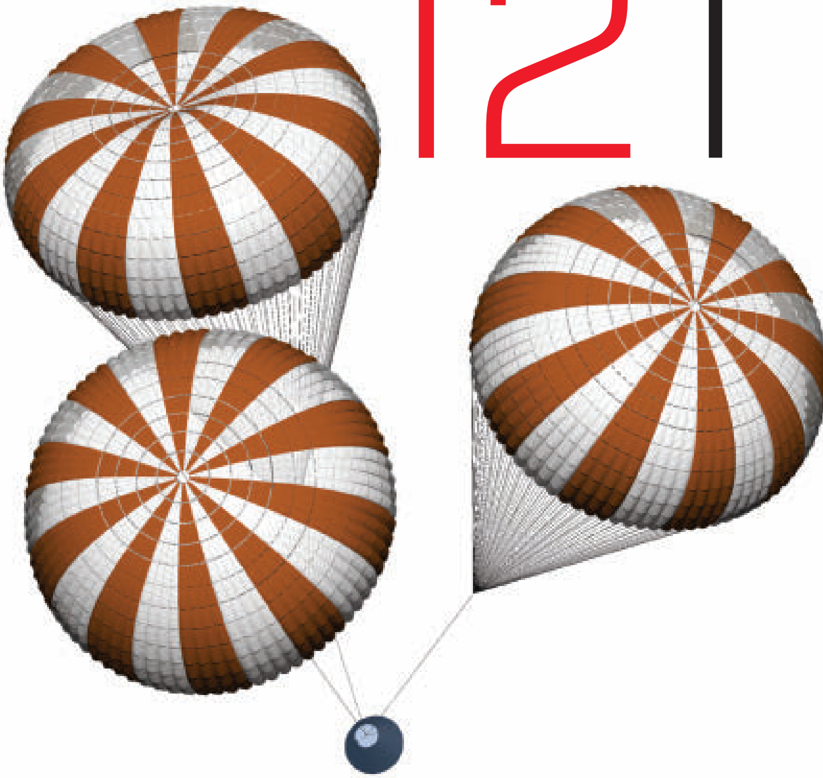

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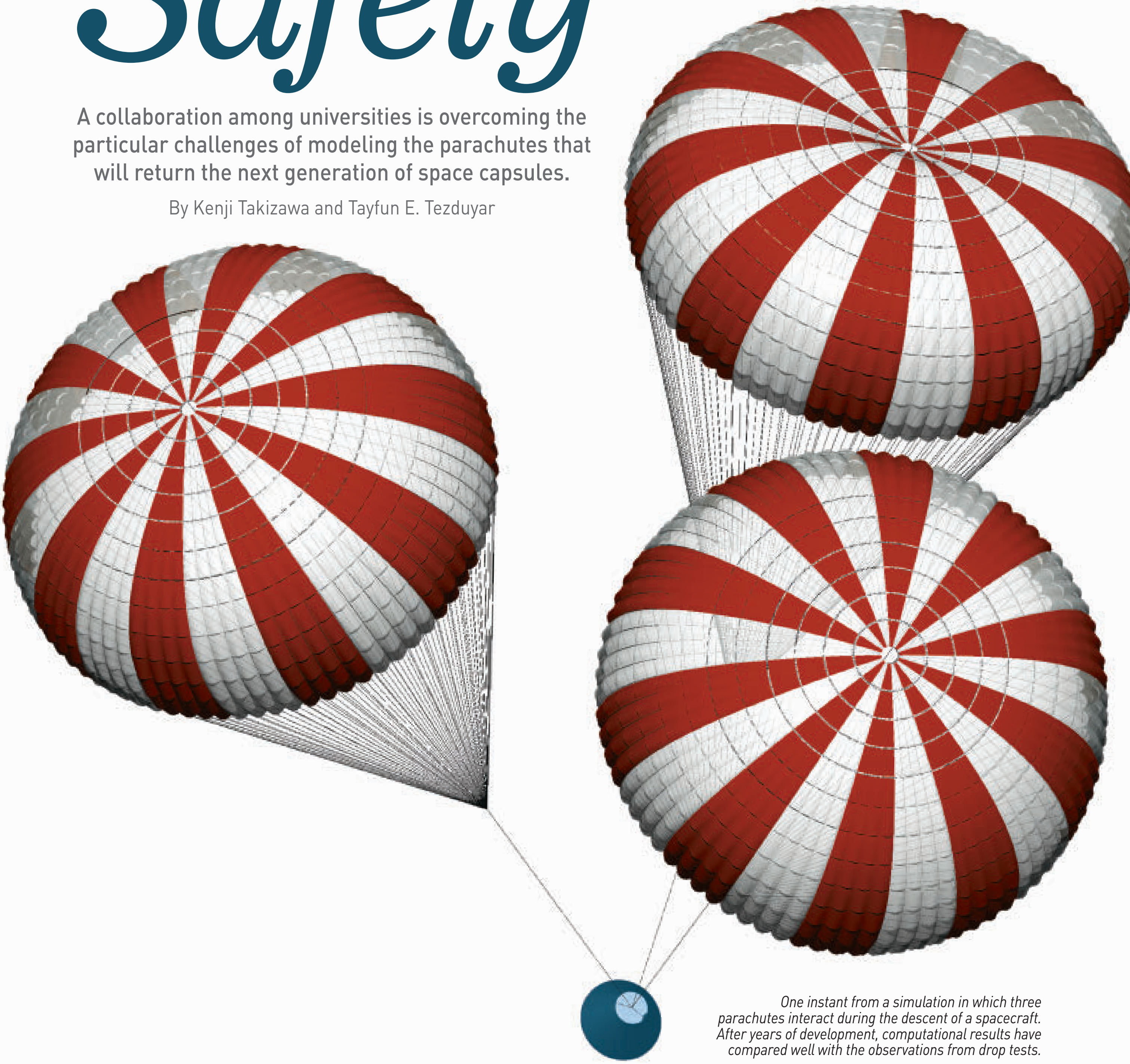
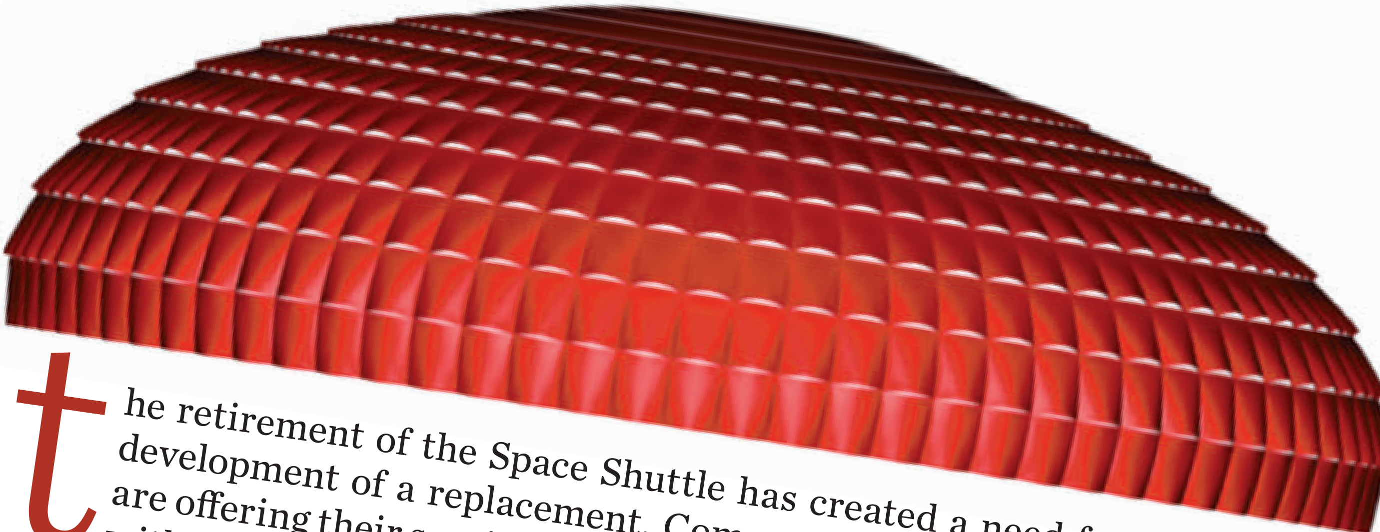
bringing them down *Safely*

A collaboration among universities is overcoming the particular challenges of modeling the parachutes that will return the next generation of space capsules.

By Kenji Takizawa and Tayfun E. Tezduyar



One instant from a simulation in which three parachutes interact during the descent of a spacecraft. After years of development, computational results have compared well with the observations from drop tests.



The retirement of the Space Shuttle has created a need for accelerated development of a replacement. Commercial developers of spacecraft are offering their services. A capsule from SpaceX has already docked with the station and returned to Earth. • Meanwhile, NASA is working on its next generation system for sending astronauts into space. And as always, much of the design challenge lies in getting them back safely. • NASA's proposed design for the return of Orion crew module to Earth is in one way, at least, harking back to an earlier time. The astronauts will finish their trip not in a winged glider but in a capsule drifting down on parachutes, much like the earliest manned flights into space. • The parachutes will be of unprecedented size, 80 feet in diameter. There will be three of them working together to bring the crew through the last stage of their descent. • In those details lies a particular challenge: Designing, predicting the behavior of, and testing parachutes of this size is particularly challenging, especially when they are used in clusters and involve multiple stages of opening. • The parachute is a very light and flexible structure. The structure's shape affects airflow, and air pressure changes the shape of the structure. Complicating matters more, the three parachutes supporting the capsule will interact with each other. • There is no economical way to test them. An 80-foot-wide parachute will not fit into a wind

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tunnel. One cannot study a miniature version and mathematically scale up the results with any kind of accuracy, because parachutes of different sizes behave differently.

NASA will have to test each design by building a full-scale prototype and dropping it from a plane over the desert. Each test could costs hundreds of thousands of dollars.

In an effort to keep those test costs down, the Team for Advanced Flow Simulation and Modeling (T*AFSM) at Rice University in Houston and Waseda University in Tokyo is developing computational technology that can reliably predict the performance of various NASA parachute designs. The data from these simulations permits NASA to focus on a few of the most promising designs for testing, and also lets designers explore a greater number of alternative designs.

Computer modeling of parachutes is a numerical challenge because it involves fluid–structure interaction, where the aerodynamics of the parachute depends on the canopy shape and the deformation of the canopy depends on the aerodynamic forces. The two systems need to be solved simultaneously, in a coupled fashion.

Actually, because the structure is light compared to the air masses involved in the parachute dynamics and very sensitive to changes in the aerodynamic forces, the shape/force exchange has to be simultaneous at any instant of the computation.

Spacecraft parachutes are typically very large ringsail constructions. They are made of a large number of gores, slices of the canopy held between radial reinforcement cables running from the parachute vent at the top down to the skirt. In the case of Orion parachutes, there are 80 gores. Ringsail parachute gores are not continuous, but constructed from rings and segments of fabric called sails. There are four rings and nine sails to a gore, and four ring gaps and eight sail slits, resulting in a parachute canopy with hundreds of gaps and slits through which air flows. The complexity created by this geometric porosity makes modeling inherently challenging.

One technique the T*AFSM has developed to deal with this complexity is to analyze a design in stages. The team begins by modeling a slice of four gores of a canopy. When they have solved for the air flow through the gaps and slits of that slice, they derive an equivalent fabric porosity from that. They calculate a coefficient of porosity for each of the 14 patches of a gore. A patch contains a gap or a slit, and half of a ring or sail on each side. The first and last patches contain only half of a ring or sail.

Even in the fully open configuration, the parachute canopy goes through a periodic breathing motion where the diameter varies between its minimum and maximum values. The shapes and areas of the gaps and slits vary significantly during this breathing motion. Research has shown, however, that the porosity coefficients have very good invariance properties with respect to these shape and area changes. That is, the porosity remains reasonably consistent even when the gaps and slits change shape with the breathing of the parachute, and this is a very important factor in making the computer modeling accurate.

to explore farther

This research was supported by NASA Johnson Space Center and is an outcome of much collaboration with and guidance from NASA engineers, especially Ricardo Machin and Jay LeBeau. Many current and former members of the T*AFSM contributed to this research; they are the coauthors of the articles listed below, which are the source of much of the information in this article.

Readers can find material on this subject, and some movies, at our Web sites, www.tafsm.org and www.jp.tafsm.org. A comprehensive review of the core and special space–time FSI techniques used in spacecraft parachute modeling can be found in [9].

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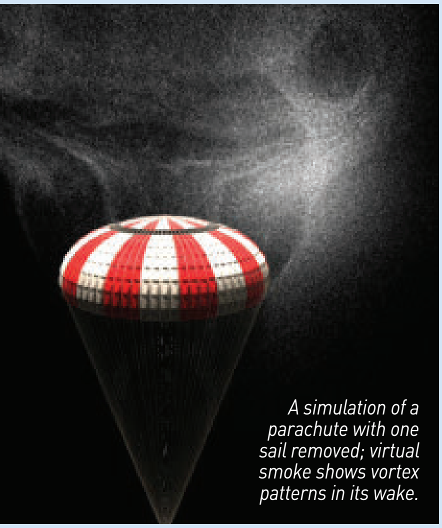
[6] K. Takizawa, T. Spielman, C. Moorman, and T.E. Tezduyar, "Fluid-Structure Interaction Modeling of Spacecraft Parachutes for Simulation-Based Design," *Journal of Applied Mechanics*, 79, 010907 (2012).

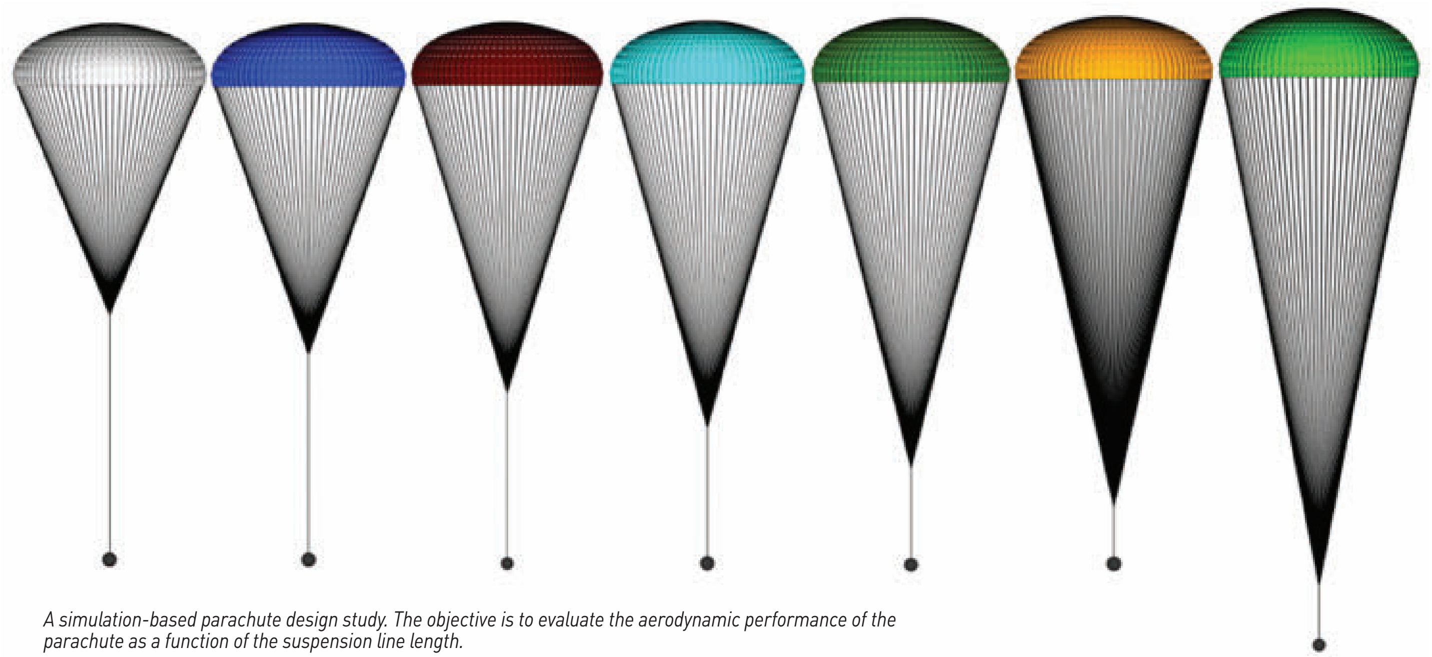
[7] K. Takizawa, S. Wright, C. Moorman, and T.E. Tezduyar, "Fluid-Structure Interaction Modeling of Parachute Clusters," *International Journal for Numerical Methods in Fluids*, 65 (2011) 286-307.

[8] K. Takizawa, T. Spielman, and T.E. Tezduyar, "Space-Time FSI Modeling and Dynamical Analysis of Spacecraft Parachutes and Parachute Clusters," *Computational Mechanics*, 48 (2011) 345-364.

[9] K. Takizawa and T.E. Tezduyar, "Computational Methods for Parachute Fluid-Structure Interactions," *Archives of Computational Methods in Engineering,* 19 (2012) 125-169.



A simulation of a parachute with one sail removed; virtual smoke shows vortex patterns in its wake.



A simulation-based parachute design study. The objective is to evaluate the aerodynamic performance of the parachute as a function of the suspension line length.

The T*AFSM modeled a base design that NASA put through a drop test over the desert, and the team was very pleased to see that the predictions of its model held up well against data from that NASA test.

For instance, the computer model predicted a descent speed of 21.4 feet per second, which was within 10 percent of the average speed observed in the test. Other predictions—such as the rate of swinging and breathing periods—were well within 10 percent of the observed behavior of parachutes in the physical test.

With confidence gained from comparing computational results with test data, the team members carried out simulation-based studies of alternative parachute designs. They were able to evaluate, for example, the aerodynamic performance of the parachute with different lengths of suspension line or in response to removing one of the sails of the canopy. Examination of these kinds of variations would be very time-consuming and costly if each one had to be performed by physical testing.

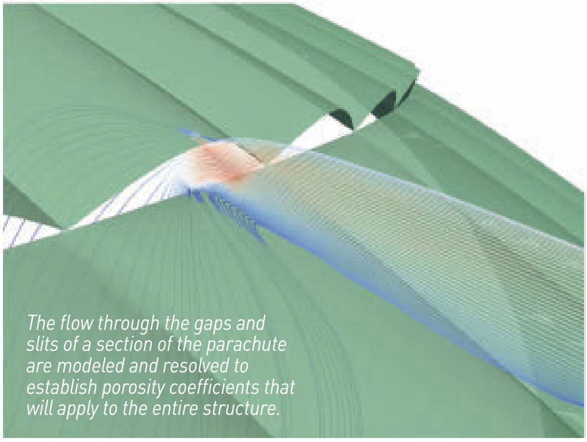
The contact between the canopies of a spacecraft parachute cluster is a formidable computational challenge that the T*AFSM has also addressed successfully. It is fairly new and complex method, and the reader interested in how the method works can find information in T*AFSM journal publications. The team used a picture from a NASA drop test showing the actual parachutes in contact and compared the observed canopy shapes with those that the model predicts when two parachutes of a cluster are in contact. The comparison showed that the result from the computer model was very much in agreement with the data from the drop test.

The T*AFSM parachute computations show that computer modeling of parachutes reached a new level and can contribute truly valuable information and analysis to the spacecraft parachute design and testing process. In particular, the parachute cluster computations show that spacecraft parachute modeling can now be done under actual conditions.

The results did not happen overnight, however. T*AFSM parachute fluid-structure interaction computations started as early as 1997 with axisymmetric computations, and the team's work with 3-D computations goes as far back as 2000.

The T*AFSM believes it is the only resource in the world that can properly conduct the computer modeling of spacecraft parachutes.

The team's parachute modeling work played a key role in the recognition of author Kenji Takizawa, T*AFSM leader at Waseda University in Tokyo, with the 2012 ASME Applied Mechanics Division's Thomas J.R. Hughes Young Investigator Award. He is the youngest ever to receive that award. ■



The flow through the gaps and slits of a section of the parachute are modeled and resolved to establish porosity coefficients that will apply to the entire structure.