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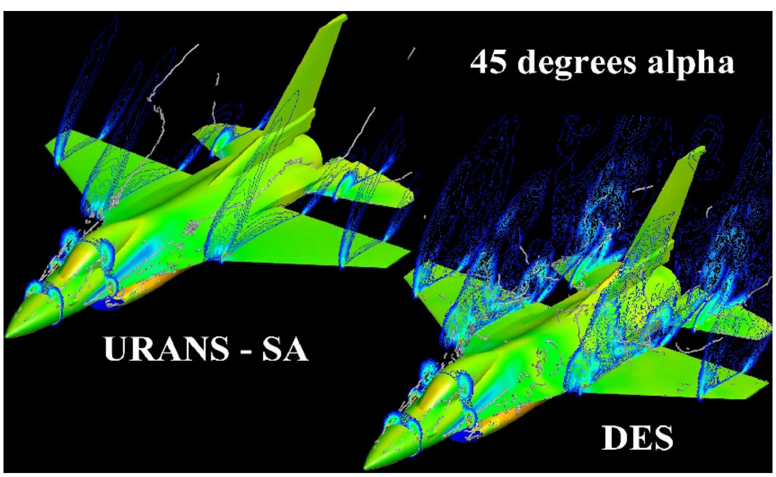

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One of the greatest challenges facing Computational Fluid Dynamics is in accurately calculating massively separated flows at high Reynolds numbers. In 1997, Spalart *et al.* [2] proposed Detached-Eddy Simulation (DES) with this challenge in mind. The method is a hybrid, combining Reynolds-averaged Navier Stokes (RANS) and Large Eddy Simulation (LES). DES combines the efficiency of Reynolds-averaged approaches in the boundary layer and the accuracy of the Large Eddy Simulation in separated regions. LES and therefore DES requires a time-accurate and three-dimensional solution. As grid densities are increased, more unsteady flow features are resolved. The need for time-accurate solutions on dense grids implies that high performance parallel computation can substantially enhance DES efforts. The DoD High Performance Computing and Modernization Office granted a Challenge project to research this topic. This manuscript summarizes the progress of the Challenge project, "Analysis of Full Aircraft with Massive Separation Using Detached-Eddy Simulation". Numerous flows are examined, including a cylinder, two- and three-dimensional forebodies, a prolate spheroid, a supersonic base flow, a delta wing, a notional truck, the C130, the F-16, and the F-15E. All of the calculations described above are performed on structured and unstructured grids using a flow solver – Cobalt – which uses Message Passing Interface (MPI) for parallel solution. Calculations have been performed on a variety of high performance machines. Depending on the problem size, solutions are obtained on as many as 512 processors, providing full aircraft, unsteady solutions in approximately one day.

Introduction

MOST of the flow fields encountered in DoD applications occur within and around complex devices and at speeds for which the underlying state of the fluid motion is turbulent. While Computational Fluid Dynamics (CFD) is gaining increased prominence as a useful approach to analyze and ultimately design configurations, efficient and accurate solutions require substantial effort and expertise in several areas. Geometry description and grid generation, numerical solution of the Navier-Stokes equations, and efficient post-processing are all key elements.

While advances have taken place in areas such as grid generation and fast algorithms for solution of systems of equations, CFD has remained limited as a reliable tool for prediction of inherently unsteady flows at flight Reynolds numbers. Current engineering approaches to prediction of unsteady flows are based on solution of the Reynolds-averaged Navier-Stokes (RANS) equations. The turbulence models employed in RANS methods necessarily model the entire spectrum of turbulent motions. While often adequate in steady flows with no regions of reversed flow, or possibly exhibiting shallow separations, it appears inevitable that RANS turbulence models are unable to accurately predict phenomena dominating flows characterized by massive separations. Unsteady massively separated flows are characterized by geometry-dependent and three-dimensional turbulent eddies. These eddies, arguably, are what defeats RANS turbulence models, of any complexity.

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To overcome the deficiencies of RANS models for predicting massively separated flows, Spalart *et al.* [2] proposed Detached-Eddy Simulation (DES) with the objective of developing a numerically feasible and accurate approach combining the most favorable elements of RANS models and Large Eddy Simulation (LES). The primary advantage of DES is that it can be applied at high Reynolds numbers as can Reynolds-averaged techniques, but also resolves geometry-dependent, unsteady three-dimensional turbulent motions as in LES. The initial applications of DES were favorable and formed the main motivation for developing the Challenge proposal.

For time-accurate and three-dimensional calculations of turbulent flows in complex configurations, high performance computation is essential. The authors were awarded a Department of Defense (DoD) Challenge project by the High Performance Computing Modernization Office (HPCMO), giving the team high priority on DoD supercomputers. This paper is a summary of the first year effort on the Challenge project – "Analysis of Full Aircraft with Massive Separation Using Detached-Eddy Simulation". Due to the large scope of the project, only brief summaries of the various calculations that have been undertaken will be provided, with references to more detailed treatments.

The compressible Navier-Stokes solver forming the backbone of this effort is Cobalt_{60} (Strang *et al.* [6]) and Cobalt. Cobalt is a commercial version of Cobalt_{60} – a compressible flow solver developed at the Air Force Research Laboratory in support of the Common High Performance Software Support Initiative (CHSSI). The relevant improvements available in the commercial version and central to the success of this proposal are rigid body motion, faster per-iteration times, the inclusion of SST-based DES, improved tripping, ability to calculate time-averages and turbulent statistics, an improved spatial operator, and improved temporal integration. Strang *et al.* [6] validated the code on a number of problems, including the Spalart-Allmaras model (which forms the core of the DES model). Tomaro *et al.* [7] converted Cobalt_{60} from explicit to implicit time integration, enabling CFL numbers as high as one million. Grismer *et al.* [8] then parallelized the code, yielding a linear speedup on as many as 1024 processors. Forsythe *et al.* [5] provided a comprehensive testing/validation of the RANS models. Parallel METIS domain decomposition library of Karypis and Kumar [9], Karypis *et al.* [10] is incorporated in Cobalt. ParMetis divides the grid into nearly equally sized zones that are then distributed one per processor.

Computational Approach

Spalart-Allmaras Model

The Spalart-Allmaras (SA) one-equation model [12] solves a single partial differential equation for a variable $\widetilde{\nu}$ which is related to the turbulent viscosity. The differential equation is derived by "using empiricism and arguments of dimensional analysis, Galilean invariance and selected dependence on the molecular viscosity."[1] The model includes a wall destruction term that reduces the turbulent viscosity in the log layer and laminar sublayer and trip terms that provides a smooth transition from laminar to turbulent flow. As illustrated in the subsequent sections, the trip terms are used in some of the calculations to match conditions of particular experiments.

In the S-A RANS model, a transport equation is used to compute a working variable used to form the turbulent eddy viscosity,

$$\begin{aligned}\frac{D\widetilde{\nu}}{Dt} &= c_{b1}[1-f_{t2}]\widetilde{S}\,\widetilde{\nu} - \left[c_{w1}f_w - \frac{c_{b1}}{\kappa^2}f_{t2}\right]\left[\frac{\widetilde{\nu}}{d}\right]^2 \\ &+ \frac{1}{\sigma}\left[\nabla\cdot((\nu+\widetilde{\nu})\nabla\widetilde{\nu}) + c_{b2}\,(\nabla\widetilde{\nu})^2\right], \\ &+ f_{t1}\,\Delta U^2, \end{aligned} \quad (1)$$

where $\widetilde{\nu}$ is the working variable. The eddy viscosity ν_t is obtained from,

$$\nu_t = \widetilde{\nu}\, f_{v1}, \qquad f_{v1} = \frac{\chi^3}{\chi^3 + c_{v1}^3}, \qquad \chi \equiv \frac{\widetilde{\nu}}{\nu}, \quad (2)$$

where ν is the molecular viscosity. The production term is expressed as,

$$\widetilde{S} \equiv f_{v3}S + \frac{\widetilde{\nu}}{\kappa^2 d^2} f_{v2}, \quad (3)$$

$$f_{v2} = \left(1 + \frac{\chi}{c_{v2}}\right)^{-3}, \quad (4)$$

$$f_{v3} = \frac{(1+\chi f_{v1})(1-f_{v2})}{\chi}, \quad (5)$$

where S is the magnitude of the vorticity. The production term as written in (3) differs from that developed in Spalart and Allmaras[12] via the introduction of f_{v3} and re-definition of f_{v2}. These changes do not alter predictions of fully turbulent flows and have the advantage that for simulation of flows with laminar separation, spurious upstream propagation of the eddy viscosity into attached, laminar regions is prevented. This modification was crucial for successful simulation of the flow around forebody section summarized below. The function f_w is given by,

$$\begin{aligned} f_w &= g\left[\frac{1+c_{w3}^6}{g^6+c_{w3}^6}\right]^{1/6}, \\ g &= r + c_{w2}\,(r^6 - r), \qquad r \equiv \frac{\widetilde{\nu}}{\widetilde{S}\kappa^2 d^2}. \end{aligned} \quad (6)$$

The function f_{t2} is defined as,

$$f_{t2} = c_{t3}\exp(-c_{t4}\chi^2). \quad (7)$$

The trip function f_{t1} is specified in terms of the distance d_t from the field point to the trip, the wall vorticity ω_t at the trip, and ΔU which is the difference between the velocity at the field point and that at the trip,

$$f_{t1} = c_{t1} g_t \exp\left(-c_{t2}\frac{\omega_t^2}{\Delta U^2}\left[d^2 + g_t^2 d_t^2\right]\right) , \qquad (8)$$

where $g_t = \min(0.1, \Delta U/\omega_t \Delta x)$ and Δx is the grid spacing along the wall at the trip. The constants are $c_{b1} = 0.1355$, $\sigma = 2/3$, $c_{b2} = 0.622$, $\kappa = 0.41$, $c_{w1} = c_{b1}/\kappa^2 + (1 + c_{b2})/\sigma$, $c_{w2} = 0.3$, $c_{w3} = 2$, $c_{v1} = 7.1$, $c_{v2} = 5$, $c_{t1} = 1$, $c_{t2} = 2$, $c_{t3} = 1.1$, and $c_{t4} = 2$.

Detached-Eddy Simulation

Most of the turbulent flows modeled in this project are computed using Detached-Eddy Simulation. The original DES formulation is based on a modification to the Spalart-Allmaras RANS model[12] such that the model reduces to its RANS formulation near solid surfaces and to a subgrid model away from the wall[2]. The basis is to attempt to take advantage of the usually adequate performance of RANS models in the thin shear layers where these models are calibrated and the power of LES for resolution of geometry-dependent and three-dimensional eddies. The DES formulation is obtained by replacing in the S-A model the distance to the nearest wall, d, by $\widetilde{d}$, where $\widetilde{d}$ is defined as,

$$\widetilde{d} \equiv \min(d, C_{DES}\Delta) . \qquad (9)$$

In Eqn. (9), for the computations performed in this project, Δ is the largest distance between the cell center under consideration and the cell center of the neighbors (i.e., those cells sharing a face with the cell in question). In "natural" applications of DES, the wall-parallel grid spacings (e.g., streamwise and spanwise) are at least on the order of the boundary layer thickness and the S-A RANS model is retained throughout the boundary layer, i.e., $\widetilde{d} = d$. Consequently, prediction of boundary layer separation is determined in the 'RANS mode' of DES. Away from solid boundaries, the closure is a one-equation model for the SGS eddy viscosity. When the production and destruction terms of the model are balanced, the length scale $\widetilde{d} = C_{DES}\Delta$ in the LES region yields a Smagorinsky eddy viscosity $\widetilde{\nu} \propto S\Delta^2$. Analogous to classical LES, the role of Δ is to allow the energy cascade down to the grid size; roughly, it makes the pseudo-Kolmogorov length scale, based on the eddy viscosity, proportional to the grid spacing. The additional model constant $C_{DES} = 0.65$ was set in homogeneous turbulence[3]. Strelets [4] introduced a DES model based on Menter's Shear Stress Transport model[13] that has been included in Cobalt during the course of this project.

Representative Results

Presented in this section is a brief synopsis of the various flows that have been computed during the first year of the Challenge project. Important in application, assessment, and improvement of a relatively new computational technique for predicting turbulent flows such as Detached-Eddy Simulation is the building of an experience base that can be used to provide insight and experience useful for addressing potential problems and guiding the success of future efforts as the method is applied to new configurations and extended to new areas. Each of the flows summarized below possesses elements that have been valuable in advancing the computational approach and improving DES capabilities for engineering and scientific applications.

Circular cylinder

An important feature of DES is that prediction of boundary layer separation is accomplished using a RANS model, taking advantage of the reasonable range of flows for which the S-A model yields adequate predictions. High Reynolds number flows experiencing turbulent boundary layer separation are out of reach of whole-domain LES since the boundary layer needs to be resolved, rather than modelled if the near-wall flow is computed. This becomes impractical for high Reynolds number flows and, consequently, DES offers strong advantages as an approach for high Reynolds number prediction. Figure 1 shows the flow over a section of a circular cylinder at a super-critical (turbulent boundary layer separation) Reynolds number. Note that boundary layer separation is delayed relative to sub-critical flows that experience laminar boundary layer separation. The separation prediction in Figure 1 is handled by the RANS (S-A) model. The shear layers that detach from the cylinder rapidly grow new instabilities and chaotic, three-dimensional structures quickly fill the wake.

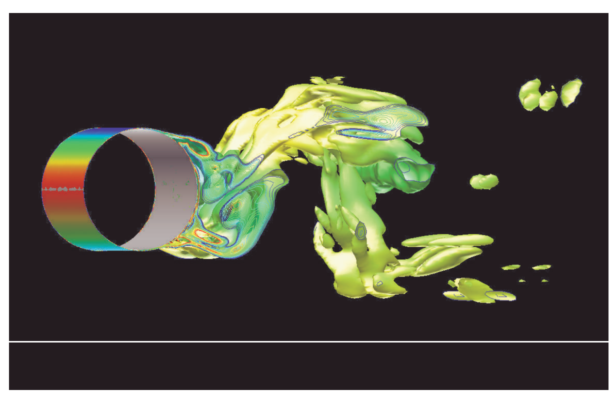

Fig. 1 DES prediction of the flow over a circular cylinder at $Re = 800,000$. Isosurface of vorticity colored by pressure.

Rounded Square

One of the most significant factors affecting spin characteristics for modern fighters is the forebody, with its complex vortical flows and long moment arm. Laboratory measurements of spin characteristics are of limited utility since it is not possible to resolve important Reynolds number effects because of the range of available tunnels. A "building-block" flow considered as part of the Challenge project is that around a canonical forebody cross section, the rounded-corner square. The flow visualization shown in Figure 2 illustrates the complex and highly three-dimensional structure that develops in the wake. The Reynolds number of the calculation is high enough that whole-domain LES would be impractical. Squires *et al.* [11] have shown that the high Reynolds number DES predictions of the flow around the forebody are in good agreement with measurements.

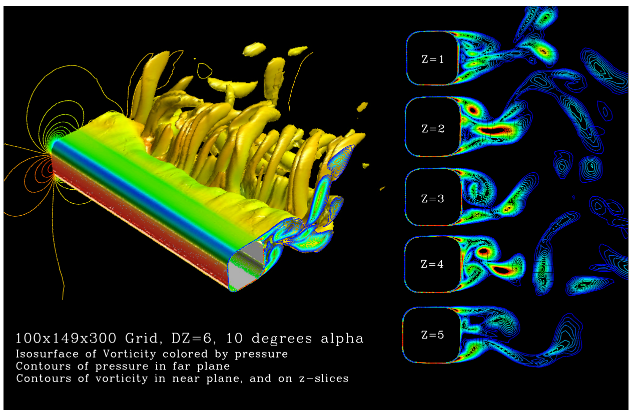

Fig. 2 DES prediction of the flow over a rounded-corner square at $Re = 800,000$.

Delta Wing

The flow over a 70° delta wing has been computed at a Reynolds number of 1.56×10^6[14]. In this effort, a key finding was that the RANS model (S-A) was able to accurately predict the secondary separation, while the LES capability accurately resolved the windings that have been documented in experiments. The vortex burst location and resolved turbulent kinetic energy were in good agreement with experimental measurements. Figure 3 shows a comparison of DES and RANS, with DES giving a more realistic prediction of the flow. The RANS model, in fact, fails to predict a vortex burst at all.

Supersonic Axisymmetric Base

Flow over the supersonic axisymmetric base of Herrin and Dutton [15] was predicted using DES and compared to LES and RANS results[16]. The effect of compressibility corrections and testing of SST based DES were key elements investigated in this work. Vorticity contours are presented in Figure 4, showing significant resolution of the turbulent structures in the

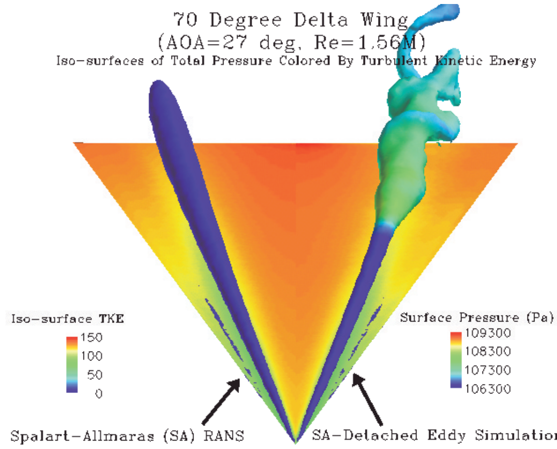

Fig. 3 DES prediction of the flow over 70° swept delta wing.

wake. DES predictions exhibited substantial improvements over RANS models in the ability to predict both the overall base drag, and the flat pressure distribution on the base itself. DES predicted the correct boundary layer thickness prior to the base because of its RANS treatment. Whole-domain LES, on the other hand, was unable to adequately resolve the boundary layer, resulting in an under-prediction of its thickness. Off body Mach contours and turbulent statistics compared favorable with experiments.

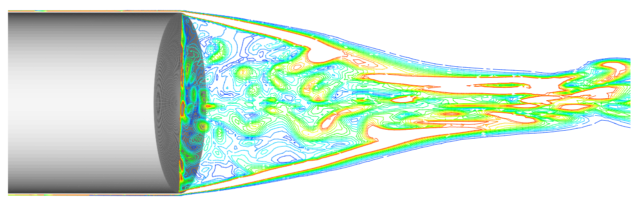

Fig. 4 DES prediction of flow over an axisymmetric base at Mach 2.46. Contours of vorticity.

NACA 0012 pitch-up

The main goal of the present research is to develop an accurate and computationally feasible method for predicting aircraft spin. DES is formulated to provide accurate predictions of the massively separated flows characterizing a spin. The other key component in predicting spin is the ability to compute an aircraft undergoing rigid body motion. Cobalt recently introduced this capability. As a test of the new capability, the pitchup of 2-D NACA 0012 airfoil was computed for the same conditions as reported by Morgan and Visbal [17]. The calculation was at a Reynolds 12,600, no explicit turbulence model was used. The grid was provided by Morgan and Visbal [17], enabling a code-to-code comparison as validation for Cobalt. Vorticity contours are shown in Figure 5 during the pitch maneuver. Lift coefficient vs. angle-of-attack were virtually identical to the calculations of

Morgan and Visbal [17]. Angles of the primary, secondary, and tertiary vortex formation also agreed well with the previous computations and the experiments of Gendrich [18].

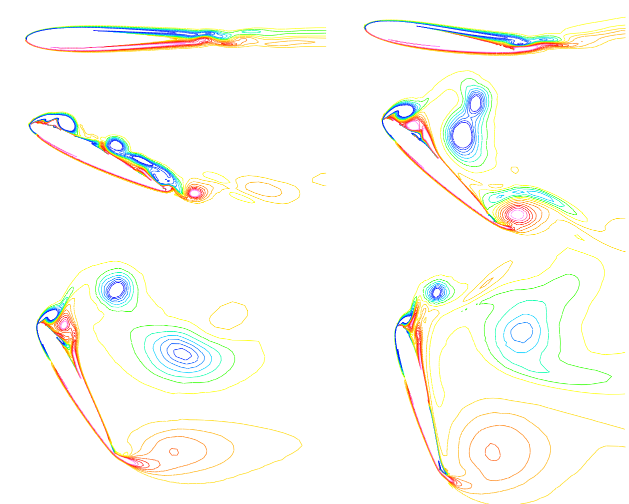

Fig. 5 Unsteady pitch up of a NACA 0012 airfoil – contours of vorticity.

Prolate Spheroid

Flow over a prolate spheroid is a challenging test case for models. A complex separation develops over the body at incidence, the structure of the separated flow being sensitive to the angle of attack. Shown in Figure 6 is the surface distribution of the skin friction over the spheroid. The main experimental database for evaluation of DES predictions tripped the flow at $x/L = 0.2$. For the calculations, the trip terms summarized above in the S-A model are needed and activated at $x/L = 0.2$ to produce the effect of transition to turbulence. The abrupt change in the skin friction pattern in the figure demonstrating this capability in the current computations.

Forebody

In addition to the rounded-corner square summarized above, another forebody study has been undertaken. Unlike the rounded-corder square, the forebody shown in Figure 7 is three-dimensional, more closely approximating the shape of the forebody of an aircraft. Also motivating the flow is the existence of rotary balance data for the geometry that exists for angles of attack of 60 and 90°. Shown in Figure 7 is a snapshot of the instantaneous flow at 90° angle of attack. The flow visualization is from a computation at a Reynolds number based on the body width of over 2×10^6, showing a relatively strong spanwise variation that would be impractical to resolve using whole-domain LES and for which RANS models are inadequate. DES predictions to date compare favorably with measurements, enabling the next phase of the computations in which the flow over the rotating body will be computed.

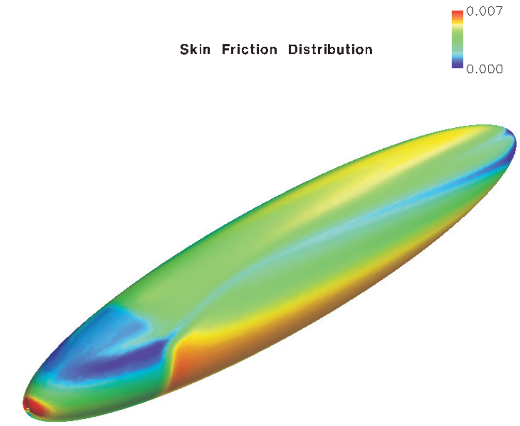

Fig. 6 DES prediction of the flow over a prolate spheroid. Skin friction contours shown for the flow at 20° angle of attack.

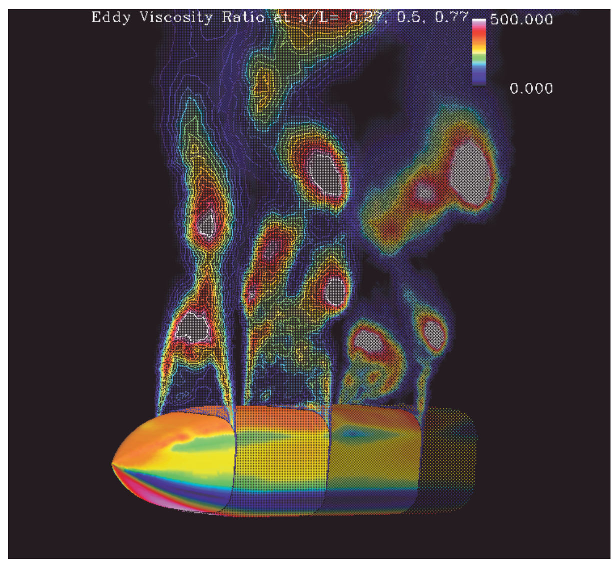

Fig. 7 DES prediction of flow over a three-dimensional forebody at 90° angle-of-attack.

Notional Tractor-Trailer

Predicting the forces accurately on a tractor-trailer is another natural application of DES since the flow is massively separated. A reliable computational tool would allow engineers to more effectively design trucks that would be more energy efficient, among other advantages. Storms, *et al.* [19] performed a comprehensive wind tunnel test on a notional tractor-trailer to provide a reliable test case for developing numerical tools for the prediction of the flows around tractor-trailer configurations. DES predictions have been performed, matching wind tunnel tests conditions, and a visualization is shown in Figure 8. The truck is exposed to a 10° sideslip, simulating a strong crosswind. The ability of DES to resolve unsteady flow features in a computationally feasible way is crucial to attempting such a simulation. Quantitative comparison to the experiments has not been undertaken since it is not an Aerospace application, and therefore of low priority for a DoD project.

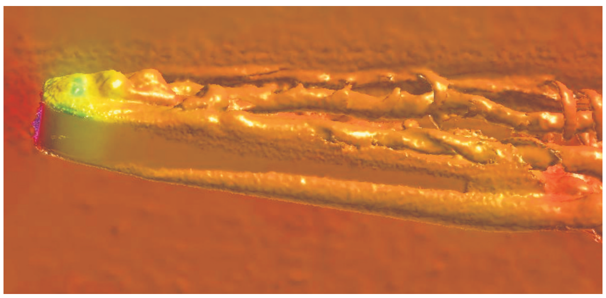

Fig. 8 DES prediction of the flow over a notional tractor-trailer – isosurface of vorticity colored by pressure

C-130

Paratroopers whose chutes fail to deploy when static line jumping out of the cargo bay ramp of the C-130 get caught in the highly energetic separated flow region and are often injured. Because of this problem, tailgate static lines are not employed. Using CFD in concert with experiments to design an aircraft modification to this problem would enhance the capability of the C-130. A side-by-side water tunnel and CFD investigation was performed[20]. These initial calculations were conducted to match the low Reynolds number present in the water tunnel. Consequently, a turbulence model was not employed in the calculations. Figure 9 shows the cause of the problem - two counter rotating vortices are shed off the alternating sides of the cargo door, and create a large upward velocity in the plane of symmetry. Future computations may be performed with DES at free-flight Reynolds numbers to examine what effect Reynolds number has on the flow structures.

F-16

The first DES calculation over an aircraft was made by Squires *et al.* [21] on the F-16 at 45° angle-of-attack. The grid consisted of 3.1×10^6 cells for half the aircraft, with cells concentrated in the strake vortex. A comparison between DES and RANS was undertaken, shown in Figure 10. While unsteady RANS converged to a steady state solution, DES predicted a highly energetic turbulent flow. Strong pressure oscillations on the surface due to the vortex burst are apparent in Figure 11. Although there is no data to compare the vortex burst location, the delta wing studies of Morton *et al.* [14] lend credibility to these results. RANS calculations failed to predict a vortex burst, as also the case in the delta wing study. The success of this calculation on a relatively coarse grid (by LES standards) provided strong evidence that full aircraft calculations with DES were practical in the near future. The calculation required 12.5 hours on 432 SP3 processors to compute 100 non-dimensional time units (made dimensionless using the chord and freestream velocity).

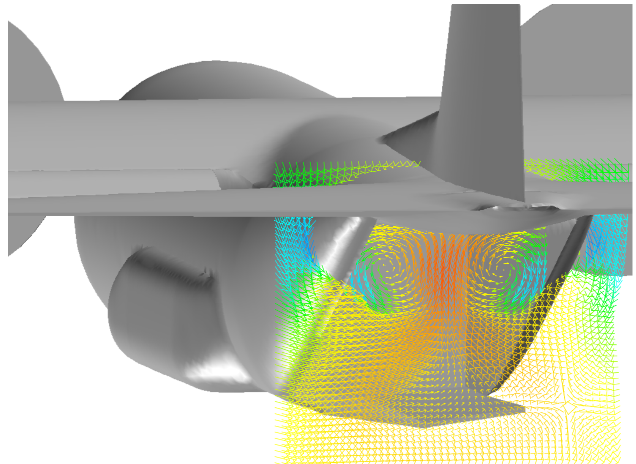

Fig. 9 Laminar simulation of the C-130 with back door open – vectors colored by upward component of velocity

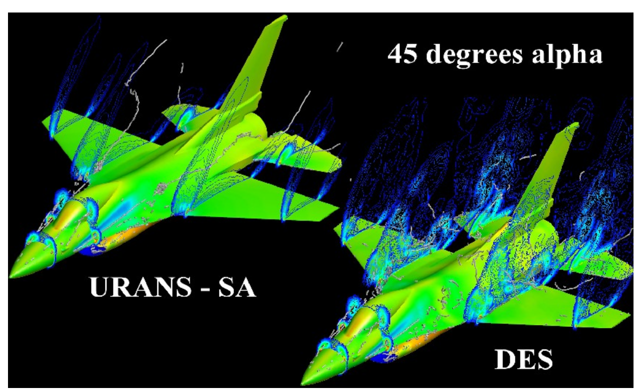

Fig. 10 DES predictions of the flow over the F-16 at 45° angle-of-attack – DES vs. Unsteady RANS. The surface is colored by pressure, contours are of vorticity, and gray filaments are auto-detected vortex cores.

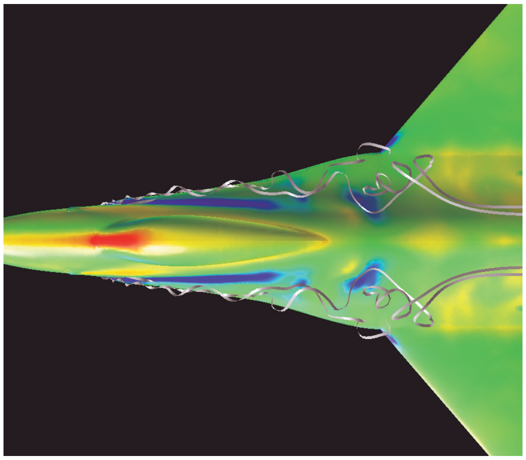

Fig. 11 DES prediction of flow over the F-16 at 45° angle-of-attack – surface colored by pressure, and streamlines.

F/A-18E

DES Calculations were performed on the F/A-18E to support the Abrupt Wing Stall program. Wind tunnel testing at transonic speeds revealed unsteady shock oscillations on the wing. Reynolds-averaged models appear to be capable of predicting this unsteady oscillation. DES calculations have qualitatively produced the shock oscillation as shown in Figure 12 – showing two separate timesteps. The plane of x-vorticity behind the wing shows the fine scale structures captured by DES in this flow. More quantitative comparisons are underway with the aim of presenting results from that study next year.

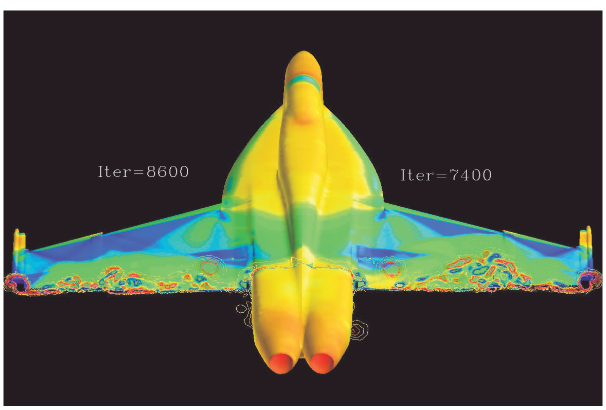

Fig. 12 DES prediction of flow over the F/A-18E – surface colored by pressure, and contours of vorticity.

F-15E

Another of the natural applications of DES is for spin prediction since spins occur at high alpha and in flows characterized by massive separation. The F-15E was selected for the calculations since it underwent a comprehensive flight-test spin program, and therefore provides an excellent validation case. DES and RANS calculations on the F-15E at 65° angle-of-attack have been performed by Forsythe *et al.* [22]. A timestep and grid sensitivity study comprised a key element of this work. The cells sizes of the meshes used for the grid sensitivity study were 2.5×10^6, 5.9×10^6, and 10.0×10^6 cells. Calculations were run on as many as 256 processors, requiring about four days on the finest grid to obtain sufficient samples to represent the time-averaged flowfield. DES and RANS isosurfaces of vorticity are contrasted in Figure 13, with DES demonstrating an ability to predict unsteady flow features. The effect of grid refinement is shown in Figure 14. DES resolves more unsteady flow features as the grid density is increased. The fine grid DES results were within 5% of the flight-test data, with relatively little sensitivity to grid refinement.

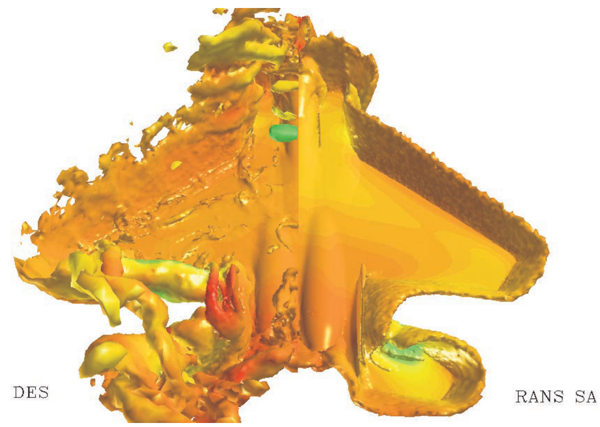

Fig. 13 DES prediction of flow over the F-15E at 65° angle-of-attack – DES vs. RANS. Isosurface is of vorticity colored by pressure.

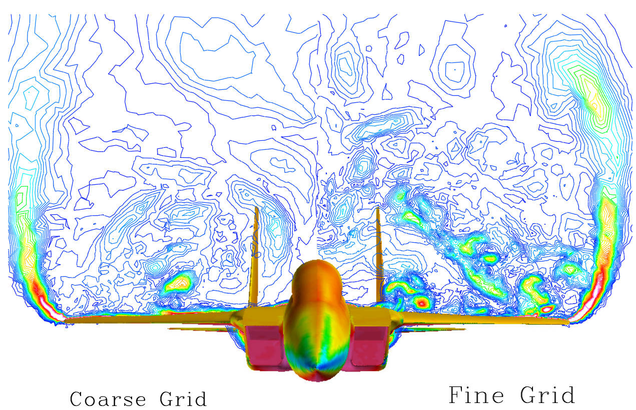

Fig. 14 Instantaneous vorticity contours at 680 inches behind the aircraft reference point. Coarse-grid prediction in left-half plane, fine-grid result in right-half plane.

Concluding Remarks

The first year of the Challenge project "Analysis of Full Aircraft with Massive Separation Using Detached-Eddy Simulation" has provided key advances in application, assessment, and improvement of Detached-Eddy Simulation. Computation of building-block flows such as two- and three-dimensional forebodies and delta wings established a foundation for resolution of several issues important to using DES to predict the flow field around full aircraft, helping to establish important guidelines in grid issues, turbulence treatments, and numerical parameters. The subsequent application of DES to the F-16 and F-15E has further enhanced our confidence level with lift and drag predictions that are accurate compared to flight test data. These developments will eventually provide aircraft designers with a powerful new tool for the prediction of massively separated flows over complex configurations and at flight conditions. The successful pressure predictions on the supersonic axisymmetric base reveals DES as capable of predicting missile afterbody flows. Successful calculations on the prolate spheroid could extend application of DES to maneuvering vehicles such as submarines. The availability of high performance computing and Challenge status continues to accelerate the development of this powerful new technique.

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