LASER-BASED VIBRATION MEASUREMENT USING DIFFRACTIVE BEAM SAMPLERS FOR VIBRATION MONITORING OF LARGE-SCALE BRIDGES

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Abstract - This paper introduces an innovative design for a laser-based apparatus employing diffractive beam sampling technology, with the primary purpose of characterizing vibration frequencies induced within large-scale bridges. The functioning principle of the device hinges upon its ability to discern minute alterations in the relative positions of a subset of the laser beam, resulting from the oscillatory behavior of a laser pendulum mechanism. The captured dynamic variations are seamlessly integrated into a real-time monitoring framework through the utilization of an adept image sensor, complemented by sophisticated software functionalities. Noteworthy for its amalgamation of straightforward implementation and remarkable precision, the proposed methodology stands as a potent instrument poised to ensure the secure and robust surveillance of the structural well-being of large-scale bridges.

Key words - Laser-based vibration measurement; diffractive beam sampler; large-scale bridges; laser pendulum; image sensor.

1. Introduction

Structural health monitoring for infrastructures is considered as important as health monitoring for humans. The hidden fault-induced collapses result in severe damage to both humans and property. Most of these accidents come from poor surveillance of structural health. However, in some specific constructions, regular surveillance is very challenging for many reasons. The difficulty may come from the location of the construction. Some buildings are in a very harsh environment making them a huge challenge for the devices as well as inspectors to approach. In addition, some infrastructure possesses very sophisticated geometrical design, like cable-stayed bridges. This also makes frequent surveillance burdensome.

Several studies have been conducted to overcome the mentioned problems in structural health monitoring [1-5]. Especially, the high-tech solutions of failure-induced vibration analysis have been proposed in both theory and experiment. The striking feature of these techniques is the fact that they employ laser-based devices. Particularly, they can be laser Doppler vibrometers [6-8] or fiber optics-based sensors [9-11]. Nevertheless, in this case, the device is demonstrated not to be very susceptible to the vibration of the construction where they are located. Moreover, these devices are very complicated to implement. Hence, they are not appropriate for long-term usage and thus cannot fulfill frequent surveillance of structural health [12].

In this paper, a design of a precise and robust laser vibrometer for structural health monitoring is proposed. The device combines a miniaturized laser system with a physical pendulum to characterize the fault-induced vibration of constructions. The laser system includes a laser diode, a diffractive beam sampler, and an image sensor. The laser source and diffractive beam sampler are tied to the pendulum. When there exist hidden failures inside a structure, the failure-induced vibration frequencies can be detected by the variation of sampled fraction beam positions on an image sensor. These optical elements are demonstrated to be very simple to implement with image sensor software. This device promises to provide a safe and robust way to monitor structural health in giant infrastructures.

When a construction contains hidden structural faults, it will generate unexpected vibrations under trivial external forces such as wind and seismic vibrations. The levels of these vibrations are expressed through the amplitude of each frequency mode. By installing a pendulum inside a structure, the structural vibration based on the vibration of this pendulum can be monitored. The vibration frequencies of the pendulum include its natural frequency and the vibration frequencies of the structure. However, because the failure-induced vibrations are typically very small, one cannot recognize these vibrations by just observing the pendulum with one's naked eyes. In this case, the highly sensitive image sensor should be installed, and a laser source should be tied to the pendulum to resolve the variation of the pendulum during the vibration of the structure. In the following section, a unique laser-based vibrometer is designed to precisely resolve the vibration of the pendulum and thus characterize the vibration frequencies of the monitored construction.

2. Design of laser-based vibrometer

The design of the device is described in Figure 1. It includes a long solid bar with rails tied to a measured point. There is a movable mass that can slide freely through the bar. This mass relates to one end of the bar through a robotic arm composed of two solid rods. The mass is then connected with a laser diode and a diffractive beam sampler that splits the laser into sampled beams at a specific angle.

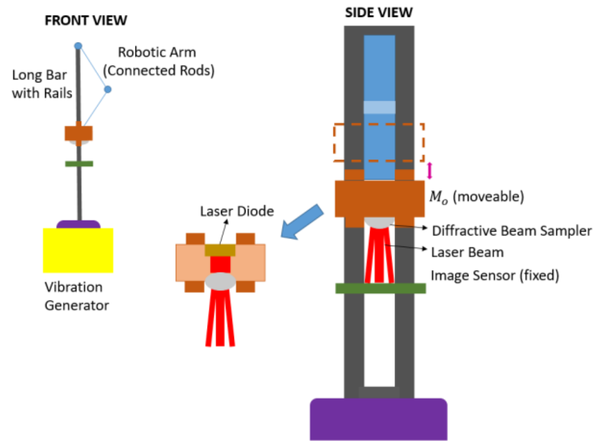

Figure 1. *Schematic of the experimental setup*

Below the mass that it cannot reach, there is an image sensor that can obtain the image of the beam spot from the laser diode. As explained in the previous section, when the structure vibrates, the solid long bar will also vibrate and induce the alternating slide of the mass. The position variation of the mass leads to the position variation of beam spots on the image sensor. The real-time analysis of this variation can produce the vibration frequencies of the solid long bar as well as those of the structure.

A diffractive beam sampler splits the incident collimated laser beam into several sampled beams at specific angles based on the diffraction process. Typically, it can be a grating plate. The propagation angles are different for different grating periods. Figure 2 indicates the diffractive beam sampler used for the proposed device. The incident collimated beam is divided into several parts and only -1, 0, 1 order diffractive sampled beams are visible. The 0-order beam occupies the largest power of around 97.5 %, while -1 and 1-order beams occupy around 1%. The splitting angle α is precisely 2.07° [13, 14]. For the limited area of the optical sensor, only distance between 0 and 1 order sampled beams are monitored. The oscillation of this distance over time can be expressed as the following:

$$\Delta = \sum_{k=1}^{n} A_k \cos \omega_k t + B \cos \omega_o t, \quad (1)$$

Where, A_k and ω_k are the amplitudes and frequencies of different oscillation modes of the structure; ω_o is a natural frequency of the laser pendulum and B is an arbitrary constant.

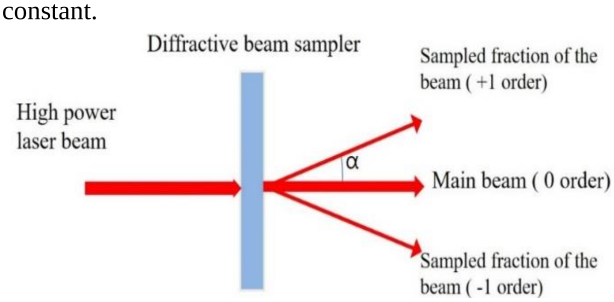

Figure 2. *Schematic diagram of a diffractive beam sampler [13]*

The image sensor as well as its software are developed uniquely to read the distance between two beam spots based on the positions of their peak intensities [15].

The peak intensities are scanned automatically on the image sensor and sent to its software. The recorded distance is in pixel units. The response time of the sensor is 0.02 s, and the pixel size is 4.5 µm. Because the image sensor can determine the distance between spots based on peak intensities, it is independent of their shapes. The speed and stability of the device can also be adjusted by tuning the threshold values, minimal spot radius, and beam blob area as filtering parameters (Figure 3). In all cases, one can always make sure that 0 and 1-order sampled beams impinge the optical sensor of the device and the software can indicate the whole image of beam spots.

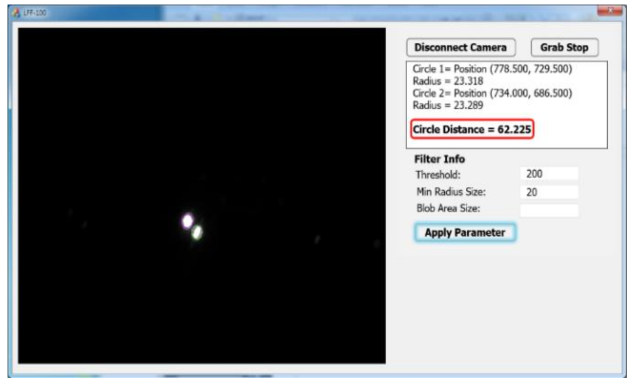

Figure 3. *Interface controlling system of image sensor software [14]*

3. Results and discussions

The simulation system is described as the schematic in Figure 2. The long solid bar experiences angular vibration using a vibration generator at the bottom. The mass carrying mentioned optical elements including a laser diode and diffractive beam sampler slides along the bar and the image sensor acquired the sampled beams. The time-dependent sampled beam spots are recorded and automatically Fourier transformed to acquire the frequency amplitude spectrum.

The friction between the mass and the long bar rails cannot be neglected for long-term usage. Thus, the comparison between vibration in friction and that in an ideal case, and the results are shown in Figures 4 and 5. Figure 4 shows the time-dependent vibration and Figure 5 indicates the frequency amplitude spectrum of the laser pendulum at an excitation signal of 4 Hz. The result shows the natural frequency of the laser pendulum of 10 Hz and the vibration mode of the long solid bar of 4 Hz. The width of the obtained frequency peak is around 0.5 Hz for 4 Hz mode and 0.25 Hz for 10 Hz mode, which correspond to the errors in time of 0.03 s and 0.0025 s. These values are well around the response time of 0.02 s of the detector. The impact of friction is revealed clearly in the time domain vibration when the erratically decreasing amplitude is observed. This friction is an inevitable artifact of environmental impact and mechanical defects during fabrication and long-term usage in harsh environments. However, the result points out that these factors do not reduce the resolution of the detection of vibration modes in amplitude spectra. In both cases (with and without friction), the spectrum indicates exactly the externally generated vibration mode and natural mode with the minima signal-to-noise ratio of approximately 100 that ensures the consistency of the device. In real measurement, one can optimize the alignment to obtain the beam spots with better shapes (more circular). This helps the sensor to detect the distance faster and more accurately.

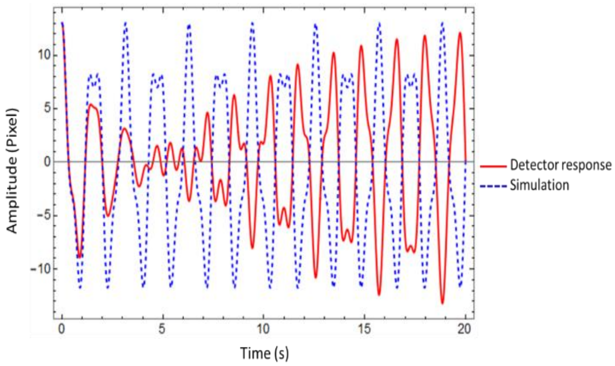

Figure 4. *Detector and simulated time domain response for 4 Hz excitation signal*

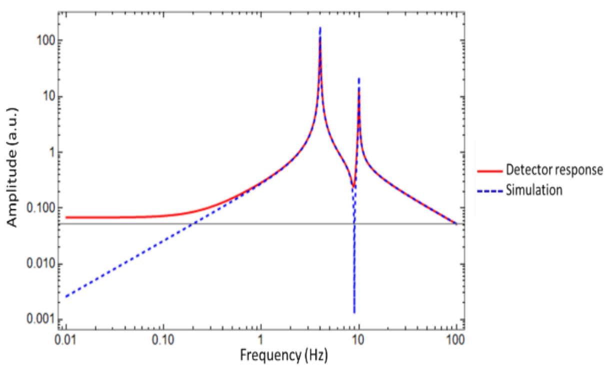

Figure 5. *Detector and simulated frequency amplitude spectrum for 4 Hz excitation signal*

4. Conclusions

This paper has presented a novel optomechanical device design that offers a precise, stable, and uncomplicated method for effectively tracking structural vibrations resulting from failures.

Through the orchestrated manipulation of an oscillating laser diode, the proposed system facilitates a comprehensive analysis of structural vibrations. Integral to the system's architecture is conventional optical components, including the incorporation of a diffractive beam sampler and a dynamically adjustable image sensor.

From the comparison between the simulation and detector response, it can be observed that the inherent friction within the system does not compromise the resolution of vibration frequency modes, thereby ensuring sustained system stability and coherence.

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