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Scaling properties of the aerodynamic noise generated by low-speed fans

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A B S T R A C T

The spectral decomposition algorithm presented in the paper may be applied to selected parts of the SPL spectrum, i.e. to specific noise generating mechanisms. It yields the propagation and the generation functions, and indeed the Mach number scaling exponent associated with each mechanism as a function of the Strouhal number. The input data are SPL spectra obtained from measurements taken during speed ramps.

Firstly, the basic theory and the implemented algorithm are described. Then, the behaviour of the new method is analysed with reference to numerically generated spectral data and the results are compared with the ones of an existing method based on the assumption that the scaling exponent is constant. Guidelines for the employment of both methods are provided. Finally, the method is applied to measurements taken on a cooling fan mounted on a test plenum designed following the ISO 10302 standards. The most common noise generating mechanisms are present and attention is focused on the low-frequency part of the spectrum, where the mechanisms are superposed.

Generally, both propagation and generation functions are determined with better accuracy than the scaling exponent, whose values are usually consistent with expectations based on coherence and compactness of the acoustic sources. For periodic noise, the computed exponent is less accurate, as the related SPL data set has usually a limited size. The scaling exponent is very sensitive to the details of the experimental data, e.g. to slight inconsistencies or random errors.

1. Introduction

Nowadays, reducing the aerodynamic noise radiated by single-rotor fans is probably a task as important as the improvement of the aerodynamic performance. Numerical methods for the noise prediction have strongly improved in the last decade, see for example [1–3], but experimental investigations are still essential in order to identify the noise generating mechanisms. Namely, proper techniques for the analysis of experimental data are required. According to Neise and Barsikow [4], Mongeau et al. [5,6], and Blake [7], the received noise results from the combination of two aspects whose properties must be investigated case by case: the noise generating mechanisms and the interaction of the radiated acoustic waves with the solid parts of the fan and of the operating environment, that is the propagation effects. As reported by Lu et al. [8], for single-rotor fans the noise generated by the rotor usually overwhelms the one generated by stationary parts. This eases the development of techniques for the analysis of experimental data, since the rotor constitutes the only relevant source.

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Nomenclature

a_0	speed of sound
d	path length
D	rotor diameter
f	frequency
$f_{\max}$, $f_{\min}$	extremes of the investigated f range
F	source spectral distribution function
$\mathfrak{I}$	non-dimensional function in Eq. (1).
G	propagation function
He	Helmholtz number
$He_{\max}$, $He_{\min}$	extremes of the investigated He range
h	index related to f and He
i	index related to iteration
K	constant in Eqs. (13) and (14).
k	index related to Ω
Ma	Mach number at the rotor tip
n	rotational speed expressed in rev/min index related to St
N_g	number of uncorrelated noise generating mechanisms
OASPL	overall SPL, ref. 20 μPa
p	acoustic pressure
$p_{t,in}$	total pressure at the fan inlet
p_{out}	static pressure at the fan discharge
p_{ref}	reference acoustic pressure, 20 μPa
Q	volume flow rate
r	distance between rotor centre and receiver
S_{pp}	one-sided auto power spectral density of p
SPL	sound pressure level spectrum, ref. 20 μPa
t_{aer}	$= 2\pi/\Omega$, aerodynamic time scale
t_{ac}	$= D_{tip}/a_0$, acoustic time scale
z	rotor blade number
α	Mach number scaling exponent
Γ	$= 20\log_{10}G$, level of the function G
Δf	bandwidth, frequency resolution
ΔHe	He number resolution
ΔSt	Strouhal number resolution
$\Delta\Omega$	rotational speed increment
ρ	air density
φ	$= 8Q/\pi\Omega D_{tip}^3$, flow coefficient
Φ	$= 20\log_{10}F$, level of the function F
Ψ	auxiliary function employed in the algorithm
Ω	rotational speed expressed in rad/s
$\Omega_{\max}$	final Ω in a speed ramp
$\Omega_{\min}$	initial Ω in a speed ramp

Subscripts

BB	related to broadband parts
dec	value employed in the standard technique
dir	related to the direct radiation path
$filt$	related to filtered SPL, Eq. (47).
hub	related to rotor hub
$refl$	related to waves reflected by the floor
sc	related to scaled SPL, Eq. (46).
tip	related to blade tip
0	related to the ambient conditions
Ω	related to variations at $\Omega = const$
St	related to variations at $St = const$
500, 1000	related to $\Omega_{\min}$
2300, 3000	related to $\Omega_{\max}$

Superscripts

AI	related to aerodynamic interaction
BB	related to broadband parts, computed by means of the 2nd procedure
$refl$	related to waves reflected by the floor
std	related to the method of Ref. [20].
1^{st}	related to the first procedure
2^{nd}	related to the second procedure
$*$	first guess value

Acronyms

AI	aerodynamic interaction
BB	Broadband
BPF	$= z\Omega/2\pi$, blade passing frequency
LS	large scale flow structures
SS	small scale turbulence
TCS	turbulence control screen
TE	trailing edge
TLF	tip-leakage flow

The spectral decomposition, [4–6,9–22], is an effective method commonly employed to distinguish between spectral properties of the noise generating mechanism and the acoustic response of the system. It consists in taking acoustic measurements at several rotational speeds, thus varying the time scale of the aerodynamic phenomena while keeping constant the acoustic time scale. Then, the SPL spectrum dependence on the rotational speed is expressed by means of the Mach number raised to a scaling exponent, e.g. see [4,9,23–25]. Eventually, based on the similarity theory, the contributions of generation and propagation are separated by means of suitable algorithms. In the standard version, the scaling exponent is arbitrarily assigned, resulting in very robust procedures. Unfortunately, approximations yield if noise generating mechanisms associated with different propagation functions or characterised by different scaling exponents are simultaneously present; this aspect has been treated by Mongeau et al. [6], Quinlan and Krane [13], Stephens and Morris [17,18], Wu et al. [19].

The SPL dependence on the rotational speed is an important property and the basic theory for a fluctuating point force indicates a dependence on the 6th power, as shown by Curle [26], Lowson [27], and Ffowcs Williams and Hawkings [28]. Deeper theoretical analyses indicate that radiation efficiency of the source region is also involved and may decrease the dependence down to the 5th power, e.g. see [5, 7, p. 951, 29–31].