Advanced modeling of active control of fan noise for ultra high bypass turbofan engines

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Abstract

An advanced model of active control of fan noise for ultra high bypass turbofan engines has been developed. This model is based on a boundary integral equation method and simulates the propagation, radiation and control of the noise generated by an engine fan surrounded by a duct of finite length and cylindrical shape, placed in a uniform flow. Control sources, modeled by point monopoles placed along the wall of the engine inlet or outlet duct, inject anti-noise into the duct to destructively interfere with the sound field generated by the fan. The duct inner wall can be lined or rigid. Unlike current methods, reflection from the duct openings is taken into account, as well as the presence of the evanescent modes. Forward, as well as backward (i.e., from the rear of the engine), external radiation is computed.

The development of analytical expressions for the sound field resulting from both the fan loading noise and the control sources is presented. Two fan models are described. The first model uses spinning line sources with radially distributed strength to model the loading force that the fan blades exert on the medium. The second model uses radial arrays of spinning point dipoles to simulate the generation of fan modes of specific modal amplitudes. It is shown that these fan models can provide a reasonable approximation of actual engine fan noise in the instance when the modal amplitude of the propagating modes or the loading force distribution on the fan blades, is known.

Sample cases of active noise control are performed to demonstrate the feasibility of the model. The results from these tests indicate that this model 1) is conducive to more realistic studies of active control of fan noise on ultra high bypass turbofan engines because it accounts for the presence of evanescent modes and for interference between inlet and outlet radiation, which were shown to have some impact on the performance of the active control system; 2) is very useful because it allows monitoring of any region of the acoustic field; 3) is computationally fast, and therefore suitable to conduct parametric studies.

Finally, the potential that active noise control techniques have for reducing fan noise on an ultra high bypass turbofan engine is investigated. Feedforward control algorithms are simulated. Pure active control techniques, as well as hybrid (active/passive) control techniques, are studied. It is demonstrated that active noise control has the potential to reduce substantially, and over a relatively large far field sector, the fan noise radiated by an ultra high bypass turbofan engine. It is also shown that a hybrid control system can achieve significantly better levels of noise reduction than a pure passive or pure active control system, and that its optimum solution is more robust than the one achieved with a pure active control system.

The model has shown to realistically predict engine acoustic behavior and is thus likely to be a very useful tool for designing active noise control systems for ultra high bypass turbofan engines.

Dedications

Cette thèse est dédiée à mes parents, mes grand-parents et ma soeur. Papa, maman, pépé, mémé, Céline, merci pour tout. Vous êtes, pour moi, chacun à votre manière, une grande source d'inspiration. Je vous adore!

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List of symbols

Symbol	**Description**
~	used in Chapters 2, 3 and 4 to denotes that a quantity is dimensional when appearing over a variable.
a	axial coordinate of the duct trailing edge (m)
A	axial coordinate of the duct trailing edge in the stretched moving reference frame
A_{mn}	complex amplitude of the (m,n) mode (Pa)
b	axial coordinate of the duct leading edge (m)
B	axial coordinate of the duct leading edge in the stretched moving reference frame
BPF	blade passing frequency (Hz)
c	speed of sound (m / s)
$d, D, D_{\bar{n}}$	integral equation operators
F, F_r, F_ψ, F_z	loading force per unit span and its components (N / m)
G	Green’s function
h	harmonic number
h_{m_d}	multi-dimensional delta function (1 / m)
H	step function
J_m	Bessel function of the first kind and of order m
j'_{mn}	inflection point of the Bessel function of order m

k	wave number (1 / m)
k_r^{mn}	radial wavenumber of the (m,n) mode (1 / m)
k_z^{mn}	axial wavenumber of the (m,n) mode (1 / m)
k_ψ^{mn}	circumferential wavenumber of the (m,n) mode (1 / m)
$k_{r\psi}^{mn}$	radial-circumferential wavenumber of the (m,n) mode (1 / m)
m	circumferential mode order
M	forward flight Mach number
n	radial mode order
n_h	harmonic number
N	number of fan blades
p_{mn}	acoustic pressure field due to the (m,n) mode (Pa)
p_t, p_i, p_s	total, incident and scattered pressure (Pa)
Δp	pressure jump across the duct surface (Pa)
$\Delta p_{\bar{n}}$	normal derivative of the pressure jump across the duct surface (Pa / m)
r, ψ, z	cylindrical coordinates
r_d	duct radius (m)
r_l	radial coordinate of the tip of the fan blades
$s, S, S_{\bar{n}}$	integral equation operators
t	time variable (s)
u_r	radial component of the acoustic velocity (m / s)
V	forward speed of the engine (m / s)
$\vec{V}_g$	group velocity vector (m / s)
Z	axial coordinate in the stretched moving reference frame
Z_{imp}	specific acoustic impedance (kg / s / m^2)

Greek

β	stretching coefficient of the moving reference frame
δ	Dirac Delta function
∇	divergence operator
∇^2	Laplacian operator
ρ_0	density of the medium (kg / m^3)
θ_{peak}^{mn}	angle of the main lobe of radiation of the (m,n) mode
Ω	shaft speed of fan (rad / s)
ξ	mode cut-off ratio

Abbreviations

EPNL	Effective Perceived Noise level
PNL	Perceived Noise Level
SPL	Sound pressure Level
SPWL	Sound Power Level
UHB	Ultra High Bypass