G THE DISTANCE

Advances in Computational Fluid Dynamics have enabled engineers to predict the instantaneous fluid flow characteristics around complicated configurations such as aircraft. Today, numerical simulations are increasingly used to predict the stability or range of control of an aircraft, the energy required to propel an aircraft, payload or cargo weight limitations, and maximum distance and speed. These predictions are possible due to the detailed understanding of the airflow characteristics that contribute to the drag and lift of an airplane. In aircraft design, the requirements for propulsion, aircraft structure, controllability, speed, distance and altitude are all sensitive to aerodynamics, which emphasize the importance of accurate simulation tools.

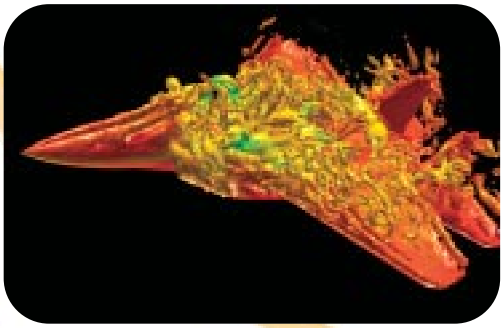
Traditionally, numerical simulations for aerodynamics applications have been based on solutions known as the **Reynolds-Averaged Navier-Stokes (RANS) equations**. The RANS equations use models to represent all effects of three-dimensional, unsteady turbulent motions. RANS methods are computationally feasible; however, for many applications they are not sufficiently accurate for engineering analysis and design. The deficiencies of RANS methods necessitate the use of techniques that promise higher fidelity. The **Large Eddy Simulation (LES)** method is more accurate than RANS and offers engineers access to greater levels of detail regarding the instantaneous properties of airflow around aircraft. LES resolves many of the details of turbulent flow structures, which RANS methods do not. This is particularly important in simulations involving chemical reactions, such as the combustion of fuel in an engine. The limitation engineers have found when utilizing LES, unfortunately, is that it is computationally expensive when applied to aircraft at flight conditions and requires computing resources that do not exist today.

In 1997, a new simulation technique, **Detached Eddy Simulation (DES)**, a hybrid of RANS and LES, was proposed to overcome the modeling errors of RANS and the high computational cost of LES. DES combines the best elements of RANS and LES in a single simulation. The technique initially uses a RANS model to predict the fluid flow properties in very close proximity to solid surfaces and then switches to an LES treatment in other regions. The DES method was designed to apply to flows that are characterized by massive separation, such as a fighter aircraft at a high angle of attack. Since its inception, DES has been applied to simple shapes such as cylinders, spheres and aircraft forebodies, as well as complete aircraft at flight conditions. The accuracy of this new methodology has far surpassed RANS methods and overcomes the limitations that plague LES.

A team of ASU engineers was approached to apply computational fluid dynamics to the sports equipment industry; specifically, to the golf ball. In the past, simulations of fluid dynamics around golf balls have utilized RANS, the same methods applied to predict the airflow around aircraft. As with aircraft, RANS methods produced inaccurate predictions of the force of the airflow on the golf ball and had limited value in computing the distance the golf ball could travel on a drive. This posed a significant problem for the team since RANS-based models form the standard for most industry practice. Therefore, the team decided to apply DES to determine the airflow around the traveling golf ball.

The aerodynamics of golf balls have not been well understood, primarily because the aerodynamic performance of golf balls is critically dependent on the details of the airflow over the ball, and those details are controlled by many factors. As the golf ball flies through the air, it develops lift and drag forces that depend on its velocity, spin rate, atmospheric conditions, and most importantly, the shapes of the individual dimples and their arrangement over the ball's surface.

The team planned to model the aerodynamics of the golf ball in order to ultimately design a ball that delivers maximum efficiency on the golf course. In order to do this, the progress of the golf ball once it is struck had to be noted. As soon as the ball leaves the club, its motion is governed by the laws of aerodynamics and the force of gravity. The trajectory of the golf ball is independent of its construction and the only important characteristics are its geometrical shape, size, mass and its moment of inertia. That is, the shape and distribution of the dimples on a golf ball, together with its size and inertial characteristics, completely determine its aerodynamic performance. To the DES method, the team applied conditions corresponding to the drive. Then, the team studied the effect of the dimple pattern on the airflow structure that develops over the traveling golf ball and how that structure influences the forces that act on the golf ball. It was determined that these influences have important consequences for the golf ball trajectory, particularly its carry distance, the interval between the tee and ground impact, maximum trajectory height, and the angle of incidence at the point where it hits the ground.



Colorized isosurfaces of the flow vorticity around an F-15E at 65° angle of attack show the range of air pressure *the trajectory of the golf ball is independent of its construction*

A demonstration of the team's progress to date was presented this past February. SRIXON, the sponsoring company for the golf ball project, attended as well as representatives from major sports technology and equipment makers and marketers, including Ping, Dunlop and VyaTek Sports. The presentation prompted inquiries about the possibility of the ASU team broadening its study to other applications. This next stage of research might introduce biomechanics, for example, allowing researchers to examine and simulate with extensive precision how new club designs perform with the vast styles of golfers' swings.

The ASU research team consists of project leader Kyle Squires, professor in mechanical and aerospace engineering, Dan Stanzione, director of the High Performance Computing Initiative, Clinton Smith, mechanical engineering graduate research assistant, and the staff at Decision Theater at Arizona State University.

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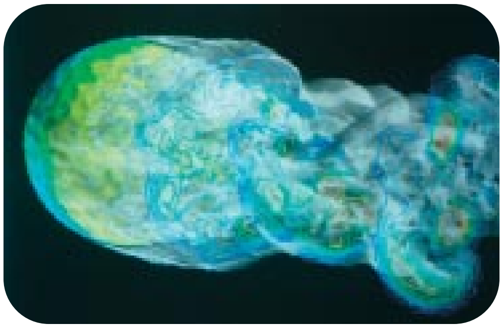
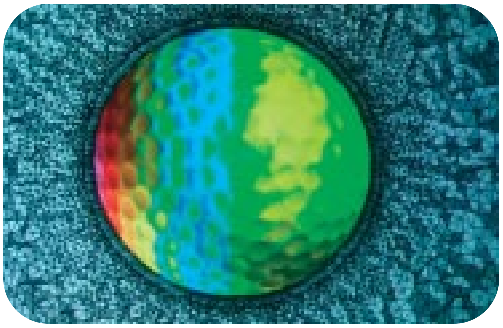
In order to produce the visual demonstration to present to industry, the unsteady, three-dimensional, compressible Navier-Stokes equations had to be solved on a large network of grid points. The calculations were incremented in time, and then the equations were solved at all of the grid points for the next point in time. A post-processing program queried the output solution files. This step in the process was important to find the critical and scientifically interesting segments of the fluid flow solution around the ball in order to produce a clear and understandable visualization.

Airflow properties such as vorticity, a flow variable that contains information about the structure of turbulent motions that develop around the golf ball, are used to create an isosurface, a continuous surface that connects points in three-dimensional space that have the same value. The isosurfaces are then colored to demonstrate variations to discern how the airflow changes as it moves over the ball. The ASU engineers also used other techniques to investigate their solutions, including examination of vector and streamline plots.

Through three-dimensional visualizations, an intricate view of the fluid dynamics around the rotating golf ball was possible. The visualization illustrated that velocity and intensity of turbulence could be measured, patterns depicted, and that air travel over, into and out of individual dimples on the ball could be tracked. This depiction established that computational modeling, high-performance computing, and advanced visualization can be utilized in combination for real-world applications and within time-frames that impact design decisions in "real-time."

Isosurfaces and contours of the instantaneous flow field around a golf ball rotating at 2400 rpm





The computational mesh and contours of the high (red) and low (blue) air pressure on a golf ball in flight

Based on the findings of its initial research, the team is performing additional calculations using its DES model and is beginning to apply Direct Numerical Simulation (DNS), which is a simulation technique that makes no modeling assumptions and directly calculates all of the turbulent variations in the fluid flow. The investigation of fundamental aspects flow by DNS will lead to improvements in the DES model, in turn lending itself to a variety of other applications where optimizing aerodynamic configurations will enhance practical applications — e.g., golf clubs, NASCAR and Formula One racers.

Ultimately, through computational product design, the team will be able to provide real-time modeling. In terms of golf, this capability will one day enable a player to choose a club and ball based on real-time weather conditions and other factors, such as the type of shot, in order to achieve maximum efficiency on the course.

In the long term, the increased use of computational modeling in the analysis and design process of new products will represent huge cost savings to sports manufacturing companies. The technology put forth by the ASU team could save companies from spending vast resources on prototype development and testing. Through computational product design, companies will be able to test products in a virtual setting that provides the same outcomes as physical testing procedures, in addition to details that are beyond measurement in physical tests. Practically anything that moves through the air can be calculated and modeled with sophisticated fluid dynamics to impart precise answers to efficiency questions on practical and commercial applications.