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Flyable Mirror: Airborne laser Doppler vibrometer for large engineering structures

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Abstract. Large engineering structures are subjected to extreme loads that may lead to early damage and hazards for the national economy and public safety. The laser Doppler vibrometer (LDV) has been widely used for conducting ambient vibration testing (AVT) of large structures, such as towers and historical buildings. Its superior sensitivity and the possibility to measure at hard-to-reach locations make it a versatile tool. However, two challenges limit LDV performance significantly for AVTs of large structures: (a) optically inaccessible surfaces in which the LDV beam cannot reach the spot or the beam has a flat incline; and (b) significant optical deficiencies in long-range measurements due to air turbulence and laser speckle effects. In this paper, we report the development progress of a new LDV-based measurement system, Flyable Mirror. This system consists of a commercial LDV with novel noise suppression means at the ground and an optical beam steering unit (a mirror) carried by an unmanned aerial vehicle. Several preliminary experiments were conducted to build and test the first airborne LDV. Flyable Mirror will enable new insights into monitoring structural-aging mechanisms for which ground-mounted LDVs cannot be used.

1. Introduction

Large historical buildings are examples of structures that are subjected to extreme wind loads, and their design life is usually extended beyond its nominal limit for economic and heritage reasons [1–4]. This may lead to safety-critical conditions, as shown by the sudden collapse of the Civic Tower in Pavia, Italy in 1989 [4] and of the bell tower of St. Magdalena in Goch, Germany in 1993 [3]. Such damage risks can be minimized by increasing the level of knowledge of the structural properties and their aging performance using structural health monitoring techniques, such as ambient and forced testing methods [5]. This paper focuses on ambient vibration testing (AVT) because applying external excitations to most large structures is either forbidden (e.g., for historical structures) or inessential due to significant ambient excitations [5, 6]. AVT is a dynamic characterization method for structures that are excited by significant ambient loads, such as wind forces and nearby traffic activities. It does not interfere with the normal use of the structure and includes a wide band of excitation frequencies that are sufficient for identifying significant modal parameters. A typical AVT practice is installing tens to hundreds of accelerometers at critical points in the structure [6, 7]. However, in addition to hardware complexity and

the high cost of this practice, it is difficult to mount accelerometers on all critical zones, particularly on large structures with many inaccessible zones.
Laser Doppler vibrometry is a promising sensing technology for conducting efficient and fast AVT of many types of large structures [8]. It enables the noncontact measurement of distant surfaces by measuring the Doppler frequency shift of a reflected laser beam due to the movement of the target surface. The technical feasibility of its use for monitoring civil and historical structures has been intensively reviewed in the lab and in situ by many research projects [8–11]. It has been shown that structural damage and cracks are practically detectable by signal features from data obtained from a laser Doppler vibrometer (LDV) under ambient excitation conditions.

Recently, several successful case studies used an LDV to measure the dynamic responses of large structures. Hu et al. [8] utilized a long-range LDV to monitor the lateral displacement feature of a skyscraper at a distance of 245 m. This feature showed an effective performance criterion for preventing damage to the brittle building elements of the skyscraper. Esposito et al. [9] proposed an arrangement comparison using an LDV carried by an industrial lifter (Figure 1, left) to increase the LDV incident angle and signal strength. Gioffré et al. [10] utilized an LDV and a radio frequency interferometer to measure the dynamic responses of inaccessible tie rods on a monumental temple. The LDV measurements were used to estimate the tensile axial force in the tie rods, which reflects the structural integrity and health. Although this research was conducted on a large historical structure, the LDV was utilized only for a small structural volume. Liarakos [11] presented a case study for damage detection on a masonry structure under ambient excitation using a scanning LDV, as shown in Figure 1 (right). The Fourier amplitudes for the LDV displacements clearly indicate an abnormal stress concentration in a potential damage zone.

Figure 1. (Right) Laser Doppler vibrometer-based ambient vibration testing for a masonry structure, including a color map for dynamic displacement distribution [11]. A laser Doppler vibrometer is carried by a lifter to monitor a large building [9].

The state of the art shows the restricted applicability of long-range LDVs for the dynamic characterization of large structures due to partially inaccessible surfaces and geometric restrictions for the measurement arrangement. The LDV's laser beam should be directed as perpendicularly as possible to the surfaces to measure the out-of-plane vibration from the reflective beam with sufficient signal strength. However, in previous studies, the LDV was located on the ground at a large distance approximately equal to the height of the target scanning point. With this distance, the LDV's signal strength is significantly reduced by the beam tilt angle, which has a maximum value of 45° or 50% loss of out-of-plane signal strength.

To overcome the aforementioned challenges, a new LDV-based measurement system, Flyable Mirror, is introduced and discussed in in this paper.

2. Flyable Mirror concept

The aim of Flyable Mirror is to enhance the applicability of LDVs for monitoring remote irregular surfaces, as shown in Figure 2. These kinds of surfaces are common in many aerospace and civil structures. The principles of Flyable Mirror were first introduced by Ismail [12] and further investigated in [13, 14]. It is a reflective mirror attached to a drone for the redirection of the LDV beam to a remote and inaccessible irregular surface. Reflective mirrors are typically thin, light sheets that require microdrones with payload capacities of a few hundred grams. A fully airborne LDV carried by a drone has great potential for remote vibration monitoring of remote irregular surfaces. However, there are many complicated problems, including the need for aircraft noise cancelation, which affects multiple internal elements of the LDV unit [15].

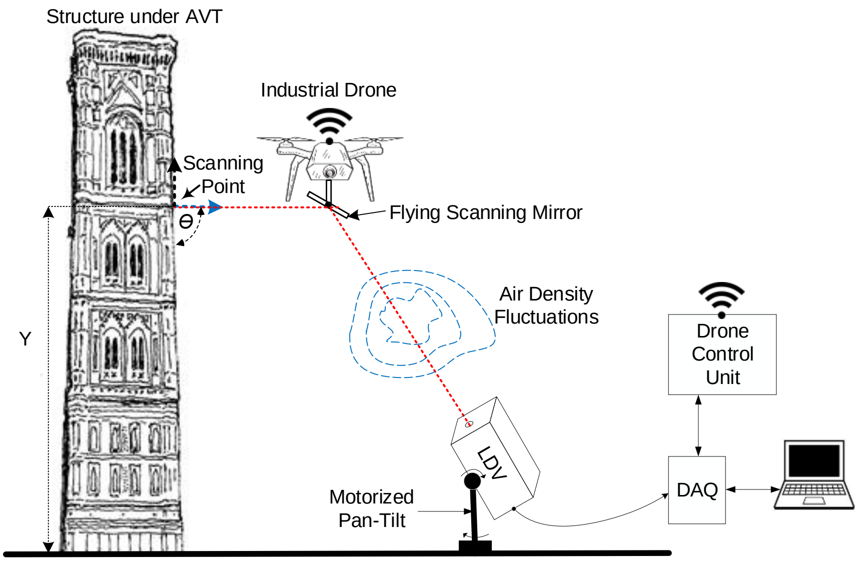


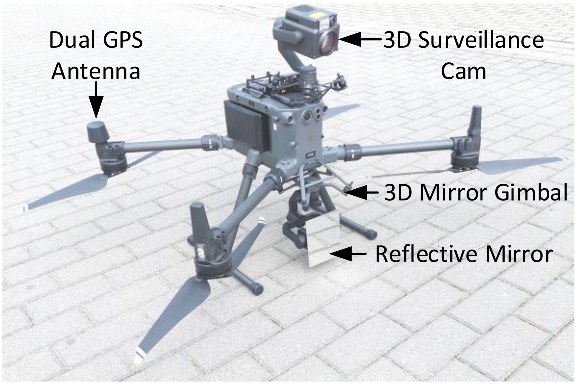
Figure 2. Conceptual design of the Flyable Mirror assembly, including a ground LDV and a reflective mirror installed on a drone. The target structure is under ambient vibration testing.

3. Experiment setup

The arrangement of the first field experiment is shown in Figure 3 (right). A reference vibration excitation from an eccentric shaker was remotely measured by the Flyable Mirror setup and a conventional accelerometer attached directly to the shaker table. The objective of this experiment was to compare the vibration measurements from the Flyable Mirror setup with those from the accelerometer.

The Flyable Mirror setup consisted of a commercial LDV, model Qtec® from Polytec [16], and a modified industrial drone based on DJI M300 with real-time kinematic (RTK) GPS positioning features. RTK was crucial for such an application to provide ± 2 cm positioning accuracy. The drone had a motorized mirror gimbal mounted on the bottom side, as shown in Figure 3 (left). The shaker provided multi-excitation frequencies in the range of 1–140 Hz. A seismic accelerometer (model KS48C [17]) was used to monitor the shaker's vibration. Both the accelerometer and the LDV data were connected to the National Instrument data question system with a sampling frequency of 50 kHz.

Photographs of the first Flyable Mirror experiment are shown in Figure 4. In this experiment, the drone position was manually controlled with respect to the shaker position, while the next experiments included fully automatic drone positioning.



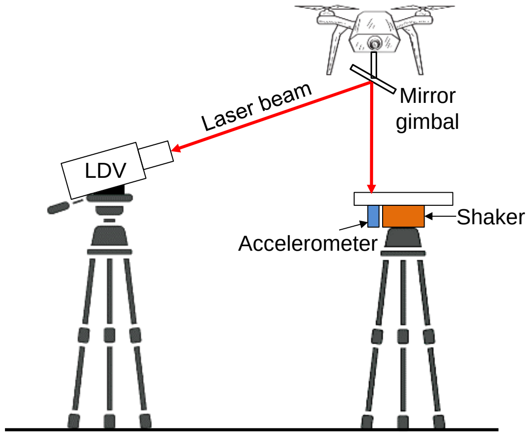


Figure 3. Picture of the drone payloads (left) and schematic of the test setup (right).

Figure 4. Photographs of the first Flyable Mirror experiment. Drone movement was executed manually. The laser Doppler vibrometer beam on the drone mirror is visible in the right photograph.

4. Results and discussion

Assuming that the measurement by the accelerometer is not affected by drone movements and vibrations, the experiment must reveal the disturbances of the measurement with a commercial single-beam LDV. Figure 5 shows four independent experiments of differently excited vibrations of the shaker. For low amplitudes (experiments 1), there was a good match between the LDV and accelerometer measurements. When the vibration amplitudes were increased (via the shaker controller) in experiment 2 and 3, the LDV measurements showed a varying vibration spectrum due to unstable conditions. Comparing the accelerometer and LDV measurements revealed that the single-beam LDV measurement suffers additional disturbances, such as instability of the measurement position, which seems to be more critical for large amplitudes. This also includes positioning errors due to the manual control of the drone during wind gusts during the experiment. Experiment 4 shows a significant mismatch between LDV and the accelerometer data also vibration amplitudes were small. We need to examine the quality of the drone positioning errors using only LDV data (in future, the GPS data will be used) to understand this behavior.

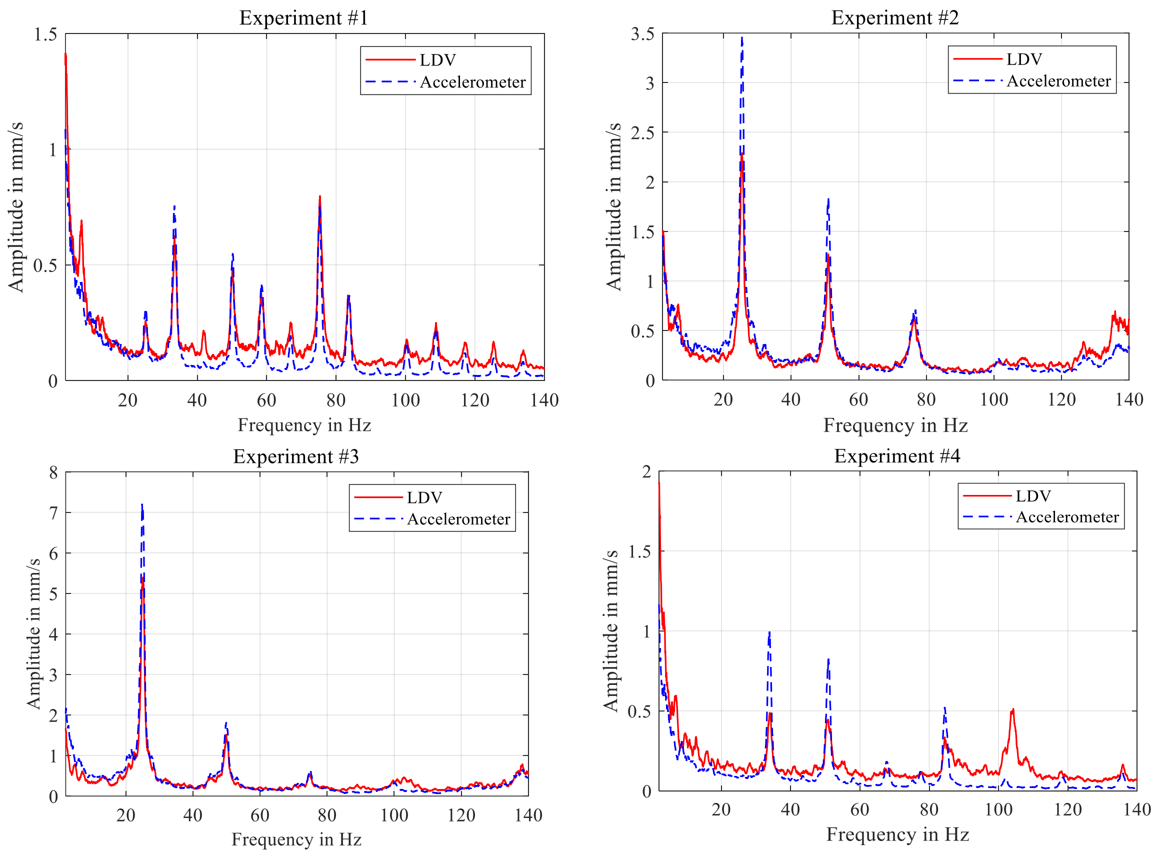


Figure 5. Vibration measurements (resolution bandwidth: 0.9 Hz) with a LDV and an accelerometer acquired from the same target (eccentric shaker in Figure 3).

The quality of the LDV measurements is examined by estimating the spectral entropy for each experiment. Spectral entropy of a signal has a value between 0 to 1 and it is a measure for its complexity or whiteness [18]. From a previous research, we found that the drone positioning errors induce unsteady state transients for LDV data because the laser beam is not focused on a single point [19]. Such transients can be quantified by their spectral entropy levels. Matlab® function "pentropy" was used for estimating spectral entropy of LDV data for each experiment. Spectral entropy for the accelerometer data is almost stable with an average value of 0.7. We used this value as a threshold to study LDV data. In Figure 6, there are two spectral entropy examples for experiments 1 and 4. We selected these experiments in Figure 5 because they have low vibration amplitudes but different spectrum quality. In experiment 1, about 24% of spectral entropy data is above the threshold level (0.7), while it is only 16% for experiment 4. This means that the measurement quality of experiment 1 is much higher than experiment 4. This clearly explains the results in Figure 5 for experiment 1 and 4 in which both has low vibration amplitudes but dissimilar positioning errors due to the manual drone control. The overall spectral entropy ratio for all experiments are shown in Figure 7 (left). A second source of measurement instability is shown in Figure 7 (right), in which the shaker table is tilted at large vibration amplitudes due to the low stiffness of the shaker tripod (experiment 2 and 3). In this case, the LDV measurements were slightly decreased by $\cos(\theta)$ with respect to the accelerometer measurements. There is no significant spectral entropy change in this case because the LDV signal is subjected to stable scaling rather than unsteady state transients. In the future, to identify the inclination of the target surface (e.g., the tilted shaker table), we plan to use a kind of laser-based distance measurement capability to be coaxial with an LDV beam.

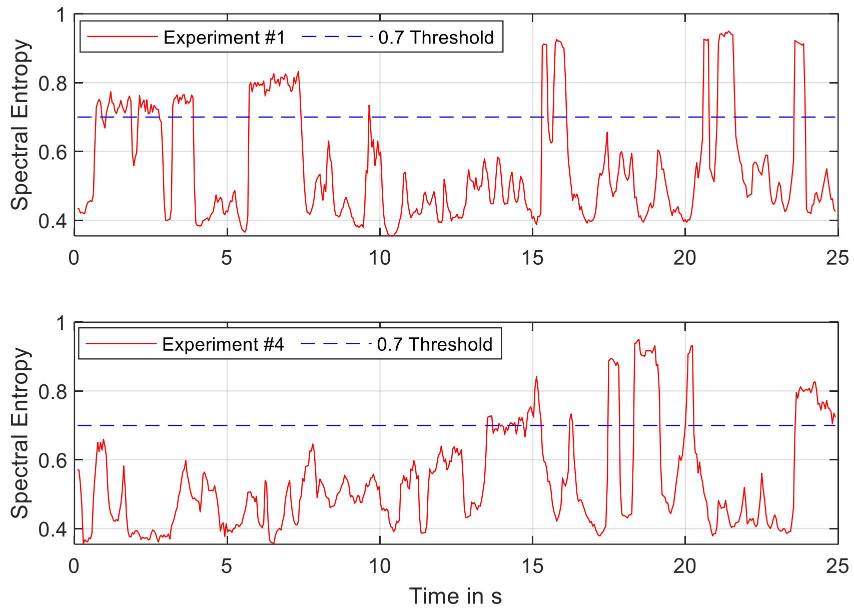


Figure 6. Examples of spectral entropy for LDV measurements for experiments 1 and 4. In experiment 1, about 24% of spectral entropy data (quality index) is above the threshold level of 0.7, while it is only 16% for experiment 4.

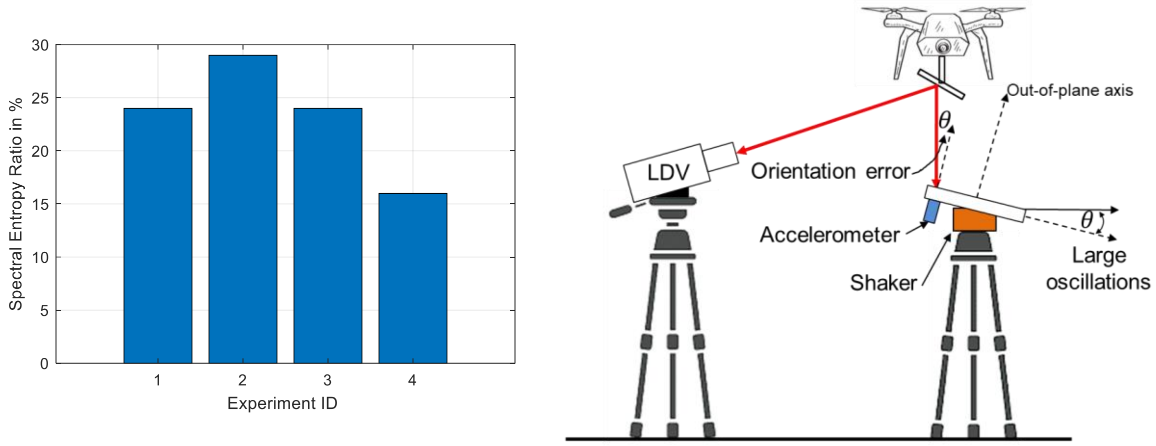


Figure 7. The spectral entropy ratios for all experiments in Figure 5 (left). Example of an unstable measurement position for the shaker table at large amplitudes.

5. Conclusion

The Flyable Mirror setup, comprising a ground-mounted LDV and a mirror attached to a drone, enables new insights for using LDV to conduct AVT of large engineering structures. The first experiment showed good performance in measuring the vibration excitation of a vertically mounted shaker for low amplitudes of less than 1 mm/s if the drone position error is not significant. The influence of the drone position error was examined using spectral entropy measure for LDV data. High positioning errors introduce short time transients in LDV data that decreasing the spectral entropy value. The proposed procedure of a Flyable Mirror for LDV was demonstrated successfully for the first time. However, for larger amplitudes and larger drone positioning errors, the measurement performance deteriorated due to the unstable position of the shaker table and the drone manual control. Investigating the influence of larger incident angles of the vibration targets using a fully automated drone are planned for future work.

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