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On a two-dimensional mode-matching technique for sound generation and transmission in axial-flow outlet guide vanes

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ABSTRACT

The present work deals with the analytical modeling of two aspects of outlet guide vane aeroacoustics in axial-flow fan and compressor rotor-stator stages. The first addressed mechanism is the downstream transmission of rotor noise through the outlet guide vanes, the second one is the sound generation by the impingement of the rotor wakes on the vanes. The elementary prescribed excitation of the stator is an acoustic wave in the first case and a hydrodynamic gust in the second case. The solution for the response of the stator is derived using the same unified approach in both cases, within the scope of a linearized and compressible inviscid theory. It is provided by a mode-matching technique: modal expressions are written in the various sub-domains upstream and downstream of the stator as well as inside the inter-vane channels, and matched according to the conservation laws of fluid dynamics. This quite simple approach is uniformly valid in the whole range of subsonic Mach numbers and frequencies. It is presented for a two-dimensional rectilinear-cascade of zero-staggered flat-plate vanes and completed by the implementation of a Kutta condition. It is then validated in sound generation and transmission test cases by comparing with a previously reported model based on the Wiener-Hopf technique and with reference numerical simulations. Finally it is used to analyze the tonal rotor-stator interaction noise in a typical low-speed fan architecture. The interest of the mode-matching technique is that it could be easily transposed to a three-dimensional annular cascade in cylindrical coordinates in a future work. This makes it an attractive alternative to the classical strip-theory approach.

1. Introduction

Axial-flow turbomachines are known as key contributors to the aerodynamic noise of modern aircrafts, from the standpoint of the propulsive systems causing environmental issues as well as from the standpoint of air-conditioning units involved in cabin comfort. Dealing with external noise, the evolution of modern turbofan engines toward larger bypass ratios in the past decades has led to a continuous jet-noise reduction, making rotating-blade noise the dominant

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Nomenclature

Latin characters

a	Inter-vane channel width
A_j	Vortical inter-vane channel coefficient
B	Rotor blade number
B_n	Vortical transmission coefficient
C	Vane chord
c_o	Sound speed
D_q	Acoustic downstream channel coefficient
k	Acoustic wavenumber
$k^{\pm}$	Generic axial acoustic wavenumber
k_n	Acoustic wave number at the n-th BPF order
M	Axial Mach number
M_t	Tangential Mach number
(r, θ, x)	Cylindrical duct coordinates
R_0	Radius of a cylindrical cut
R_s	Acoustic reflection coefficient
T_s	Acoustic transmission coefficient
u	Inter-vane phase angle
U_q	Acoustic upstream channel coefficient
V	Stator vane number
V_j	Vortical coefficient induced by the Kutta condition
(x, y, z)	Cartesian coordinates
w	Generic wake velocity-deficit notation
W_x	Axial mean-flow velocity

Greek characters

α	Generic azimuthal wave number
β	Compressibility factor
β_r	Rotor exit-flow angle
$\mathbf{\Gamma}$	Pressure-axial velocity vector
Θ	Angle of propagation of the incident acoustic wave
$\underline{\boldsymbol{\varphi}}, \underline{\mathbf{\Psi}}$	Modal projection constants
ρ_0	Mean fluid density
σ	Solidity
ϕ	Acoustic potential
ω	Angular frequency
Ω	Rotor rotational speed
Ω_0	Strength of the vortical Dirac delta function

Subscripts and superscripts

n	Blade-Passing Frequency (BPF) order index
m	Inter-vane channel index
i, r, d, u, t	Incident, reflected, downstream channel, upstream channel, transmitted components
μ, s, q, j, n_i	Modal orders
$+, -$	Superscripts for downstream/upstream propagating waves
$\mathbf{x}$	Vector
$\underline{\mathbf{x}}$	Matrix

contribution, especially during approach and landing operation. More precisely the fan and its outlet guide vanes (OGV) in the annular duct are recognized as the main sources of noise. Dealing with internal noise, the contribution of the small-size ducted fans used in on-board air-conditioning circuits tends to grow in terms of relative levels, especially as a lower propulsion noise is transmitted inside the cabin. Facing this new context and the more and more stringent requirements in terms of noise reduction, the understanding and the modeling of the noise-generating mechanisms are crucial needs for aircraft manufacturers and equipment suppliers.

The common features of the turbofan and air-conditioning fan can be reduced to a single sound-producing rotor-stator stage, with ideally an axial mean flow upstream of the rotor and downstream of the OGV (see Fig. 1). Elucidating the role of the OGV in the aeroacoustic behavior of the stage is the main motivation of the present work. As long as the rotor-stator distance is large enough to avoid the strong coupling that takes place when the leading edges of the stator vanes enter the near-wake region of the rotor blades, this role is twofold and can be analyzed as follows. Firstly the wakes issuing from the rotor impinge on the vanes, inducing unsteady loads that are responsible for what is referred to as wake-interaction noise.

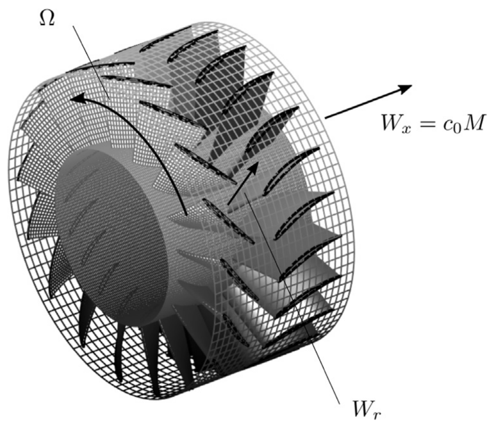

Fig. 1. Typical axial-flow fan stage used in air-conditioning systems for aircraft, featuring the rotor rotating in the counter-clockwise direction and the stator (outlet guide vanes).