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Technical note

Modification of turbulent boundary layer model based on wall fluctuations measurement

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A B S T R A C T

A modified turbulent boundary layer (TBL) model based the measurement performed in wind tunnel is proposed to investigate the turbulent boundary layer excitation which usually causes serious vibration of the aircraft structure. The Corcos model is the widely used and classical TBL model to simulate the fluctuating pressure excitation over the aircraft structure. However, the assumption of the non-pressure gradient in boundary layer limits its application in a high-speed flow. To extend the classical model to satisfy the high-speed flow, a modified model based on the measurement in wind tunnel is used to modify the Corcos model. To show the superiority of the modified model developed in this study, different TBL models are used to describe theoretical results and experimental results, respectively. The research results demonstrated that the modified model of TBL excitation could make a better agreement with the test results in wind tunnel than that of the classical Corcos model. Meanwhile, such simpler expression of the modified model shows its great convenience to resolve the engineering problems.

1. Introduction

Aircrafts generally endures cruel wall pressure fluctuations which will induce a serious structural vibration during its high-speed flight. It is very important to estimate the wall pressure fluctuations caused by turbulent boundary layer (TBL) and develop effective ways to describe the pressure fluctuations for the structural design of aircrafts.

The wavenumber-frequency analysis is one of the most effective ways to describe the wall pressure fluctuations induced by turbulent boundary layer. Earlier in 1960s, Corcos [1] proposed a TBL model and named as Corcos model which is still widely used till now. However, this classical TBL model is only appropriate to simulate the low speed flow. Cockburn et al. [2] extended the classical TBL model to simulate the wall pressure fluctuations generated by typical flow environment, consisting of attached flow, separated flow and shock wave oscillation, at transonic flow. The Efimtsov model [3,4] and the Chase model [5] are also the frequently used TBL models developed from the classical Corcos model. To compare with the different TBL models and find the most appropriate model for cabin noise prediction, the sound radiated of a plate was investigated under the excitation by different TBL models [6]. The random excitation is also a kind of TBL excitation mostly used to study the vibro-acoustic response of a plate in one study [7]. Hwang et al. [8] concluded the TBL model developed in the past 50 years and compared the pressure spectra measured under different Reynolds number and boundary layer thickness. To investigate the wall pressure fluctuations of the supersonic flow, DeChant et al. [9] derived an approximate TBL frequency spectra for the compressible boundary layer flows of the supersonic flow.

The wind tunnel test is another mostly used method to obtain the wall pressure fluctuations and correct the wavenumber-frequency models. Even the classical Corcos model [1] was also concluded from the fluctuation pressure measured in wind tunnel. In 1967, Bull [10] investigated the wall pressure fluctuating in a subsonic turbulent boundary transited from laminar to turbulent flow by an experiment perform on a smooth wind tunnel wall. Lauchle et al. [11] introduced the wall pressure measurements of the turbulent flow fully developed in a long pipe. Arguillat et al. [12] performed measurements of the wall pressure fluctuations in a wind tunnel to separate the exciting loading, consisting of acoustic and aerodynamic pressure caused by TBL. In addition, wind tunnel tests are also providing an effective way to modify the wavenumber-frequency spectrum model. Jones et al. [13] used digital technique to describe the local wavenumber-frequency spectrum of a fluctuating velocity field based on the measurement in a low-turbulence wind tunnel by two probes. Arguillat et al. [14] employed a rotative array to measure the wavenumber-frequency spectrum directly in an anechoic wind tunnel.

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Wall pressure fluctuations caused by TBL have been widely investigated for a long time. However, the works still need to be continuing for some unsolved issues. Most of TBL models are only appropriate to simulate the low speed flow with no pressure gradient internal the turbulent boundary layer. Although some TBL models have been extended to satisfy the high-speed TBL, the boundary layer thickness needed to be computed or measured for high-speed flow. Some research [15,16] has showed that the measurement of boundary layer thickness is very complex and costed, especial for the distribution of boundary layer thickness over the whole structure. So, in this study, a modified TBL model is proposed to simulate the TBL excitation without knowing the boundary layer thickness of TBL by wind tunnel measurements. The remainder of the study is structured as follows. Section 2 introduces the classical Corcos model and the wall pressure fluctuations performed in wind tunnel. The TBL modification based the measurements is developed in Section 3. The results obtained by different TBL models are compared in Section 4. In the final section, Section 5, the conclusions concerning the research are presented.

2. TBL excitation

Two kinds of different methods, consisting of the TBL models and the wall fluctuation measurement in the wind tunnel, are mostly employed to obtain the TBL excitation over the aircrafts.

2.1. TBL model

The Corcos model proposed by Corcos [1] has been widely used for many different types of TBL problems during the last few decades. Subsequently, some new models were developed to describe the wall pressure fluctuations induced by turbulent boundary layer, including the Efimtsov model [3,4] and the Chase model [5]. However, these models proposed subsequently were all inspired by the classical TBL model. Here, the Corcos model is employed to simulate wall pressure fluctuations of the TBL.

The Corcos model assumed that the cross power spectral density at two different points separated by the vector ξ could be expressed as [2,17,18]:

$$S_{pp}(\xi_1,\xi_2,\omega) = S_{pp}(\omega)e^{-\alpha_x\left|\frac{\omega\xi_x}{U_c}\right|-\alpha_y\left|\frac{\omega\xi_y}{U_c}\right|-j\frac{\omega\xi_x}{U_c}} \tag{1}$$

U_c indicates the convection velocity. Its range is $0.5{\cdot}U_0 \leqslant U_c \leqslant 0.7{\cdot}U_0$, $U_c = 0.65U_0$ is suggested in this study with U_0 is the velocity of mean flow. ξ_x and ξ_y indicate the separation distances in the stream-wise and span-wise directions, respectively. α_x and α_y are the decay rates. Generally, α_x and α_y are obtained from the measurement.

2.2. Wind tunnel test

Wall pressure fluctuation tests in the wind tunnel are mostly used to measure the TBL excitation over the aircraft for the engineering problems. In this study, a fluctuating pressure measurement is designed to measure the wall pressure fluctuations generated by turbulent boundary layer. Fig. 1 shows the test model of the pressure fluctuations and the test points. A typical aircraft layout is chosen as the test model here (seeing from Fig. 1(b)). The fluctuating pressure was measured by sensors (Kulite XCL-100, USA) distributed equally spaced on the upper surface of the model with an equal distance 5 mm between two sensors. The signals from sensors are gathered with a data acquisition system (VXI-16026A) and then transferred to a PC during the tests. The test was performed in the FD-12 wind tunnel at Chinese Academy of Aerospace Aerodynamics. The FD-12 wind tunnel is an intermittent wind tunnel and the test section of the wind tunnel is 1.2 m × 1.2 m. The range of the achievable flow Mach numbers for the FD-12 wind tunnel is from Ma = 0.4 to Ma = 4.0. Here, the investigation only focuses on measuring the TBL excitation induced by the transonic flow due to its complex aerodynamics environment.

3. TBL model modification

The Corcos model is the classical TBL model used to indicate the TBL excitation. Eq. (1) releases that the amplitude (Fig. 2a) of TBL excitation described with the Corcos model decays both along the stream-wise direction and the span-wise direction, and the phase (Fig. 2b) of the TBL excitation varies just along the stream-wise directions. The amplitude decay of TBL excitation is determined by α_x and α_y. The phase variation is determined by the term $\left(j\frac{\omega\xi_x}{U_c}\right)$ in Eq. (1). However, the Corcos model has its limitation that it is only appropriate to simulate the low speed flow with no pressure gradient internal the turbulent boundary layer. Hence, the TBL excitations, consisting of the pressure power spectrum density and the phase, present their symmetrical distribution over the surface of the structure (Fig. 2) for the low speed flow.

Assuming no pressure gradient is only reasonable for the low speed flow. But for the high-speed flow, consisting of the transonic flow, the supersonic flow and the hypersonic flow, a sharp pressure gradient usually arises in the turbulent boundary layer, which will induce a non-uniform distribution of the pressure fluctuations. So, the Corcos model is no longer appropriate to describe the TBL excitation of the high-speed flow. To resolve this problem, an extended model based on the classical Corcos model was proposed by Robertson [2]. A new variation named by the thickness of boundary layer was introduced into the extended model to simulate the effect of the pressure gradient internal the turbulent boundary layer. The extended Corcos model could be expressed as in the Ref. [2]:

$$S_{pp}(\xi_1,\xi_2,\omega) = S_{pp}(\omega)e^{-\left(\alpha_x\left|\frac{\omega\xi_x}{U_c}\right|+\beta_x\frac{|\xi_x|}{\delta_l}\right)-\left(\alpha_y\left|\frac{\omega\xi_y}{U_c}\right|+\beta_y\frac{|\xi_y|}{\delta_l}\right)-j\frac{\omega\xi_x}{U_c}}, \tag{2}$$

where the $\beta_x\frac{|\xi_x|}{\delta_l}$ and $\beta_y\frac{|\xi_y|}{\delta_l}$ terms are the extra terms introduced into the TBL model. β_x and β_y are constant here and δ_l indicates the local boundary layer thickness. Seeing from Eq. (2), boundary layer thickness δ_l is one of the primary variation to influence the TBL excitation.

Otherwise, to simulate the TBL excitation of the high-speed flow, the Efimtsov model [3] considering the effect of the boundary layer thickness and the wide range of Mach number is extended to the range of Ma = 0.4 to Ma = 2.1 (Ref. [17]). However, the exact boundary layer thickness is difficult to obtain by measurements or numerical computations [15,16], especially for the complex aircraft structure in engineering application. To avoid resolving the boundary layer thickness, the modification of the TBL model is developed here basing on the measurement results of TBL excitation. The modified model of the TBL excitation could be expressed as:

$$\begin{aligned} &\text{If } \xi_1 \geqslant 0, \quad S_{pp}(\xi_1,\xi_2,\omega) = S_{pp}(\omega)e^{-\alpha_{xup}\left|\frac{\omega\xi_x}{U_c}\right|-\alpha_y\left|\frac{\omega\xi_y}{U_c}\right|-j\frac{\omega\xi_x}{U_c}},\\ &\text{Else} \quad S_{pp}(\xi_1,\xi_2,\omega) = S_{pp}(\omega)e^{-\alpha_{xdown}\left|\frac{\omega\xi_x}{U_c}\right|-\alpha_y\left|\frac{\omega\xi_y}{U_c}\right|-j\frac{\omega\xi_x}{U_c}}, \end{aligned} \tag{3}$$

where α_{xup} and α_{xdown} indicate the decay factors of the TBL excitation in the upstream and the downstream of the structure, respectively.

4. Results discussion

The wavenumber-frequency model provides a way to describe the distribution of the wall pressure fluctuations over the structure induced by TBL. Due to that the boundary layer thickness is needed for the extended model in Eq. (3), an assumption of linear growing for the boundary layer thickness is employed here for TBL excitation simulation. The results for two different frequencies, consisting of 30 Hz and 100 Hz, are presented in Fig. 3. The decay factors for different TBL