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Computation of instantaneous and time-averaged active acoustic intensity field around rotating source

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ABSTRACT

A vector aeroacoustics method is developed to analyze the acoustic energy flow path from the rotating source. In this method, the instantaneous and time-averaged active acoustic intensity vectors are evaluated from the time-domain and frequency-domain acoustic pressure and acoustic velocity formulations, respectively. With the above method, the acoustic intensity vectors and the acoustic energy streamlines are visualized to investigate the propagation feature of the noise radiated from the monopole and dipole point sources and the rotor in subsonic rotation. The result reveals that a portion of the acoustic energy spirals many circles before moving towards the far field, and another portion of the acoustic energy firstly flows inward along the radial direction and then propagates along the axial direction. Further, an acoustic black hole exists in the plane of source rotation, from which the acoustic energy cannot escape once the acoustic energy flows into it. Moreover, by visualizing the acoustic intensity field around the rotating sources, the acoustic-absorption performance of the acoustic liner built in the casing and centerbody is discussed.

1. Introduction

Noise radiated from the rotating sources has been a hot research topic for decades. The analytical studies have been conducted by many famous researchers, such as Ffowcs Williams [1], Lowson [2,3], Morfey [4–6], Prentice [7,8], Crighton [9,10] and Chapman [11,12]. Since 1980s, various analytical formulations have been developed to predict the sound of the rotating sources, and the corresponding methods can be classified into three groups. The first is the time-domain numerical method (TDNM), in which formulations 1A [13] and Q1A [14] are employed for predicting the time-domain signal of the acoustic pressure. The second is the frequency-domain numerical method (FDNM), which includes the work of Prieur [15], Hanson [16], Gennaretti et al. [17], Tang et al. [18] etc. The third one is the spherical harmonic series expansion method (SHSEM) for the rotating monopole [19], dipole [20] and quadrupole [21] point sources. More detailed discussions on the above methods are presented in Refs. [18,20,22]. Additionally, some semi-empirical models have also been developed to predict the trailing-edge and leading-edge broadband noise of rotating blades (see, for instance [23–32]). All the aforementioned methods and models have the capability for predicting the acoustic pressure field around the rotating sources.

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Nomenclature

c_0	speed of sound in unperturbed medium, m s^{-1}
f	data surface function
f_r	rotational frequency of source, Hz
f_0	source frequency, Hz
g	time-domain Green's function
G	frequency-domain Green's function
$H(\cdot)$	Heaviside function
$\mathbf{I}$	instantaneous acoustic intensity vector, W m^{-2}
$\bar{\mathbf{I}}$	time-averaged acoustic intensity vector, W m^{-2}
$\tilde{\mathbf{I}}$	frequency-domain acoustic intensity vector, W m^{-2}
L_i	components of local loading intensity, Pa
L_M	L_iM_i, Pa
L_r	$L_i\hat{r}_i$, Pa
$\dot{L}_r$	$(\partial L_i/\partial\tau)\hat{r}_i$, Pa s^{-1}
m	harmonic number
$\mathbf{M}$	source Mach number vector, $\boldsymbol{v}/c_0$
M	$\lvert\mathbf{M}\rvert$
M_r	$M_i\hat{r}_i$
$\dot{M}_r$	$(\partial M_i/\partial\tau)\hat{r}_i$, s^{-1}
n_i	components of unit vector normal to the data surface
p'	time-domain acoustic pressure, Pa
$\tilde{p}'$	frequency-domain acoustic pressure, Pa
r	distance between source and receiver, $\lvert\mathbf{x}-\mathbf{y}\rvert$, m
r_i	components of vector in radiation direction, x_i-y_i, m
$\hat{r}_i$	components of unit vector in radiation direction, r_i/r
T_{int}	interval length of time-domain integration, s
t	observer time, s
$\mathbf{u}'$	time-domain acoustic velocity, m s^{-1}
$\tilde{\mathbf{u}}'$	frequency-domain acoustic velocity, m s^{-1}
u_i	components of fluid velocity, m s^{-1}
u_n	local normal fluid velocity of data surface, m s^{-1}
v_n	local normal data surface velocity, m s^{-1}
$\mathbf{x}$	observer position vector, m
x_i	components of observer position vector, m
$\mathbf{y}$	source position vector, m
y_i	components of source position vector, m
ϕ	azimuth angle, rad
θ	elevation angle, rad
ρ	local fluid density, kg m^{-3}
ρ_0	fluid density of unperturbed medium, kg m^{-3}
ρ'	density perturbation, kg m^{-3}
$\delta(\cdot)$	Dirac delta function
σ_{ij}	components of viscous stress tensor, Pa
τ	source time, s
ω	angular frequency, rad s^{-1}

Superscript

$*$	conjugate of the complex quantity

Subscripts

0	fluid variable in unperturbed medium
x	observer quantity
y	source quantity

Abbreviations

IAI	instantaneous acoustic intensity
AAI	active acoustic intensity
AES	acoustic energy streamline
TDNM	time-domain numerical method
FDNM	frequency-domain numerical method
RMPS	rotating monopole point source
RRDPS	rotating radial dipole point source
RCDPS	rotating circumferential dipole point source
RADPS	rotating axial dipole point source

Except for the acoustic pressure, the acoustic velocity and acoustic intensity vectors are also the important physical parameters to characterize the sound. Moreover, the above vector quantities have an advantage to visualize the flow direction of the acoustic energy and to identify the source location [33]. An analytical acoustic pressure gradient formulation G1A proposed by Lee et al. [34] can be utilized to compute indirectly the acoustic velocity. Recently, Ghorbaniasl et al. [35] has proposed an analytical time-domain acoustic velocity formulation V1A for sources in arbitrary motion, and after that, two types of the frequency-domain acoustic velocity formulations FV1A and FV2A for the rotating sources have also been deduced by employing the FDNM and SHSEM, respectively [36].

Various experimental techniques and facilities, such as the P-P and P-U acoustic intensity probes [33,37], the particle image velocimetry [38] and Doppler global velocimetry [39], have been developed to measure the acoustic intensity vector. However, to the best knowledge of the authors, no literature has published the numerical assessment of the acoustic intensity vector for the rotating sources. In the present paper, both the instantaneous acoustic intensity (IAI) and time-averaged active acoustic intensity (AAI) fields around the rotating sources are computed numerically and visualized.

The remainder of the paper is organized as follows. Section 2 reviews both the time-domain and frequency-domain acoustic pressure and acoustic velocity formulations and the definitions of the acoustic intensity. In Section 3, the IAI and AAI fields around the rotating monopole and dipole point sources and a rotor are computed, respectively, to validate the present acoustic intensity prediction method and to investigate the fundamental radiation characteristic of the rotating sources. With the visualization technique of the acoustic field, it is observed that there are three acoustic radiation modes for the rotating sources and some related discussions have also been carried out. Section 4 draws some conclusions.