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A scaling procedure for panel vibro-acoustic response induced by turbulent boundary layer

Zhao Xiaojian *, AI Bangcheng, Liu Ziqiang, Li Dun

China Academy of Aerospace Aerodynamics, Beijing 100074, China

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ABSTRACT

A new method of predicting structure vibration based on scaled model is proposed for panel vibration induced by turbulent boundary layer. The aerodynamic effects such as the variation of TBL excitation and its frequency for a scaled model used, and the material properties are also considered in the proposed scaling law. The contributions of resonant modes dominate the energy of low-frequency vibration, and the scaling procedure is derived with the analytical expansion method. For high-frequency vibration, the SEA method is used to derive the scaling law because of the highly coupled modes in the frequency range of analysis. A criterion is also proposed to identify the boundary between high-frequency and low-frequency vibration. For the validation of the proposed scaling procedure, an experiment is conducted with scaled plate models under external excitation. Despite slightly offset of resonant frequencies in the low frequency range likely caused by the difference in the condition of panel fixing, the results reveal that the proposed scaling procedure is effective.

1. Introduction

In recent years, the continual development of well-streamlined silent aircraft has inspired an increasing number of investigations on fuselage-airflow induced sound and vibration in the cabin. If the problem is to be tackled successfully, it must be addressed at the design stage. So it is necessary to develop a simple model of the noise generation process which can be used to formulate design criteria. Usually, a simple support plate is used to simulate the aircraft panel for vibro-acoustic study. Although many studies have investigated the noise and vibration of plate induced by turbulent boundary layer (TBL), most of them adopted theoretical approaches.

Analytical methods and numerical algorithms have been developed to calculate the vibro-acoustic behavior of plate. The sound radiation of a flat and elastic plate under the excitation of turbulent boundary layer was investigated in Ref. [1], which showed that the main factors affected the radiated sound are structural damping, skin stiffness and the number of reinforcement constraints for bare cabin walls. To study the influence of interior cabin treatment on the noise level induced by the boundary layer excitation, an extended model of predicting the response of a flat plate with internal surface treatment was developed in Ref. [2]. In order to determine which the most appropriate TBL excitation model for cabin noise prediction, Graham proposed several models and compared them [3]. Li [4] developed an analytical solution for the self and mutual radiation resistances of a rectangular plate, and represented them in the power series of non-dimensional acoustic wavenumber. This method can save multiple orders of magnitude of time compared with traditional

* Corresponding author.
E-mail address: zhaox0714@126.com (Z. Xiaojian).

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Nomenclature

a,b	streamwise and crosswise plate length
h	plate thickness
f	excitation frequency
D	plate stiffness
E	Young's modulus
r, s	arbitrary point on plate
S_{pp}	peak value of TBL excitation
S_p	power spectral density of the wall pressure distribution
S_w	power spectral density of plate displacement
U	free stream velocity
Uc	convective velocity
S_w	displacement power spectral density of plate due to TBL
S_v	velocity power spectral density of plate due to TBL
$S_{\bar{v}}$	mean velocity power spectral density of plate due to TBL
j_x, j_y	integers for identifying the mode
Z_j	plate dynamic impedance for the jth mode
k_c	convective wavenumber
N	total mode numbers in bandwidth
n_f	mode density in bandwidth
M_{jk}	overlap of jth mode and kth mode
S_F	power spectral density of the excitation force
m	mass for each part of plate

Greek symbols

ρ	material density
ω	circular excitation frequency
ω_j	natural circular frequency of jth mode
ν	Poisson's ratio
a_x, a_y	streamwise and crosswise correlation coefficient
ξ_x, ξ_y	streamwise and crosswise spatial separation
γ_j	generalized mass coefficient for jth mode
η	structure damping factor
ψ_j	jth mode shape of the bare plate
Π_{in}	power input of plate
Δ	bandwidth of the frequency
σ	scaling coefficient

numerical integration schemes. Maury et al. proposed the wavenumber approach to evaluate the validity of several simplifying assumptions, and the statistical response of an aircraft panel excited by TBL were predicted with the formulas derived in [5]. With the continual development of computing capacity, numerical algorithms [7,8] using the Boundary Element Method (BEM) and Finite Element Method (FEM) were also developed to investigate plate vibration induced by TBL more recently.

Although the low-frequency vibration could be effectively simulated with analytical and numerical methods, approximation methods are often more preferable than the exact methods in predicting high-frequency structure responses, for example, the energy flow analytical method [9–11]. Mace examined the properties of Statistical Energy Analysis (SEA) parameters and the frequency-domain characteristics of the "rain-on-roof" excitation [12]. The result revealed the theoretical assumptions required for a system to be simulated with a SEA model.

Wind tunnel provides a most effective and widely used means of simulating the airflow around structures and studying their behavior under TBL excitation. Theoretically, the result of wind tunnel tests of scaled structure model can be used to predict the vibro-acoustic response of plate under TBL excitation. The core of such vibro-acoustic prediction in wind tunnel is to derive the scaling procedure relating the scaled model and the original model. The method of predicting structure vibration based on scaled model was first proposed in Ref. [13], and a scaling law was developed for multi-component analysis of one-dimensional rod with the FEM and SEA method. In Ref. [14], the Asymptotical Scaled Modal Analysis (ASMA) was proposed to reduce the physical size of the solution domain and lower the computational cost in computing the dynamic response of an isolated system. When the result derived with the ASMA was compared with those obtained with the SEA and ED models. The ASMA was then used to predict the flexural vibration of a more complex structure, a two-plate and two-beam assembly in Ref. [15]. The ASMA result was compared with the results obtained with the standard techniques of both classical modal analysis and SEA. In Ref. [16], a dimensionless representation of the universal solution of the vibration of plate under TBL excitation was proposed for more efficiently deriving the numerical solutions of the fluctuating pressure field induced by the TBL excitation at the wall and of the induced structural response. The scaling procedure revealed in the dimensionless representation was validated after being applied to four data sets measured under different conditions both in wind tunnels and in a towing tank.

In this paper, a new scaling method is proposed. Compared with other scaling methods that only considered the scaling of structure, the aerodynamic effects such as the variation of TBL excitation and its frequency for a scaled model used, and the influence of material are also considered. Hence, the proposed scaling method is more complete for engineering applications. The work in this paper is presented as follows: Section 2 describes the theoretical models of plate vibration induced by TBL excitation. Furthermore, the proposed scaling laws are derived from the theoretical models introduced in Section 3. In Section 4, experiments conducted to validate the scaling procedure are presented. In Section 5, the scaling laws are validated based on theoretical calculation and measurement. Section 6 gives conclusions of all the work in this paper.