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13. **SUPPLEMENTARY NOTES**

14. **ABSTRACT**

15. The focus of the grant was the use of Application Visualization System (AVS), developed by Advanced Visual Systems, Inc., for animating supersonic turbulent flows computed using Large Eddy Simulation (LES). Three flow configurations are visualized: a turbulent flat plate supersonic boundary layer, an 8 deg supersonic compression corner and a 25 deg supersonic compression corner. The animations display the quantitative and qualitative features of the turbulence production and the complex physics of the shock wave turbulent boundary layer interaction.

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AASERT Grant on
Large Eddy Simulation of
Three-Dimensional High Speed Aerodynamics Flows

Final Technical Report
1 July 1997 - 30 June 2000

AFOSR AASERT Grant F49620-97-1-0453

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September 29, 2000

Abstract

This report presents the accomplishments of AFOSR AASERT Grant F49620-97-1-0453. The focus of the grant was the use of the Application Visualization System (AVS), developed by Advanced Visual Systems, Inc., for animating supersonic turbulent flows computed using Large Eddy Simulation (LES). Three flow configurations are visualized: a turbulent flat plate boundary layer, an 8° compression corner and a 25° compression corner. The animations of the flat plate supersonic turbulent boundary layer illustrates the developing process of the large eddies. Large turbulent streaky structures are clearly observed in the instantaneous contour plots of the vorticity modulus in agreement with experiment. The qualitative validation of generating the inflow condition by our rescaling and reintroduction method is shown by comparing the flowfield at the downstream and inflow stations. Flowfield animations for the 8° compression corner display the effect of the shock wave on the flow downstream the corner. The interaction of the shock wave with the boundary layer and the incoming flow is visualized through comparing the temperature, streamwise velocity and streamwise vorticity at the cross sections before and after the shock wave. The flowfield of the 25° compression corner over a period of time are visualized by a sequence of animated contours of the streamwise velocity and the temperature, respectively. The instantaneous flow separation zone is indicated by the negative streamwise velocity. The significant changes in the flowfield caused by the strong shock wave formed around the corner are found.

Contents

1 Introduction

The accurate prediction of compressible turbulent flow plays a significant role in engineering design including, for example, propulsion and aerodynamics. Computational fluid dynamics (CFD) is widely recognized as an effective method of flow analysis for high speed vehicles. The use of CFD can greatly reduce the length of the design cycle and the cost. Conventional Reynolds-averaged Navier-Stokes (RANS) methods yield accurate predictions for those flow regions which exhibit little or no separation. However, they fail to provide accurate predictions of critical engineering data, *e.g.*, the mean and rms fluctuating surface pressure and surface heat transfer, mean surface skin friction and locations of primary and secondary separation in those flows involving strong viscous-inviscid interaction [1]. Large Eddy Simulation (LES), an alternative to RANS, has been demonstrated to be both a useful research tool for understanding the physics of turbulence and also a predictive method for flows of engineering interest. In LES, the influence of the unresolved scales is simulated using a subgrid-scale (SGS) model or the inherent dissipation of the numerical scheme, denoted by Monotone Integrated Large Eddy Simulation (MILES) by Boris *et al* [2].

Large Eddy Simulations of three flow configurations (a supersonic flat plate turbulent boundary layer, an 8° and a 25° compression corner at Mach 3 and $Re_\delta = 2 \times 10^4$) have been visualized using the Application Visualization System (AVS) developed by Advanced Visual Systems, Inc. AVS is the leading 3D, multi-platform, data visualization environment and provides an ideal framework for the delivery and implementation of visual applications. The details of the grid system and the numerical method are presented in [5, 6, 7]. The visualization provides insight and understanding into the complex physics of these flows which are characterized by very large databases. We have successfully applied AVS to animate the turbulent flowfields of the three flow configurations. The turbulence characteristics (*e.g.*, the turbulent streaky structures, the development and movement of the large eddies and their interaction with the shock waves) are demonstrated. Five video animations have been produced. The contents of the videos are described in the following section.

2 Results

Five video animations were produced (see Section 3.1). They are classified into three different flow configurations. The contents of the videos are described below. Copies of the videos were forwarded to AFOSR as they were produced. Additional copies can be obtained from Prof. Doyle Knight.

2.1 Flat Plate Boundary Layer

A Mach 3 supersonic turbulent flat plate boundary layer at $Re_\delta = 2 \times 10^4$ is presented in video no. 3. The streamwise, transverse and spanwise dimensions are $L_x = 14.8\delta, L_y = 3.4\delta$ and $L_z = 4.4\delta$, respectively, where δ is the incoming boundary layer thickness.

The video illustrates the accuracy of our dynamic turbulent inflow boundary condition obtained by an instantaneous rescaling of the boundary layer at a downstream location to the inflow boundary. The development of the turbulent inflow boundary condition was a major landmark of our research. Prior to the development of this inflow condition, LES of a supersonic turbulent boundary layer was computationally expensive because the computational domain had to extend from upstream of the leading edge of a flat plate (*i.e.*, where the inflow boundary condition was known, namely, uniform flow). Our inflow condition allows the supersonic turbulent boundary layer to be generated with a finite inflow boundary layer thickness. Our inflow condition extends to compressible flows the method of Lund *et al* [3]. At each time step, the flowfield at a selected downstream station ($x = 11.8\delta$, where x is measured from the inflow boundary and δ is the inflow boundary layer thickness) is rescaled and reintroduced at the inflow boundary. The video displays animated plots of the instantaneous kinetic energy, temperature and vorticity modulus at $z = 2.2\delta$ with closeups at the inflow and outflow. The video shows that the inflow boundary condition does not create any spurious features. Comparison of quantitative turbulence statistics with experimental data confirms the accuracy of the inflow boundary condition [5].

The video also illustrates the turbulent structures in the flat plate boundary layer. A particularly striking feature is the strong coupling of the temperature and velocity field evident in the animation of the combined temperature contours with the velocity vectors at a cross section of $x = 11.8\delta$. The turbulence production in the viscous sublayer is clearly seen and agrees with experimental flow visualization [4]. The entrainment by the large eddies generates intense changes in the static temperature field. A cross sectional combined animation of streamwise vorticity with the velocity vector highlights the regions of turbulence production. The contours of the vorticity modulus at $y = 0.02\delta$ and $y = 0.1\delta$ clearly exhibit the sublayer streaks in agreement with experiment.

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2.2 Supersonic 8° Compression Corner

An 8° supersonic compression corner at Mach 3 and $Re_\delta = 2 \times 10^4$ is presented in video nos. 1, 2 and 4. The computational domain is $-6.0\delta \le L_x \le 6\delta$ where x is measured from the corner. The height and width of the computational domain are $L_y = 3.4\delta$ and $L_z = 4.4\delta$.

Four animations are presented for the flowfield at $z = 2.2\delta$. The animations show the instantaneous kinetic energy, density, temperature and streamwise vorticity. The shock boundary layer interaction significantly affects the flow turbulence as indicated in the instantaneous contours of the streamwise vorticity, temperature and streamwise velocity at two different cross sections ($x = \pm 3\delta$).

The movement of the shock wave and its interaction with the incoming flow is visualized by several 3-D animations. These combine an instantaneous isosurface of static pressure (which define the instantaneous $\lambda-$shock) with contours of streamwise velocity (which define the instantaneous separation region). Additionally, the pressure isosurface is colored with the instantaneous contours of static temperature. These animations illustrate the distortion of the $\lambda-$shock by the incoming large eddies. The size spanwise ripples of the $\lambda-$ shock are in good agreement with experiment [5]. Although the mean flow is unseparated, regions of local instantaneous separation appear periodically.

2.3 Supersonic 25° Compression Corner

A 25° compression corner at Mach 3 and $Re_\delta = 2 \times 10^4$ is presented in video no. 5. The computational domain is $-20\delta \le x \le 8\delta$ where x is measured from the corner. The height and width of the computational domain are $L_y = 3.4\delta$ and $L_y = 2.2\delta$.

The animations are composed of a slice within the boundary layer at constant distance above the wall. When the supersonic turbulent flow interacts with the shock wave generated by the compression corner, significant changes in the flowfield appear. Animations of the contours of the instantaneous streamwise velocity and temperature show the enhancement of turbulent mixing due to the shock boundary layer interaction. The mean flow is separated at the corner. The instantaneous flow separation zone differs substantially from the mean separation region due to the significant motion of the $\lambda-$shock. The spanwise ripples of the $\lambda-$shock are in good agreement with experiment [6].

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References

[1] D. Knight and G. Degrez, "Shock Wave Boundary Layer Interactions in High Mach Number Flows – A Critical Survey of Current CFD Prediction Capabilities", AGARD AR-319, Volume 2, 1998.

[2] J. Boris, F. Grinstein, E. Oran and R. Kolbe, " New insights into Large Eddy Simulation", *Fluid Dynamics Research*, 10:199–228, 1992.

[3] T. Lund, X. Wu, and K. Squires, "Generation of Turbulent Inflow Data for Spatially- Developing Boundary Layer Simulations", *Journal of Computational Physics*, 140(2):233–258, 1998.

[4] E. Spina, A. Smits and S. Robinson, "The Physics of Supersonic Turbulent Boundary Layers", *Annual Review of Fluid Mechanics*, 26:287–319, 1994.

[5] G. Urbin, D. Knight, and A. Zheltovodov, "Compressible Large Eddy Simulation using Unstructured Grid: Supersonic Turbulent Boundary Layer and Compression Corner", AIAA Paper 99-0427, 1999.

[6] G. Urbin, D. Knight and A. Zheltovodov, "Large Eddy Simulation in Compressible Corner Part I", AIAA Paper 2000-0398, 2000.

[7] B. Chernyavsky, H. Yan and D. Knight, "Analyses of Some Numerical Problem in LES", AIAA Paper 2001-0436, 2001.

3 Personnel and Publications

3.1 Videos Produced

1. R. Murray, G. Urbin and D. Knight, "Large Eddy Simulation of Supersonic Compression Corner", Nov 1998.

2. R. Murray, G. Urbin and D. Knight, "Shock Wave Boundary Layer Interaction Over a Supersonic Compression Corner", Jan 1999.

3. E. Strohle, G. Urbin and D. Knight, "Large Eddy Simulation of Flat Plate Boundary Layer", 1999.

4. E. Strohle, G. Urbin and D. Knight, "Large Eddy Simulation of Supersonic Compression Corner", April 1999.

5. K. Higgins, G. Urbin and D. Knight, "Large Eddy Simulation of Supersonic Compression Corner", Jan 2000.

A copy of each video was forwarded to AFOSR as it was prepared. Additional copies may be obtained from Prof. Doyle Knight.

3.2 Personnel

The personnel supported by the AFOSR AASERT grant are listed in Table 1. The personnel supported by the companion AFOSR grant on Large Eddy Simulation are listed in Table 2.

Table 1: Personnel supported by AFOSR AASERT Grant F49620-97-1-0453

Name	Title	Period of Participation
Robert Murray	Graduate Research Assistant	1997 - 1998
Eric Strohle	Graduate Research Assistant	1998 - 1999
Kathryn Higgins	Graduate Research Assistant	1999 - 2000

Table 2: Personnel supported by AFOSR Grant F49620-99-1-0008

Name	Title	Period of Participation
Prof. Doyle Knight	Principal Investigator	1997 - present
Dr. Gerald Urbin	Postoctoral Associate	1998 - 1999
Dr. Hong Yan	Postoctoral Associate	1999 - present

3.3 Papers Published or in Print

1. N. Okong'o, and D. Knight, "Compressible Large Eddy Simulation Using Unstructured Grids: Channel and Boundary Layer Flows", AIAA Paper No. 98-3315, July 1998.

2. N. Okong'o, D. Knight, and G. Zhou, "Large Eddy Simulations Using an Unstructured Grid Compressible Navier-Stokes Algorithm", *International Journal of Computational Fluid Dynamics*, to appear, 2000.

3. G. Urbin, D. Knight, and A. Zheltovodov, "Compressible Large Eddy Simulation using Unstructured Grid: Supersonic Turbulent Boundary Layer and Compression Corner", AIAA Paper 99-0427, 1999.

4. G. Urbin, and D. Knight, "Compressible Large Eddy Simulation Using Unstructured Grid: Unstructured Boundary Layer", Second AFOSR Conference on DNS/LES, Rutgers University, June 7-9, 1999, Kluwer Academic Publishers, pp. 443-458.

5. G. Urbin, D. Knight and A. Zheltovodov, "Large Eddy Simulation in Compressible Corner Part I", AIAA Paper 2000-0398, 2000.

6. H. Yan, G. Urbin, D. Knight and A. Zheltovodov, "Compressible Large

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Eddy Simulation Using Unstructured Grid: Supersonic Boundary Layer and Compression Ramps", 10th International Conference on Methods of Aerophysical Research, Institute of Theoretical and Applied Mechanics, Russian Academy of Sciences, Novosibirsk, Russia, July 2000.

7. B. Chernyavsky, H. Yan and D. Knight, "Analysis of Some Numerical Problem in LES", AIAA Paper 2001-0436, 2001.

3.4   Papers Submitted

1. G. Urbin and D. Knight, "Large Eddy Simulation of a Supersonic Boundary Layer Using an Unstructured Grid", submitted to *AIAA Journal*, under revision.