MODIFICATION OF NOISE SOURCES BY VIRTUE OF BLADE SWEEP IN LOW SPEED FAN

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Three fans designed with forward, backward and unswept blades are analysed in the present work. The simulations are performed using Reynolds-Averaged Navier Stokes equations using $k - \omega$ SST turbulence closure model. The $y^+ \sim 1$ is maintained on blade surfaces and computational domain is discretized using hybrid mesh. The predicted overall performances agree reasonably well with experiments and reproduce the observed hysteresis. The analysis of flow field and noise predictions are assessed at design point i.e at 5083CMH and 1400RPM. The mean flow field before and after the fans also agree well with laser Doppler anemometry measurements. The farfield noise is predicted using Amiet’s model for leading edge and trailing edge noise sources separately. The former is found dominant and the latter negligible. Secondary flow such as tip vortices are significantly contributing to the noise spectrum confirming that tip noise is a dominant noise source in such machines.

1. Introduction

In modern world, turbomachines and transportation system are integral part of human life. Nonetheless, inherited involuntary noise generation annoys their usage. Among wide range of turbomachines, low speed fans are the most commonly used in daily commute and also in domestic applications. The vital evaluation of such fans primarily depend upon two conditions i.e. higher aerodynamic efficiency and lower noise levels. Among different design features, blade designed with sweep can suffice them [1]. Although the improved lift-drag ratio for aeroplane wings was well known in advance, in early turbomachines the sweep was an accidental bi-product of a manufacturing process. According to recent studies, blade sweep is particularly important for the low speed machines because of its ability to improve stall margin and efficiency [2]. Incorporating sweep in design also modifies 1. meridional flow, 2. blade to blade flow and 3. boundary layer growth [3]. However, these modifications induce distinct tip flow, corner vortex and passage vortex patterns which are conveniently ignored during design process. The complexity of such secondary flows are not completely understood yet because existing insufficient experimental
data visualisation techniques and confined computations limit their insight. Recently, experiments collaborated with computational study, dedicated to the understanding of tip flow behaviour of unswept fan blade [4, 5] showed that tip leakage flow leads to composite flow formation which contributes to the noise in far field. It is significantly identified as dominant narrowband hump in the spectra. Composite near tip flow and its noise emission interdepend upon blade shape and end wall treatment of the fan i.e. free tip fan and ringed fan [6]. In general, dominant noise sources located near tip relate to the increased circumferential velocity from hub to tip, quite well-known rule $V_{tip}^6$ [7]. At Friedrich-Alexander University Erlangen-Nuremberg, the systematic study performed on design variations of blade sweep features and vast amount of experimental data available for validation motivated author to perform computational analysis on selective fans [7]. This acquired knowledge of noise sources persuades to rediscover latent excellence of sweep in modern way.

To begin with, three free tip fan blades i.e. forward sweep (S1F), backward sweep (S1B) and unswept blade (S1U), are selected from Zenger’s swept blade matrix. However, as mentioned, the intricacy of secondary flows are still not completely understood. Therefore, to simplify the problem, investigation is divided into two computational approach. The single blade passage flow is simulated using traditional method that is steady state Reynolds Averaged Navier Stokes model (RANS). The obtained results from RANS analysis are compared with experimental data for aerodynamic characteristics and mean flow field. These results are used in analytical models to compute leading edge (LE) and trailing edge (TE) noise and to compare with available noise spectrum from experiments for each fan.

2. Design of low speed fan

The ducted fans designed at Friedrich-Alexander University Erlangen-Nunberg using blade element theory for low solidity fan as shown in Fig. [1] are investigated. Design parameters are as follows: fan diameter 495mm, tip gap 2.5mm, hub diameter 124mm, 9 blades and rotational speed 1400RPM. The skewed versions were derived from unswept fan (S1U) with $\pm$ 45$^\circ$ sweep angle. In broader sense, sweep is recognised as azimuthal displacement of blade in direction of flow or away from flow, however practical implementation is quite complex. The forward sweep fan (S1F) has positive sweep angle in flow direction and backward sweep fan (S1B) has negative sweep angle away from flow direction. Presently, we have followed Zenger’s sweep definition and for further clarification on current fan design, one can refer to Ph.D. thesis by Zenger [7]. To achieve similar performance in all three fans, sweep angle correction and modified chord length were applied during design to account for reduction in spanwise lift [8], however other design parameters were kept same for all fans.

2.1 Numerical set up

During experiment, the fan is tested under standardized axial fan inlet test chamber. However, to simplify the problem, axisymmetric flow around fan blades is assumed and aerodynamic flow field is modelled using a single blade passage. The periodic boundary condition is applied on either side of the blade passage, cylindrical inlet and outlet zones are modelled by keeping in mind the experimental set up. The computational domain as exhibited in Fig. [1] is discretized with unstructured hybrid mesh i.e. near wall is resolved with prism layers by achieving $y^+ \sim 1$ and bulk fluid is discretized with tetrahedral elements and total mesh count is $12 \times 10^6$ cells. The rotating fan is modelled with moving reference frame while duct as stationary. The simulation is performed by solving steady state incompressible RANS equations and turbulence is modelled with $k-\omega$ SST. The similar numerical strategy is applied to study all three fans in the present work.
2.2 Aerodynamic characteristics

The characteristics curve for pressure rise ($\Delta P$) versus volumetric flow ($Q$) for 3 different fans are plotted in Fig. 2a. It is observed that all three fans are going through a hysteresis loop from 3000CMH to 5500CMH and includes design flow rate as well, i.e. 5083CMH. For the S1U fan, we could produce two pressure rise values, which justifies the presence of a hysteresis loop. However, for forward sweep simulation over predicted pressure rise by 10% and for backward sweep under predicted pressure rise by 12% than experiments. This is because, sweep is changing tip flow behaviour drastically and induces unsteady, complex flow behaviour, which can not be accurately captured with steady state RANS simulation [9]. Markedly, for lower flow rates, secondary flows dominates and are essentially influenced by neighbouring blades, therefore modelling such behaviour with periodic boundary condition may equivocate. Despite, the existence of unsteadiness, the single blade passage simulations are able to predict pressure rise which are in reasonable agreement with the experiments.

2.3 Analysis of flow field

In this study, the flowfield is investigated for design point condition only. The vortex structures is analysed by calculating imaginary part of complex eigen values of velocity gradient, referred as $\lambda_{ci}$. It indicates the measure of swirling strength of a vortex. The corner and passage vortex structures are visualised with isosurface of $\lambda_{ci}$ by selecting threshold of 100. However, highly turbulent, complex and 3D tip vortex structures examined by plotting isosurface of $\lambda_{ci}$ by setting threshold of 315. Forward sweep displaces vortex formed near tip in the blade passage along the chord while unswept and backward swept blade induce thicker tip vortex which move azimuthally to interact with the following blade, as illustrated in Fig. 2b (top). Relatively, vortex near tip of backward sweep interacts more with neighbouring blade which is traced as broader subharmonic humps in the noise spectrum. Horseshoe vortex formed near hub dominates for forward sweep blade among all as shown in Fig. 2b. The horseshoe vortex leg formed on suction side exhibits solitary behaviour for forward sweep. It subdivides into two traces of counter rotating vortices as shown in Fig. 2b (bottom). However, other two blades form weaker horseshoe vortex.

Data recorded using laser doppler anemometry in experiment, plotted for axial velocity and turbulence kinetic energy (TKE) are compared with simulations in Fig. 3 and 4 for suction side. Axial velocity contours show the flow distributed along the blade and reverse flow through tip gap while higher levels
Figure 2: a. Aerodynamic characteristics curve for all three fans (left); b. Isosurface of $\lambda_{ci}$ (315, 100) clipped respectively to visualize tip vortex and passage/corner vortex separately and colored by helicity ranging from -1 to 1 (right).

Figure 3: Data averaged azimuthally extracted near suction side for axial velocity and TKE.
Figure 4: Experimental phase averaged data extracted near suction side (top) for axial velocity and TKE compared with simulation (bottom) respectively; S1F (left), S1B (right), S1U (middle)

of TKE exhibits high shear and strong tip vortices.

3. Far field broadband noise prediction

The far field noise is predicted using Amiet’s models for leading edge and trailing edge interactions [10]. The model inputs are extracted from the above RANS simulations. The basic assumption is that the broadband noise sources are uncorrelated over the span and strip theory can be affiliated. For low solidity fan, the noise is analysed by considering isolated airfoil at each radius and then integrated over the number of blades. More details can be found in [10, 11]

3.1 Leading edge noise

The power spectral density (PSD) of the far-field acoustic pressure for a given observer location ($\vec{x}$) and received frequency $\omega$ radiated from leading edge is expressed as

$$S_{pp}^{LE}(\vec{x}, \omega) = \left( \frac{\rho_0 \omega b}{c_0 S_0} \right)^2 \pi U d |L^{LE}(\vec{K}_x, \vec{K}_y)|^2 \Phi_{ww}(k_x, k_y)$$

(1)

where $\rho_0$ and $c_0$ are density and speed of sound in free field, $U$ is uniform flow velocity, $b$ is half chord of the modelled profile, $d$ is its span. $S_0$ is a corrected distance to account for the acoustic waves by the flow. The radiation integral formulated for a flat plate due to leading edge scattering, $L^{LE}$ is calculated for convective $k_x$ and spanwise $k_y$ wavenumbers. The wavenumbers are normalised by chord length, hence represented by overbar i.e. $\vec{K}_x, \vec{K}_y$.

The turbulence spectra of upwash velocity advancing onto the leading edge is modelled using a Von Kármán spectrum as below:

$$\Phi^{VK}_{ww}(k_x, k_y) = \frac{4}{9\pi} \frac{\hat{u}^2 (k_x^2 + k_y^2)}{k^2_0 (1 + k_x^2 + k_y^2)^{7/3}}$$

(2)
where \( \bar{u}_2^2 \) is mean square of velocity fluctuation, dimensionless wavenumber \( \hat{k}_i = \frac{k_i}{k_e} \), \( k_e \) is wavenumber of most energetic scales.

### 3.2 Trailing edge noise

The power spectral density of the acoustic far field pressure at given frequency and at receiver location \( \vec{x} \) is calculated as below:

\[
S_{pp}^{TE}(\vec{x}, \omega) = \left( \frac{\omega CX_3}{2\pi c_0 S_0^2} \right)^2 \mathcal{L}_{TE}^2(k_x, k_y) \Phi_{pp}(\omega) l_y(\omega)
\]

(3)

The spanwise correlation \( l_y \) is calculated using Corcos model. \( \mathcal{L}_{TE} \) including backscattering correction developed by Roger and Moreau\(^{[12]} \) is considered here. The spectrum of pressure fluctuations imparted on wall is computed using Rozenberg’s improved model for adverse pressure gradient as below:

\[
\Phi_{pp}(\omega) \frac{U_e}{r_w^2 \delta^*} = \frac{0.78 (1.8\Pi \beta_C + 6) \left( \frac{\omega \delta^*}{U_e} \right)^2}{\left[ \left( \frac{\omega \delta^*}{U_e} \right)^{0.75} + C_1' \right]^{3.7} + \left[ C_3' \left( \frac{\omega \delta^*}{U_e} \right) \right]^{7}}
\]

(4)

where \( C_1' = 0.105 \) and \( C_3' = 3.76R_T^{-0.57} \). Clauser’s parameter is \( \beta_C = (\theta / \tau_w)(dp/dx) \) and \( \Pi \) is Coles’ parameter of wake law. The parameters such as displacement thickness (\( \delta^* \)), momentum thickness (\( \theta \)), edge velocity (\( U_e \)), wall shear stress (\( \tau_w \)) are calculated using equation given below. The input required for these calculations are extracted from the performed simulation. The extraction is conducted near trailing edge at 85% of the chord length. The suction and pressure side pressure fluctuation spectra near wall are computed separately to compute radiated noise.

\[
\hat{U}(\delta) = 0.99 U_e, \quad \delta^* = \int_0^\delta (1 - U(y)/U_e) \, dy, \quad \beta_C = (\theta / \tau_w) \cdot (dp/dx)
\]

The spanwise distribution of boundary layer parameters near the trailing edge of all blades are extracted and compared in Fig. 5. The best suitable models for low speed fan and parameter extraction method are selected from study performed by Sanjose and Moreau\(^{[11]} \). However, the radiation integral \( \mathcal{L} \) doesn’t
Figure 6: Noise spectra comparison from experiments and Amiet’s model prediction, leading edge noise (left), trailing edge noise (right)

yet account for blade sweep. The noise predictions obtained are compared with noise spectra from experiments in Fig. 6. For trailing edge noise the forward and backward swept are slightly more tip-loaded than the unskewed blade resulting in thicker boundary layers at the trailing edge (Fig. 3) and consequently larger trailing-edge noise. Yet, this self noise is negligible compared to measurements up to 10 kHz. The dominant noise source is clearly the LE noise that recover the overall wide broadband hump for all fans over the whole frequency range on-line with previous results on the H380EC1 fan [10, 11]. In such fans, tip noise is therefore the dominant noise source even at design. The missing noise component is the narrow band subharmonic humps that cannot be captured by the selected models, and that mostly make the difference between the different fans. Note that the differences in flow topology in the tip region between the three fans do not quite reproduce the experimental differences in broadband noise even at high frequencies where the subharmonic humps are negligible, which suggests that the acoustic effects of sweep need to be accounted for.

4. Conclusion

Two swept blades i.e. forward, backward and one unswept blade are studied in the present work. Aerodynamic performance and mean flow field analysed from RANS simulations are in fair agreement with experiments. These simulations also capture the hysteresis phenomenon around the design conditions seen experimentally in these fans. These simulations results also compare well with Laser Doppler Anemometry measurements upstream and downstream of the fan at design. Thus, the single blade passage simulation proved to be a quick and efficient tool compared with modelling full fan and experimental set up instead.

The RANS results are then used to predict broadband noise coming from the trailing edge (or self noise) and from turbulence injection coming from the shear between the main flow entering the fan and the recirculating one in the tip gap at design. These predictions based on Amiet’s models show that self-noise is negligible in these fans up to 10 kHz and that turbulence-interaction noise provide the levels and the overall broadband shape of the measured spectra. The available models are capable to compute uncorrelated response of the blade which is the source of broadband noise. However, the tonal noise peak at blade passing frequency and its harmonics can be calculated by integrating correlated response of the
blade which can be captured with transient simulation. In addition, those models do not account for the observed subharmonic humps that are the main differences between all the fans. Therefore present study limits their prediction. To understand the complex flow behaviour responsible for this extra tip noise and get more accurate noise predictions at all frequency range, unsteady high resolution simulations such as the hybrid LBM-VLES method is needed.

References


