform different time-based cross spectrums into the same time base, a factor α must be multiplied to its base spectrum. Siringoringo [4] also warns that since the factor α is calculated using auto spectrum only, it does not eliminate the effect of correlated noise at the reference laser measurement. And thus, to reduce noise, it is necessary to choose as the reference laser position the measurement point with the largest signal-to-noise ratio.

Peak-picking Method using Cross Power Spectrums

The peak-picking approach used in this research was adopted from Fujino, et.al. [1]. The RLDV measures the vibration of a single reference point whereas the SLDV measures the vibration at all the predetermined measurement points. Based on the derived equations from [1], we can express the mode shape ratio between a reference point r and measurement point p in terms of the cross spectrum $G_{pr}(\omega)$ between r and p, and the auto spectrum $P_{rr}(\omega)$ at r.

$$\frac{\phi_{i^*p}}{\phi_{i^*r}} \approx \frac{G_{pr}(\omega)}{P_{rr}(\omega)} \tag{4}$$

The modal frequencies are identified by determining the frequency peaks in the cross spectrum. The amplitudes of the mode shapes are determined by taking the absolute value of equation (4). From the angle of equation (4) we can determine whether the mode is in- phase or out-of-phase: in-phase when the angle is within the range from $-\pi/2$ to $\pi/2$ and out-of-phase when the angle is between $-\pi$ and $-\pi/2$ and $\pi/2$ to π. In order to improve the accuracy, the ambient vibration record is divided into frames and the resulting cross and auto spectrums averaged.

EXPERIMENTATION

The main objective of the experiment in the laboratory is to verify the effectiveness of the noise compensation. The figure below shows the experiment set-up. The LDV was placed on optical rails which are rigidly connected to the table. The measurement plate was rigidly clamped to the optical rails. Velocimeter 1 was attached to the LDV for compensation while Velocimeter 2 was attached to the plate to measure its vibration. Velocimeter 3 was placed on the rail for comparison.

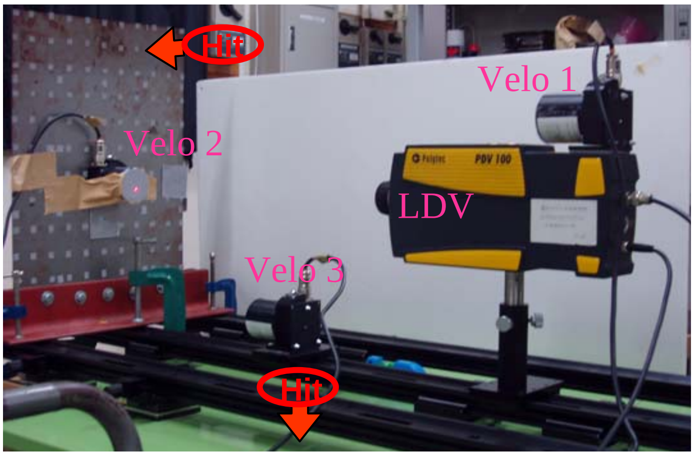
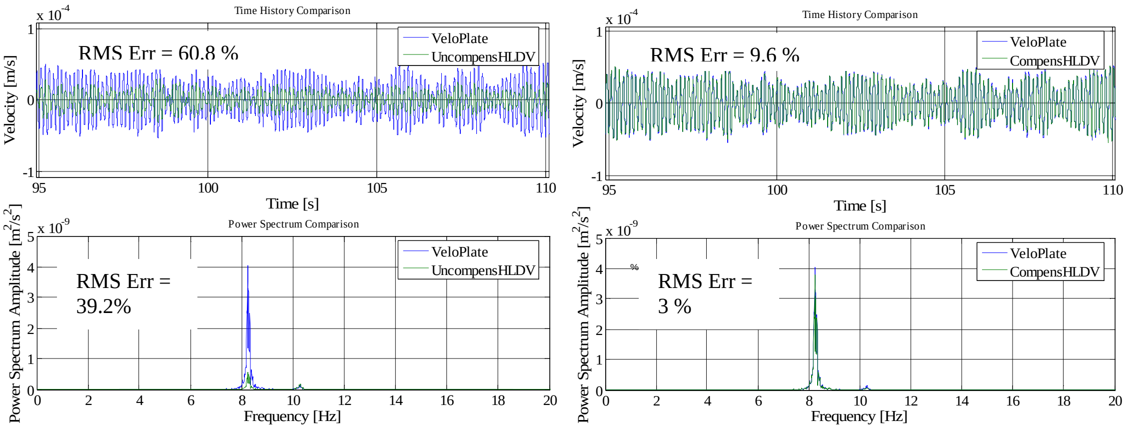


Figure 3. Experimental Set-up

Experimental Results



Without Compensation

With Compensation

Figure 4. Ambient Vibration

Figure 4 shows the time-history and Power spectrum for ambient vibration before and after compensation. Note that only a portion of the time-history is shown. Averaging was employed, to further improve the power spectrum comparison. The percentage RMS error was computed for both cases, it is clear that with the compensation the LDV is capable of measuring ambient vibrations even in the presence of noise.

FIELD INVESTIGATION

During field measurements, a total of 11 points on the surface of an RC viaduct were selected, two per column and three on the main beam. Figure 5 shows the location of the measurement points, whereas Figure 6 shows the equipment set-up on the field. The equipment were set-up about 30 m. facing the viaducts.

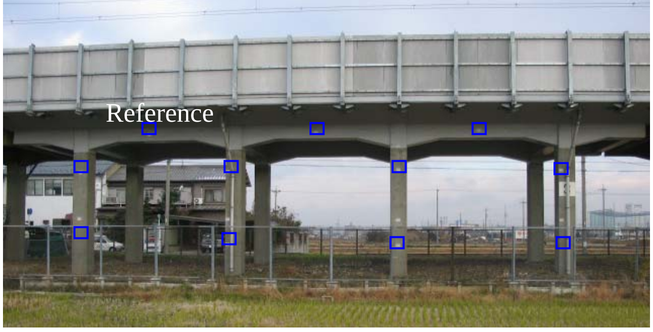


Figure 5: Location of Measurement (Scan) Points

Figure 6: Equipment Set-up

The data acquisition system was set at a sampling rate of 1000 Hz. The left most measurement point on the beam was chosen as the reference. Once all of the measurement point coordinates were identified for scanning, the vibration at each point was measured in succession using the SLDV for 10 min per point, continuously. Thus, the record consists of ambient and train-induced vibration data which were separated during analysis.

MODAL CHARACTERISTICS OF A VIADUCT

Global Mode Shapes and Natural Frequencies

The modal identification procedure described in the data processing section of this paper was used to identify the natural frequencies and mode shapes of the existing viaduct. To determine the global modal properties, after noise and angle compensation, the cross spectrum of the ambient vibration data between reference and scan points were computed. Figure 7 below shows one of the cross spectrums and Figure 8 shows the cross spectrum of the same ambient vibration data with averaging of 30 sec frames in order to improve the estimate of the natural frequencies. The peaks identify the global mode natural frequencies of the viaduct: 2.833 Hz, 2.933 Hz and 3.033 Hz.

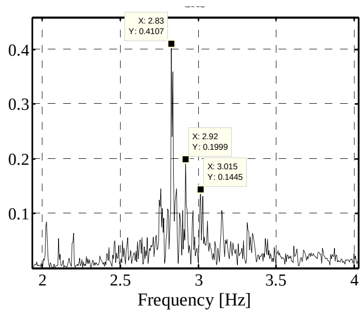


Figure 7: Cross Spectrum

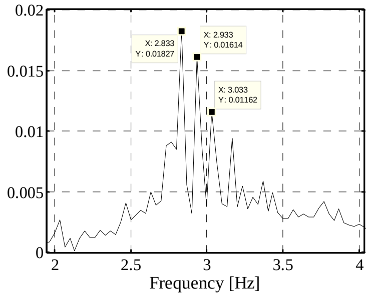
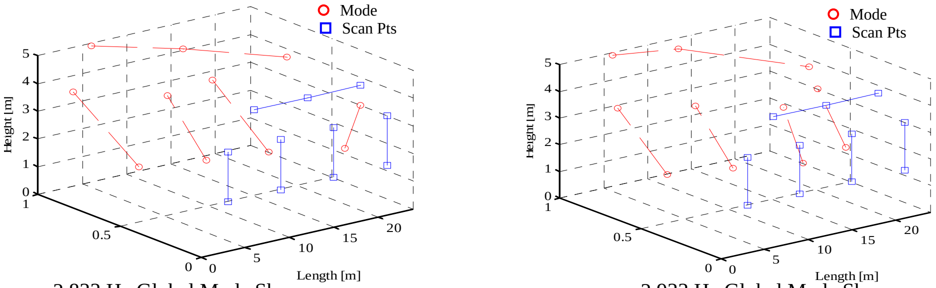


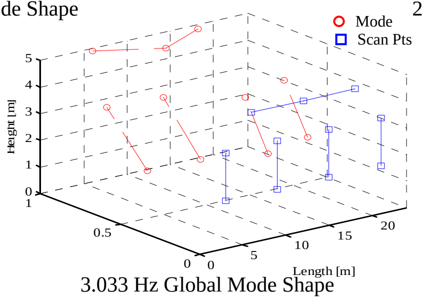
Figure 8: Averaged Cross Spectrum

A viaduct has three global modes of vibration, namely: longitudinal, torsional and lateral modes. We identified the global mode natural frequencies but in order to distinguish between frequencies we must determine the mode shape for each. Again, using the modal identification procedure, the following mode shapes were determined for each global mode natural frequency:



2.833 Hz Global Mode Shape

2.933 Hz Global Mode Shape



3.033 Hz Global Mode Shape

Figure 9: Global Mode Shapes

Based on the global mode shapes derived from the measurement, we can conclude that the 3.033 Hz is the lateral mode shape but we cannot distinguish which is the torsional or longitudinal mode between the 2.833 Hz and 2.933 Hz frequencies. Actually, a close examination of the unidentified mode shapes reveal that they are a combination of torsional and lateral modes. This phenomena can be explained by the presence of dynamic structure interaction between adjoining viaducts due to the presence of the continuous rails.

Column Mode Shapes and Natural Frequencies

From analysis, we observed that ambient and train-induced vibrations of the viaduct are not enough to excite the column local modes. Thus, we came up with a simple way of exciting the column modes by hitting the columns with a wooden hammer. Two types of columns were investigated, an ordinary RC column and one retrofitted with steel jackets. Four points on each column were selected and measured simultaneously. Figure 10 below shows a typical impact vibration record together with its fourier transform for a regular column. The first column mode natural frequency is 62 Hz and the second column mode natural frequency is 153 Hz.

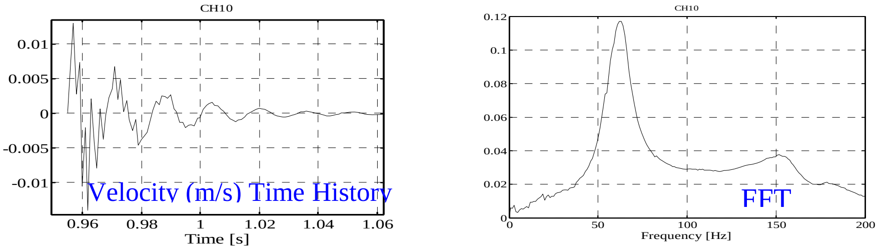


Figure 10: Typical Impact Vibration Record

Once the column natural frequencies are determined, a butterworth filter was used to separate the free vibration response for the different modes. Then based on the free vibration at the measurement points for each mode, the mode shapes are drawn. Figure 11 shows the comparison between the retrofitted and unretrofitted column modes, one observes that the change in mode shape is minimal but is more pronounced in the second mode shape. Thus, this confirms that higher modes are more sensitive to changes in the structural member.

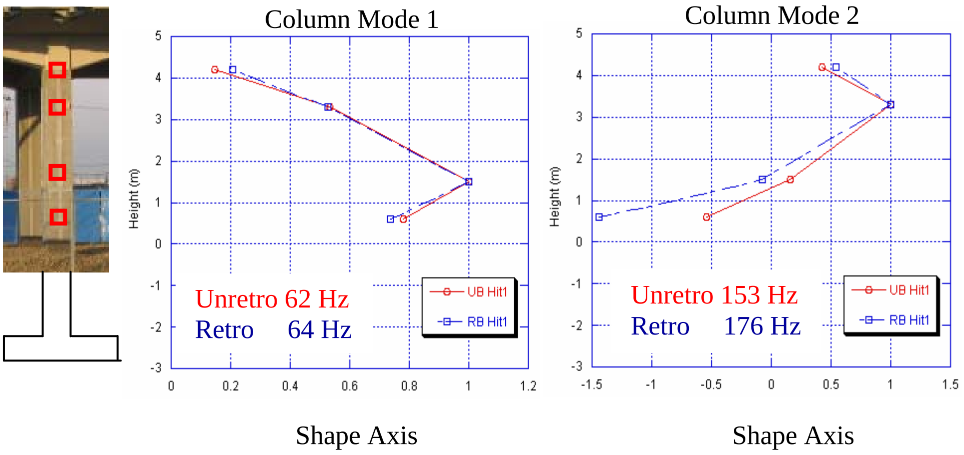


Figure 11: Comparison of Retrofitted and Unretrofitted Column Modes

CONCLUSIONS AND FUTURE WORK

A new measurement system using LDV was developed for monitoring RC viaducts. During ambient vibration measurements, compensation for noise from the environment was implemented using a velocimeter attached to the LDV. The noise vibrations measured by the velocimeter are directly deducted from the LDV record. The complete system is superior to the impact test not only in terms of advanced technology used but also for safety and efficiency.

In this research, the modal characteristics of RC viaducts were determined. Three closely spaced global mode natural frequencies were computed from ambient vibration measurements: 2.833 Hz, 2.933 Hz and 3.033 Hz. Based on the mode shapes, the lateral mode natural frequency was determined to be 3.033 Hz. Also, it was observed that the other two modes appear to be combinations of lateral and torsional modes. This finding is indicative of the presence of dynamic structure interaction between adjoining viaducts because of the continuous rails. Furthermore, the local column modes of a regular and retrofitted column were determined and compared.

Future work, includes the identification of a damage sensitive feature that can be used for monitoring RC viaducts, other than the changes in the natural frequency currently being used by JR. A finite element model of a viaduct can be developed to help in distinguishing the torsional and longitudinal modes. Using the same FEM model, replicated and connected in series, dynamic structure interaction between adjoining viaducts can also be modeled.

ACKNOWLEDGEMENT

The authors would like to acknowledge the help of Fumiaki Uehan of Railway Technical Research Institute (RTRI) for his valuable advice regarding data compensation of noise vibrations.

REFERENCES

1. Fujino Y., Kaito K., and Abe M. 2001 *Detection of structural damage by ambient vibration measurement using Laser Doppler Vibrometer*. Proceedings of SPIE 4337, 167.
2. Kim J.T. and Stubbs N. *2002 Improved Damage Identification Method Based on Modal Information.* Journal of Sound and Vibration 252, 223-238.
3. Miyashita T. 2005 *Advanced Measurement System using Laser Doppler Vibrometers for Monitoring of Civil Infrastructures.* PhD Thesis, Univ. of Tokyo.
4. Siringoringo D.M. 2002 *Identification of Dynamic Characteristics of Structural Joints and Its Application in Damage Detection.* Master Thesis, Dept of Civil Engineering, Univ of Tokyo.

.