Excellence in Engineering Simulation

Best of Aerospace and Defense

Powered by Innovation  Going Great Guns  The New Space Race
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### Realize Your Product Promise®

If you’ve ever seen a rocket launch, flown on an airplane, driven a car, used a computer, touched a mobile device, crossed a bridge, or put on wearable technology, chances are you’ve used a product where ANSYS software played a critical role in its creation. ANSYS is the global leader in engineering simulation. We help the world’s most innovative companies deliver radically better products to their customers. By offering the best and broadest portfolio of engineering simulation software, we help them solve the most complex design challenges and engineer products limited only by imagination.

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Aerospace and defense companies share many commonalities in the type of products they produce, the harsh environments these products operate in, and their overriding focus on safety and reliability. However, the commercial aircraft, space and defense sectors each face unique market trends. In this aerospace and defense-focused magazine, we explore how these trends drive technology innovation and the way leading companies leverage simulation-driven product development to deliver tangible business impact.

By Rob Harwood, Director, Industry Marketing, ANSYS

**Commercial Aerospace**

Volatile and rising fuel cost coupled with green initiatives drive the development of technologies that reduce the cost and environmental impact of flight. Pratt and Whitney, known for game-changing product innovations, deployed simulation to design an engine that delivered over 15 percent improvement in fuel burn while reducing its noise footprint and carbon emissions. (See article on page 7). Competition to capture the growing number of air travelers means an increased focus on passenger comfort. Aircraft climate control experts at Tianjin and Purdue universities employed systems-level simulation and detailed thermal analysis to meet industry standards for environmental control system design (page 13).

Innovation must be achieved in an evolving, highly regulated safety framework — all while controlling development costs. To certify braking systems for safety, software developers must test for each possible input to the brake control software, as well as for a broad range of operating events. Crane Aerospace & Electronics, which performed these tests virtually, has been able to meet government guidelines, tight budgets and even tighter schedules (page 3).

**Defense**

While striving to deliver a technological edge in the least amount of time, many defense organizations and their suppliers operate on the principle of design for affordability. By using simulation, Piaggio Aero Industries converted an executive jet into an unmanned aerial vehicle (UAV) in one-third the time that would have been required using traditional design methods (page 31).

As the nature of military engagements evolves, the importance of intelligence, surveillance and reconnaissance (ISR) has never been higher. Lighter-than-air blimps can replace or complement drones on ISR missions. Worldwide Aeros Corp. used multiphysics analysis to design new airships 40 percent faster than for the previous generation. The savings arose from the ability to share data between simulation types and run automated processes. Virtual testing provided far more accurate estimates of performance than traditional methods (page 24).

Engineering for sustainability and optimizing operational availability of assets is critical for the defense community. By leveraging the power of multiphysics simulation, Raytheon Corporation achieved robust electronics design for high-power antennas and microwave components. The simulations helped engineers understand how failure could occur and how to correct the design to prevent it (page 27).

**Space**

With the emergence of commercial space entrepreneurs and new spacefaring nations, product development processes in the space industry are changing rapidly. Firefly Space Systems, one of the leaders in the “new space” industry, explains how the company changed its culture to include a diverse group of engineers and flatten the engineering function (page 38).

New space or old, products must perform first time, every time in one of the most extreme operating environments. Because conditions change quickly during atmospheric flight, space vehicles require thermal insulation to protect the payload and sensitive internal equipment from generated heat. Coupled multiphysics simulation saved SpaceX hundreds of thousands of payload-equivalent dollars per launch by calculating the exact amount of insulation required to safeguard the launch vehicle — approximately 50 pounds less than the amount used in the first demonstration flight (page 42).

It wouldn’t be a space race without the goal of delivering products in the shortest possible time. This means reducing reliance on physical testing by building confidence in simulation. Virtual analysis provided NPO Energomash designers with confidence that their force measurement system could test rocket engines with up to 800 metric tons-force of thrust (page 34).

In addition to relying on advanced simulation technologies and performing virtual prototypes, aerospace and defense industry leaders focus on design process compression. While investigating heat flux prediction points for improved engine efficiency, Rolls-Royce Germany reduced its coupled simulation time by 80 percent using a cloud approach — and without building prototypes (page 17).

For the near future, aerospace and defense is leading the way in realizing the digital twin concept, which couples simulation with the operation of the physical product. Whether embarking on simulation for the first time and investigating the power of advanced simulation technologies or spearheading a digital twin initiative, companies across the aerospace and defense spectrum are leveraging the power of ANSYS simulation-driven product development solutions.
Safe Landing

Esterel solutions help Crane Aerospace & Electronics to design braking systems that are certified for safety.

By Gregory Mooney, Systems Software Engineering Lead — Landing Systems
Crane Aerospace & Electronics, Burbank, U.S.A.

Crane Aerospace & Electronics’ mission-critical products help to ensure the safety of millions of airplane passengers. The company must meet stringent government safety regulations aimed at ensuring that these products — in this case, braking systems — will perform as expected under a broad range of real-world conditions.

Crane pioneered the antiskid braking industry in 1947 by developing the Hydro-Aire Hytrol Mark I antiskid system for the B-47. Since then, Crane has provided both private- and public-sector aircraft customers with a wide range of brake control systems and other products — including power, cabin, fluid management and sensing systems. The company’s guiding principle is to exceed the needs of its customers, a responsibility Crane’s engineering team takes very seriously.

Crane is the industry leader in aircraft brake control systems, with 65 percent of the commercial market and 80 percent of the Western military market. The company has more than 25,000 systems in service worldwide today. These braking systems are critical in ensuring passenger safety during routine landings, as well as during challenging rejected takeoffs. (See sidebar.) Brake control systems designed and manufactured by Crane include a number of mechanical and hydraulic parts, such as control, shutoff and parking brake valves as well as wheel speed and pedal position sensors. However, the most complex component in Crane’s electronic controllers is an invisible one: the thousands of lines of embedded software code that ensure efficient, reliable brake control when required during landing.

To support reliable software performance, the United States Federal Aviation Administration (FAA) has drafted a set of guidelines under its Federal Aviation Regulations requiring proof that software “performs intended functions under any foreseeable condition.” A means to comply with these regulations — that is, a way to show that the system meets its safety objectives — is a standard called RTCA/DO-178B, Software Considerations in Airborne Systems and Equipment Certification. This standard aims to assure
Braking control systems manufactured by Crane Aerospace include a number of mechanical and hydraulic components — all controlled by thousands of lines of mission-critical software code.

Today, while the basic mechanics of braking have not changed, brake control systems continue to evolve as an incredibly complex blend of control software, electronically controlled actuators, and high-speed digital communication interfaces with other onboard systems (as well as humans). For instance, in case of an electrical short or other unexpected event, the software not only ensures continuing brake performance, it alerts the flight crew about the issue and sends an automatic alert to maintenance staff to address the problem once the plane lands. Obviously, the underlying code is mission critical, because the consequences for brake failure can be truly catastrophic.

This new complexity has created exceptional challenges for software developers, who must test for each input to the brake control software — as well as for a broad range of operating events. This dictates extremely rigorous, broad-scope testing and verification tasks, even as Crane’s customers are working against aggressive development schedules.

Prior to 2010, the company’s software engineers managed the requirements of DO-178B via a time- and labor-intensive process, which had some evident drawbacks. Because of the manual nature of the process, the finest details of functionality were hidden in the underlying code. The impacts of customer requirements and system updates were not fully visible — and thus could not be completely verified by Crane’s engineering team — until the software was fully developed and implemented.

There were often surprises when software was run in a Crane in-house testing facility or customer lab replicating actual aircraft configuration — which meant that Crane’s engineers had to go back to the drawing board and rewrite the code. This was an expensive and time-consuming proposition at such a late stage of software development, especially after hundreds of development hours had been invested.

The resulting high costs, large amount of rework and scheduling issues negatively impacted the company’s customer satisfaction levels. In addition, Crane’s engineering team had to assemble a wealth of documentation at every stage to satisfy FAA requirements. Crane realized that to accelerate and streamline the software development process — without sacrificing ultimate product integrity or regulatory compliance — it needed to identify an advanced technology solution that would model and predict real-world performance of these smart systems at a much earlier stage.

**SCADE PUTS THE BRAKES ON MANUAL WORK**

Crane evaluated a number of model-based development environments before choosing SCADE Suite. The company selected SCADE because it is a purpose-built software development tool qualified to meet the standards of DO-178B up to Level A, the highest level of safety for the aerospace industry. In addition, engineers were impressed by the support that they would receive from Esterel while installing and running SCADE solutions.

**Software developers must test for each possible input to the brake control software — as well as for a broad range of operating events.**
Since implementing SCADE Suite in 2010, Crane Aerospace has realized significant cost, speed and efficiency benefits in its safety-critical software development, verification and validation process. From the earliest stages of code development, the SCADE tool enables software engineers to simulate and confidently predict real-world results, eliminating surprises and rework at later stages. SCADE Suite automates the code-generation process and enables the testing of embedded software code against thousands of inputs, without the need for a target. This significantly reduces the need for manual work involved in code generation as well as related software development, verification and validation tasks.

During software simulations, SCADE Suite allows the engineering team to subject the design to thousands of inputs and events to ensure that the software will function exactly as expected when installed in an actual plane.

SCADE allows customers like Crane to build customized libraries that include general-utility operators, primary and ancillary brake functions, and system interfaces. These reusable libraries make software development even faster. In addition, SCADE Suite generates much of the process documentation automatically, eliminating hours of work that once were invested in meeting stringent government requirements for record keeping.

MOVING BEYOND CODE VERIFICATION

While there are many ways to verify that software performs accurately against customer requirements, Crane engineers leverage SCADE to take logic and control a step further — by validating that software requirements make sense and protect passenger safety. Because simulation makes system behaviors visible, SCADE allows engineers to flag exceptions and identify problems with initial requirements. If not detected and addressed, oversights in initial software requirements can result in late-stage issues that delay projects and add to cost.

IN-PROGRESS SIMULATION OF FAULT DETECTION SUBSYSTEM

Since Crane Aerospace first implemented SCADE, the solution has identified more than 150 errors in preliminary system requirements and more than 180 flaws in corresponding software requirements. These errors, some major and some minor, were caught and eliminated in early validation exercises — before the systems ever existed in the real world. Prior to the SCADE implementation, these flaws might not have been discovered until very late in the manual software development process — resulting in significant rework for Crane’s software engineers.

Today when errors are detected, what-if scenarios in SCADE Suite allow software engineers to quickly see the ultimate impact of any design changes on system reliability and braking performance. They can quickly identify the problems in underlying requirements and adapt the software model accordingly.

VISUAL MODELS OFFER OBVIOUS BENEFITS

A number of features in SCADE Suite make it easy to communicate defects and other issues to aerospace customers. SCADE
enables Crane software engineers to generate easy-to-understand graphic models and reports that reveal the inner workings of software code in a way that all process stakeholders — including Crane customers — can quickly comprehend. During simulations, users can view real-time software performance values and easily understand the immediate impacts of model changes.

SCADE Suite translates lines of unintelligible software code (bottom) into intuitive graphics (top). These reveal the software's underlying logic in a highly visual manner that all stakeholders can quickly understand.

CUSTOMER SATISFACTION TAKES OFF

With the incredible pressures that aircraft manufacturers face today, SCADE Suite supports Crane’s efforts to help its customers meet tight budgets and schedules — by providing faster, highly accurate software development. Shortly after implementing SCADE, Crane successfully used the software’s intuitive libraries and graphical models to meet a two-week turnaround for a scaled-down customer demo of a new control system.

Today, Crane is able to deliver on customer requirements, as well as meet the stringent demands of the FAA’s DO-178B guidelines, via a compressed development schedule. Day-to-day engineering work is much more quick and efficient, and errors are detected at a much earlier stage.

In addition, SCADE software has increased Crane’s agility and speed in adapting to new developments in braking control systems, such as improved microprocessors, offering more robust and sophisticated fault-detection software. Using SCADE Suite positions Crane to easily incorporate any new brake control innovations as it simulates how software code functions as part of a larger aircraft system.

In some cases, Crane’s customers have actually used SCADE’s systems-level models and what-if simulations to consider enhancements to overall braking system prototypes during iron-bird testing, a dimensionally accurate structure specially fabricated to replicate the aircraft. Instead of identifying “surprise” software performance variations while in the iron-bird environment, customers are uncovering new systems-level insights that inform the entire brake control environment. Supported by SCADE software, Crane can offer its customers industry-leading, forward-looking braking system technologies, on-time delivery and the high product quality they rely on every day.

Aborted Takeoffs: A Special Engineering Challenge

Rejected (or aborted) takeoffs pose special challenges for brake control systems. During a rejected takeoff (RTO), an airplane has much more energy than during a normal landing due to higher speed and a significantly heavier weight. Moreover, an aircraft has typically used up much of the available runway when the pilot has to make the difficult decision to abort. While most landings may use only 20 to 30 percent of the plane’s available braking capability, during an aborted takeoff up to 100 percent can be needed to stop safely, and, thus, the control software must ensure near-ideal performance. Since pilots are usually focused on the conditions that led to the rejected takeoff, Crane brake control systems offer an automatic braking function that applies full brakes during an RTO. Because rejected takeoffs represent such a great challenge, Crane's software engineers focus particular attention on this demanding event during their SCADE simulations.
Known for game-changing product innovations, Pratt & Whitney has relied on engineering simulation to fuel its design process for over 35 years. Al Brockett, former vice president of engineering module centers, discusses the role of robust design in delivering revolutionary new products with a high degree of confidence.
Since 1925, Pratt & Whitney has been a global leader in the design, manufacture and service of aircraft engines, auxiliary and ground power units, small turbojet propulsion products, and industrial gas turbines. From its first 410-horsepower, air-cooled Wasp engine to its award-winning PurePower® engine with patented Geared Turbofan™ technology, the company continues to revolutionize engine design to anticipate changing customer needs. Pratt & Whitney’s large commercial engines power more than 25 percent of the world’s mainline passenger fleet. The company also provides high-performance military engines to 29 armed forces around the world.

For over three decades, Pratt & Whitney has leveraged the power of engineering simulation to launch its groundbreaking innovations with the incredibly high degree of confidence required in the aerospace and defense industry. Al Brockett, who recently retired as vice president of engineering module centers, relied on the power of simulation throughout his long career at Pratt & Whitney. Under his direction, the company’s global engineering team consistently redefined what is possible via engineering simulation — making Pratt & Whitney one of the world’s most sophisticated users of simulation processes and tools.

Brockett recently spoke with ANSYS Advantage about the changing role of simulation at the company, as well as Pratt & Whitney’s increasing emphasis on robust design as a vehicle for launching its highly innovative products quickly, cost-effectively and confidently.

As a longtime advocate of engineering simulation, how have you seen its application evolve at Pratt & Whitney?

Over the course of my career, I’ve seen simulation transform from simple numerical calculations to the incredibly complex, multiphysics problems we’re solving today. Historically, Pratt & Whitney used complex simulations only for post-design analysis and verification. But today — thanks to advances in high-performance computing, process automation and software tools — we’re leveraging simulation from the earliest stages of conceptual design through detailed design, through after-market service, to improve both speed and fidelity of our product development efforts and management of our products in service. Simulation has been critical to our efforts to lead our industry with entirely new classes of engine designs — and these represent a true step change over traditional architectures.

In the last 15 years, we’ve seen the speed and power of engineering simulation improve dramatically, along with the graphic capabilities and breadth of simulation software. Those tremendous advancements allow us to visualize problems in greater detail, consider multiple physics simultaneously, and conduct simulations that consider millions of degrees of freedom, all at a pace that matches the design cycle — something we couldn’t have imagined at one time.

These improvements also allow us to respond much faster to our customers’ increasing demands for new approaches to engine designs that answer their pressing needs for better fuel efficiency, lighter weight and reduced emissions. With fuel costs now accounting for 45 percent of an airline’s operating expenses, this is a particular concern in our industry — and simulation continues to enable Pratt & Whitney to set the industry standard in maximizing fuel efficiency.

I’ve seen simulation transform from simple numerical calculations to the incredibly complex, multiphysics problems we’re solving today.
What role has engineering simulation played in some of your revolutionary product launches, like the new PurePower® engine?
The new products that we develop represent a multi-billion-dollar investment. Simulation helps to protect this investment by ensuring that our thousands of engineers and operations staff around the world are working efficiently, integrating functionality whenever possible, and minimizing costly rework.

In the case of the PurePower engine, we could not have developed this product, or sold it to customers, without incorporating engineering simulation. First, we needed simulation to design the Geared Turbofan technology that lies at the heart of this innovative new engine. (See sidebar “Gearing Up Performance.”)

Next, we leveraged simulation to demonstrate and prove the product to our customers around the world. This engine represents a technology shift — and delivers so many huge performance benefits — that our customers were naturally skeptical. To show them the Geared Turbofan™ engine in action, it would have been necessary to build a demonstration rig, run it for thousands of hours, and transport it around the world. And simulation gave us the capability to do exactly that, in the virtual realm. When we showed our simulation results to customers, alongside physical evidence of the engine’s reliability, they could not argue with the performance benefits.

As a result, we have sold five different variations of the PurePower engine to five different customers — and that leads me to the final way that simulation is helping us.

Simulation allows our engineers to move seamlessly among these five product platforms as we customize the PurePower engine design for Bombardier, Mitsubishi, Airbus, Irkut and Embraer. This is an unprecedented level of design activity at Pratt & Whitney. While we are developing five products simultaneously, they are based on a similar architecture. The teams can rapidly move from one product to another very seamlessly, and they can completely build off of one simulation to the next. We have been able to reduce the size of the overall development team needed to deliver these five product platforms, while maximizing the learning that takes place from one effort to the next.

Tell me about Pratt & Whitney’s internal robust design initiative, Design for Variation.

A common approach to product design is to utilize nominal geometry with some assumed variation in material properties. This method ignores the fact that parts/products are never completely produced at nominal geometry; it leads to conservatism in margins that are built in to explain the difference between predicted capability and actual capability. Controlling variation has become one of the keys to improving performance while also improving part yield and quality. Pratt & Whitney’s Design for Variation (DFV) program was created to help us improve our products by quantifying and controlling variability, uncertainty and risk. Many companies, including ANSYS, refer to this as robust design.

DFV is really a paradigm shift that forces our engineers to statistically analyze a broad range of product geometries, boundary conditions and materials types. The program has changed from a special initiative focused on statistical training to a high-visibility strategic priority. (See sidebar “Robust Design at Pratt & Whitney.”)

The DFV concept is straightforward: If we assign a numerical value to our risks, we can manage them by making targeted changes in our designs, materials and processes that increase on-wing time for engines by managing the key sources of variation.

Pratt & Whitney’s Design for Variation program was created to help us improve our products by quantifying and controlling variability, uncertainty and risk.
We can look at multiple physics very deeply, even assessing off-design conditions and the product system’s reaction.

We examine thousands of design variations, each one slightly different, based on the probability that they will fail to meet operating requirements. We can then focus on a handful of factors that truly affect engine performance and reliability, and ignore those design points that are unimportant.

This obviously makes strategic sense, as it improves engine uptime, reduces component and maintenance costs, and protects passenger safety. But it’s a massive undertaking to conduct this kind of parametric analysis.

Simulation makes DFV possible by running thousands of iterations quickly in an automated fashion. Our engineers can rapidly focus on those few design points and operating conditions that are truly critical. We can look at multiple physics very deeply, even assessing off-design conditions and the product system’s reaction. The recent improvements in simulation technology are allowing us to move toward high-fidelity systems-level design, in which we will be able to isolate a dozen or so key points over an entire product system. That’s exciting to consider.

Gearing Up Performances

Pratt & Whitney’s PurePower® engine design represents one of the biggest advances in jet engines in the past 50 years. Pratt & Whitney engineers recognized that engine performance could be significantly improved if the fan and turbine that drives it could be operated at their own optimal speeds. To answer this challenge, Pratt & Whitney developed an innovative Geared Turbofan (GTF) engine design. Instead of connecting the fan directly to the low-pressure turbine via a shaft — as in conventional engine design — Pratt & Whitney engineers introduced a new reduction gearbox into the drive train.

In the resulting compact design, the bypass ratio has been improved from 5:1 to an impressive 12:1, and the low-pressure turbine develops more work in fewer stages. That means fewer airfoils, fewer life-limited parts and, ultimately, lower maintenance costs. The real-world performance results are also impressive:

- Over 15 percent improvement in fuel burn
- Up to 75 percent reduction in noise footprint
- Annual per-plane reduction in carbon emissions of over 3,000 metric tonnes

Already five major aircraft manufacturers have placed orders for the game-changing PurePower engine. Mass production is slated to begin later this year.
What advice would you give other engineering teams that want to increase their organization’s focus on robust design?

I’m an advocate of what I call “design simulations”: putting the right tools in the hands of designers to speed up the overall product development process. If your organization is serious about robust design, the first step is to make sure you have the right technology tools in place to manage large parametric simulations and drive rapid results.

Because robust design considers so many variables, any organization focused on this area is going to be running large simulations. An investment in high-performance computing resources is essential so that work can be accomplished and shared quickly. In just the last four years, Pratt & Whitney has quadrupled its computing capacity for a simple reason: We did not want computing power to be an obstacle to innovation and product integrity. For a small investment relative to the impact on our products, we are running large multiphysics simulations that support our DFV initiative — which allows us to reduce the risk of design mistakes that could result in large downstream warranty costs.

While technology is important, education and training are also critical. I believe that the engineering community needs to place a greater emphasis on statistical analysis, which lies at the heart of robust design. Our engineering students today are not being adequately trained in this area, and I’d like to see that change. As performance demands in every industry become more complex — and cost pressures escalate — engineers need to become proficient at quantifying the impacts of different materials, part geometries and other factors on ultimate performance. They also need to understand and analyze for the interactions of multiple physical effects, since the systems we are developing are becoming increasingly complex.

Finally, at the organizational level, a key robust design concept is standardizing work processes, which has been a real focus at Pratt & Whitney for the last decade. When you are exchanging...
In a search for a nominal design that is robust to variability and uncertainty, Pratt & Whitney created an automated workflow for its Mid-Turbine Frame that would ensure design robustness by considering a range of manufacturing, temperature and stress variations.

One of the tools for critical driver identification and insight into interaction between parameters is global variance-based sensitivity analysis. Global sensitivity analysis uses the results generated by executing the analysis workflow over a prescribed designed experiment. These same results are used to develop emulators for identification of feasible design regions. When needed, more detailed exploration can be executed for refinement of local design solutions.

Probably the most important contribution that ANSYS has made is allowing Pratt & Whitney engineers to push the envelope of previous engine designs, all in a very-low-risk virtual environment. We can see quickly what is possible, without making a huge investment in prototype construction and testing. Recently, we used multiphysics simulations — combining ANSYS Mechanical and ANSYS Fluent for example — to convince a major customer that they were making a design request that was not practical, because their modification would add significant weight to the engine. By showing them the real-world effects of their request via ANSYS simulations, which the customer also used, we avoided increasing complexity that we believe would have led to numerous issues. Without ANSYS software, some of these issues would not have been visible until installation. Today we are using ANSYS solutions in ways we never thought possible. ANSYS is definitely supporting our efforts to stay out in front of our industry as a leader and innovator.

How would you describe your relationship with ANSYS?

Since we are an advanced user of engineering simulation, we have collaborated with ANSYS on many projects and have given ANSYS a lot of product feedback. ANSYS software is a widely used commercial tool, which has led to a much broader implementation of DFV at Pratt & Whitney. Our younger engineers are familiar with ANSYS solutions, and they can easily fit the tools into our standard workflows. They like being exposed to multiple physics and seeing all the parts of a specific problem.

The collection of automated workflows, variability and uncertainty analysis, and emulators allowed the Pratt & Whitney team to address its design challenges more quickly than by using traditional analysis strategies. For example, when aerodynamics refinements led to topological changes, the team used the established tools and process to efficiently adapt the toolset and continue the design activities. This enabled the team to design an A320 MTF that is robust with regard to uncertainty in thermal profiles — while exceeding life, weight and efficiency requirements and adhering to the design schedule.
Reliably comfortable and safe commercial air travel requires creating a cabin that is a hospitable in-flight environment throughout a wide range of extreme external climatic conditions. To successfully design a cabin for passenger comfort, a system of aircraft components must work in concert within industry standards for cabin climate control to maintain suitable pressure and temperature inside the plane.

An airliner’s environmental control system (ECS) consists of several key parts, including heat exchangers, pipelines, compressors, fans, turbines and a water separator. At a cruising altitude of 30,000 to 40,000 feet, the outside air temperature is around –50°C to –60°C (–58°F to –76°F) and the pressure is 0.3 atm to 0.2 atm (4.2 psi to 2.9 psi). These conditions are much too low for traveler safety and comfort, and must be raised inside the cabin. To do this, several systems must effectively work together. For example, in a two-wheel ECS system, hot high-pressure air bled from the engine is cooled by ram air in a heat exchanger. A compressor then further pressurizes the air to reach the desirable pressure but at a high temperature. The hot air is cooled again in the main heat exchanger and, after passing through a turbine, the air temperature is cooled to the required cooling temperature and a suitable pressure. The cooling process leads to water vapor condensation so the condensed water is removed by a water separator. Finally the cool air mixes with the filtered return air from the cabin to deliver a suitable temperature and pressure. The ECS then distributes air from the mixing manifold to the cabin to remove heat in cabin air produced by passengers, crew and equipment, and to maintain a pressure in the cabin similar to that at around 6,000 feet above sea level.

SYSTEMS SIMULATION

For the benefit of ECS designers, it is important to understand the interaction of these components before testing them during an actual flight. Researchers at Tianjin University in China and Purdue University created a systems-level simulation and detailed thermal analysis to meet industry standards.

To successfully design a cabin for passenger comfort, systems must work together to maintain suitable pressure and temperature inside the plane.
Researchers have been investigating the behavior of an ECS using both systems-level and CFD simulation tools from ANSYS.

University in the U.S. have been investigating the behavior of an ECS using both systems-level and computational fluid dynamics (CFD) simulation tools from ANSYS. The two universities work together using ANSYS software to study the problems related to human health, safety and comfort in the field of transportation. Aircraft manufacturers such as Boeing and the Commercial Aircraft Corporation of China (COMAC) are members of the Cabin Air Reformative Environment (CARE) consortium, as is ANSYS. The universities’ work supports CARE goals.

At the overall system level, the cabin thermal environment is regulated by a temperature controller, in which feedback signals from the cabin are used to modify the flow rate of the supplied engine bleed air. The controller contains proportional–integral–derivative (PID) logic, which the research team implemented into a systems-level model using the built-in PID module in ANSYS Simplorer. At the detailed level, the team created a 3-D model of the first-class cabin of an MD-82 jet in ANSYS Academic Research CFD (ANSYS Fluent) software using geometry obtained from a laser tracking system and employing a mesh with 6.4 million cells.

Researchers then coupled the Simplorer and Fluent models to analyze the transient impact of the ECS on the cabin thermal environment. During the coupled simulation, Simplorer predictions of the air temperature supplied to the cabin provided boundary conditions to the detailed CFD cabin model. CFD predictions of temperature at various cabin locations were compared to the desired temperature set point, and any deviations directed the temperature controller to adjust the flow rate of engine bleed air. This flow rate was a new boundary condition for the Simplorer ECS model, and iteration proceeded to completion.

GROUND-BASED CLIMATE CONTROL

Prior to modeling the ECS, however, the team needed to evaluate the effectiveness of simulation on a climate-control system that did not require them to physically conduct in-flight testing. The first step was to analyze the ground air-conditioning cart (GAC) system, in which a mobile vehicle pipes outside air into the plane while it is idle at the airport. The GAC contains a heating coil, a cooling coil and a centrifugal fan that can heat the cabin in cold months and cool the cabin during warmer months. The team followed a similar process to build a systems-level model of the GAC in Simplorer, and then coupled it to the CFD model of the MD-82 cabin.
Researchers evaluated the impact of different locations for the sensors sending data to the PID modules controlling flow. The first temperature feedback location studied was at the GAC outlet pipe sending air into the plane, while the second location was inside the cabin at passenger breathing height. Air temperature and velocity test data measured from an MD-82 cabin in Tianjin during January and June — with respective outside temperatures of about –5 C (23 F) and 35 C (95 F) — agreed closely with predictions made by the Simplorer GAC system model and the detailed CFD cabin model. The results helped the team learn that locating temperature feedback sensors closer to passenger seats provided more uniform temperature distribution at different heights within the cabin.

IN-FLIGHT CLIMATE CONTROL

Having developed and validated this simulation procedure, the research team then used the coupled Simplorer–Fluent analysis to simulate ECS behavior for conditions that a commercial aircraft would encounter during the typical seven stages of a short flight. These conditions included a four-minute taxi on the runway, one minute for takeoff, 15 minutes of climbing, five minutes of cruising, 20 minutes descending, 40 seconds for landing, and five minutes to taxi back to the gate. Simplorer predicted the changing mass flow rate of engine bleed air required to keep the cabin at the desired temperature set point of 23 C (73 F) during all seven flight stages. As expected, CFD simulations predicted that the in-flight cabin air velocity and temperature would fluctuate more when it is hot at ground level because of the larger temperature difference between the ground and the flight altitude.

Over the course of seven different coupled simulations of GAC and ECS cases, the team typically completed model setup in Simplorer and Fluent

The researchers coupled ANSYS Simplorer and ANSYS Fluent models to analyze the transient impact of the ECS on the cabin thermal environment.
in about four hours. Simpler models ran very quickly, while a typical highly detailed transient CFD analysis of cabin airflow during simulated flight conditions required about 60 hours running on 32 processors. Work is continuing to implement a reduced-order model (ROM) representation of the ANSYS Fluent CFD model of the cabin so that overall system simulation time can be drastically reduced without sacrificing the accuracy of the simulation output.

The Tianjin and Purdue team shared its findings with researchers at Boeing and COMAC through the CARE consortium. Early indications are that these manufacturers will be setting up their own virtual platforms for simulation of future ECS designs. Future experimental validation of the team’s ECS predictions done in collaboration with CARE industry partners is also on the horizon to help further elevate the performance of such aircraft systems.

**CFD simulations predicted that the in-flight cabin air velocity and temperature would fluctuate more when it is hot at ground level.**
Cloud computing reduces by 80 percent the time required for a coupled CFD and structural simulation.

By Marius Swoboda, Head of Design Systems Engineering, and Hubert Dengg, Thermal Analyst
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Rolls-Royce reduces the wall-clock time to perform the simulation by 80 percent.

Rolls-Royce uses an in-house, specialized structural code to determine the operating temperature of jet engine components such as turbine disks. The thermal boundary conditions for such an analysis are usually determined by mounting thermal sensors on the components and capturing heat flux measurements while the engine is running. One problem with this approach is that the thermal design of a new engine cannot begin until late in the product development process, when the first prototype becomes available. At this point, changes to the design are expensive, limiting what can be done to optimize thermal performance.

Rolls-Royce is a leader in the implementation of a new high-performance computing (HPC) cloud approach in which its structural solver is coupled with the ANSYS Fluent computational fluid dynamics (CFD) solver to provide heat flux predictions at many points on component walls without reference to a physical prototype. Performing this coupled simulation requires a high level of computational power because the solution is time-dependent. This means that CFD and structural solutions must be computed to convergence at each time step as the solution progresses. Rolls-Royce reduced the wall-clock time to perform the simulation by 80 percent by running the simulation on a hosted, shared HPC cloud system.

Challenge of Higher Inlet Temperatures

Engine manufacturers continue to increase turbine entry temperatures as they strive to improve engine efficiency. In this process, engineers must often redesign the engine’s cooling and sealing systems to prevent the overheating of critical internal components. Rolls-Royce engineers determine the operating temperatures of these components by performing a thermal analysis with an in-house, specialized structural code. One of the inputs to the thermal analysis is the transient heat flux at an array of points on the walls of the components under study. Engineers believed that they could achieve major improvements in the design process by determining the heat flux with CFD, then coupling the CFD code to the structural...
code to exchange the data at each computational cycle. The goal was to achieve an iterative loop with smooth exchange of information between the structural and CFD simulations so that the team could ensure consistent temperature and heat flux on the coupled metal–fluid domain interfaces. This continuous update of the heat transfer information to the components gives an accurate representation of the range of temperatures they will experience during startup and steady operation.

The conjugate heat transfer simulation process is very computationally demanding, especially when 3-D CFD models with more than 10 million cells are required. With internal HPC resources at full capacity, Rolls-Royce engineers considered using cloud resources to access HPC capabilities for this application. Engineers had to overcome several challenges. An interface between structural and CFD codes was available but had to be upgraded to allow for HPC. The other challenge was configuring the ANSYS Fluent process to run on several machines when called from the structural software. While a Fluent calculation spawned flawlessly on multiple cores, only one machine was used for the structural code within the coupling procedure. A change to the use of dedicated Fluent licenses in the cloud allowed the process to run independently of the in-house licensing and the queuing system. In the end, the licensing process ran much faster in the cloud than in-house.

**RUNNING SIMULATION IN THE CLOUD**

Rolls-Royce selected CPU 24/7 GmbH & Co. KG to provide remote HPC computing power on demand. The computation was performed on an HPC cluster using Intel® Xeon® E5-2690 processors and FDR Infiniband® interconnects. The calculation was done in cycles in which either the structural solver or the Fluent CFD solver alternately ran and then passed data to the other when the cycle was completed. The CFD solution supplied heat flux at the walls, and temperature and swirl velocity as outputs to the structural code. The structural code provided temperature at the walls and inlets as boundary conditions for the CFD code. At each step, multiple iterations of CFD and structural solvers ran with solvers exchanging data until their calculated wall temperatures matched. The simulation ran for a total of 6,000 seconds of simulation time, which included startup, low-power and high-power engine operation. As expected, the bulk of the computational resources were consumed by the CFD calculation. The CFD part of the calculation was run on all 32 cores, while the structural part ran on only one.

CPU 24/7 contributed considerable expertise to the project, including how to set up a cluster, how to run applications in parallel based on a message passing interface (MPI), how to create a host file, how to handle the FlexNet® licenses, and how to prepare everything needed for turnkey access to the cluster. During the whole process, CPU 24/7 supplied comprehensive and expedient technical support. It took only one month from the initial concept of executing the project on the cloud to the completion of the first calculation on the remote cluster. This rapid startup was possible because of the smooth collaboration between ANSYS and the CPU 24/7 team.

The results of the coupled CFD–structural simulation were validated with physical testing results. Because of the near-linear scalability of Fluent, running
Running the coupled fluid-structural simulation on the HPC cluster in the cloud was five times faster wall-clock time than running the problem on a local workstation.

The coupled fluid-structural simulation on the HPC cluster in the cloud was five times faster wall-clock time than running the problem on a local workstation. By outsourcing the computation workload to an HPC cloud provider, HPC resources were elastically provisioned and released. Rolls-Royce engineers were able to expand or shrink HPC capacity as needed, thus increasing their operational IT efficiency and better utilizing HPC resources. For example, the availability of cloud computing resources makes it possible to scale up HPC to run even bigger models that provide more detailed insights into the physical behavior of the system.

There is currently no physical way to determine the performance of a proposed cooling and sealing design until the hardware is built and tested. At that point, so much time and money have been invested in the design that changes are very expensive. It is also impossible to evaluate more than a few alternatives using the build-and-test method. Simulation is the only answer. One significant advantage of running a coupled structural-fluid simulation in the HPC cloud is the potential to iteratively optimize the entire cooling and sealing system design in the early stages of the product development process. An experiment can be designed to explore the complete design space, and then engineers can select the best possible design for prototyping and testing. Rolls-Royce is aggressively pursuing this HPC cloud approach, which has the potential to achieve significant improvements in jet engine performance.
GOING GREAT GUNS

Finite element analysis helps to improve design of a maintenance trainer for a tracked combat vehicle.

By Jose R. Gonzalez, Lead Senior Mechanical Engineer

Building full-scale maintenance training systems for military applications is a relatively low-margin business. It requires paying strict attention to costs to meet specifications requirements while remaining profitable.

One of Kratos Defense & Security Solutions’ many defense products is a hands-on trainer used to teach students how to maintain the turret and main components of a combat vehicle that uses continuous tracks for propulsion. The trainer is designed to support up to 17 students, so it must be validated to support their weight with a minimum safety factor for noncritical components of 2.0. Other companies in this industry validate trainer design by building a physical prototype; they often have to make changes after testing the prototype, which adds cost and time to the product design and development process.

Instead, Kratos utilized structural mechanics software in the ANSYS Workbench environment to simulate the initial concept design of the trainer and to develop a virtual prototype. Engineers found several problems with their initial structural design concept; by correcting these prior to cutting any metal, they minimized physical prototyping. The result was that the first trainer the company built met all of the customer’s safety and functionality design requirements, saving approximately several hundred thousand dollars in development cost and time, compared to the traditional engineering design approach.

The Technology & Training group at Kratos helps military organizations to optimize performance by improving training outcomes while reducing training time and costs — empowering a workforce that is fully equipped to maintain critical systems availability. Kratos’ areas of expertise include command, control, communications, computing, combat systems, intelligence, surveillance and reconnaissance (C5ISR), as well as unmanned systems, cyber warfare, cyber security, information assurance, critical infrastructure security and weapons systems lifecycle support.

DESIGNING TRAINING SYSTEMS

Kratos received a contract to build a number of U.S. Army tracked combat vehicle full-scale maintenance training systems (MTSs). The MTS provides training in critical field-level repair and maintenance tasks at the Army’s Armor School Center. Each combat vehicle MTS has more than 15,000 components, weighs about 24,000 pounds, and is designed to carry an additional 3,500 pounds, including students and training equipment.

In the early stages of the project, Kratos engineers created a detailed 3-D model concept design of the combat vehicle MTS using Autodesk® Inventor® CAD
software. The structure incorporates a replica of the combat vehicle turret, which is surrounded by a turret stand along with a platform that holds the class of students and instructor operator station. This station includes a computer that controls the training systems and provides feedback information to instructor and class. The traditional design process (used at a number of Kratos’ competitors) involves building a physical prototype and performing physical proof-of-concept development testing to verify that the structure supports the required load with the necessary margin-of-safety factor.

**BEST PRACTICES**

Kratos, however, has implemented an optimized design process that utilizes structural engineering simulation in the initial design process to identify problems with the concept design before building a physical assembly. This method ensures robustness of the design despite manufacturing variability, reduces the cost of product design and development, increases development team productivity, and delivers a better product in less time.

Kratos looked at a number of different simulation solutions and selected ANSYS structural mechanics technology for several reasons. The ANSYS portfolio provides the highest existing level of reliable product design and simulation technology, and it continues to steadily improve for existing and new applications. ANSYS supports an extremely broad range of engineering applications at a fair price and provides excellent technical support to users.

During the design process, engineers followed simulation best practices developed by Kratos. The team created detailed 3-D model geometry to ensure high-fidelity mass and inertial properties and assigned correct materials and physical properties for each component during the virtual prototype design process. They optimized the design by fully constraining the 3-D CAD geometry assembly and component models with the mating contact surfaces to ensure that they remain in full contact. Engineers cleaned up the large 3-D CAD geometry assembly model that contained more than 15,000 components to eliminate gaps and protruding surfaces between components.
Kratos engineers optimized the 3-D models by eliminating small holes and threaded surfaces with little effect on the overall structure design; this decreased the number of nodes, subsequently reducing meshing and solution times. They also eliminated small fillet radii in the 3-D CAD models to avoid the stress riser effect when the model is solved. Each 3-D CAD model was grounded to adjacent components to avoid the potential for movement of floating components, which could create connection and meshing errors. When the CAD model geometry initial design was complete, Kratos engineers imported it into the ANSYS Workbench environment.

An FEA mesh was successfully generated using shell and beam modeling for the tracked combat vehicle trainer structure with more than 1.7 million total nodes, 404,000 elements, and over 10.6 million degrees of freedom. For structural analysis settings, the load of 3,550 pounds was applied in the form of 18 separate forces. These included 17 students at 200 pounds each and an instructor operator station at 150 pounds. Five supports were set with four jack-screw pads and the rear stairs. A static structural analysis was then run on the model. The initial analysis results showed that a minimum safety factor was below the required 2.0 in the cross-beam side-tube supports and bottom 45-degree tube supports located in the turret stand structural assembly. The minimum safety factor was also below 2.0 in the base-forward support posts located in the turret’s structural assembly.

Kratos engineers made a number of structural reinforcement design changes to address these concerns in the virtual prototype 3-D model geometry. They inserted two horizontal steel structural tubes on the bottom frame front corners. They added eight upper-lateral steel cross beams and eight lower-lateral steel cross beams on each vertical post corner. Engineers changed the material from aluminum to steel on the turret base-forward support posts. They added a tactical-base basket-steel material component to the turret basket support assembly. These changes added 193.27 pounds to the turret stand structural assembly and 68.27 pounds to the turret structural assembly.

Kratos engineers then reran the static structural analysis for the reinforced design. The minimum safety factor for noncritical components in the reinforced design was 2.312, above the 2.0 design requirement.
Engineers optimized and validated design of a maintenance training system for a tracked combat vehicle without building a physical prototype.

reinforced structure to evaluate the effect of design changes. They applied the same loads to the structure and concluded that all critical-area safety factors were above 5.0. The final results showed a minimum safety factor of 2.312, which occurred only in a noncritical component located on the turret structure upper section. When the combat vehicle simulators were physically built and tested, the final results matched the virtual prototype simulation predictions — so no changes were required to the final design. Without engineering simulation, the system as initially designed and developed would have failed testing; it would have required revisions at considerable expense and additional development time.

Using ANSYS structural mechanics software and Workbench to perform simulation helped to substantially improve Kratos’ product design process. Engineers optimized and validated the product design based on the 3-D virtual prototype without having to build a physical prototype. In addition to reducing the cost involved in product design and manufacturing, simulation shortened time to market and deployment to the customer’s military bases. The combat vehicle maintenance training systems were developed on time and on budget, ready to be shipped to the customer by the end of the year. The excellent results in getting the product design right the first time helped to validate the effectiveness of Kratos’ simulation and design optimization methodology.

Partially due to the success of this program, Kratos was awarded a contract extension to upgrade tracked combat vehicle maintenance simulators for an army training center. The company has also received industry recognition for its efforts, most recently by being named top simulator and training company for 2011 by Military Training Technology magazine.
Drones offer many potential advantages for intelligence, surveillance and reconnaissance (ISR) applications, such as threat identification and documentation, anti-terrorism, border security, harbor and port security, and loss prevention. However, there are many instances in which drones are not practical because they don’t meet regulatory or safety requirements, because their limited payloads can’t accommodate the required surveillance equipment, or because they can’t stay in the air long enough to accomplish the mission. Lighter-than-air (LTA) airships, also known as blimps, are being used increasingly to replace or complement drones: This type of aircraft faces far fewer regulatory and safety issues, can carry much larger and more varied payloads, and can stay in the air for longer periods of time.

Worldwide Aeros Corp.’s 40E Sky Dragon is the newest LTA platform that supports ISR mission success and efficiency with multipayload mounting systems and the flexibility to cover more ground with less manpower requirements. Compared to the previous generation — the 40D Sky Dragon airship, which entered service in 2007 — the 40E offers a larger payload and a number of accommodation and operational improvements. Substantial design changes were involved in the 40E. For example, increasing the airship payload required increasing the helium volume and upgrading

ANSYS multiphysics software enables engineers to design new airships 40 percent faster than for the previous generation.

By Armen Amirian, Senior Mechanical Designer, and Simon Abdou, CFD Engineer, Worldwide Aeros Corp., Montebello, U.S.A.
the propulsion system and landing gear. Aeros engineers used ANSYS multi-physics simulation tools from the beginning of the design process to deliver the 40E six to 12 months faster, or in about 40 percent less time, than would have been required using previous design methods.

**PREVIOUS DESIGN METHODS**

In designing the company’s previous-generation 40D Sky Dragon airship, engineers used hand calculations to establish the basic parameters of design, such as evaluating aerodynamic profiles, determining where to put flaps, sizing the engines, etc. Engineers felt that the time involved in performing simulation with the tools available at that time made it inappropriate for use during the concept design stage. Once they had tentatively established basic design parameters, engineers used simulation tools, including computational fluid dynamics (CFD) and finite element analysis (FEA), to perform a more-detailed evaluation of the proposed concept designs.

When Aeros began work on the 40E, the company decided to take advantage of advances that had been achieved in the intervening years in simulation software. Simulation tools have improved to the point that it is now possible to much more quickly model the behavior of proposed designs as well as rapidly iterate through a wide range of design alternatives, without the need for an engineer to manually model each proposed design.

Aeros selected ANSYS simulation software because, first of all, ANSYS is a proven technology, so the results are well accepted not only by Aeros engineers but also by existing customers. Second, ANSYS provides a full range of tools that cover nearly every aspect of the airship design process — including aerodynamics, static and dynamic structural analysis, signal and power integrity, and many others — within a single environment. This breadth saves time by making it possible to move data easily between different types of simulations and run automated simulation processes that incorporate multiple types of simulation.

Aeros engineering management made the decision to use simulation from the beginning of the design process. They used ANSYS Fluent CFD to evaluate the aerodynamics of the new airship. Engineers performed a detailed aerodynamic simulation of the complete airship in about 24 man-hours over a period of 72–96 hours, including modeling and solution time. Pressures from the aerodynamic simulation were used as boundary conditions in ANSYS Mechanical to evaluate mechanical performance of many of the 40E’s systems and components. At various stages of the design process, engineers used ANSYS DesignXplorer to rapidly iterate through the entire design space and select alternatives that provided the highest possible level of specified design objectives. Simulation provided far more accurate estimates of the performance of design alternatives than were obtained in the past with hand calculations. Using simulation early in the design process saved time and money by identifying and solving problems much sooner.

**NEW LANDING GEAR DESIGN**

The new landing gear for the 40E Sky Dragon is a good example of how
simulation was used. The landing gear now enhances performance, safety and operator empowerment by providing real-time static lift data for airship pilots during takeoff, while improved damping force control ensures smoother landings. The airship’s flight management system actively controls shock absorber dampening properties. The height of the landing gear was increased for greater clearance between propellers and ground, which increases safety for the landing crew. The landing gear was also upgraded to handle the heavier new airship.

**RIGID BODY DYNAMICS**

Engineers modeled the structural components, springs, shock absorbers and tires in the landing gear using the ANSYS Rigid Body Dynamics module. The maximum loading on the landing gear is defined by a drop test designed to reproduce the landing of a fully loaded airship. Engineers ran a series of rigid body dynamics simulations of the airship landing at various speeds and approach angles. The simulation was iterated to tune the springs and shock absorbers. A number of different performance characteristics were used to evaluate each design iteration, such as the minimum propeller/ground clearance distance, loads at various points, and number and height of tire bounces off the ground during landing.

**STRUCTURAL ANALYSIS**

Loads calculated by the Rigid Body Dynamics module were used as boundary conditions for structural analysis of individual components using ANSYS Mechanical. Other ANSYS Mechanical simulations were performed using the aerodynamic simulation results as boundary conditions. Engineers used DesignXplorer for many components to find the lightest possible design that would meet structural and functional requirements. Even though the 40E is significantly heavier than the 40D, the weight savings achieved through simulation made it possible to reduce the weight of a number of key components without increasing stress levels. For example, one part that was 0.5 inches thick in the 40D was reduced to a thickness of just over 0.25 inches, resulting in a 40 percent weight reduction.

In about six weeks, Aeros engineers performed hundreds of system-level and component-level simulations. The result was a landing gear design that met all design requirements yet was very close to the overall weight of the previous-generation landing gear. At this point, a prototype of the new landing gear design was built; its performance matched the simulation results within +/−10 percent or less. The prototype passed the drop test and all other required testing and was used without further significant modifications in the 40E.

**ESTIMATED TIME SAVINGS OF MORE THAN SIX MONTHS**

Aeros engineers estimate that, if the landing gear had been designed using the company’s previous design methods, at least four months would have been required to reach the stage for which the design was ready to prototype. They also estimate that at least two, and more likely three, prototype iterations would have been required, with six months being required for each iteration. So the time savings on the landing gear design was between 8.5 and 20.5 months. Substantial cost savings were also achieved in both engineering and prototype-building expenses.

Aeros engineers believe that simulation made it possible to significantly reduce the weight of many components in the 40E compared with the design methods used on the 40D. These savings reduce manufacturing costs and will also save fuel for Aeros customers over the life of the airship. These manufacturing savings are probably many times larger than the savings that were achieved in the prototyping process.

Similar magnitude savings were achieved in the design of other 40E Sky Dragon systems. Aeros engineers estimate that the use of a more—simulation-intensive design process will make it possible to bring the 40E to market six to 12 months faster than if the previous design methods had been used. The first 40E is under construction and is expected to be completed in late 2015. It will enter service after Type Certification by the Federal Aviation Administration.
The aerospace and defense industry is charged with delivering advanced electronics systems faster and at a lower cost than ever before. Antenna and microwave design engineers must balance competing requirements for reduced size, high power delivery, rock-bottom cost and excellent reliability. The result is that antennas and microwave components operate at higher power levels and higher frequencies while being contained in smaller form factors. The inevitable outcome is increased risk that temperatures will greatly impact product performance. Traditionally, electrical design and thermal design are the responsibility of two different groups, each operating

Antennas and microwave components operate at higher power levels and higher frequencies while being contained in smaller form factors.
with their own separate requirements and analysis tools — and with only limited cross-group interaction. This common failure to more fully account for design dependencies has, in some documented cases, resulted in serious product malfunctions.

For example, the heat generated by microwave components can increase the dielectric loss tangent of some materials; the consequence is more heat production and the potential for a runaway reaction. In extreme cases, product failure could prevent a mission from being accomplished or even cause loss of life. Combining electrical, thermal and structural simulations often provides unprecedented insight toward preventing failures and improving product performance. Raytheon Corporation — a technology and innovation leader specializing in defense, security and civil markets throughout the world — uses comprehensive robust electronic design solutions to improve the reliability of its products, reduce time to market, and control engineering and manufacturing costs.

**MULTIPHYSICS SIMULATION — A BRIEF HISTORY**

Engineers have long been interested in combining high-frequency electromagnetic simulation with thermal analysis, but before the turn of the millennium, there was no efficient way of doing so. About 2002, Raytheon management encouraged investigation into the potential for coupled simulation capabilities. This led to the selection of ANSYS HFSS to enable coupling between electromagnetic and thermal analysis. Raytheon engineers began using the tools extensively to design microwave systems with excellent results. In 2007, the group needed to add vibration and fluid dynamics capabilities to the coupled analysis toolkit. With HFSS integrated into the broader ANSYS simulation portfolio (for example, ANSYS Mechanical and ANSYS Fluent), it was easy and intuitive to perform multiphysics simulations within ANSYS Workbench.
In an example from a recent project, a high-power signal is received by the antenna plane. The effective received radiation signal flows to a microwave feed circuit. Although both the electrical and thermal groups signed off on the design, a voltage breakdown occurred at a microwave junction, where a coaxial pin connects to a microstrip trace at the frequency of interest. Shortly after power was turned on, excessive heat destroyed the connector. To address this, Raytheon engineers modeled the components in HFSS. This software accurately models microwave components, such as tuning screws and probes, to a fine level of detail. HFSS employs the finite element method, using small unstructured mesh elements when needed, along with large elements when small elements are not needed, to reduce processing time without sacrificing accuracy. Adaptive meshing refines the mesh automatically in regions in which field accuracy needs to be improved.

Raytheon engineers took advantage of integration capabilities in ANSYS Workbench to capture electromagnetic and thermal interdependencies.

VOLTAGE BREAKDOWN AT MICROWAVE JUNCTION

In an example from a recent project, a high-power signal is received by the antenna plane. The effective received radiation signal flows to a microwave feed circuit. Although both the electrical and thermal groups signed off on the design, a voltage breakdown occurred at a microwave junction, where a coaxial pin connects to a microstrip trace at the frequency of interest. Shortly after power was turned on, excessive heat destroyed the connector. To address this, Raytheon engineers modeled the components in HFSS. This software accurately models microwave components, such as tuning screws and probes, to a fine level of detail. HFSS employs the finite element method, using small unstructured mesh elements when needed, along with large elements when small elements are not needed, to reduce processing time without sacrificing accuracy. Adaptive meshing refines the mesh automatically in regions in which field accuracy needs to be improved.

Raytheon engineers imported initial design geometry from a computer-aided design (CAD) file. They defined the electrical properties of the materials, such as permittivity, dielectric loss tangent and bulk electrical conductivity for the Kovar® housing, alumina substrate, Teflon® insulator, and beryllium, copper and Kovar pins. Engineers then defined boundary conditions that specify field behavior on the surfaces of the solution domain and object interfaces. They defined ports at which energy enters and exits the model. HFSS computed the full electromagnetic field pattern inside the structure, calculating all modes and ports simultaneously for the 3-D field solution. (The dielectric properties of the materials are temperature dependent.) The HFSS electrical field analysis at 25°C showed that the electrical field in the area in which the failure occurred does not exceed 1.5 x 10^6 volts per meter (V/m), as compared to the 2.952 x 10^6 V/m value for voltage breakdown in air.

COUPLING ELECTRICAL AND THERMAL SIMULATION

The real-life situation is more complex because ambient temperature affects the dielectric properties of the materials, and the dielectric properties of the materials affect the heat that is generated by microwave components. Raytheon engineers took advantage of the integration built into ANSYS Workbench between HFSS and ANSYS Mechanical to capture these interdependencies. The HFSS model was coupled to ANSYS Mechanical to perform a transient thermal simulation. Boundary conditions for natural convection cooling were added on the bottom face. The temperature distribution was used to perform a static structural analysis.

Engineers employed ANSYS Workbench coupling to apply temperature fields (determined by physical measurements) to ANSYS Mechanical to calculate the thermal stresses associated with these temperatures. The structural simulation showed high stresses and deformation up to 22 µm in the inner connector. Thermal analysis indicated that temperatures actually reached 86°C on the bond ribbon and the pin near the point where they connect, which translated into a lower breakdown voltage. Raytheon
engineers re-analyzed the components at 86 C using the dielectric properties at the higher temperature and discovered that the electrical fields in the area where the failure occurred exceeded the 2.45x10⁶ value for voltage breakdown in air at this temperature.

The simulation results helped Raytheon engineers understand how the failure occurred, and they corrected the design to eliminate future failures. The team solved the electromagnetic model at the initial temperature, sent the electromagnetic loss to the thermal simulation to determine the impact of the losses on temperature, sent the temperatures back to the electromagnetic model to calculate losses on the new temperatures, and continued to iterate until steady-state temperature changes were reached. After a few more changes to the materials used in the product, the simulation showed that the design worked perfectly, and this was confirmed by physical testing.

The simulation showed that the design worked perfectly; this was confirmed by physical testing.
The use of unmanned aerial systems (UASs) for intelligence, surveillance and reconnaissance (ISR) missions has shown explosive growth. As their value continues to be demonstrated, this growth shows no sign of slowing. The UAS sector must address a number of key technical and manpower challenges in developing autonomously controlled aircraft. Engineers from Piaggio Aero faced the challenge of transforming the company’s conventional manned P.180 Avanti II executive jet into a UAS. The vehicle command-and-control architecture needs to be certified against first-generation requirements while supporting a design roadmap that foresees growing functionality to support different configurations. This job had to be done with a strictly controlled number of engineers to limit overhead and succeed in a very short time. Piaggio engineers accomplished these goals with a new development process in which ANSYS SCADE models were created from scratch, or, if Matlab/Simulink® models were available, they were translated via the SCADE Suite Gateway for Simulink®. From the SCADE model, the embedded source code was generated automatically with the SCADE KCG qualified code generator. The vehicle control and management system (VCMS) — the digital infrastructure performing aircraft command and control — was tested continually, first at the model phase, then on the host, and

The first flight of the aircraft was successfully completed less than two years after the project began.
finally in the target environment so that the team could identify problems and correct them at the earliest possible point.

Piaggio Aero Industries S.p.A. is a multinational aerospace manufacturing company headquartered in Genoa, Italy. It designs, develops, constructs and maintains aircraft, aero-engines and aircraft structural components. Powered by two Pratt & Whitney Canada PT6-66B turbo-prop engines, Piaggio’s newly developed P.1HH Hammerhead will provide sophisticated standoff (deployed at a distance) capabilities for any surveillance and security need. The VCMS manages flight control, propulsion, electrical power generation and distribution, landing gear, braking, ice detection and protection, navigation and communications systems. Partitioning techniques were used to create a segregated environment in which software applications of each function run without interfering with each other to avoid propagating failures.

DEVELOPING SOFTWARE REQUIREMENTS

In the first months of the project, the team developed the engine and flight control laws; it also created the other requirements for the embedded software. High-level requirements for the VCMS were available in several different formats. Systems engineers collected some requirements in textual form as functions, interfaces and redundancies. Other requirements were captured in text from operating manuals such as the P.180 Pilot Operational Handbook. Control laws, algorithms and equations involved in flying the plane were written, simulated and validated in MathWorks® Simulink. Requirements were generated in the IBM®
Rational® DOORS® requirements management environment. Test cases were also written in DOORS and linked to operational requirements using the SCADE Requirement Management Gateway. For each test case, test steps and expected results were defined.

For this project, the software must comply with DO-178B, the de facto standard used to qualify avionics software by the FAA, EASA and other certification authorities. Piaggio selected ANSYS SCADE as the development environment for the VCMS, since SCADE automatically generates source code from the model and minimizes the effort required to verify that the source code corresponds to the system model. The ANSYS SCADE KCG code generator is qualified as a DO-178B development tool, so conformance of the code to the input model is trusted, eliminating the need for verification activities related to the coding phase. SCADE’s model-based methodology enables system engineers to model each function autonomously and check its performance on a host computer before the real hardware is available.

CREATING MODELS

SCADE models were created based on functional requirements from scratch by systems engineers for the textual document, automatically via the Simulink Gateway for the existing Simulink models. The SCADE Requirements Management Gateway was used to link the requirements to the embedded system design in the SCADE model. Engineers employed the SCADE Semantic Checker to verify the semantics of the model. Problems were identified and resolved in the host on the PC environment rather than in the much more expensive and complicated target hardware environment. A small portion of the code, primarily low-level layers such as input/output, was developed in C using traditional methods.

To ensure that the Simulink model was correctly translated to the SCADE environment, Simulink test vectors were translated into the SCADE environment. The test cases were translated to SCADE Input Scenarios. Then the test vectors were run in both Simulink and SCADE, and the results were compared to ensure that the translated SCADE model had the same functional behavior as the original Simulink model.

SOFTWARE VERIFICATION

DO-178B verification requires proof that the functional tests performed by the test vectors fully cover model functionality. The SCADE Model Test Coverage (MTC) tool checked the model coverage and identified several areas that were lacking. Additional tests were designed and performed to provide the needed coverage.

Verification activities exponentially increase as the number of inputs of each model grows and as the number of models increases. In the early stages of the project, test vector generation, validation and configuration were issues. SCADE LifeCycle Qualified Test Environment (QTE) provided a solution by automatically running the tests in the host environment, comparing the results to the expected values and highlighting any errors.

Similar activities were performed on the target computer, sending test vectors into the executable code generated from the models. Piaggio engineers wrote a simple test application tool that runs on the target and plays a role similar to QTE by running the application with the SCADE input scenario then comparing results with the output generated by the same application and input on the host.

SYSTEM INTEGRATION

Models to handle different functional aspects of the VCMS were progressively integrated on the host computer to build a virtual VCMS to check interoperability of the applications well in advance of system integration. These verification activities were used to identify and solve many integration problems even before performing system integration on real hardware. As a result, the problems found during system integration were small in number, and all were mainly due to hardware/software/subsystem integration issues rather than to design errors. Once system integration was completed and the final tests executed, data from the real world were fed into the test vectors to further verify the model.

The entire project was completed in about 18 months, starting with model development performed directly by the system engineers and proceeding to compilation, integration and verification of the approximately 125,000 lines of source code that comprise the VCMS. The working team — in terms of equivalent full-time manpower — was limited to less than 20 engineers (system and software) who worked in tight coordination from the early design stages up to final system integration to meet the challenging target. As a result, the VMCS was developed and verified in an estimated one-third the time that would have been required had the code been handwritten.

The first flight of the aircraft was successfully completed in November 2013, less than two years after the project began. The VCMS worked perfectly. The P.1HH configuration will grow through incremental software releases that will add new functionalities to expand mission capabilities of the P.1HH.
Testing the Next Generation of Rockets

Structural analysis provides additional thrust for analyzing rocket engine test equipment.

By Vladimir Tkach, Head of Stress Engineering, Alexander Milov, Lead Stress Engineer, Alexander Loshkarev, Lead Stress Engineer, and Denis Merzljakov, Lead Stress Engineer, NPO Energomash, Khimki, Russia
Space exploration is entering an exciting new era. With active national space programs accelerating in India and China and commercial entrants such as SpaceX showing success, traditional space-faring nations can see that the race is on to provide greater payloads at competitive costs.

Located northwest of Moscow, NPO Energomash has a pioneering history of successful research, development and deployment of liquid-propellant rocket engines (LPREs). The company’s technology has powered launch vehicles since the dawn of the space age. These include the rockets that carried the first artificial satellite, Sputnik 1, in 1957; the first human space flight aboard Vostok 1 in 1961; and the long-serving Soyuz vehicles that are still in service today for transporting crew and cargo to the International Space Station. NPO Energomash develops several classes of engines, including the RD-170 and variants that provide the highest thrust of any engine ever used on space-launch vehicles.

The modern RD-171 engine is a four-chamber LPRE that burns kerosene and liquid oxygen to power the first-stage strap-on boosters for the Zenit category of vehicles for land- and sea-based launches. The engine can provide up to 800 metric tons-force (1.75 million pounds-force) of thrust, helping the Zenit achieve a lower cost of payload weight per launch relative to other types of launch vehicles. Future heavy-lift launch vehicles, however, will require the ability to lift even greater masses into low-Earth orbit and beyond.

To meet these future needs, NPO Energomash has been designing a more powerful LPRE that will generate thrust of 1,000 metric tons-force (2.2 million pounds-force). Rather than spend millions of dollars to purchase and construct a new test facility, the organization determined that it was more reasonable to analyze the existing testing infrastructure; the company had a horizontal test bench force measurement system that was designed for the RD-171. Before test-firing a new prototype, stress engineers there needed to evaluate the ability of the current test bench to withstand forces generated by a higher thrust. The team used ANSYS Mechanical APDL to perform a static strength analysis of the test bench system.

For the purpose of the structural simulation, the test bench was divided into many different load-bearing frames, belts, rods, bolts and pins to determine whether the structures would meet safety factors required by the Russian Federal Space Agency (Roscosmos) when loaded by the more powerful engine. Two such loading conditions are emergency thrusting at 105 percent of nominal (1,050 metric-tons force) and inertial back-blow, or recoil, which occurs at engine cutoff. The stationary part of the bench consists primarily of the two largest frames, which are

Before test-firing a new prototype, NPO Energomash stress engineers needed to evaluate the test bench’s ability to withstand the forces that would be generated.
connected by pins to a load-carrying ring permanently fixed to the ground. The movable part of the bench makes up the remaining frames, belts, rods and bolts, and is connected to the stationary part by springs and force sensor systems. These connectors allow the movable part to slide along the stationary part in the horizontal (x) direction.

The NPO Energomash team used SHELL181 elements to virtually represent the largest frame parts and BEAM188 elements for smaller frames and frame legs. LINK8 rod elements, which allow only tension or compression, represented the engine frame, belts, sensors, pins and most of the rods. The engineers used CERIG rigid connections to represent the engine’s center of gravity and the centers of the four nozzles that are connected by gimbals to the engine frame. From experience, the team knew that the highest strains and deformations are localized in areas where the frames are welded, so it was logical to evaluate part strength based on these regions. Since the weld seam metal is weaker than the steel sheets that comprise the frames, conservatism dictated that two variants be used during the structural analysis: the first with the frame modeled using steel properties and the second using weld seam metal properties.

Using a two-step simulation process, the team first performed stress analyses assuming a linear elastic state. After detecting the regions with the highest stress concentrations, engineers performed mesh refinement studies and then ran nonlinear elastic-plastic calculations of stress-strain behavior in these areas. Taking advantage of symmetry of several load-bearing parts helped to reduce some of the computational expense. Using a desktop machine with eight cores, a typical linear static analysis could be completed in five minutes or less, while a typical nonlinear analysis accounting for material plasticity ran in under 30 minutes. Overall, the engineers spent three months performing the calculations and preparing reports for approximately 100 individual simulations.

Predictions using ANSYS structural mechanics software showed that all of the test bench parts studied would withstand the 1,050 metric tons-force of engine thrust and subsequent recoil forces at engine cutoff. However, many of the parts did not meet the Roscosmos-mandated reserve factors requiring a load capacity of 50 percent to 60 percent above the maximum expected design load. NPO Energomash engineers used this information to design reinforcement modifications for specific frames, rods, bolts and pins in question. By analyzing many potential reinforcement modifications, the team is

ANSYS technology is a critical tool for modern design engineers who know the value of time, money and prestige to their organizations.
Displacement results of original (left) and modified (right) frames, showing noticeable reduction in the new design.

Equivalent stress results for flange at the bottom of original (left) and modified (right) frames. Reinforcing fins are shown to provide increased strength to this part of the frame.

Simulation results gave bench designers confidence that their force measurement system could meet the needs of testing the next generation of rocket engines.

From the company’s point of view, the technology offered by ANSYS is a critical tool for modern design engineers who know the value of time, money and prestige to their organizations. The simulation results thus gave bench designers confidence that their force measurement system could meet the needs of testing the next generation of rocket engines.

NPO Energomash is supported in this work by CADFEM CIS.
Firefly Beta represents the second vehicle in a scalable family of launchers specifically designed to address the needs of the light satellite.

DIMENSIONS: You often use the term “new space” when describing Firefly’s mission. What does “new space” mean to you?

THOMAS MARKUSIC: The “old space” paradigm was based on government control of space access, a culture characterized by bureaucracy and rules, and relatively slow, methodological progress. By contrast, “new space” is about picking up where the pioneers of the 1950s and the 1960s left off. It’s about having a bold vision of providing high-speed space transport for civilians, creating re-usable vehicles that can orbit the Earth, and eventually colonizing other planets. Firefly wants to democratize space by dramatically lowering the cost of access and dramatically increasing spaceflight opportunities for more people. By privatizing the space industry, we want to subvert the dominant big aerospace paradigm of slow progress and high costs. As a new space company, we are shifting to mass production methods, rapid application of real-world lessons, and ubiquitous use of advanced design tools, such as simulation, that can help us move quickly.
D: Firefly was founded on the tenets of innovation and disruption. How are those ideas reflected in your business model, your culture and your engineering team?

TM: First of all, we chose to base our operations in Austin, Texas, specifically to remove ourselves from the traditional “old space” business model. We’re a new kind of company, with new partnerships, new ideas and new ways of working. If you raise your eyebrows when you hear we’re headquartered in Austin, that’s the reaction we’re looking for.

Furthermore, Firefly has rejected many traditional job titles and personnel hierarchies. We’ve created a flattened organization in which ranks and organizational boundaries are inconspicuous, where people truly feel that they are part of one organization with a singular mission for success. We’ve deliberately fostered a communication infrastructure in which every person in the organization is able to clearly see, and is able to articulate, how his or her work contributes to the profitability and success of the company as a whole.

Finally, we’ve worked hard to create a very diverse team at Firefly. We have senior engineers from the traditional space industry working beside recent college graduates. Why is this important? Because diversity produces a wide range of human capital, ideas, strengths and leadership styles that result in innovation. As of mid-2015, 12 percent of our engineers are women, which I would guess is a fairly high percentage for an aerospace company — and a statistic that Maureen Gannon, our vice president of Business Development, takes great pride in. She is a huge champion of diversity within our business. (See sidebar, “STEM: Not a Man’s World.”)

D: Can you tell us more about how you have flattened the engineering function in particular?

TM: In the engineering organization, we are deliberately working to eliminate job titles such as analyst, drafter, etc. We firmly believe that, given today’s integrated design tools environments, the same engineer who is designing the part can easily generate a physical definition of the part, in addition to performing part-level and system-level finite element analysis (FEA) and computational fluid dynamics (CFD) simulation. This is not always easy because many people tend to get very comfortable with one task. However, we challenge our engineers to be accountable for their products as part of a system — and ensure that they deeply understand their product’s cradle-to-grave requirements, functionality, manufacturability and operability.

D: How has your disruptive philosophy influenced your engineering team’s use of technology?

TM: When making product design decisions, we perform a series of multidisciplined, collaborative trade studies and analyses before we choose a design path. Our selection of IT and software tools is no different. We did not start Firefly with one single software in mind. We have initiated a number of parallel studies utilizing various computer-aided design, computer-aided manufacturing, FEA, CFD, integrated design environment and software development kit solutions to select the ones that best suit our company and vision. We have been proactive in implementing configuration resources, product life-cycle and enterprise resource-management tools in addition to our technical software tool sets — even at the company’s early stage when we have a relatively small team and only one product. We are designing our IT from the ground up and with purpose, before it gets too complicated and forces us to choose a suboptimum system for our company.
STEM: 
NOT A MAN’S WORLD

Maureen Gannon loves her position as vice president of Business Development for Firefly Space Systems, Inc. She embraces working with the company’s engineers and crafting business solutions to match their plans of filling the sky with satellites launched by the company. On occasion, however, she reflects on her own educational and career path — and has often wondered why she didn’t become an engineer herself.

“I was always passionate about science and engineering but, as a young girl, I was not encouraged in school to pursue those areas either as a field of study or a future profession,” recalled Gannon. “At the time, I felt it was not an option available to me.”

After earning a B.A. in international relations and an M.A. in international management, Gannon began her career in technology companies both in the U.S. and abroad — and quickly realized that most engineers she interfaced with were men. She eventually decided to pursue her engineering goals and enrolled at the University of California at Berkeley to gain some technical background. Again, she looked around and found herself surrounded by men. “It started to dawn on me that perhaps I was not the only young girl who had been interested in science and engineering, but had not been encouraged or felt comfortable to explore it as a career,” said Gannon.

Today, helping girls and young women pursue careers in science, technology, engineering and math (STEM) is a personal passion for Gannon. As a client of Virgin Galactic in 2009, she pitched and cofounded its now nonprofit foundation called Galactic Unite. She personally raised more than a million dollars to fund the group’s first of many STEM scholarships for women. Through funding, education and outreach, Galactic Unite continues to offer the encouragement and support that young people need to pursue careers in STEM disciplines.

In addition to her role as VP of Business Development at Firefly, Gannon strives to continue making a difference in STEM education. She has begun by forming new partnerships with local universities, high schools and even elementary schools to spread the word about engineering and other STEM-related careers and continues to build Firefly’s internship program. “We work to attract not just young women, but students of all genders, ethnicities and backgrounds, to careers in science,” noted Gannon. “Firefly was founded to break new ground in the aerospace industry — and that means bringing in new thinkers with many different perspectives. The more diversity in our company and our industry, the more diverse our ideas will be. That increases our chances of driving true innovation.”

“We work to attract not just young women, but students of all genders, ethnicities and backgrounds, to careers in science.”

**D:** Since the space industry is heavily regulated, how are you cutting time and costs out of the standard approval process — which must be lengthy and complicated?

**TM:** The space industry is heavily regulated for practical reasons. Even if you’re launching a rocket from a remote location such as the middle of the ocean, that launch requires careful planning, since various propulsive stages of the rocket inevitably cross habitable areas during ascent. As a U.S. company, Firefly is governed by Federal Aviation Administration laws and regulations, regardless of our launch locations around the globe. The process of acquiring a launch license requires involving many governmental and commercial entities. There are human and property safety considerations. There are also environmental impact considerations that require careful engineering analyses.

To navigate these approvals as quickly as possible, Firefly needs to have the ability to completely simulate and execute a launch from ground to orbit — considering a number of predictable and unpredictable boundary conditions such as weather, pressure, electromagnetic and electrostatic conditions, and even solar storms. Other design, analysis and simulation activities at Firefly focus on calculating instantaneous impact points in case of an errant flight. The possibility of terminating a flight requires many worst-case analyses and computationally intensive simulations.

While the traditional methods for mitigating launch failures involve a large footprint of resources and manpower, Firefly is leveraging engineering simulation to design and verify a new generation of built-in safety assurance mechanisms for our first rocket — and it will meet the strictest government standards. By demonstrating that our technology works, simulation is helping us to obtain regulatory approvals and get to space faster.

**D:** Firefly is not only seeking to democratize space by cutting costs, but to create greener, more-sustainable technologies. How do your engineers balance these priorities, which are typically at odds with each other?
Lower-cost, green, well-designed and well-functioning are not mutually exclusive requirements. When science, engineering and the laws of nature are harmonized, surprisingly, things work better. You can see this all around you, in better modern buildings, bridges, roads, clean energy and even high-performance cars. For example, it is inevitable that cars of the future, regardless of the source of energy, will utilize electric motors as the propulsive force. It’s just meant to be that way. Electric motors are rotating machines. They utilize some of the most elegant laws of nature, such as electromagnetism, in the right form and in a functional way. They produce force and motion at greater than 90 percent efficiency. For over 100 years, we have invested our engineering R&D talents into perfecting the reciprocating internal combustion heat engine. Imagine what could be possible if that same amount of engineering resources could be expended toward more-refined products that are better harmonized with nature, rather than working against it.

At Firefly, we’re adopting a similar philosophy. We’re looking at every possible option to take advantage of physical and natural laws to make our rockets better, simpler, more efficient, more affordable and, yes, greener. Our rockets utilize technologies that maximize energy transfer and provide a “simpler, sooner” product for accessing space.

Few companies are able to revolutionize an industry like Firefly. What’s unique about the DNA of these companies? Revolutionary companies are also ambitious, hard-working and dedicated to achieving results quickly. As an engineer myself, I’m incredibly impressed with the pace of progress accomplished by the Firefly development team. It is the most productive team that I have worked with, and they have a lot of fun getting stuff done.

Within just 20 months of operation, we will have built world-class facilities and run rocket engine tests using designs completely developed in-house. Nothing drives a technical team to success like a clear vision of an important goal.

Prior to founding Firefly Space Systems, Inc., Thomas Markusic served in a variety of technical and leadership roles in new-space companies: vice president of Propulsion at Virgin Galactic, senior systems engineer at Blue Origin, director of the Texas Test Site, and principle propulsion engineer at SpaceX. Prior to his new-space work, Markusic worked at NASA and the USAF as a research scientist and propulsion engineer. He holds a Ph.D. in mechanical and aerospace engineering from Princeton University.

I believe that all disruptive companies are problem-solvers. They create products, services and tools that address societal and global challenges, sometimes in an unexpected way. And everyone from the CEO down must be passionate and focused on solving that problem.
Keeping the **Space Race** from Heating Up

Coupled multiphysics simulation saves hundreds of thousands of payload-equivalent dollars per launch for SpaceX.

By Michael Colonna, Chief Aerodynamic Engineer, SpaceX, California, U.S.A.

Space Exploration Technologies (SpaceX), a privately funded rocket venture founded by entrepreneur Elon Musk, is developing its Falcon family of launch vehicles from the ground up. SpaceX aims to change the paradigm of space flight by introducing a family of launch vehicles that will ultimately reduce the cost of space access by a factor of ten. As designers of the first launch vehicle developed entirely in the 21st century, Falcon engineers have the opportunity to take advantage of the latest design and analysis technologies.

One area of concern for the engineering design team was the amount of thermal insulation required to protect the payload and sensitive internal equipment from heat generated by high-speed atmospheric flight. Thermal insulation is required to protect the vehicle’s metallic skin, in addition to sensitive electronic equipment that can malfunction at high temperatures. At higher temperatures, metals can lose critical structural performance as their material properties change. During the first demonstration flight, engineers erred on the side of safety by installing a conservative amount of thermal insulation. Optimizing the amount of insulation used for future flights is vital because every pound of excess insulation reduces the payload of the vehicle.

To optimize the insulation prior to the second demonstration flight, a simulation that integrated computational fluid dynamics (CFD) and finite element analysis (FEA) was performed to calculate surface and body temperatures expected during the flight. The main challenge of the coupled simulation was passing the heat loading for the surface of the launch vehicle, calculated by the CFD code, to the ANSYS Mechanical FEA model for structural and thermal analysis, and then passing the skin temperatures calculated by the FEA code back to the CFD analysis.

The temperature distribution on the launch vehicle throughout the entire flight was determined to ensure that sensors, instruments, propellant lines and other critical components were maintained at safe temperatures. Launch vehicle aerodynamics are uniquely challenging because there is no cruise condition. Instead, the conditions change continually and rapidly during the critical few minutes in which the rocket moves from sea level to the near-vacuum conditions at the edge of the atmosphere. The maximum heat transfer typically occurs high in the atmosphere when the speed of the launch...
AEROSPACE

CFD contours demonstrate the heat load on the surface of the launch vehicle 152 seconds into the flight.

The Falcon 1 launch vehicle

FEA mesh created for the Falcon 1

These contours represent the initial skin temperatures used for FEA simulation of the Falcon 1 launch vehicle.

vehicle is very high and the density of air is very low. Heat transfer typically drops off to a much smaller value as the launch vehicle approaches its designated orbit.

With conditions changing so quickly during the atmospheric flight, multiple iterations of the simulation were required to capture the physics. Each of these iterations required both a fluid simulation of the air around the launch vehicle and a structural/thermal simulation of the launch vehicle itself. Since each code is dependent upon the results of the other, a series of iterations must be performed at each time step in order to converge to an accurate solution. Finally, since the amount of thermal insulation used also affects the heat transfer in the launch vehicle and the resulting vehicle skin temperatures, multiple repetitions of the entire simulation were required to examine the effect of varying the amount of insulation used.

SpaceX engineers used a CFD code designed for the high Mach numbers experienced during the launch vehicle’s flight through the earth’s atmosphere. The CFD code was used to calculate the increase in vehicle skin temperature that occurs due to the interaction between the vehicle body and the air through which it passes. The values for heat loading on the skin that are produced by the CFD code were then used as inputs for the ANSYS Mechanical simulation. This structural/thermal analysis then modeled the dissipation of the heat into the insulation and launch vehicle, which resulted in a new set of values for skin temperatures. These temperatures were then mapped back to the CFD simulation and the two codes run sequentially until they converged, such that the CFD results for heat loading were consistent with the skin temperatures determined by the structural/thermal code.

SpaceX engineers developed a Matlab® routine, which automatically controlled the analysis by generating the appropriate input files for each code. These inputs included the correct atmospheric conditions and insulation amounts, in addition to mapping the results from each code to the other. The ANSYS Mechanical parametric design language (APDL) greatly simplified automation of the simulation process by providing a computer-aided design-based (CAD) application programming interface that enabled the integration code, in this case Matlab, to draw the model with a fraction of the number of commands — the launch vehicle model was defined with just a few lines of code. Using APDL, engineers were also able to create layered shell elements to represent the various layers of the skin of the launch vehicle, reducing solution time as compared to using solid elements.

After SpaceX engineers automated the process of running thousands of iterations, the minimum amount of insulation that would protect the launch vehicle was calculated to be approximately 50 pounds less than the amount used in the first demonstration flight. The temperature measurements taken during the second demonstration flight in March 2007 closely matched those predicted by the simulation, demonstrating that the reduced insulation performed as expected and within the requirements of the design.

As a result of simulation, the reduction in insulation weight makes it possible to increase the payload capacity of future Falcon 1 missions. With a number of launches scheduled over the next few years for the Falcon 1, and the larger Falcon 9 as well, SpaceX can now expand its range of potential customers and increase revenue on a payload mass equivalent basis.
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