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Effects of tube system and data correction for fluctuating pressure test in wind tunnel

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Abstract The accuracy of fluctuating pressure test in wind tunnel is affected by the tube system. By employing contradistinctive experimental method, systematic study was conducted to investigate the effects of the tube system on fluctuating pressure. The analyzed tube system parameters include tube length, inside diameter, curvature, deflection angle, thickness, material, restrictor length, restrictor inside diameter, and restrictor place. It is found that all the tube system parameters mentioned above except tube curvature have non-negligible effects on fluctuating pressure. Based on the research results, test methods were presented for the fluctuating pressure measurement in low-speed wind tunnel, which can obviously improve the data accuracy but not lose test efficiency. The effectiveness of the method is verified by the wind tunnel test.

1. Introduction

The fluctuating pressure test in wind tunnel is the main approach to gain the unsteady aerodynamic loads. In low-speed wind tunnel tests, the dynamic pressure sensor sometimes cannot be placed on the model surface directly because of the size, especially for the thin model such as the control plane of the aircraft. In this situation, the sensor is commonly placed inside the model, and a tube system is used to connect the pressure measurement point and the sensor.[1] In this way of measurement, fluctuating pressure has been distorted while transferred to the sensor by the tube system,[2] which leads to a great reduction of data accuracy. To solve this problem, the first step is to analyze the relationship between fluctuating pressure and parameters of the tube system, such as length, inside diameter, curvature, deflection angle, thickness, and material.

The effects of the tube system on fluctuating pressure can be described by the Frequency Response Function (FRF) of the tube system,[3] which is the ratio of the pressure at the inlet and outlet in frequency domain. Bergh and Tijdeman[4] derived the theoretical formulas of FRF. It can also be obtained by the experiment. The FRFs of different tube systems were analyzed[5–16] by the theoretical or experimental method, and the tube system design method was established based on the

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optimistic algorithm and restrictor.[17–22] According to the design method, the tube system is divided into several sections, and the length and inside diameter of every section are calculated by optimization algorithm. The short section with small inside diameter is always called restrictor. The designed tube system could remarkably improve the accuracy of magnitude of fluctuation pressure.

In the engineering application, some shortcomings are found for the tube system optimization design method. First, in the FRF theoretical formulation and optimization design method mentioned above, only two parameters—tube length and inside diameter—can be considered. But in the practice of wind tunnel test, other tube parameters may dramatically affect fluctuating pressure, such as tube curvature, deflection angle, thickness, and material. Second, the optimization design method for the tube system may enlarge the error of phase, though it could improve the accuracy of magnitude. The reason is that the magnitude of FRF is chosen as the optimization objective but the phase is not concerned by the optimization design method. It will have no problem if every single channel of fluctuating pressure is analyzed independently. If the relativity between several channels is concerned, the phase error leads to an absolutely wrong result.[23,24] For example, when the dynamic load on the control plane is calculated through surface integral of fluctuating pressure, the accuracy of the result is greatly dependent on the phase of fluctuating pressure. Third, the optimization design method for the tube system could only be effective in a limit frequency range, and the range is proportional to the complexity of the tube system. Fourth, the tube system designed by the optimization method is always so complex that it is difficult to manufacture and a non-ignorable error may be induced between the ideal results and actual measurements.[19]

In this paper, systematic study is conducted to investigate the effects of tube system parameters on fluctuating pressure by contradistinctive experimental method. The analyzed tube system parameters include tube length, inside diameter, curvature, deflection angle, thickness, material, restrictor length, restrictor inside diameter, and restrictor place. Then in order to eliminate the effects of the tube system and improve the data accuracy, test methods are presented for the fluctuating pressure measurement in low-speed wind tunnel. The results of the wind tunnel test are given to verify the effectiveness of the methods.

2. Methods for contradistinctive experiment

In order to analyze the difference between the pressure collected with and without the tube system, two Pressure Measurement Points (PMP) (denoted as PMP-1 and PMP-2) with the same pressure are set at first. PMP-1 is connected to a dynamic pressure sensor (denoted as Sensor-1) directly, while PMP-2 is connected to a dynamic pressure sensor (named Sensor-2) by a tube system. The difference between the signals collected by the two sensors may reflect the effect of the tube system on fluctuating pressure.

In the experiment, the two small holes on the organic glass plate are used to form PMP-1 and PMP-2, which is verified by having the same pressure. The results of the verifying experiment are presented later in this paper. A loud speaker is used to create fluctuating pressure. The schematic diagram of the contradistinctive experiment is shown in Fig. 1. Fluctuating pressure signals are collected and analyzed by ENDEVCO 8510B-1 dynamic pressure sensor and LDS-Dactron Foucs Ⅱ dynamic analyzer. The main parameters of the 8510B-1 sensor are as follows: measuring range of 0–1 psi (1 psi = 6894.76 Pa), sensitivity of 200 mV/psi, and resonance frequency of 55 kHz.

The swept frequency excitation in range of 0–165 Hz is applied to generate fluctuating pressure. The signals of Sensor-1 and Sensor-2 are collected synchronously at sampling rate of 375 Hz for 4096 points. These two pressure signals collected by Sensor-1 and Sensor-2 are denoted as $p_1(t)$ and $p_2(t)$. Their Fourier transform are denoted as $P_1(f)$ and $P_2(f)$ correspondingly. In the symbols, t represents time, and f represents frequency.

The FRF of the tube system is provided as follows:

$$H_{2,1}(f) = \frac{P_2(f)}{P_1(f)} \tag{1}$$

Twenty time average is used to improve the smoothness of the FRF. The analyzing frequency is limited in range of 0–165 Hz.

The magnitude and phase of FRF can reflect the effects of the tube system on fluctuating pressure. If $|H_{2,1}(f)|$ (magnitude of FRF) is greater than 1, it means that the magnitude of fluctuating pressure has been amplified. On the contrary, the magnitude of fluctuating pressure has been minified. In theory, $\phi_{2,1}(f)$ (phase of FRF) is less than 0 rad, which means that the pressure signal is delayed by the tube system. Absolute phase is denoted as $|\phi_{2,1}(f)|$. The effects of the tube system are small if $|H_{2,1}(f)|$ and $\phi_{2,1}(f)$ are close to 1 and 0 rad correspondingly. On the contrary, the effects are great.

PMP-1 and PMP-2 are desired to have the same pressure. The conformity is verified by the experiment, in which PMP-1 and PMP-2 are directly connected to Sensor-1 and Sensor-2 respectively without the tube system. The results of verifying experiment are given in Figs. 2 and 3. Fig. 2 shows $|H_{2,1}(f)|$, $\phi_{2,1}(f)$ and $\mathrm{Coh}_{2,1}(f)$ (coherence function between the two pressure signals[25]). Fig. 3 shows the comparison between signals collected by Sensor-1 and Sensor-2 in time domain. According to the results, $|H_{2,1}(f)|$ and $\mathrm{Coh}_{2,1}(f)$ are very near to 1, and $\phi_{2,1}(f)$ is very near to 0 rad. In conclusion, the conformity is perfect, and the two small holes on the organic glass plate can be used as PMP-1 and PMP-2 with the same pressure.

3. Effects of various parameters on FRF

3.1. Effects of tube length

By the contradistinctive experiment method, FRFs are obtained for tubes with different length (denoted as L). The PolyVinyl Chloride (PVC) tube with 1.2 mm inside diameter and 2.2 mm outside diameter (denoted as 1.2 × 2.2) is used in the experiment. This type of tube is often used in the low-speed wind tunnel for fluctuating pressure test. This type of tube is used as the default type later in this paper if not specially specified.

For tubes with different length, the magnitude and phase of FRF are shown in Figs. 4 and 5. According to the results, the length of tube has great effects on the magnitude and phase of FRF. As length increases, there are decreases in terms of the

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