Journal of Wind Engineering & Industrial Aerodynamics 168 (2017) 141–151

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Experimental extraction of indicial lift response function by an iterative correction method

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ARTICLE INFO

Keywords:
Correction method
Indicial response function
Wind tunnel experiment

ABSTRACT

In this study, the wind tunnel experiment is conducted to extract the indicial lift response functions of an airfoil and a flat plate. Since the step-function gust is almost impossible to be simulated, an iterative correction method is proposed and proved to be capable of extraction of the indicial response function from the response of an imperfect step-function excitation. The performance of this method is analytically evaluated. With the wavelet analysis, applied to remove noise in the response, and the correction method proposed, the indicial lift response function is obtained experimentally.

1. Introduction

Transient aerodynamic forces exerted on a structure induced by a gust might differ significantly from the quasi-steady ones. Taneda (1972) studied the transient lift of an abruptly started elliptic cylinder in a water tank test and an obvious peak was found right after the starting. Nomura et al. (1999) investigated the transient drag acting on a square cylinder subjected to a sudden change of mainstream wind speed, and reported that the trends of measured drag and calculated one compared well if a term, proportional to the wind speed acceleration, was added to the quasi-steady drag in the calculation. Takeuchi and Maeda (2013) studied the unsteady drag and lateral forces on an elliptic cylinder under a short-rise-time gust in a wind tunnel test. It was proposed that the overshoot coefficient be determined by the expanded non-dimensional rise time of the gust. Similar transient phenomena may occur not only in cylindrical structures but also in a three dimensional vehicle. Volpe et al. (2014) investigated the yaw moment and lateral force coefficients of a simplified car model by means of a wind tunnel test, and reported that overshoot occurred for both coefficients.

To study the transient aerodynamic response of a cylindrical structure, the frequency domain method has been predominantly conducted, but an alternative time domain method can also be applied. Regarding experimental studies by the time domain method, the response of a model subjected to the step-function excitation is measured, from which the indicial response function is extracted. The function characterises the transient response to the unit-step function excitation. In the airfoil theory, the unsteady aerodynamic force acting on a thin airfoil, either due to the unsteady motion of the airfoil or a variable gust, can be obtained based on the indicial response function. The step-function excitation refers to the excitation that grows abruptly from the dormant state to a state with a certain stable value. However, a perfect step-function excitation is almost impossible to be experimentally generated. That is because the excitation rise duration always exists physically for the realization of the step-function excitation. For example, the excitation in this study is the gust. The ideal step-function gust and the real gust generated in a wind tunnel are shown in Fig. 1. The ideal step-function gust is shown by Fig. 1(a), where the moving path and speed of the model is shown by the arrow and denoted by U. The gust is blowing along the direction vertical to the moving path of model. The profile of the gust is a step-function and no gust-rise duration exists between the gust-free area and the uniform gust area. In contrast, the real gust generated in the wind tunnel is shown in Fig. 1(b). The gust-rise duration, denoted as D_r, always exists between the gust-free area and the uniform gust area. Therefore, it is usually an imperfect step-function gust that is generated in the experiment. The term 'imperfect' refers in this study to the excitation rise duration, D_r, which is physically inevitable for the realization of an abrupt step-input excitation.

Due to the difficulty in generation of a step-function excitation, the excitation with a small excitation rise duration, which is close to the step-function but not a perfect one, was considered in previous studies as adequate in order to experimentally obtain an indicial response function. In the study of Yoshimura et al. (1985), a sharp-edged gust approximated

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http://dx.doi.org/10.1016/j.jweia.2017.05.009
Received 7 April 2016; Received in revised form 18 March 2017; Accepted 21 May 2017

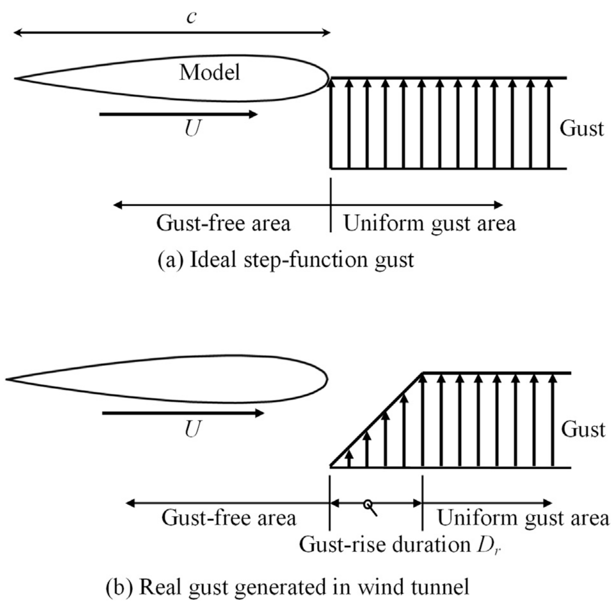

Fig. 1. Ideal gust and generated gust.

to the step-function was simulated by a towing water tank and the transient lift responses of simple bluff prismatic sections were investigated. This kind of transient lift response corresponded to the Küssner function in the thin airfoil theory. In the study of Caracoglia and Jones (2003), the indicial response functions of an airfoil model and a model with a rectangular fairing attached in the windward edge of the airfoil section and excited by a step-function change of the attack angle were investigated by a wind tunnel experiment. The indicial lift-growth function corresponded to the Wagner function in the thin airfoil theory. The excitation rise duration for realization of the step-function excitation for these studies, if expressed by the dimensionless time τ_r, was around 1 and 2, respectively. No correction was carried out to exclude the effect caused by this excitation rise duration τ_r. In the study of Shiraishi et al. (1983), the indicial response function of several cylindrical structures excited by a step-function change of the mainstream wind velocity was experimentally investigated, where the Duhamel's integral was applied to take consideration of the response induced by the excitation rise duration. We should note that the indicial response function in that study differed from the Küssner and Wagner functions. Because the indicial response function was unknown in advance, it was tentatively assumed and adjusted repeatedly according to the experimental response. The indicial response function was identified until the calculated response became consistent with the experimental one. This method worked but was inefficient.

In the study of Gaunaa et al. (2011), an empirical relation was proposed in order to estimate the Wagner function from the profile geometry of the finite-thickness airfoil. The empirical relation was obtained by means of panel code simulations. Considering the transient lift response to the gust, the Küssner function has been developed theoretically to characterise the transient lift of a thin airfoil traversing a sharp-edged gust, which can be approximated as linear combination of exponential terms (Jones, 1940; Fung, 1993). However, there are few examples in the literature wherein the Küssner function is directly extracted by wind tunnel experiment. In addition, the static wind tunnel experiments has been conducted to gain the equivalent Küssner functions of the square and H section cylindrical structures by the frequency domain method, while the dynamic wind tunnel experiment by the time domain method has been seldom applied in previous studies.

In this study, the Küssner functions of a thin airfoil and a flat plate are extracted by a dynamic wind tunnel experiment. Considering the difficulty in the generation of a step-function gust by a wind tunnel test, an iterative correction method is proposed to allow extraction of the indicial response function from the response of an imperfect step-function gust. With the assumption that the linear system holds, its reliability is proved mathematically and its performance is also evaluated. By a combination of a wavelet analysis to exclude noise from the response and the proposed method, the Küssner functions of the airfoil and the flat plate are experimentally obtained.

2. Effect of excitation rise duration

Firstly, the dimensionless time τ involved in the following sections is defined as that in accordance with the thin airfoil theory (Jones, 1940),

$$\tau = \frac{2Ut}{c} \tag{1}$$

where U is model speed, c is the chord length of the model as shown in Fig. 1(a) and t denotes the time. The dimensionless time of the excitation rise duration is denoted as τ_r.

In a previous study (Caracoglia and Jones, 2003), it was proposed that if a generated excitation satisfied a proper condition, then the excitation was considered to be adequate to obtain the indicial response function experimentally. The condition was $\tau_r \ll \tau_{0.9}$, where $\tau_{0.9}$ is the dimensionless time for the indicial response function developing to 90% of its steady value. However, we should treat this rule carefully. In this section, this condition is tested.

If the step-function excitation and its corresponding response are respectively normalized by their steady value, the excitation becomes a unit-step function $w(\tau)$, and its corresponding response becomes the indicial response function $\psi(\tau)$. To study the effect of excitation rise duration on the obtained indicial response function, the responses induced by the perfect unit-step function excitation $w(\tau)$ and the imperfect one $w^*(\tau)$ are compared. Given a certain indicial function $\psi(\tau)$, the former is exactly the indicial response function $\psi(\tau)$. The latter can be obtained by the Duhamel's integral and regarded as the indicial response function $\psi^*(\tau)$ obtained from the imperfect step-function excitation $w^*(\tau)$. Here, $w^*(\tau)$ satisfies the condition $\tau_r \ll \tau_{0.9}$. Besides, we restrict ourselves to a linear system and the principle of superposition holds. Then it can be evaluated that to what extent the excitation rise duration affects the indicial response function by checking the similarity between $\psi^*(\tau)$ and $\psi(\tau)$.

In this study, the end of the excitation rise duration is taken as the origin of coordinates. Therefore, for a given excitation $w^*(\tau)$,

$$w^*(\tau) = \begin{cases} 0 & \tau < \tau_0 \\ w_r(\tau) & \tau_0 \le \tau < 0 \\ 1 & \tau \ge 0 \end{cases} \tag{2}$$

where $w_r(\tau)$ is the profile in excitation rise duration $[\tau_0, 0)$, the corresponding response $\psi^*(\tau)$ can be calculated by the Duhamel's integral

$$\psi^*(\tau) = \int_{\tau_0}^{\tau} w(\tau^*) h(\tau - \tau^*) d\tau^* \tag{3}$$

where $h(\tau)$ is the impulse response function corresponding to $\psi(\tau)$ and is expressed as follows (von Kaman and Biot, 1940)

$$h(\tau) = \psi(0)\delta(\tau) + \frac{d\psi(\tau)}{d\tau} \tag{4}$$

where $\delta(\tau)$ is the Dirac's delta function. Three types of $w_r(\tau)$ are defined, which correspond to the straight line, concave curve, and convex curve, and they are denoted as w_{ra}, w_{rb}, and w_{rc}, respectively. Besides, three types of the indicial response function, which correspond to the Küssner function, the Wagner's function and the equivalent Küssner function of a square cylindrical structure (Shiraishi et al., 1983), are chosen and denoted as ψ_a, ψ_b, and ψ_c, respectively. They are listed in Table 1.

In this part, w_{ra} is applied to describe the profile of the excitation rise