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We modeled the receptivity of the laminar boundary layer on a semi-infinite flat plate with a modified-super-elliptic leading edge using a spatial direct numerical simulation. The incompressible flow was simulated by solving the governing full Navier-Stokes equations in general curvilinear coordinates by a finite-difference method. First, the steady basic-state solution was obtained in a transient approach using spatially varying time steps. Then, time-harmonic oscillations of the freestream streamwise velocity, modeling sound or spanwise vorticity, were applied as unsteady boundary conditions, and the governing equations were solved to evaluate the spatial and temporal developments of the perturbation leading to instability waves in the boundary layer. The effects of leading-edge radius and geometry on receptivity were determined. The work was closely coordinated with the experimental program. The computational work was also extended to solve the parabolized Navier-Stokes equations for the evolution of Görtler vortices in the presence of concave and convex curvature. Experiments were conducted on the receptivity of T-S waves to freestream sound in four different cases. (1) Two-dimensional roughness elements; (2) the interaction and control of T-S waves with 2-D roughness; (3) three-dimensional roughness elements; and (4) the leading edge. T-S wave amplitudes were measured as a function of freestream sound level and the roughness height for both 2-D and 3-D roughness elements. The position of the 2-D element was changed to selectively interfere with the T-S wave generated at the leading edge and a mechanism for the control of naturally occurring T-S waves was proposed. The model was changed to a thin flat plate with a 40:1 modified-super-ellipse leading edge and the receptivity of this geometry was directly measured.


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FINAL REPORT

Submitted to

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# ABSTRACT


## Computations

We modeled the receptivity of the laminar boundary layer on a semi-infinite flat plate with a modified-super-elliptic (MSE) leading edge using a spatial direct numerical simulation (DNS). The incompressible flow was simulated by solving the governing full Navier-Stokes equations in general curvilinear coordinates by a finite-difference method. First, the steady basic-state solution was obtained in a transient approach using spatially varying time steps. Then, time-harmonic oscillations of the freestream streamwise velocity, modeling sound or spanwise vorticity, were applied as unsteady boundary conditions, and the governing equations were solved to evaluate the spatial and temporal developments of the perturbation leading to instability waves (Tollmien-Schlichting waves) in the boundary layer. The effects of leading-edge radius and geometry on receptivity were determined.

The work was closely coordinated with the experimental program of Professor William Saric, also at Arizona State University, examining the same problems. Whenever appropriate, we matched our results from the spatial simulation with triple-deck theory.

The computational work was also extended to solve the parabolized Navier-Stokes equations for the evolution of Görtler vortices in the presence of concave and convex curvature.

## Experiments

Experiments were conducted on the receptivity of Tollmien-Schlichting waves to freestream sound in four different cases. (1) Two-dimensional roughness elements; (2) the interaction and control of T-S waves with 2-D roughness; (3) three-dimensional roughness elements; and (4) the leading edge. T-S wave amplitudes were measured as a function of freestream sound level and the roughness height for both 2-D and 3-D roughness elements. The position of the 2-D element was changed to selectively interfere with the T-S wave generated at the leading edge and a mechanism for the control of naturally occurring T-S waves was proposed. The model was changed to a thin flat plate with a 40:1 modified-super-ellipse leading edge and the receptivity of this geometry was directly measured.

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## 1. Introduction

In this progress report, Section 2 contains a statement of work and Section 3 lists the significant accomplishments under this Grant. Section 4 describes our computational research to examine boundary-layer receptivity to freestream sound waves and spanwise vorticity. The personnel involved in this project are described in Section 5.

## 2. Statement of Work

*Computations*

We modeled the receptivity of the laminar boundary layer on a semi-infinite flat plate with a modified-super-elliptic (MSE) leading edge using a spatial direct numerical simulation (DNS). The statement of work consists of a list of tasks accomplished as part of this grant activity.

1. Simulate the incompressible flow by solving the governing full Navier-Stokes equations in general curvilinear coordinates by a finite-difference method.
    1.1 First, obtain the steady basic-state solution in a transient approach using spatially varying time steps.
    1.2 Then, apply time-harmonic oscillations of the freestream streamwise velocity, modeling sound or spanwise vorticity, as unsteady boundary conditions, and solve the governing equations to evaluate the spatial and temporal developments of the perturbation leading to instability waves (Tollmien-Schlichting waves) in the boundary layer.
2. For 2D time-harmonic, freestream oscillations, modeling sound or spanwise vorticity, catalogue the effects of leading-edge radius and geometry on receptivity.
3. Evaluate role of triple-deck theory of Kerschen, Goldstein, and Hultgren.
4. Compare with available experiments where possible.
5. Use the parabolized Navier-Stokes equations and solve for the nonlinear evolution of Görtler vortices under conditions of concave and convex curvature (see Saric and Benmalek 1991 and Benmalek and Saric 1994).

*Experiments*

An experiment was established to conduct detailed measurements of the receptivity of Tollmien-Schlichting (T-S) waves to freestream sound under conditions of different geometries. The statement of work consists of a list of tasks accomplished as part of this grant activity.

6. Establish the Blasius flow on a flat plate in a low turbulence tunnel, introduce sound into the test section, and measure T-S waves generated by a two-dimensional roughness element. Vary the sound amplitude and the height of the roughness element. (see Saric et al. 1991). Compare with the theory of Kerschen.

7. Vary the chordwise position of the roughness element and create either constructive or destructive interference with the T-S wave from the leading edge (see Saric and Kosorygin 1994).
8. Introduce 3-D roughness elements and carry out a receptivity experiment like the 2-D work (see Spencer 1992).
9. Make a new flat plate model that has the modified-super-ellipse leading edge machined directly on the plate. Examine leading edge receptivity and compare with the triple-deck theory of Goldstein and Kerschen and the DNS work of Reed and her students (see Saric and Rasmussen 1994 and Wei and Saric 1994).

## 3. Significant Accomplishments

In the past 4 years, 5 PhD students and 5 MS students were supervised, 30 publications were written or are in preparation, and 36 talks and lectures were given.

## Publications

1. "Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, accepted Physics of Fluids A, 1994.
2. "Numerical Studies of Leading-Edge Receptivity to Sound," N. Lin, H.L. Reed, and W.S. Saric, in preparation.
3. "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.
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. "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.
6. "Simulations of Boundary-Layer Receptivity," H.L. Reed, AFOSR Meeting on Turbulence Structure and Control, Columbus, April 1-3, 1991.
7. "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.
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. "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.
11. "Numerical Investigation of Receptivity to Freestream Vorticity," T.A. Buter and H.L. Reed, AIAA Paper 93-0073.
12. "Direct Numerical Simulation of Transition: The Spatial Approach," H.L. Reed, Invited Paper, AGARD Course in Transition Prediction and Modeling, VonKarman Institute and Madrid, March 1993.
13. "Leading-Edge Receptivity of Acoustic Disturbances," D.A. Fuciarelli and H.L. Reed, ICASE/LaRC Workshop on Transition, Turbulence, and Combustion, NASA/Langley Research Center, June 7-July 2, 1993.
14. "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.
15. "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.
16. "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.
17. "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.
18. "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.
19. "Low-Speed Experiments: Requirements for Stability Measurements," W. S. Saric, *Instability and Transition, Vol. I*, Ed: Y. Hussaini, Springer-Verlag, 1990, pp. 162 - 174.
20. "Görtler Vortices With Periodic Curvature," W.S. Saric and A. Benmalek, *Proc. ASME-FED Vol. 114, (Boundary-Layer Stability and Transition to Turbulence)*, June, 1991, submitted *J. Applied Mechanics*.

21 "Boundary-Layer Receptivity to Sound with Roughness," W.S. Saric, J.A. Hoos, Y. Kohama, and R.H. Radeztsky, *Proc. ASME-FED Vol. 114, (Boundary-Layer Stability and Transition to Turbulence)*, June, 1991, submitted *J. Fluids Engineering*.

22. "The ASU Transition Research Facility." W.S. Saric, *AIAA Paper No. 92-3910.*

24. "Laminar-Turbulent Transition: Fundamentals," W.S. Saric, *Special Course on Skin Friction Dra , Reduction, AGARD Report 786*, March 1992.

25. "Boundary-Layer Transition: Experimental Evidence," W.S. Saric, *Special Course on Progress in Transition Modeling, AGARD Report 794*, March 1993.

26. "Low-Speed Boundary Layer Transition," W.S. Saric, *ICASE/NASA Short Course on Experimental Methods Related to Instabilities and Transition to Turbulence*, June 2, 1993.

27. "Görtler Vortices," W.S. Saric, *Ann. Rev. Fluid Mech. Vol.* 26, 1994.

28. "Effects of Curvature Variation on the Nonlinear Evolution of Görtler vortices," A. Benmalek and W.S. Saric, *Phys. Fluids*, submitted.

29. "Laminar boundary layer sound receptivity and control," V.S. Kosorygin and W.S. Saric, Proc. 4th IUTAM Symp. Laminar-Turbulent Transition, 1994.

30. "Effect of leading edge on sound receptivity," W. Wei and W.S. Saric, Proc. 4th IUTAM Symp. Laminar-Turbulent Transition, 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 15, 1991.
12. "Theoretical/Numerical Research in Boundary-Layer Transition," H.L. Reed, Institute of Fluid Science, Tohoku University, Sendai, Japan, January 10, 1992.
13. "Stability of Wall-Bounded Flows," H.L. Reed, Invited Seminar, EcoDynamics/University of Colorado at Denver, September 14, 1992.
14. "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.
15. "Leading-Edge Receptivity to a Vortical Freestream Disturbance: A Numerical Analysis," T.A. Buter and H.L. Reed, AIAA-93-0073.
16. "Direct Numerical Simulations of Transition: The Spatial Approach," H.L. Reed, Invited Paper, AGARD Course in Transition Prediction and Modeling, VonKarman Institute and Madrid, March 1993.
17. "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.
18. "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.

19. "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.
20. "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.
21. "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.
22. "Boundary-Layer Receptivity: Experiments," *(Invited)*, Third International Congress of Fluid Mechanics, Cairo, Egypt, January 2-4, 1990.
23. "Boundary-Layer Receptivity, Part 1.: Freestream Sound and 2-D Roughness Strips," *13th National Congress of Applied Mechanics,* Univ. Arizona, Tucson, May 21-25, 1990.
24. "Summary of Görtler Vortex Research -- Euromech 261 and The Future," *(Invited), Görtler Vortex Flows, EUROMECH 261*, June 14, 1990, Nantes, France.
25. "Visualization of Low-Reynolds-Number Flow Fields Around Receptivity Elements," 43rd Annual Meeting of the American Physical Society, November 18-20, 1990, *Bull. Amer. Phys. Soc. Vol. 35*, p. 2262.
26. "Boundary Layer Transition Control Using Receptivity," AFOSR Mtg on *Turbulence Structure and Control*, April 1-3, 1991.
27. "Görtler Vortices With Periodic Curvature," *Proc. Boundary-Layer Stability and Transition to Turbulence*, ASME/FED, June 17, 1991.
28. "Boundary Layer Receptivity to Sound with Roughness," *Proc. Boundary-Layer Stability and Transition to Turbulence*, ASME/FED, June 18, 1991.
29. "Thither Transition To Turbulence," *(Invited Plenary Lecture)*, (a) *ASME Applied Mechanics Division Summer Meeting*, June 12, 1991; (b) *Symposium in Honor of Eli Reshotko*, NASA-Langley/ICASE, July 28, 1991.
30. "Laminar-Turbulent Transition: Fundamentals," *Special Course on Skin Friction Drag Reduction, AGARD Report 786*, Brussels, March 1992.
31. "The ASU Transition Research Facility." AIAA 17th Aerospace Ground Testing Conference, July 6, 1992, *AIAA Paper No. 92-3910.*
32. "Nonlinear Development of Görtler Vortices over Variable Curvature Surfaces." (a) NASA-Langley Research Center, July 30, 1992, (b) International Taylor-Couette Symposium, Nice, France, March 30, 1993.

33. "Boundary-Layer Receptivity: Freestream Sound on an Elliptical Leading Edge." 45th Annual Meeting of the American Physical Society, November 22-24, 1992, *Bull. Amer. Phys. Soc. Vol. 37*, 1720.
34. "Boundary-Layer Transition: Experimental Evidence," *Special Course on Progress in Transition Modeling, AGARD Report 794*, (a) Madrid, Spain March 22, 1993, (b) Brussels, March 29, 1993.
35. "Low-Speed Boundary-Layer Transition," *ICASE/NASA Short Course on Experimental Methods Related to Instabilities and Transition to Turbulence*, June 2, 1993.
36. "Receptivity: Initial-Value Problems for Transition to Turbulence," *(Invited G.I. Taylor Lecture)*, ASCE/ASME/SES *Summer Meet'n '93*, Univ. Virginia, June 8, 1993.

## Post-Doc and Visiting Scientists

Dr. Vladimir Kosorygin, Institute of Theoretical and Applied Mechanics, USSR Academy of Sciences, Novosibirsk, Sept 1990-May 1991.

## Ph.D. Students

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

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

A. Benmalek, 1993. "Nonlinear Development of Görtler Vortices over Variable Curvature Walls," May 1993.

D.A. Fuciarelli, "Leading-Edge Receptivity," NASA Graduate Fellowship in Aeronautics, expected Summer 1995.

W. Wei, 1996. "Effects of Geometry and Sound Angle on Leading-Edge Receptivity," expected Dec 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.

J.A. Hoos, 1990. "Boundary-Layer Receptivity To Freestream Sound," May 1990.

S.A. Spencer, 1992. "Boundary-Layer Receptivity To Freestream Sound and 3-D Roughness Elements," May 1992.

B.K Rasmussen, 1993. "Boundary Layer Receptivity - Freestream Sound on an Elliptical Leading Edge," May 1993.

D.D. Staggers, "Boundary-Layer Receptivity to Freestream Streamwise Vorticity," NASA Space Grant Fellow, expected Summer 1995.

**Undergraduate Students**

T. Krutckoff, "Visualization of Low-Reynolds-Number Flow Fields Around Two-Dimensional Roughness Elements," (*Honors Thesis*) Dec 1991.

D.D. Staggers, "Grid Generation for Leading-Edge Studies," completed December 1993.

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-Verlag, New York, 1992. This paper introduces the Modified Super Ellipse geometry and also finds that receptivity is linear to freestream amplitude up to levels of 5%.

"Leading-Edge Receptivity to a Vortical Freestream Disturbance: A Numerical Analysis," T.A. Buter and H.L. Reed, ICASE Workshop on Stability and Transition, ed. M.Y. Hussaini, Springer-Verlag, New York, 1992. This paper includes the effects of freestream vorticity in the receptivity problem.

"Direct Numerical Simulations of Transition: The Spatial Approach," H.L. Reed, Invited Paper, AGARD Course in Transition Prediction and Modeling, VonKarman Institute and Madrid, March 1993. This paper reviews spatial direct numerical simulations including receptivity studies.

"Computational Aspects of Nonparallel Effects in Boundary-Layer Receptivity," N. Lin, T.A. Buter, D.A. Fuciarelli, and H.L. Reed, Invited Paper, IUTAM Symposium on Nonlinear Stability of Nonparallel Flows, Clarkson University, July 1993. This paper shows good comparison between receptivity computations and experiments.

# 4. Computational Results for Leading-Edge Receptivity

## 4.1 Introduction

The state-of-the-art in transition prediction involves the use of linear stability theory (e.g. Arnal 1993), an amplitude-ratio method. But, these free or self-excited oscillations are generally initiated by some externally forced disturbances such as sound or freestream turbulence. The role of receptivity, not accounted for in linear stability theory, is key to the overall process as it defines the initial disturbance amplitude (that is, $A_o$). 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).

## 4.2 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

$$[1-x/(AR\ L)]^{m(x)} + [y/L]^n = 1, \quad 0 < x/L < AR \tag{1}$$

$$m(x) = 2 + [x/(AR\ L)]^2 \quad \text{and} \quad n = 2 \tag{2}$$

where L is the half-thickness of the plate 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.

### 4.2.1 Receptivity to Plane Freestream Sound

For low-speed flows, freestream-sound wavelength is typically one or two orders of magnitude larger that 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.

To review previous numerical efforts, Murdock (1980, 1981) studied the receptivity of an incompressible boundary layer on both a flat plate with zero thickness and a parabolic body (favorable pressure gradient everywhere); he considered the boundary-layer response due to a plane sound wave parallel to the freestream direction. For the flat plate, his integration domain did not include the leading edge and he therefore had to impose an inflow boundary condition obtained by solving the unsteady boundary-layer equations. His numerical results were sensitive to the upstream-boundary location relative to the leading edge (see the first paragraph of Section 4.2). For a parabolic body, a sharper leading edge (smaller nose radius) was found to be more receptive, a result similar to that found theoretically by Hammerton & Kerschen (1991) for the parabolic body. Gatski & Grosch (1987) solved the full incompressible Navier-Stokes equations for flow over an infinitely thin, semi-infinite flat plate and found no clear development of T-S waves (again see the first paragraph of Section 4.2).

Lin et al. (1991, 1992, 1993, 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 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:

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

(b) 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.

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

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

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

(iii) The disturbance originated from the location of the maximum in adverse pressure gradient.

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

Appendix C contains the relevant publications related to this work.

### 4.2.2 Receptivity to Oblique Freestream Sound

Fuciarelli & Reed (1993) are extending the work described in Section 4.2.1. In our work, the receptivity of a flat-plate boundary layer to freestream oblique sound is being investigated through the numerical solution of the Navier-Stokes equations in the leading-edge region. The chosen leading-edge geometry is the MSE, which has the property of continuous curvature at the flat-plate/leading-edge juncture. This allows us to concentrate the effort on the investigation of receptivity caused by the leading edge alone. The Reynolds number, based on leading-edge curvature, is to be varied parametrically along with the aspect ratio of the MSE in order to examine the stability of a wide variety of basic states. The use of various aspect ratios covers the range from a sharp leading edge to a blunt leading edge.

The main feature of the numerical work here is the use of a body-fitted curvilinear coordinate system to calculate the flow at the elliptic leading-edge region with fine resolutio[illegible] First, a basic-state solution is obtained by solving the governing equations for steady, incompressible flow with a uniform freestream using a transient approach. Then the basic flow is to be disturbed by applying oblique time-dependent, forced perturbations as unsteady boundary conditions. The unsteady flow and the temporal and spatial development of the perturbations are then to be determined by numerically solving the unsteady governing equations.

In order to accomplish this goal, the development of four different computer codes is necessary: an inviscid code, a grid-generation code, a basic-state solver, and a disturbance code. Each code undegoes four stages in the development process: method selectic ethod formulation, programming, and debugging/validation. The progress made thus Mr. Fuciarelli is outlined in the next paragraphs.

The inviscid code, which will provide farfield boundary conditions for the basic-state solver, is completed. Since we are interested in nonlifting bodies, a source-distribution method was employed. The resulting pressure-coefficient distributions for a series of MSE of varying aspect ratios are shown in Figure 1. The code was verified by a comparison with the experiments of Saric & Rasmussen (1993) on a 40:1 MSE; the chordwise pressure-coefficient distributions measured 14.8 mm above the flat plate are compared in Figure 2 and the agreement is exceptional.

The grid-generation code is completed. A body-intrinsic scheme proved unsatisfactory because the resulting grid was not completely orthogonal. Orthogonality was again difficult to achieve with an elliptic solver. Further investigation led to a hyperbolic grid-generation procedure, which guarantees orthogonality everywhere but requires the local specification of the Jacobian. This last concern was overcome by first generating an algebraic grid and then numerically computing the Jacobian.

The basic-state code is a 2-D incompressible Navier-Stokes solver in a general coordinate system. One of the prime considerations is speed, and many algorithms were considered. An alternating direction implicit (ADI) stream-function/vorticity formulation was selected. The ADI method results in a tridiagonal system which can be solved very efficiently. Moreover, continuity is guaranteed. In addition, the dispersion errors involved in the convective terms become manageable without resorting to staggered grids or artificial viscosity. The resulting system consists of two coupled equations. However, if the stream-function coefficients in the vorticity-transport equation are lagged, then the equations are effectively decoupled and each can be solved sequentially and independently. With the time-splitting method, the result is therefore four tridiagonal systems to be solved for each iteration. The results from the basic-state code compare very well with the work of Lin et al. (1992).

The disturbance code is presently in the debugging/validation stage. This solver is similar to that for the basic state except for the following modifications. First, the convective terms coupling the basic state and the disturbance state are retained, but this results in only a small degree of added

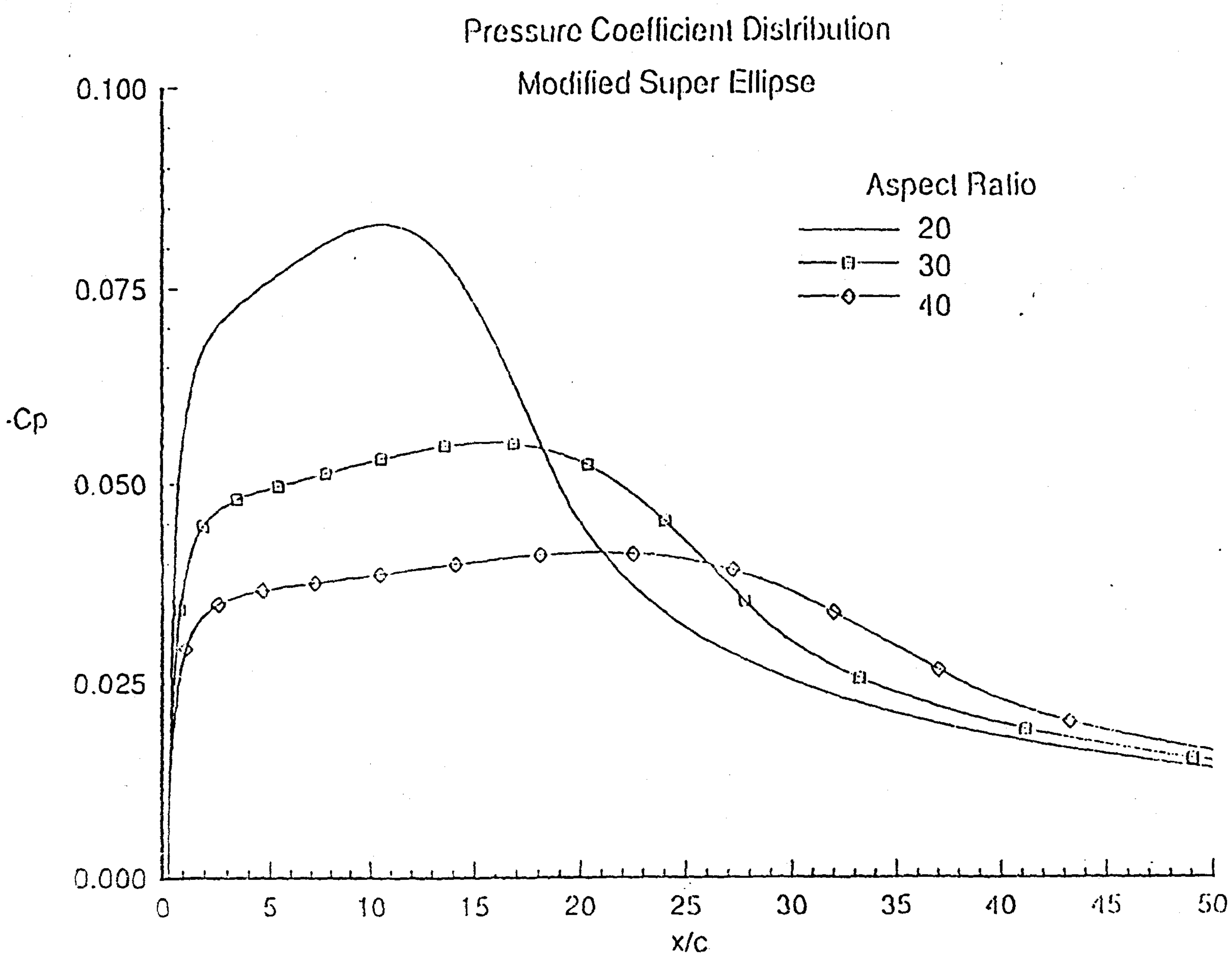


Figure 1. Pressure-Coefficient Distribution for Modified Super Ellipses of Varying Aspect Ratio.

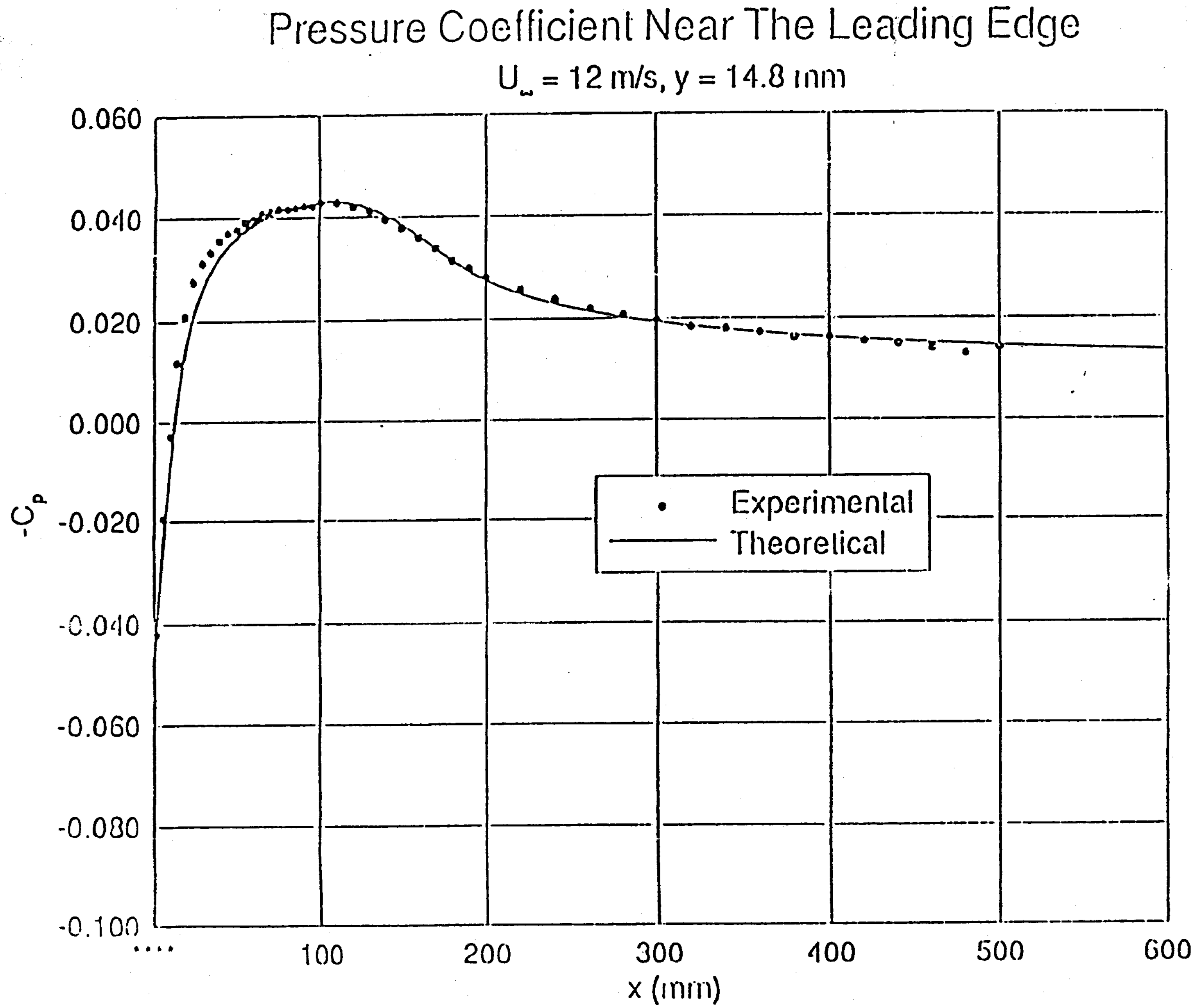


Figure 2. Comparison of Pressure-Coefficient Distribution for a 40:1 Modified Super Ellipse.

complexity to the code. Second, the code is now time accurate, which involves an additional iteration loop. Third, a buffer zone is appended to the downstream boundary. The buffer-zone treatment was first developed by Streett & Macaraeg (1989) and then modified by Liu & Liu (1993). A buffer zone is a region downstream in which both the Reynolds number and a coefficient multiplying the second derivative of the vorticity with respect to x are decreased as one progresses closer to the outflow. This effectively provides a condition at the outflow which will not reflect instability waves back into the interior solution domain by making the equations convectively dominated in the direction tangent to the surface and diffusion dominated in the direction normal to the surface.

Preliminary results from the disturbance code are encouraging and show similar features with the work of Lin et al. (1992). Further results incorporating multigrid are forthcoming.

Once the code development is completed, studies of receptivity mechanisms are possible. In particular, the effect of leading-edge geometries (bluntness) on receptivity for 2-D oblique sound waves will be catalogued. The simplicity of the basic state allows this to be done parametrically. The exciting advantage of the simulations over the experiments is that we now have detailed information on velocities and vorticity in the attachment-line region. How the disturbances develop will be examined analytically and graphically. Moreover, the advantage of the computations over triple-deck theory is that the theory can only address local effects and cannot include the continuous curvature and finite thickness of the leading edge; the computations include all these effects in an integrated fashion and can be used selectively to determine the relative importance of these various effects.

For 2-D time-harmonic, oblique, irrotational, freestream oscillations, we will catalogue the effects of a) different frequencies, b) different incidence angles, and c) different leading-edge geometries. In this case we will assume the wave angle is small, in the range of 1-10 degrees, or, in other words, u' is much larger than v'. We will concentrate on frequency parameters of F = 230 (for validation against the results of Lin et al. 1993) and F = O(80), and elliptic aspect ratios of 6 (ala Lin et al. 1993) and 20 and 40 (ala the ASU experiments). Freestream amplitudes are the same as those initiated by Saric in the experiments.

Throughout this work, we will locally evaluate the role of the triple-deck theories of Kerschen, Goldstein, and Hultgren whenever appropriate. Also, the work has been and continues to be closely coordinated with the experimental program of Saric, also at Arizona State University, examining the same problem. It has been demonstrated as part of this grant activity that clean receptivity experiments are feasible, and so we look forward to very close interaction between the two efforts. It is only through a close coordination among theory, computations, and experiments that we will solve the receptivity problem.

**4.2.3 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.

To review previous computational efforts, Kachanov et al. (1978) solved the incompressible flow over an infinitely thin flat plate, using the Navier-Stokes equations linearized for small disturbances, and considered both a transverse acoustic wave across the leading edge and a vortex street passing far above the plate surface. In the latter case, no evidence of T-S waves was found.

Buter & Reed (1992a,b, 1993, 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 then 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:

(a) As the disturbance convected 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).

(b) 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).

(c) 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.

(d) 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.

(e) Modifications to the geometry which increased the surface pressure gradient along the nose increased receptivity.

(f) 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.

(g) 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.

Appendix C contains the relevant publications related to this work.

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 be possible.

## 5. Computational Results on Görtler Vortices

The essential results of all aspects of the Görtler vortex computations are contained in Saric and Benmalek (1991) and the PhD thesis of Benmalek all of which are part of Appendix C

## 6. Experimental Results on Receptivity

### 6.1 Sound and 2-D roughness

The results of this work are contained in Saric and Krutckoff (1990) and Saric et al. (1991) which is attached in Appendix C.

### 6.2 Control of T-S waves with 2-D roughness

The details of this work will be published in Kosorygin and Saric (1994) and is summarized by Radeztsky et al. (1991) and Saric (1993).

### 6.3 Three-Dimensional Roughness

The MS thesis of Shelley Spencer is attached as Appendix C. The work was reported on in Spencer et al. (1992) and a manuscript is under preparation. It is summarized in Saric (1993).

### 6.4 Leading Edge Receptivity

The work on the 40:1 modified super ellipse was completed in the MS thesis of Brenda Rasmussen which is attached as Appendix C. It is summarized in Saric and Rasmussen (1993) and Wei and Saric (1994).

## 7. Personnel

Thomas A. Buter, Nay Lin, and Ali Benmalek received their PhD's under this grant. Dr. Buter worked with H.L. Reed and is presently an Assistant Professor at the Air Force Institute of Technology, Dr. Lin worked with H.L. Reed and is presently at DynaFlow, Inc., working under the direction of Professor Thorwald Herbert, and Dr. Benmalek worked with W.S. Saric and is now a postdoctoral fellow at ASU working with Professor Tong on heat transfer problems.

David Fuciarelli, a PhD student of H.L. Reed, is a NASA Graduate Fellow in Aeronautics, a US citizen, and is continuing the work examining receptivity to oblique sound waves and normal vorticity. He achieved a 3.9/4.0 GPA as an undergraduate in Aerospace Engineering at ASU, 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 began graduate work in the Fall 1992. He has spent/will spend several weeks of each summer, beginning with the summer 1993 and until his graduation, at NASA/Langley Research Center, interacting with NASA and ICASE personnel.

Wei Wei, a PhD student under W.S. Saric is Graduate Research Assistant in Aerospace Engineering and is continuing the experimental work on the leading-edge receptivity problem. Mr. Wei obtained his BS degree in Aerospace Engineering from Ohio State University with a 3.73/4.0 GPA. After one year at ASU he successfully passed the PhD qualifying examination and went directly into the PhD program.

Jon Hoos, Shelly Spencer, and Brenda Rasmussen completed their MS degrees with W.S. Saric under the support of this grant. Mr. Hoos is now working at Ball Aerospace in Boulder Colorado, Ms. Spencer is working at NASA-Langley Research Center, and Ms. Rasmussen is working at Edwards Air Force Base.

Tonja Krutckoff graduated from the Honors College at ASU and did her honors thesis on the visualization of the flow over receptivity roughness elements. After her BS, she successfully passed the PhD qualifying examination at ASU and is now doing computational work on free-surface flows in microgravity under the direction of W.S. Saric.

David Staggers, a US citizen, is beginning companion work examining leading-edge receptivity to freestream streamwise vorticity. He graduated with a Bachelor's degree in Mechanical Engineering at ASU in December 1993, having achieved a 3.7/4.0 GPA, and entered the MS program at ASU in January 1994. Last summer 1993 he began work with Dr. Reed on grid generation. He was the recipient of a NASA Space Grant/Graduate Fellowship for the spring semester 1994. He will graduate with his PhD in August 1997,

Helen L. Reed 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 computational, theoretical, and experimental aspects of laminar/turbulent transition and 3-D separation; recent work includes 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; an ICASE Consultant with NASA/Langley Research Center; the Originator and Editor 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 AIAA Fluid Dynamics Technical Committee; the current Chair of both the Junior Awards Committee and the Fluid Mechanics Committee of the Applied Mechanics Division of ASME; a Member of the Board of Directors of the Society of Engineering Science; and the Associate Editor of the Annual Review of Fluid Mechanics. Her resume is attached as Appendix A.

William Saric received his Ph.D. in Mechanics in 1968 from IIT. He worked at Sandia Laboratories for a total of ten years in the Re-entry Vehicle Division and the Atomic and Fluid Physics Division with a concentration of experimental and theoretical work in hypersonic flows. He spent the next nine years at VPI&SU and he joined the faculty at ASU in the Fall of 1984. For the past sixteen years, he has been conducting detailed theoretical and experimental studies of boundary-layer stability and transition problems for flight applications. Dr. Saric is a Member of the U.S. National Transition Study Group and a Member of the AGARD Fluid Dynamics Panel. He is a Fellow of ASME and APS and in 1993 received the G.I. Taylor Medal from the Society of Engineering Science for outstanding contributions in fluid mechanics. His resume is attached as Appendix B.

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Appendix A.

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## *1. EDUCATION*

Ph.D., Engineering Mechanics, VPI&SU, Dec. 1981.
M.S., Engineering Mechanics, VPI&SU, June 1980.
A.B., Mathematics, Goucher College, May 1977.

## *2. AREA OF TEACHING AND RESEARCH*

Low-Cost Space Experimentation, Satellite Design, Separated and Transitional Flows, Supersonics/Hypersonics, Hydrodynamic Stability, Laminar Flow Control, Receptivity, 3-D Boundary Layers, Aerodynamics, Computational Fluid Dynamics, Perturbation Methods.

## *3. POSITIONS HELD*

August 1993 - present, Director, Aerospace Research Center, ASU.
July 1992 - present, Full Professor, ASU.
Aug. 1985 - July 1992, Associate Professor (Tenure awarded Apr. 1988), ASU.
Sept. 1991-June 1992, Assoc. Prof. (Sabbatical), Inst. Fluid Sci., Tohoku Univ., Sendai, Japan.
Sept. 1982-Aug. 1985, Assistant Professor, Stanford Univ.
Jan. 1982-Aug. 1982, Assistant Professor (Non-tenure track), VPI&SU.
June 1977-Dec. 1981, Aerospace Technologist, NASA/Langley Research Center.
Summer 1976, Mathematics Aid, NASA/Langley Research Center.

## *4. HONORS / DISTINCTIONS*

Phi Beta Kappa
Recipient of a NASA fellowship, 1976
Outstanding Summer Employee Award from NASA/Langley Research Center, 1976
Torrey Award for Excellence in Mathematics, Goucher College, 1977
Outstanding Achievement Award from NASA/Langley Research Center, 1978
Cunningham Fellowship Award from Virginia Polytechnic Institute & State Univ., 1981
Presidential Young Investigator Award, National Science Foundation, 1984
AIAA Excellence in Teaching Award, Arizona State University, Fall 1988
Professor of the Year, Pi Tau Sigma, Arizona State University, 1988-1989
Associate Fellow, American Institute of Aeronautics and Astronautics, December 1990
Faculty Awards for Women in Science and Engineering, National Science Foundation, 1991

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"Effect of Curvature on Stationary Crossflow Instability of a 3-D Boundary Layer," Lin, Reed, *AIAA J.*, 31, 9, 1611, 1993.
"A Catalogue of Linear Stability Theory Results," Reed, Gasperas, acc. *Ann. Rev. Fluid Mech.*, 27, 1995.
"A Numerical Model for Circulation Control Flows," Holz, Hassan, Reed, acc. *AIAA J.*
"Transition Correlations in 3-D Boundary Layers," Reed, Haynes, acc. *AIAA J.*
"Linear Disturbances in Hypersonic, Chemically Reacting Shock Layers," Stuckert, Reed, acc. *AIAA J.*
"Numerical Investigation of Receptivity to Freestream Vorticity," Buter, Reed, acc. *Physics of Fluids A.*
"Development/Decay of Pressure-Driven, Unsteady, 3-D Flow Separation," Henk, Reed, submit. *AIAA J.*
44 refereed national conference proceedings papers (8 invited)
8 books and 8 articles edited
7 technical reports

## 6. *PROFESSIONAL SERVICE*

Member, Presidential Young Investigator Workshop on *U.S. Engineering, Mathematics, and Science Education for the Year 2010 and Beyond*, Wash., D.C., Nov. 4-6, 1990. This is an advisory group to President Bush's Science Advisor, Allen Bromley, concerning directions U.S. education *must* take for preparation and training of U.S.'s future scientists and lay people.
Member, *National Academy of Sciences/National Research Council Aerodynamics Panel* which is part of *Committee on Aeronautical Technologies of the Aeronautics and Space Engineering Board, Commission on Engineering and Technical Systems*, Nov. 1990-Mar. 1992. This is the advisory group to NASA and U.S. Congress concerning directions NASA *must* take in order to enable U.S. to remain competitive in world arena.
Member, *U.S. National Transition Study Group* under the direction of Eli Reshotko, 1984-Pres.
Associate Editor, *Annual Review of Fluid Mechanics*, 1986-Present.
Originator, *Annual Picture Gallery of Fluid Motions* at annual meetings of the *American Physical Society*, Nov. 1983, Houston. Responsibility for gallery at Brown University, Nov. 1984; Eugene, Nov. 1987; Buffalo, Nov. 1988; Palo Alto, Nov. 1989; Cornell, Nov. 1990; Scottsdale 1991; Albuquerque, 1993.
ICASE Consultant, NASA/Langley Research Center (Current)
Member, *AIAA Technical Committee on Fluid Dynamics*, 1984-1989.
Member, *Board of Directors, Society of Engineering Science*, 1993-Present.
Chair, *Fluid Mechanics Tech. Committee* of *Applied Mechanics Div. of ASME*, 1993-Pres. Member 1984-Present.
University Representative, *National Science Foundation Fluids Engineering Workshop*. Group Leader and Coordinator of final document for Unsteady Flow Panel, Savannah, Sept. 17-20, 1986.
Chair, *ASME Junior Awards Committee* 1989-1993. Vice-Chair 1987-1988.
Member, Scientific Committee 1992-3 *IUTAM Symp. on Nonlinear Stability of Nonparallel Flows*, 1990-1993.
Chair, *2nd Annual Arizona Fluid Mechanics Conference*, Arizona State University, Apr. 4-5, 1986.
Technical Chair, *AIAA 19th Fluid, Plasma Dynamics, and Lasers Conference*, Honolulu, June 1987.
Co-Chair, with Jankowski, *44th American Physical Soc./Div. of Fluid Dynamics Meeting*, Scottsdale, Nov. 1991.
Co-Organizer with Dr. Daniel Reda (Sandia National Laboratories) of *Symposium on Experimental and Theoretical/Numerical Studies of Boundary-Layer Stability and Transition*, at the *First Joint ASME/JSME Fluids Engineering Conference*, Portland, June 23-26, 1991.
Chair, *Annual Meeting of the Society of Engineering Science*, Arizona State University, October 1996.
Chair of 23 various symposia and sessions at international conferences.

Appendix B.

**WILLIAM S. SARIC, P.E.**
Professor
Mechanical and Aerospace Engineering
Arizona State University
Tempe, AZ 85287-6106
(602) 965-2822

## 1. PERSONAL DATA

Date of Birth: [redacted]
Social Security [redacted]

## 2. EDUCATION & REGISTRATION

B.S. in Mechanical Engineering, January 1963, *Illinois Institute of Technology*, Chicago, Illinois. Recipient of the Pi Tau Sigma Award to the "Outstanding Mechanical Engineering Graduate" of his class. Thesis: "Design, Construction and Performance of a Dynamic Balancing Machine," Advisor - Dr. R.J. Bonthron.

M.S. in Mechanical Engineering, June 1965, *University of New Mexico* (thesis not required).

Ph.D. in Mechanics, June 1968, *Illinois Institute of Technology*, Chicago, Illinois. Thesis: "The Hydrodynamic Stability of Heterogeneous Couette Flows." Advisor - Dr. Zalman Lavan.

P.E. Registered Professional Engineer in Virginia, Lic. No. 13427.

## 3. EXPERIENCE

August 1984 - Present: *Arizona State University*, Professor, Mechanical and Aerospace Engineering. Chairman: Dr. D.L. Boyer. Duties include teaching, research, and student advisement.

September 1991 - July 1992: *Tohoku University, Sendai, Japan*, Professor, Aeronautics and Astronautics. Chairman: Dr. Inooka. Duties include teaching, research and student advisement.

September 1975 - August 1984: *Virginia Polytechnic Institute and State University*, Professor, Engineering Science and Mechanics. Chairman: Dr. D. Frederick. Duties included teaching, research, and student advisement. Tenure awarded, May 1978. Promoted from Associate Professor to Professor, May 1979.

July 1968 - August 1975: *Sandia National Laboratories, Albuquerque*, Staff Member, Atomic and Fluid Physics Division. Manager: Dr. K.J. Touryan. Duties included research and advising the Aerodynamics Projects group on problems of reentry ablation studies, boundary-layer transition, transpiration cooling, heat transfer, and applied mathematics. Research projects included experimental and theoretical studies in liquid-layer stability, boundary-layer stability, explosive welding, nonlinear dynamics, nonlinear oscillations of bubbles, and stability of controlled fusion of deuterium-tritium with electron beams.

January 1966 - June 1968: *Illinois Institute of Technology*, Full-time Instructor, Mechanics Department. Chairman: Dr. P. Chiarulli. Duties involved teaching undergraduate Mechanics courses, textbook review and selection, course organization, and supervision of a graduate teaching assistant.

January 1963 - January 1966: *Sandia National Laboratories, Albuquerque*, Staff Member. Supervisors: H.D. Sivinski and K.J. Touryan. Worked in environmental testing organization for two years on high-velocity impact. Duties involved feasibility studies and design of simulation facilities for various environments and writing budget proposals for new facilities. One year in Reentry Vehicle Research Division working on Magnetohydrodynamic entrance flows and high-speed boundary-layer flows.

Summer 1962: *Illinois Institute of Technology*, NSF Undergraduate Research Fellow. Supervisor: Dr. R.J. Bonthron. Worked on undergraduate thesis.

December 1957 - October 1960: *Dewey and Almy Chemical Company* of W.R. Grace, Chicago, Illinois, Chemical Mixer. Duties included responsibility of second-shift production of concrete admixture products.

## 4. CONSULTING

May 1984 - June 1985: *Lawrence Livermore National Laboratories.* Consulted on problems of isotope separation using a gas centrifuge.

January 1977 - June 1986: *Lockheed-Georgia,* Marietta, Georgia. Consult on problems of laminarization of flow over airfoils for subsonic transports and on experiments on boundary-layer stability.

September 1975 - Present: *Sandia National Laboratories, Albuquerque.* Conducted research on the stability of controlled nuclear fusion, magnetohydrodynamic power generation, convection in porous media, reactor safety problems, and hypersonic boundary-layer transition.

## 5. PROFESSIONAL ACTIVITIES

### 5.1 Scientific and Professional Societies

Fellow, American Physical Society (APS)
Fellow, American Society of Mechanical Engineers (ASME)
Associate Fellow, Amer. Inst. of Aeronautics and Astronautics (AIAA)
Member, American Academy of Mechanics
Tau Beta Pi (Honorary)
Pi Tau Sigma (Honorary)

### 5.2 Professional Recognition, Honors, and Service to the Profession

Recipient of the *G. I. Taylor Medal* from the Society of Engineering Science, Jun 1993.

Recipient of VPI & SU 1984 *Alumni Award for Research Excellence* for "...contributions to the understanding of nonlinear flow stability and subharmonic transition to turbulence."

Winner of *Gallery of Fluid Motions* Contest "...for visualization of different transition mechanisms," at the 26th Annual Meeting of the APS Division of Fluid Dynamics, November 1983.

Awarded *Certificate of Teaching Excellence*, VPI & SU, 1978.

Named Fellow of the American Physical Society "...for his contributions to the understanding of the stability of shear layers," Dec 1982.

Invited guest of the U.S.S.R. Academy of Sciences (3 times), Jun 8 - Jul 6, 1976; Sep 2 - 10, 1979; August 16, - Sep 6, 1981. Gave lectures and toured facilities at the Institute of Theoretical and Applied Mechanics, Institute of Hydrodynamics, and the Institute of Thermal Physics in Akademgorodok/Novosibirsk and at the Moscow State University and the Center for Computing in Moscow. Worked on joint wind-tunnel experiments at the Institute of Theoretical and Applied Mechanics.

Fellow, Japan Society for the Promotion of Science. Gave a series of lectures in Japan during Sep / Oct 1989.

Associate Editor, *Applied Mechanics Review*, 1984-1994

Associate Editor, *J. Fluids Engineering*, 1993-1996.

Chairman, ASME Applied Mechanics Division, 1991/1992. Member, Executive Committee, 1986-1992.

Chairman, Fluid Mechanics Technical Committee, ASME Applied Mechanics Division, 1984 - 1987 (member, 1982-1984).

Vice Chairman, Executive Committee, APS Division of Fluid Dynamics, 1985-1986.

Member of AGARD Fluid Dynamics Panel, 1989-1995 (Publications Comm., TES Comm., vice-chair Working Group 18 "Hypersonics").

Member of AIAA Technical Committee on Fluid Dynamics and the Fluids Liaison to the AIAA Technical Committee on Plasma Dynamics, 1975-1978.

Member, U.S. Boundary-Layer Transition Study Group, 1981 - present.

Member of SAE Technical Committee on Aerodynamics, 1984-1991.

Member of AIAA Technical Committee on Ground Testing, 1983-1986

Member of National Academy of Sciences, National Research Council, Aerodynamics Panel for the NRC Workshop on *Aeronautical Technology in the Year 2000.* University of Texas, Austin, Jan 16-19, 1984.

Member of Scientific Committee of the 2nd IUTAM Symposium on Laminar-Turbulent Transition, Jul 9-13, 1984, Novosibirsk, U.S.S.R. and the 3rd IUTAM Symposium on Laminar-Turbulent Transition, Toulouse, France, Sep 11-15, 1989.

Member of Steering Committee of *NSF Engineering Fluid Mechanics Workshop*, Sep 17-20, 1986.

General Chairman, *AIAA 11th Fluid and Plasma Dynamics Conference*, Seattle, Washington, Jul 10-12, 1978. With 115 papers presented and 280 attendees, responsibilities included organizing the technical committee, paper review, session topics, invited papers, etc.

Co-chairman of Symposium *Use of Artificial Excitation to Control Fluid Flows by Manipulating Their Large-Scale Structure*, ASME Applied Mechanics Conference, San Antonio, Jun 17-21, 1984.

Co-chairman of Symposium *Stability and Convection*, ASME 106th Winter Annual Meeting, Miami Beach, Nov 17-21, 1985.

Co-Chairman of International Workshop on *Stability and Transition in Bounded Shear Flows*, Tucson, Arizona, Nov 22-23, 1985.

Co-Chairman of International Workshop on *Dynamics of Structure and Intermittencies in Turbulence*, Tempe, Arizona, May 20-24, 1991.

Chairman of 25 technical sessions at National and International Meetings.

Listed: Who's Who in Aviation and Aerospace: 1st Edition (U.S.) 1983.

Listed: American Men and Women in Science, 1982.

### 5.3 Current Fields of Interest

Theoretical and experimental studies in the areas of hydrodynamic stability, boundary-layer transition, nonlinear waves, transpiration cooling and heat transfer, laminar flow control, stability of stratified flows, and control liquid sheets in micro-gravity environments.

## 6. TEACHING

### 6.1 Arizona State University

General

Served on 15 Ph.D. Committees and 12 M.S. Committee.

Post-Doc and Visiting Scientists

Dr. Shohei Takagi, National Aerospace Laboratories, Nov 1985-Oct 1987 and Jan-Mar 1991.

J.R. Dagenhart, NASA-Langley Research Center, "Thompson Fellow," Aug 1986-Aug 1987.

Dr. Yasuaki Kohama, Tokoku University, Sendai, Japan, Oct 1989-Aug 1990.

Dr. Vladimir Kosorygin, Institute of Theoretical and Applied Mechanics, USSR Academy of Sciences, Novosibirsk, Sept 1990-May 1991.

Dr. Vsevolod Shidlovskii, Computing Center, USSR Academy of Sciences, Moscow, Mar-Apr 1991.

Ph.D. Students Supervised

J.R. Dagenhart, 1992. "Crossflow Stability and Transition Experiments on a Swept Wing," Dec 1992 (VPI & SU).

A. Benmalek, 1993. "Nonlinear Development of Görtler Vortices over Variable Curvature Walls," May 1993.

R.H. Radeztsky, Jr. 1994. "Experiments on the Interaction of T-S Waves and Crossflow Vortices," Mar 1994.

M.S. Reibert, 1995. "Roughness Induced Transition in 3-D Boundary Layers," expected Dec 1995.

W. Wei, 1996. "Effects of Geometry and Sound Angle on Leading-Edge Receptivity," expected Dec 1996.

T.K. Krutckoff, 1997. "Stability and Control of Liquid Sheets in Microgravity," expected May 1997.

M.S. Students Supervised

M.C. Mousseux, 1988. "Flow Quality Improvements in the ASU Unsteady Wind Tunnel," Aug 1988.

P.T. Pupator, 1988. "Control of Random Two-Dimensional Disturbances in a Boundary Layer," Dec 1988.

J.A. Hoos, 1990. "Boundary-Layer Receptivity To Freestream Sound," May 1990.

S.A. Spencer, 1992. "Boundary-Layer Receptivity To Freestream Sound and 3-D Roughness Elements," May 1992.

B.K. Rasmussen, 1993. "Boundary Layer Receptivity - Freestream Sound on an Elliptical Leading Edge," May 1993.

Senior Projects Supervised

J. Bellis, "Design of a Wind-Tunnel Test Section," Dec 1984.

T. Chesebrough, "Design of a Three-Dimensional Hot-Wire Positioning Device," Dec 1984.

T. Grochowski, "Software Design for Wind Tunnel Data Acquisition System," Dec 1985.

L. Rottman, "3-D Graphics Interface on a Tektronix Plotter Using a PC," Dec 1985.

J. Frazier, "Measurement of Drag in the Aerodynamic Wind Tunnel," May 1987.

B. Yonkovich, "Wind Tunnel Test-Section Design," May 1987.

C. Kaus, "3-D Traverse Design," Dec 1987.

D. Grady, "Design of a Wind Tunnel Heat Exchanger," Dec 1988.

T. Hendricks and P. Simonich, "Design of a Turning Vane Heat Exchanger," May 1989.

M. Gersten, "Design of Special Optics for a Laser-Doppler Anemometer," Aug 1989.

T. Krutckoff, "Visualization of Low-Reynolds-Number Flow Fields Around Two-Dimensional Roughness Elements," (*Honors Thesis*) Dec 1991.

Staff Supervised

T. Crosswhite, Oct 17, 1985 to Apr 30, 1986, Half-Time Technician on the Wind Tunnel Project.

D. Clevenger, Nov 1986 to present: Full-Time Wind-Tunnel Technician at the Unsteady Wind Tunnel.

J. Hawthorne, Jul 1986 to Sep 1987, M. Peña, Nov 1987 to Feb 1990, C. Petiford, Apr 1990 to Jul 1991, and C. Leatherman, Aug 1992 to present: Full-Time Administrative Assistants (shared with Dr. Helen Reed).

Committees

University: Council for Research and Creative Activities, 1985-1986.

College of Engineering: Co-Chair, Aerospace Research Center Committee for Aerodynamics, 1988-1989; Research Council, 1985-1987; Personnel Committee, 1988-1991.

MAE: Chair, Fluids Group, 1984-1985, 1986-1987; Executive Committee, 1984-1985, 1986-1987, 1992-1993; Promotion, Tenure, and Retention Committee, 1984-1987, 1992-present, Chair, 1993 -1994; Graduate affairs 1984-1985; Merit Committee, 1988-1989; Publicity Committee, 1990-1991; Facilities Committee, 1992-1993; Chair, Aerospace Graduate Degree Program Committee, 1988-1989.

### 6.2 Virginia Polytechnic Institute and State University

General

Adjunct Professor, 1974 Academic Year

Developed new text material for students of ESM 6540, Hydrodynamic Stability; ESM 4040, Intermediate Fluid Mechanics; and ESM 5980, Boundary-Layer Stability and Transition.

Group leader for 29 engineering students on a two-week tour of the U.S.S.R., Mar 1979. Also organized the scientific and educational visits to the Academy of Science Computing Center, Moscow State University, and Latvian State University.

Served on 15 Ph.D. Committees and 8 M.S. Committees.

Ph.D. Students Supervised

J. Floryan, "Stability of Boundary-Layer Flows over Curved Surfaces," Jan 1980.

G. Reynolds, "Experiments on the Stability of a Flat-Plate Boundary Layer with Suction," Jan 1982.

M.S. Students Supervised

G. Reynolds, "Experiments on the Stability of Boundary-Layer Flows," May 1979.

G. Tice, "Experimental Investigation on the Stability of Taylor-Couette Flow," Dec 1981.

C. Costis, "Excitation of Wave Packets and Random Disturbances in a Boundary Layer," May 1982.

L. Yeates, "The Three-Dimensional Flow Field Over Swept-Leading-Edge Models," Sep 1984.

J. Crouch, "A Flying Hot-Wire Study of Separation over a FX-63-137 Airfoil," Jul 1985.

Senior Projects Supervised

W. Cousins, "Design and Construction of a 3-D Traverse Mechanism for Wind Tunnels," Mar 1978.

R. Gram, "Design of a Boundary-Layer Suction Device for Laminar Flow Control," Jun 1978.

L. Peach, "Airfoil Design for Man-Powered Aircraft," Jun 1978.

T. Burton, "A Digital Control and Servo for a Three-Dimensional Traverse Mechanism," May 1980.

B. Spigel, "The Design and Construction of Wall Bumps for the 3-D Flow over a Flat Plate," May 1980.

M. Holland, "The Design and Construction of a Taylor Vortex Apparatus," May 1981.

T. Shanahan, "Comparison of Techniques Used for Drag Measurement on Automobiles," May 1981.

R. Williams, "A Design of a Lightweight Test Section for the VPI Stability Tunnel," May 1981.

C. Harvey, "Design of a Versatile Test Section for the VPI & SU Stability Tunnel," May 1983.

R. Henk, "Computer Controlled Wind-Tunnel Experiment," May 1983. Recipient of the D.H. Pletta Award for the outstanding senior project.

C. May, "A Panel-Method Code to Design Wind-Tunnel Modifications for Pressure Gradients on Models," May 1983. Runner-up for the D.H. Pletta Award for the outstanding senior project.

J. Carter, "A Lagrangian Code for Streakline Calculations," Jun 1984.

G. Rose, "Use of Piezioelectric Polymer Films to Detect Transition to Turbulence," Jun 1984.

J. McCay, "Design of a Hot-Wire Traverse Mechanism to Operate in High Dynamic Pressure, Cryogenic Environments," Aug 1984.

Staff Supervised

D. Weber, Apr 1978 to Jul 1981, W. Alford, Jul 1982 to Sep 1983, and B. Farmer, Sep 1983 to Aug 1984: Full-Time Lab Mechanics working as technicians on the experimental fluid mechanics projects. Supported directly from research grants.

R. Frederick, Jun 1978 to Sep 1978: Full-Time Graduate Engineer working on wind-tunnel model design. Supported directly from research grants.

L. Bedwell, Sep 1982 to Mar 1983 and C. Hawley, Mar 1983 to Aug 1984: Full-Time Secretaries. Supported directly from research grants.

Committees

College of Engineering: Personnel, Planning and Publicity Committee, 1981-1983; Promotion and Tenure Committee, 1981-1984; Chairman, Allocation of University Resources Committee, 1982-1983.

ESM: Faculty Recruiting Committee, 1979-1982; Promotion and Tenure Committee, 1982-1984; Ph.D. Qualifying Exam Committee, 1979-1982; Laboratory Committee, 1977-1979; Self-Study Committee, Building and Facilities, 1976; Executive Committee, 1982-1984.

### 6.3 Sandia National Laboratories

Taught graduate level courses to the technical staff on "Hydrodynamic Stability" and "Perturbation Methods" as part of noon-hour educational program, Spring and Fall 1970.

Developed and taught an intensive (45 hours), 3-week course on "Perturbation Methods" to the technical staff in Albuquerque and to the technical staffs of Sandia Labs and Lawrence Livermore Labs in Livermore, California, Spring and Summer 1974.

Supervised experimental Ph.D. thesis of B. Marshall conducted at Sandia while Marshall was a student at Oklahoma State University.

### 6.4 University of New Mexico

Adjunct Professor, 1972.
Course Taught: ME 504 Heat Conduction

### 6.5 Illinois Institute of Technology

Had responsibility for teaching large (greater than 100 students) sections of the Engineering Science Curriculum. Taught: ES 202 Statics and Dynamics, ES 203 Strength of Materials, and ES 204 Fluid Mechanics.

## 7. SCHOLARLY AND CREATIVE CONTRIBUTIONS

### Publications - Journal and Society Papers


1. "Incompressible Magnetohydrodynamic Entrance Flow in a Plane Channel," W.S. Saric and K.J. Touryan, *Phys. Fluids, Vol. 12*, 1969, pp. 1412-1419.
2. "Nonlinear Resonances in the Motion of Rolling Reentry Bodies," A.H. Nayfeh and W.S. Saric, *AIAA Paper No. 71-0047*, January 1971.
3. "Nonlinear Kelvin-Helmholtz Instability," A.H. Nayfeh and W.S. Saric, *J. Fluid Mech., Vol. 46, No. 2*, 1971, pp. 209-232.
4. "Stability of Circular Couette Flow of Binary Mixtures," W.S. Saric and Z. Lavan, *J. Fluid Mech., Vol. 47, No. 1*, 1971, pp. 65-80.
5. "Stability of a Fluid Film," A.H. Nayfeh and W.S. Saric, *AIAA J., Vol. 9, No. 4*, 1971, pp. 750-752.
6. "An Experimental Investigation of the Stability of a Thin Liquid Layer Adjacent to a Supersonic Stream," W.S. Saric and B.W. Marshall, *AIAA J., Vol. 9*, 1971, pp. 1546-1553.
7. "Surge Waves in Stranded Springs," A.H. Nayfeh, W.S. Saric and D. Rodriquez, *J. of Engr. for Industry, Vol. 94, Series B, No. 3*, 1972, pp. 942-948, and *ASME Paper No. 71-VIBR-94*.
8. "An Analysis of a Asymmetric Rolling Bodies with Nonlinear Aerodynamics," A.H. Nayfeh and W.S. Saric, *AIAA J. Vol. 10, No. 8*, 1972, pp. 1004-1022 and *AIAA Paper No. 71-0932*.
9. "Nonlinear Waves in a Kelvin-Helmholtz Flow," A.H. Nayfeh and W.S. Saric, *J. Fluid Mech., Vol. 55, No. 2*, 1972, pp. 311-327.
10. "Nonlinear Stability of a Liquid Film Adjacent to a Supersonic Stream," A.H. Nayfeh and W.S. Saric, *J. Fluid Mech., Vol. 53, No. 1*, 1973, pp. 39-51.
11. "Nonlinear Acoustic Response of a Spherical Bubble," A.H. Nayfeh and W.S. Saric, *J. of Sound and Vibration, Vol. 30*, 1974, pp. 445-453.
12. "Stability of Nonparallel Flows," A.H. Nayfeh, W.S. Saric and D.T. Mook, *Archives of Mechanics, Vol. 26, No. 3*, 1974, pp. 401-406.
13. "Stability of Liquid Layers Adjacent to Compressible Streams," G.L. Bordner, A.H. Nayfeh and W.S. Saric, *ZAMP, Vol. 26*, 1975, pp. 771-783.
14. "Nonparallel Stability of Boundary-Layer Flows," W.S. Saric and A.H. Nayfeh, *Phys. Fluids, Vol. 18*, 1975, pp. 945-950.
15. "Compressible Boundary Layers over Wavy Walls," S.G. Lekoudis, A.H. Nayfeh and W.S. Saric, *Phys. Fluids, Vol. 19*, 1976, pp. 514-519.
16. "Experiments on the Stability of Liquid Films Adjacent to Supersonic Boundary Layers," W.S. Saric, A.H. Nayfeh and S.G. Lekoudis, *J. Fluid Mech., Vol. 77*, 1976, pp. 63-87.
17. "Stability of Slag in Turbulent MHD Boundary Layers," W.S. Saric, K.J. Touryan and M.R. Scott, *J. Energy, (AIAA) Vol. 1*, 1977, pp. 108-114 and *AIAA Paper No. 76-0314*, July 1976.
18. "Third-Order Resonant Wave Interactions," S.G. Lekoudis, A.H. Nayfeh and W.S. Saric, *Phys. Fluids, Vol. 11*, 1977, pp. 1793-1795.
19. "Nonparallel Stability of Boundary Layers with Suction," W.S. Saric and A.H. Nayfeh, *Proceedings No. 244, AGARD Symposium on Laminar-Turbulent Transition*, May 2-4, 1977, Copenhagen, Denmark.
20. "Stability of Görtler Vortices in Boundary Layers," J.M. Floryan and W.S. Saric, *AIAA Journal, Vol. 20, No. 3*, 1982, pp. 316-324 and *AIAA Paper No. 79-1497*.

21. "Experiments on the Nonlinear Stability of Waves in a Boundary Layer," W.S. Saric and G.A. Reynolds, In: *Laminar-Turbulent Transition*, Springer-Verlag, 1980.
22. "Wavelength Selection and Growth of Görtler Vortices," J.M. Floryan and W.S. Saric, *AIAA Journal, Vol. 22, No. 11*, pp. 1529-1538, and *AIAA Paper No. 80-1376.*
23. "Nonlinear Wave Interactions in Supersonic Wind-Generated Waves," S.G. Lekoudis, A.H. Nayfeh and W.S. Saric, *Phys. Fluids, Vol. 25, No. 9*, 1982, pp. 1524-1531.
24. "Experiments on the Stability of a Flat-Plate Boundary Layer with Suction," G.A. Reynolds and W.S. Saric, *AIAA Journal, Vol. 24, No. 2*, 1986, pp. 202-207, and *AIAA Paper No. 82-1026.*
25. "Effect of Suction on the Görtler Instability of Boundary Layers," J.M. Floryan and W.S. Saric, *AIAA Journal, Vol. 21, No. 12*, 1983, pp. 1635-1639.
26. "Effect of Suction and Mass Injection Boundary-Layer Transition," W.S. Saric and H.L. Reed, *AIAA Journal, Vol. 24, No. 3*, pp. 383-389, 1986 and *AIAA Paper No. 83-0043.*
27. "On the Visualization of Stream Structures in a Boundary Layer," (in Russian) A.V. Dovgal, V.V. Kozlov, I.P. Nosyrev and W.S. Saric, *Publication No. 37-81 of USSR Acad. Sci.*, Sib. Div., I.T.A.M.
28. "An Orthogonal Coordinate Grid Following the Three-Dimensional Viscous Flow Over a Concave Surface," J.R. Dagenhart and W.S. Saric, *Proceedings of Symposium on Grid Generation Techniques*, ASME Fluids Engineering Conference, June 1983.
29. "Forced and Unforced Subharmonic Resonance in Boundary-Layer Transition," W.S. Saric, V.V. Kozlov and V. Ya. Levchenko, *AIAA Paper No. 84-0007*, January 1984.
30. "Design of High-Reynolds-Number Flat Plate Experiments in the NTF," W.S. Saric and J.B. Peterson, *AIAA Paper No. 84-0588*, March 1984.
31. "Generation of Crossflow Vortices in a Three-Dimensional Flat-Plate Flow," W.S. Saric and L.G. Yeates, *Laminar-Turbulent Transition, Vol. 2*, V. Kozlov ed., Springer-Verlag, June 1985.
32. "Experiments on the Subharmonic Route to Transition," W.S. Saric and A.S.W. Thomas, *Turbulence and Chaotic Phenomena in Fluids*, Ed: T. Tatsumi, North-Holland, 1984.
33. "Formation of Three-Dimensional Structure at Transition in a Boundary Layer," (in Russian) V.V. Kozlov, V. Ya. Levchenko and W.S. Saric, *Mekanika Zhidkosti i Gaza, No. 6*, pp. 42-50, November 1984, (authors listed alphabetically).
34. "Experiments on the Stability of Crossflow Vortices in Swept-Wing Flows," W.S. Saric and L.G. Yeates, *AIAA Paper No. 85-0493*, January 1985.
35. "Oscillating Hot-Wire Measurements Above An FX63-137 Airfoil," J.D. Crouch and W.S. Saric, *AIAA Paper No. 86-0012*, January 1986.
36. "Visualization of Different Transition Mechanisms," W.S. Saric, *Phys. Fluids, Vol. 29, No. 9*, 1986, p. 2770.
37. "Boundary Layer Transition to Turbulence: The last five years," W.S. Saric, *Proc. 10th Symposium on Turbulence*, September 1986.
38. "Three-Dimensional Stability of Boundary Layers," W.S. Saric and H.L. Reed, *Perspectives in Turbulence*, Eds: U. Meier and P. Bradshaw, Springer-Verlag, 1987.
39. "Fundamental Requirements for Freestream Turbulence Measurements," W.S. Saric, S. Takagi, and M.C. Mousseux, *AIAA Paper No. 88-0053*, January 1988.
40. "Stability of Three-Dimensional Boundary Layers," H.L. Reed and W.S. Saric, *Ann. Rev. Fluid Mech. Vol. 21*, 1989.
41. "Experiments in Swept-Wing Transition," W.S. Saric, J.R. Dagenhart, and M.C. Mousseux, *Numerical and Physical Aspects of Aerodynamic Flows, Vol. 4*, Ed: T. Cebeci, Springer-Verlag, 1990.

42. "Control of Random Disturbances in a Boundary Layer," P.T. Pupator and W.S. Saric, *AIAA Paper No. 89-1007*, March, 1989.

43. "Crossflow-Vortex Instability and Transition on a 45-Degree Swept Wing," J.R. Dagenhart, W.S. Saric, M.C. Mousseux, and J.P. Stack, *AIAA Paper No. 89-1892*, June, 1989.

44. "Boundary Layer Stability and Transition," W.S. Saric, *Proc. 5th International Conference on Numerical Ship Hydrodynamics*, Hiroshima, Japan, September 25-28, 1989.

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**Talks and Lectures by W.S. Saric**

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2. "Sandia Liquid-Layer Stability Program," Reentry Vehicle Nosetip Symposium, Aerospace Corporation, San Bernadino, California, August 22, 1969.

3. "The Stability of Circular Couette Flow of Binary Mixtures," 6th U.S. National Congress of Applied Mechanics, Harvard University, Boston, Massachusetts, June 1970.

4. "An Experimental Investigation of the Stability of a Thin Liquid Layer Adjacent to a Supersonic Airstream," 3rd AIAA Fluid and Plasma Dynamics Conference, Los Angeles, California, June 1970, *AIAA Paper No. 70-0801*.

5. "Nonlinear Kelvin-Helmholtz Instability," 23rd Meeting of the Division of Fluid Dynamics, American Physical Society, Charlottesville, Virginia, November 23-25, 1970, *Bull. Amer. Phys. Soc. 15*, 1970.

6. "Experimental and Theoretical Investigations of the Stability of Liquid Films," (a) Workshop on Transpiration Cooling in Three-Dimensional Flow Fields, Aerospace Corporation, January 5, 1971, (b) Virginia Polytechnic Institute and State University, Engineering Science and Mechanics Seminar, April 18, 1971.

7. "Nonlinear Motion of an Asymmetric Body with Variable Roll Rate," AIAA Guidance, Control, and Flight Mechanics Conference, Hofstra University, Hampstead, NY, August 16-18, 1971, *AIAA Paper No. 71-0932*.

8. "Stability of Liquid Films Interacting with Supersonic Streams: Theory and Experiment," (a) XII International Congress of Theoretical and Applied Mechanics, Moscow, U.S.S.R., August 21-26, 1972; (b) New York University, Guggenheim School of Aeronautics Seminar, December 12, 1972; (c) Illinois Institute of Technology, Mechanical and Aerospace Engineering Seminar, December 13, 1972.

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10. "Applications of Singular Perturbation Methods to Nonlinear Problems in Applied Mechanics," Reactor Analysis and Safety Division Seminar, Argonne National Laboratories, April 23, 1974.

11. "Nonparallel Boundary-Layer Stability," (a) Mechanical Engineering Seminar, Illinois Institute of Technology, April 22, 1974; (b) Mathematics Seminar, Rensselaer Polytechnic Institute, April 29, 1974; (c) Mechanics Seminar, The Johns Hopkins University, May 7, 1974; (d) Institute of Theoretical and Applied Mechanics, U.S.S.R Academy of Sciences, Novosibirsk, July 1, 1974; (e) Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 31, 1974; (f) University of Waterloo, Ontario, Canada, May 9, 1975; (g) Proceedings Second Low-Speed Boundary Layer Transition Workshop, RAND Corp., Santa Monica, California, September 13-15, 1976, *RAND/P-6119*, January 1978.

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48. "Oscillating Hot-Wire Measurements Above an FX63-137 Airfoil," (a) AIAA 24th Aerospace Sciences Mtg., January 1986, *AIAA Paper 86-0012*; (b) 2nd Annual Arizona Fluid Mechanics Meeting, Tempe, April 4-5, 1986.

49. "Initiating Chaos in Boundary Layers," *(Invited)* Chaotic Motion in Open Flows Workshop, UC Nonlinear Studies, Lake Arrowhead, California, February 7-9, 1986.

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60. "Stability and Transition in Three-Dimensional Boundary Layers," *(Invited)*, AGARD Symposium on Fluid Dynamics of Three-Dimensional Turbulent Flows and Transition, Cesme, Turkey, October 3-6, 1988.

61. "Secondary Instabilities Leading to Transition," (*Invited*), E.R.C.O.F.T.A.C., Course on Physics of Transition from Laminar to Turbulent Flow, Politecnico di Torino, Torino, Italy, October 13, 1988.

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64. "Control of Random Disturbances in a Boundary Layer," (a) 2nd AIAA Shear Flow Control Conference, March 13-16, 1989, *AIAA Paper No. 89-1007*; (b) Fifth Arizona Fluid Mechanics Conference, February 1989.

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72. "Summary of Görtler Vortex Research -- Euromech 261 and The Future," *(Invited), Görtler Vortex Flows, EUROMECH 261*, June 14, 1990, Nantes, France.

73. "Visualization of Low-Reynolds-Number Flow Fields Around Receptivity Elements," 43rd Annual Meeting of the American Physical Society, November 18-20, 1990, *Bull. Amer. Phys. Soc. Vol. 35*, p. 2262.

74. "Boundary Layer Transition Control Using Receptivity," AFOSR Mtg on *Turbulence Structure and Control*, April 1-3, 1991.

75. "Surfaces Nonuniformity Effects on Stability and Transition," (a) NASA-Langley Research Center, April 24. 1991, (b) NASA-Ames Research Center, May 16, 1991, (c) 44th Annual Meeting of the American Physical Society, November 24-26, 1991, *Bull. Amer. Phys. Soc. Vol. 36*, 2630.

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81. "Laminar-Turbulent Transition: Fundamentals," *Special Course on Skin Friction Drag Reduction, AGARD Report 786*, Brussels, March 1992.

82. "The ASU Transition Research Facility." AIAA 17th Aerospace Ground Testing Conference, July 6, 1992, *AIAA Paper No. 92-3910.*

83. "Nonlinear Development of Görtler Vortices over Variable Curvature Surfaces." (a) NASA-Langley Research Center, July 30, 1992, (b) International Taylor-Couette Symposium, Nice, France, March 30, 1993.

84. "Boundary-Layer Receptivity: Freestream Sound on an Elliptical Leading Edge." 45th Annual Meeting of the American Physical Society, November 22-24, 1992, *Bull. Amer. Phys. Soc. Vol. 37*, 1720.

85. "Boundary-Layer Transition: Experimental Evidence," *Special Course on Progress in Transition Modelling, AGARD Report 794*, (a) Madrid, Spain March 22, 1993, (b) Brussels, March 29, 1993.

86. "Low-Speed Boundary-Layer Transition," *ICASE/NASA Short Course on Experimental Methods Related to Instabilities and Transition to Turbulence*, June 2, 1993.

87. "Receptivity: Initial-Value Problems for Treansition to Turbulence," *(Invited G.I. Taylor Lecture)*, ASCE/ASME/SES *Summer Meet'n '93*, Univ. Virginia, June 8, 1993.

88. "Nonlinear Stability and Transition in 3-D Boundary Layers," (a) Hypersonics Workshop, NASA-Langley Research Center, November 1, 1993; (b) University of Minnesota, March 26, 1994.

## 8. SPONSORED RESEARCH ACTIVITIES

### 8.1 Arizona State University

Principal investigator on external research and equipment projects with sponsor totals of *$2,788,472*. Levels of responsibility on these projects total *$2,517,529* during nine years.

ACTIVE

1. "Transition Studies on a Swept-Wing Model," NASA Langley Research Center, Grant NAG1-937, 1/Oct/88 - 15/Jan/94, *$550,495.*

2. "Control of Unstable Waves in Three-Dimensional Boundary Layers," NASA Langley Research Center, Fellowship GR-NAG1-1111, 23/Feb/90 - 22/Feb/94, *$201,996.*

3. "Hybrid Laminar Flow Control Experiments in the NASA-Ames 11-foot Tunnel" NASA-Ames Research Center, University Consortium Interchange NCA2-745, 1/Sep/92 - 31/Mar/93, *$11,893.*

4. "Receptivity in Boundary-Layer Transition to Turbulence," Air Force Office of Scientific Research, 1/May/93 - 30/Sep/95, *$253,284.*

INACTIVE

5. "Flat Plate Experiments in the National Transonic Facility," NASA Langley Research Center, 22/Oct/84 - 30/Dec/87, *$101,137.*
6. "Three-Dimensional Structure of Transitional Boundary Layers," Air Force Office of Scientific Research, 5/Jun/85 - 14/Nov/89, *$393,654.*
7. "Boundary-Layer Stability in Laminar Flow Control," NASA Langley Research Center Grants NAG 1-598, NAG 1-805, and NAG 1-1032, 15/Jun/85 - 31/Dec/89, *$180,278.*
8. "Unsteady Low-Reynolds-Number Aerodynamics," Office of Naval Research, 16/Jun/85 - 30/Sep/89, *$217,600.*
9. "Multi-Axis, 3-D, Scanning LDA System for Unsteady Aerodynamics," Air Force Office of Scientific Research, 1/Oct/86 - 30/Sep/88, *$148,974.*

10. "Stability and Transition of Hypersonic Boundary-Layer Flows," Air Force Office of Scientific Research, Contract F49620-88-C-0076, 16/May/88 - 15/May/91, Co-Principal Investigator with Helen Reed, *$282,264, Responsible for $142,132.*

11. "Effect of Sound on Boundary-Layer Stability," NASA Ames Research Center, Co-operative Agreement NCC2-659, 16/Nov/89 - 31/Jul/92, *$94,106.*

12. "Transition Receptivity and Control," Air Force Office of Scientific Research, Grant AFOSR-90-0234, 2/Jan/90 - 15/Dec/92, Co-Principal Investigator with Helen Reed, *$353,391, Responsible for $222,580.*

### 8.2 Arizona State University: Unsteady Wind Tunnel Project

The *ASU Unsteady Wind Tunnel* is a major research facility that was established at ASU by W. S. Saric. This effort involved the acquisition and transport of key elements from the Klebanoff tunnel at the National Bureau of Standards, building construction at ASU, redesign and construction of 75% of the tunnel, purchase of supplies, tools, and instrumentation, and the accounting and subcontracting as well as the supervision of staff and student workers. The building was completed June 1985 and the tunnel became operational December 1987 with total expenditures of over $1,000,000 from University, Federal Agency, and Local Industry support. Present worth $1,600,000.

## 8.3 Virginia Polytechnic Institute and State University

Principal or Co-Principal Investigator on research and equipment projects with sponsor totals of *$2.0 million*. Levels of responsibility on these projects total *$1.4 million* during nine years.

1. "Application of Stability Theory to Laminar Flow Control," NASA Langley Research Center, $180,000, A.H. Nayfeh and W.S. Saric - Co-Principal Investigators, 10/1/75 - 11/1/78. Responsible for $90,000.
2. "Experiments on the Stability and Transition of Two-Dimensional and Three-Dimensional Boundary Layers with Suction," NASA Langley Research Center, $127,000, W.S. Saric - Principal Investigator, 12/1/76 - 2/1/79. Responsible for $127,000.
3. "Experiments on the Nonparallel Stability of Boundary-Layer Flows," W.S. Saric and A.H. Nayfeh, National Science Foundation, $56,000, W.S. Saric - Principal Investigator, 2/15/78 - 5/1/79. Responsible for $56,000.
4. "Experiments to Verify Nonparallel Stability Theory," NASA Langley Research Center, $293,000, W.S. Saric - Principal Investigator, 4/1/79 - 1/15/83. Responsible for $293,000.
5. "Application of Nonlinear Stability Techniques to Boundary-Layer Transition," Naval Surface Weapons Center, White Oak, $31,938, W.S. Saric and Th. Herbert - Principal Investigators, 7/1/81 - 5/1/82. Responsible for $8,500.
6. "Aspects of Transition in Low-Reynolds-Number Aerodynamics," Office of Naval Research, $67,431, Th. Herbert and W.S. Saric - Principal Investigators, 1/1/83 - 12/15/83. Responsible for $33,700.
7. "Experiments on the Three-Dimensional Structure of Boundary Layers Undergoing Transition to Turbulence," A.F.O.S.R., $117,000, W.S. Saric - Principal Investigator, 6/1/82 - 12/15/83. Responsible for $117,000.
8. "An Analysis of Wave Interactions in Swept-Wing Flows," NASA Langley Research Center, $61,427, W.S. Saric and H.L. Reed - Principal Investigators, 10/7/82 - 1/31/84. (Joint with Stanford University.) Responsible for $27,900.
9. "Experiments on the 3-D Interactions of Disturbances in Boundary Layers," NASA Langley Research Center, $171,000, W.S. Saric - Principal Investigator, 6/1/82 - 9/15/84. Responsible for $171,000.
10. "An Analysis of the Nonlinear Stability of Circular Couette Flow," U.S. Army Research Office, $109,816, Th. Herbert and W.S. Saric - Principal Investigators, 6/16/82 - 6/15/84. Responsible for $12,000.
11. "High Reynolds Number, Flat-Plate Experiments in the National Transonic Facility," NASA Langley Research Center, $114,624, W.S. Saric - Principal Investigator, 7/26/82 - 7/25/84. Responsible for $114,624.
12. "Nonlinear Mechanisms in Unstable Plane Poiseuille Flow," National Science Foundation, $132,618, Th. Herbert and W.S. Saric - Principal Investigators, 10/16/82 - 8/31/84. Responsible for $30,000.
13. "Aspects of Low-Reynolds-Number Aerodynamics," Office of Naval Research, $160,000, Th. Herbert, J.F. Marchman and W.S. Saric, Principal Investigators, 12/15/83 - 8/31/84. Responsible for $75,100.
14. "On the Three-Dimensional Structure of Boundary Layers Undergoing Transition to Turbulence," A.F.O.S.R., $93,041, W.S. Saric and Th. Herbert, Principal Investigators, 2/16/84 - 8/31/84. Responsible for $60,000.
15. "432/CDS-VAX11/750 System for DoD University Research Instrumentation Program," Office of Naval Research, $263,903, W.S. Saric, D.P. Telionis, E.G. Henneke, and K.L. Reifsnider, Principal Investigators, 7/25/83 - 7/24/84. Responsible for $164,000.

Appendix C.