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On the dynamic behavior of composite panels under turbulent boundary layer excitations

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ABSTRACT

In this work high Mach number aerodynamic and structural measurements acquired in the CIRA (Italian Aerospace Research Center) transonic wind tunnel and the models used to analyze the response of composite panels to turbulent boundary layer excitation are presented. The two investigated panels are CFRP (Carbon Fiber-Reinforced Polymer) composite plates and their lay-up is similar to configurations used in aeronautical structures. They differ only for the presence of an embedded viscoelastic layer. The experimental set-up has been designed to reproduce a pressure fluctuations field beneath a turbulent boundary layer as close as possible to those in flight. A tripping system, specifically conceived to this aim for this facility, has been used to generate thick turbulent boundary layers at Mach number values ranging between 0.4 and 0.8. It is shown that the designed setup provides a realistic representation of full scale size pressure spectra in the frequency range of interest for the noise component inside the fuselage, generated by turbulent boundary layer. The significant role of the viscoelastic layer at reducing panel's response is detailed and discussed. Finally, it is demonstrated that at high Mach number the aeroelastic effect cannot be neglected when analyzing the panel response, especially when composite materials are considered.

1. Introduction

The interaction of an elastic structure with a turbulent flow is one of the classical problems in the engineering and bio-engineering fields. Its comprehension will improve the knowledge of several interdisciplinary problems as for example the fatigue life of launchers and pipes as well as the instability of the cardiac valves. In the transportation engineering, it is well-known that the turbulent boundary layer (TBL) is able to induce high vibrations and noise levels in aircraft, commercial ships, high speed trains and automobiles, and further to produce disturbances on the on-board sensors of military and research vessels.

During the last fifty years, the problem has been analyzed from a fluid-aerodynamic point of view by many authors, both from the experimental side [1–4] with the aim at developing semi-empirical models for wall pressure fluctuations (WPFs) [5–8] and, even if to a lesser extent, from the numerical side [9,10]. The vibro-acoustic behavior has been also analyzed by

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Nomenclature

a	stream-wise plate length
$\tilde{a}$	elementary point source area
A_{QjQk}	joint acceptance between the jth and kth modes
Area	plate area
b	cross-stream plate length
c	sound speed
E	Young's modulus
$\mathbf{G}$	Green function matrix
G	Green function
G_{12}	shear module
h	plate thickness
H_i	ith term of the diagonal structural transfer functions matrix for the plate in finite element approach ($NM * NM$)
i	imaginary unit
k_a	aerodynamic wavenumber
k_b	bending wavenumber
k_c	convective wavenumber
k_s	structural wavenumber
k_x	stream-wise wavenumber
k_y	cross-wise wavenumber
$\mathbf{K}$	stiffness matrix
$\mathbf{K}_f$	acoustic impedance matrix
$\mathbf{M}$	mass matrix
M	Mach number
n	plate flexural modal density
NG	number of solution points for the evaluation of the mean response or number of grid of the finite element mesh
NM	number of retained structural eigensolutions for evaluating the response
r	source–receiver distance
R	correlation function
Re_x	Reynolds number based on the distance from the leading edge
Re_θ	Reynolds number based on the momentum thickness
R_s	non-dimensional metric response
$\mathbf{S}_{FF}$	load matrix in finite element approach [$NG * NG$]
S_p	auto spectral density of the wall pressure distribution due to the turbulent boundary layer
S_w	auto spectral density of the plate displacement
$\overline{S}_W$	mean auto spectral density of the plate displacement
$\mathbf{S}_\phi$	modal random load matrix in finite element approach [$NM * NM$]
$\mathbf{T}$	differentiation matrix
u_t	friction velocity
U_∞	free stream (undisturbed) speed
U_c	convective flow speed ($U_c = \beta_c U_\infty$)
v	source velocity
v_n	out-of-plane velocity of the plate
w	out-of-plane displacement of the plate
x	stream-wise reference axis or propagating wave direction
$X_{pp'}$	spatial cross spectral density of the wall pressure distribution due to the turbulent boundary layer
X_w	cross spectral density matrix of the plate displacement
y	cross-wise reference axis
z	through the panel thickness axis
Z_j	plate dynamic impedance for the plate jth mode

Greek

α_x	stream-wise correlation coefficient
α_y	cross-wise correlation coefficient
β_c	convective constant
γ_j	generalized mass coefficient for the plate jth mode
δ	boundary layer thickness
δ_n	nominal value of the boundary layer thickness
Γ	coherence function
Δx	extension of each finite element in stream wise direction
Δy	extension of each finite element in cross stream direction
η	structural damping factor
η_{12}	Poisson ratio
θ	momentum thickness
ν	Poisson coefficient
ν_0	cinematic viscosity
ξ_x	stream-wise separation distance
ξ_y	cross-stream separation distance
ρ	material density
ρ_0	fluid density
ψ_j	jth analytical mode shape of the plate, jth column vector belonging to $\mathbf{\Phi}$
$\mathbf{\Phi}$	matrix of the modal shape in finite element modal approach [$NG * NM$]
$\Phi_{pp'}$	wavenumber cross spectral density of the wall pressure distribution due to the turbulent boundary layer
ϕ	convected field potential function
φ	heading angle
φ_x	x-axis rotational vector
ω	circular excitation frequency
ω_j	natural circular frequency of the jth mode

adopting a number of different methodologies, including Finite Element Approach (FEA) and Statistical Energy Analysis (SEA), theoretical and reduced order models [11–19].

A few flight measurements also exist, but unfortunately only part of these data are of public domain. Among these, it is worthwhile to cite the first comprehensive flight test campaign devoted to WPFs, vibration and interior noise