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NUMERICAL STUDIES OF

BOUNDARY - LAYER RECEPTIVITY

A Progress Report for

GRADUATE PROGRAM IN AERONAUTICS

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ABSTRACT

Direct numerical simulations (DNS) of the acoustic receptivity process on a semi-infinite flat plate with a modified-super-elliptic (MSE) leading edge are performed. The incompressible Navier-Stokes equations are solved in stream-function/vorticity form in a general curvilinear coordinate system. The steady basic-state solution is found by solving the governing equations using an alternating direction implicit (ADI) procedure which takes advantage of the parallelism present in line-splitting techniques. Time-harmonic oscillations of the farfield velocity are applied as unsteady boundary conditions to the unsteady disturbance equations. An efficient time-harmonic scheme is used to produce the disturbance solutions. Buffer-zone techniques have been applied to eliminate wave reflection from the outflow boundary. The spatial evolution of Tollmien-Schlichting (T-S) waves is analyzed and compared with experiment and theory. The effects of nose-radius, frequency, Reynolds number, angle of attack, and amplitude of the acoustic wave are investigated.

This work is being performed in conjunction with the experiments at the Arizona State University Unsteady Wind Tunnel under the direction of Professor William Saric. The simulations are of the same configuration and parameters used in the wind-tunnel experiments.

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1. Introduction

In this progress report, Section 2 contains a list of experience and accomplishments under this Fellowship. Section 3 describes our past computational research leading to the present work. Section 4 contains a summary of the present work to examine boundary-layer receptivity to oblique sound waves. The personnel involved in this project are described in Section 5. The candidate for this fellowship is Mr. David Fuciareili, a Ph.D. student and U.S. citizen. Mr. Fuciarelli recently successfully completed his comprehensive examinations in August 1995, a major step toward the completion of his degree.

2. Experience and Technical Accomplishments

In the past 6 years, 4 students were supervised, 28 publications were written or are in preparation, and 29 talks and lectures were given.

Publications

1. "Curvature Effect on Stationary Crossflow Instability of a Three-Dimensional Boundary Layer," R.-S. Lin and H.L. Reed, AIAA Journal, Volume 31, Number 9, Page 1611, September 1993.

2. "Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, Physics of Fluids A, Volume 6, Number 10, Page 3368, 1994.

3. "Linear Stability Theory Applied to Boundary Layers," H.L. Reed, W.S. Saric, and D. Arnal, Annual Review of Fluid Mechanics, Volume 28, 1996.

4. "Boundary-Layer Receptivity: Navier-Stokes Computations," H.L. Reed, N. Lin, and W.S. Saric, Invited Paper, in Applied Mechanics Review, Volume 43, Number 5, Page S175, May 1990.

5. "Leading-Edge Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, Royal Aeronautical Society Conference on Boundary-Layer Transition and Control, Cambridge UK, April 1991.

6. "Simulations of Boundary-Layer Receptivity," H.L. Reed, AFOSR Meeting on Turbulence Structure and Control, Columbus, April 1-3, 1991.

7. "Curvature Effects in Three-Dimensional Boundary Layers," R.-S. Lin and H.L. Reed, Stability and Transition Symposium, National Aerospace Laboratory, Tokyo, March 16-18, 1992.

8. "Leading-Edge Receptivity to a Vortical Freestream Disturbance: A Numerical Analysis," T.A. Buter and H.L. Reed, Instability, Transition, and Turbulence, eds. M.Y. Hussaini, A. Kumar, and C.L. Streett, Springer-Verlag, New York, 1992.

9. "Effect of Leading-Edge Geometry on Boundary-Layer Receptivity to Freestream Sound," N. Lin, H.L. Reed, and W.S. Saric, Instability, Transition, and Turbulence, eds. M.Y. Hussaini, A. Kumar, and C.L. Streett, Springer-Verlag, New York, 1992.

10. "Streamline Curvature Effect in Three-Dimensional Boundary Layers," H.L. Reed, R.-S. Lin, and M. Petraglia, SAE 921987, AEROTECH '92 (Aerospace Technology Conference and Exposition), Anaheim, October 5-8, 1992.

11. "Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, AIAA Paper 93-0073.

12. "Leading-Edge Receptivity of Acoustic Disturbances," D.A. Fuciarelli , H.L. Reed, ICASE/LaRC Workshop on Transition, Turbulence, and Combustion, NASA/Langley Research Center, June 7-July 2, 1993.

13. "Computational Aspects of Nonparallel Effects in Boundary-Layer Receptivity," N. Lin, T.A. Buter, D.A. Fuciarelli, H.L. Reed, Invited Paper, IUTAM Symposium on Nonlinear Stability of Nonparallel Flows, Clarkson University, July 26-30, 1993.

14. "The Receptivity of Flat Plate Boundary-Layer to Free-Stream Disturbances," R. Kobayashi, Y. Fukunishi, T. Ishii, and H.L. Reed, International Symposium on Computational Fluid Dynamics, Sendai, Japan, August 31-September 3, 1993.

15. "Direct Numerical Simulation of Transition: The Spatial Approach," H.L. Reed, Invited Paper, AGARD Course in Transition Prediction and Modelling, AGARD Report No. 793, VonKarman Institute and Madrid, March 1994.

16. "Direct Numerical Simulation of Leading-Edge Receptivity to Freestream Sound," D.A. Fuciarelli and H.L. Reed, Application of Direct and Large Eddy Simulation to Transition and Turbulence, AGARD CP 551, Chania, Crete, Greece, April 1994.

17. "Leading-Edge Receptivity to Sound: Experiments, DNS, Theory," W.S. Saric, H.L. Reed, and E.J. Kerschen, Invited Paper, AIAA-94-2222, Colorado Springs, June 20, 1994.

18. "Direct Numerical Simulations of Leading-Edge Acoustic Receptivity," AIAA-96-0182, Reno, January 1996.

19. "Boundary-Layer Receptivity: Computations," N. Lin, H.L. Reed, and W.S. Saric, Bulletin of the American Physical Society, Volume 34, Number 10, Page 2249, November 1989.

20. "Boundary-Layer Receptivity to Sound: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, Bulletin of the American Physical Society, Volume 35, Number 10, Page 2260, November 1990.

21. "Navier-Stokes Simulation of Stationary Crossflow Vortices on a Swept Wing," R.-S. Lin and H.L. Reed, Bulletin of the American Physical Society, Volume 36, Number 10, November 1991.

22. "Analysis of High-Frequency Secondary Instabilities in Three-Dimensional Boundary Layers," H.L. Reed and D.A. Fuciarelli, Bulletin of the American Physical Society, Volume 36, Number 10, November 1991.

23. "Stationary Cross-Flow Vortices," D.A. Fuciarelli and H.L. Reed, in Gallery of Fluid Motion, Physics of Fluids A, Volume 4, Number 9, Page 1880, September 1992.

24. "Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, Bulletin of the American Physical Society, Volume 37, Number 10, November 1992.

25. "The Marriage of Theory, Computations, and Experiments," H.L. Reed, Invited Presentation, G.I. Taylor Medal Symposium in Honor of William S. Saric, Society of Engineering Science Meeting, University of Virginia, June 8-10, 1993.

26. "Leading-Edge Receptivity to Oblique Acoustic Waves," D.A. Fuciarelli and H.L. Reed, Bulletin of the American Physical Society, Volume 38, Number 10, November 1993.

27. "The Receptivity of Flat-Plate Boundary Layers with Two-Dimensional Roughness Elements," Y. Fukunishi, R. Kobayashi, Y. Kohama, T. Nishikawa, T. Ishii, W.S. Saric, and H.L. Reed, Bulletin of the American Physical Society, Volume 38, Number 10, November 1993.

28. "Leading-Edge Receptivity to Acoustic Disturbances," D.A. Fuciarelli and H.L. Reed, Bulletin of the American Physical Society, Volume 39, Number 9, Page 1970, November 1994.

Presentations

1. "Boundary-Layer Receptivity: Computations," N. Lin, H.L. Reed, and W.S. Saric, Bulletin of the American Physical Society, Volume 34, Number 10, Page 2249, November 1989.

2. "Boundary-Layer Receptivity: Computations," N. Lin, H.L. Reed, and W.S. Saric, Third International Congress of Fluid Mechanics, Cairo, January 1990.

3. "Boundary-Layer Receptivity," H.L. Reed, Invited Seminar, Michigan Technological University, February 9, 1990.

4. "Boundary-Layer Receptivity: Navier-Stokes Computations," H.L. Reed, N. Lin, and W.S. Saric, Invited Paper, in Applied Mechanics Review, Volume 43, Number 5, Page S175, May 1990.

5. "Navier-Stokes Simulations of Boundary-Layer Receptivity," H.L. Reed, Keynote Speaker, 22nd Turbulence Symposium, National Aerospace Laboratory, Tokyo, July 25-27, 1990.

6. "Boundary-Layer Receptivity to Sound: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, Bulletin of the American Physical Society, Volume 35, Number 10, Page 2260, November 1990.

7. "Navier-Stokes Simulations of Boundary-Layer Receptivity," H.L. Reed, Invited Seminar, University of Cincinnati, February 1, 1991.

8. "Simulations of Boundary-Layer Receptivity," H.L. Reed, AFOSR Meeting on Turbulence Structure and Control, Columbus, April 1-3, 1991.

9. "Leading-Edge Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, Royal Aeronautical Society Conference on Boundary-Layer Transition and Control, Cambridge UK, April 1991.

10. "Role of Initial Conditions on Unstable Waves Evolving to Turbulence in Open Systems: Navier-Stokes Computations," Helen L. Reed et al., Workshop on Dynamics of Structures and Intermittencies in Turbulence, Arizona State University, May 20-24, 1991.

11. "Computational Aspects of Complex Flows," H.L. Reed, Hitachi, Japan, November 1 5, 1991.

12. "Navier-Stokes Simulation of Stationary Crossflow Vortices on a Swept Wing," R.-S. Lin and H.L. Reed, Bulletin of the American Physical Society, Volume 36, Number 10, November 1991.

13. "Analysis of High-Frequency Secondary Instabilities in Three-Dimensional Boundary Layers," H.L. Reed and D.A. Fuciarelli, Bulletin of the American Physical Society, Volume 36, Number 10, November 1991.

14. "Theoretical/Numerical Research in Boundary-Layer Transition," H. L. Reed, Institute of Fluid Science, Tohoku University, Sendai, Japan, January 10, 1992.

15. "Stability of Wall-Bounded Flows," H.L. Reed, Invited Seminar, EcoDynamics/University of Colorado at Denver, September 14, 1992.

16. "Streamline Curvature Effect in Three-Dimensional Boundary Layers," H.L. Reed, R.S. Lin, and M. Petraglia, Invited Paper, SAE 921987, AEROTECH '92 (Aerospace Technology Conference and Exposition), Anaheim, October 5-8, 1992.

17. "Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, Bulletin of the American Physical Society, Volume 37, Number 10, November 1992.

18. "Leading-Edge Receptivity to a Vortical Freestream Disturbance: A Numerical Analysis," T.A. Buter and H.L. Reed, AIAA-93-0073.

19. "Direct Numerical Simulations of Transition: The Spatial Approach," H.L. Reed, Invited Paper, AGARD Course in Transition Prediction and Modeling, Von Karman Institute and Madrid, March 1993.

20. "The Marriage of Theory, Computations, and Experiments," H.L. Reed, Invited Presentation, G.I. Taylor Medal Symposium in Honor of William S. Saric, Society of Engineering Science Meeting, University of Virginia, June 8-10, 1993.

21. "Leading-Edge Receptivity of Acoustic Disturbances," D.A. Fuciarelli , H.L. Reed, ICASE/LaRC Workshop on Transition, Turbulence, and Combustion, NASA/Langley Research Center, June 7-July 2, 1993.

22. "Computational Aspects of Nonparallel Effects in Boundary-Layer Receptivity," H.L. Reed, Invited Paper, IUTAM Symposium on Nonlinear Stability of Nonparallel Flows, Clarkson University, July 1993.

23. "The Receptivity of Flat Plate Boundary-Layer to Free-Stream Disturbances," R. Kobayashi, Y. Fukunishi, T. Ishii, and H.L. Reed, International Symposium on Computational Fluid Dynamics, Sendai, Japan, August 31-September 3, 1993.

24. "Leading-Edge Receptivity to Oblique Acoustic Waves," D.A. Fuciarelli and H.L. Reed, Bulletin of the American Physical Society, Volume 38, Number 10, November 1993.

25. "The Receptivity of Flat-Plate Boundary Layers with Two-Dimensional Roughness Elements," Y. Fukunishi, R. Kobayashi, Y. Kohama, T. Nishikawa, T. Ishii, W.S. Saric, and H.L. Reed, Bulletin of the American Physical Society, Volume 38, Number 10, November 1993.

26. "Navier-Stokes Simulations of Boundary-Layer Receptivity," H.L. Reed, Invited Seminar, University of Arizona, April 28, 1994.

27. "Navier-Stokes Simulations of Boundary-Layer Receptivity," H.L. Reed, Distinguished Lecturer, Ohio Aerospace Institute, September 21, 1994.

28. "Leading-Edge Receptivity to Oblique Acoustic Disturbances," D.A. Fuciarelli and H.L. Reed, Bulletin of the American Physical Society, Volume 39, Number 10, November 1994.

29. "Direct Numerical Simulations of Leading-Edge Acoustic Receptivity," AIAA-96-0182, Reno, January 1996.

Ph.D. Students

R.S. Lin, "Stationary Crossflow Instability on an Infinite Swept Wing," completed August 1992.

T.A. Buter, "Numerical Simulation of Leading-Edge Receptivity to FreestreamVorticity," completed December 1992.

N. Lin, "Receptivity of the Boundary Layer over a Flat Plate with Different Leading-Edge Geometries: Numerical Simulations," completed December 1992.

D.A. Fuciarelli, "Leading-Edge Receptivity to Oblique Acoustic Disturbances," expected Spring 1996.

MS Students

N. Lin, "Receptivity of the Boundary-Layer Flow over a Semi-Infinite Flat Plate with an Elliptic Leading Edge," completed August 1989.

Undergraduate Students

D.A. Fuciarelli, "High-Frequency Breakdown in Three-Dimensional Boundary Layers," NASA Undergraduate Trainee, completed May 1992.

The technical accomplishments thus far are documented in the publications listed above. A brief description follows.

"Receptivity of the Boundary Layer on a Semi-Infinite Flat Plate with an Elliptic Leading Edge," N. Lin, H.L. Reed, and W.S. Saric, Arizona State University Report CEAS 90006, Sept. 1989. This report establishes the platform upon which our receptivity studies are based.

"Leading-Edge Receptivity: Navier-Stokes Computations," N. Lin, H.L. Reed, and W.S. Saric, Royal Aeronautical Society Conference on Boundary-Layer Transition and Control, Cambridge UK, April 1991. This paper includes the effects of non-infinite Reynolds number curvature discontinuities.

"Effect of Leading-Edge Geometry on Boundary-Layer Receptivity to Freestream Sound," N. Lin, H.L. Reed, and W.S. Saric, ICASE Workshop on Stability and Transition, ed. M.Y. Hussaini, Springer-Vedag, New York, 1992. This paper introduces the Modified Super Ellipse (MSE) geometry and also finds that receptivity is linear to freestream amplitude up to levels of 5%.

"Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, Physics of Fluids A, Volume 6, Number 10, Page 3368, 1994. This paper includes the effects of freestream vorticity in the receptivity problem.

"Curvature Effect on Stationary Crossflow Instability of a Three-Dimensional Boundary Layer," R.-S. Lin and H.L. Reed, AIAA Journal, Volume 31, Number 9, Page 1611, September 1993. It is shown that surface curvature is stabilizing and streamline curvature is destabilizing.

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"Analysis of High-Frequency Secondary Instabilities in Three-Dimensional Boundary Layers," H.L. Reed and D.A. Fuciarelli, Bull. Amer. Phys. Soc., Vol. 36, No. 10, November 1991. (Also Gallery of Fluid Motion) Breakdown in a swept-wing boundary layer is shown to be due to a high-frequency, inflectional instability.

"Direct Numerical Simulation of Transition: The Spatial Approach," H.L. Reed, Invited Paper, AGARD Course in Transition Prediction and Modelling, AGARD Report No. 793, VonKarman Institute and Madrid, March 1994. This paper reviews spatial direct numerical simulations including receptivity studies.

"Leading-Edge Receptivity to Sound: Experiments, DNS, Theory," W.S. Saric, H.L. Reed, and E.J. Kerschen, Invited Paper, AIAA-94-2222, Colorado Springs, June 20, 1994. This paper shows good comparison between receptivity computations and experiments.

3. Review of Previous Work in Leading-Edge Receptivity

3.1 Introduction

The most popular method of transition prediction in industry today is the Smith/Van-Ingen e^N method (Reed et al. 1996). This method is useful but must be well correlated with empirical data obtained from experiments. The empirical data provides the important initial conditions for the subsequent growth of instabilities. This information is highly dependent upon the experimental environment and particularly sensitive to freestream disturbances. The process by which instabilities enter the boundary layer and excite instabilities, thus providing the sought after initial conditions, is called receptivity. Transition to turbulence will never be successfully understood or predicted without answering how freestream acoustic signals and turbulence enter the boundary layer and ultimately generate unstable T-S waves. Clearly then, the study of receptivity promises significant advance in practical transition-prediction methods.

In this Section, computational efforts to determine the process by which longer-wavelength external disturbances lead to instabilities in the boundary layer are reviewed with an emphasis on leading-edge effects. High-Reynolds-number asymptotics have identified that the conversion of long-wavelength freestream disturbances to shorter-wavelength instability waves takes place in regions where the mean flow locally exhibits rapid variations in the streamwise direction (Goldstein 1983, 1985; Kerschen 1990, 1991). Such regions include the leading edge, roughness, suction strips, discontinuities in surface slope and curvature, etc., anything that can scatter long-wavelength waves into shorter components that can match to instability waves in the boundary layer.

The complete receptivity question requires consideration of a combination of all the effects, including, for example, roughness, geometry, associated pressure gradients (both favorable and adverse), vibrations, sound, and freestream turbulence, and it is here that computations by spatial DNS excel. A variety of different geometric conditions and freestream disturbances can be implemented with this technique and the response of the boundary layer quantified and catalogued (Reed 1993).

3.2 Leading-Edge Effects

With the spatial computational method, finite curvature can be included in the leading-edge region-- a feature that was left out of some early unsuccessful receptivity models. Use of an infinitely thin plate (zero thickness or computationally a straight line) to study leading-edge effects, although popular, is strongly discouraged. The attachment-line or stagnation region is a critical source of receptivity as large streamwise gradients occur there, and an infinitely thin plate features infinite vorticity there (per the simple Blasius solution). No computational simulation can resolve infinite vorticity. By stipulating the plate to have finite curvature at the leading edge, the singularity there is removed and a new length scale is introduced.

Experimentally, the most popular receptivity model has been the flat plate with an elliptic leading edge. Thus it is reasonable that computational models consider the same geometry.

However, the curvature at the juncture between the ellipse and the flat plate is discontinuous and provides a source of receptivity (Goldstein & Hultgren 1987). Lin et al. (1992, 1993) introduced a new leading-edge geometry based on a super-ellipse. The shape of this modified super-ellipse (MSE) is given by

$$\left(1 - \frac{x}{AR}\right)^{2 + \left(\frac{x}{AR}\right)^2} + y^2 = 1$$

where x and y have been non-dimensionalized with the minor-axis of the MSE and AR is the aspect ratio of the "elliptic" nose. For a usual super-ellipse, both m and n are constants. These super-ellipses will have the advantage of continuous curvature (zero) at the juncture with the flat plate as long as m > 2 at x/L = AR. The MSE, with m(x) given above, has the further advantage of having a nose radius and geometry (hence a pressure distribution) close to that of an ordinary ellipse with m = 2 and n = 2.

Use of a C-grid rather than an H-grid is recommended to avoid singularities in the metric terms in the sensitive nose region. Again, it is important to include and resolve the attachment-line region accurately.

3.2.1 Receptivity to Freestream Sound

For low-speed flows, freestream-sound wavelength is typically one or two orders of magnitude larger than instability wavelengths in the boundary layer. Receptivity is defined to be the amplitude at Branch I normalized with the freestream-sound amplitude. The quantity U is the freestream speed.

Lin et al. (1991, 1992, 1993) simulated the receptivity of the laminar boundary layer on a flat plate by solving the full Navier-Stokes equations in general curvilinear coordinates by a second-order finite-difference method with vorticity and stream function as dependent variables.

They used a C-type orthogonal grid and included the finite-thickness leading edge and curvature. Geometries tested included elliptic, polynomial-smoothed elliptic, and MSE leading edges of different aspect ratios (with smaller aspect ratio corresponding to a blunter nose). Various sound-like oscillations of the freestream streamwise velocity were applied along the boundary of the computational domain and allowed to impinge on the body. Problem parameters under investigation included disturbance amplitude and frequency, as well as leading-edge radius and geometry. They found the following:

- T-S waves appearing in the boundary layer could be linked to sound present in the freestream.

- Receptivity occurred in the leading-edge region where rapid streamwise adjustments of the basic flow occurred. Variations in curvature, adjustment of the growing boundary layer, discontinuities in surface geometry, and local pressure gradients there introduce length scales to diffract long freestream disturbances.

- The magnitude of receptivity and the disturbance response depended very strongly on geometry. As examples:

  - For plane freestream sound waves, T-S -wave amplitude at Branch I decreased as the elliptic nose was sharpened.

  - When the discontinuity in curvature at the ellipse/flat-plate juncture was smoothed by a polynomial, receptivity was cut in half.

  - The disturbance originated from the location of the maximum in adverse pressure gradient.

- The receptivity to plane freestream sound appeared to be linear with freestreamdisturbance amplitude up to levels of about 5%U. Thus a linear Navier-Stokes solution could be used up to these levels.

3.2.2 Receptivity to Freestream Vorticity

The characteristic length scale for freestream spanwise vorticity is the convective wavelength which is approximately 3 times that of the amplified T-S wave at that frequency.

Buter & Reed (1994) simulated the receptivity of the laminar boundary layer on a flat plate by solving the full Navier-Stokes equations in general curvilinear coordinates by a second-order finite-difference method with vorticity and stream function as dependent variables. They used a C-type orthogonal grid and included the finite-thickness leading edge and curvature.

Geometries tested included an aspect-ratio-6 elliptic and polynomial-smoothed elliptic leading edge. A simple model of time-periodic freestream spanwise vorticity was introduced at the upstream computational boundary. This signal was decomposed into a symmetric and asymmetric streamwise velocity component with respect to the stagnation streamline. Then the computations were performed with these individual components specified as boundary conditions. For small disturbances, the results could thus be linearly superposed. Moreover, the effect of a transverse-velocity component at the leading edge could be ascertained as the asymmetric-velocity case had this feature while the symmetric-velocity did not. Problem parameters under investigation included disturbance amplitude and orientation, as well as nose geometry. They found the following:

- As the disturbance convicted past the body, it was ingested into the upper part of the boundary layer, decaying exponentially toward the wall. This was consistent with the findings of Kerschen (1989) and Parekh et al. (1991).

- Different wavelengths were evident in the boundary-layer response. Signals at the T-S wavelength were dominant near the wall, while toward the edge of the boundary layer, disturbances of the freestream convective wavelength were observed. This was consistent with the experimental observations of Kendall (1991).

- T-S waves appearing in the boundary layer could be linked to freestream vorticity acting near the basic-state stagnation streamline. Clear evidence of the T-S wavelength appeared aft of the location of the maximum surface pressure gradient.

- For the particular geometric and flow conditions considered in this study, receptivity to vorticity was found to be smaller than receptivity to sound by a factor of approximately three.

- Modifications to the geometry which increased the surface pressure gradient along the nose increased receptivity.

- For both the symmetric and asymmetric freestream velocity perturbations, the T-S response was linear with forcing over the range of amplitudes considered; symmetric: up to 4.2% U and asymmetric: up to 2.1% U.

- A superharmonic component of the disturbance motion was observed at all forcing levels for the asymmetric forcing. [See also Grosch & Salwen (1983).] This was initially observed in the stagnation region where the interaction of the asymmetric gust with the basic flow induced a large transverse velocity component which interacted with the adverse pressure gradient upstream of the nose to transfer disturbance energy to the superharmonic frequency. Depending upon geometry, flow conditions, and disturbance frequency and amplitude then, it is possible that this nonlinearity observed in the nose region could impact transition behavior.

It is therefore unlikely that the linear response found in (f) for the asymmetric case will persist to the same level of freestream forcing as that observed for the symmetric case.

These results begin to provide the link between the freestream and the initial boundary-layer response and can provide the upstream conditions for further simulations marching through the transition process toward turbulence. In this way, more realistic predictions and modeling of the turbulent flowfield downstream will eventually be possible.

4. Present Work

Direct numerical simulations of the receptivity process are performed by solving the Navier-Stokes equations in a general curvilinear coordinate system. The geometry of interest is the MSE devised by Lin et. al. (1992). Long-wavelength acoustic waves impinging upon the finite-curvature and -thickness leading edge produce instabilities within the boundary layer whose wavelengths are an order of magnitude smaller. To examine this phenomenon the incompressible Navier-Stokes equations are solved in a stream-function/vorticity form and are separated into the steady basic-state and unsteady disturbance equations. The basic state is found by solving the steady incompressible Navier-Stokes equations using an ADI procedure. The unsteady disturbance computations are performed by using either a time-harmonic fully implicit procedure or a time-harmonic strongly-implicit (SIP) numerical method. For the symmetric cases the linear disturbance equations are solved by inverting a fully implicit finite-difference matrix operator. For the asymmetric cases the SIP method is used due to the large memory and large computational times involved in the fully-implicit procedure. In the SIP procedure the nonlinear terms are retained and therefore the examination of nonlinear forcing is possible.

The basic state is solved in a two-step process. In the first step the incompressible inviscid Navier-Stokes equations are solved to determine the inviscid velocity field. This computation is performed by using a panel-method code. This solution provides the far-field boundary conditions for the basic-state code. The second step involves solving the incompressible steady Navier-Stokes equations in a general curvilinear coordinate system. The governing equations are formulated using a transformation to a Cartesian computational domain and then solved using an ADI method. The ADI method used takes advantage of the vector processors available on CRAY supercomputers. Since each grid line is represented by a tridiagonal matrix operator that is effectively decoupled at each iteration from the other grid lines, they may be solved concurrently. Although the solution of a tridiagonal system by a lower-upper decomposition technique has data dependencies and is therefore inherently a sequential process, by solving many of these systems, one may take advantage of the parallel nature of the vector processor. Because of this feature, the ADI scheme runs efficiently on CRAY supercomputers.

The basic-state code has been verified by comparison with known analytic solutions and by comparison with experiments performed at the ASU Unsteady Wind Tunnel (Saric et al. 1994). Grid-convergence studies have been performed and the locations of the downstream and farfield boundaries have been examined. Results have appeared in previous reports.

For the symmetric forcing, a time-harmonic fully implicit code was used. Previous research in acoustic receptivity by Lin et al. (1991, 1992, 1993) showed that the instabilities generated were at the same frequency as the forcing acoustic wave and that nonlinear effects were negligible for forcing amplitudes up to 5% of the freestream velocity. Because of these two facts, a linear time-harmonic code was devised. In the time-harmonic approach, the linear-disturbance solutions are assumed in the form:

$$u'(x,y,t) = \hat{u}(x,y)e^{i\omega t} + C.C.$$

Substituting this into the linearized governing equations yields a set of steady, complex equations. The time dependence has been removed. In previous research, the time-dependent equations were solved at each time level and required an extensive amount of computational resources. The time-harmonic feature requires only one solution for all time and is therefore a more efficient means for computing the disturbance solution. However, because the solution represents all time, the outflow boundary conditions must be of a non-reflective type to prevent traveling waves from "bouncing" back into the domain and corrupting the solution. Non-reflective boundary conditions are imposed by the buffer-domain technique (Streett & Macaraeg, 1989). In the buffer-domain

technique used, the streamwise diffusion terms are multiplied by a smoothly decreasing function in an artificially added computational domain. The function effectively makes the equations convectively dominated and eliminates reflections from the outflow boundary.

For the symmetric cases a sinusoidally time-varying velocity was imposed at the farfield. The vertical component of the velocity was zero. Solving the linearized disturbance equations in this manner leads to two decomposable solutions. The first is a Stokes-wave or oscillating-plate solution. The second solution is the traveling-wave instability. Two methods for decomposing the solutions have been applied. In the first method, which is applicable only in the flat-plate region of the flow, the classical Stokes-wave solution is subtracted. In the second method, the linearized disturbance equations with zero basic state are solved and the result is subtracted from the total disturbance solution. The two methods compare favorably in the flat-plate region of the flow and the second method allows decomposition in places with finite curvature. For a leading edge of aspect ratio 6, a comparision of the disturbance profile after decomposing the Stokes-wave solution using the second method described above and a solution of the Orr-Sommerfeld equation is shown in figure 1. Decomposed disturbance solutions also show the formation of a T-S wave whose amplitude is $O(0.6)$ very near the leading edge as shown in figure 2. This compares with the LUBLE theory which predicted an amplitude of $O(1)$ at the same location. (Saric, Reed, & Kerschen, 1994).

The experimental comparisons are achieved by using linear stability theory. For lower frequencies the numerical simulations are difficult to perform with branch I present within the computational domain. In the experiments the instability waves are difficult to measure until the wave has nearly reached branch II. In order to compute and compare receptivity coefficients, both the experimental and numerical data were extrapolated using linear theory to the branch I amplitudes. A comparison of the results is shown in figure 3 for a leading edge of aspect ratio 20. Note that the numerical simulations did not predict the narrow-band frequency response found in the experiments although the magnitudes of the coefficients are comparable.

An ADI code very similar to the one described above was formulated to solve the disturbance equations. However, at lower frequencies ($F=O(86 \times 10^{-6})$) this code produced reflections from the downstream boundary that corrupted the interior solution. All attempts to eliminate this feature failed to produce adequate results. Among the various ideas attempted were: different buffer-zone techniques, expansion or contraction of the buffer zone, grid clustering, grid refinement and coarsening, and parameter manipulation. These reflected waves were evident in the decomposed solution and produced non-physical disturbance velocity profiles. Reaseach continues to find the reason for these reflected waves at lower frequencies. This is the reason the costly fully implicit code was used to produce results in the symmetric case. Note that the fully-implicit code produced results with no discernable reflections at lower frequencies.

The nonlinear and asymmetric forcing cases are considered next. This part of the research is still in the development phase. An SIP procedure has been formulated and coded. The SIP procedure was chosen after the ADI scheme failed to predict the correct solution and it was realized that the fully implicit code would be too memory intensive. As the name would suggest, the SIP method contains more characteristics of a fully implicit procedure. This is necessary because of what has been learned empirically about splitting methods (such as ADI) coupled with buffer-zone techniques. The SIP method can been formulated as follows. Consider the matrix system formed by using a fully implicit centrally spaced second-order-accurate finite-difference stencil as depicted in figure 4. This system is represented by the equation:

$$Ax = b$$

Now consider the equation that represents the system depicted in figure 5. The matrix in this case is:

$$M = LU = A + C$$

which differs from A in the extra super- and sub-diagonals which are contained in C. Suppose we add a vector to both sides of the original equation as follows:

$$Ax + Cx = b + Cx$$

Then this equations becomes:

$$(A + C)x = Mx = LUx = b + Cx$$

Now we take the right-hand-side unknown to be evaluated at the kth iteration level and the left -hand-side unknown to be evaluated at the $(k+1)^{th}$ iteration level. The final system to be solved is:

$$LUx^{(k+1)} = b + Cx^{(k)}$$

This system can be easily solved because of its convenient form. In addition the system requires much less memory since only the six diagonals of L and U need to be stored. In addition it has been shown (Schneider & Zedan 1981) that this system converges much faster than traditional splitting methods such as ADI.

Applying the time-harmonic approach to the nonlinear disturbance equations was done by assuming a Fourier-series solution. This technique is similar to the Galerkin spectral method. To illustrate the method consider the nonlinear disturbance equations in stream-function/vorticity form:

$$\frac{\partial^2 \psi'}{\partial x_j \partial x_j} = -\omega'$$

$$St \frac{\partial \omega'}{\partial t} + u'_k \frac{\partial \Omega}{\partial x_k} + U_k \frac{\partial \omega'}{\partial x_k} + u'_k \frac{\partial \omega'}{\partial x_k} = \frac{1}{Re} \left[\frac{\partial^2 \omega'}{\partial x_j \partial x_j} \right]$$

where the capital letters denote basic-state quantities, St is the Strouhal number, and Re is the Reynolds number based upon the minor-axis of the MSE and the freestream velocity. We assume disturbances of the form:

$$\psi'(x,y,t) \cong \sum_{n=-N}^{N} \tilde{\psi}_n(x,y)e^{int}$$

and

$$\omega'(x,y,t) \cong \sum_{n=-N}^{N} \tilde{\omega}_n(x,y)e^{int}$$

where time has been non-dimensionalized with the forcing frequency of the acoustic wave and the approximate symbol is used since the Fourier series has been truncated to a finite number of terms.

Substituting into the vorticity-transport equation yields (the Poisson equation is linear and is not illustrative of the procedure):

$$St \sum_{n=-N}^{N} in\tilde{\omega}_n e^{int} + \frac{\partial \Omega}{\partial x_j} \sum_{n=-N}^{N} \tilde{u}_{j,n} e^{int} + U_j \sum_{n=-N}^{N} \frac{\partial \tilde{\omega}_n}{\partial x_j} e^{int}$$

$$+ \left(\sum_{n=-N}^{N} \tilde{u}_{j,n} e^{int} \right) \left(\sum_{m=-N}^{N} \frac{\partial \tilde{\omega}_m}{\partial x_j} e^{imt} \right) = \frac{1}{Re} \left[\sum_{n=-N}^{N} \frac{\partial^2 \tilde{\omega}_n}{\partial x_j \partial x_j} e^{int} \right] + R$$

where R is the residual due to truncation. This equation can be manipulated into the following form:

$$\sum_{n=-N}^{N} \left(inSt\tilde{\omega}_n + \tilde{u}_{j,n} \frac{\partial \Omega}{\partial x_j} + U_j \frac{\partial \tilde{\omega}_n}{\partial x_j} - \frac{1}{Re} \frac{\partial^2 \tilde{\omega}_n}{\partial x_j \partial x_j} \right) e^{int} + \sum_{n=-N}^{N} \sum_{m=-N}^{N} \tilde{u}_{j,n} \frac{\partial \tilde{\omega}_m}{\partial x_j} e^{i(n+m)t} = R$$

In the same sense as a spectral Galerkin method, the residual is forced to be orthogonal to a set of trial functions. In this case a logical choice for these trial functions is a Fourier basis. That is we force:

$$\int_{-\infty}^{\infty} R(x,y,t) e^{ikt} dt = 0$$

Performing this operation yields:

$$ikSt\tilde{\omega}_k + \tilde{u}_{j,k} \frac{\partial \Omega}{\partial x_j} + U_j \frac{\partial \tilde{\omega}_k}{\partial x_j} - \frac{1}{Re} \frac{\partial^2 \tilde{\omega}_k}{\partial x_j \partial x_j} + \sum_{l=-N}^{N} \tilde{u}_{j,k} \frac{\partial \tilde{\omega}_{k-l}}{\partial x_j} = 0 \text{ for } k = -N...N$$

This forms a set of coupled equations for each of the k modes. In the finite-difference approximation to these equations the nonlinear terms are simply lagged to the previous iteration level thus providing a set of linear equations.

The nonlinear time-harmonic SIP program described above is being verified in the current phase of this research. Preliminary results for linear asymmetric forcing are promising and show none of the reflected wave characteristics of the ADI method. Results for nonlinear forcing are forthcoming.

5. Personnel

David Fuciarelli, a PhD student and US citizen, is the candidate for the Fellowship. He achieved a 3.9/4.0 GPA as an undergraduate in Aerospace Engineering at ASU and presently has a 4.0/4.0 GPA as a graduate student, was the recipient of a NASA Undergraduate Research Trainee Fellowship, was the recipient of the distinguished Senior award by the College of Engineering, and was a winner in the 1991 American Physical Society/Division of Fluid Dynamics Gallery of Fluid Motion. He very successfully passed the Qualifying examinations for the PhD program in April 1993 and the comprehensive examination in August 1995, major steps toward the completion of his degree.. He received the 1995 Bronze (ASU) President's Medal for Team Excellence.

The principal investigator for this work is Helen L. Reed. She received her Ph.D. in Engineering Mechanics in 1981 from Virginia Polytechnic Institute & State University and joined the faculty at Stanford University in September 1982. In the Fall of 1985, she began her appointment as Associate Professor at Arizona State University and was promoted to Full Professor in July 1992. On August 1, 1993. she became Director of the Aerospace Research Center at Arizona State University. She also worked at NASA-Langley in the Aeronautical Systems Division and at Sandia Laboratories in the Applied Mathematics Division. Her research interests include low-cost space experimentation and satellite design, and computational, theoretical, and experimental aspects of laminar/turbulent transition and 3-D separation; recent work includes the design, fabrication, and launch of ASUSat 1, a 10-pound-class satellite designed, built, and launched by the students at ASU for low-cost Earth imagery, and proof-of-concept experiments dealing with ionospheric plasma in low Earth orbit; Navier-Stokes simulations of boundary-layer receptivity to freestream disturbances, including freestream vorticity and sound; and stability of 3-D supersonic and hypersonic boundary layers. She is a Member of the U.S. National Transition Study Group; the Originator of the Gallery of Fluid Motions of the American Physical Society; a past Member of the National Academy of Sciences/National Research Council Aerodynamics Panel; a past Member of the NASA Federal Laboratory Review Task Force; a past Member of the AIAA Fluid Dynamics Technical Committee; the current Chair of the Fluid Mechanics Committee of the Applied Mechanics Division of ASME; a Member of the Board of Directors of the Society of Engineering Science; a Member of the NASA Computational Aerosciences Review and Planning Team; a Member of the NASA Aeronautics Advisory Committee; a Member of the NATO/AGARD Fluid Dynamics Panel; and the Associate Editor of the Annual Review of Fluid Mechanics. She received the 1993-94 Undergraduate Teaching Excellence Award in the College of Engineering & Applied Sciences, the 1994-95 Outstanding Graduate Faculty Mentor Award from the Graduate College at Arizona State University, and the 1995 Bronze (ASU) President's Medal for Team Excellence.

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Reed, H.L., Saric, W.S., and Arnal, D. 1996, Linear Stability Theory Applied to Boundary Layers, Annual Review of Fluid Mechanics, Volume 28, 1996.

Saric, W.S., Wei, W., and Rasmussen, B. 1994 Boundary-layer receptivity: freestream sound on an elliptical leading edge, IUTAM Symposium on Laminar-Turbulent Transition, Sendai, Japan,

Schneider, G.E. and Zedan, M. 1981, A Modified Strongly Implicit Procedure for the Numerical Solution of Field Problems," Numerical Heat Transfer vol. 4, pp. 1-19.

Streett, C.L. and Macaraeg, M.G. 1989. Spectral multi-domain for large scale fluid dynamic simulations, Applied Numerical Mathematics 6, 1, 23.

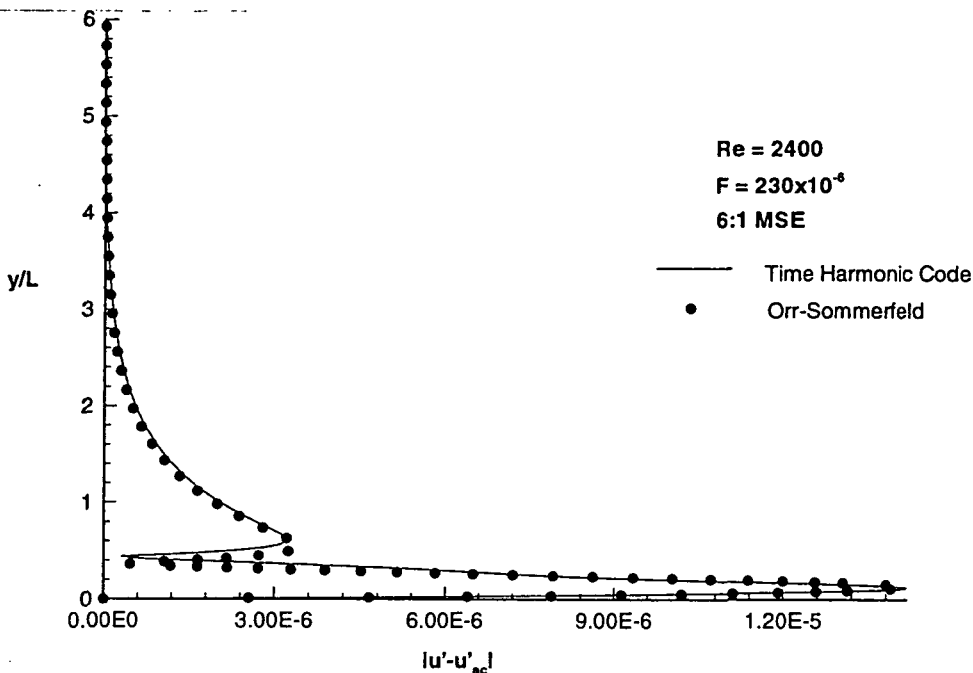**Comparison with Linear Stability Theory**

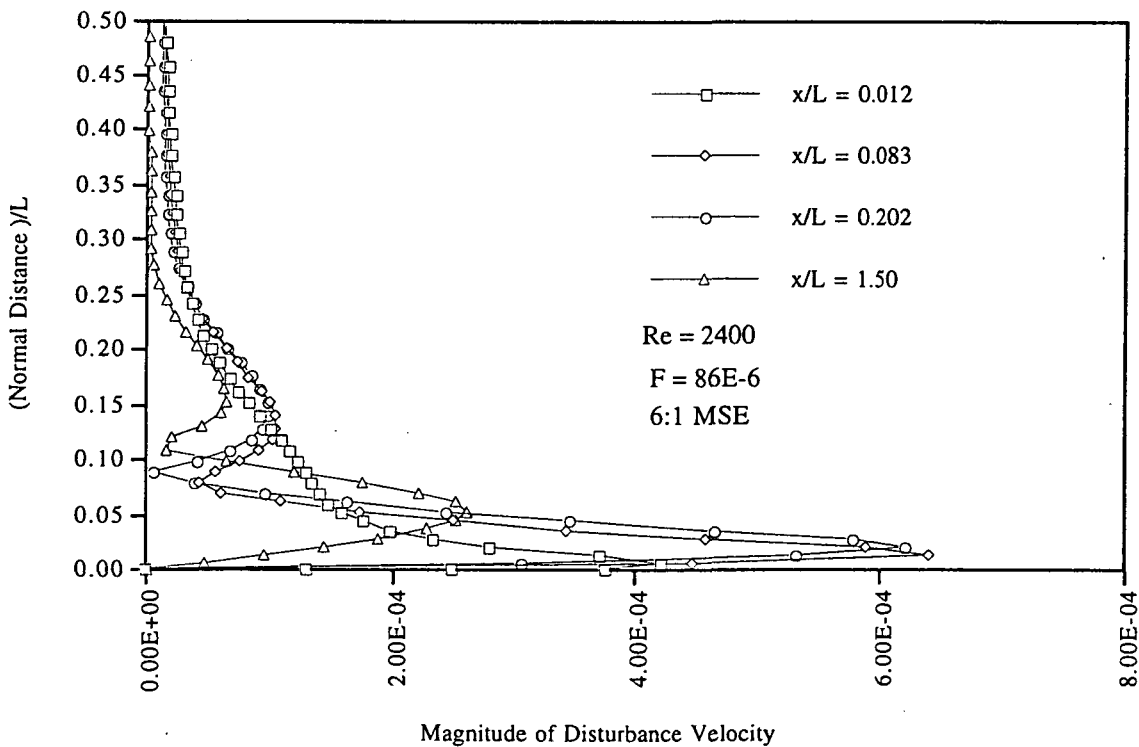Figure 1. Comparison of TS eigenmodes from time-harmonic code and linear stability theory. The forcing amplitude was 1×10^{-3}.

Figure 2. Disturbance velocity profiles near the stagnation point. The forcing amplitude was 1×10^{-3}.
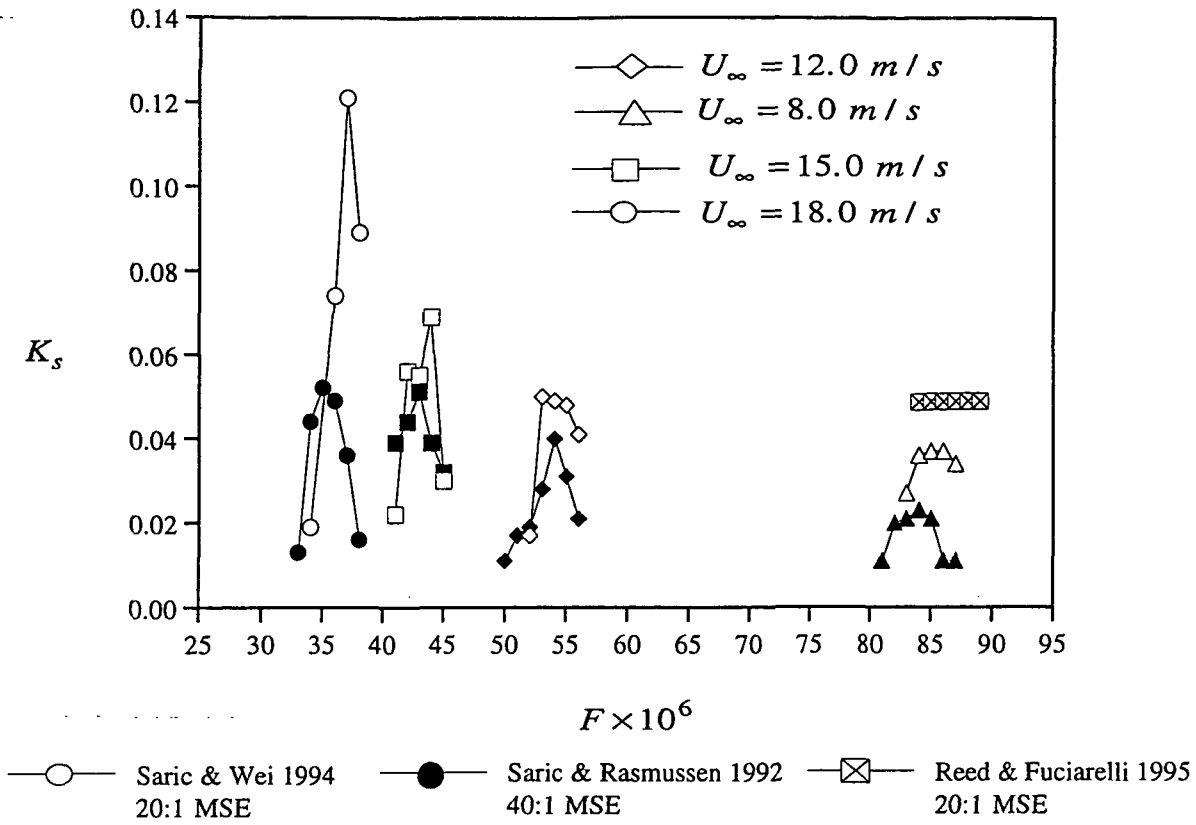
Receptivity Coefficient

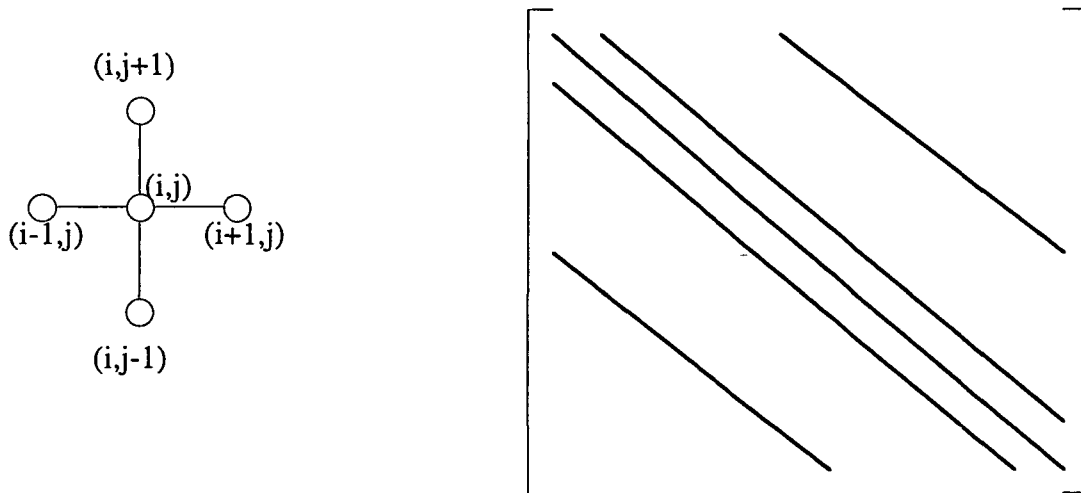Figure 3. Comparison of receptivity coefficients with experiment

Figure 4. Second order finite difference stencil and the resulting implicit matrix
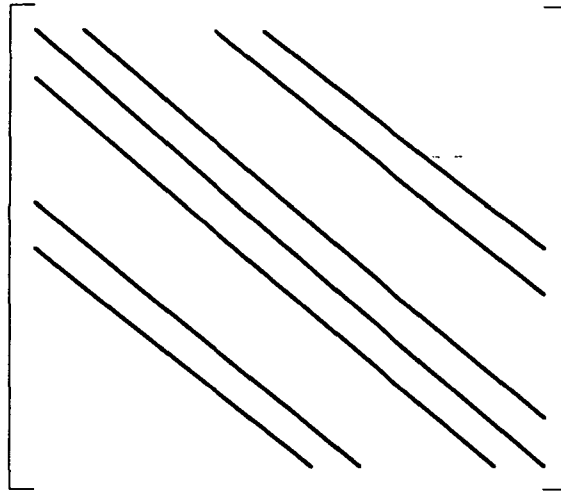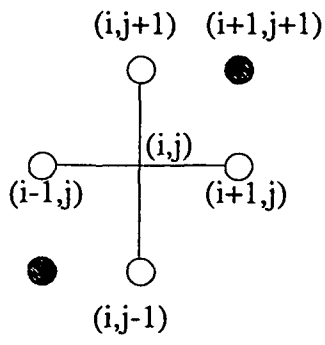
Figure 5. Modified stencil and the resulting matrix.

APPENDIX   A

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Professional Experience:

August 1993-Present	Director, Aerospace Research Center (ARC), Arizona State University (ASU)
December 1994-Present	Associate Director, NASA Space Grant Program, ASU
July 1992-Present	Professor, Mechanical & Aerospace Engineering, ASU
August 1985-June 1992	Associate Professor, Mechanical & Aerospace Engineering, ASU
September 1982-August 1985	Assistant Professor, Mechanical Engineering, Stanford University
June 1977-December 1981	Aerospace Technologist, NASA/Langley Research Center

Awards and Recognitions:

1995	Bronze (ASU) President's Medal for Team Excellence
1994-95	Outstanding Faculty Graduate Mentor Award from the Graduate College, ASU
1993-94	Undergraduate Teaching Award from College of Engineering & Applied Sciences, ASU
1988-89	Professor of the Year, Pi Tau Sigma, ASU
1988	AIAA Excellence in Teaching Award, ASU
1991	Faculty Awards for Women in Science and Engineering, National Science Foundation
1984	Presidential Young Investigator Award, National Science Foundation
1978	Outstanding Achievement Award from NASA/Langley Research Center
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Service:
Member, NASA Federal Laboratory Review Task Force, NASA Advisory Council (NAC), September 94-March 95
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Member, NATO/AGARD Fluid Dynamics Panel, 1995-1998
Member, Board of Directors of the Society of Engineering Science, 1993-1995
Member, NASA Computational Aerosciences Review and Planning Team, 1994-Present
Member, U.S. National Transition Study Group, 1984-Present
Member, Presidential Young Investigator Workshop on U.S. Engineering, Mathematics, and Science Education for
the Year 2010 and Beyond,, November 4-6, 1990
Member, National Academy of Sciences/National Research Council Aerodynamics Panel which is a part of the
Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, Commission
on Engineering and Technical Systems, November 1990-March 1992
Originator, Gallery of Fluid Motions of the American Physical Society/ Division of Fluid Dynamics, since 1983
Member, AIAA Fluid Dynamics Technical Committee, 1984-1989
Chair, Fluid Mechanics Committee of Applied Mechanics Division of ASME, 1993-Present; Member, 1984-Present
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Research Interests:
Computational, theoretical, and experimental aspects of laminar/turbulent transition and 3-D separation, and low-cost
space experimentation and satellite design; recent work includes the design, fabrication, and launch of ASUSat 1, a
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amateur radio operators; Navier-Stokes simulations of boundary-layer receptivity to freestream disturbances,
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Publications:

"Flow over Plates with Suction through Porous Strips," Nayfeh, Reed, Ragab, *AIAA J.* 20, 5, 587, 1982.

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"Flow over Bodies with Suction through Porous Strips," Nayfeh, Reed, Ragab, *Phys. Fluids*, 29, 7, 2042, 1986.

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Associate Fellow, American Institute of Aeronautics and Astronautics (AIAA)

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Member, American Society of Mechanical Engineers (ASME)

Member, Mathematical Association of America (MAA)

Member, Society for Industrial and Applied Mathematics (SIAM)

Member Board of Directors, Society of Engineering Science (SES)