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Case Studies of LDV-aided Dynamic Testing

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Abstract. The laser Doppler vibrometer is a non-contact sensing technique developed based on the Doppler effect of a laser beam emerging from a subject surface. As a vibration transducer, the laser Doppler vibrometer offers many advantages over the conventional contact vibration sensors. It allows remote, non-intrusive measurement of structural vibration and it is very useful in scenarios when traditional contacting measurement is inconvenient. In this paper, four laser-based structural dynamic studies were presented and some results were briefly reported, which include laboratory dynamic testing of a bolted steel beam, a scaled-down high-rise building model, and a prestressed concrete reaction wall, and field vibration measurement of a viaduct bridge. Through these demonstrating cases, it is anticipated to help civil engineers get familiar with the laser-based sensing technology and to extend their selections for effective measurement approaches during experimental research.

Introduction

Structural health monitoring (SHM) technologies have been developed for civil infrastructure recently [1]. Various sensors, such as accelerometers, strain gauges, the linear variable differential transducers (LVDTs), are required to be installed on a target structure to collect data of interest for a typical structural health monitoring system. The number of sensors used in a SHM system for a large scale civil structure can be more than several hundreds, as the cases for typical bridge SHM systems in Hong Kong [2]. Field deployment of traditional contact sensors is time consuming. Wireless communication has been developed to reduce the effort of hardwiring long cables [3-5]. However, it is still essential to get in touch with the target structure to mount sensors. This may cause troubles if it is difficult in getting access to the target. Other problems associated with the contact measurement include durability and power supplying of the sensor devices.

Remote sensing or noncontact sensing, which collects the same physical parameters that contacting sensors measure, alleviates sensor installation efforts. Noncontact sensors are not fixed attached to a target structure and can be used repeatedly. The laser Doppler vibrometer (LDV), as one of laser-based noncontact sensing methods, shows its advantage in engineering measurements [6]. It uses the Doppler shift effect to help obtain vibration information of the structure. The LDV find its applications in many experimental studies. Nassif et al. [7] validated the LDV measurement with traditional contact sensors, including the LVDTs and geophones, during field testing of a bridge. The LDV was used by Lee and Shinozuka [8] as a comparative measurement method to justify deflection values of a steel box girder bridge, which were obtained by digital image analysis. Sohn et al. [9] developed a method to detect façade delamination and debonding using wavelength images from a LDV. Dai et al. [10] used a LDV system in field vibration measurement of a steel girder bridge for a finite element model validation. To further appreciate the potential usability of the laser Doppler vibrometer system in structural dynamic testing, four application cases were briefly described in this paper, including both lab and field vibration measurements. It is expected that these demonstrating cases can help civil engineers get familiar with laser-based sensing technologies.

LDV Aided Dynamic Testing: Case Studies

The LDV systems used in case studies are commercially available products from the Polytech, including a portable digital vibrometer PDV-100 and a scanning vibrometer system PSV-400. The PDV measures a single point vibration velocity of a target structure; while the PSV-400 is a full range vibration device that can scan multiple points of a target surface for vibration measurements. For technical specifics about these two laser devices, please refer to the information provided by the Polytech [11,12].

Structural Dynamic Study of a Prestressed Concrete Reaction Wall. A new structural laboratory was constructed on the Jiading campus of Tongji University, China. A group of advanced testing facilities were equipped, including an array of four shaking tables, an advanced fatigue testing system, several pieces of reaction walls, and a strong floor. To get an idea of vibration characteristics of the prestressed reinforced concrete reaction wall the new lab, measurements were implemented on one piece of the reaction wall. The wall structure was excited with ambient vibration induced by operating the main crane in the lab. The PDV-100 potable laser vibrometer and the seismometer (EpiSensor from Kinemetrics) were both used to measure structural vibration (Fig. 1). The laser pointed at the wall surface while the three-axis seismometer was positioned at the wall top. A typical velocity time history and its spectrum obtained from the laser were shown in Fig. 2. The first bending mode frequency of the reaction wall from the laser measurement and from the seismometer record is 14.27 Hz and 13.81 Hz, respectively, which is close with a difference of 3.3%.

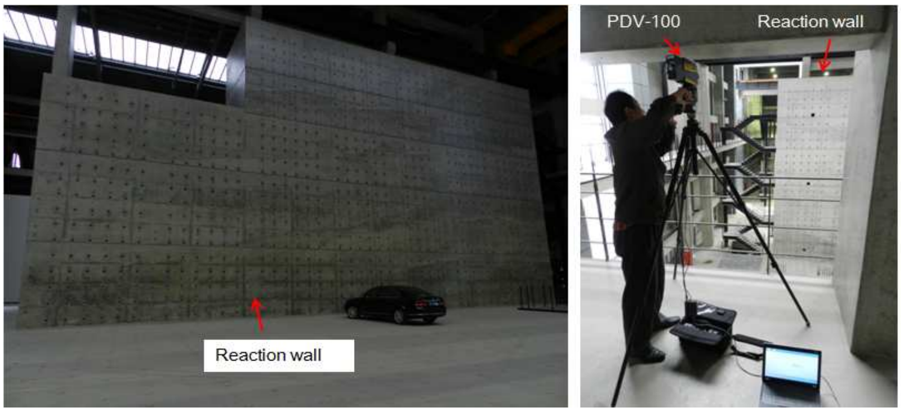

Fig. 1 Prestressed reaction wall modal frequency measurement

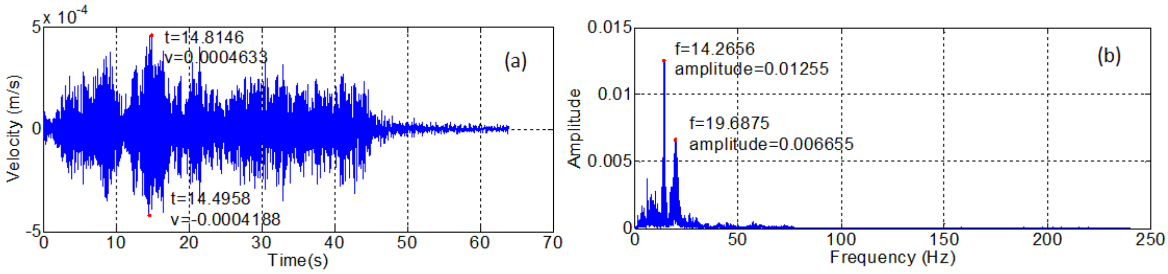

Fig. 2 Typical laser measured velocity time history and its spectrum

Field Testing of a Viaduct Bridge. Field testing of a viaduct bridge was conducted using the PDV-100 to explore its usage for in-situ experimentation. Vibrations of the bridge deck and the pier due to traffic were measured (Fig. 3). A typical bridge deck vibration time history and its spectrum are shown in Fig 4; while a typical vibration time history of the pier and the corresponding spectrum are shown in Fig. 5. From the measurements, it is concluded that fundamental frequencies for the bridge deck and the pier are 5.29 Hz and 14.68 Hz, respectively. But it was realized during result analysis that the laser vibrometer measures vibrations of the structure relative to the laser device. During the field testing, the laser support can be excited. Vibration of the laser device itself needs to be quantified in order to derive structural movements relative to the ground. Technical discussions was performed to propose a design to include this function into the laser device.

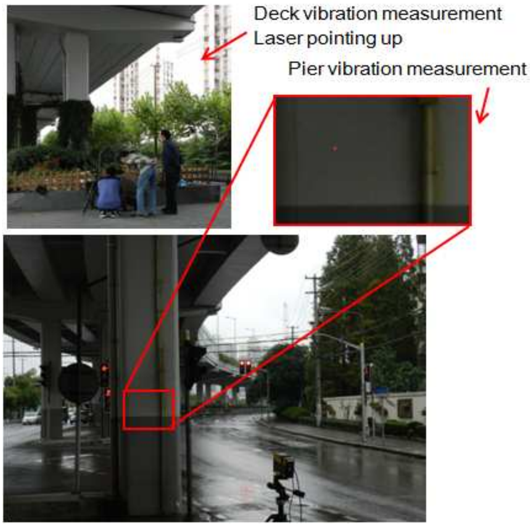

Fig. 3 Bridge vibration field testing

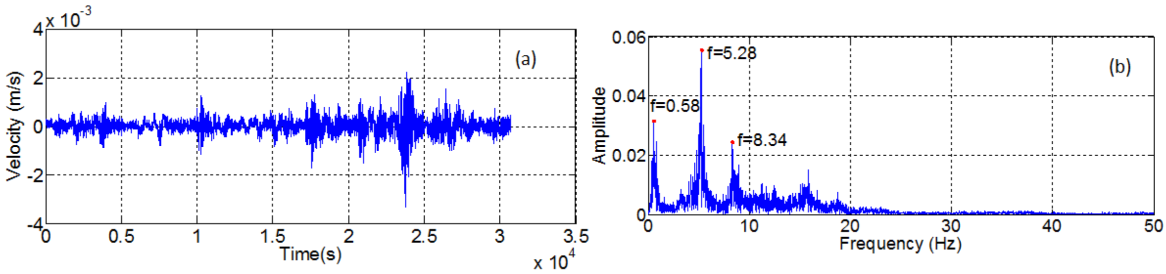

Fig. 4 A typical vibration measurement of the bridge deck: (a) Velocity time-history; (b) Vibrational velocity spectrum

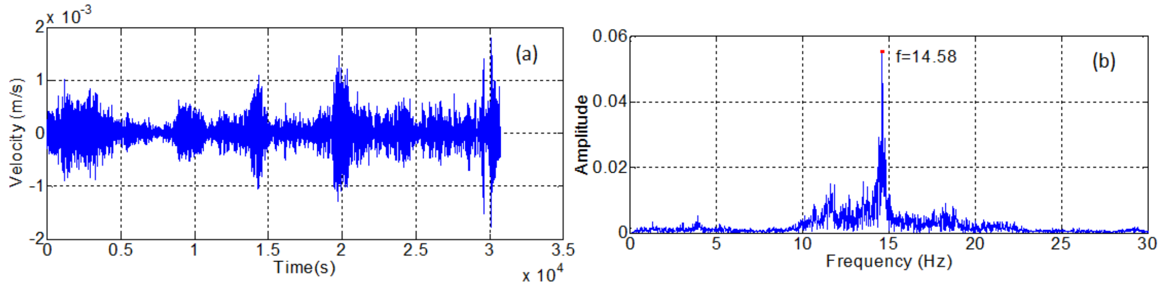

Fig. 5 A typical vibration measurement of the bridge pier: (a) Velocity time-history; (b) Vibrational velocity spectrum

Modal Study of a Bolted Beam for FE Model Validation. A modal study was performed to build up knowledge associated damage detection of bolted structures. Two steel beams with identical square sections were connected with bolted flanges. The geometry information of one beam is shown in Fig. 6. Three-dimensional solid finite element (FE) models were established both for the bolted beam and the single beam under the ABAQUS environment. The elastic parameters used in the FE models include: (1) Young's modulus: 2×10^{11} N/m^2, (2) Poisson's ratio: 0.3, (3) Steel density: 7.85×103 kg/m^3. Experimental modal studies were conducted on both the single beam and the bolted beam under the suspended condition in order to validate the FE models. During the tests, the beam was excited by the shaker with a frequency sweep mode (10 Hz to 2000 Hz). The PVD-100 was used as a reference sensor while the PSV-400 scanned the entire structure to obtain modal behaviors of the beam. Fig. 6 shows the shop drawing of one beam section and the testing set-up. Mode shapes of the first three bending modes of the two beams are shown in Fig. 7. Table 1 compares natural frequencies between FE modeling and modal testing for both the single beam and the bolted beam. Research is on-going to construct a reliable FE model for the connected beam with loosen bolts based on the testing results.

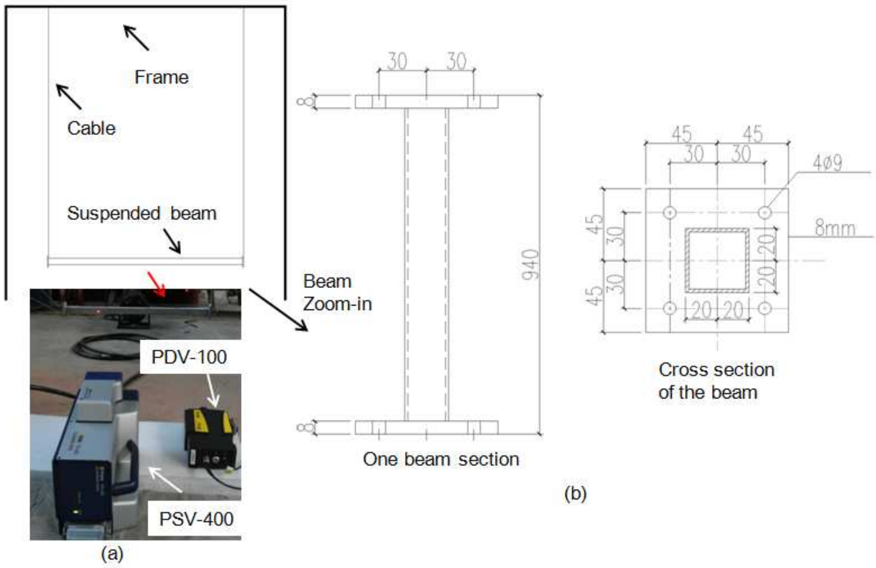

Fig. 6 Modal testing: (a) Testing set-up; (b) Beam geometry

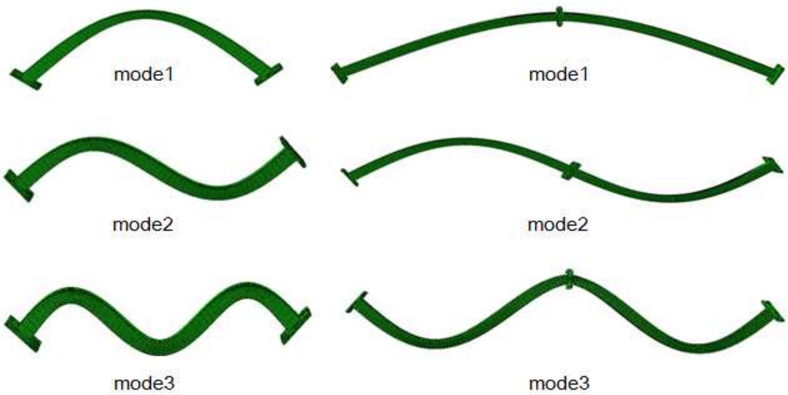

Fig. 7 Typical mode shapes

Table 1 Frequency comparison of the beam vibration

Mode	Single beam FE [Hz]	Single beam testing [Hz]	Difference [%]	Single beam FE [Hz]	Single beam testing [Hz]	Difference [%]
1	210.88	207.5	1.6	49.38	49.34	0.08
2	623.37	613.75	1.5	174.38	173.79	0.34
3	1226.9	1205.63	1.7	274.38	283.14	3.19%

Structural Vibration Measurement of a High-rise Building Model. Both the PDV-100 and the PSV-400 were set up to measure structural vibration of a high-rise building model during a shaking table test (Fig. 8). The target structure was a mega-frame building model with 55 stories. The model was designed based on the scale-down ratio of 1/25 and it was testing on the 4 meter by 4 meter, six-degree-of-freedom shake table of Tongji University. Structural vibrations of the model were collected at two locations: 2.18 m (A in Figs. 8 and 9) and 1.3 m (B in Figs. 8 and 9) above the structure foundation, by using the PDV-100 and PSV-400, respectively. Base excitations along the direction of laser beam in the test include the white noise ('WN') and acceleration time-histories developed from two natural earthquakes, the EI Centro earthquake and the Taft earthquake. Spectra of structural vibration signals under white noise excitations collected by the laser vibrometers were analyzed directly to obtain fundamental frequency of the structure. It is found that the fundamental frequency of the building decreases from 6.47 Hz to 5.88 Hz after the structure was shaken with large earthquakes, indicating deterioration of the overall structural stiffness.

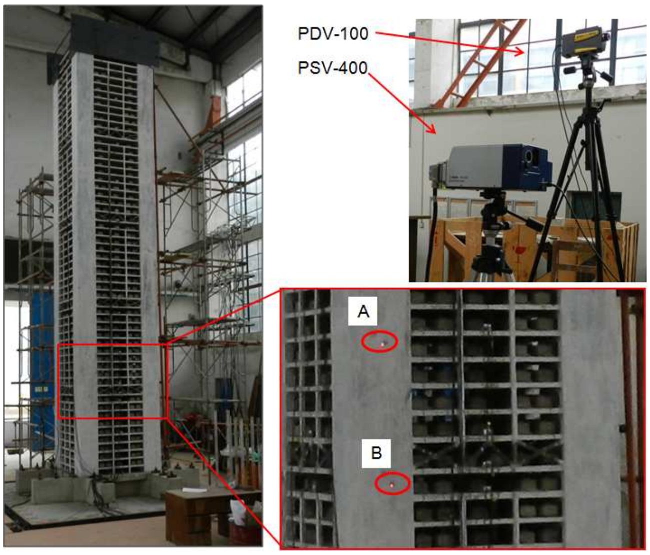

Fig. 8 LDV vibration measurement during a shaking table test

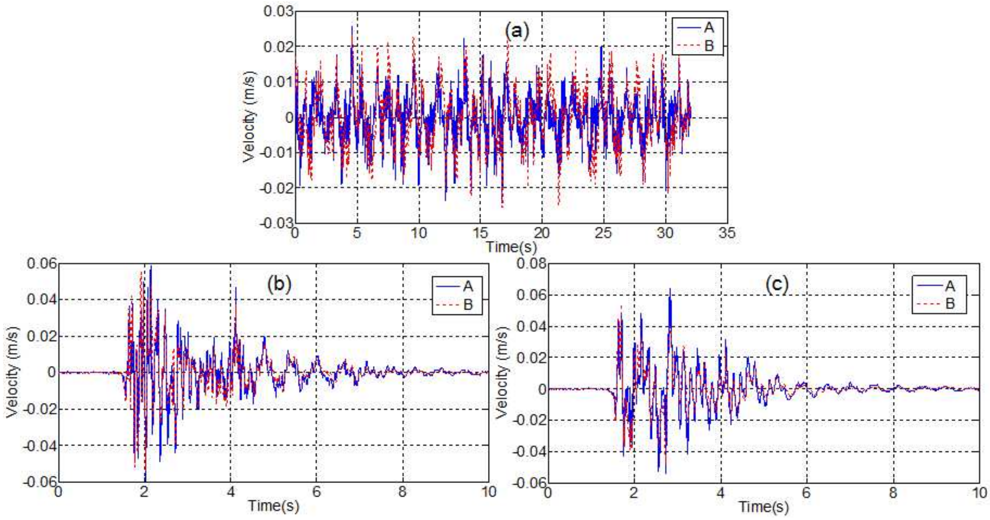

Fig. 9 Typical structural vibration velocities: (a) White noise excitation; (b) EI Centro earthquake; (c) Taft earthquake

Discussion and Conclusion

Case studies of using two laser Doppler vibrometry systems for dynamic testing were presented in this paper. Applications of the LDVs were demonstrated for both laboratory experiments and field testing. Vibration velocity response time histories of various scales of structural elements, including the prestressed reaction wall, the viaduct bridge deck and pier, the scale-down high-rise building model, and steel beams, were remotely measured. Frequency domain data of these measurements provide modal behaviour information of these structures. Through the testing, it is shown that the LDV is capable of performing remote, non-intrusive measurements of structural vibrations. However, what the laser vibrometer collects is the vibration of the target structure relative to the laser device. Noise from the laser head itself vibration may affect the validity of using the measurement as the target structure vibration. It is proposed to estimate the laser device vibration during a dynamic testing to ensure the measurements from the LDV are structural vibrations that the engineer expects to measure. It is suggested to mount a sensor on or inside the laser head to measure the laser device vibration and use the measurement to compensate the laser head motion if necessary.

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