Towards Quieter Air-Cooling Systems: Rotor Self-Noise Prediction for Axial Cooling Fans

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***Abstract*—Aeroacoustic noise is seen as a major threat to the survival of air cooling for electronics systems. The application of numerical noise prediction methods is highly constrained by computational costs. A reduced-order model (ROM) was proposed in this study to predict the rotor self-noise for axial cooling fans based on the blade element theory (BET), lifting line theory and Amiet's trailing-edge noise model. The accuracy of this ROM was validated against available benchmark case and experimental data. The ROM is able to accurately predict the fan characteristic and the broadband noise in the high frequency range (above 2 kHz), while the computational speed is more than 3 orders of magnitude than a high-fidelity simulation method, making it appropriate for low-noise fan design and optimization.**

***Keywords*—electronics cooling, aeroacoustics, reduced-order modeling, fan curve, blade element theory, Amiet's model**

I. Introduction

The continued evolution in cooling requirements of modern, high-end datacom equipment has inevitably resulted in increased noise levels. The high-level acoustic noise caused by cooling fans may endanger human health and decrease operational reliability of electronic system such as hard disk drive (HDD) enclosure [1]. Therefore, how to reduce the fan noise is regarded as an urgent issue to extend the life of air cooling in data centers [2].

Trailing-edge (TE) noise has broadband characteristics in nature and is a dominant rotor self-noise source in many cases [3]. It is challenging to accurately and efficiently predict TE noise produced by fan-cooled electronics. Wasala et al. [1] carried out a large eddy simulation (LES) combined with the Ffowcs Williams and Hawkings (FW-H) acoustic analogy for a counter-rotating cooling fan. An excellent match was observed compared to their experimental results. However, the simulation time for each back-pressure case needs about 5 days using 80 CPU cores at a supercomputer, equivalent to around 9600 core hours. High-fidelity computational fluid dynamics (CFD) combined with computational aeroacoustics (CAA) techniques are viable solutions for simulating cooling fan noise [4]. However, these methods are computationally very expensive and hard to integrate into a design and optimization procedure.

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Regarding the low-fidelity modelling methods, Amiet [5] analytically studied the scattered noise near the trailing edge of a flat plate. Due to its simplicity and flexibility, Amiet's model is extensively used in numerous rotating blades applications, including automotive cooling fans [6] and propellers [7].

The wall pressure spectrum (WPS) near the trailing edge is a key input for Amiet's model, which affects the accuracy of the noise prediction [8]. Rozenberg et al. [6] experimentally tested a low-speed axial fan without shroud and used the measured WPS data as an input for Amiet's model. Sanjosé et al. [9] extracted the flow information for an automotive fan from Reynolds-averaged Navier-Stokes simulations, and combined with Rozenberg's WPS model [10] to calculate the wall pressure data. Li et al. [11] proposed a method to predict the TE noise of a open rotor, combining blade element momentum theory (BEMT) [12], XFOIL vortex panel method [13], Lee's WPS model [14], and Amiet's TE noise model [5]. The blade element momentum theory is a widely used analytical method for the flow calculation of open rotor blades [12]. However, this theory is not valid to a shrouded or ducted rotor with back pressure effect [15]. Therefore, the majority of the existing models either model the fan blades as flat plates or still rely on the flow information from CFD simulations.

The present paper focuses on the developments and validations of a reduced order model (ROM) to fast evaluate the aerodynamic and aeroacoustic performance of electronics cooling fans. An analytical model is proposed based on the blade element theory, lifting line theory and XFOIL vortex panel method for the aerodynamic analysis of the fan with shroud. The wall pressure data near the trailing edge is obtained by six recently developed WPS models, and the far-field noise is calculated by Amiet's TE noise model. Finally, the proposed ROM is validated against both a published experimental case and a real commercial fan case. All models in this ROM code are implemented in MATLAB.

II. Methodology

In this section, the numerical approaches proposed for aerodynamics and acoustics are introduced.

A. Aerodynamic model

The analytical method is developed based on the blade element theory (BET) combined with the lifting-line theory. This theory assumes that each spanwise element is independent and ignores any spanwise flow. This assumption is normally valid for the fan operating at non-stall regions, where the spanwise flow is negligible. The inflow schematic of a typical fan element is illustrated in Fig. 1. Based on the conventional BET mothod [12], the thrust dT and torque dM for a radial element dr can be expressed as

$$dT = \frac{1}{2}\rho B \frac{\Omega^2 r^2 (1-a')^2}{\cos^2\phi} c(C_l \cos\phi - C_d \sin\phi) dr \quad (1)$$

$$dM = \frac{1}{2}\rho B \frac{\Omega^2 r^2 (1-a')^2}{\cos^2\phi} c(C_l \sin\phi + C_d \cos\phi) r dr, \quad (2)$$

where c is the blade sectional chord length, B is the number of blades, v is the effective velocity at each radial element ($v = \sqrt{{u_n}^2 + {u_t}^2}$). u_n and u_t are the axial velocity and tangential velocity respectively. a' is the tangential induction velocity factor ($u_t = \Omega r\,(1-a')$). ϕ is the flow induction angle and $\phi = \tan^{-1} u_n/u_t$. C_l, C_d are the lift coefficient and drag coefficient, respectively. These two coefficients are calculated based on the angle of attack α using the integrated XFOIL solver [13]. The sectional angle of attack equals $\alpha = \beta - \phi$, where β is the geometrical twist angle. For the sake of the numerical robustness and efficiency, all the C_l and C_d data of 2D airfoils were pre-calculated in the angle of attack range from $-20°$ to $+20°$, and the Viterna method [16] was then used to extend the data to the full $\pm180°$ range of angles of attack.

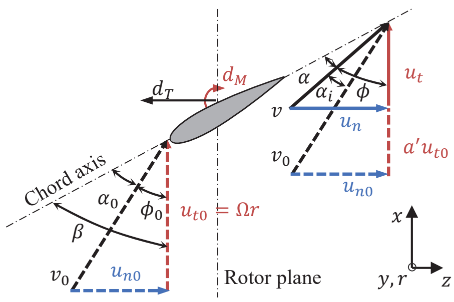

Fig. 1. Velocities and forces at a typical blade element.

In this work, a lifting-line theory-based method was developed combined with the aforementioned BET method for fan flow calculations. An elliptical lift distribution is assumed along the fan blade. Based on the continuity equation, the axial velocity for the fan with a cylindrical shroud should be constant ($u_{n0} = u_n$). Provided a finite span blade with geometrical aspect ratio AR, the induced angle of attack can be calculated as $\alpha_i = C_l/\pi AR_{eff}$ [17]. In the proposed method, the effective aspect ratio AR_{eff} is defined as the geometric aspect ratio multiplied by a correction factor M_{AR} ($AR_{eff} = AR \times M_{AR}$). The effect of the shroud suppressing tip vortices is taken into account using the correction multiplier M_{AR}, which can be seen as an increase in effective aspect ratio ($M_{AR} > 1$). The tangential velocity factor a', which decreases the tangential velocity, can be written as

$$a' = \frac{v_0}{\Omega r} \sin\phi \tan\left(\frac{C_l}{\pi AR_{eff}}\right), \quad (3)$$

where v_0 is the total velocity at the blade leading edge ($v_0 = \sqrt{{u_{n0}}^2 + {u_{t0}}^2}$). The lift coefficients C_l are corrected based on the effective aspect ratio AR_{eff} to take into account the effect of 3D finite blades.

By combining Eq. (3) with Eq. (1) and (2), and solving these equations iteratively, the local velocity and angle of attack along the blade span can be obtained. For each blade section, the XFOIL code is invoked to calculate flow and force information, which is further required for the calculation of the wall pressure fluctuation.

B. Aeroacoustic model

In this study, Amiet's model [5] is employed to calculate the rotor trailing edge (TE) noise. For a far-field observer located at position (x, y, z), the acoustic power spectral density S_{pp} can be written as

$$S_{pp}(\omega) = 4\left(\frac{\omega c z}{4\pi c_0 \sigma^2}\right)^2 l_y(\omega) \frac{s}{2} |\mathcal{L}|^2 \Phi_{pp}(\omega), \quad (4)$$

where c is the chord length, c_0 is the speed of sound, s is the span length, $\sigma^2 = x^2 + \beta^2(y^2+z^2)$, $\beta^2 = 1 - Ma^2$, Ma is the Mach number ($Ma = v/c_0$), $|\mathcal{L}|$ is the norm of the transfer function of the airfoil at (x, y, z) location and $\Phi_{pp}(\omega)$ is the surface pressure spectrum near the trailing edge [5]. The convection velocity U_c was assumed to be $U_c = 0.8v$, and the spanwise correlation length $l_y(\omega)$ is computed as $l_y(\omega) \approx 2.1U_c/\omega$ [5]. It is worth noting that an extra factor of four is added in Eq. 4 to account for the scattering effect from the opposite side. A detailed explanation for this correction can be found in [18].

The surface pressure spectrum Φ_{pp} is calculated by six semi-empirical wall pressure spectrum (WPS) models, namely those by Goody [19], Rozenberg [10], Kamruzzaman [20], Hu [21], Catlett [22] and Lee [14]. All the boundary layer parameters were extracted at 99% of the chord by the XFOIL code [13]. The semi-empirical WPS models were commonly calibrated based on the empirical database at intermediate to high Re flows, and lack validation cases at low Re flows (chord based $Re < 10^5$). Therefore, for assessing the WPS models at low Re flows, they are pre-classified into two groups using the boundary layer momentum thickness-based Reynolds number Re_θ, which are low Re models (Rozenberg, Lee, Kamruzzaman, $Re_\theta \leq 1000$) and high Re models (Goody, Hu, Catlett, $Re_\theta > 1000$), respectively. Finally, the far-field sound pressure level (SPL) at position (x, y, z) can be expressed as

$$SPL(f) = 10\log_{10}\left[\frac{2\pi S_{pp}(\omega)\Delta f}{P_{ref}^2}\right], \quad (5)$$

where $P_{ref} = 2 \times 10^{-5}$ Pa and Δf is the spectral resolution.

III. Experimental Setup

Experimental studies were carried out in a half-scaled test plenum in accordance with ISO 10302 [23] to validate the reduced-order model (ROM) described in Sec. II. The selected fan is a high-speed 80 mm electronics cooling fan used in a commercial multiple HDD enclosure system. Noise measurements were taken with one single G.R.A.S. 40PH microphone positioned 1 m perpendicular to the fan rotor plane, as shown in Fig. 2. For each measurement, a sampling frequency of 51.2 kHz and a recording period of 20 s were employed. The acoustic signals were separated into 239 Hanning-windowed blocks with 50% overlap, corresponding to a frequency resolution of 6 Hz. It is worth noting that the test environment is not an anechoic room. Figure 3 compares the noise levels of the fan, unloaded motor without any blades and the background. The fan noise was measured at the zero back pressure condition. It is clear that the relative contribution of the background noise is roughly below 500 Hz. Therefore, the fan noise data above 500 Hz was used to validate the ROM.

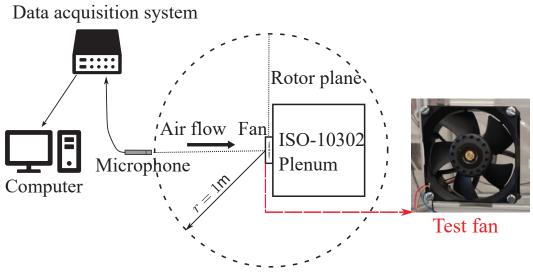

Fig. 2. The set-up of noise measurements.

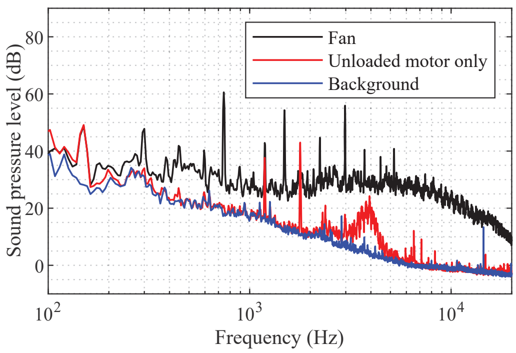

Fig. 3. Sound pressure level (SPL) comparison between fan, motor and background noise.

IV. Results

A. Aerodynamic validation

The aforementioned single impeller cooling fan case was selected to validate the aerodynamic solver. It is a 5-blade fan with a nominal speed of 9000 RPM. The tip radius of the fan blade is 37.5 mm, and the hub radius is 18.7 mm. This fan operates at a tip Mach number close to 0.1 and maximum chord-based Reynolds number of approximately $60,000$. The twist and chord distributions were extracted from ten radial sections of the computer aided design (CAD) file. The chord length for the mid-span section is 26.3 mm and the twist angle is 32.2° with respect to the rotor plane. The aerodynamic C_l and C_d data was pre-calculated by XFOIL [13] for each angle of attack using the sectional airfoil coordinates extracted from the CAD file. In this study, the aspect ratio correction multiplier M_{AR} selected is 3.

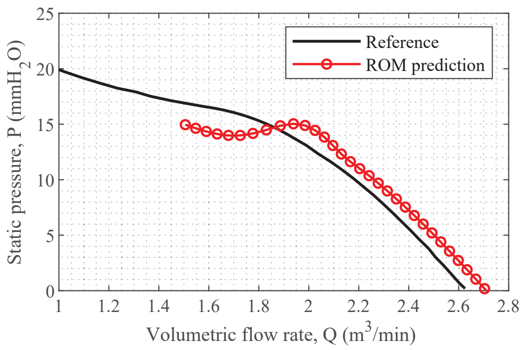

Fig. 4. Results comparison between reference data and ROM prediction for fan P-Q curve.

Figure 4 shows the predicted fan performance (P-Q) curve compared to the reference data from the fan manufacturer. The predicted results reasonably match with the reference data. It slightly overpredicts the performance at low back pressure conditions. Some discrepancies are observed at the stall region, which could be attributed to the radial flow effect making the assumption of independent elements invalid.

B. Aeroacoustic validation of a 2D airfoil

The aeroacoustic model was validated against a published airfoil case at low Re flows, which shares a similar flow condition with the cooling fan. The case selected is a NACA 0012 airfoil with a 25.4 mm chord and 457.2 mm span. The inflow velocity is 28.8 m/s with an angle of attack of 0°, corresponding to a chord-based Re of $50,000$. The experimental data was obtained from [24]. Their prediction data for trailing edge noise, namely the results of BPM model, was also retrieved for comparison. More details about the experiments and BPM model can be found in [24].

Figure 5 shows the noise comparison in third octave bands between the measurement data, BPM prediction and six WPS model predictions. It is clear that each model captures the basic trend. The low Re models (i.e., Rozenberg [10], Lee [14], Kamruzzaman [20]) show better agreement with the measurement data.

C. Aeroacoustic validation of a cooling fan

The aeroacoustic model was then validated against the experimental data obtained in Sec. III for the axial cooling fan. From Fig. 6, it can be seen that the acoustic models have better performance in the high frequency range (above 2 kHz) and major discrepancies were found in low frequencies. This could be due to that the Amiet's model is more accurate in the

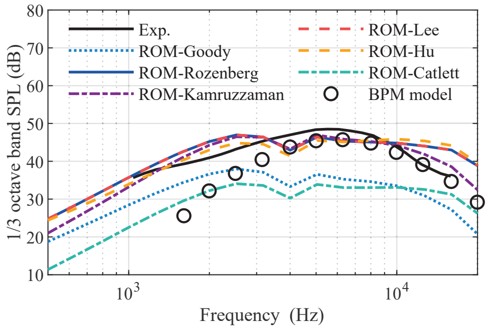

Fig. 5. Far-field noise comparison between the experiments, BPM prediction and the ROM prediction for a 2D airfoil ($Re \approx 50,000$).

range where $2\pi f c/c_0 > 1$ [18]. Therefore, for the blade with 26.3 mm chord, the valid frequency range should be higher than around 2 kHz. The low Re models (i.e., Rozenberg [10], Lee [14], Kamruzzaman [20]) show better agreement with the measurement data than the high Re models, which is in line with the 2D airfoil's results.

This ROM code is implemented on the MATLAB platform. The total execution time is about 10 mins on an Intel Xeon E5-2660v3 CPU at 2.2 GHz using 8 cores (1.3 core-hours), which is more than 3 orders of magnitude than the high-fidelity method (9,600 core-hours) reported in [1].

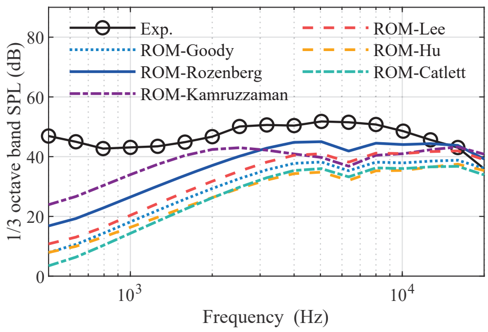

Fig. 6. Far-field noise comparison between the experiments and the ROM prediction for the cooling fan ($Re \approx 60,000$).

V. Conclusion

In this study, a reduced-order model (ROM) was proposed to efficiently analyze the aerodynamic and aeroacoustic performance of rotor blades from electronics cooling fans. The proposed ROM was shown to be capable of predicting the fan performance curve and the high frequency rotor trailing-edge noise accurately, while requiring ultra-low computational cost.

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