DIGITAL INDUSTRIES SOFTWARE

Aircraft ice protection systems design

Anti-icing and de-icing equipment for next-generation aircraft

Executive summary

Ice protection systems are an integral part of the aircraft certification process. With safety as a backdrop, aircraft manufacturers must avoid build-up of ice in cold weather flight conditions while balancing energy efficiency.

Developing anti-icing and de-icing systems from component level to systems integration should be considered early in the design stage to stay on budget and schedule. Simulation and testing play a major role in the development and certification process to ensure the flight safety of next-generation aircraft that fly under icing conditions.

SIEMENS

Introduction

Virtually all systems that carry crew and/or passengers must pass one or more icing-related standards to be certified. Many uncrewed systems face similar certification requirements. Therefore, systems to prevent or mitigate ice accumulation are used on many aircraft. Designing, optimizing and testing these systems is a significant engineering challenge.

Ice protection systems and components play a crucial role in safe aircraft operation under icing conditions. Icing damages the aerodynamic shape, increases aircraft drag and reduces its controllability. This impacts flight performance and safety. Such systems are usually installed in wings, nacelle intakes, pitot tubes, stabilizers and propeller and helicopter rotor blades. These safety-critical systems follow a certification requirement per Code of Federal Regulations (CFR) part 23, 25, 27, 29 and others, for the various types of aircraft and rotorcraft as well as engines.[1] Therefore, it is a part of the certification process and must be considered during the aircraft program development and testing.

The Siemens Xcelerator portfolio provides an open digital business platform featuring a curated portfolio of the internet of things (IoT)-connected hardware and software. This enables aircraft programs to be on time and budget from the initial ideas to the full comprehensive digital thread that is used to manage all related documentation. Simcenter™ simulation software and test solutions enable various virtual and physical testing capabilities of ice protection components and systems to evaluate their performance under ideal and worst-case scenarios. Simcenter is part of Siemens Xcelerator portfolio, the comprehensive and integrated portfolio of software, hardware and services.

This white paper provides an overview from system and component simulation to physical testing to investigate the ice protection performance from optimization to certification.

System simulation for ice protection systems optimization

Most aircraft use bleed air (hot air extracted from the engines) to heat the aircraft interior solid skin and raise the surface temperature, which will melt the ice or prevent its accretion. Some recent aircraft, such as the Boeing 787, use electric power with heater mats, which heats up the aircraft structure. Other systems such as Tecalemit-Kilfrost-Sheepbridge Stokes (TKS) known as weeping wing or piezoelectric actuators may also be used.

Before choosing the type of ice protection and/or de-icing system, there is a need to easily perform top-level tradeoff studies (power budgeting or air mass flow sizing). The most significant advantage of system simulation is its ability to aid in early engineering work. By coupling system simulation with 2D ice accretion code, the system's power requirements could be refined accounting for various operating and icing conditions.

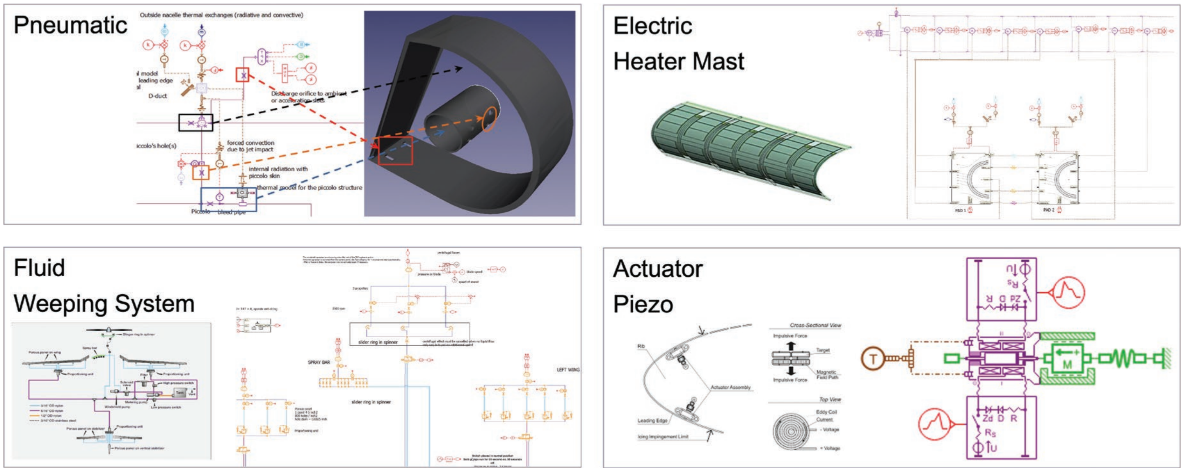

Figure 1. Ice protection systems architecture tradeoff.

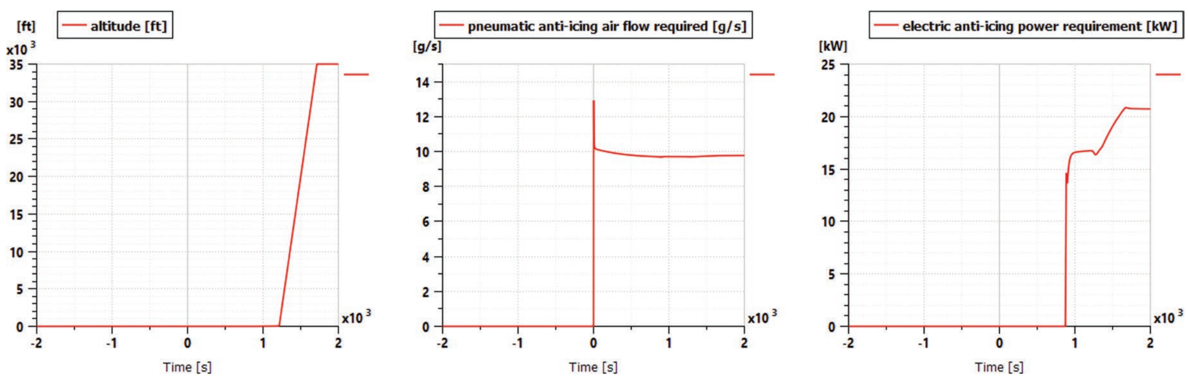

Figure 2. Engine nacelle requirements

Using the example of nacelle anti-icing, figure 2 demonstrates how much air is required if it's air-deicing or how much power is required if it's electric de-icing.

Once a tradeoff study is done and the design space narrows down, system simulation enables you to zoom in on the design candidates and focus on presizing various components of the de-icing system.

Choosing pneumatic de-icing as one of the candidates, we can use system simulation to evaluate geometries and presize some of its individual components, such as the piccolo tubes or piccolo exhaust holes. Essentially, we can evaluate the entire ducting and the impact of these geometries on the leading-edge nacelle temperature.

N	number of angular segment considered	4	
Nh	number of holes in the bleed pipe	200	
Di	internal (piccolo) pipe diameter	40	mm
Li	internal (piccolo) pipe length	1000/N	mm
ei	internal (piccolo) pipe thickness	2	mm
De	d-duct hydraulic diameter	150	mm
pe	d-duct wetted perimeter	500	mm
Le	d-duct length	Li	mm
ee	d-duct thickness	2	mm
dp	piccolo holes diameter	0.25	mm
dex	exhaust holes diameter	0.5	mm
rhole	leading edge material density	2702	kg/m**3
rhob	bleed pipe material density	7000	kg/m**3
vol	d-duct volume estimation	N*Le*0.25*PI*D...	mm**3
volseg	d-duct segment volume estimation	vol/N	mm**3

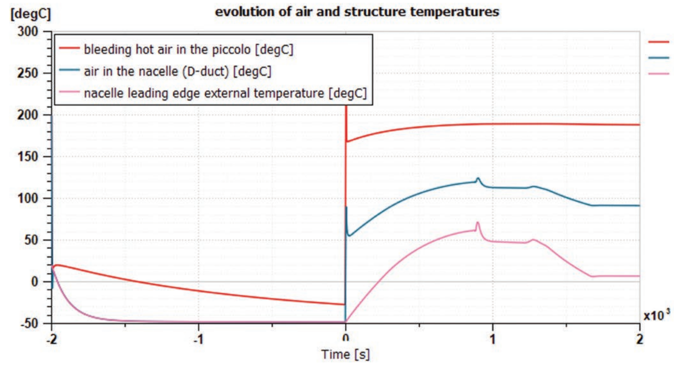

Figure 3. Nacelle anti-icing components pre-sizing.

Finally, system simulation enables a smooth integration of the resulting ice protection system with other pneumatic consumers and their coupling with the engine bleed air system (to see how it will impact the consumers and vice-versa). It enables you to perform what-if analyses like air leaking from a bleed pipe and the impact on the overall system.

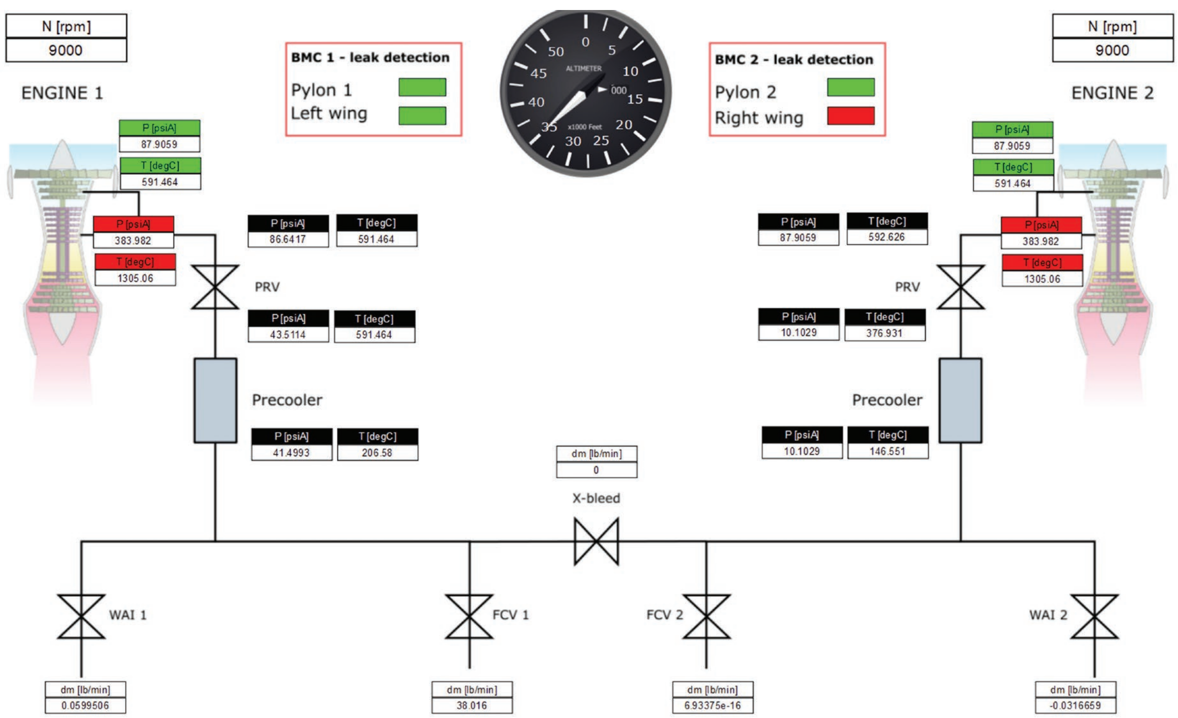

Figure 4. Nacelle anti-icing integration with bleed air system.

3D CFD simulation for anti-icing component analysis

After the system type is chosen and the component and performance sizing is completed in the system simulation, the components require a more detailed 3D CFD simulation for their individual performance and optimization.

The most common anti-icing type is the piccolo tube. In the advent of the carbon-neutral aviation industry, development efforts are focused on hybrid and electric aircraft and heater foils or mats find increased interest (figure 5). These foils attached to critical zones, such as the leading edges of wings and engine nacelle intakes, will be electrically heated. Additionally, the first concepts of induction heating coils that heat up the metal leading edge or embedded metal mesh in the composite leading edges are in development and will make it into the future aircraft.

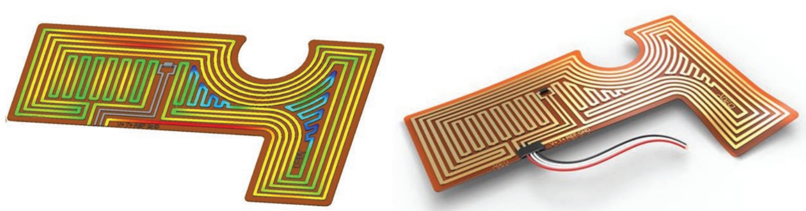

Figure 5. Example of a heater foil and thermal simulation showing temperature distribution (left) in detailed analysis (curtesy of ELiNTER AG).

In the early design of such devices, engineers must conduct computational fluid dynamics (CFD) simulations for the flow and thermal performance of these components. Such simulations can be done for preliminary studies to evaluate the general performance of a component itself as well as the installed component into its environment to consider its performance under real conditions.

In the case of heater foils, the general foil design, meander distribution, equal distributed heating performance and other parameters such as analyzing the limits of the component can be conducted early. The next stage would be to integrate the foil onto a wing leading edge and simulate the heat distribution over the airfoil under icing conditions to evaluate that enough heat is provided to prevent or remove ice buildup (figure 6). Parameters such as temperature and heat transfer coefficient distribution over the wing's leading edge are important to evaluate the component's performance.

Such simulations can be easily conducted early in the development process and under various conditions. The component performance can then be fed back into or coupled with a system simulation model with more accurate parameters to increase system simulation accuracy.

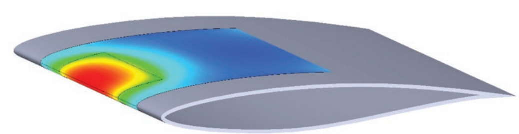

Figure 6. Heater foil simulation integrated onto a wing leading edge showing the surface temperature and around the heater foil application.

Aerospace manufacturers can address a number of icing-related engineering challenges by using Simcenter. First off, droplet collection efficiency can be calculated for complex 3D configurations experiencing icing conditions. An example of this is shown in figure 7: predicted collection efficiency is shown on the nacelle of a Boeing 737 engine.

Figure 7. Predicted collection efficiency on a Boeing 737 engine nacelle.

In addition to collection efficiency, ice accretion can also be predicted on full 3D geometries. The prediction is based on a first-principles simulation of all the relevant physics, which allows the ice shape to be captured in a time-dependent fashion. The impact of the accumulating ice on lift, drag, or any other engineering quantity of interest can also be tracked to make sure the system maintains the needed aerodynamic performance throughout the flight envelope under icing conditions. Figure 8 provides an example of this, where accumulation on a swept wing has been predicted, featuring prominent horns and scalloping.

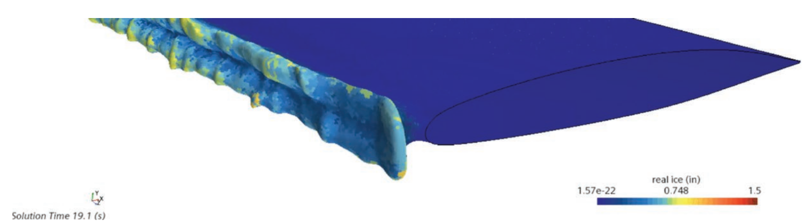

Figure 8. Predicted ice accretion on the GLC-305 wing.

As an example of engineering challenges related to de-icing systems, an optimization study can be performed to determine the best placement and orientation of the holes on a piccolo tube anti-icing system. Hot air is blown through these holes to warm the skin at the leading edge of the wing. The study's objective is to maximize the average temperature of the wing surface. Figure 9 shows the study's constraints.

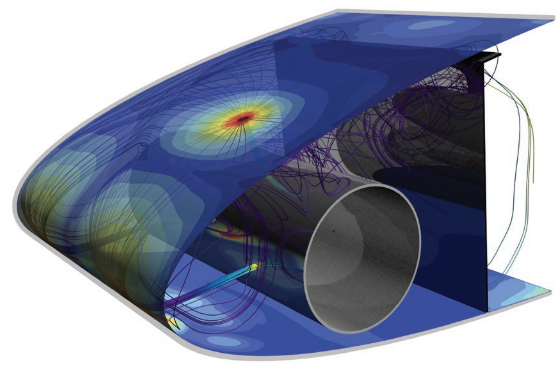

Figure 9. Anti-icing piccolo tube design optimization study – maximum temperature is less than or equal to 121 degrees Celsius, minimum temperature is greater than or equal to 1 degree Celsius and change in temperature (suction – pressure side) is greater than or equal to 3.5 degrees Celsius.

Due to the modular multi-physics approach, users can achieve a high level of fidelity by activating an appropriate subset of the models implemented in Simcenter. For example, droplets can be modeled as a dispersed phase (Eulerian physics) or as individual particles (Lagrangian physics) as needed. Similarly, impinging droplets can be set to all stick to the surface upon impact, or to have some bounce back into the air based on local conditions.

Water on the surface is incorporated into a film layer, which may freeze immediately or run back over the heated surface before freezing. Additional models allow the prediction of phenomena such as droplets being stripped off the liquid film by the air blowing past. Not every model will be needed for each case, but users can rest easily knowing the tools are in the toolkit if they are required.

Wing anti-icing systems testing

Wing anti-icing systems are commonly fitted in the internal slat structure and run throughout its span in between the ribs (figure 10). Given its critical function, such a system must pass a qualification test. The test specification is dictated by international standards, such as The Radio Technical Commission for Aeronautics (RTCA) document (DO)-160G *Environmental Conditions and Test Procedures for Airborne Equipment*, which describes the vibration environmental testing process. The standard prescribes several dynamic tests, including random, shock and sine excitation tests, to be carried out to study their effect on the parts composing the anti-icing system. Target vibration levels are defined at the attachment locations of the system to the wings' ribs. However, one issue specific to the anti-icing system is its dimension. The system runs through the wingspan, which makes it a very slender body (length is much larger than cross-section area).

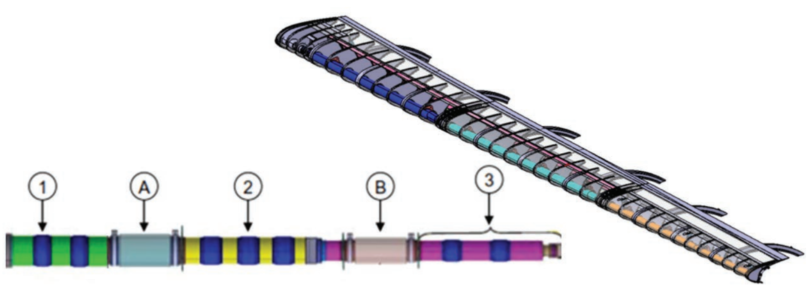

Figure 10. Piccolo tube installation in the slat internal structure.

Such a flexible structure is cumbersome to excite with a traditional single shaker setup. An even bigger challenge is to establish a uniform and representative excitation level at the attachment points. Multiple-output, multiple-input (MIMO) technology can help you overcome these difficulties and make sure each excitation point is simultaneously excited with the appropriate loading.[2]

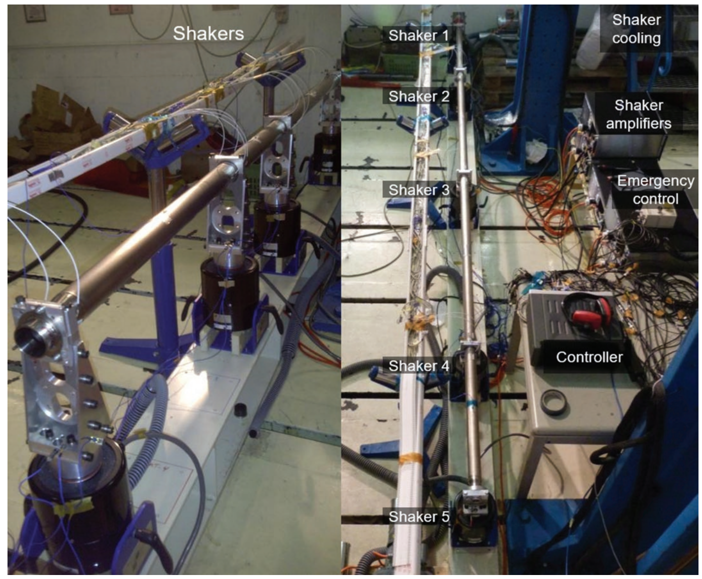

Figure 11. Multi-exciter setup for piccolo tube vibration testing.

In figure 11, up to five shakers have been mounted at the locations where the loads are transmitted to the structure. The amplitude levels are maintained at the prescribed levels using state-of-the-art MIMO control algorithm from Simcenter testing software and hardware. The system can be exposed to the right level of vibration at each location, drastically reducing the uncertainties related to its operational exposure to ordinary (ground-air-ground) and extra-ordinary (fan blade out) vibratory loads. Using this state-of-the-art technique enables test engineers to increase efficiency in the whole vibration qualification process.

Conclusion

Various ice protection systems must be tested and certified for use. Full development of such systems, from component level to systems integration, should be considered through simulation early in the development stage to reduce development cost and time. Simcenter helps you:

- Define the optimal system layout and system sizing earlier in the design cycle through system simulation
- Refine the design and improve performance of components and verify the system integration through 3D CFD simulation
- Accelerate the physical verification phase through a more efficient and more accurate multi-exciter testing approach

Whether it is pneumatic boots in older airplane models or induction heated leading edges in the new all-electric or hybrid aircraft generations, simulation and test play a major role in the development and certification process for safe flights of any aircraft meant to fly under icing conditions.

Since ice protection systems are mission-critical systems, their design, development, verification and certification fit into the Siemens Xcelerator product design and engineering, model-based systems engineering (MBSE) and verification management digital threads, where Simcenter performance engineering skill tools provide required engineering data to support aircraft programs and processes. Not only do Simcenter solutions enable the sizing and optimization of the detailed design, but they also provide the elements for the proof of compliance based on virtual and physical test data. This effectively contributes to aircraft program execution excellence by enabling you to stay on time and budget.

References

1. Code of Federal Regulations (CFR), Title 14 Chapter I Subchapter C, available at: https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C (accessed: 03 August 2022).

2. R. Van Der Vorst, S. Vandenberk, A. Carrella, J-L. Magerman, B. Bernay. “Qualification test of an aircraft piccolo tube using Multiple Input Multiple Output control technology”, SAE International, 2012.

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