Fan design: Past, Present and Future

Alain GODICHON
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The fan industry 45 years ago

The main challenges in fan engineering:

– Fan performance accuracy
– Prediction of fan noise
– Cost competitiveness

And above all:
– Technical reliability
The fan industry 45 years ago

• The tools we were using:
  – We were at the beginning of mainframe computers:
    
    For the programming in industry, we were still using paper tape, as can be seen on the right, on which instructions were read by the computer.

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The fan industry 45 years ago

• The tools we were using in the 1970s:

Then came the use of cards (already used for decades for Jacquard weaving machines) to register instructions for the mainframe computer.
... and 25 years ago

• The tools we were using in the 1990s:

But things changed fast. By the 1990's a university student would typically own his own computer and have exclusive use of it in his room.
PERFORMANCE ACCURACY

• Model testing in the 1970s:
Fan noise

- Noise performance data measurement in the 1970s:

Inlet power acoustic level

Calculation for the full size fan from model results

Full size fan measured

Model

Global noise 1/3 octave band analysis

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Fan design in the 1970s

• Theoretical analysis:
  - Rayleigh & Ritz, for rotor Dynamics.
  - Jacob Pieter Den Hartog who describes theoretically and experimentally a number of vibration phenomena, in particular for rotating machines.
  - Stephen Timoshenko, for the calculation of structures.

Stephen Timoshenko (1878-1972) is often referred to as the father of applied mechanics. He wrote seminal works in the areas of engineering mechanics, elasticity and the strength of materials, some of which are still in regular use.

Source: Wikipédia
Stress and strain analysis

• Experimental methods in the 1970s:

*Instrumentation of a fan impeller with strain gauges*
Stress and strain analysis

- Experimental methods in the 1970s:

*brittle lacquer used for stress evaluation with centrifugal forces*
Technical reliability

(Fan catastrophic failure in a steel plant in the early 70s).
Technical reliability

- Vibration analysis:

Real time analysis of an impeller

Visualization of disc vibration modes
Technical reliability

The premises of the Finite Element Analysis method:

1975

models today containing millions of elements.

2015

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Technical reliability

- FEA results post-processing

**Haigh diagram (fatigue analysis)**

Dynamic loading vs static loading on an axial blade: plot of actual dynamic stress vs allowable dynamic stress
Progress on fan performance

• Progress on fan performance:

  Fan efficiency:
  ➢ Large improvement on the complete fan-motor system, thanks to the use of variable speed motors.
  ➢ Gradually the use of mechanical devices like inlet vanes or inlet dampers to regulate flow decreases with the benefit of a variable speed drive.
Optimisation of fan performance

From Euler equation...

to

... the resolution of 3-D Navier-Stokes equations through CFD analysis

At the end of 1990s, CFD results correlate previous experimental results
Optimisation of fan performance

**Claude-Louis Navier** (1785 –1836), was a French engineer and physicist who specialized in mechanics. Navier is therefore often considered to be the founder of modern structural analysis. But his major contribution however remains the Navier-Stokes equations (1822), central to fluid mechanics.

The Navier-Stokes equations are named after him and **George Gabriel Stokes**.

**George Gabriel Stokes** (1819 - 1903), 1st Baronet, was a British mathematician and physicist. His major contributions concern fluid mechanics, optics and geodesy. His mathematical approach describing the flow of an incompressible Newtonian fluid in three dimensional space, adding a viscous force from the Euler equations (General principles of fluid motion, 1755), is the source of Navier-Stokes equations.

Source: Wikipédia
Using CFD to design high performance fans

3-D CFD prediction playing a key role in the aerodynamic design of High performance fans

Authors: Dr Wilfried Rick, Dr Eribert Benz, Alain Godichon

ABB review 2 / 2000
Optimisation of fan performance

Cut-away of a forced draft fan, showing the inlet boxes with the adjustable guide vanes, the double inlet impeller and the scroll housing.

Computational grid for the scroll housing and impeller.

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Optimisation of fan performance

Vector flowfield at part load (impeller centerplate). The large positive incidence onto the leading edge results in the formation of a leading edge vortex.
Optimisation of fan performance

- Use of CFD to predict better fan performance

New Heart for the ONERA S1MA wind tunnel

2009 / Wind Tunnel International
Wind Tunnel S1MA Modane

Source: courtesy of ONERA

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Wind Tunnel S1MA Modane

Contra-Rotating Fan Specifications
Number of blades: 12 (V1) + 10 (V2)
Fan diameter: 49.2 feet (15 m)
Fan blade mean chord: 4.6 feet (1.4 m)
Blade length: 12.3 feet (3.75 m)
Maximum power available: 88 MW
Total mass of the fans: 55 tonnes

Source: courtesy of ONERA

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Design improvement using CFD analysis on 2 high efficiency contrarotative axial fans

Configuration of the two-stage counter-rotating fan,

Example of CFD grid for the original blade design

Source: courtesy of ONERA
Optimisation of fan performance

Pressure distribution on the new blade profile

Source: courtesy of ONERA
Optimisation of fan performance

– From Euler equation to CFD analysis

Design improvement using CFD analysis on 2 high efficiency contrarotative axial fans (ONERA)

Mach number at h/H = 0.125 for Q = 9000 kg/s
comparison between old design (left), ONERA 2 (center left) and ONERA 3 (center right), and ONERA4 (right)

Source: courtesy of ONERA and Howden Solyvent-Ventec
Optimisation of fan performance

– Fan efficiency (CFD results)

Source: courtesy of ONERA and Howden Solyvent-Ventec
Wind Tunnel S1MA Modane – Fan model test

Fan Performance Comparison Test
(April - October 2005)

- FSV test rig 1/12.5 scale
- Fan model diameter 47 inches (1.2 m)
- Power: 2 x 55 kW motors
- Fan speed = 1500 rpm

Source: courtesy of ONERA and Howden Solyvent-Ventec
Fan model test

The model test rig, with both counter-rotating stages fitted and the wind tunnel elbow upstream of the fan also modeled to more accurately simulate fan inlet flow-field.

Source: courtesy of ONERA and Howden Solyvent-Ventec
Optimisation of fan performance

• Comparison of model test with CFD results:

Fan Efficiency

![Graph showing fan efficiency versus mass flow](image-url)
Fan acoustics in the 1970’s

- Fan noise and acoustic calculation

Lycée du Parc de Lyon – Maths sup’ – 1966-67 – class of Physics with Mr Paul Ponsonnet.

1972 – Paul Ponsonnet: « Fan noise and acoustic calculation on fan installations »
Using CFD to predict Aeroacoustic fan performance

Large-eddy Simulation of the Aerodynamic and Aeroacoustic Performance of a Ventilation fan

Authors: S. Bianchi, D. Borello, A. Corsini, F. Rispoli and A.G. Sheard
Using CFD to predict Aeroacoustic fan performance
CFD in Acoustics

Predicted fan broadband noise and spectrum
Other applications of CFD

- Use of CFD to predict fan erosion

Study of particle erosion in industrial turbomachines:

Authors: A. Corsini, L. Cardillo, G. Delibra, P. Venturini
Other applications of CFD

Particle Cloud Tracking (PCT) approach (*Baxter, 1989*)

A huge number of particles can be simulated within each cloud
Few clouds covers the whole domain
Particle distribution is assumed to be Gaussian within a cloud
Cloud size varies with turbulence characteristics of the flow
Knowledge Management in Tailor Made Industrial Fans
Knowledge Management in Tailor Made Industrial Fans

• An increasing proportion of industrial fans are custom designed for the application as a consequence of the desire to both maximise aerodynamic efficiency and fit with the gas transportation requirements.
• The result of these requirements is that the fan dimensions and the fan technology are defined on a case by case basis adapted to the specific needs of individual project applications.
• Adapting the fan dimensions on a case by case basis results in the same design rarely, if ever, being used twice.
• A benefit of a custom industrial fan design process is that the resultant fan is optimised for the application. A weakness is a requirement for a unique aerodynamic and mechanical design, and the associated risk of design related errors.
Knowledge Management in Tailor Made Industrial Fans

Industrialization of Selection Tools

Customer-oriented design
Authors: Alain Godichon, Fläkt Solyvent-Ventec, France & Geoff Sheard, Fläkt Woods Ltd, UK

International Cement review – October 2009
Customer-oriented design

- An automated selection-and-design program which enables full details of the range of centrifugal process fans to be available at the quotation stage.

- The program covers fan aerodynamics, acoustical calculations, the mechanical design of the complete fan, and detailed price calculations.

- The program has the capacity to provide customers with prompt solutions to their requirements in the form of high-quality technical and price offerings.
The Program Architecture

Input Target Pressure and Flow

Pre-Aerodynamic Selection

Aerodynamic Calculation

Acoustic Calculation

Mechanical Calculation (Rotating Parts)

Mechanical Calculation (Static Parts)

Parts Fit?

No

Yes

Pricing Calculation

Technical Reports (Including automatic general arrangement drawing and 3d CAD block)

Output to Automatic Drawing Generator

With the courtesy of Howden Solyvent-Ventec

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Web-Based Engineering Tool

• A unique web based engineering tool available to all design engineers to:
  – Select and tune a fan solution against customer specifications
  – Design all components following embedded technical rules
  – Produce General Assembly Drawing at tendering
  – Generate most of the components manufacturing drawings, reducing engineering cycle.
Aerodynamic Selection

With the courtesy of Howden Solyvent-Ventec
Mechanical Calculation (Rotating Parts)

Mechanical calculation includes

the impeller design,
the shaft design,
the bearing and the coupling selections:

Impeller design is done through an algorithm in which minimum material thicknesses, selection of materials constitutes the basis.

- Stress and vibration criteria
- Definition of wear protection
- Shaft-and-impeller assembly
Mechanical Calculation (Rotating Parts)

Mechanical calculation includes the impeller design, the shaft design, the bearing and the coupling selections:

• Hub and shaft and bearing design are mainly supported by a rotor dynamic analysis.
  – Different shaft models are defined for the different fan arrangements and for different types of assemblies between the impeller and the shaft.
  – The selected model is modified by successive iterations in order to reach the minimum requirement or an imposed value for the first critical speed.
  – Bearing properties and more particularly the stiffness properties of the sleeve bearings which are affecting directly the installed resonant speed are calculated thanks to a direct link with a sleeve bearing selection program.
Mechanical Calculation (Rotating Parts)

Hydrodynamic bearing dynamic characteristics

Dynamic properties of hydrodynamic (sleeve) bearings are characterized by 8 parameters: direct and cross coefficients for stiffness ($K_{xx}$, $K_{xy}$, $K_{yy}$, $K_{yx}$), direct and cross coefficients for damping properties ($C_{xx}$, $C_{xy}$, $C_{yy}$, $C_{yx}$). The following equations govern the oil film forces on the shaft, with the following conventional axis.

\[
F_x = -(K_{xx} \Delta x + K_{xy} \Delta y + C_{xx} \dot{\Delta}x + C_{xy} \dot{\Delta}y)
\]

\[
F_y = -(K_{yx} \Delta x + K_{yy} \Delta y + C_{yx} \dot{\Delta}x + C_{yy} \dot{\Delta}y)
\]

Where $\Delta x$ and $\Delta y$ represent the shaft displacements and $\dot{\Delta}x$, $\dot{\Delta}y$ the shaft velocities respectively in the x and y directions; $F_x$ and $F_y$ are the resulting forces in the x and y directions, respectively.
The Automatic Drawing Capability

With the courtesy of Howden Solyvent-Ventec

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The Automatic Drawing Capability

• The aerodynamic and mechanical design process outputs a set of technical specifications and reports that may be used by a design engineer to produce manufacturing drawings.

• The data produced during the aerodynamic and mechanical design process may also be produced as a set of parametric attributes that can be used to drive parametric CAD models.

• Parametric attributes may be used to drive a parametric general arrangement model.

• Once a general arrangement drawing has been automatically created, the general arrangement drawing can be used to generate additional parametric attributes that can then be used to generate individual component manufacturing drawings.

• A 3-D model of the complete fan may also be produced, with the exact dimensions for its integration in a 3-D plant model. This facilitates a full understanding of the fan installation and possible adjustments of requirements.

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Automatic Shaft Manufacturing Drawing

With the courtesy of Howden Solyvent-Ventec

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Summary

• Knowledge management through the selection and design tool:
  – Ensures that the same design rules are consistently applied.
  – Ensures that when an error is occurred and the error is then fixed in the code, that fix is systematically applied to all future designs.
  – The software allows relatively inexperienced users to make a contribution without risking the introduction of basic errors.

• Concerning the automatic production of drawings:
  – Automatic production of the General Arrangement Drawing ensures that all manufacturing drawings start from a technically correct origin.
  – Automatic production drawings ensure that a consistent approach is applied to all manufacturing drawings.
Conclusion
Conclusion

The fantastic capabilities offered by the development of computers and numerical analysis:

Historically at first, the mechanical design thanks to FEA analysis.
The aerodynamic design through CFD simulation.
Now and in the future
The capability to perform acoustic prediction.

The future of fan design seems to be oriented today in practice towards the concept of a virtual product which can be fully created from customer requirements within a system handling design, costing and manufacturing.