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Scaling procedures of cabin noise generated by turbulent boundary layer excitation

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Abstract This paper presents a new method for measuring the cabin noise of a structure in a wind tunnel. A method for scaling the cabin sound was derived to obtain the cabin noise of a structure, and the derivation of the scaling procedure was based on a theoretical hypothesis regarding the cabin noise prediction for a scaled model in a wind tunnel. A frequency offset was generated because of the error introduced by model manufacture and installation, and a proposed modal test method was used to eliminate the frequency offset. Both a full-scale structure and scaled structure were measured in the wind tunnel tests. The cabin noise of the full-scale model was compared with the results obtained using the scaling procedure based on the scaled model. The comparisons of the measurement results indicate that the scaling procedures developed in this paper are effective for vibro-acoustic predictions in wind tunnels. Moreover, background noise tended to affect the results of the cabin sound for the wind tunnel test, and thus background noise should be prevented through specific design efforts.

1. Introduction

Interior noise alleviation is an issue of primary interest in the design of modern aircraft. The acoustic nuisance inside the cabin may adversely influence passenger comfort, particularly in helicopter and propeller-driven aircraft. The typical sources for generating cabin noise include the fuselage boundary layer and airborne and structure-borne noise, which may cause unacceptable ride discomfort and impact the fatigue life of the structure.

Investigations on the cabin noise induced by Turbulent Boundary Layers (TBLs) began early on. In Ref. [1], the contribution of TBLs to cabin noise was studied, and the problem was formulated as a sequence of two linear couplings, namely, the TBL fluctuations exciting the fuselage skin in lateral vibrations and the skin vibrations inducing sound inside the fuselage. Moreover, it was assumed that the boundary layer was locally homogeneous and the fuselage skin was flat, and only outgoing waves were considered. Airplane interior broadband noise under the cruise condition was considered to be dominated by the TBL. For the prediction of cabin noise, a mathematical model[2] was derived from the Statistical Energy

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Analysis (SEA) technique to evaluate the interior TBL noise of a Boeing 737 airplane. A method for measuring the in-flight noise and vibration of an aircraft, developed by SAAB (Svenska Aeroplan AktieBolaget),[3] was shown to be a powerful tool for monitoring the quality of an aircraft. In Ref. 4, ground and flight measurements were conducted on a pusher-propeller configuration with different interior furnishings. The main objective of the measurements was to identify the sources of interior noise on a specific airplane and revise the computer program so that it could be used to predict the noise effects of interior treatment modifications. A new wavenumber-based approach for predicting sound transmission through an aircraft fuselage was introduced in Ref. 5. The proposed method was accurate at mid-frequencies, for which the method involved nearly no approximation for a large doubly periodic panel. A new stochastic model of simulating the surface pressure fluctuations that induced cabin noise was developed in Ref. 6. The method proved to be efficient when a random particle mesh method with recursive filters was used. Ref. 7 investigated the cabin noise generated by engine noise, and the proposed methodology considered the engine as a spatially extended source and assumed that the jet-mixing source was a line source distributed on the engine axis. With a focus on the cabin noise induced by TBL excitation, the interior noise environment in a Large Civil TiltrotoR (LCTR2) was assessed in Ref. 8. The contributions of different aero-acoustic sources to the cabin noise of an aircraft, including the TBL, jet noise and the air conditioning system, were compared in Ref. 9. Extensive measurements with microphones mounted at various longitudinal positions were used to assess the cabin noise. Ref. 10 presented the results of flight measurements, including the field of pressure fluctuation on the fuselage and cabin noise, and identified the main sources of noise.

The methods developed for assessing cabin noise typically only provide tools to support the noise control in the cabin of the aircraft. Ref. 11 reported the reduction of the engine rotor vibration-induced cabin noise of DC-9 due to several improvement designs. Ref. 12 investigated the control of low-frequency cabin noise and proposed a concept based on intrinsic tuning and damping of fuselage structural elements. Ref. 13 discussed the performance of various structural and cabin sidewall treatments applied to reduce cabin noise, and the measurement and analysis were conducted on a DC-9 test section. Passive vibration absorbers are often ineffective for the analysis of frequencies below 500 Hz because the wavelength is large compared to the thickness of a damping layer. Thus, an active control system for cabin noise consisting of actuators and sensors was used in Refs. 14–17.

The precision of the simulated TBL excitation typically limits the cabin noise assessment. A wind tunnel test is the most effective method for simulating TBL excitations over an aircraft with a scaled model. Thus, this paper proposes to assess the cabin noise of a craft induced by TBL excitation in a wind tunnel. Moreover, scaling laws are developed to relate the cabin noise of a scaled model with the full-scale model. The remainder of the paper is organized as follows. Section 2 describes the cabin noise scaling procedures, which are derived from the theoretical models of cylindrical shell vibrations induced by TBL excitations. Furthermore, to validate the derived scaling procedures, theoretical results are presented in Section 3. In Section 4, the measurements are introduced, and the experimental results are discussed in Section 5. The last section provides conclusions concerning the work in this paper.

2. A scaling procedure for cylindrical shell response

The scaling procedures used to predict the structural response of a typical aircraft when subjected to TBL excitations were derived based on a curved cylindrical shell (Fig. 1). In Fig. 1, a and b indicate the length and the width of the cylindrical shell, respectively, and R is the curvature. The scaling laws of the structure response induced by TBL excitation introduced in Section 2.1 were developed in Refs. 18,19 Because the interior sound distribution is also an important factor that must be considered in the structural design of an actual aircraft, the other scaling procedure was developed in Section 2.2 to relate the cabin noise distribution of scaled aircraft structures with that of full-scale aircraft structures. The scaling procedures developed can provide theoretical support for predicting cabin noise in a wind tunnel.

2.1. Scaling procedure of structure response

The differential equations governing the vibration of a curved cylindrical shell (as presented in Refs. 20,21) are as follows:

$$D\nabla^4 w + \nabla_\kappa^2 w - \mu\omega^2 w = 2p^i - 2p^r \tag{1}$$

$$Eh\nabla_\kappa^2 w - \nabla^4 \zeta = 0 \tag{2}$$

where w is the transverse displacement of panel.

$\mu = \rho h$, which indicates the area density; h is the thickness of the curved cylindrical shell and ρ is the density of structure. $D = Eh^3/12(1-\nu^2)$, where ν is Poisson's ratio of the shell, E is Young's modulus; $p^i = \exp[\mathrm{j}(\omega t - k_x x - k_y y - k_z z)]$, which indicates an incident wave acting on the shell, k_x, k_y, k_z are the wave number along x, y, z, respectively, p^r denotes the acoustic pressure radiated by the shell, ζ is Airy's stress function,ω is circular excitation frequency, t is the time, ∇_κ^2 indicates the second-order operator, ∇^4 indicates the forth-order operator, j is the imaginary unit.

If the scaling coefficient is denoted as σ, each side of the scaled curved cylindrical shell can be expressed as $\bar{a} = \sigma a$, $\bar{b} = \sigma b$, and $\bar{h} = \sigma h$. The parameters with '¯' correspond to the scaled model.

The relationship characterizing the velocity Power Spectral Density (PSD) response between the scaled model and the full-scale model is as follows:[18,19]

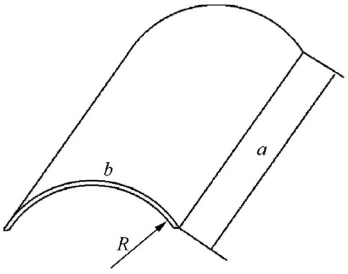

Fig. 1 Schematic of cylindrical shell.

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