DIGITAL INDUSTRIES SOFTWARE

Hydrogen-powered aircraft design

Using a digital twin to reimagine aircraft configurations for sustainable flight

Executive summary

This white paper examines the challenges facing aerospace engineers that are designing sustainable aircraft. It investigates the use of hydrogen-powered jet engines and hydrogen fuel cell technology in driving next-generation propulsion systems and their implications for subsystems, culminating in the need to reimagine aircraft configurations.

Siemens Digital Industries Software's Simcenter™ software supports digital twin technology to give aerospace engineering organizations the ability to optimize aircraft performance using virtual and physical testing of the fluid, thermal, mechanical and other system domains impacted by green aviation. Simcenter is part of the Siemens Xcelerator portfolio, the comprehensive and integrated portfolio of software, hardware and services.

Introduction

Aviation currently accounts for nearly 5 percent of global greenhouse gas emissions,[1] which has made switching to carbon-neutral propulsion systems a top priority for aircraft manufacturers. As critically important as this transition is now, the problem is compounded by the fact that there are currently around 500,000 people in the air at any given time[2] and twice as many air travelers are expected in 2037 as there are today.[3]

Caught between market demand and the United Nations' Framework Convention on Climate Change (UNFCCC) carbon dioxide (CO_2) emissions goals, aerospace engineers are tasked with designing next-generation aircraft capable of transporting passengers with the capacity, speed and range of kerosene-fueled jet engines but none of the environmental impact.

The power density of kerosene jet engines versus alternatives

To appreciate the complexity of the task at hand, it's necessary to understand how the power density of leading alternative energy solutions for powering next-generation aircraft stack up against today's status quo.

The standard kerosene fuel powering most modern commercial and military aircraft turbines is known as Jet A. Jet A has an impressive energy density of around 12,000 watt-hours per kilogram (Wh/kg), but in addition to high levels of noise, the disadvantage of kerosene-powered jet engines is its CO_2 and non-CO_2 emissions.

A much quieter and cleaner approach to powering aircraft is the use of electric motors. Batteries are a potential source of electricity for powering these motors, but current aviation-grade batteries flown in prototype aircraft have energy densities of only 160 to 180 Wh/kg.[4] Although this energy density is nowhere near enough to power long-haul airliners, it is sufficient to power smaller aircraft used for shorter-range commuter flights. For example, Bye Aerospace[5] specializes in the design and manufacturing of electric aircraft, including light aircraft for flight training. Bye Aerospace has two electric aircraft projects well underway in the Federal Aviation Administration (FAA) aircraft certification process, one being the two-seat eFlyer 2 training aircraft.

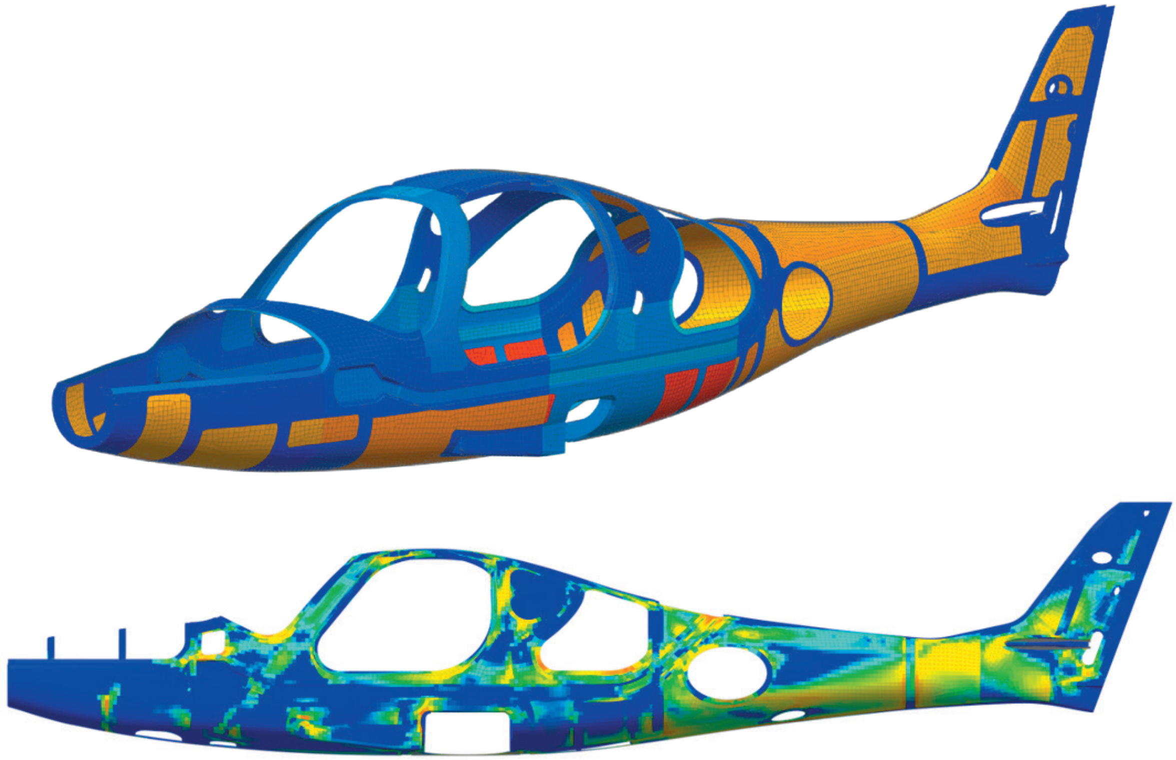

Figure 1. Using Simcenter, NX and Fibersim helped Bye Aerospace enhance productivity with 66 percent fewer engineering staff when designing all-electric aircraft.

Another option is hydrogen power. In addition to being the simplest chemical component known to man, hydrogen provides the highest energy density of any fuel at ~33,500 Wh/kg, which means it packs three times the power of kerosene per unit of mass.

Generating hydrogen and converting it into usable energy

There are currently two main contenders based on hydrogen energy sources for creating carbon-neutral long-haul aircraft. One is by means of liquid hydrogen-powered jet engines and the other is to employ hydrogen fuel cells that combine hydrogen and oxygen to produce electricity that can be used to power electric motors.

Liquid hydrogen and hydrogen fuel cell technologies are actively being investigated by many companies and organizations, including Siemens[6] and Airbus,[7] as zero-carbon alternatives for air travel. In both cases, the main byproduct of using hydrogen as a source of energy is environmentally friendly water.

Although hydrogen offers many advantages as a power source for aviation, generating it is a nontrivial task. Although it is abundant, it's almost always found as part of another compound such as water (H_2O) or methane (CH_4) from which it must be separated.

There are several common ways to produce hydrogen,[8] but to power a sustainable aircraft the most practical method to date is electrolysis. In electrolysis, an electric current is used to split water into hydrogen and oxygen. If the electricity is produced by renewable sources such as solar or wind, the resulting hydrogen is considered renewable.

Once produced, hydrogen can be stored in gaseous or liquid form. Storing gas typically requires high-pressure (5,000 to 10,000 pounds per square inch) tanks, while storage as a liquid requires cryogenic temperatures because the boiling point of hydrogen at one atmosphere pressure is -252.8 Celsius (C°).[9]

Due to the costs associated with producing, storing and transporting hydrogen, it is currently more expensive than fossil fuels. But compared to the complexity of its production, using hydrogen to generate power is conceptually simple.

Aerospace engineers developing hydrogen-based sustainable aircraft propulsion systems have three main options: electric motors powered by fuel cells, pure hydrogen-powered gas turbines or hybrids involving both fuel cells and hydrogen-powered gas turbines. In the case of a hydrogen-powered jet engine, which is a type of internal combustion engine, air is sucked into the inlet, compressed, mixed with the hydrogen and ignited to generate a high-temperature flow.

In the case of a hydrogen fuel cell, hydrogen and oxygen are passed through an anode (positive terminal) and cathode (negative terminal) of the cell, respectively. A catalyst is used at the anode to split the hydrogen molecules into their electrons and protons. The protons pass through a special membrane while the electrons are used to power the aircraft's electric motors and other systems. The protons, electrons and oxygen are subsequently recombined at the cathode where they end up as water molecules.

Challenges of hydrogen-powered aircraft

The biggest challenge associated with developing hydrogen-powered aircraft is that it's new territory for most engineers. Designing a burner for a hydrogen gas turbine, for instance, requires special features and structures. Then there's the nature of hydrogen itself, which burns much faster and hotter than kerosene.

For example, a hydrogen burner must be designed to prevent flashbacks, plus the acoustic frequencies generated by the burner and the turbine have to be damped to minimize interaction between the flame and the rotor and the combustion chamber and the turbine.

It's also necessary to understand the fluid dynamics along with any stresses that occur at thermal boundary conditions of these hydrogen and electric-powered propulsion systems – including the operational phenomenon they encounter such as flashbacks, thermoacoustics, thermal gradients and embrittlement.[10, 11, 12, 13]

Another challenge is that although hydrogen provides three times the energy density of kerosene per unit of mass, it requires four times the volume of kerosene to achieve the same result. This means that irrespective of whether the aircraft employs hydrogen turbines or hydrogen fuel cells to drive electric motors, there are major ramifications for aircraft's airframe. Either the cargo capacity, the number of passengers or both must be reduced to accommodate a hydrogen fuel source, or the entire aircraft configuration must depart from conventional designs.

Figure 2. The increased fuselage space of blended wing body aircraft can be used to store batteries, hydrogen or hydrogen and fuel cells without sacrificing passenger or cargo capacity.

One exciting possibility is a blended wing body (BWB) aircraft like the Airbus ZEROe BWN concept aircraft,[14] in which the wings and fuselage are blended into a single entity (figure 2). Also known as a "flying wing," the entire aircraft provides the lift required for flight. A major advantage of a flying wing configuration is the increased fuselage space can be used for carrying payloads such as cargo, passengers, batteries, hydrogen and fuel cells.

Rising to the challenge

The task of creating carbon-neutral, long-haul hydrogen-powered aircraft is complex and cost, time and resource limitations mean that evolving a series of physical prototypes is no longer a viable design strategy. The solution is to employ multi-physics simulations to investigate the behavior of power generation systems, engines and the entire aircraft in a virtual world.

This is a monumental undertaking as it requires a convergence of design domains and a coordinated effort between all the engineering disciplines involved in aircraft development. This goes beyond just propulsion systems to include fluids, thermal, mechanical, dynamics, acoustics, etc. Engineering data from these interrelated systems must be shared between teams in an efficient manner so designers can continue operating efficiently within their native development environments.

One way to achieve this is to adopt digitization tools that are available in the Siemens Xcelerator portfolio, the comprehensive and integrated portfolio of software, hardware and services. Simcenter simulation and testing solutions, which are part of the Siemens Xcelerator portfolio, are used to break down silos between the various disciplines required to build hydrogen-powered aircraft by providing an integrated design suite that can fully support multi-disciplinary aerospace engineering teams, helping them model, analyze and test the impact of alternative energy sources and propulsion systems.

In other words, it enables the creation of a physics-based digital twin (figure 3).

Figure 3. Using Simcenter, engineers can build a digital twin to accurately predict aircraft performance, optimize designs and innovate faster with greater confidence.

Within the Simcenter environment, system simulation modeling capabilities enable the evaluation of engine architectures, gas turbines, fuel storage, fuel cells, batteries and other components as well as their weight (figure 4).

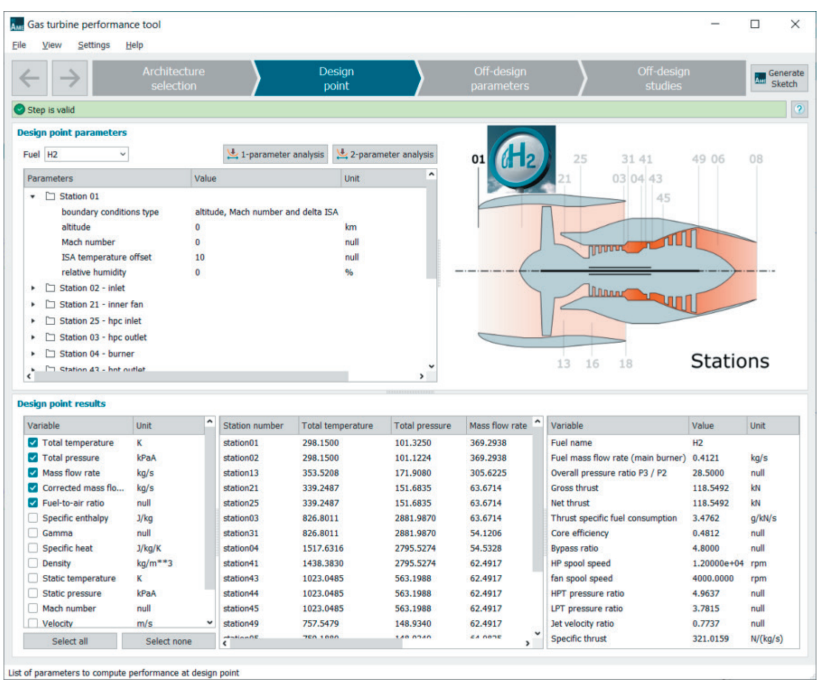

Figure 4. The Simcenter Amesim model enables engineers to evaluate the thermodynamic cycle of the hydrogen-powered turbofan.

Then engineers can leverage in parallel fluids, thermal and mechanical 3D simulations as well as computer-aided design (CAD) capabilities to design each of these subsystems.

From the sloshing of cryogenic fuels, hydrogen combustion and turbine inlet temperature measurement to durability performance and dynamic system response, various advanced physics are delivered in robust and validated Simcenter models (figure 5). The design workflow is then performed in automated workflows and design space explorations to consider conflicting interests from various disciplines. Components such as the burner and vanes, assemblies, the engine, various subsystems and eventually the entire aircraft can be designed using a similar approach to meet different design purposes.

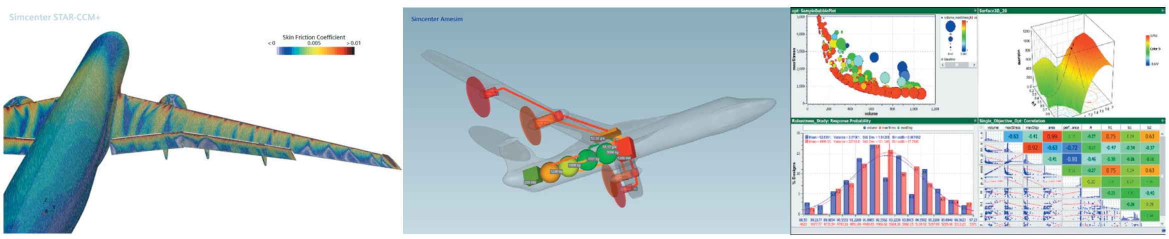

Figure 5. This multi-domain design exploration rendering of a hybrid cryogenic H2 burn propulsion system was generated using Simcenter 3D, Simcenter STAR-CCM+, Simcenter Amesim and HEEDS software tools to accurately represent the design's aeroelasticity.

Simcenter models – including those co-developed with Siemens partners – are generated and executed with real-world fidelity to allow aerospace companies to design and deliver real-world systems (figure 6). Simcenter outputs can be combined with the Siemens Xcelerator portfolio to account for component and system manufacturability as well.

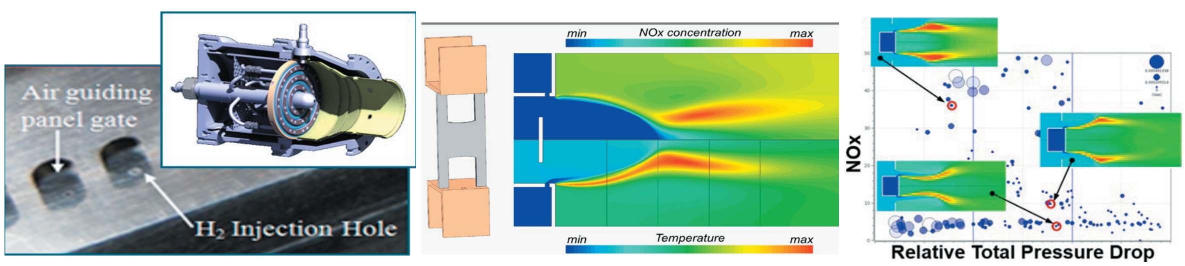

Figure 6. This multi-physics design exploration of an H2 micromix burner leverages NX CAD, Simcenter STAR-CCM+ and Simcenter 3D driven by the HEEDS automated optimization tool. (source: B&B AGEMA, RWTH Aachen and Kawasaki)

Conclusion

Companies like Siemens Energy,[17] Rolls-Royce[18] and Airbus[19] are currently performing extensive evaluations, in some cases creating concepts and prototypes of hydrogen and hydrogen-hybrid aircraft.

However, it's important to understand that moving away from fossil fuels means updating much more than just the aircraft. These activities are just the beginning of a decades-long effort of reimagining aircraft configurations and addressing materials supply chains, energy production, distribution and logistics networks, airport fuel delivery systems and more (figure 7).

The capabilities of the Siemens Xcelerator portfolio and the Simcenter tool suite are focused on supporting the digitalization efforts that will be required to scale the aviation industry into this sustainable future.

Figure 7. Moving away from fossil fuels requires updating energy production and logistics networks, including airport fuel delivery systems.

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