The innovative Launch Abort Motor turn-flow nozzle manifold designed by ATK Aerospace Systems awaits static testing.

Structural Optimization Helps Launch Space Payloads

Aerospace company employs **simulation software to reduce weight** in the Launch Abort Motor manifold for the **Orion Multi-Purpose Crew Vehicle**.

By **Blaine E. Phipps, Michael H. Young and Nathan G. Christensen**

Alliant Techsystems Inc. (ATK) Aerospace Systems, headquartered in Magna, Utah, U.S.A., produces solid rocket propulsion systems and is a leading supplier of military and commercial aircraft structures. It also has extensive experience supporting human and space payload missions.

That experience came into play on a recent project for the National Aeronautics and Space Administration's (NASA) Orion Multi-Purpose Crew Vehicle (MPCV). ATK served as the subcontractor responsible for the Launch Abort Motor, designed to lift the space crew module off the primary launch vehicle in an emergency on the launch pad and during launch up to 300,000 ft of flight.

The Launch Abort Motor – 17 ft long, 3 ft in diameter and capable of generating a half-million pounds of thrust – was designed to include composite motor case turn-flow nozzle manifold technology to reduce overall launch system weight, critical to space missions, while ensuring crew safety. Unlike conventional rocket motors, the innovative exhaust turn-flow manifold is positioned at the forward end of the motor – so that the combustion thrust gases are compressed evenly through four nozzle ports angled away from the crew capsule (aft) end, creating a forward-thrust reaction (pulling force) on the crew module.

The initial design, steel manifold, weighed slightly less than 2,000 lbs and supported an early concept flight test (see YouTube "Pad Abort 1"). However, to meet the weight target of 1,300 lbs or less, ATK and Lockheed Martin Space Systems Company agreed to change the manifold material to a high fracture toughness titanium for the much lower weight, flight weight nozzle manifolds. Using specialized optimization techniques, ATK further reduced the manifold weight by 300 lbs while meeting all strength requirements and deflection limits.

Lighter is Better

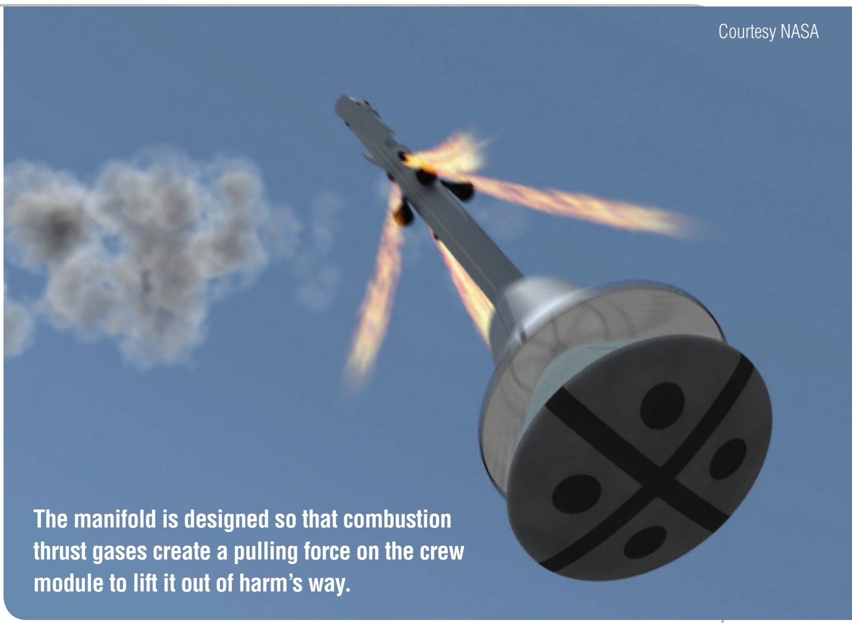
When launching payloads into space, every pound saved matters. So when the project allocated new mass requirements to hit performance requirements, further weight reduction throughout the launch abort system was needed. Although already within the weight budget, to support the program, ATK stepped up to further reduce weight on the Launch Abort Motor nozzle manifold using structural optimization on the entire manifold.

ATK engineers pursued a two-phased simulation strategy. This approach applied operational pressures and line loads to both computer simulations and to a physical test specimen in a specially designed test fixture. The test specimen validated computer simulations of motor operation in a complex flight loading environment.

ATK had a team of ballistics, structural, fluids and thermal engineers working on this complex project. The optimization problem was set up in the following manner. First, engineers identified the design variables and design space, which also included external surfaces of the manifold body.

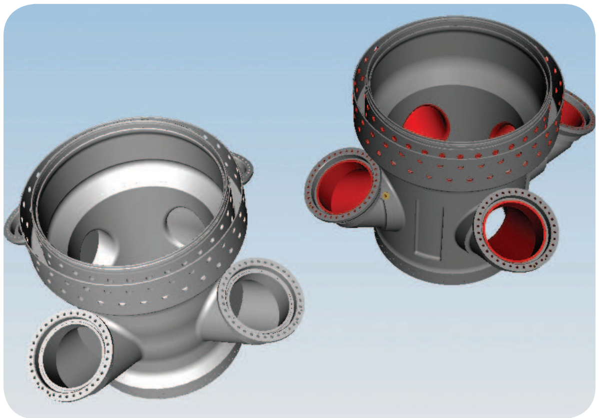
Next, the responses of what could be measured were established. The mass and the von Mises stress in the manifold also needed to be considered.

The final objective was to minimize the manifold mass using a simulation-driven design methodology for the given constraints' performance target.



Courtesy NASA

The manifold is designed so that combustion thrust gases create a pulling force on the crew module to lift it out of harm's way.



The optimized titanium manifold (left) weighs approximately 1,000 lbs versus the steel version (right), which weighs around 2,000 lbs.

ATK conducts a ground test of the Launch Abort Motor at its facility in Utah.

ATK Focused Forward

Alliant Techsystems Inc. (ATK) is a Fortune 500 aerospace, defense, security and sporting company with more than 18,000 employees and operations in 24 states, Puerto Rico and internationally. It was launched as an independent company in 1990 when Honeywell spun off its defense businesses to shareholders. ATK Aerospace Systems, ATK Armament Systems, ATK Missile Products, and ATK Security and Sporting comprise the business lines.

ATK expanded into the aerospace market with the acquisition of Hercules Aerospace Company in 1995 and Thiokol Propulsion in 2001, which transformed the company into the largest supplier of solid propellant rocket motors and a provider of high-performance composite structures.

ATK Aerospace Systems products and services include solid propulsion systems and rocket motors; advanced composite structures and components; and satellite structures, components and systems. In addition, this business structure provides advanced antennae and radomes for weapons and ships, energetic materials, military flares and decoys, and space engineering services.

As part of ATK Aerospace Systems, ATK Space Launch Systems is focused on NASA's human spaceflight programs. Space Launch products include the Space Shuttle's Reusable Solid Rocket Motor, the abort motor for NASA's Orion MPCV Launch Abort System, the Booster Separation Motors and Booster Deceleration Motors for the Space Shuttle and Liberty Launch Vehicle.

Getting Off the Ground

Optimization of the flight weight nozzle manifold offered its own set of challenges considering that, along with the approximate 60% weight density reduction, the modulus of elasticity is also reduced about 60% compared to steel. This complicates many structural issues in the nozzle manifold such as strain deflection limits and joint rotations at critical seal interfaces. Switching from titanium to steel is not simply trading out the materials!

The optimization model started with the baseline steel manifold working towards an optimized flight weight manifold using titanium mechanical properties. Next, engineers "smoothed" all external surfaces of the steel manifold configuration, making uniform thickness thrust ports. These actions reduced the weight of the steel manifold from approximately 2,000 lbs to 1,300 lbs on the titanium design.

ATK engineers then analyzed the performance of the manifold/nozzle assembly taking into consideration operational pressures based on computational fluid dynamics (CFD) results and axial line loads. Later, virtual simulations on the manifold/hydroproof test fixture were performed to determine a proof test pressure that would envelope the stress response in the manifold for operational conditions.

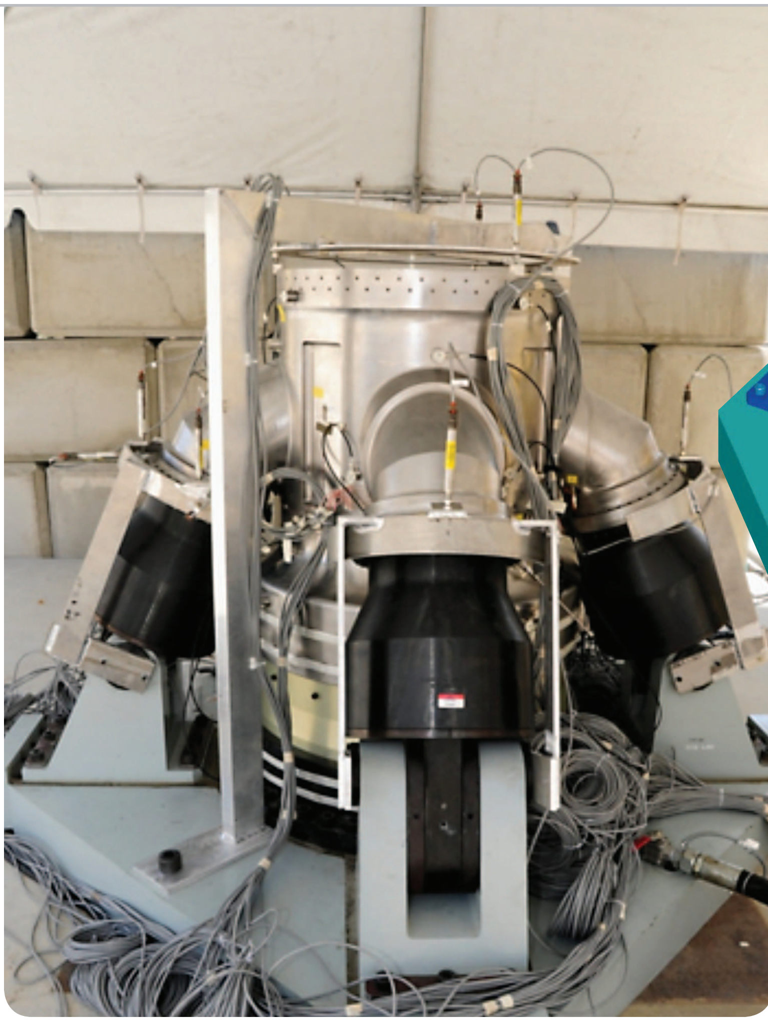
Since the proof test is the most severe loading environment, the manifold was optimized to the proof test loads and configurations.

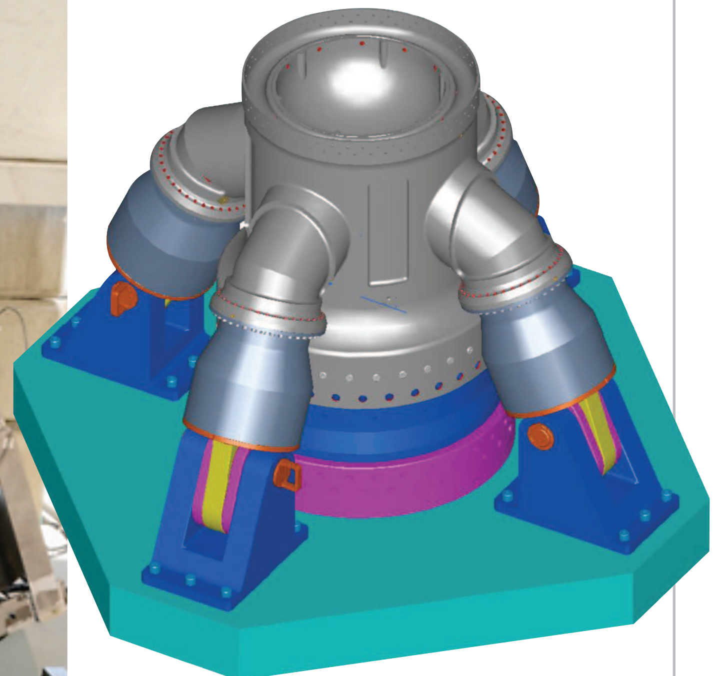
The Outer Limits

Because requirements dictated that the manifold's inner-profile remain unchanged, the only way to reduce weight was to remove material from the outside profile. The topological optimization methodologies employed in Altair Engineering, Inc.'s OptiStruct were chosen for the task.

OptiStruct's free-shape optimization capabilities enabled engineers to treat every node on the outer surface of the manifold's finite-element model (FEM) as an individual design variable. OptiStruct then automatically generated shape design variables for each surface node so that each node could move inward or outward as needed.

Stress and displacement constraints were prescribed for the manifold weight optimization, and the operational pressure loading was applied. As the optimization proceeded, the outer profile of the manifold started to thin where it could without violating the stress, strain or displacement constraints.





ATK also employed simulation to determine proof test pressure loads to validate the manifold for predicted operational loads.

As part of the iterative process, the configuration of the nodes changed during the thinning process, requiring engineers to remesh some of the manifold's components. The nozzle ports, for example, were slightly out of round as a result of the port geometry and the distribution of the pressure loads. It was critical to keep the nozzle stiff so it wouldn't deflect too far when under nozzle thrust loads and adversely affect the motor's performance. In addition, the integrity of the seals between the primary and secondary O-ring joints needed to be verified; the software predicted O-ring gaps between both interfaces.

The operational analysis determined a stress value for the motor. Because those stresses were well under stress threshold levels, the optimization cycle was repeated until the manifold reached optimum weight.

Proof Test

The second part of the two-phased strategy involved optimizing the manifold to the proof test loads and configurations. For the titanium manifold proof test configuration, mounting the manifold onto a composite pressure vessel was simulated and a thrust relief piston attached to each of the nozzle ports. Fluid was pumped into the system to simulate the operational pressures.

During an operational flight, there is a variable internal pressure distribution within the manifold. To simulate actual flight conditions in the proof test, the thrust relief piston was designed to move down, reacting thrust loads at each of the nozzle port locations to simulate axial thrust and pressure loads.

A FEM of this test proof configuration was used in the optimization process. A study was performed to determine what proof pressure was required in the proof test configuration to match operational stresses.

Engineering requirements for the test simulation were constant pressure inside the manifold and axial and symmetric boundary conditions, including an axial thrust load over 500,000 lbf.

On a Mission

The Orion Launch Abort System (LAS) was designed to save astronauts' lives in the event of a malfunction of the launch vehicle. NASA envisioned the components including a fairing assembly that covered the crew vehicle, a motor stack and a nose cone.

The fairing assembly would protect the crew module from atmospheric debris, aerodynamic pressure and heating, and the abort motor exhaust plumes. The motor stack would include three solid propellant motors that would carry out the abort, attitude control and jettison functions. The nose cone would make the vehicle aerodynamic as it traveled through the atmosphere.

In May 2011, NASA announced that the Orion crew exploration vehicle would serve as the agency's new Multi-Purpose Crew Vehicle for robust human exploration beyond low Earth orbit. Currently NASA is planning to continue with the Lockheed Martin current crew capsule design and is expected to utilize the entire flight weight Launch Abort System on future launch systems. Also, it is expected that the R&D efforts that went into developing the Launch Abort Motor will be applicable and aid future space programs.

Given the data, the required proof pressure was determined to achieve an envelope operational stress. The pressure load was adjusted so that the desired stress limits in the part would be at least as great as operational flight.

Automation Assets

Prior to using OptiStruct, manual methods were employed to approach similar problems. FEMs were built, estimating where material should be removed, and then the models were rebuilt. Each iteration could take half a day or more.

Using the simulation software, it was discovered that the optimization routines were taking material out of places which were not intuitive. OptiStruct did all the work. Consequently, ATK engineers did not need to create new geometry models, FEMs or boundary conditions for each iteration.

What previously took months to determine by trial and error was reduced to days with OptiStruct. Overall, design time was cut on this project by 30% – and weight reduced from 1,300 lbs to approximately 1,070 lbs. What's more, the maximum stress in the manifold came in under the constraint value.

A Solid Solution

The Launch Abort Motor Nozzle Manifold did not lend itself well to conventional physical testing. ATK needed to innovate at every step, coming up with ways to develop the loads, perform design iterations, carry out the proof testing and replicate a complex loading environment. Simulation software enabled ATK to find a solid solution to this engineering challenge.

Simulation software was essential to the Launch Abort Motor Nozzle Manifold redesign. OptiStuct was critical to meeting and exceeding the target weight goal on the Launch Abort Motor.

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For more information about Altair OptiStruct, visit www.altair.com/c2r