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SOUND TRANSMISSION THROUGH AIRCRAFT PANELS SUBJECTED TO BOUNDARY LAYER PRESSURE FLUCTUATIONS

Bilong Liu

Institute of Acoustics, Chinese Academy of Sciences, 100080, Beijing, P.R.China

liubl@mail.ioa.ac.cn

Abstract

In an earlier paper, a deterministic approach based on modal expansion and modal receptance method was developed in predicting random noise transmission through curved aircraft panels with stringers attachments [1]. In this paper, the method was extended to predict the sound radiation of stiffening panels subjected to turbulent boundary excitation. The Corcos and Efimtsov models were used to characterize the dynamic surface pressure cross-spectra. Closed-form solutions for the panel displacements, radiation and transmission pressures were obtained. Numerical examples are presented to illustrate the influence of the stringers and structural dissipation on the structural and acoustic response of the panel.

INTRODUCTION

The boundary layer induced noise in aircraft has received increasing attention recently [2-7]. The contribution of boundary layer induced noise is already significant in the current generation of aircraft, and is likely to become more important in the future as engine noise levers are further reduced. Measurements conducted by Boeing showed that a typical pressure spectrum on an aircraft surface is resulting from the same order contributions of jet noise and turbulence boundary layer noise below 800 Hz, and is dominated by the boundary lay pressures between 1 and 2 kHz [2-4]. Further measurements conducted by Wilby and Gloyna [5-6] on aircraft showed that jet noise is more efficient exciter of vibration at lower frequencies, above 500 Hz the situation reverse, and the boundary layer induced response dominates.

Research on the response of fuselage-like structure to various forms of excitation abounds in the literature. However, theoretical models directly concerned with the boundary layer noise problem are restricted to a small flat panel without stringer attachments. An earlier analytical model to predict TBL induced noise was made by Graham [7], where an analytical expression to evaluate the modal excitation terms was successfully developed and the calculation time of the excitation field was thereby significantly reduced. Another recent attempt to predict boundary layer induced noise was made by Han, who wished to do so by energy flow analysis [8-9]. The method is proved to be successful in predicating response of a flat isotropic panel subjected to TBL excitation, but not very satisfied with noise radiated by the panel. The reason is rooted in accurate predicting of radiation efficiency of panel. As far as aircraft panel with ring frame and stringer attachments is concerned, two difficulties arise for this method. First, it is difficulty to have a close form expression for the infinite panel impedance, and second, it is difficulty to estimate the radiation efficiency of the panel.

The receptance method is a dynamic flexibility technique which is commonly used in the free vibration analysis of stiffened structures. Wilken and Soedel [10-11] considered an exact and approximate method for studying the modal characteristics of ring-stiffened cylinders with the aid of a receptance method. Lin [12] investigated the forced vibration properties of stiffened flat plates, with an application to ship structures. In an earlier paper [1], The author extended this method to predict noise transmission through curved aircraft panel with stringers attachments. In this paper, the method was used to predict the noise radiation of stiffening panel subjected to TBL excitation. The stringer and damping effects on sound radiation were specially investigated.

TBL INDUCED NOISE FOR A RECTANGULAR PANEL WITH STRINGER ATTACHMENTS

2.1 Governing equations and velocity response

Consider a simply supported, curved rectangular panel with stringer attachments in the axial direction, see Figure 1. The panel is driven by a boundary layer pressure fluctuation p_t. The governing equation then satisfies.

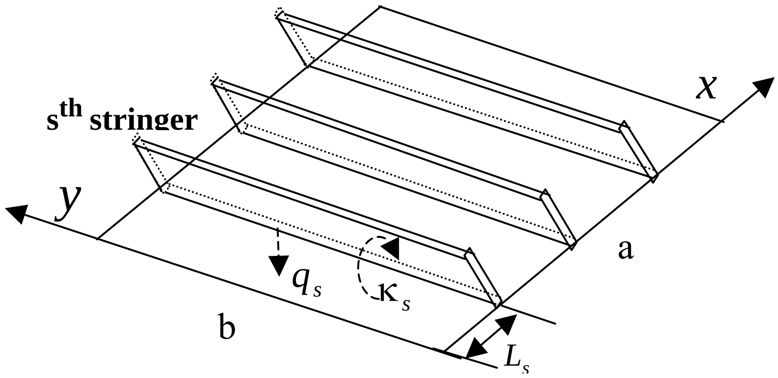

Figure 1 Schematics of stiffened rectangular panel

$$D\nabla^4 w - m_p\omega^2 w = p_t - p_0 - p_1 - \sum_{s=1}^{S} q_s\delta(y-L_s) - \sum_{s=1}^{S} \kappa_s\delta'(y-L_s)\,, \tag{1}$$

where $p_t(x,y,z,\omega)$ is the boundary pressure fluctuation, $p_0(x,y,z,\omega)$ and $p_1(x,y,z,\omega)$ are the external and internal acoustic pressures. L_s represents the distance between s^{th} stringers and boundary , q_s κ_s represents the radial force and moment exerted on the shell wall by stringers, respectively, S represents the total number of stringers.

The governing equations of the stiffener flexural and torsional displacement given in reference [13]

$$\left(D_s\, d^4/dx^4 - m_s\omega^2\right)w_s = q_s\ , \tag{2}$$

$$\left(T_s\, d^2/dx^2 - EI_w\, d^4/dx^4 + \rho_s I_p\omega^2\right)\theta_s = \kappa_s\ , \tag{3}$$

where D_s and T_s are respectively the bending and torsional stiffness of the beam stiffener, I_w is the warping constant of the stiffener, m_s is the mass per unit length of the stringer, η_s is loss factor of the stiffeners, I_p is the polar moment of inertia for the beam.

An eigenfunction describing the panel deflection is again assumed as

$$\phi_{mn}(x,y) = \phi_m(x)\phi_n(y) = \frac{2}{\sqrt{ab}}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}\,. \tag{4}$$

Following the same procedure in reference [1], the modal velocities of the panel are then

$$V_{mn} = Y_{mn}\left(P_{mn}^{t} - \sum_{n'} P_{mn}^{t} Y_{mn'} \mathbf{\Phi}_{n'} \right), \tag{5}$$

where the skin/stringer coupling function $\mathbf{\Phi}_{n'}$ is given by reference 1, and the modal admittance Y_{mn} is

$$Y_{mn} = \frac{j\omega}{m_p}\left\{\omega_{mn}^2\left[1 + j\eta_{mn}^e\right] - \omega^2\right\}^{-1}, \tag{6}$$

and ω_{mn} is (m,n)th eigenfrequency and the modal η_{mn}^e is the effective loss factor, defined by

$$\omega_{mn}{}^2 = \frac{D}{m_p}\left[(\frac{m\pi}{a})^2 + (\frac{n\pi}{b})^2 \right]^2 , \tag{7}$$

$$\eta_{mn}^e = \eta + \frac{(\rho_1 c_1 + \rho_2 c_2)}{m_p}\frac{\omega\sigma_{mn}}{\omega_{mn}^2} . \tag{8}$$

Where η is the material damping, and σ_{mn} is the modal radiation efficiency.

2.2 The radiated power spectrum

The spectrum of the acoustic power radiated inwards by the plate, $II_r(\omega)$, is given by [7]

$$2\pi\delta(\omega - \omega')II_r(\omega) = 2\int_0^a\int_0^b \mathrm{Re}\left[\overline{p_1(x,y,0,\omega)v^*(x,y,0,\omega)}\right]dydx = 2\sum_{m,n}\mathrm{Re}\left[\overline{p_{1mn}v_{mn}}\right] \tag{9}$$

where the overbar denotes an ensemble average and δ is the Dirac delta function. On using equation (5) (without coupling terms) to write p_{1mn} and v_{mn} in term of forcing pressure, we find

$$II_r(\omega) = 2\sum_{mn}\left|Y_{mn}\right|^2\sigma_{mn}\left(\Theta_{mn} - 2\Theta_{mn}\,\mathrm{Re}\left\{Y_{c,mn}\mathbf{\Phi}_n\right\} + \sum_{n'}\Theta_{mn'}\left|Y_{c,mn'}\mathbf{\Phi}_{n'}\right|^2 \right) \tag{10}$$

where Θ_{mn} is the terms of modal forcing. An analytical expression for the modal excitation term based on Corcos and Efimtsov model is given by reference [7].

For per unit area of the panel, the averaged dimensionless sound radiated power spectrum based on 1/3 octave band can be calculated by:

$$II_{av} = \frac{1}{ab\Delta\omega}\int_{\omega}^{\omega+\Delta\omega} II_{nd}(\omega)d\omega \tag{11}$$

where $II_{nd}(\omega)$ is a non-dimensional form of $II_r(\omega)$, given by reference [7], viz., $II_{nd}(\omega) = \dfrac{\omega^2 U_\tau}{\tau_w^2\delta U_c^2}II_r$. The Eq. (10) and (11) are used to evaluate the sound radiation of aircraft panel subjected to TBL excitation.

NUMERICAL RESULTS AND DISCUSSION

It is of interest to see how stringer affects sound radiation for a typical aircraft panel. Table 1 shows the panel used in numerical simulation for this purpose. In Table 1, Panel A is an aluminum panel with aluminium stringer attachments, The stringers attached to the panel are assumed with rectangular cross-section (Table 2). The stringers are equally spaced and the distance between two stringers is 0.2m. Apart from the panel parameters, the typical acoustical parameters for aircraft are show in Table 3.

Table 1 Panels used in calculation

Panel	Material	Size m^2	Skin area density kg/m^3	Young's modulus N/m^2	Loss factor
A	Aluminum	1.1×0.55	5.4	6.85E+10	0.02

Table 2 Stringers attached to the panels used in calculation

Panel	Material	Thickness mm	Height mm	Density kg/m^3	Young's modulus N/m^2	Stiffener Number	Loss factor
A	Aluminum	1.5	30	2700	6.85E+10	6	0.015

Table 3 Acoustical parameters used in calculation

Free stream velocity U_∞	$225\,m/s$	Convection velocity U_c	$0.7U_\infty$
Friction velocity U_τ	$0.03U_\infty$	Boundary layer thickness δ	0.1m
External air density	$0.44\,kg/m^3$	External sound speed	$300\,m/s$
Internal air density	$1.21\,kg/m^3$	Internal sound speed	$340\,m/s$

Fig.1 shows the sound radiation of the panel A subjected to TBL excitation. The results from the same panel without stringer attachments are also plotted for a comparison. Fig.1 reveals that the stringers have a significant influence on sound radiation power spectrum below 1kHz. In most case, the stringer seems increasing sound radiation below 1kHz, and above 1kHz, the subpanels (the panel area between two stringers and two ring frames) are more likely responding independently of one another and the stringer effects are therefore not obvious.

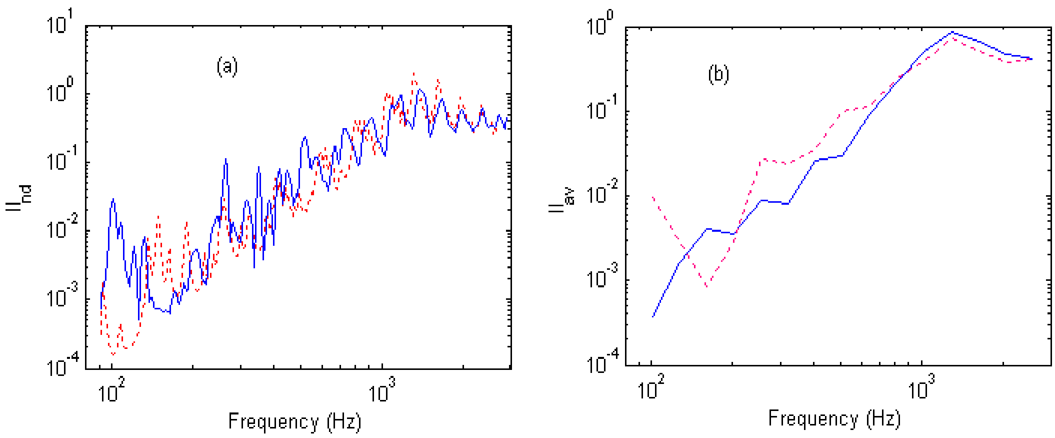

Fig. 1. Predicted stringer influence on TBL induced sound radiation for Panel A: (a) non-dimensional power spectrum; (b) averaged dimensionless power spectrum; ------ without stringers; ——— with stringers.

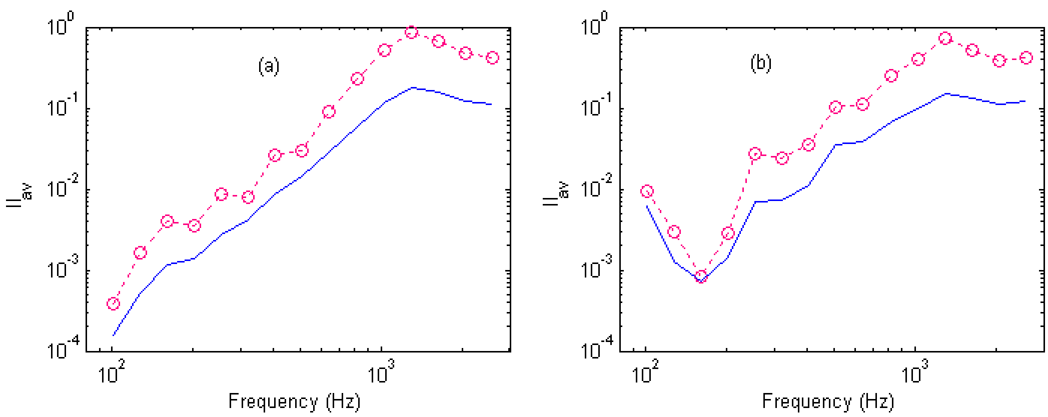

Fig.2. Predicted skin damping influence on TBL induced sound radiation for Panel A: (a) without stringers; (b) with stringers; ---○--- $\eta = 0.02$; ——— $\eta = 0.1$.

Fig. 2 shows the damping influence on the TBL induced sound radiation for panel A, with and with stringers attachments. Increasing the skin loss factor from 2% to 10% will reduce TBL induced noise radiation dramatically. The damping is effective in all frequency range, regardless of stringer attachments. This is not like the airborne sound transmission, where the damping influence is not obvious for the forced sound transmission.

CONCLUDING REMARKS

A deterministic approach based on modal expansion and modal receptance method was developed in predicting the sound radiation of stiffening panels subjected to turbulent boundary excitation. The Corcos and Efimtsov models were used to characterize the dynamic surface pressure cross-spectra. Closed-form solutions for the panel displacements, radiation and transmission pressures were obtained.

For the panel studied here, numerical results reveal that the stringers have a significant influence on sound radiation. The stringer increases sound radiation below 1kHz, and above 1kHz, the subpanels are responding independently of one another and the stringer effects is therefore not obvious. The example also indicates that increasing the skin loss factor will reduce TBL induced noise radiation dramatically. The damping is effective in all frequency range, regardless of stringer attachments.

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