A Through-flow Analysis Method of Axial Fan with BPF and Broadband Noise Models

Chan Lee¹ and Hyun Gwon Kil¹

¹Department of Mechanical Engineering, University of Suwon
Wauan-Gil 17, Hwaseong, 18323, Korea, clee@suwon.ac.kr, hgtkil@suwon.ac.kr

Abstract

The present paper proposes and describes a through-flow analysis method of axial fan coupled with BPF and broadband noise prediction models. The flow and performance predictions of axial fan are made by streamline curvature method with empirical correlations for flow deviation and pressure losses. After the computation of streamline curvature method, the predicted flow velocity, flow angle and wake thickness distributions along fan blade span are used for calculating the acoustic pressures produced from BPF and broadband noise sources. The present method is applied to several automotive and air-conditioning fans for verifying its prediction accuracy. The fan flow, performance and noise prediction results by the present method are compared with the CFD and the measurement results. From the comparison results, the present method is shown to provide favorable prediction results within a few percent relative errors and can be used as a reliable design tool of high efficiency and low noise fan at the actual fan design practice.

Keywords: Fan, Through-flow analysis, Noise models

1. Introduction

Axial flow fans have been widely used in air-conditioning and automotive applications and the recent main concerns of fan designers are to improve fan efficiency as well as to reduce fan noise. Thus, in actual fan design process, it is very important for fan designers to investigate the effects of blade design parameters on fan noise and performance.

Recent advances in computational fluid dynamics(CFD) and computational aero-acoustics(CAA) techniques[1,2] provide the prediction capabilities on fan performance and noise, but CFD and CAA modellings still require skillful expert, a lot of modeling works and long computation time. For this reason, fan industries call for simpler and less time-consuming prediction method on fan performance and noise than the CFD and the CAA.

Therefore, the present study provides a new through-flow analysis method of axial flow fan coupled with fan noise models, which can be used for high efficiency and low noise fan development. The performance prediction of the present method is conducted by the through-flow modeling with flow deviation and total pressure loss models. Fan noise models for blade passing frequency and broadband noise sources are also applied to the through-flow calculation results to predict fan’s overall noise level and noise spectrum. The fan flow, performance and noise calculation results by the present method are compared with measurement and CFD results to verify the prediction accuracy and suitability of the present method used in fan design practice.

2. Through-flow analysis method with fan noise models

2.1 Streamline curvature method

For the analyses of fan flow and performance, the present study uses SCM(Streamline Curvature Method) as one of the through-flow methods, which can be easily coupled with fan noise models. As shown in Fig. 1, once three dimensional fan blading design is obtained, the through-flow analysis by SCM is conducted to predict pitch-averaged and spanwise flow distributions of air between the designed fan blades and then the mass-averaging of the flow calculation results yields fan’s overall performance curves.

In the present study, SCM is applied to 17 streamlines along blade span and calculates spanwise distributions of flow velocity, flow angle and pressure at fan blade outlet through solving radial equilibrium equation with Euler work equation, flow deviation and pressure loss models [3,4,5,6,7]. When SCM is applied to forward or backward-swept fan, all the design and flow variables should be defined and computed in the swept-blade coordinate [8].

* The abstract of this article was presented at the 15th Asian International Conference on Fluid Machinery, held at Busan, Republic of Korea, September 25-28, 2019.
2.2 Fan noise models

Fan noise is composed of BPF (Blade Passing Frequency) and broadband noise components. BPF noise is produced at blade passing frequency and its harmonics while broadband noise is produced over wide frequency band. The present study proposes the following noise prediction models for BPF and broadband noise components, which are deduced from the SCM flow calculation results.

(1) BPF Noise Model

BPF noise is produced due to the aerodynamic force and the blade interaction of rotating fan blades. The BPF noise by the aerodynamic force of fan blades can be analysed by Gutin’s theory[9] under the assumption that fan blades are compact moving noise sources, and its sound pressure levels at BPF and the corresponding harmonics are expressed by the following equations:

\[ SP_{mB} = \frac{N}{R_a} \left( \cos \beta \sin \sigma - \frac{\sin \beta}{ME} \right) mBf_{mB}(mBM_c \cos \sigma)X_aX_b \]

\[ L_T = B \int_{tip}^{hub} \rho \frac{V^2}{c} \times \frac{2}{(l)} \cos \alpha_m(tan \alpha_1 tan \alpha_2) \]  

where \( SP_{mB} \) is peak sound pressure at mB mode( B: no. of fan blade, m: 1,2,3 … ), N is fan rotating frequency, \( L_T \) is total steady lift of fan blades which is determined by combining cascade theory for section lift(l) and predicted through-flow field results for flow angle(\( \alpha \)), and velocity(\( V \)). Here, \( X_a \) and \( X_b \) are chord and span spectrum functions, and \( c \) and \( \beta \) are fan blade chord and setting angles. In addition, \( a_n \), \( R \) and \( \sigma \) represent the speed of sound, the measuring distance and the elevation angle form fan blade tip respectively.

The blade interaction noise due to the secondary flow and the tip leakage flow within fan blades is produced also at multiple BPFs( mB mode ), and its sound pressure is expressed by

\[ SP_{mB} = \frac{M_c}{2\pi r_c} D_p L_{sec} E \rho_m mBx_w x_a \]

where \( L_{sec} \) is the lift fluctuation due to secondary and tip leakage flows, \( w \) and \( E \) are the width and the number of load excursion, and \( \rho_m \), \( p_m \) mean blade loading spectrum function, loading solidity. In calculating \( L_{sec} \), the present study assumes that the lift fluctuation due to secondary flow as 20% of the steady lift, \( L_T \), and the Sarajona’s correlation[10,11] is used to calculate the lift fluctuation due to tip leakage flow.

(2) Broadband Noise Model

Broadband noise is produced over entire frequency range due to turbulent boundary layer on blade surface, inflow turbulence and blade wake. According to the theory of fan sound radiation by Carlous[12], acoustic power spectral density function(PSDw) of a fan is expressed as
\[
PSD_w(f) = \frac{dW(f)}{df} = \frac{\pi}{4 \rho \omega^2 \Delta f^2} \left( PSD_{F_{,IFT}} + PSD_{F_{,TBL}} \right) + BPSD_{TE}
\]

where \( r_t \) and \( r_h \) represent tip and hub radii of fan, subscripts IFT, TBL, TE mean inflow turbulence, turbulent boundary layer and trailing edge wake vortex respectively.

The spectral density function of aerodynamic force fluctuation on blade surface (PSD) is obtained and approximated by the following surface integral on the blade surface as

\[
PSD_p(f) = \int \int PSD_{sp}(f, x_1, x_2) A_c(f, x_1, x_2) dx_1 dx_2 \approx \int_{hub}^{tip} PSD_{sp}(f, r) A_c(f, r) c(r) dr
\]

where \( A_c(f) \) and \( c(r) \) are correlation area and chord length varied along blade span. Here, because chordwise variation of PSD is much smaller than spanwise one, the surface integral of eq. (4) can be approximated by spanwise integration.

For three broadband noise mechanisms due to inflow turbulence(IT), turbulent boundary layer(TBL) and trailing edge wake(TE), the present study employs the semi-empirical models of the surface pressure fluctuation(PSDsp) and the or the analyses of fan flow correlation area(Ac) of IT and TBL, and a 1/3-octave band semi-empirical model for the TE noise prediction(refer to reference [12]). It is noted that all the flow parameters used in calculating PSDsp are obtained from the through-flow analysis results by SCM.

(a) Inflow turbulence

\[
PSD_{sp} = \frac{1}{4} (0.9\pi)^2 \rho W^2_1 PSD_{w_2}
\]

\[
PSD_{w_2} = \frac{V_T u^2 A_x 10^{-PSD_{L^*_c}}}{(log(Sr_A))^3}
\]

\[
PSD_{L^*_c}(Sr_{A_c}) = -9.874 - 19.001 (log(Sr_{A_c})) - 5.548 (log(Sr_{A_c}))^2 - 0.060 (log(Sr_{A_c}))^3
\]

where \( \rho \), \( W_1 \), \( V_T \) and \( A_x \) are the density, the relative velocity, the axial velocity, the turbulence intensity and the turbulence length scale of air at fan rotor blade inlet. In eq. (5), the Strouhal number(Sr_{A_c}) is defined as \( Sr_{A_c} = \frac{f_{A_c}}{V_T} \) and f is frequency.

(b) Turbulent boundary layer

\[
PSD_{sp}(f) = \rho^2 W^3 \delta^2 \left( \frac{0.01}{1+4.1985 \delta^4+0.4545 \delta^5} \right)
\]

\[
A_c(f) = \begin{cases} \frac{W_1 c^4 (r_t-r_h)}{5nf} & \text{when } \pi Sr_c \leq 2 \\ \frac{2W_1^2 c^2 (r_t-r_h)}{5n^2 f^2} & \text{when } 2 \leq \pi Sr_c \leq 15/\pi \\ \frac{6W_1^2 (r_t-r_h)}{\pi^2 f^3} & \text{when } \pi Sr_c \geq 15/\pi \end{cases}
\]

Here \( \delta^2 \) is the trailing edge displacement thickness of turbulent boundary layer developed on a blade element surface, which can be calculated by the profile loss correlation[5] of SCM, and two relevant Strouhal numbers are defined as

\[
Sr_{\delta^2} = \frac{f_{\delta^2}}{W_1} \text{ and } Sr_c = \frac{f_c}{W_1}
\]

(c) Trailing edge wake

\[
PSD_{TE}(f) = 7.079 B\delta^2 M^5 (r_t - r_h) \frac{4\pi c^2(f)}{d f_{1/3oct}}
\]

\[
G(f) = \frac{4(f/f_{pea})^{2.5}}{(1+(f/f_{pea})^{2.5})^{1.2}} \text{, } f_{peak} = \frac{0.02W_1 M^{-0.6}}{\delta^2}
\]

where M is relative Mach number of air at blade inlet and \( df_{1/3oct} \) is the bandwidth of each 1/3-octave band.

3. Analysis results and discussions

The flow distribution results calculated by the present analysis method are compared with the measurement of NASA 23B compressor rotor blade(refer to the detailed design specifications of NASA TP-1523[13]). As shown in Figs. 2-3, the predicted distributions of relative flow angle, relative and axial flow velocities agree well with the measurement along blade span height. These good comparison results mean that the present through-flow analysis method is very suitable for predicting fan flow field...
with high prediction accuracy.

![Fig. 2 Relative flow angle distribution of NASA compressor rotor blade](image)

![Fig. 3 Relative and axial flow velocity distributions of NASA compressor rotor blade](image)

Fig. 2 Relative flow angle distribution of NASA compressor rotor blade

Fig. 3 Relative and axial flow velocity distributions of NASA compressor rotor blade

Fig. 4 also shows the performance prediction result of forward-swept or unswept fan operating at 3700 RPM, which is designed with the tip diameter of 38 cm, the hub to tip ratio of 0.46, the number of fan blades of 6[2]. As can be seen in Fig. 4, the predicted static pressure curves of two fans agree well with the measurement results regardless of blade sweep. The results also show a good agreement over air flow capacity of 30 CMM, while different trend of the distributions appears at the lower air flow capacity. The reason of this different trend between numerical results and experiment data can be found from the present flow deviation angle model used for SCM, which is less accurate at the lower air flow capacity conditions with stalling incidence angles. Fig. 5 also shows the aero-acoustic performance map of automotive fan designed with the tip diameter of 35.6 cm and the rotation speed of 3900 RPM. The comparison results between the present prediction and the measurement[14] show good agreements in the aspects of overall pressure, efficiency and noise level. Especially, the variation of overall noise level over entire flow capacity range is well predicted by the present noise model.

![Fig. 4 Static pressure curves of forward-swept and unswept fans operating at 3700 RPM](image)

![Fig. 5 Aero-acoustic performance map of automotive fan operating at 3900 RPM](image)

Fig. 4 Static pressure curves of forward-swept and unswept fans operating at 3700 RPM

Fig. 5 Aero-acoustic performance map of automotive fan operating at 3900 RPM

Furthermore, the present method is applied to the three fan models with different blading design cases by free vortex(FV), combined vortex(CV) and controlled blading design methods. The present study conducts CFD calculations on the three fan models by using the ANSYS CFX code with the mesh system of Fig. 6, and the present CFD simulations employ frozen rotor scheme and SST k-ω turbulence model. Performance tests on the three fan models are also conducted in a chamber-type test facility which is constructed and operated according to AMCA standard. Fig. 7 shows the comparisons between the present prediction(FANDAS), the CFD and the test results[15] with very good agreements over entire flow capacity ranges. From the comparison results, it is known that the present through-flow method by SCM is suitable for predicting the change of performance curve due to different fan blading design.
Flow capacity [CMH]
Static pressure [Pa]
FANDAS (FV)
FANDAS (CV: DR = 0.82)
FANDAS (Controlled blading)
CFD (FV)
CFD (CV: DR = 0.82)
Test (Controlled blading)

The predicted fan noise spectra by the present method are also compared with the measurement results of three fan models with forward-swept, straight or backward-swept blades as shown in Fig. 8. The noise spectrum measurements on the three fan models are carried out in an anechoic room of chamber-type fan test facility by using FFT analyzer with the narrow-band of Δf = 1 Hz. From the results of Fig. 8, it is shown that the effect of blade sweep on fan noise spectrum can be predicted very accurately by the present through-flow method coupled with noise model. As can be known in Fig. 8, applying forward or backward blade sweep to fan blade stacking design, BPF noise components produced in fan blade elements along span height are phase-shift cancelled and then the magnitudes of BPF harmonics are significantly reduced when they are compared with the fan model with no sweep (“straight blade”).

![Fig. 6 Mesh system and CFD results of fan](image)
![Fig. 7 Static pressure curves of fans with different blading designs](image)

(a) Straight blade with no sweep Blade  (b) Blade with backward-sweep of -30 deg  (c) Blade with forward-sweep of +30 deg

**Fig. 8** Noise spectra of three fan models with different blade sweep angles

### 4. Conclusions

The present study provides a new through-flow analysis method for axial fan performance and noise predictions. The present through-flow analysis with flow deviation and pressure loss models is conducted on designed fan blades by streamline curvature method to calculate pitch-averaged flow distributions along blade span and compute overall fan performance map by mass-averaging of the calculated flow parameters. The present through-flow analysis method also evaluates fan’s overall noise level and noise spectrum by combining BPF and broadband noise models with the flow distribution calculation results. The fan flow, performance and noise prediction results by the present method are compared with the CFD and the performance/noise measurement results of several axial flow fans. The comparison results show that the present through-flow analysis method has high prediction accuracies for fan performance and noise evaluations and is very suitable as a design tool at actual fan development practice.

### Acknowledgments

This work was supported by the Energy Technology Development Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) granted financial resource from the Ministry of Trade, Industry and Energy, Republic of Korea (No.20172010106010).
References


