A Computerized System, the FANDAS Code, for Design, Flow, Performance and Noise Predicitions of Industrial Axial FAN

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Abstract: FANDAS (FAN Design and Analysis System) code is developed for the design, the performance and the noise predictions of industrial axial fan. In the FANDAS code, the 3-D geometrical designs for impeller blades and casing of fan are made through blade angle distribution, camber line determination and blade airfoil thickness distribution processes along blade span height, and their results are shown in GUI(Graphic User Interface) window. Based on the design fan geometry, the FANDAS code automatically predicts the flow field inside fan and the overall performance map of fan by using flow deviation and pressure loss models. The noise level and spectrum of designed fan are also evaluated by the FANDAS code which contains noise analysis models for discrete frequency and broadband noise components of axial fan. All the performance and the noise prediction results are displayed on GUI windows. The simulation technique of the FANDAS code is coupled with the CFX code and applied to an actual air-conditioning fan design practice for optimizing design variables to maximize efficiency and minimize overall noise level of fan. The optimal fan design obtained from the FANDAS simulation results shows about 10% efficiency improvement and 11dB noise reduction compared with the commercial market product of a reference model, and its simulation results are well-agreed with the measurement within a few percent relative error.

1 INTRODUCTION

Axial flow fans are widely used rotating machines in industrial, ventilation and air-conditioning systems. However, air-born noise of the axial flow fan is strongly related with the aerodynamic flow field and the performance of fan, so the noise control and reduction of fan must be attempted with the consideration of the interaction between aerodynamic and acoustic characteristics. For this reason, the actual fan design practice in industry calls for reliable analysis method for predicting both performance and noise level. With the recent advances in computational fluid dynamics and aero-acoustic methods, the flow, the performance and the noise predictions have been being attempted by many previous researchers (Belamri et al., 2005; Carolus et al., 2007). However, because their methods are based on computational fluid dynamics techniques so have still shortcomings requiring a lot of input data, complicated modeling work, long computing time and skillful engineer's experience for successful iterative computation, they still remain as analysis tools and can't be applied to the actual design stage of axial fan.

Therefore, the present study introduces a simpler and less time consuming fan design-analysis method, FANDAS(FAN Design and Analysis System), for design and performance/ noise predictions. The fan design process of FANDAS gives 3-D rotor and stator blade geometries from fan design requirements and specification, and can transfer them to CFD code. FANDAS also analyzes the internal flow field and the performance of designed fan by combining quasi-3D inviscid computation scheme, flow deviation and pressure loss models. With the predicted fan flow field and performance data, FANDAS predicts the discrete frequency fan noise at blade passing frequency and its harmonics due to rotating steady aerodynamic lift and blade by secondary and tip leakage flows. Broadband noise of fan is predicted with the use of the correlation model expressed in terms of the performance parameters.

The present study applies the FANDAS method coupled with CFX code to optimize actual air conditioning fan. Through the parametric study by FANDAS, optimal fan design variables are firstly determined for high efficiency and low noise, and more optimized fan geometry is achieved by the 3-D CFD simulation of CFX code. Furthermore, the FANDAS prediction results are compared with measured results to verify the reliability and the prediction accuracy of FANDAS.

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2 DESIGN AND ANALYSIS METHOD OF FANDAS

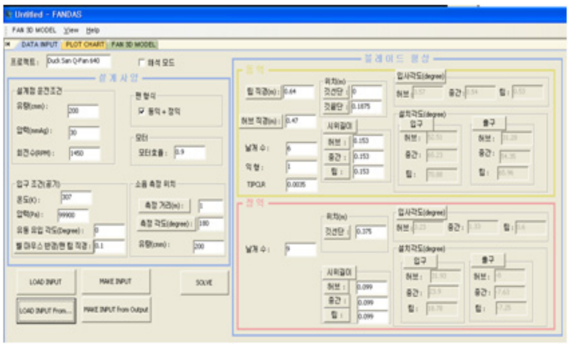
2.1 FAN Blade Design Method

Once fan design requirements are given from the GUI of FANDAS as shown in Fig. 1(a), FANDAS determines fan rotor and stator blade geometries by using conventional design processes through spanwise blade angle distribution, camber line determination, airfoil thickness distribution to blade section element stacking. Fig. 1(b) shows the fan blade geometry designed by FANDAS. For the design versatility of fan, FANDAS contains various airfoil geometry data base for NACA, DCA, C4 and even curved plate, and also can export the designed fan blade geometry to CFD code.

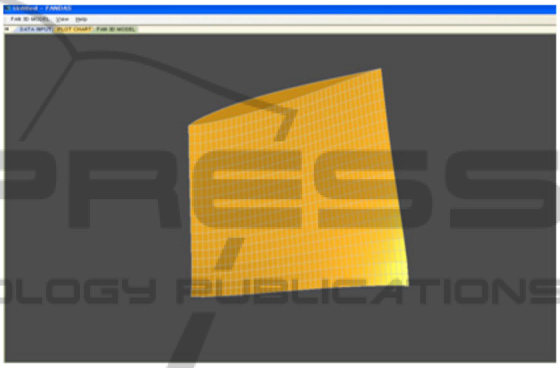
2.2 FAN Flow and Performance Analysis Models

Based on designed fan blade geometry, FANDAS conducts internal fan flow field analysis by the through-flow technique using the assumption of axisymmetric flow within fan blades, so all the flow variables such as flow angle, velocity, pressure loss and so on, are computed on the pitch-averaged flow surface. The computing scheme of the present through-flow is applied to each streamline from hub to tip, and uses and combines inviscid pitch-averaged Navier-Stokes equation, Euler work equation, flow angle and pressure loss models. The present flow angle and pressure loss models use already well-verified correlations available from open literature and previous related researches (Lieblein, 1959; Lieblein, 1960; Horlock and Lakshiminarayana, 1973; Koch and Smith, 1976; Lee and Chung, 1991).

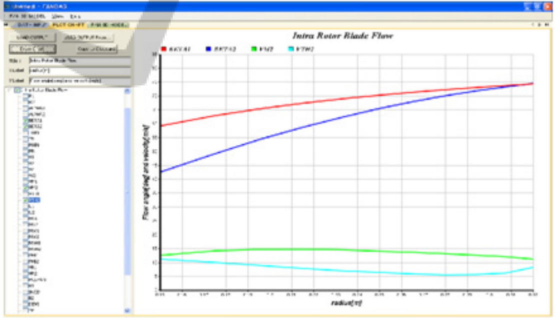
It is noted all the flow angle and pressure loss models are very complicated functions expressed in terms of various fan blade design parameters and flow variables, so the through-flow analysis requires iterative computation process. Once iterative computation on flow filed is carried out until satisfying overall and local mass conservations, spanwise flow distributions for all the flow variables can be achieved and then overall performance parameters such as pressure rise, power and efficiency are also calculated by the mass-averaging of computed flow variables along blade span height(Refer to Fig. 1(c) and Fig. 1(d)).



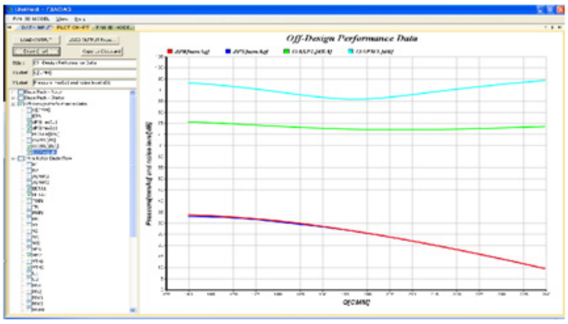
(a) Input data window



(b) 3-D blade geometry design



(c) Spanwise flow velocity and angle distributions



(d) Aeroacoustic performance map

Figure 1: FANDAS input and output results.

2.3 FAN Noise Analysis Models

After the flow distribution and the fan operating condition are determined by above-mentioned through-flow method, fan noise level and spectrum are predicted by the noise analysis method of FANDAS that is constructed as a combination of two models for the discrete frequency noise due to BPF (blade passing frequency) and blade interaction, and for the broadband noise due to turbulent boundary layer and wake vortex shedding. The discrete frequency noise for rotating steady fan blade thrust is analyzed by Gutin's theory(Wright, 1976) where fan blades are assumed as compact moving sources, and its sound pressure level at BPF or its harmonics can be expressed by the following equation:

$$SP_{mB} = \frac{NL_T}{Ra_o}(\cos\beta\sin\sigma - \frac{\sin\beta}{M_e})mBJ_{mB}(mBM_e\cos\sigma)\chi_a\chi_b$$

$$L_T = B\int_{span}\ell dr = B\int_{span}[\frac{1}{2}\rho V^2 c\times\frac{2}{(c/s)}\cos\alpha_m(\tan\alpha_1 - \tan\alpha_2)]dr$$

$$\chi = \frac{\sin x}{x}, x = mB\pi\rho, \rho_a = \frac{c}{2\pi r_e}, \rho_b = \frac{b}{2\pi r_e M_e\cos\sigma}, M_e = \frac{2\pi N r_e}{a_o} \qquad (1)$$

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(α), and velocity(V). Here, r_e is effective radius as the 80% of fan blade tip radius and c, b and β are fan blade chord, span and setting angles. In addition, a_o, R and σ 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

$$SP_{mB} = \frac{M_e}{2\pi r_e R} D_p L_{sec} E \rho_w mB \chi_w \chi_a \chi_b$$

$$\chi_w = \frac{\sin(\pi mB\rho_w)}{\pi nB\rho_w}, \rho_w = \frac{w}{2\pi r_e},$$

$$D_p = \begin{cases} \cos\beta\sin\sigma & if\,\theta = 0^o \\ \sin(\sigma + \beta) & if\,\theta = 90^o \end{cases} \qquad (2)$$

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 θ means the azimuth angle between blade tip and sound measuring location. In calculating L_{sec}, the present study assumes the lift fluctuation due to secondary flow as 20% of steady lift, L_T, and uses the Sarajona's correlation for the tip leakage flow (Lee and Chung, 1991; Sjolander and Amrud, 1987).

The broadband noise is modeled by the Mugridge's correlation (Mugridge, 1976) as shown in eqn.(3). In his model, fan sound power level and its spectrum are expressed in terms of fan performance parameters such as efficiency, flow and pressure rise coefficients, which can be predicted through the through-flow analysis mentioned before in the section 2-1 of this paper.

$$PWL(f)=K_2+25\log_{10}P_s - 2 + 10\log_{10}Z + F_2(f)\ [dB]$$

$$Z=[(1-\eta_s)/\eta_s][(\varphi^2+1-\psi+\psi^2/2)/\psi]^{3/2} \qquad (3)$$

where Ps, φ,ψ and ηs are fan static pressure, flow coefficient, pressure rise coefficient and efficiency. In addition, K_2 and $F_2(f)$ are given by Fig. 2.

As shown in Fig. 3, fan noise levels, sound power and pressure spectra are obtained from the prediction results by the above-mentioned fan noise models.

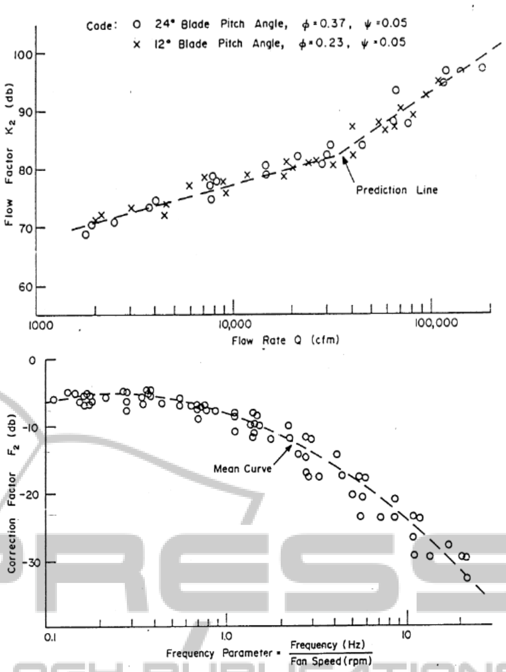
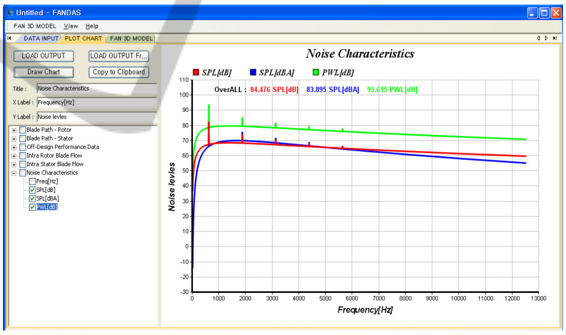


Figure 2: Flow (K_2) and correction (F_2) factors.



Title : Noise Characteristics

X Label : Frequency[Hz]

Y Label : Noise levles

- ☐ Blade Path - Rotor
- ☐ Blade Path - Stator
- ☐ Off-Design Performance Data
- ☐ Intra Rotor Blade Flow
- ☐ Intra Stator Blade Flow
- ☐ Noise Characteristics
  - ☐ Freq[Hz]
  - ☑ SPL[dB]
  - ☑ SPL[dBA]
  - ☑ PWL[dB]

OverALL : 84.476 SPL[dB] 83.895 SPL[dBA] 95.615 PWL[dB]

Figure 3: Fan noise spectrum predicted by FANDAS.

3 FAN DESIGN OPTIMIZATION BY FANDAS

3.1 FAN Design Requirements and Specifications

For verifying the reliability of FANDAS in actual fan design practice, FANDAS is applied to the actual air-conditioning fan design problem under the following design requirements:

- Static pressure: 30 mmAq
- Flow capacity: 200 m^3/min
- Efficiency: maximum
- Sound pressure level: lower than 84 dBA @ 1m

Table 1 also summarizes fan design specifications of this study.

Table 1: Fan design specifications and methods.

RPM	1170	Stator chord	0.1 m
Tip diameter	0.63 m	No. of stators	11
Hub/tip ratio	0.44	Angle distrib.	Free vortex
Rotor chord	**0.09-0.11 m**	Camber design	Circular arc
No. of rotors	**8-12**	Rotor airfoil	NACA65-010
Tip clearance	0.0025 m	Stator airfoil	Cambered plate

3.2 Parametric Study and CFD Verification

As shown in Table 1, this study is focused to optimize fan rotor blades design variables such as chord length and number of rotor blades for maximizing fan efficiency. The parametric study results on the two design variables by FANDAS are represented in Figs. 3-5.

From the results of Figs. 4 and 5, it is noted that the number of rotor blades should be larger than 11 to meet the design requirements for fan static pressure and noise level. In addition, Fig. 6 shows the best fan efficiency of 78% is achieved at the rotor chord length of 0.1 m and the number of rotor blades of 12, which are optimum design conditions.

The 3-D CFD simulation by CFX code is carried out on the firstly optimized fan blades, and uses frozen-rotor scheme and SST(shear stress transport) turbulence model for numerical computation. Fig. 7 shows the computed results at three spanwise locations by CFX code and they are compared with FANDAS quasi 3-D analysis results. The predicted flow angle and velocity distributions are well agreed between the FANDAS and the CFX.

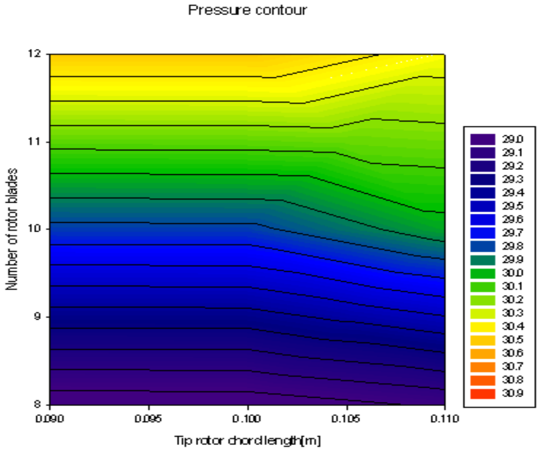


Figure 4: Parametric studies for fan pressure.

As shown in the CFD results of Fig. 7, the effect of tip leakage flow is very remarkable at 90% span location while air flows at hub and mid-span regions are streamlined along blade section surfaces with no flow separation. However, in the aspect of pressure loss, the CFD analysis results show the hub region produces more pressure loss than the mid-span region. From these CFD analysis results, it can be judged that the chord length of rotor blade section at hub can be somewhat reduced to decrease the pressure loss within the range to secure attached and streamlined flow along hub blade surface. Therefore, final optimal design of fan rotor blade is chosen with the spanwise chord length distribution from 0.07m(hub) to 0.1m(tip) and the number of blades of 12.

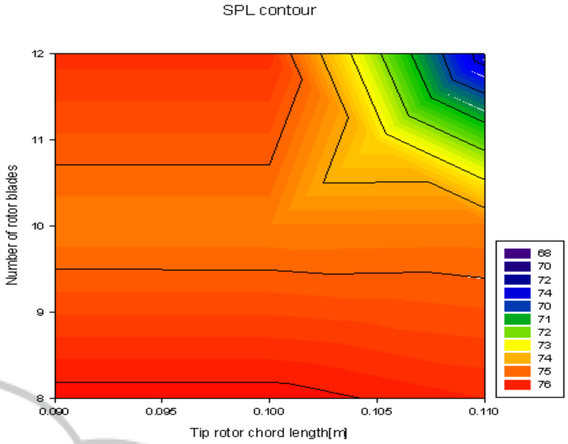


Figure 5: Parametric studies for fan noise.

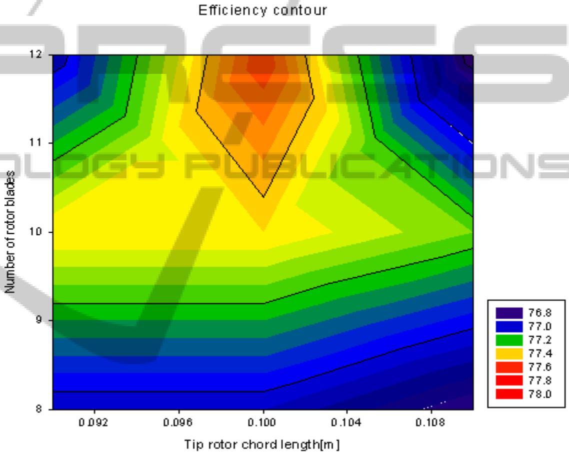


Figure 6: Parametric studies for fan efficiency.

3.3 FAN Performance and Noise Tests

The 3-D shapes of optimized rotor and stator are presented in Fig. 8, and manufactured fan model is shown also in Fig. 9. The performance and noise tests for the optimized fan model are conducted in the chamber test facility of KTC(Korean Testing Certification) according to AMCA and ISO standards. The test results at design point are compared with the FANDAS prediction results in Table 2, and they are very well agreed within a few percent relative error. It is also shown from Table 2 that the optimization by FANDAS can improve fan efficiency by 10% and reduce noise level by 10 dB compared with the market product of Korea, not optimized one.

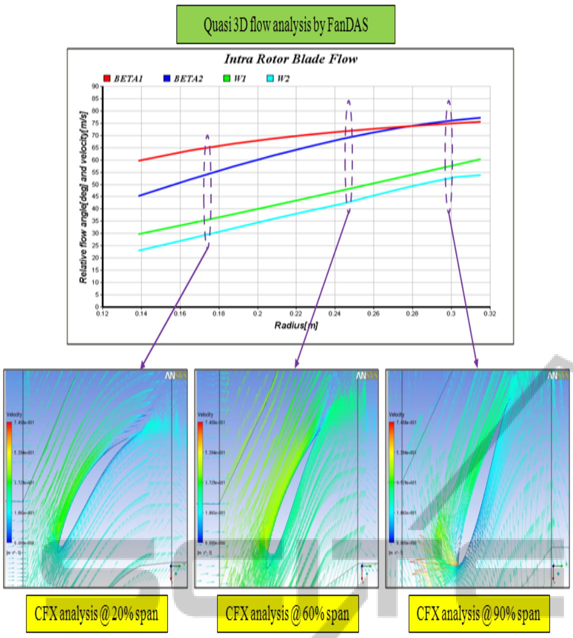


Figure 7: Flow analysis results by FANDAS and CFX.

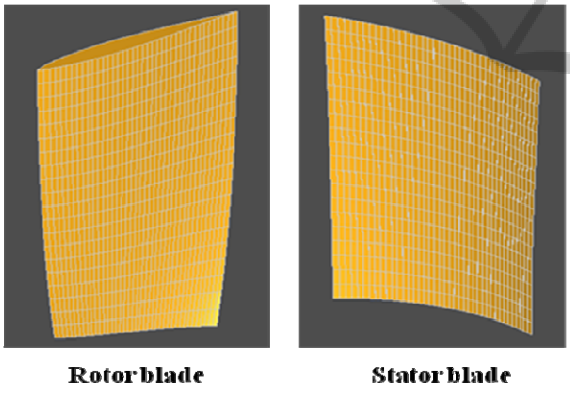


Figure 8: 3-D Fan blade geometries(optimized).

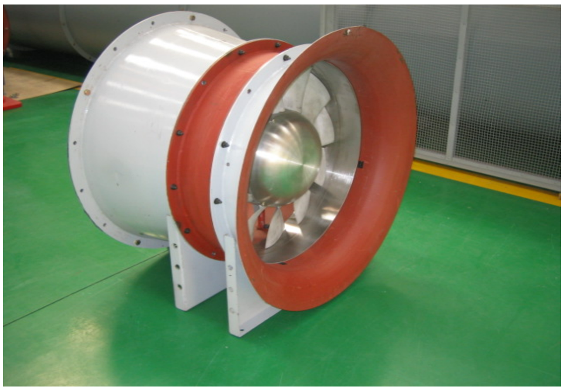


Figure 9: Manufactured fan model(optimized).

Table 2: Performance and noise test results.

Model	Pred	Flow m^3/min	Pressure mmAq	Effici. %	PWL dB	SPL dBA
Optimal model	FANDAS	200	32.4	78.2	91.3	78.09
	Test	200	36.0	75.0	90.0	79.00
Market product	Test	210	34.5	65.0	101.0	90.00

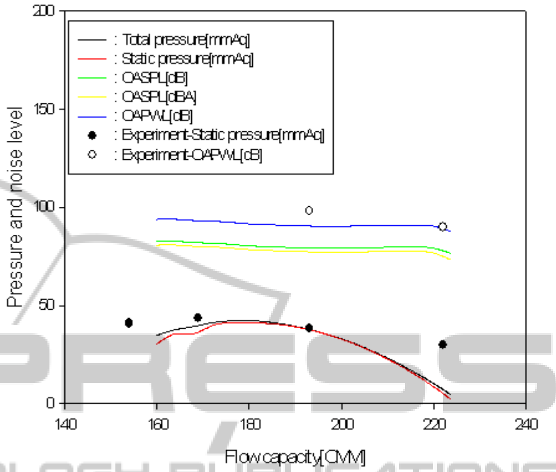


Figure 10: Aero-acoustic performance map.

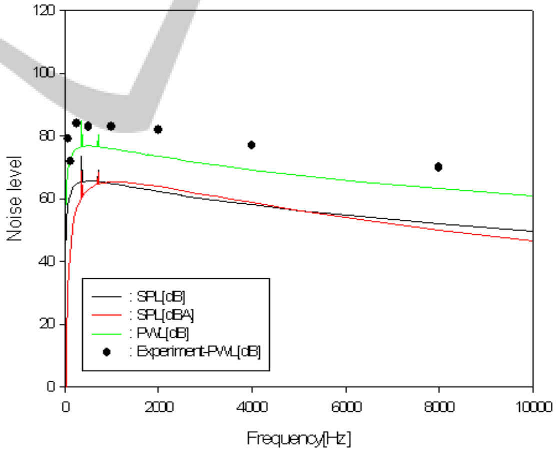


Figure 11: FAN noise spectrum.

Fig. 10 compares the aero-acoustic performance results by FANDAS with the test, and the FANDAS analysis method is known to give reliable prediction for the performance and noise level at off-design condition. Fig. 11 also shows the good agreement between the FANDAS prediction and the test results on the noise spectrum at Q=220 m^3/min.

4 CONCLUSIONS

The FANDAS code is developed with GUI for design, flow, performance and noise analyses of axial flow fan.

The FANDAS code is applied to high-efficiency and low-noise air conditioning fan development case, and its design results are verified by the comparison with CFD and test results within a few percent relative errors. The fan design optimization by the FANDAS code can improve fan efficiency by 10% and reduce noise level by 10 dB compared with the conventional market product as baseline one.

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