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Vibrational characteristics of sphere model installed in wind tunnel test section†

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Abstract

The vibrational characteristics of a sphere model installed in a wind tunnel test section were quantitatively investigated using a non-contact laser vibrometer. The sphere was supported by two fine wires passing perpendicularly through the center of the model in an X-shape. Each end of the wire was fastened firmly to the frame of the test section with a secure turnbuckle. This fixation method was evaluated by laser vibrometry measurement of the vibration of the sphere and by spectral analysis. The maximum displacement of the sphere was found to be less than 30 nm with the characteristic frequency on the order of hundreds of kilohertz. The effects of the vibrational displacement and frequency of the model were negligible considering the model dimensions and the shedding frequency of the sphere wake.

Keywords: Vibrational characteristics; Laser vibrometry; Wind tunnel test; Sphere

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1. Introduction

A sphere is considered to be an idealized model of a three-dimensional axi-symmetric bluff body, which typically causes flow separation, unsteady flow, and complicated vortex shedding. Typical bluff bodies that are sphere-shaped include balloons, particles, towed sonars, bombs, oil-storage tanks, and raindrops. A sphere does not have a fixed flow separation point, since the separation point moves along the sphere surface according to the boundary layer developed there and the condition of the surrounding flow.

Because the sphere is a basic body with a great potential for various practical applications, many researchers have studied the flow around it. Most have focused on the vortex shedding phenomena, using hot-wire anemometry to measure the dominant shedding frequencies. They have also studied wake structures, using qualitative flow visualization methods [1-7].

Experimental measurement of turbulent flow around a sphere is not easy, due to several factors such as the difficulty of supporting a sphere in a wind tunnel test section, the unsteady flow field, the large area of separated flows, and the complicated, three-dimensional flow structure itself. If a sphere is towed in a towing tank, the passage must be long enough to ensure a steady target velocity. If a sphere is supported by a rear rod, the sphere wake can reattach to that rod, thereby distorting the downstream flow field [8]. Three-dimensional models supported by a magnetic suspension system in a wind tunnel test section also have been trialed [9-10].

In the present study, the vibrational characteristics of a sphere model installed in a wind tunnel test section using thin wires were examined by non-contact laser vibrometry and fast Fourier transform (FFT) analysis.

2. Experimental method

Fig. 1 is a schematic diagram of the experimental set-up for measuring the structural vibration by laser vibrometry. The dimensions of the wind tunnel test section were $6.75^L \times 0.72^W \times 0.6^H$ m^3. The free stream velocity was fixed at U_o = 2.2 m/s, where the turbulence intensity was lower than 0.08%. A sphere made of acryl and having a diameter of 75 mm was used as the test model. The sphericity of the sphere was 0.6%, and the surface uniformity was less than 0.1%. Based on the free stream velocity and the sphere diameter (d), the Reynolds number (Re) was equal to 11,000. Measurements were conducted in both the x–y and x–z planes (Fig. 1(a)). The laser vibrometer, consisting of a controller (Polytec OFV 3001) and a fiber interferometer (Polytec OFV 511), had a spatial resolution of 2 nm and a maximum sampling frequency of 40 MHz. Fig. 1(b) shows the experimental set-up for measuring the structural vibration of the sphere model.

To support the sphere in the wind tunnel, two piano wires of 0.17 mm diameter were passed perpendicularly through its center in an X-shape (Fig. 1(c)). The ends of each wire were

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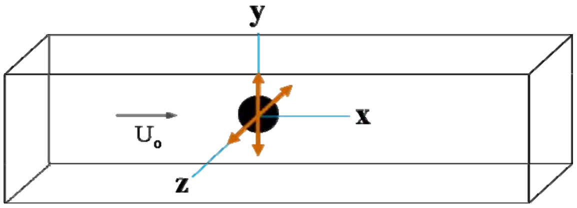
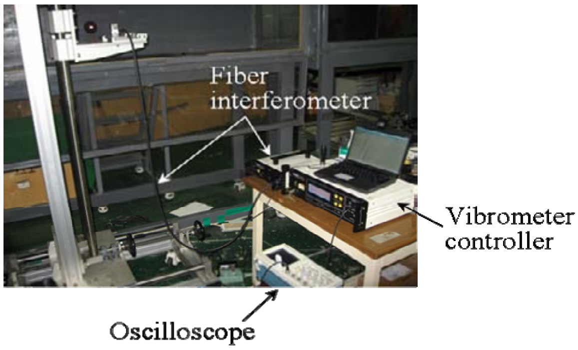


(a) Experimental coordinates



(b) Instruments for measuring model vibration

(c) Sphere installation

Fig. 1. Experimental set-up for measuring structural vibration of sphere model.

fastened firmly to the frame of the test section with a secure turnbuckle. The blockage ratio of the sphere, including the wires and frame, was about 2.3%. The sphere, installed in the center of the wind tunnel test section, showed no visible vibration in the stream-wise or cross-sectional planes with the free stream velocity applied in this study.

The method of supporting a sphere with fine piano wires has been employed by Sakamoto and Haniu [11] and Do et al. [12] in water channel tests. Cannon et al. [13] also used this method, in their case to visualize the flow around axi-symmetric bodies in a wind tunnel experiment. These investigations notwithstanding, studies specifically focusing on quantitative analysis of vibrational characteristics of a sphere models have been few.

In the present study, the structural vibration of a sphere model installed in a wind tunnel test section with fine wires was evaluated by non-contact laser vibrometry. A laser Doppler vibrometer, which functions based on the concept of optical interference, was employed. The vibrometer requires two coherent light beams having light intensities I_1 and I_2, which come to interfere with each other (Fig. 2). The resulting intensity is modulated according to the following formula [14].

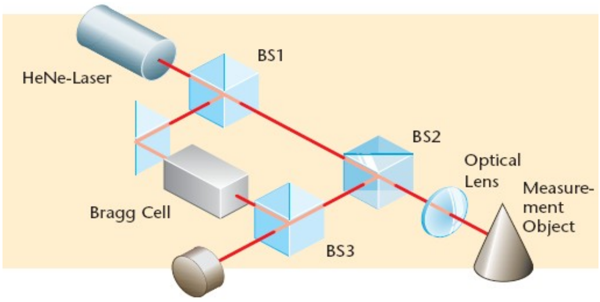


Fig. 2. Schematic diagram of laser Doppler vibrometer [14].

$$I_{tot} = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[2\pi(r_1 - r_2)/\lambda]. \quad (1)$$

In Eq. (1), λ corresponds to the wavelength of the laser beam. Because the wavelength of the reference beam I_2 was constant over time (r_2 = const), the movement of the test object [$r_1 = r(t)$] generated a dark and bright (fringe) pattern on the detector. This is typical of optical interferometry. The change in the optical path length, as a function of time, manifested itself as the Doppler frequency shift of the measurement beam.

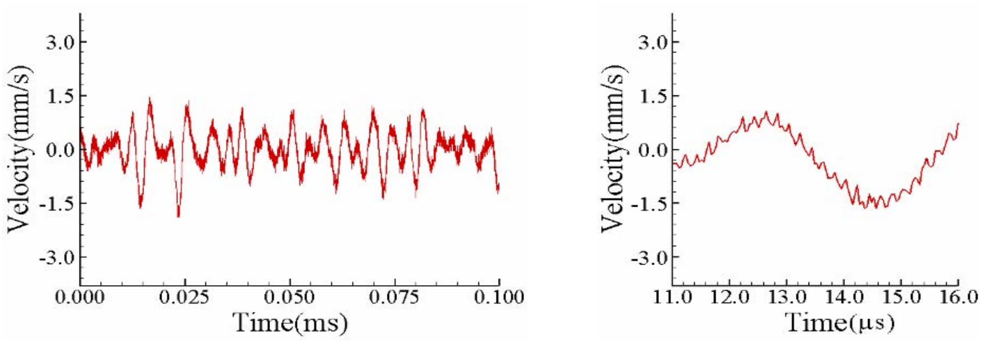
The modulation frequency of the interferometric pattern was directly proportional to the moving velocity of the object. Initially, the temporal variation of the vibrational velocity was measured at a temporal resolution of 25×10^6 - 5×10^2 Hz, and the measured time-series data were spectrally analyzed using FFT analysis to extract the dominant vibrational frequency, random vibrational frequency, and maximum vibrational displacement.

3. Results and discussion

Quantitative information on the structural vibration of the sphere model was obtained experimentally. Fig. 3 shows the variation of the dominant z-directional vibration velocity as a function of acquisition time at a sampling frequency of 25 MHz. Fig. 3(b) is a magnified view of a typical cyclic variation of the vibrational velocity. The maximum velocity is –1.6 mm/s, and the time-averaged period is about 3.9 µs. If the structural vibration occurs at this maximum velocity over the entire period, the maximum vibrational displacement (VD_{max}) falls to less than 6 nm.

Fig. 4 plots the power spectral density (PSD) of the z-directional vibration velocity signal, obtained by FFT analysis of the time-series data. Three peaks can be seen in Fig. 4(a). Among them is the dominant frequency at which the model vibration occurs in the z-direction, f_v = 256 kHz. The sectional magnified view of the sphere at low frequency, Fig. 4(c), does not show any peak, implying that there is no dominant vibration in the z-direction in this low-frequency range.

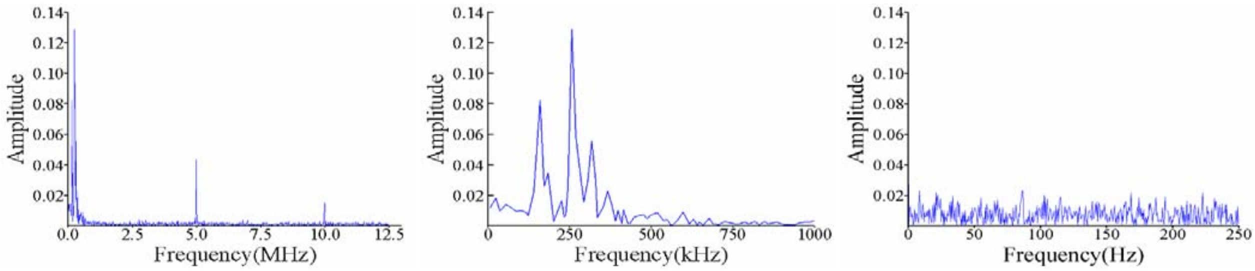
Figs. 5 and 6 represent the vibrational characteristics of the sphere model in the y-direction. The maximum displacement in the y-direction is smaller than 11 nm, and the dominant frequency is about f_v = 171 kHz.



(a) Vibrational velocity signal

(b) Magnified signal in 5 μs

Fig. 3. Variation of z-directional vibration velocity.

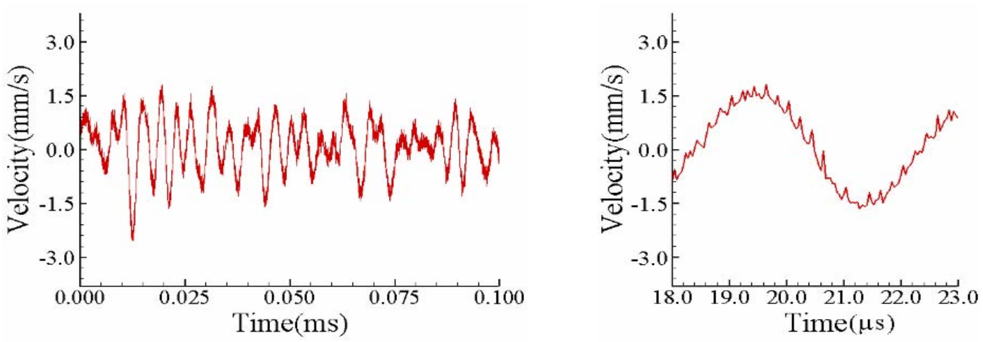


(a) Full range

(b) Within 1,000 kHz

(c) Within 250 Hz

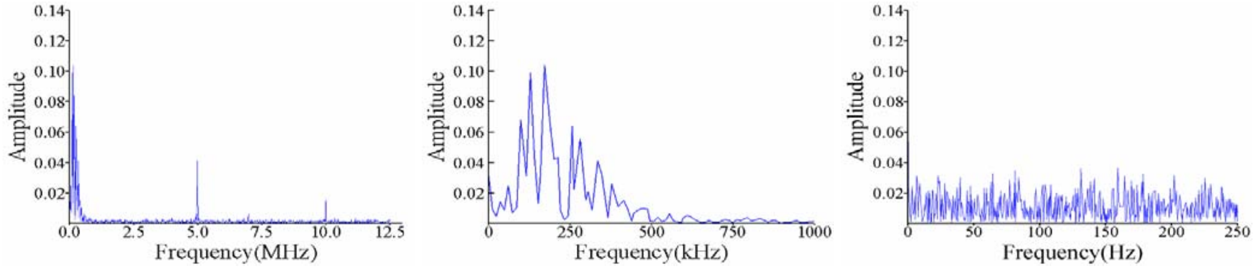
Fig. 4. Power spectral density (PSD) of z-directional vibration signal.



(a) Vibrational velocity signal

(b) Magnified signal in 5 μs

Fig. 5. Variation of y-directional vibration velocity.

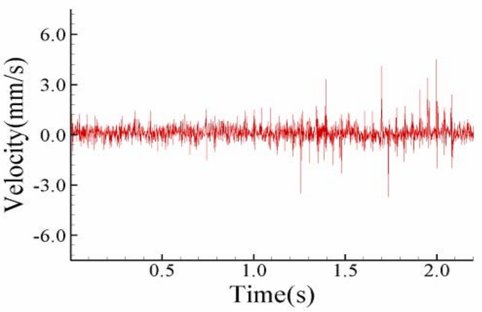


(a) Full range

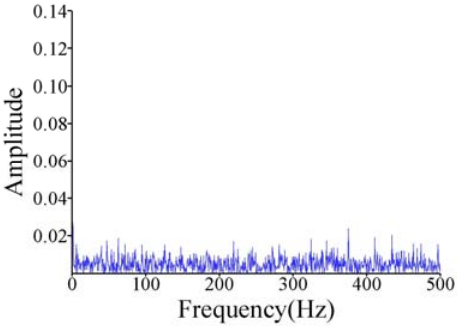
(b) Within 1,000 kHz

(c) Within 250 Hz

Fig. 6. Power spectral density (PSD) of y-directional vibration signal.



(a) Vibrational velocity



(b) Power spectral density (PSD)

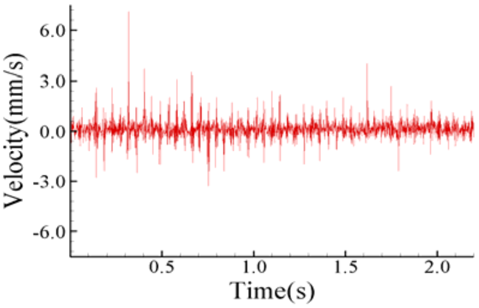
Fig. 7. Characteristics of random vibration in z-direction.

In investigating the maximum vibrational displacement, the random vibrational characteristics were examined. Fig. 7 shows the random vibration in the z-direction, which was acquired at a sampling rate of 1 kHz over 2.2 s. During this long time span, the maximum vibrational velocity occurred randomly in the 3-5 mm/s range (Fig. 7(a)). If the vibration occurred at this maximum velocity on the characteristic time scale, the maximum random vibrational displacement would be less than 20 nm. Further, no peak was observed (see Fig. 7(b)), indicating that the vibrational characteristics were random and irregular. The general pattern of random vibration in the y-direction was very similar to that in the z-direction. The maximum random vibrational displacement in the y-direction was less than 30 nm (Fig. 8).

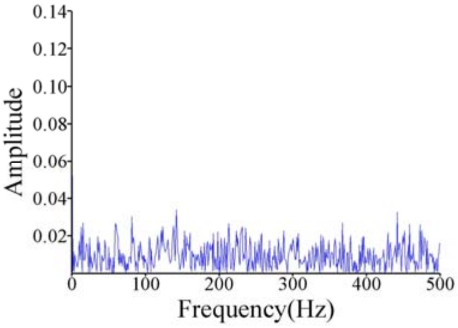
Table 1 summarizes the dominant vibrational frequency and maximum displacements of the sphere model in the z-and y-directions. Considering that the vortex shedding frequency of the same sphere model in the study by Jang and Lee [7] was less than 1 Hz with a sphere diameter of 75 mm, we can conclude that the effects of vibration on wake flow is negligible. The order of magnitude in the model vibrational frequency and displacement was almost irrelevant. In addition, non-even tension in supporting wires can influence vibrational characteristics. The quantitative measurements obtained in the present study included that effect, and subsequent repeated measurements showed similar results.

Table 1. Dominant vibrational frequency and maximum displacement.

Direction	Dominant vibration		Random vibration	
	Frequency	Maximum displacement	Frequency	Maximum displacement
z	256 kHz	6 nm	·	20 nm
y	171 kHz	11 nm	·	30 nm



(a) Vibrational velocity



(b) Power spectral density (PSD)

Fig. 8. Characteristics of random vibration in y-direction.

4. Conclusions

A method of installing a three-dimensional sphere model was verified by measuring dominant and random vibrations using non-contact laser vibrometry and spectral analysis. The sphere model was supported in the center of the wind tunnel test section by two fine wires passed perpendicularly through the center of the sphere in an X-shape. Each of the four ends of the wire was firmly fastened to the frame of the test section using a turnbuckle.

The maximum vibrational displacement of the sphere model was less than 30 nm with characteristic frequency on the order of hundreds of kilohertz. The effects of the sphere model vibrational displacement and the dominant frequency on the sphere wake were quantitatively measured and analyzed.

These experimental results, providing useful experimental data for validation of numerical simulations, can contribute to a basic understanding of wake flow around a three-dimensional bluff body.

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