Wind tunnel study shows hypersonic jet engine flow can be controlled optically

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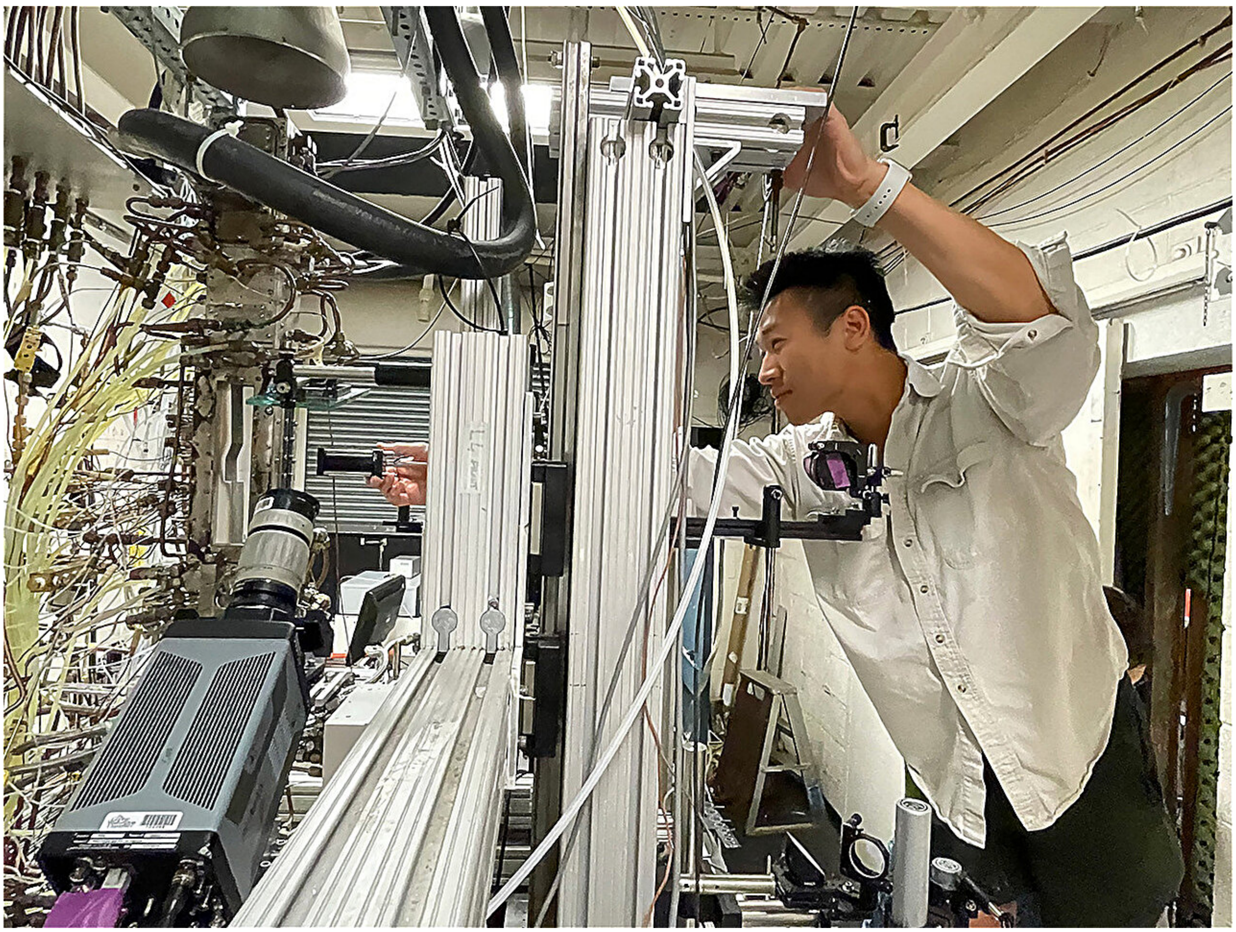

Doctoral student Max Chern takes a closer look at the wind tunnel setup where University of Virginia School of Engineering and Applied Science researchers demonstrated that control of a dual-mode scramjet engine is possible with an optical sensor. Credit: Wende Whitman, UVA Engineering

What if the future of space travel were to look less like Space-X's rocket-based Starship and more like NASA's "Hyper-X," the hypersonic jet plane that, 20 years ago this year, flew faster than any other aircraft before or since?

In 2004, NASA's final X-43A unmanned prototype tests were a milestone in the latest era of jet development—the leap from ramjets to faster, more efficient scramjets. The last test, in November of that year, clocked a world-record speed only a rocket could have achieved previously: Mach 10. The speed equates to 10 times the speed of sound.

NASA culled a lot of useful data from the tests, as did the Air Force six years later in similar tests on the X-51 Waverider, before the prototypes careened into the ocean.

Although hypersonic proof of concept was successful, the technology was far from operational. The challenge was achieving engine control, because the tech was based on decades-old sensor approaches.

This month, however, brought some hope for potential successors to the X-plane series.

As part of a new study, University of Virginia School of Engineering and Applied Science researchers published data in the June issue of the journal Aerospace Science and Technology that show for the first time that airflow in supersonic combusting jet engines can be controlled by an optical sensor. The finding could lead to more efficient stabilization of hypersonic jet aircraft.

In addition, the researchers achieved adaptive control of a scramjet engine, representing another first for hypersonic propulsion. Adaptive engine control systems respond to changes in dynamics to keep the system's overall performance optimal.

"One of our national aerospace priorities since the 1960s has been to build single-stage-to-orbit aircraft that fly into space from horizontal takeoff like a traditional aircraft and land on the ground like a traditional aircraft," said professor Christopher Goyne, director of the UVA Aerospace Research Laboratory, where the research took place.

"Currently, the most state-of-the-art craft is the SpaceX Starship. It has two stages, with vertical launch and landing. But to optimize safety, convenience and reusability, the aerospace community would like to build something more like a 737."

Goyne and his co-investigator, Chloe Dedic, a UVA Engineering associate professor, believe optical sensors could be a big part of the control equation.

"It seemed logical to us that if an aircraft operates at hypersonic speeds of Mach 5 and higher, that it might be preferable to embed sensors that work closer to the speed of light than the speed of sound," Goyne said.

Additional members of the team were doctoral student Max Chern, who served as the paper's first author, as well as former graduate student Andrew Wanchek, doctoral student Laurie Elkowitz and UVA senior scientist Robert Rockwell. The work was supported by a NASA ULI grant led by Purdue University and principal investigator T. Pourpoint.

Stopping 'unstart' to stay in control

NASA has long sought to prevent something that can occur in scramjet engines called "unstart." The term indicates a sudden change in airflow. The name derives from a specialized testing facility called a supersonic wind tunnel, where a "start" means the wind has reached the desired supersonic conditions.

UVA has several supersonic wind tunnels, including the UVA Supersonic Combustion Facility, which can simulate engine conditions for a hypersonic vehicle traveling at five times the speed of sound.

"We can run test conditions for hours, allowing us to experiment with new flow sensors and control approaches on a realistic engine geometry," Dedic said.

Goyne explained that "scramjets," short for supersonic combustion ramjets, build on ramjet technology that has been in common use for years.

Ramjets essentially "ram" air into the engine using the forward motion of the aircraft to generate the temperatures and pressures needed to burn fuel. They operate in a range of about Mach 3 to Mach 6. As the inlet at the front of the craft narrows, the internal air velocity slows down to subsonic speeds in a ramjet combustion engine. The plane itself, however, does not.

Scramjets are a little different, though. While they are also "air-breathing" and have the same basic setup, they need to maintain that super-fast airflow through the engine to reach hypersonic speeds.

"If something happens within the hypersonic engine, and subsonic conditions are suddenly created, it's an unstart," Goyne said. "Thrust will suddenly decrease, and it may be difficult at that point to restart the inlet."

NASA's B-52B launch aircraft cruises to a test range over the Pacific Ocean carrying the third and final X-43A vehicle, attached to a Pegasus rocket, on Nov. 16, 2004. Credit: NASA

Testing a dual-mode scramjet engine

Currently, like ramjets, scramjet engines need a step-up to get them to a speed where they can intake enough oxygen to operate. That may include a ride attached to the underside of a carreir aircraft as well as a rocket boost.

The latest innovation is a dual-mode scramjet combustor, which was the type of engine the UVA-led project tested. The dual engine starts in ramjet mode at lower Mach numbers, then shifts into receiving full supersonic airflow in the combustion chamber at speeds exceeding Mach 5.

Preventing unstart as the engine makes that transition is crucial.

Incoming wind interacts with the inlet walls in the form of a series of shock waves known as a "shock train." Traditionally, the leading edge of those waves, which can be destructive to the aircraft's integrity, have been controlled by pressure sensors. The machine can adjust, for example, by relocating the position of the shock train.

But where the leading edge of the shock train resides can change quickly if flight disturbances alter mid-air dynamics. The shock train can pressurize the inlet, creating the conditions for unstart.

So, "If you are sensing at the speed of sound, yet the engine processes are moving faster than the speed of sound, you don't have very much response time," Goyne said.

He and his collaborators wondered if a pending unstart could be predicted by observing properties of the engine's flame instead.

Sensing the spectrum of a flame

The team decided to use an optical emission spectroscopy sensor for the feedback needed to control the shock train leading edge.

No longer limited to information obtained at the engine's walls, as pressure sensors are, the optical sensor can identify subtle changes both inside the engine and within the flow path. The tool analyzes the amount of light emitted by a source—in this case, the reacting gases within the scramjet combustor—as well as other factors, such as the flame's location and spectral content.

"The light emitted by the flame within the engine is due to relaxation of molecular species that are excited during combustion processes," explained Elkowitz, one of the doctoral students. "Different species emit light at different energies, or colors, offering new information about the engine's state that is not captured by pressure sensors."

The team's wind tunnel demonstration showed that the engine control can be both predictive and adaptive, smoothly transitioning between scramjet and ramjet functioning.

The wind tunnel test, in fact, was the world's first proof that adaptive control in these types of dual-function engines can be achieved with optical sensors.

"We were very excited to demonstrate the role optical sensors may play in the control of future hypersonic vehicles," first author Chern said. "We are continuing to test sensor configurations as we work toward a prototype that optimizes package volume and weight for flight environments."

Building toward the future

While much more work remains to be done, optical sensors may be a component of the future Goyne believes will be realized in his lifetime: plane-like travel to space and back.

Dual-mode scramjets would still require a boost of some sort to get the aircraft to at least Mach 4. But there would be the additional safety of not relying exclusively on rocket technology, which requires highly flammable fuel to be carried alongside large amounts of chemical oxidizer to combust the fuel.

That decreased weight would allow more room for passengers and payload.

Such an all-in-one aircraft, which would glide back to Earth like the space shuttles once did, might even provide the ideal combination of cost-efficiency, safety and reusability.

"I think it's possible, yeah," Goyne said. "While the commercial space industry has been able to lower costs through some reusability, they haven't yet captured the aircraft-like operations. Our findings could potentially build on the storied history of Hyper-X and make its space access safer than current rocket-based technology."

More information: Max Y. Chern et al, Control of a dual-mode scramjet flow path utilizing optical emission spectroscopy, *Aerospace Science and Technology* (2024). DOI: 10.1016/j.ast.2024.109144

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