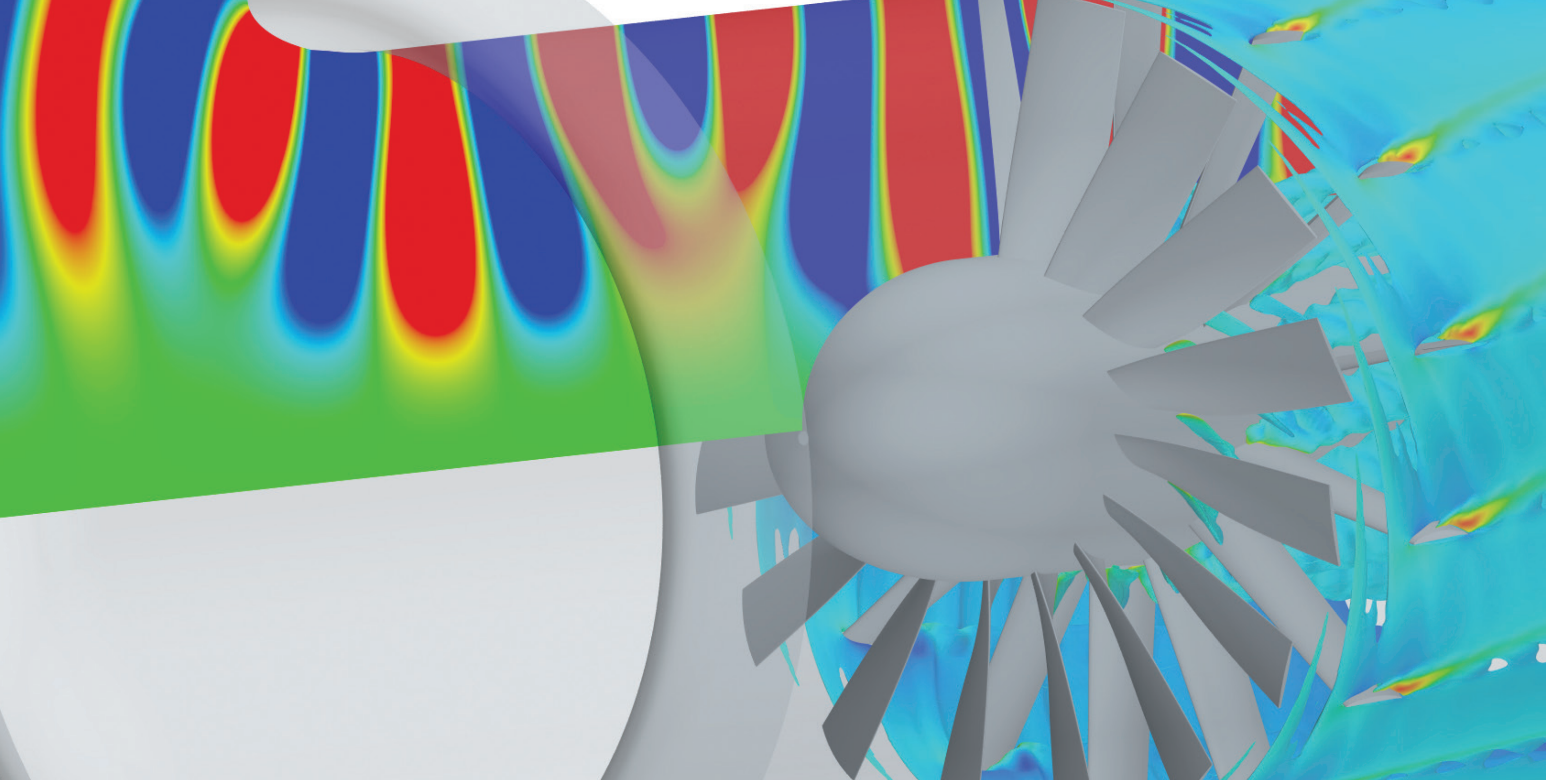

DIGITAL INDUSTRIES SOFTWARE

Reducing aircraft engine noise

Using simulation to design quieter aircraft engine fans

Executive summary
Fan noise is becoming a dominant source of engine noise for most flight phases. For conventional turbofan architectures, this can be linked to the continuous increase in bypass ratio (hence fan diameters) and the reduction of nacelle inlet length. For electrified powertrain concepts that rely on fans to produce thrust, such as urban air mobility applications, reducing noise emissions is critical for certification and market success due to the lower flight altitude and flight routes within urban environments.

This white paper shows how you can use Simcenter™ software to simulate fan noise from its generation to propagation in the environment. Simcenter is part of the Siemens Xcelerator portfolio, the comprehensive and integrated portfolio of software, hardware and services.

Sylvain Pluchart
Simcenter Application Specialist Turbomachinery
Siemens Digital Industries Software

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Introduction

To mitigate the environmental and societal impacts of commercial aviation, pollutant emissions regulations have become increasingly stringent. As an example, the Advisory Council for Aeronautics Research in Europe (ACARE) sets a target of 65 percent reduction in noise for the aviation industry by 2050, relative to the 2000 baseline.

Many industry sectors, including commercial aviation, face the global energy challenge. This calls for engineers to use the available energy more efficiently and adopt alternative energy sources. As explained in a Siemens blog titled "How electrified aircraft propulsion impacts design processes," one example of this involves using simulation to understand the benefits of powertrain electrification.

On top of the energy supply aspect, pollutants are left out in the environment due to aircraft development and operations. Carbon dioxide (CO_2) and nitrogen oxides (NO_X) are examples known for their adverse effects on climate and health. But pollutants do not simply refer to the undesirable chemical species released at the back of the engine, it is also about the propagation of noise and its impact on animal and human life.

This white paper focuses on aircraft engine noise. First, it explains a specific noise generation mechanism and then discusses how you can use Simcenter to produce high-fidelity simulations with a reduced computational effort, making it usable in an industrial context. This digital workflow enables you to further explore the available design space with a reduced allocation of time, staff and monetary resources that are typically required for physical testing.

Regulations and societal acceptance

There are two major incentives for mitigating aircraft noise emissions. The first one is regulatory, with limits imposed by the certification process. It consists of noise levels measured during fly-over tests at specific locations relative to the runway (on the side or in the axis) and for different operating conditions, such as approach before landing or takeoff at full power.

The standards set by the International Civil Aviation Organization (ICAO) become more stringent as new generations of aircraft are developed.[1]

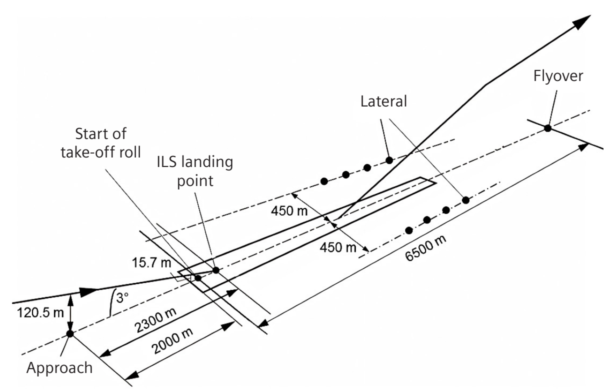
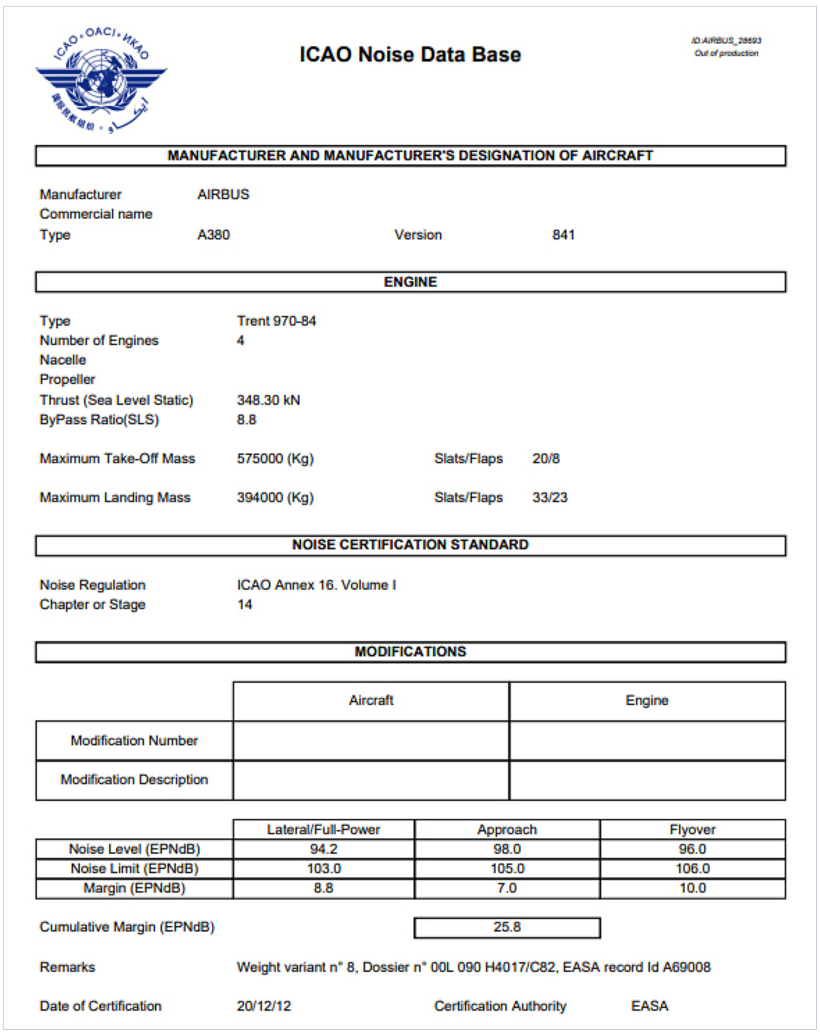


Figure 1. The black dots represent the positions of measuring points for aircraft noise certification. (image courtesy of American Institute of Aeronautics and Astronautics)

Regulation authorities are not the only driving forces. Noise pollution has a direct impact on populations living close to airports and might cause airport infrastructure projects to be rejected. Societal acceptance of commercial aviation cannot be guaranteed without proper integration of noise pollution regulations in populated areas.

This is even more critical for the emerging market of urban and regional air mobility. Many aircraft concepts are developed for short and medium ranges to connect smaller regional airports. Consequently, most of the flight will happen at lower altitudes and over densely populated areas.



ICAO Noise Data Base

ID:AIRBUS_28693
Out of production

MANUFACTURER AND MANUFACTURER'S DESIGNATION OF AIRCRAFT

Manufacturer AIRBUS
Commercial name
Type A380 Version 841

ENGINE

Type Trent 970-84
Number of Engines 4
Nacelle
Propeller
Thrust (Sea Level Static) 348.30 kN
ByPass Ratio(SLS) 8.8

Maximum Take-Off Mass 575000 (Kg) Slats/Flaps 20/8

Maximum Landing Mass 394000 (Kg) Slats/Flaps 33/23

NOISE CERTIFICATION STANDARD

Noise Regulation ICAO Annex 16. Volume I
Chapter or Stage 14

MODIFICATIONS

	Aircraft	Engine
Modification Number		
Modification Description		

	Lateral/Full-Power	Approach	Flyover
Noise Level (EPNdB)	94.2	98.0	96.0
Noise Limit (EPNdB)	103.0	105.0	106.0
Margin (EPNdB)	8.8	7.0	10.0

Cumulative Margin (EPNdB) 25.8

Remarks Weight variant n° 8, Dossier n° 00L 090 H4017/C82, EASA record Id A69008

Date of Certification 20/12/12 Certification Authority EASA

Figure 2. Example of noise measurement results for an Airbus A380. (image courtesy of ICAO)

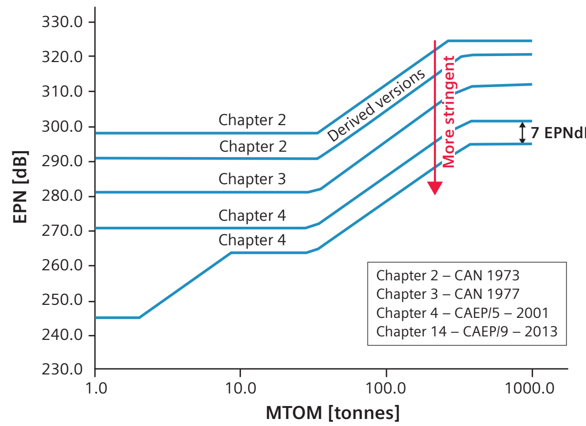


Figure 3. Progression of the ICAO noise standards for airplanes. (image courtesy of ICAO)

The success of this new market segment will depend on the aircraft ability to stay quiet. “Silent” might even be part of the name, as seen in the Silent Air Taxi concept from German company e.SAT.

Let’s not forget the noise perceived by crews and passengers. Some airplanes, such as the Airbus A380, are particularly praised for the cabin acoustic comfort and provide a competitive advantage for their operators.

Figure 4. Artist’s view of the Silent Air Taxi concept. The propulsion is ensured by ducted fans powered by a hybrid-electric powertrain. (image courtesy of e.SAT)

Noise generation mechanisms for fan-based aircraft propulsion

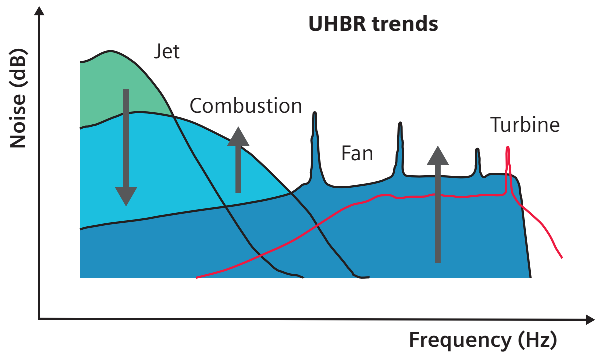


Figure 5. Typical turbofan noise source spectrum and trends. (image courtesy of University of Sherbrooke)

When considering a conventional turbofan architecture where the fan is powered by a gas turbine, there are different contributions to the overall noise produced by the engine. In the following figure, these contributions are sketched as a function of the frequency.

Two important facts are conveyed in figure 5. First, we see that some noise generation mechanisms are spread over a large range of frequencies, while others tend to peak at certain frequencies. The former is called broadband noise and the latter is called tonal noise.

The second piece of information in figure 5 is the evolution of these contributions, represented by the arrows. We see that the contribution of fan noise (orange area) is expected to increase. Why is that?

When fan noise takes over

The main reason why fan noise will likely be a dominant source of future designs ties back to the quest for better efficiency. A turbofan has essentially two streams: the core (or hot) stream where the combustion occurs and the bypass (or cold) stream where the air going through the fan is directly exhausted to produce thrust. The ratio from the bypass stream to the core stream is called the bypass ratio.

Both streams contribute to thrust generation but increasing the amount of air that goes through the bypass produces a more efficient engine. One way to do that is to increase the fan diameter, which has the problematic consequence of promoting fan noise.

For an electrified powertrain, when the fan is powered by an electric machine instead of a gas turbine, the other mechanisms identified, such as combustion, are simply not present.

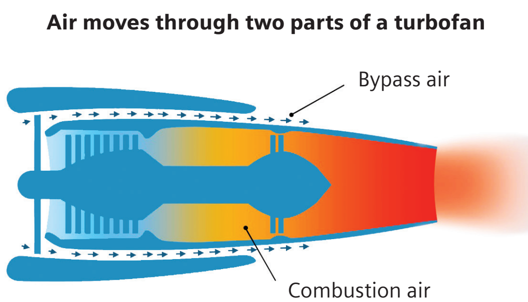


Figure 6. The overview of existing engine bypass ratios. (image courtesy of Boldmethod)

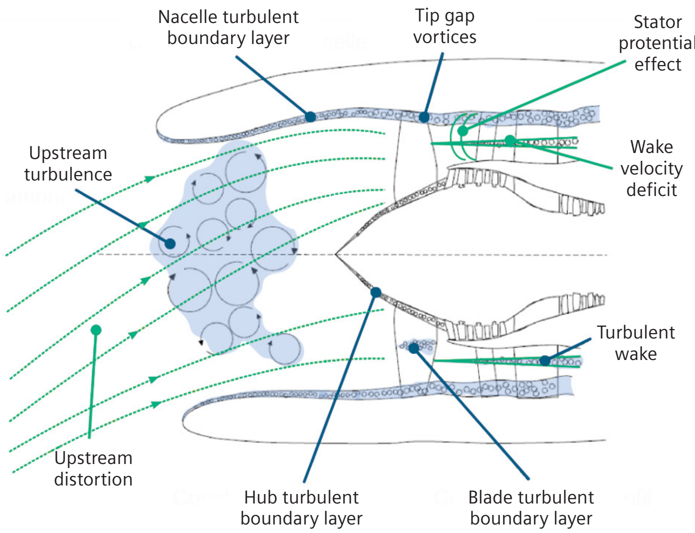


Figure 7. Sketch of the noise sources associated with a rotor-stator assembly. The tonal mechanisms are highlighted in green and broadband in blue. (image courtesy of University of Sherbrooke)

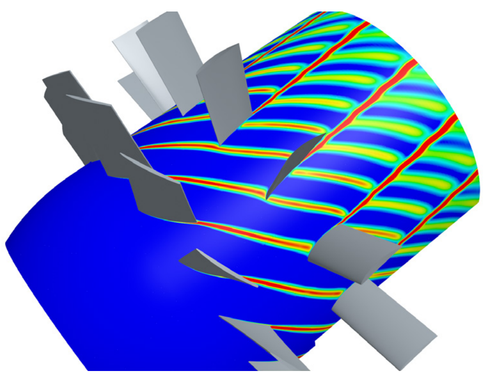


Figure 8. The rotor wakes are propagating downstream and are chopped by the stator vanes. Renderings generated using Simcenter STAR-CCM+; regions of higher vorticity are colored at mid-span.

Rotor-stator interaction

Since fan noise is of specific interest, it's important to identify various noise generation mechanisms. Figure 7 categorizes them as broadband or tonal.

The relative contribution of the different mechanisms depends on the operating conditions and the geometry of the engine. Here, the focus is on the wake velocity deficit, which is of primary importance for many designs.

A wake velocity deficit corresponds to the zone where the flow streams from the pressure and the suction side of the rotor blades mix and propagate downstream. These zones are characterized by a higher vorticity and a lower velocity compared to the surrounding flow.

Propagating downstream, the rotor wakes will impact the stator vane, triggering pressure fluctuations on their surfaces and acting as a noise generation mechanism.

The magnitude and phase of these fluctuations, hence the noise generated, will depend on the geometry and the flow conditions. Some design parameters will have an impact on the rotor-stator interaction: rotor blade and stator vane count, rotor-stator axial gap or the stator vane "sweep" angle (inclination in the axial direction) to name a few. The next step is to predict noise levels and analyze design alternatives.

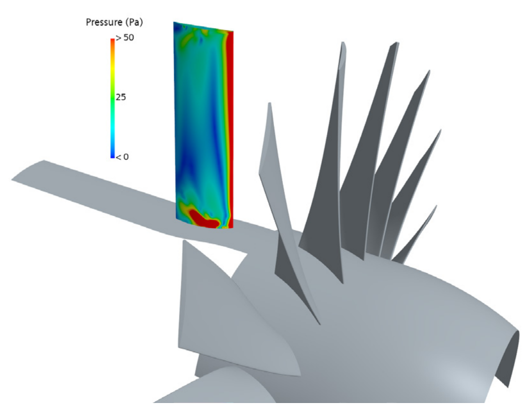


Figure 9. Magnitude of pressure fluctuations on a vane calculated using Simcenter STAR-CCM+. On this geometry, fluctuations are mainly located on the leading edge and the tip and root of the vane.

Using simulation to support quieter aircraft engine designs

ANCF test bed

To illustrate how you can use simulation to predict and mitigate rotor-stator interaction, we will model the Advanced Noise Control Fan (ANCF). The ANCF (initially the Active Noise Control Fan) is an experimental setup developed by NASA and used in the design, test, and evaluation of innovative fan noise reduction technologies.[2]

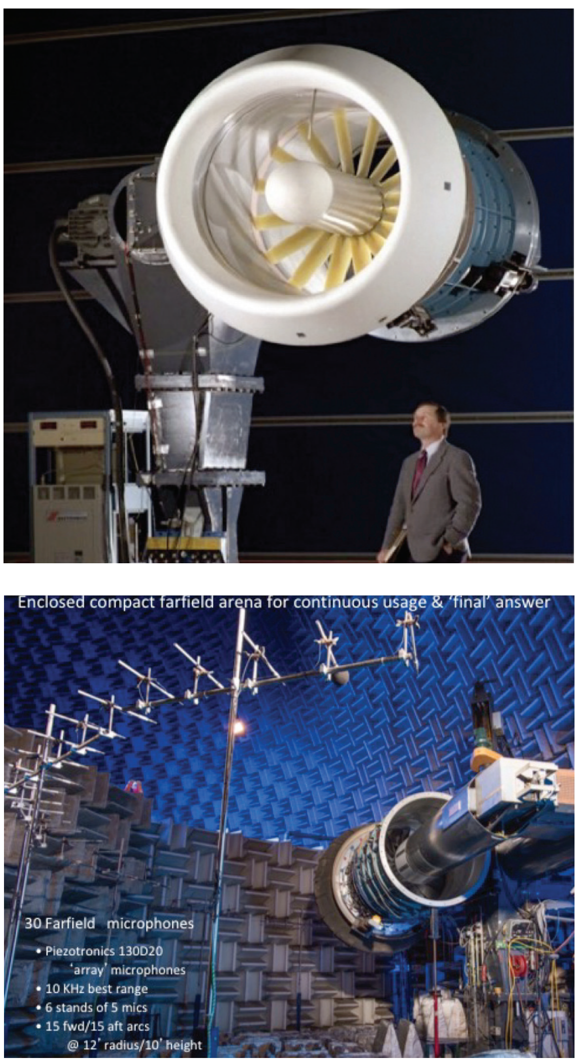


Figure 10. The ANCF early days. (image courtesy of NASA)

It is composed of a rotor-stator assembly with 16 rotor blades and 14 stator vanes in the configuration that is simulated. The fan operates at 1800 revolutions per minute (rpm), resulting in a blade passing frequency of 480 hertz (Hz) and an inlet Mach number of around 0.15.

Using Simcenter STAR-CCM+ to simulate the rotor-stator interaction

Rotor-stator interaction is an unsteady phenomenon, as the variable of interest is the pressure fluctuation on the stator vane surface. Traditional computational fluid dynamics (CFD) methods such as Unsteady Reynolds Averaged Navier-Stokes (URANS) can be extremely time-consuming, as they require you to construct a time-marching scheme and simulate multiple sectors of the machine. In the case of the ANCF geometry, one URANS simulation leads to a simulation of half of the machine (eight rotor blades and seven stator vanes) and can take up to several weeks.[3]

You can use Simcenter STAR-CCM+™ software with a method called harmonic balance that is suited to model periodically repeating flow fields that occur in turbomachinery such as compressors, turbines and fans. It is a full decomposition of the Navier-Stokes equations in the frequency domain. The unsteady, transient flow is represented in the frequency domain as a Fourier series in time. As a result, the computational burden is reduced to only three to six times longer than a steady simulation. On top of that, the method allows you to simulate a single passage only for the rotor and the stator, which decreases the computational effort even more.

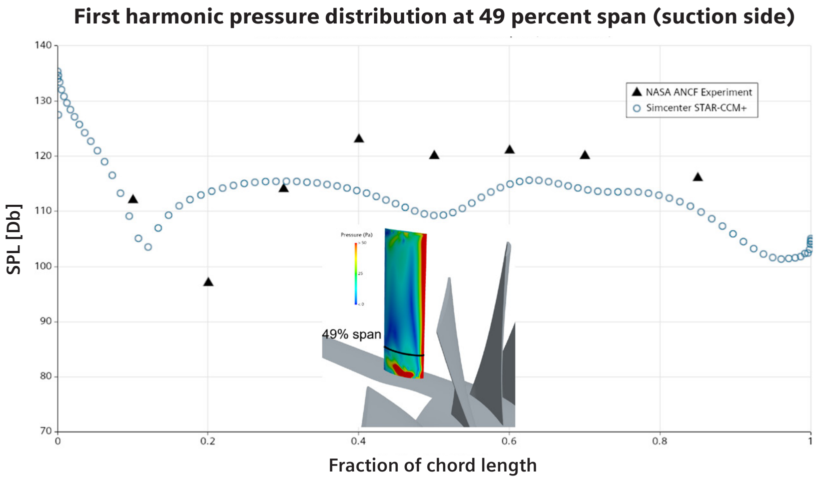


Figure 11. Magnitude of the pressure fluctuation on the vane surface at 49 percent of the shroud radius.

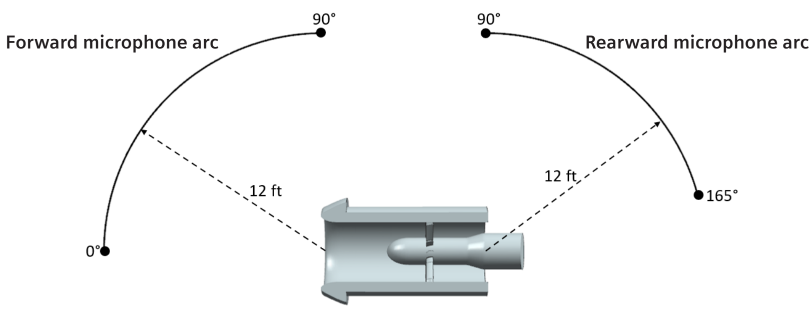


Figure 12. The experimental setup used to measure the noise directivity. Results from simulations using Simcenter are compared with virtual microphones positioned at the same locations.

Once applied to the ANCF, you can complete the unsteady flow simulation within less than 200 central processing unit hours (CPU.hrs). One can typically complete the study overnight by leveraging parallel processing capabilities. The resulting flow field captures the rotor wakes impinging on the stator and the resulting pressure fluctuations. Figure 11 shows that simulation can reasonably capture the magnitude of the pressure fluctuations measured on the test bed.

Using Simcenter 3D to propagate to the far-field

Once you characterize the noise generation mechanism, the next step is to propagate to the observers located in the far-field. As previously stated, observers might represent a populated area next to the runway or the passengers in the cabin enjoying their flight.

In the case of the ANCF, perform acoustics measurements were done with two arcs of microphones located at the front and the back of the fan, at 3.66 meters (m) as shown in figure 12.

You can re-use the result from the previous Simcenter STAR-CCM+ case as a load condition for propagation within Simcenter 3D. Then you can project the unsteady pressures onto the acoustic mesh and re-use an efficient finite element method adaptive order (FEMAO) method.

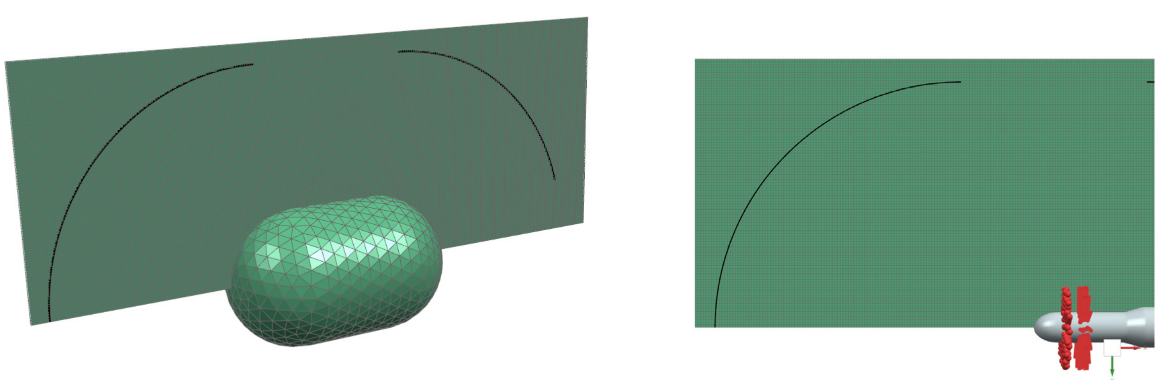


Figure 13. For acoustic propagation, a 3D domain is created around the machine. The far-field propagation is visualized with a 2D microphone mesh together with 1D microphone arcs to capture the directivity (left). The acoustic loads extracted using Simcenter STAR-CCM+, the fan self-noise and the vane noise, are visualized in red (right).

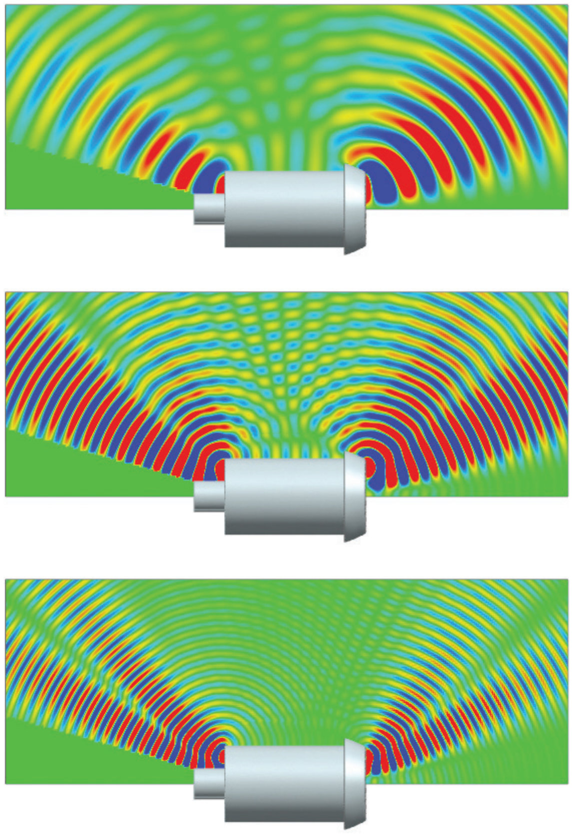


Figure 14. Using Simcenter 3D to visualize acoustic pressure contours for 1BPF, 2BPF and 3BPF.

FEMAO automatically adapts the order for each frequency of interest, which means the model is represented each time with the correct number of degrees of freedom to reach the desired accuracy. This yields faster computation times compared to the fixed number of degrees of freedom (DOF) approach used by the standard finite element method (FEM). This also improves performance in preprocessing. FEMAO allows you to use large elements in the acoustic domain, resulting in fewer elements than an equivalent standard FEM model.

Figure 14 shows the resulting pressure field for multiples of the blade passing frequency (BPF) and figure 15 shows a directivity plot comparing the noise level measured on the ANCF test bed and the simulation results. The maximum level and the associated directivity are well captured. You can also compare Simcenter results with two other simulations: simulation 1 uses a time-marching technique that requires approximately 200 times more computational power. Simulation 2 is a method that runs the CFD and the acoustic propagation in a single model, making the method less suitable for complex propagation scenarios with obstacles, for example.

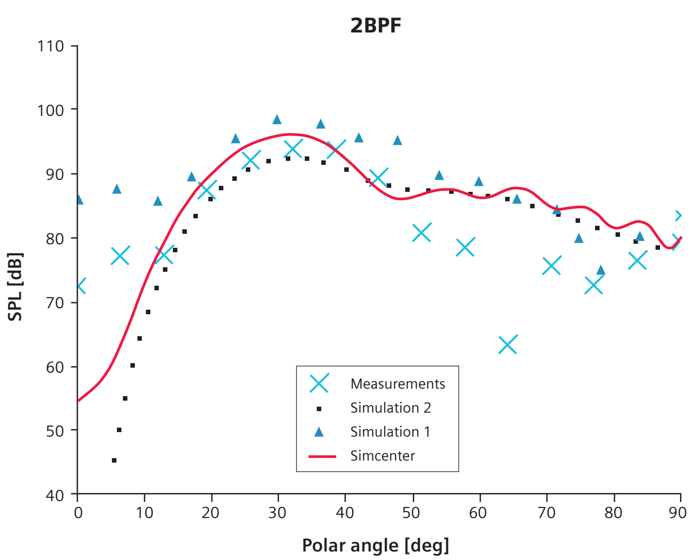


Figure 15. Directivity plot for the forward arc at 2BPF = 960 Hz.

Workflow and simulation data management

The resulting workflow connects data and models from different environments, potentially generated by different stakeholders within an organization. Any change in the data, such as a geometry update on one computer-aided design (CAD) object must be properly propagated to all dependent simulation items.

An example, in the context of our fan acoustic simulation, would be that a change in the operating conditions (such as a change in rotational speed) would impact the noise generation mechanism and you would need a new CFD analysis to characterize it. But you can re-use other items, like the propagation model with FEMAO, without any change. You can use Teamcenter® Simulation software to access this workflow and data management capability. By tracking the relationship between data and simulation models, you can improve analyst productivity and simulation efficiency. Figure 16 shows how you can capture relations between the CAD, the CFD analysis and the acoustic propagation analysis for the fan noise simulation.

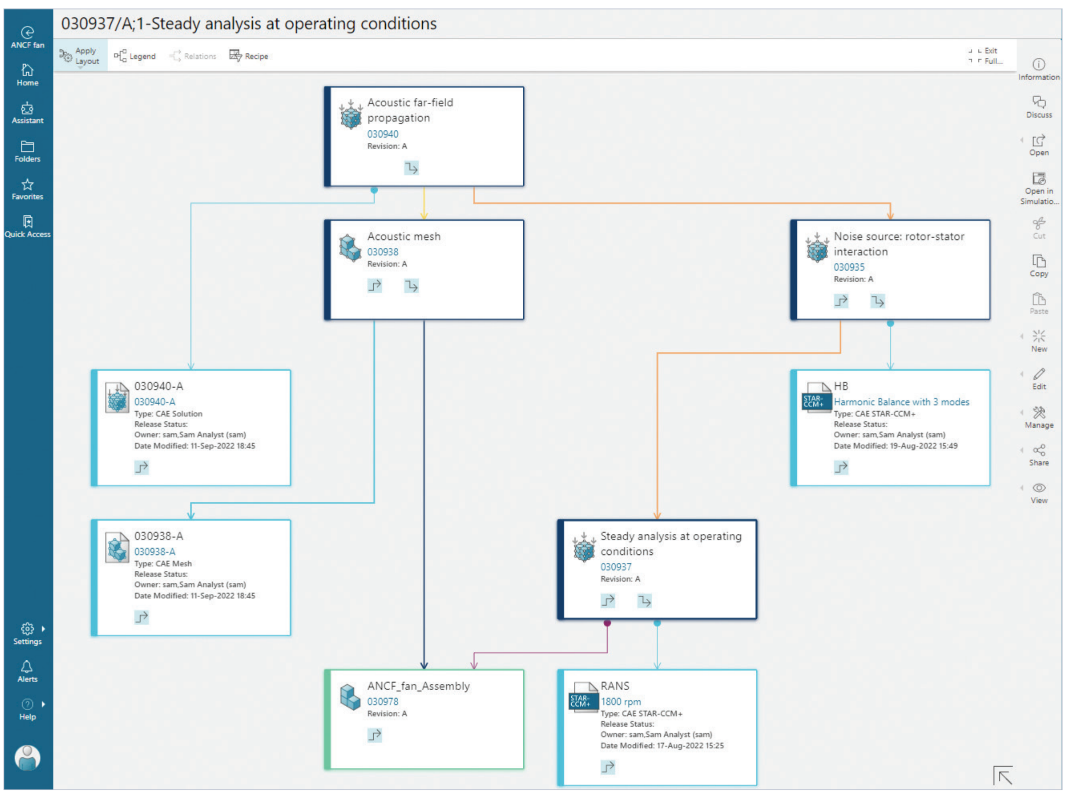


Figure 16. A relations diagram is automatically created using Teamcenter Simulation. It shows the connectivity between the different simulation items such as CAD objects or CFD studies.

Conclusion

Finding ways to mitigate the noise generation of future aero engines is critical, considering environmental impact and societal acceptance. For turbofan and electric fan architectures, the fan noise will likely dominate at all operating conditions.

When preparing for certification, simulation can help you understand how design parameters, such as rotor-stator spacing or using acoustic damping material can influence the noise perceived by the observers.

The simulation workflow presented in this white paper leverages the capabilities of the Simcenter portfolio and how you can use it to reduce the turnaround time of such analysis. By going faster, you can run simulations in an industrial context and explore more possibilities.

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