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19. ABSTRACT (Continue on reverse if necessary and identify by block number) The research concerns the understanding of 3-D shock wave-turbulent boundary layer interactions. During the past year a collaborative effort has focused on theoretical and experimental investigations of the 3-D swept compression corner at Mach 3 for a compression angle of 24 deg sweep angle of 60 deg, and two different Reynolds numbers. The present author has computed the flowfield utilizing the 3-D Reynolds-averaged compressible Navier-Stokes equations, with turbulence incorporated through the Baldwin-Lomax algebraic turbulent eddy viscosity model. In separate efforts, Prof. S. Bogdonoff and his colleagues at the Princeton Gas Dynamics Laboratory have performed detailed experimental studies of the flowfield, and Dr. C. Horstman at NASA Ames has also computed the same configuration using the Jones-Launder turbulence model. The computed surface pressure profiles at the lower Reynolds number display significant disagreement with experiment. The computed surface pressure and boundary layer profiles of pitot pressure and vaw angle are in good agreement with experiment at the higher Reynolds number. On the basis of detailed particle pathlines, the (continued)			
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is computed

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→ principal flowfield feature is observed to be a large vortical structure aligned approximately with the compression corner. This structure is qualitatively identical to the vortical structure observed for the 3-D sharp fin under the same external flow conditions.



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Report RU-TR-165-MAE-F

***Theoretical Investigation of
3-D Shock Wave-Turbulent Boundary Layer Interactions
Part V***

Doyle D. Knight

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Interim Report for Period 1 October 1985 to 30 September 1986
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February 1987

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PREFACE

This report presents the research accomplishments
of the research investigation entitled "Theoretical Investigation of Three-
Dimensional Shock-Wave Turbulent Boundary Layer Interactions".

The research has benefited from the assistance of several individuals, including Dr. James Wilson (Air Force Office of Scientific Research), Dr. C. Horstman (NASA Ames Research Center), and Dr. James Keller and Mr. Manuel Salas (NASA Langley Research Center). The interactions with S. Bogdonoff, R. Kimmel, M.-F. Mao, R. Ruderich, B. Shapey and L. Smits are acknowledged.

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Section I. Objectives

The principal objectives of the research program are :

1. **Develop and Validate Theoretical Model(s) for 3-D Shock Wave - Turbulent Boundary Layer Interaction**

The understanding of complex 3-D shock wave-turbulent boundary layer interactions ("3-D turbulent interactions") requires the development of accurate theoretical models. A wide range of theoretical approaches have been employed, extending from simplified control volume analyses (Paynter 1980)* to the Reynolds-averaged three-dimensional compressible Navier-Stokes equations (Horstman and Hung 1979; Knight 1984a, 1984b, 1984c; Knight et al 1986) with turbulence incorporated through a turbulent eddy viscosity model. The present research effort has successfully followed the latter approach, utilizing the algebraic turbulent eddy viscosity of Baldwin and Lomax (1978). The equations are solved numerically using a hybrid explicit-implicit numerical algorithm developed by the present investigator (Knight 1984a). The validation is achieved by comparison of computed and experimental results for 3-D turbulent interactions in simplified geometries. This validation has been a continuous element of the research.

Every theoretical model, however, contains inherent limitations, and efforts must be focused on its improvement. In this regard, a close collaboration between theory and experiment is mandatory. A basic question is always, "How well does the theoretical model incorporate the physics of the flowfield?" In the context of the Reynolds-averaged Navier-Stokes equations, this question specifically refers to the efficacy of the turbulence model. Consequently, the present research effort focuses on the improvement of the theoretical model, as well as the determination of its accuracy.

2. **Determine the Physical Structure of 3-D Turbulent Interactions for Selected Geometries**

A second objective is the determination of the physical flowfield structure of 3-D turbulent interactions in simplified geometries (e.g., 3-D sharp fin and 3-D swept compression corner). This understanding is naturally linked to the development and verification of accurate theoretical model(s) for 3-D turbulent interactions, and as such requires a coordinated effort between theory and experiment. During the fourth year, the collaboration of C. C. Horstman (NASA Ames Research), B. Shapey and S. Bogdonoff (Princeton) and the author led to a better understanding of the flowfield structure of the 3-D sharp fin configuration (Knight et al 1986). During the fifth year (1 October 1985 - 30 September 1986), a similar collaboration has led to the understanding of the flowfield structure for the 3-D swept compression corner at Mach 3 for $(\alpha, \lambda) = (24, 60)$ deg (Section II.A).

* References are included in Section V

3. Investigate Methods for Control and Modification of 3-D Turbulent Interaction Flowfields

An exciting prospect is the examination of methods for control and modification of the mean flowfield structure of 3-D turbulent interactions. This effort represents a natural succession to the previous objectives, and may suggest specific practical applications in aerodynamics and propulsion. On the basis of the success in developing a flowfield model for the 3-D sharp fin, an initial research effort is focused on this configuration for the present year. Several hypotheses have been proposed concerning the behavior of the flowfield structure, and a series of computations are proposed. This research is closely linked with a corresponding proposed experimental effort at the Princeton Gas Dynamics Laboratory.

4. Develop a Unified Understanding of the Flowfield Structure of 3-D Turbulent Interactions

A fourth objective is the understanding of the flowfield structure within broad families of 3-D turbulent interactions. The research effort to date has focused on the family of dimensionless 3-D shock generators (e.g., 3-D sharp fin and 3-D swept compression corner). The goal is to determine the common features of the flowfield structure in these interactions. Significant progress has been achieved towards this objective during the fifth year. In particular, the flowfield structure of the 3-D swept compression corner at Mach 3 for $(\alpha, \lambda) = (24, 60)$ was observed to be qualitatively identical to the structure of the 3-D sharp fin at Mach 3 for $\alpha = 20$ deg (Section II.A).

The research program has achieved significant progress these objectives. The present report details the progress during the period 1 October 1985 - 30 September 1986, and describes the research program for the present year (1 October 1986 - 30 September 1987).

Section II. Research Accomplishments for the Fifth Year and Research Program for the Sixth Year

A. Research Accomplishments for the Fifth Year (1 October 1985 - 30 September 1986)

The research activities for the fifth year focused on the examination of the 3-D swept compression corner at Mach 3. Two specific tasks were detailed in the program plan (Knight 1985), namely, 1) the analysis of the 3-D swept compression corner for $(\alpha, \lambda) = (24, 60)$ deg at $Re_{\delta_{\infty}} = 1.4$ to 2.3×10^5 , and 2) the calculation of the 3-D swept compression corner for $(\alpha, \lambda) = (24, 60)$ deg at $Re_{\delta_{\infty}} = 9 \times 10^5$. These efforts focused on three of the objectives of the overall research effort (Section I), namely, the development and validation of theoretical models for 3-D turbulent interactions (Objective No. 1), the determination of the physical structure of 3-D turbulent interactions for selected geometries (Objective No. 2), and the development of a unified understanding of the flowfield structure of 3-D turbulent interactions (Objective No. 4). The theoretical model employed the Reynolds-averaged three dimensional compressible Navier-Stokes equations, with turbulence incorporated using the algebraic eddy viscosity model of Baldwin and Lomax (1978). The governing equations were solved using the hybrid algorithm of Knight (1984a).

1. Analysis of 3-D Swept Compression Corner for $(\alpha, \lambda) = (24, 60)$ deg at $Re_{\delta_{\infty}} = 1.4$ to 2.3×10^5

A series of three calculations were performed for the 3-D swept compression corner for $(\alpha, \lambda) = (24, 60)$ deg at $Re_{\delta_{\infty}} = 1.4$ to 2.3×10^5 . These calculations were performed in the fourth year (Summer 1985) and the early part of the fifth year (Fall 1985). The selection of this configuration was motivated by the poor agreement observed in a previous computation of this case by Horstman (1984) using the Jones-Launder (1972) two equation (k- ϵ) turbulence model. The three cases were chosen to examine 1) the effects of the grid spacing in the spanwise direction and 2) the nature of the upstream profile. In the first instance, the effect of the refinement of the spanwise grid spacing in the vicinity of the centerline plane of symmetry was evaluated. In the second instance, two separate upstream profiles were examined, corresponding to a boundary layer developing from a straight and swept leading edge, respectively.

The analysis of the $(\alpha, \lambda) = (24, 60)$ deg, $Re_{\delta_{\infty}} = 1.4$ to 2.3×10^5 configuration was completed during the fifth year. The results were discussed in part in the final report for the fourth year (Knight 1986a), and in further detail in a recent paper by Knight et al (Knight 1987 - see Section VI). The principal conclusions are :

a. Surface Pressure

The computed surface pressure profiles were compared with the experimental measurements of Settles and Teng (1984), and the calculated profiles of Horstman (1984). The following observations were made :

- The computed upstream propagation is in good agreement with the experimental data for both turbulence models (Figs. 6 and 7, Section VI).
- The computed pressure *profiles* differ significantly from the experiment for both turbulence models (Figs. 6 and 7, Section VI). In particular, the computed profiles fail to reproduce the initial rapid pressure rise, and the drop in pressure immediately upstream of the corner.
- The peak corner pressure is accurately predicted.
- The computed upstream pressure propagation (using the Baldwin-Lomax model) is insensitive to the variations in upstream boundary layer thickness δ_∞ by a factor of two.
- The computed surface pressure is insensitive to refinement of the grid spacing in the spanwise direction near the center symmetry plane.
- The failure to accurately predict the surface pressure profile may be attributable to insufficient streamwise grid resolution and/or limitations of the turbulence model. Further research is in progress.

b. Flowfield Structure

The flowfield structure for the $Re_{\delta_\infty} = 1.4$ to 2.3×10^5 is qualitatively similar to the $Re_{\delta_\infty} = 9 \times 10^5$ configuration (see below). The flow is dominated by a large vortical structure aligned approximately with the corner line. A significant fraction of the incoming boundary layer is swept into the vortex. The structure is qualitatively similar for both turbulence models, and is described in Fig 32, Section VI.

2. Calculation of 3-D Swept Compression Corner for $(\alpha, \lambda) = (24, 60)$ deg at $Re_{\delta_\infty} = 9 \times 10^5$

During the fifth year, a combined experimental and theoretical effort was focused on the 3-D swept compression corner for $(\alpha, \lambda) = (24, 60)$ deg and $Re_{\delta_\infty} = 9 \times 10^5$. The participants included Prof. S. Bogdonoff (Princeton University) and the staff of the Princeton Gas Dynamics Laboratory, Dr. C. Horstman (NASA Ames Research Center), and Prof. Doyle Knight. The choice of this configuration was based on two factors :

a. Concurrence with Experimental Effort at Princeton Gas Dynamics Laboratory

A series of meetings were held with Professor Bogdonoff and Dr. C. Horstman during 1985 to determine the appropriate configurations for joint experimental and theoretical investigation of 3-D turbulent interactions. Previous collaborative experimental and theoretical efforts had focused on the 3-D sharp fin configuration at Mach 3 (Knight et al 1986). The consensus of the participants was to focus on the 3-D swept compression corner at Mach 3 for $(\alpha, \lambda) = (24, 60)$ deg and $Re_{\delta_\infty} = 9$

$\times 10^5$. This configuration provides a significant opportunity for comparison with the previous study (Knight et al 1986) of the 3-D sharp fin at Mach 3 for $\alpha = 20$ deg and $Re_{\delta_{\infty}} = 9 \times 10^5$. In particular, these two configurations possess the same incoming boundary layer, and exhibit approximately the same pressure rise. They differ only in the nature of the geometry which generates the shock wave.

- b. Examine the Effects of Reynolds Number for the 3-D Swept Compression Corner at $(\alpha, \lambda) = (24, 60)$ deg

The configuration provides an examination of Reynolds number effects through comparison with the previous results for the $(\alpha, \lambda) = (24, 60)$ deg and $Re_{\delta_{\infty}} = 1.4$ to 2.3×10^5 .

The overall research effort included separate calculations of the 3-D swept compression corner by Knight and Horstman. The calculation of Knight employed the Baldwin-Lomax turbulence model, and was performed on the VPS 32 (CYBER 205) at NASA Langley Research Center. The calculation of Horstman employed the Jones-Launder turbulence model, and was performed on the CRAY X-MP 4/8 at NASA Ames Research Center. A series of detailed experiments were performed at the Princeton Gas Dynamics Laboratory. The experimental data included surface pressure, surface flow visualization, and boundary layer profiles of pitot pressure and yaw angle.

The results of the study are presented in Knight et al (1987) (see Section VI). The conclusions are the following :

- a. Surface Pressure

The computed surface pressure profiles are in good agreement with experiment for both turbulence models. The Jones-Launder model provides a closer prediction of the upstream propagation. Both models accurately predict the corner pressure. The calculated profiles are within 8% of the experimental data downstream of the corner.

- b. Pitot Pressure

The computed pitot pressure profiles are in reasonable agreement with experiment, with closer agreement observed downstream of the corner line. The pitot pressure is relatively insensitive to the turbulence model.

- c. Yaw Angle

The computed yaw angle profiles away from the surface (i.e., $y > 0.1\delta_{\infty}$) are in general agreement with experiment, and are relatively insensitive to the turbulence model. In the immediate vicinity of the surface (i.e., $y < 0.1\delta_{\infty}$), the yaw angle profiles are sensitive to the turbulence model, with the Jones-Launder model providing closer agreement with experiment. The average absolute deviation in the surface yaw angle predicted by the Jones-Launder model and the experiment is 3.5 deg

within the 3-D interaction region. The average absolute difference in the surface yaw angles computed by the Baldwin-Lomax and Jones-Launder model is 5.7 deg within the 3-D interaction region. Overall, these differences are modest, since the surface yaw angle reaches values as large as 55 deg.

d. **Surface Flow Visualization**

The computed surface skin friction lines displayed general agreement with the experimental surface flow visualization obtained using the kerosene lampblack technique (Figs. 25-27 of Section VI). The experimental line of coalescence was observed to form an angle of 45 deg relative to the spanwise coordinate. The computed lines of coalescence were 50 deg and 46 deg for the Baldwin-Lomax and Jones-Launder models, respectively.

e. **Flowfield Structure**

An extensive examination of fluid streamlines ('particle tracing') was performed for both computed flowfields. This technique was utilized previously for the 3-D sharp fin (Knight et al 1986). The particle tracing was performed on the CYBER 205 at the John von Neumann Supercomputer Center, Princeton, NJ, and the results displayed using locally-developed graphics software on the Sun graphics workstation at Rutgers.

The principal flowfield feature is a large vortical structure, aligned approximately with the corner (Figs. 28-32, Section VI). The structure is qualitatively the same for both the Baldwin-Lomax and Jones-Launder models. In the immediate vicinity of the surface, the streamlines obtained from the flowfields computed using the Baldwin-Lomax and Jones-Launder models display modest differences associated with the respective differences in the yaw angle profiles.

The principal vortical structure is qualitatively identical for the 3-D swept compression corner at $(\alpha, \lambda) = (24, 60)$ deg and the 3-D sharp fin at $\alpha = 20$ deg. The incoming boundary layer is identical for both configurations (Mach 3, $Re_{\delta_{\infty}} = 9 \times 10^5$), and the overall pressure rise is approximately the same. Consequently, the flowfield structure is insensitive to the details of the shock-generating mechanism for these cases. This represents a significant development in the understanding of the flowfield structure of 3-D turbulent interactions.

B. Research Program for the Sixth Year (1 October 1986 - 30 September 1987)

The research program for the sixth year is described in detail in Knight (1986b). The overall effort is focused on the four research objectives enumerated in Section I. The detailed tasks for the present year are :

1. Develop and Validate Theoretical Models for 3-D Shock Wave-Turbulent Boundary Layer Interactions

a. Development of Second Theoretical Model

The existence of unsteady 2-D shock-wave laminar boundary layer interactions is investigated for a compression ramp. The focus of this research is the determination of the existence of unsteady shock wave motion associated with the formation of the separated region in the corner. It is intended that this effort will lead to a better understanding of low-frequency unsteadiness in shock wave-boundary layer interactions, and to the development of alternate theoretical models.

b. Further Examination of Efficacy of Original Theoretical Model

The 'original' theoretical model employs the Reynolds-averaged three-dimensional compressible Navier-Stokes equations, with the effects of turbulence incorporated through the algebraic turbulent eddy viscosity model of Baldwin and Lomax. The efficacy of this theoretical model is further examined through calculation of 3-D swept compression corner for $(\alpha, \lambda) = (24, 40)$ deg at $Re_{\delta_{\infty}} = 2.5 \times 10^5$.

2. Determine the Physical Structure of 3-D Turbulent Interactions for Selected Geometries

a. Development of Sophisticated Graphics Tools

The examination of the immense amount of flowfield data requires sophisticated graphics tools. The research effort in this area includes the further development of the flow streamline ('particle pathline') software for Sun Workstations, and the development of an interactive, menu-driven user interface for graphics software on Sun Workstations

b. Development of Flowfield Structure Models

The flowfield structure of the 3-D swept compression corner at $(\alpha, \lambda) = (24, 40)$ deg is examined using the flow streamline software, and compared with the previous results at $(\alpha, \lambda) = (24, 60)$ deg.

3. Investigate Methods for Control and Modification of 3-D Turbulent Interactions

The development of a flowfield structure model for the 3-D sharp fin (Knight et al 1986) provides the opportunity for investigating methods for *control* of the vortical structure. The conventional technique of boundary layer bleed in the interaction region is investigated in order to determine its effect on the flowfield structure. Additional 'control' or modification techniques may include modified spanwise vorticity distribution (e.g., wall jet, external vortex).

4. Develop a Unified Understanding of the Flowfield Structure of 3-D Turbulent Interactions

The flowfield structures of the 3-D sharp fin for $\alpha = 10$ to 20 deg and the 3-D swept compression corner for $(\alpha, \lambda) = (24, 40)$ and $(24, 60)$ deg are examined for unifying characteristics.

A complete description of the three year research program (1 October 1986 - 30 September 1989) is included in Knight (1986b).

Section III. Publications and Scientific Interactions

A. Written Publications - Cumulative Chronological List

1. 1 October 1981 - 30 September 1982

- a. Knight, D., "Application of Curvilinear Coordinate Generation Techniques to the Computation of Internal Flows", in *Numerical Grid Generation - Proceedings of a Symposium on the Numerical Generation of Curvilinear Coordinates and their Use in the Numerical Solution of Partial Differential Equations*, North-Holland, New York, 1982, pp. 357-384.***
- b. Knight, D., "A Hybrid Explicit-Implicit Numerical Algorithm for the Three-Dimensional Compressible Navier-Stokes Equations", AIAA Paper No. 83-0223, AIAA 21st Aerospace Sciences Meeting, January 10-13, 1983. Published in *AIAA J.*, Vol. 22, Aug 1984, pp. 1056-1063.***
- c. Visbal, M., and Knight, D., "Generation of Orthogonal and Nearly Orthogonal Coordinates with Grid Control Near Boundaries", *AIAA J.*, Vol. 20, No. 3, March 1982, pp. 305-206.*****

2. 1 October 1982 - 30 September 1983

- a. Knight, D., "Calculation of a Simulated 3-D High Speed Inlet Using the Navier-Stokes Equations", AIAA Paper No. 83-1165, AIAA/SAE/ASME 19th Joint Propulsion Conference, Seattle, Washington, June 27-29, 1983.
- b. Visbal, M., and Knight, D., "Evaluation of the Baldwin-Lomax Turbulence Model for Two-Dimensional Shock Wave Boundary Layer Interactions", AIAA Paper No. 83-1697, AIAA 16th Fluid and Plasma Dynamics Conference, Danvers, Mass., July 12-14, 1983. Published in the *AIAA J.*, Vol. 22, July 1984, pp. 921-928.*

3. 1 October 1983 - 30 September 1984

- a. Knight, D., "Numerical Simulation of Three-Dimensional Shock-Turbulent Boundary Layer Interaction Generated by a Sharp Fin", AIAA Paper No. 84-1559, AIAA 17th Fluid Dynamics, Plasmadynamics and Lasers Conference, June 25-27, 1984. Published in the *AIAA J.*, Vol. 23, December 1985, pp. 1885-1891.*

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- b. York, B., and Knight, D., "Calculation of Two-Dimensional Turbulent Boundary Layers Using the Baldwin-Lomax Model", AIAA 23rd Aerospace Sciences Meeting, Jan 14-17, 1984. Published in the *AIAA J.*, Vol. 23, Dec 1985, pp. 1849-1850.
4. 1 October 1984 - 30 September 1985
- a. Knight, D., "Modelling of Three Dimensional Shock Wave Turbulent Boundary Layer Interactions", in *Macroscopic Modelling of Turbulent Flows*, Lecture Notes in Physics, Vol. 230, Springer-Verlag, NY, 1985, pp. 177-201.
 - b. Knight, D., Horstman, C., Shapey, B., and Bogdonoff, S., "The Flowfield Structure of the 3-D Shock Wave - Boundary Layer Interaction Generated by a 20 deg Sharp Fin at Mach 3", AIAA Paper No. 86-0343, AIAA 24th Aerospace Sciences Meeting, January 6-9, 1986. Accepted for publication in the *AIAA J.*, to appear 1987.
 - c. Ong, C., and Knight, D., "A Comparative Study of the Hybrid MacCormack and Implicit Beam-Warming Algorithms for a Two-Dimensional Supersonic Compression Corner", AIAA Paper No. 86-0204, AIAA 24th Aerospace Sciences Meeting, January 6-9, 1986. Accepted for publication in the *AIAA J.*, to appear March 1987.
5. 1 October 1985 - 30 September 1986
- a. Knight, D., Horstman, C., Ruderich, R., Mao, M.-F., and Bogdonoff, S., "Supersonic Flow Past a 3-D Swept Compression Corner at Mach 3", AIAA Paper No. 87-0551, AIAA 25th Aerospace Sciences Meeting, January 12-15, 1987. To be submitted for publication in the *AIAA J.*

**B. Meetings with Research Group at Princeton Gas Dynamics Laboratory
1 October 1985 - 30 September 1986**

1. 9 October 1985 : Meeting with Princeton Gas Dynamics Research Group

Topics

- a. Discussion of experimental surface visualization (kerosene lampblack) for 3-D sharp fin
- b. Discussion of experimental schlieren photographs for 3-D sharp fin

2. 21 October 1985 : Meeting with Princeton Gas Dynamics Research Group and C. Horstman (NASA Ames)

Topics

- a. Discussion of computed particle pathlines for 3-D sharp fin ($\alpha = 20$ deg, $\delta_\infty = 0.5$ inch)
- b. View videotape of particle pathlines
- c. Development of model for mean flowfield structure for 3-D sharp fin

3. 2 January 1986 : Meeting with S. Bogdonoff, Princeton Gas Dynamics Laboratory

Topics

- a. Planned experiments for 3-D swept compression corner at $(\alpha, \lambda) = (24, 60)$ deg and $\delta_\infty = 0.5$ inch
- b. Discussion of flowfield structure of 3-D swept compression corner

4. 12 March 1986 : Discussion with S. Bogdonoff, Princeton Gas Dynamics Laboratory

Topics

- a. Planned experiments employing heat transfer gauges

5. 17 April 1986 : Discussion with B. Shapey

Topics

- a. Provide contour plots for pitot pressure and yaw angle requested by B. Shapey for 3-D sharp fin at $\alpha = 20$ deg and $\delta_\infty = 0.5$ inch.

6. 7 May 1986 : Meeting with Princeton Gas Dynamics Research Group and C. Horstman (NASA Ames)

Topics

- a. Preparation of abstract for AIAA Aerospace Sciences Meeting in January 1987 on 3-D swept compression corner at $(\alpha, \lambda) = (24, 60)$ deg
- b. Discussion of theoretical and experimental program for FY 87

7. **20 August 1986 : Meeting with Princeton Gas Dynamics Research Group**

Topics

- a. Discussion of experimental data for 3-D swept compression corner at $(\alpha, \lambda) = (24, 60)$ deg and $\delta_{\infty} = 0.5$ inch
- b. Discussion of theoretical and experimental program for FY 87, with emphasis on planned experiments involving modification of vortical structure for 3-D sharp fin interaction

**C. Meetings with C. Horstman (NASA Ames Research Center)
1 October 1985 - 30 September 1986**

1. **22 October 1985 : Visit by C. Horstman to Rutgers University**

Topics

- a. Discussion of particle pathlines for 3-D sharp fin
- b. Discussion of flowfield structure for 3-D sharp fin
- c. Discussion of videotape of particle pathlines to be presented at AIAA Aerospace Sciences Meeting in January 1986
- d. Discussion of paper by Knight, Horstman, Shapey and Bogdonoff to be presented at the AIAA Aerospace Sciences Meeting in January 1986
- e. Discussion of new concepts in 3-D flowfield graphics
- f. Discussion of flowfield structure of 3-D sharp fin

2. **8 May 1986 : Visit by C. Horstman to Rutgers University**

Topics

- a. Discussion of particle traces for 3-D swept compression corner and creation of videotape
- b. Discussion of abstract for AIAA Aerospace Sciences Meeting in January 1987
- c. Discussion of flowfield structure of 3-D swept compression corner

- d. Discussion of turbulence modelling for hypersonic flows
- e. Discussion of methods for modifying vortical structure in 3-D sharp fin and 3-D swept compression corner
- f. Seminar by C. Horstman

**D. Spoken Papers Presented at Technical Meetings
1 October 1985 - 30 September 1986**

- 1. Knight, D., Horstman, C., Shapey, B., and Bogdonoff, S., "The Structure of a 3-D Shock Wave-Turbulent Boundary Layer Interaction Generated by a Sharp Fin", Thirty-Eighth Annual Meeting, Division of Fluid Dynamics, American Physical Society, November 24-26, 1985, *Bulletin of the American Physical Society*, Vol. 30, No. 10, November 1985, p. 1707.

**E. Seminars
1 October 1985 - 30 September 1986**

- 1. Knight, D., "Theoretical Investigation of 3-D Shock Wave - Turbulent Boundary Layer Interaction Generated by a Sharp Fin", Air Force Wright Aeronautical Laboratory, Wright-Patterson AFB, OH, 28 October 1985.
- 2. Knight, D., "Theoretical Investigation of 3-D Shock Wave - Turbulent Boundary Layer Interactions", Department of Aerospace and Mechanical Engineering, Princeton University, 3 December 1985.

Section IV. List of Personnel and Degrees Awarded

A. Personnel : 1 October 1985 - 30 September 1986

Principal Investigator :

**Prof. Doyle Knight
Department of Mechanical and Aerospace Engineering**

Graduate Research Assistants :

**Ms. Denise Raufer
Department of Mechanical and Aerospace Engineering
(Supported by AFOSR Grant 82-0040)**

**Mr. Datta Gaitonde
Department of Mechanical and Aerospace Engineering
(Supported by New Jersey Commission on Science and Technology)**

B. Degrees Awarded : 1 October 1985 - 30 September 1986

**Ong, C., "Calculation of Supersonic Flow Over a Compression Corner", PhD Thesis,
Department of Mechanical and Aerospace Engineering, May 1986.**

Section V. References

- Baldwin, B., and Lomax, H. 1978 Thin Layer Approximation and Algebraic Model for Separated Turbulent Flows. AIAA Paper 78-257.
- Horstman, C., and Hung, C. 1979 Computation of Three-Dimensional Separated Flows at Supersonic Speeds. AIAA Paper No. 79-0002.
- Horstman, C. 1984 A Computational Study of Complex Three-Dimensional Compressible Turbulent Flow Fields. AIAA Paper No. 84-1556, AIAA 17th Fluid Dynamics, Plasma Dynamics and Lasers Conference.
- Jones, W., and Launder, B. 1972 The Prediction of Laminarization with a Two-Equation Model of Turbulence. *Int. J. Heat and Mass Transfer*, Vol. 15, pp. 301-304.
- Knight, D. 1984a A Hybrid Explicit-Implicit Numerical Algorithm for the Three-Dimensional Compressible Navier-Stokes Equations. *AIAA J.*, Vol. 22, pp. 1056-1061.
- Knight, D. 1984b Modelling of Three-Dimensional Shock Wave Turbulent Boundary Layer Interactions. Workshop on Macroscopic Modelling of Turbulent Flows and Fluid Mixtures. INRIA, Nice, France. December 1984. Also, *Lecture Notes in Physics*, Springer-Verlag, Vol. 230, 1985, pp. 177-201.
- Knight, D. 1984c Numerical Simulation of 3-D Shock Turbulent Boundary Layer Interaction Generated by a Sharp Fin. *AIAA J.*, Vol. 23, No. 12, December 1985, pp. 1885-1891.
- Knight, D. 1985 Theoretical Investigation of Three-Dimensional Shock Wave-Turbulent Boundary Layer Interactions. A Three Year Proposal for the Period Beginning 1 October 1985. Submitted to the Air Force Office of Scientific Research, 1 May 1985.
- Knight, D. 1986a Theoretical Investigation of Three-Dimensional Shock Wave-Turbulent Boundary Layer Interactions : Part IV. Interim Report for Period 1 October 1984 to 30 September 1985. Report RU-TR-163-MAE-F, Department of Mechanical and Aerospace Engineering, Rutgers University January 1986.
- Knight, D. 1986b Theoretical Investigation of Three-Dimensional Shock Wave-Turbulent Boundary Layer Interactions. A Three Year Proposal for the Period Beginning 1 October 1986. Submitted to the Air Force Office of Scientific Research, 4 April 1986.
- Knight, D., Horstman, C., Shapey, B., and Bogdonoff, S. 1986 The Flowfield Structure of the 3-D Shock Wave-Boundary Layer Interaction Generated by a 20 deg Sharp Fin at Mach 3. AIAA Paper No. 86-0343. To appear, *AIAA J.*
- Knight, D., Horstman, C., Ruderich, R., Mao, M.-F., and Bogdonoff, S. 1987 Supersonic Turbulent Flow Past a 3-D Swept Compression Corner at Mach 3. AIAA Paper No. 87-0551. AIAA 25th Aerospace Sciences Meeting, January 12-15, 1987, Reno, NV.
- Paynter, G. 1980 Analysis of Multiple Weak Glancing Shock Boundary Layer Interactions. AIAA Paper No. 80-0196.
- Settles, G., and Teng, H. 1984 Cylindrical and Conical Upstream Influence Regimes of Three-Dimensional Shock/Turbulent Boundary Layer Interactions. *AIAA J.*, Vol. 22, 1984, pp. 194-200.