Study confirms hairpin vortices in supersonic turbulence

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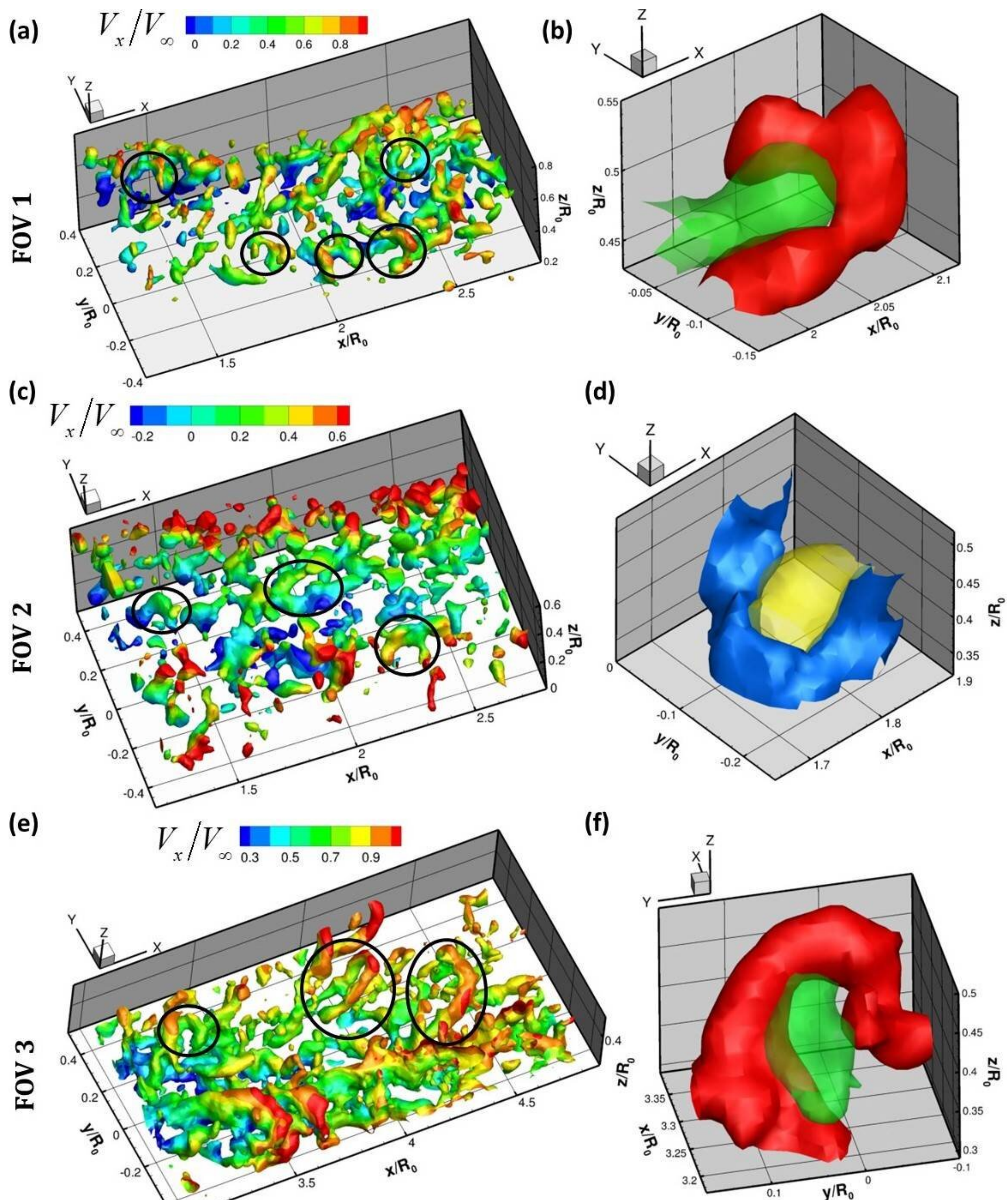

Examples of instantaneous 3-D measurement volumes demonstrating a large number of hairpin-shaped vortex structures. Credit: University of Illinois Dept. of Aerospace Engineering

The turbulence that occurs in the low-pressure region behind a rocket traveling at supersonic speeds is complex and not well understood. In the first experimental study of its kind, researchers at the University of Illinois at Urbana-Champaign helped close the knowledge gap for these flows by proving the existence of hairpin vortices in a supersonic separated flow.

"There is an instability in the flow far upstream, called the Kelvin-Helmholtz instability, where two regions of fluid pass by one another, with one moving faster than the other, and the fluid becomes unstable and trips. When it trips, it starts to rotate rapidly and the vortex can morph into a different shape as it convects," said Branden Kirchner, Ph.D. student in the Department of Aerospace Engineering. "The vortex starts off elongated along an approximately straight line. Then, as it moves further downstream, it evolves and morphs into this coherent hairpin shape. In the past there have been computer simulations of this type of flow, predicting these structures exist. But without experimental measurements of them, you can't actually confirm that they are there. This study firmly established that hairpin vortices are not only commonly present in this flow, but they also significantly contribute toward the turbulent energy and a lot of the important features that create that low-pressure, high-drag region."

The vortex structures appear at about Mach 2.5 during the cruising segment of a missile when the rockets are not burning.

Kirchner said there are actually two types of hairpin-shaped structures that occur—upright and inverted. The former has been studied since the 50s in turbulent boundary layers, but has received a lot less attention in free shear flows.

"In the flow we studied, the boundary layer vanishes when the flow separates—so there is just this shearing fluid moving through free space," he said. "One of the special consequences of not having that wall boundary when these structures form is that these hairpin structures can now form upside down. One type of hairpin forms when that initial structure morphs in one direction, and the other when it morphs in the opposite direction. They are geometrically the same type of structure, but because they're oriented inversely to one another, what they do to the flow is also backward."

What effect do hairpin vortices have on the flow? Kirchner said they still have a lot to learn.

"We know that they are one of, if not the most energetic features of the turbulence in this flow. We believe they have a significant effect on what's actually creating the low-pressure region behind the cylinder."

Kirchner said turbulence is commonly viewed as a random distribution of vortex structures with arbitrary 3-D shapes. He believes there is a clear set of physical mechanisms driving them.

"We're finding order in the chaos. We've found not just organized ordered turbulence, but that this organized turbulence is also the largest contributor to the turbulent energy in the flow. This knowledge is very useful for computationalists who try to predict this flow. If, in their simulations, they can demonstrate this same sort of structure, inducing the same type of events, and dominating the energy, then they know they're on the right track with a lot of important flow features in their simulations. It also provides a potential avenue to implement a method of flow control to, for example, raise the pressure behind the cylinder and reduce drag. You could disrupt the mechanism that generates these structures and prevent these structures from forming. Or, if the structures prove beneficial, you can create more of them, and then modify the pressure loading on the cylinder for whatever characteristics you want to have," he said.

For the experiment, Kirchner used a measurement technique which uses optical tomography, called tomographic particle image velocimetry, which is similar to how an MRI or CT scan works. Images are taken of a region from several perspectives simultaneously, and from that, you can reconstruct a three-dimensional image. Then, measurements can provide the full three-dimensional geometry of these complex turbulent events.

Kirchner said the technique is not something he developed, but Illinois has one of the only labs in the world to have ever used this measurement technique successfully in a supersonic flow.

More information: Branden M. Kirchner et al. Hairpin vortex structures in a supersonic, separated, longitudinal cylinder wake, *Physics of Fluids* (2020). DOI: 10.1063/1.5143880

Provided by University of Illinois Dept. of Aerospace Engineering

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