Applied Acoustics 140 (2018) 110–121

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

A numerical study of noise characteristics originating from a shrouded subsonic automotive fan

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ARTICLE INFO

Keywords:
Fan noise
Installation effects
Spectral decomposition
IDDES
Aeroacoustics

ABSTRACT

The characteristics of the noise radiated from a reduced automotive cooling module are numerically studied focusing on the interaction effects linked to the sound generation mechanisms and the acoustic scattering caused by the confined installation. The flow field is simulated by adopting the formulation of Improved Delayed Detached Eddy Simulation (IDDES), which is a numerical technique that enables large-scale structures to be resolved and the wall-bounded flow to be treated depending on the turbulent content within the boundary layer. By comparing the simulated fan performance to two sets of measurement data of a similar setup, the aerodynamic results obtained from IDDES are validated and conformed to the volumetric flow rate delivered for the pressure drop measured. The acoustic part of the study comprises evaluation of the sound source associated with the momentum distribution imposed on the surroundings at an interface slightly upstream of the fan. At the microphone positions upstream of the installation, the SPL falls within the SPL range measured and the acoustic power delivered by the fan conforms to the SWL obtained from the comparison method in the reverberation room. The system response function, estimated by subtracting the SWL for the free-field simulation from the SWL associated with the reduced automotive cooling module marks spectral humps at fixed frequencies, irrespectively of sound source. As such, the engineering approach to the spectral decomposition method earlier published, which enables the acoustical properties of the installation to be isolated from the source, is validated and found to hold.

1. Introduction

The noise emanating from subsonic fans placed in an installation is in addition to the properties of the sound source itself, i.e. the fan, attributed to the environment in which the fan is operating. Consequently, the sound transmission path to the far field is modified by the system boundaries as the acoustic scattering effects of nearby surfaces act to mask the spectral content of the source [1]. Geometrical properties of the system, e.g. the duct cross-sectional shape and the length determining the acoustical termination at the ends are important factors to which the sound field is critically sensitive [2,3]. Furthermore, as stressed in [4], due to the installation, it is unrealistic to assume that a fan placed in a duct will generate the same sound power as it would produce in a free field environment.

From an aerodynamic perspective, the compartment in which the rotor is confined restricts the flow as a result of the geometrical constraints of the configuration. Hence, in order to determine how a certain fan will perform aerodynamically for a given duty, it is necessary to account for the flow resistance of the system [5]. Moreover, the fan operating point, defined by the pressure rise and volume flow rate, determines the spectral shape distribution of the sound produced. Longhouse conducted experiments and presented how the sound characteristics depended strongly on the operational condition achieved by altering the fan back pressure [6]. A lightly loaded fan, indicated by a high flow coefficient, produced predominantly tonal noise while in the opposite flow situation, mainly broadband, non-rotational noise surpassed the blade passing frequency (BPF) and its harmonics. In addition, flow distortions impinging on the fan caused by the contracting effect of the entrance section [7] or from fixed objects [8], create anisotropic turbulent flow structures displayed in the spectrum as higher harmonics of the BPF. Axially elongated vortices in the air stream might also be attributed to turbulent boundary layers

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https://doi.org/10.1016/j.apacoust.2018.05.006
Received 2 December 2016; Received in revised form 27 April 2018; Accepted 4 May 2018
0003-682X/ © 2018 Published by Elsevier Ltd.

developed on the casing wall [9]. Hence, to optimize an existing installation from an aeroacoustic perspective, it is vital to simultaneously consider how the fan performs in relation to the configuration in which it operates and the statistics of the approaching flow at an early stage in the design phase. For instance, design modification to the upstream environment will affect both the aerodynamic and acoustic behavior [10].

The aim of this paper is to numerically examine the aerodynamic and acoustic installation effects [11] of a cooling module comprised of a reduced number of components. A hybrid approach is adopted that enables separation of the flow computation from the acoustic sound propagation. The unsteady flow field is resolved utilizing the method of Improved Delayed Detached Eddy Simulation (IDDES) [12]. Once the flow is fully developed, the sound sources are extracted from the flow field. Sound propagation is calculated in the frequency domain utilizing a finite element solver. The simulation results are validated with sound field measurements. In addition, the distinct features of the sound source and system response isolated from influence of each other are investigated by the spectral decomposition method [13–15]. Of special interest are the results obtained in [13] where an estimation of the fan sound characteristcs, disconnected from the masking effect of the system, was obtained by exploiting the properties of the acoustic measurement facility. Thus, the present investigation is also conducted to see if the results obtained by applying the spectral decomposition method on the data set obtained from the measurement conform to the outcome from applying the same separation technique on the simulated results.

This paper is arranged in the following way: Section 2 briefly presents the setup from which the measurement data used for validation are acquired. It also includes details about the separation technique utilized during the measurements to enable isolation of the sound source function from the acoustic transfer function. In Section 3 and Section 4, the numerical aspects of the study are outlined, both the flow and acoustic parts, respectively. Section 5 summarizes the most important findings. Finally, conclusions drawn from the results are stated in Section 6.

2. Description of the measurement setup

The conducted measurements comprise an automotive cooling package located in a wall separating an anechoic room and a reverberation room (Fig. 1). All parts come from a Scania bus cooling installation but to enable investigation of the sound characteristics, the number of components was reduced in relation to the actual underhood setup. Here, the examined components are the fan, the shroud, and a short entrance section constructed to ensure a smooth air flow at the entrance. The fan (Borg Warner XD11 750 mm) is an 11-bladed rotor of diameter 0.75 m (D) rotating at three rotational speeds, i.e. 1000, 1250 and 1450 rpm, respectively. The air stream is sucked by the rotor through the wall opening (in the direction of view of Fig. 1(a)), separating the up- and downstream side of the setup, and exhausted into the reverberation room, Fig. 1(b). The tip clearance is 5 mm. The installation will be referred to as the *reduced cooling module*.

Table 1
Non-dimensional quantites and their values and scaling factors for the operational conditions studied.

Mach number	$Ma = \Omega D_{tip}/2a_0$	{0.121, 0.144, 0.167}
Reynolds number	$Re = \Omega D_{tip}^2/2\nu$	{1.59, 1.98, 2.30} × 10^6
Strouhal number	$St = f/f_{BPF}$	f_{BPF} = {183.3, 229.2, 265.8} [Hz]
Helmholtz number	$He = fD_{tip}/c_0$	c_0 = 340 [m/s]

Table 1 gives the non-dimensional quantities that characterize the aerodynamic and acoustic properties of the setup. The tip diameter is denoted D_{tip},Ω is the rotational speed in rad/s, c_0 is the speed of sound, ν is the kinematic viscosity, f_{BPF} is the blade passing frequency calculated by multiplying the rotational speed by the number of blades and dividing by 60. The far right-hand column includes the operational conditions investigated.

Given the design of the acoustic measurement facility, it can be assumed that the two sides (anechoic room and reverberation room) are acoustically uncoupled except for frequencies below 100 Hz. Consequently, properties distinct for each room are exploited to enable separation of the acoustic modulation effect of the cooling module and the sound sources characterizing the fan. This means that, on the upstream anechoic side, the measured SPLs at fixed microphone positions are assumed to be unaffected by the surroundings of the anechoic chamber as all walls are covered by absorbing wedges preventing sound waves from being reflected; i.e. a nominally free field condition is attained. Consequently, the measured SPL represents the sound source and system effects. By contrast, a reverberation room is a room designed to create a diffuse or random incidence sound field where the principal assumption is that the measured sound is primarily caused by reflections, creating a uniform distribution of acoustic energy within the room [16]. Therefore, the SPL data taken in the reverberation room can be seen as a measure of the source strength unaffected by the system response.

(a) (b)

Fig. 1. The MWL facility used for acoustic measurements of the sound characteristics governing the *reduced cooling module*. (a): Anechoic room view, (b): Reverberation room view.

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