성능 및 소음의 Inverse Design Method를 이용한 송풍기(唤) 설계

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Integrated Design Technology

Turbo. Design Trends in 21st C.

- Extensive Optimization in a Short Period of Time
- Concurrent Engineering:
  Object Linking and Embedding (OLE) S/W
  Design for Manufacturing and Assembly
- Integration of Meanline Analysis, 3D Blade Design,
  FEA, CFD, CAD, Rapid Prototyping
Integrated Design Technology

Classical Design Product

- Conceptual
- Preliminary Engineering
- Fundamental Engineering
- Applied Engineering

Marketing:
- Concept & Payoff

Cycle Evaluation / Preliminary Design Selection

Detailed Design

Test Evaluation & Development

Manufacturing

Sales
Integrated Design Technology

Turbomachinery Designers and Test Engineers

Meanline Design Optimization:
- Design
- Analysis-Tool
- Performance Curve
- Data Reduction and Comparison

3D Geometry Generation and Throughflow Analysis
- 2D and 3D Description of Rotors and stators
- Rapid Loading Calculations
- Quasi 3D Flow Calculations
- Reverse Engineering of Existing Designs

Finite Element Analysis (FEA) Pre-Processor
- Computational Fluid Dynamics (CFD) Design Optimization
- 3D FEA for Stress and Vibration Analysis

CFD Pre-Processing

CFD Post-Processing

FEA Post-Processing
- Campbell Diagram
- Interference Diagram
- Life Evaluation

“Virtual Laboratory”:
- Pneumatic
- Laser
- Hot Film
- Thermal
- Structural
- Time Domain

Product Development System

“Synthesis”:
- Semi-Automated Comparison of Design Intent to Tested Design

Laboratory Testing for Component Development

Rapid Prototyping
- Stereo Lithography
- Sintered Casting Cores

Numerical Machining
- Ruled Surfaces
- Strip Milling
- Arbitrary Surface

Computer Aided Drafting (CAD) and Solid Modeling (SM)

System Issue:
- Gears
- Motors
- Generators
- Cooling

Rotor Dynamics
- Seals
- Bearings
- Critical Speeds
- Unbalance Response
- Forced Response

Adapted from Japikse, 1996
Aerodynamic Inverse Design Method

Aerodynamic Optimization

- **Numerical Optimization Method**
  - Maximization/Minimization of Object Function
  - Sensitivity Analysis
  - Combination with CFD Solver

- **Inverse Design Method**
  - Pre-defining the Desired Velocity Distribution
  - Multi-point Inverse Design by Selig (1994)
  - Defining Blade Loading Distribution by Zangeneh (1991)
  - 3-D CAD, CFD, Inverse Design Method by Goto (2001)
Aerodynamic Inverse Design Method

Inverse Design Method by Goto. (Blade Loading Distribution)
Aerodynamic Inverse Design Method

Inverse Design Method (Conventional Design, Goto et al.)

(a) CFD prediction
(b) Oil-film flow pattern
Aerodynamic Inverse Design Method

Inverse Design Method (Inverse Design Stage, Goto et al.)

(a) CFD prediction

(b) Oil-film flow pattern
Noise Prediction Method

Noise Sources in Fan/Blower

- **Dipole Type of Noise Source (Gutin, 1937)**
  \[ \rho_0 = \frac{1}{4\pi a_0^2} \int_{S(t_0)} \left[ \frac{R_j}{R^2C^+} \frac{\partial}{\partial \tau} \left| C^+ \right| \right] dS(\zeta) \]

- **Inflow-Turbulence Noise**
  \[ u(t) = u_\infty e^{-i\omega t} \quad f_\omega = 2\pi \frac{u_\infty \rho_0 U^2 A_b}{2} \frac{1}{(1 + 2\pi k)^{0.5}} \quad \hat{k} = \frac{\omega C}{2U} \quad I \sim \rho_0 c_0^3 M^6 \left( \frac{A_b}{\Lambda r} \right)^2 \alpha^2 \cdot \cos^2(\phi) \]

- **Trailing Edge Noise**
  \[ I \propto \rho_0 c_0^3 \cos^3(\bar{\theta}) M^5 \frac{sl}{r^2} \alpha^2 \cdot \sin(\varphi) \sin^2(\theta / 2) \]
  Amplification by \((2k_0 r_0)^{-3}\) for longitudinal and lateral quadrupoles normal to the trailing edge (Ffowcs Williams)
  Sweep wing shape, Serrated trailing edge shape (Howe, 1991)

- **Tip Noise**
  Pressure difference between suction and pressure sides results in a cross flow over the side edge of the tip

- **Noise from Separation / Stall**
  More than 10 dB increase for stalled flow relative to trailing edge noise for low angle of attack
Generalized Equations of Mass and Momentum

\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = \rho_0 u_i \delta(f) \frac{\partial f}{\partial x_i}
\]

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j + P_{ij}) = P_{ij} \delta(f) \frac{\partial f}{\partial x_j}
\]

Ffowcs Williams-Hawkings (FW-H) equation

\[
\frac{\partial^2 \rho'}{\partial t^2} - C_0^2 \frac{\partial^2 \rho'}{\partial x_j^2} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_i} (P_{ij} \delta(f) \frac{\partial f}{\partial x_i}) + \frac{\partial}{\partial t} (\rho_0 u_i \delta(f) \frac{\partial f}{\partial x_i})
\]

where the function \(f(x, t) = 0\) represents the shape of the surface and its motion.
Noise Prediction Method

- **Farassat’s Formulation 1A**

  - **Monopole Sound**

    \[
    P_M'(x,t) = \frac{1}{4\pi} \int_{f=0} \left[ \frac{\rho_o \hat{v}_n}{r(1-M_r)^2} \right] \, ds + \frac{1}{4\pi} \int_{f=0} \left[ \frac{\rho_o v_n (r\mathbf{\hat{M}} \cdot \mathbf{r} + c_o M_r - c_o M^2)}{r^2(1-M_r)^3} \right] \, ds_{ret}
    \]

  - **Dipole Sound**

    \[
    P_D'(x,t) = \frac{1}{4\pi c_o} \int_{f=0} \left[ \frac{\mathbf{\hat{F}}_{i_i}}{r(1-M_r)^2} \right] \, dS + \frac{1}{4\pi} \int_{f=0} \left[ \frac{F_r - F_i M_i}{r^2(1-M_r)^2} \right] \, dS_{ret} + \frac{1}{4\pi c_o} \int_{f=0} \left[ \frac{F_r (r\mathbf{\hat{M}}_{i_i} + c M_r - c M^2)}{r^2(1-M_r)^3} \right] \, dS_{ret}
    \]

  - **Quadrupole Sound**

    \[
    P_Q'(x,t) = \frac{1}{4\pi c_o^2} \int_{v(t_o)} \left[ \frac{\mathbf{r}_{i_j}}{r^3(1-M_r)} \frac{\partial}{\partial \tau} \left( \frac{1}{(1-M_r)} \frac{\partial}{\partial \tau} \frac{T_{i_j}}{1-M_r} \right) \right] \, dV_{ret}
    \]
Noise Prediction Method

- LES + Acoustic Analogy (Farassat’s Solver)

- Aerodynamic Sound from the DLR Axial Fan
  - Experimental Data
  - Computational Results by LES
Noise Prediction Method

- Dipole and Quadrupole Computation of Aeroacoustics from Axial Fan

AeroNet Inc.
Unsteady Loading Source Identification

Sound from airfoil

Pressure fluctuations

Feedback mechanism

- Flow separation and reattachment
- Karman vortices in wake
- Turbulence
- Flow over sharp corner
Noise Prediction Method

■ Noise Source Identification

- (a) $\alpha = 0^\circ$
- (b) $\alpha = 3\sim 6^\circ$
- (c) $\alpha = 9\sim 12^\circ$
- (d) $\alpha \geq 15^\circ$

Discrete frequency noises
Kirchhoff + BEM Prediction

Kirchhoff Surface

Unsteady loading으로 계산한
환경 전방 0.5m 지점에서의 소음의 주파수 특성
Noise Prediction Method

- Near-field and Far-field Sound by Steady+Unsteady Loadings

![Far-field and Near-field Sound Diagrams](image)
Acoustic Inverse Method

- Acoustic Field Reconstruction
  - Indirect Boundary Element Method (Zhang et al., 2000)
  - Multi-dimensional Time Domain Acoustic Inverse Method (Gustafsson et al., 2000)
Acoustic Inverse Method

Time Domain

Monopole: \( \hat{q} / r \)

Dipole: \(-\frac{\partial}{\partial x_i}\left(\frac{[f_i]}{r}\right)\)

Quadrupole: \(\frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{[t_{ij}]}{r}\right)\)

\[
\begin{bmatrix}
\hat{P}_1 \\
\hat{P}_2 \\
\vdots \\
\hat{P}_R
\end{bmatrix} =
\begin{bmatrix}
\hat{Z}_{11} & \hat{Z}_{12} & \cdots & \hat{Z}_{1S} \\
\hat{Z}_{21} & \hat{Z}_{22} & \cdots & \hat{Z}_{2S} \\
\vdots & \vdots & \ddots & \vdots \\
\hat{Z}_{R1} & \hat{Z}_{R2} & \cdots & \hat{Z}_{RS}
\end{bmatrix}
\begin{bmatrix}
[\hat{q}] \\
[f_i] \\
[t_{ij}]
\end{bmatrix}
\]

\[
\begin{bmatrix}
\tilde{P}_1(\omega) \\
\tilde{P}_2(\omega) \\
\vdots \\
\tilde{P}_R(\omega)
\end{bmatrix} =
\begin{bmatrix}
Z_{11} & Z_{12} & \cdots & Z_{1S} \\
Z_{21} & Z_{22} & \cdots & Z_{2S} \\
\vdots & \vdots & \ddots & \vdots \\
Z_{R1} & Z_{R2} & \cdots & Z_{RS}
\end{bmatrix}
\begin{bmatrix}
\tilde{q}(\omega) \\
f_i(\omega) \\
\tilde{t}_{ij}(\omega)
\end{bmatrix}
\]

BEM

Frequency Domain

\(\tilde{q}(\omega) \frac{e^{ikr}}{r}\)

\(-f_i(\omega) \frac{\partial}{\partial x_i}\left(\frac{e^{ikr}}{r}\right)\)

\(\tilde{t}_{ij}(\omega) \frac{\partial^2}{\partial x_i \partial x_j}\left(\frac{e^{ikr}}{r}\right)\)
Inverse Design of Low Noise Fan

Operating Conditions
Inverse Design of Low Noise Fan

Design Cases of Blade Loading Distribution
Inverse Design of Low Noise Fan

3-D Surface Data of Design Cases
Inverse Design of Low Noise Fan

Sound 3-D Surface Data of Design Cases

- CASE1: $P_{dist} = 1.05, C_m_{dist} = 0.95$
- CASE2: $P_{dist} = 1.50, C_m_{dist} = 0.80$
- CASE3: $P_{dist} = 1.25, C_m_{dist} = 0.65$
- CASE4: $P_{dist} = 1.90, C_m_{dist} = 0.80$
- CASE5: $P_{dist} = 1.90, C_m_{dist} = 0.50$
- CASE6: $P_s = const, C_m_{dist} = 0.70$
- CASE7: $P_s = const, C_m_{dist} = 0.80$
- CASE8: $P_s = const, C_m_{dist} = 0.50$
- CASE9: $P_s = const, C_m_{dist} = 0.63$
- CASE10: $P_s = const, C_m_{dist} = 0.63$

$C_m_{max} : R = 0.0533m$
Inverse Design of Low Noise Fan

**Inverse Method Using Singular Value Decomposition**

\[
[X] = [H][P_t] \quad \Leftrightarrow \quad [H] = [X][P_t]^{-1}
\]

\[
[X] = \begin{bmatrix}
\sqrt{10^{dB_{1,1}/10}} & \cdots & \sqrt{10^{dB_{1,10}/10}} \\
\vdots & \ddots & \vdots \\
\vdots & \cdots & \sqrt{10^{dB_{10,10}/10}}
\end{bmatrix}
\]

\[
[P_t] = \begin{bmatrix}
P_{t,1,1} & \cdots & P_{t,1,10} \\
\vdots & \ddots & \vdots \\
\vdots & \cdots & P_{t,10,10}
\end{bmatrix}
\]

\[
[P_t]^{-1} \text{는 Singular로써 SVD를 통해 Inverse Matrix 구함. 즉,}
\]

\[
[P_t] = [u][s][v]^T \quad : \text{Inverse 곤란}
\]

\[
\hat{[P_t]} = [u][\hat{s}][v]^T \quad : \text{Inverse 가능}
\]

\[
\hat{[P_t]} = [u][\hat{s}][v]^T \quad \Leftrightarrow \quad [H] = [X][\hat{P_t}]^{-1}
\]
Inverse Design of Low Noise Fan

Inverse Method Using Singular Value Decomposition

\[
[P_t]_{new} = [H]^{-1}[X]_{new}
\]

\[
[X]_{new} \quad \text{원하는 소음분포,}
\]

\[
[P_t]_{new} \quad \text{Design될 Total Pressure}
\]

Ex)

\[
[X] = \begin{bmatrix}
11.9380 \\
38.4473 \\
44.7836 \\
41.8917 \\
31.6093 \\
31.9061 \\
42.8748 \\
47.1584 \\
37.9707 \\
25.8041
\end{bmatrix}
\]

\[
[X]_{new} = \begin{bmatrix}
11.9380 \\
38.4473 \\
44.6090 \\
41.8917 \\
31.6093 \\
31.9061 \\
42.8748 \\
46.8485 \\
37.9707 \\
25.8041
\end{bmatrix}
\]
iDesignFan™ S/W

iDesignFan™ Blade Design System

- Blade Loading Distribution (Radial Total Pressure Distribution)
- 3-D Inverse Design Method
- Automatic Grid Generation
- RANS CFD Code (ANSWER™)
- Ffowcs-Williams & Hawkings + Farassat Acoustic Solver
- Acoustic Inverse Method
- BEM Code
- 3D Surface Modeling
- Rapid Proto-typing System
iDesignFan™ S/W

- iDesignFan™ Blade Design System