AD-A015 374

LOW-SPEED BOUNDARY-LAYER TRANSITION WORKSHOP

William S. King

RAND Corporation

Prepared for:

Defense Advanced Research Projects Agency
Office of Naval Research

June 1975

ARPA ORDER NO.: 189-1
6G10 Tactical Technology Office

R-1752-ARPA/ONR
June 1975

Low-Speed Boundary-Layer Transition Workshop

William S. King

A Report prepared for

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY
AND
OFFICE OF NAVAL RESEARCH

Rand
SANTA MONICA, CA. 90406

The research described in this Report was sponsored jointly by the Defense Advanced Research Projects Agency under contract No. DAHC15-73-C-0181 and by the Office of Naval Research under contract No. N00014-75-C-0047. Reports of The Rand Corporation do not necessarily reflect the opinions or policies of the sponsors of Rand research.

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I.

The report contains

Documentation of the Low-Speed Boundary-Layer Transition Workshop held at The Rand Corporation on July 16-17, 1974. The objectives of the workshop were to review the current state of the art for predicting the transition from laminar to turbulent incompressible flow and to suggest an outline of future goals for current research programs. The workshop program was divided into three sessions: Theoretical, experimental, and design. R-1752-ARPA/ONR outlines the program, lists the attendees, summarizes and discusses the sessions, and presents abstracts of the papers. (JDD)

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER R-1752-ARPA/ONR	**2. GOVT ACCESSION NO.**	**3. RECIPIENT'S CATALOG NUMBER**
4. TITLE (*and Subtitle*) Low-Speed Boundary-Layer Transition Workshop		**5. TYPE OF REPORT & PERIOD COVERED** Interim **6. PERFORMING ORG. REPORT NUMBER**
7. AUTHOR(s) William S. King		**8. CONTRACT OR GRANT NUMBER(s)** DAHC15-73-C-0181 N00014-75-C-0047
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Rand Corporation 1700 Main Street Santa Monica, Ca. 90406		**10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS**
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Adv. Research Projects Agency, Arlington, Va, 22209 and Office of Naval Research, Arlington Va 22217		**12. REPORT DATE** June 1975 **13. NUMBER OF PAGES** 54
14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)		**15. SECURITY CLASS.** (*of this report*) UNCLASSIFIED **15a. DECLASSIFICATION/DOWNGRADING SCHEDULE**

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

No restrictions

18. SUPPLEMENTARY NOTES

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Boundary Layer Transition
Underwater Vehicles
Submarines
Fluid Flow
Low-Speed Boundary Layer Transition

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

see reverse side

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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PREFACE

This report has been prepared to document the Low-Speed Boundary-Layer Transition Workshop held at the offices of The Rand Corporation July 16-17, 1974. The workshop was jointly sponsored by the Defense Advanced Research Projects Agency and the Office of Naval Research.

The workshop had as its principal goal a review and appraisal of current research in low-speed boundary-layer transition. But it had other, equally important goals, such as exposing researchers to the problems of low-speed vehicle designers and to some current design techniques. It was hoped that the exposure would inspire new efforts on the practical problem of predicting transition, as well as making the participants aware of research areas of interest to ARPA and the Navy.

SUMMARY

The objectives of the workshop--to review the current state of the art for predicting the transition from laminar to turbulent incompressible flow and to suggest an outline of future goals for current research programs--were satisfied in that prediction techniques and current research were presented, evaluated, and discussed. In the theoretical session, new approaches for numerically predicting transition were delineated and discussed by the workshop. Although current progress is encouraging, it appears that reliable and versatile numerical prediction methods are still some years away. The experimental session provided an opportunity to evaluate experiments of a similar nature that produced somewhat different results and to compare experimental techniques. Results were presented that showed wall heating could be employed to increase critical Reynolds number. It was in the design session that the argument for more controlled experiments and more orderly analysis of existing data was cogently made. Several recently derived prediction methods were presented that could benefit from a greater exposure to experimental data. The major conclusions that could be drawn from the discussions of the workshop are:

1. Progress is being made in developing numerical techniques for the solution of the Navier-Stokes equations; however, there is presently no one method that appears best from the standpoint of expediency and accuracy.
2. For axisymmetric geometries, the present engineering prediction methods are either difficult to use or inaccurate or both. Even the nominally reliable "e^9" method apparently requires some expert interpretation.
3. No definitive experiments like the Klebanoff-Tidstrom two-dimension experiments exist for axisymmetric bodies.
4. Transition Reynolds number is critically affected by axisymmetric geometric parameters, i.e., blunt versus slender bodies.

ACKNOWLEDGMENTS

The author would like to acknowledge the generous support of this workshop by the Defense Advanced Research Projects Agency and the Office of Naval Research. The author is most grateful to Mr. Robert M. Chapman of ARPA and Mr. Ralph Cooper of ONR for their helpful suggestions and ideas on the workshop program and their encouragement when the organizational problems appeared endless. Finally, the author would like to acknowledge the contributions of the session chairmen, Professor John Laufer, University of Southern California; Dr. Philip S. Klebanoff, National Bureau of Standards; Professor Eli Reshotko, Case Western Reserve University; and Dr. Carl Gazley, Jr., The Rand Corporation; and of the keynote speaker, Professor Mark V. Morkovin, Illinois Institute of Technology. In addition to their efforts during the workshop, all made noteworthy contributions to the organizing and evaluation of the workshop and to the writing of this report.

CONTENTS

1. INTRODUCTION

Designers of underwater vehicles are interested in having as much of the vehicle body as possible operate in a laminar flow region because of the large premiums obtainable, such as reductions in drag and flow noise. A crucial question currently confronting designers of vehicles for underwater applications is: What is the transition Reynolds number for a given set of flow conditions and what are the geometrical parameters that influence it? Normally the designer resorts to employing several correlations of transition Reynolds number as a function of some boundary-layer parameter, and these correlations are derived from specific data whose source is long forgotten. More probable than not, the designer will be interested in regions where either the bases for the correlation are not applicable or the correlation has not been validated by experimental data. For example, the Michel-Smith "e^9" curve has never been fully experimentally verified. Major uncertainties in the effects of crucial parameters, such as free-stream disturbances and body geometry on transition Reynolds number, indicate that this correlation is incomplete. To improve the reliability of predicting boundary-layer transition at high Reynolds numbers, empirical methods such as the Michel-Smith curve must have broader experimental verification and a sounder theoretical basis. There does not appear to be a current effort directed towards this goal.

Because it is one of the most important unsolved problems in fluid dynamics, research on boundary-layer transition is of great interest throughout the technical community. However, during the last 15 years emphasis on missile program re-entry physics has detracted funds and manpower from research in the low-speed regime and diverted them to the high-speed, compressible flow regime where the problems are quite different. Nevertheless, research on transition of low-speed boundary layers remained active. There appears to be a need to review this research in view of today's demand for reliable prediction methods.

There has been a recent revival of interest and research in transition at low speed in which the impetus has been supplied by new applications of high-performance vehicles, such as long-range, low-speed aircraft, high-speed ground transportation, and underwater vehicles. However, there is no effective means either to coordinate or to communicate this valuable research except through an archive journal, and this method is not optimal because of long delays in publication and because much of the applied research is classified. Therefore, it is very possible that current research programs and design studies are not appropriately benefiting from current research results. It was realized that a workshop devoted to low-speed boundary-layer transition could provide a medium for active researchers to present their current research, to exchange ideas with colleagues, and to establish new, viable research goals. These motives inspired The Rand Corporation to organize and manage the Low-Speed Boundary-Layer Transition Workshop.

The workshop was held at The Rand Corporation on July 16 and 17, 1974. The objective of the workshop was to review the current state of the art for predicting the transition from laminar to turbulent incompressible flow and to suggest an outline of future goals for current research programs. Attendance was by invitation; there were 82 participants and 32 invited papers. This condensed account of the workshop gives the program, summarizes and discusses the sessions, and presents abstracts of the papers.

II. LOW-SPEED BOUNDARY-LAYER TRANSITION WORKSHOP PROGRAM

Tuesday, July 16

8:00 A.M. WELCOME: Donald B. Rice, President, The Rand Corporation

8:15 A.M. KEYNOTE SPEAKER: Mark V. Morkovin, Illinois Institute of Technology

9:00 A.M. THEORETICAL SESSION: Chairman, John Laufer, University of Southern Californi[illegible]

T-1 *Disturbances in a Boundary Layer Introduced by Vortex Array Representations of Free-Stream Turbulence*, H. Rogler and E. Roshotko, Case Western Reserve University.

T-2 *Numerical Simulation of Boundary-Layer Transition on a Flat Plate*, Steven A. Orszag, Flow Research, Inc.

T-3 *Ambient Turbulence in an Oceanic Environment*, John E. Lewis, Wayne Haigh, and Al Atkinson, Techmate, Inc.

T-4 *Stability Investigation of Laminar Boundary-Layer Flows by Numerical Integration of the Navier-Stokes Equations*, H. Fasel, Institut A für Mechanik, Universität Stuttgart.

T-5 *Simulation of Boundary-Layer Transition Using Interacting, Three-Dimensional Vortex Filaments*, A. Leonard, NASA Ames Research Center.

T-6 *Reverse Transition Due to Body Force Effects*, George L. Mellor, Princeton University.

T-7 *Stability and Transition in Three-Dimensional Boundary Layers: State of the Art and Necessary Future Work*, E. H. Hirschel, DFVLR-Institut für Angewandte Gasdynamik.

T-8 *A Statistical Analysis of a Boundary Layer*, A. J. Chorin, University of California at Berkeley.

T-9 *A New Semi-Rational Model for Transition of Incompressible Boundary Layers*, R. E. Kaplan, University of Southern California.

T-10 *Numerical Simulation of Instability and Transition*, Chester E. Grosch, Institute of Oceanography, Old Dominion University.

1:30 P.M. EXPERIMENTAL SESSION: **Chairman, Philip S. Klebanoff, National Bureau of Standards, Aerodynamics Section**

E-1 *A Review of Six Stages of Natural Transition Using Visual Data*, **S. J. Kline, Stanford University.**

E-2 *Stability of a Heated Water Boundary Layer*, **R. L. Lowell, E. Reshotko, A. Strazisar, M. Nice, and J. M. Prahl, Case Western Reserve University.**

E-3 *The Effect of Sound Upon Boundary-Layer Transition*, **Patrick Leehey, Massachusetts Institute of Technology.**

E-4 *A Curious Mechanism of Transition to Turbulence Downstream of an Isolated Three-Dimensional Roughness*, **Mark V. Morkovin and R. S. Norman, Illinois Institute of Technology.**

E-5 *A Note on the Transition Observations on an Axisymmetric Body and Some Related Fluctuating Wall Pressure Measurements*, **Vijay H. Arakeri, California Institute of Technology.**

E-6 *Tentative Prediction of the Boundary-Layer Development in a Transition Region*, **R. Michel, ONERA-CERT-DERAT, Complexe Aerospatial.**

E-7 *Some Observations on the Growth of Turbulence in a Laminar Boundary Layer*, **I. Wygnanski, M. Sokolov, and D. Friedman, Tel-Aviv University.**

E-8 *Some Experimental Investigations in the Garfield Thomas Water Tunnel*, **Blaine Parkin, Pennsylvania State University Research and Development Center.**

E-9 *An Experimental Study of the Wall Pressure Bursts During Boundary-Layer Transition*, **Fred C. DeMetz, Naval Ship Research and Development Center.**

E-10 *The Turbulent Spot as a Large Vortex*, **D. Coles and S. Barker, California Institute of Technology.**

E-11 *Experimental Studies of Natural Transition*, **C. S. Wells, Jr., Advanced Technology Center, Inc.**

Wednesday, July 17

8:30 A.M. **NEW RESULTS: A. R. Wazzan, Christopher Brennen, David C. Wilcox**

10:00 A.M. **PANEL DISCUSSION: A REVIEW OF THE STATUS OF TRANSITION RESEARCH. E. Reshotko, Chairman; Mark V. Morkovin, S. J. Kline, I. Wygnanski, A.M.O. Smith, R. Michel, John Laufer**

1:30 P.M. **DESIGN SESSION: Chairman, Carl Gazley, Jr., The Rand Corporation**

D-1 *The Prediction of Transition from Laminar to Turbulent Flow in Boundary Layers on Bodies of Revolution*, **Paul S. Granville, Naval Ship Research and Development Center.**

D-2 *The "e^9" Method with Special Reference to Bodies of Revolution*, **A.M.O. Smith and Kalle Kaups, Douglas Aircraft Company.**

D-3 *On an Extension of the Two-Dimensional Michel-Smith Correlation to Axisymmetric Bodies*, **E. Van Driest and J. Aroesty, The Rand Corporation.**

D-4 *Subsonic, Axisymmetric Boundary-Layer Transition Predictions Versus Experiments*, **George H. Christoph, Naval Underwater Systems Center.**

D-5 *Axisymmetric Transition: Correlation of the Maximum Reynolds Number Limiting Applicability of the Two-Dimensional Michel-Smith Criterion to an Arbitrary Body*, **F. R. Goldschmied, Westinghouse Research Laboratories.**

Classified Papers

D-6 *A Study of the Transition and Drag Characteristics of a Family of Three Axisymmetric Bodies* **(U), R. Gulino and R. F. Mons, Westinghouse Research Laboratories (Secret).**

D-7 *Measurement of Boundary-Layer Transition on a Hemispherical Bow of the Submarine Dolphin* **(U), Brian E. Bowers, Naval Ship Research and Development Center (Secret).**

D-8 *Experimental Investigation of Boundary-Layer Transition on a Large Submarine Model: KAMLOOPS* **(U), John T.C. Shen, Naval Ship Research and Development Center (Secret).**

ATTENDEES

LOW-SPEED BOUNDARY-LAYER TRANSITION WORKSHOP

July 16, 1974

ACOSTA, Allan J.	California Institute of Technology
ALONSOS, Carlos	Naval Ship Research & Development Center
ANDERSON, Aemer D.	ACUREX Corporation (Aerotherm)
ARAKERI, Vijay	California Institute of Technology
AEROSTY, Jerry	The Rand Corporation
BARKER, Steven	California Institute of Technology
BAUM, Eric	TRW, Inc.
BOWERS, Brian E.	Naval Ship Research & Development Center
BRECKON, Richard L.	Office of Naval Research
BRENNEN, Christopher	California Institute of Technology
CAGLE, Ben	Office of Naval Research
CARAHER, James	Naval Undersea Center
CEBECI, Tuncer	McDonnell Douglas
CHAPMAN, Robert M.	Defense Advanced Research Projects Agency
CHORIN, Alexandre	University of California, Berkeley
CHRISTOPH, George H.	Naval Underwater Systems Center
COLES, Don	California Institute of Technology
COOPER, Larry	ACUREX Corporation (Aerotherm)
CONTI, Raul J.	Lockheed, Palo Alto
CROW, Steve	University of California, Los Angeles
DEMETZ, Frederick C.	Naval Ship Research & Development Center
ELLINWOOD, John W.	Aerospace Corporation
EINAV, Sam	Tel-Aviv University
FABULA, Andrew	Naval Undersea Center
FASEL, Herman	University of Stuttgart
FRANZ, Gerald	Naval Ship Research & Development Center
GAZLEY, Carl	The Rand Corporation
GOLDSCHMIED, Fabio R.	Westinghouse Research & Development
GRANVILLE, Paul	Naval Ship Research & Development Center
GRITTON, Eugene	The Rand Corporation

GROSCH, Chester	Old Dominion University
HAIGH, Wayne W.	Techmate, Inc.
HAMA, Francis	Princeton University
HIRSCHEL, Ernst H.	DFVLR, Institut für Angewandte Gasdynamik
HUANG, Tom	Naval Ship Research & Development Center
KAPLAN, Robert	University of Southern California
KAUPS, Kalle	McDonnell Douglas
KENDAL, James	Jet Propulsion Laboratory
KING, William	The Rand Corporation
KLEBANOFF, Philip S.	U.S. Department of Commerce
KLINE, Steve	Stanford University
KNIGHT, Dale	Wright-Patterson Air Force Base
KO, Denny R.S.	Flow Research, Inc.
LANG, Thomas G.	Naval Undersea Center
LAUFER, John	University of Southern California
LEEHEY, Patrick	Massachusetts Institute of Technology
LEONARD, Anthony	NASA Ames Research Center
LEWIS, John E.	Techmate, Inc.
MACK, Leslie M.	Jet Propulsion Laboratory
MAGER, Arthur	Aerospace Corporation
MANNING, Robert	Naval Sea Systems Command
McCRACKEN, Marjorie	University of California, Berkeley
McDONALD, Alan	Purdue University
MELLOR, George	Princeton University
MERKLE, Charles	Flow Research, Inc.
MICHEL, Roger	ONERA-CERT-DERAT, France
MONS, Robert F.	Oceanic Division (Westinghouse)
MORKOVIN, Mark V.	Illinois Institute of Technology
MURDOCK, John W.	Aerospace Corporation
NOH, William F.	Lawrence Livermore Laboratory
ORSZAG, Steven A.	Flow Research, Inc.
PARKIN, Blaine R.	Applied Research Laboratory
PERKINS, Francis W., Jr.	Stanford Research Institute
PHINNEY, Ralph E.	Naval Ordnance Laboratory
PIERCE, Tom	Naval Ordnance Command

REDA, Daniel C.	Naval Ordnance Laboratory
RESHOTKO, Eli	Aerospace Corporation
ROACHE, Patrick J.	Science Application, Inc.
ROGERS, Milton	Air Force Office of Scientific Research
ROGLER, H.	Case Western Reserve University
SHEN, John T.C.	Naval Ship Research & Development Center
SMITH, Apollo Milton Olin	McDonnell Douglas
STRAZISAR, A.	Tel-Aviv University
TAYLOR, Thomas D.	Aerospace Corporation
VAN DRIEST, Ed	The Rand Corporation
VICTORIA, Keith J.	Aerospace Corporation
WAZZAN, A. R.	University of California, Los Angeles
WELLS, Curtis S., Jr.	Advanced Technology Center
WILCOX, David C.	DCW Industries
WORTMAN, Andrew	Northrop Corporation
WYGNANSKI, I.	Tel-Aviv University
WOOLLEY, James P.	Nielsen Engineering & Research

III. ABSTRACTS OF PAPERS PRESENTED

INTRODUCTION

For the purpose of this discussion, the papers presented at the workshop may be placed in the following general categories:

1. Numerical solutions of the Navier-Stokes equations.
2. The effects of free-stream and wall conditions on boundary-layer transition.
3. Boundary-layer stability theory and experiments.
4. Turbulent model equations for transition prediction.
5. The role of turbulent spots in boundary-layer transition.
6. Transition prediction methods.

1. Numerical Solutions of the Navier-Stokes Equations

Five papers were presented on numerical simulation of solutions of the Navier-Stokes equations. Three of the papers (T-2, T-4, and T-10) employed different variations of finite-difference schemes to solve the equations, and the last two papers (T-5 and T-8) discussed a grid-free, numerical scheme developed by Chorin. The problem discussed by the majority of the papers was the nonlinear effects of transition produced by small disturbances in a viscous flow over a flat plate. In most cases, the results presented were of an interim nature and were neither definitive nor conclusive. However, the discussions of the papers led the writer to believe that the results from numerical simulation were encouraging, but presently they cannot be used to predict transition reliably.

The numerical methods discussed at the workshop have the common deficiencies of uncertain accuracy and uncertain boundary conditions. The only common conditions that the three finite-difference methods employed were the initial-upstream boundary condition that was derived from linear stability theory and the no-slip condition at the wall. On the other hand, the normal boundary conditions at the outer edge of the boundary layer and the downstream boundary conditions were unique to the various methods. All authors agreed that uncertainty exists in the downstream boundary condition and its effect on the flow. However, they implied that the effects of the downstream boundary condition were isolated to a region of a few wave lengths from the place where the condition was applied. Additional inferences that could be drawn from these remarks are that the equations are only weakly elliptical and that the ellipticity of the equations is dependent on the wave length of the disturbing perturbations. One could also propose the possibility of employing experimental results for boundary conditions in the numerical simulation.

2. The Effects of Free-Stream and Wall Conditions on Boundary-Layer Transition

The effects of free-stream and wall conditions on boundary-layer transition were presented in three papers. Rogler and Reshotko (T-1) discussed a simulation of free-stream turbulence by a finite array of vortices to study the effects of a disturbance on a laminar boundary layer. This study did show qualitative agreement with prior experience. Kaplan (see below) employed his model of transition to discuss the effect of free-stream turbulence and wall-roughness on transitions. A quantitative comparison of Kaplan's results and experiments was presented and the comparison was encouraging.

The paper by Lewis, Haigh, and Atkinson (T-3) discussed the effect of oceanic turbulence on boundary-layer transition. Measurements of oceanic turbulence throughout the globe were analyzed and correlated. The results were then employed in a boundary-layer transition criterion to determine the effects of free-stream turbulence on transition. It was concluded that, in general, oceanic turbulence would be a minor problem for submerged bodies operating below the thermocline.

3. Boundary-Layer Stability Theory and Experiments

Laminar boundary-layer stability theory and the flow and geometrical parameters that influence boundary-layer stability were the topics of several papers. Kaplan (T-9) presented a discussion of stability and a new model for transition. The model is basically simple to apply and has done remarkably well in the limited comparison to experimental data that it has been exposed to.

The effects of wall heating on laminar boundary-layer stability were discussed. Both theoretical and experimental research results were given in a two-part paper by Lowell, Reshotko, Strazisar, Nice, and Prahl (E-2). In the theoretical paper, it was shown that higher critical Reynolds numbers could be expected from heating the walls of a body flowing through water. This result was essentially validated by the experiments. Wazzan presented a discussion of his work on heated walls during the new results session and showed conclusions similar to those discussed in paper E-2.

4. Turbulent Model Equations for Transition Predictions

In two papers (E-6 and the one given by Wilcox during the new results session), model turbulent boundary-layer equations in conjunction with laminar boundary-layer equations were employed to estimate transition. However, in each case the authors had several parameters that could be adjusted to improve transition predictions. It would appear that both sets of model equations could benefit from more comparison with experimental data.

5. The Role of Turbulent Spots in Boundary-Layer Transition

The turbulent spot was discussed in the papers by Wygnanski, Sokolov, and Friedman (E-7), the paper by Coles and Barker (E-10), and the paper by DeMetz (E-9). In these three well-done experiments, the spots were initiated differently, and the measurements and data reduction were performed differently. The experimental results appear to lead to different interpretations of turbulent spot characteristics. For example, the experiments performed by Wygnanski, et al. resulted in the conclusion that spots have no similarity; whereas the Coles and Barker experiments indicated that similarity did exist. The DeMetz paper was in some agreement with Coles' conclusion on this point. However, one of the interesting things that resulted from these papers was the proposal by Coles that a turbulent spot could be modeled with a large vortex. The interpretations of turbulent spot data were further elaborated during the panel discussion.

6. Transition Prediction Methods

One of the more important groups of papers was concerned with the practical problem of economically and reliably predicting boundary-layer transition. These papers were presented in the Design Session.

The purpose of the Design Session was to examine the status of transition prediction techniques and their application to vehicle design. Four unclassified papers dealt with correlative and predictive methods and their comparison with existing experimental data; these methods ranged from purely empirical to semi-theoretical approaches and from simple calculation to complicated computer programs. Each was based to some extent on experimental data and thus indicated reasonably good agreement with the data used. There was considerable discussion about the experimental conditions and interpretation of the data (e.g., how did the experimenter and/or correlator define transition--Beginning of drag rise? End of drag rise? Beginning of turbulent bursts?). There appeared to be a general consensus that a standard definition of transition should be adopted (the majority appeared to favor the beginning of drag rise) and the experimental conditions such as free-stream turbulence, noise, surface finish, etc., should be carefully specified and accounted for in correlation and analysis. There also was general frustration in the lack of a common basis for comparison of the various sets of experimental data and the several prediction methods. The "e^9" method discussed by A.M.O. Smith (D-2), although not fully automated and not widely distributed, appears to be the most consistently reliable prediction method.

However, one is tempted to propose that all the numerical, axisymmetric data produced by calculations performed using the "e^9" method be carefully analyzed to determine if the results can be correlated with some boundary-layer parameter. Such a correlation could produce large economies in time and funds. Three classified papers (D-6, D-7, and D-8) presented new experimental data for a variety of shapes, sizes, and speed range; these papers were probably the high point of the workshop since these data add significantly to the available data and range of experimental variables. When fully analyzed, these new data should enable more definitive design criteria to be established. Comparison of these data with some of the existing criteria, as presented in these papers, already allows some preliminary judgments on the relative validity of the several prediction methods.

THEORETICAL SESSION

DISTURBANCES IN A BOUNDARY LAYER INTRODUCED BY VORTEX ARRAY REPRESENTATIONS OF FREE-STREAM TURBULENCE

R. Rogler and E. Reshotko
Department of Fluid, Thermal and Aerospace Sciences
Case Western Reserve University
Cleveland, Ohio

To acquire insights into the role of free-stream turbulence on laminar-turbulent transition, the interaction between arrays of single-wavenumber vortices convected at the mean free-stream velocity is studied analytically and numerically. The boundary-value problem consists of a nonhomogeneous, partial differential equation with forcing function depending on the mean flow and the free-stream disturbances. The Orr-Sommerfeld linear operator appears with phase speed unity and real wavenumber. The mathematical system is solved numerically via expansion in Chebyshev polynomials. Disturbance velocities, vorticity, energy, pressure, and Reynolds stresses were obtained over a range of the wavenumber, Reynolds number, vortex position relative to the plate, and skewing angle. Results reveal that heavy damping occurs near the wall and that the disturbances asymptotically approach the values existing if the plate were absent. A phase shift across the viscous sublayer yields a Reynolds stress as in stability theory, but this stress is small relative to the Reynolds stress near the boundary-layer edge. Disturbances may amplify or decay depending on the parameters and the position in the boundary layer.

This work is being extended to include nonparallel flow effects.

NUMERICAL SIMULATION OF BOUNDARY-LAYER TRANSITION ON A FLAT PLATE*

Steven A. Orszag

Flow Research, Inc.
Cambridge, Mass.

We have performed a variety of controlled numerical experiments to simulate transition on a flat plate with zero pressure gradient. The simulations involve numerical solution of the three-dimensional time-dependent Navier-Stokes equations in a box with leaky sides. Each component of the velocity field is resolved using 8 spanwise Fourier modes, 65 Chebyshev modes in the direction normal to the plate (box side), and 129 grid planes in the streamwise direction (or 67,080 degrees of freedom to represent each component). Numerical calculations are reported for the simulation of the controlled laboratory experiments of Klebanoff, Tidstrom, and Sargent. In these experiments, a spanwise perturbation of a two-dimensional Tollmien-Schlicting wave is applied at the upstream boundary, according to the Benney-Lin theory of transition. The downstream development of the disturbance and transition to turbulance is followed in the numerical simulation. The three-dimensionality of the flow field is crucial to the success of the mechanism.

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*This work is supported by the Westinghouse Electric Corporation and the Defense Advanced Research Projects Agency.

AMBIENT TURBULENCE IN AN OCEANIC ENVIRONMENT

John E. Lewis, Wayne Haigh and Al Atkinson

Techmate, Inc.
Torrance, Ca.

A study has been made of ambient oceanic turbulence as it relates to the problem of boundary-layer transition. A parameter has been derived on the basis of Tollmien-Schlicting instability which can be used to compare the relative hostility of one environment to another, e.g., wind tunnel to ambient ocean. An extensive review of oceanographic data has produced a limited data base from which an attempt has been made to estimate the effect of depth, sea state, and geographical location on expected turbulent levels. In addition to ambient turbulence, the "environment" produced by the wake of another body has been evaluated and compared to the ambient background as a function of various operational conditions.

STABILITY INVESTIGATION OF LAMINAR BOUNDARY-LAYER FLOWS BY NUMERICAL INTEGRATION OF THE NAVIER-STOKES EQUATIONS

H. Fasel

Institut A für Mechanik
Universität Stuttgart
Stuttgart, Germany

Stability and transition phenomena of laminar, two-dimensional incompressible boundary-layer flows are investigated by introducing forced, time-dependent perturbations into the steady flow field along a semi-infinite flat plate; the reaction of the flow is then directly determined by numerical solution of the unsteady Navier-Stokes equations using an implicit finite-difference method.

In contrast to the linear stability theory which is limited to sinusoidal disturbances of small amplitudes, this approach contains no restriction in respect to form or intensity of the perturbations as long as the calculated flow is physically meaningful, i.e., essentially two-dimensional.

Stability analysis of laminar boundary-layer flows requires numerical experimentation with Reynolds numbers that are large enough to allow physical instability and thus amplification of the introduced forced disturbances, i.e., Reynolds numbers larger than the critical Reynolds number. Therefore for the development of the numerical method special care had to be taken to avoid oscillations caused by numerical instabilities or by the built-in boundary conditions; in the unstable region such oscillations might become amplified just like the physically meaningful perturbations and thus the results might become distorted.

The main aspects of the numerical method will be described and some results discussed. For periodic perturbations of small amplitudes, the numerical calculations will be compared with results of the linear stability theory and measurements of the experiments by Schubauer and Skramstad or Ross.

SIMULATION OF BOUNDARY-LAYER TRANSITION USING INTERACTING, THREE-DIMENSIONAL VORTEX FILAMENTS

A. Leonard*

NASA Ames Research Center
Moffett Field, Ca.

Recent success in simulating unsteady two-dimensional flows,[1] including separated flows over airfoils,[2] has prompted development of a similar numerical technique for three-dimensional problems.[3] The basic idea is to model the vorticity distribution in terms of continuous, closed filaments or tubes and to track these filaments in a Lagrangian reference frame. The vorticity distribution within a filament is parameterized by a locally-defined core diameter determined dynamically by the effects of viscous diffusion and vortex stretching.

Examples of flows which have been investigated to date (April 1974) are interacting vortex rings, round jets, and interacting aircraft trailing vortices. A movie showing the essential features of these flows has been generated from cathode ray tube displays.

Additional programming to include the effects of solid boundaries has begun. When completed, simulation of boundary-layer transition and/or separation will be possible. The influence of the boundary is twofold. First, to insure tangency of the velocity field at the boundary a harmonic contribution to the velocity field must be computed at each time step. If the body shape is simple, this may be done with image vorticity. Otherwise, an appropriate Green's function must be constructed prior to the simulation. Second, vorticity must be generated at the surface in such a way to enforce the no-slip condition.

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*NRC Senior Research Associate.

[1] A. J. Chorin, J. Fluid Mech. 57, 785 (1973).

[2] R. Rogallo, private communication.

[3] A. Leonard, "Numerical Simulation of Interacting, Three-Dimensional Vortex Filaments," *Proc. Fourth International Conference on Numerical Methods in Fluid Dynamics*, Boulder, Colo., June 24-29, 1974.

REVERSE TRANSITION DUE TO BODY FORCE EFFECTS

George L. Mellor

Princeton University
James Forrestal Campus
Princeton, N.J.

Body force terms and body force-like terms which appear in the equations of motion can have a dramatic effect on turbulent flow fields. In the case of density stratified flow, turbulence can virtually be extinguished at a Richardson number of 0.21. In the case of curved flow, turbulence can similarly be extinguished when a suitable curvature parameter also reaches a critical value. A remarkable finding is that both effects can be predicted from second-moment turbulence models which are centered on hypotheses by Rotta and Kolmogoroff. No adjustable constants are required over and above those required for neutral flow.

STABILITY AND TRANSITION IN THREE-DIMENSIONAL BOUNDARY LAYERS: STATE OF THE ART AND NECESSARY FUTURE WORK

E. H. Hirschel
DFVLR-Institut für Angewandte Gasdynamik
Germany

There is a brief discussion on why work was begun at the DFVLR on transition in three-dimensional boundary layers. The work follows two directions: assessment of the existing stability and transition criteria for three-dimensional boundary-layer flows, and a more systematic approach to the stability problem of such flows.

Known mechanisms which lead to transition laminar-turbulent or turbulent-laminar in three-dimensional boundary layers are discussed, together with the existing criteria. Some comparisons between calculated and measured transition locations are presented. It is shown that our current knowledge is insufficient.

Nevertheless, if one accepts the criteria for a rough investigation of the flow on swept wings, certain results can be found, especially concerning the influence of the sweep angle on the location of instability.

There is a need for a more systematic approach. It seems to be useful to tackle first the problem of linear stability in three-dimensional boundary-layer flows, and some aspects of three-dimensional boundary layers are discussed.

There is a very urgent need for experiments, since most of the previous experimenters did not separate the different mechanisms leading to turbulence in three-dimensional boundary layers. An experimental setup is discussed which should allow a rather broad approach to some of the mechanisms, especially the cross-flow instability.

A STATISTICAL ANALYSIS OF A BOUNDARY LAYER

Alexandre Joel Chorin

Department of Mathematics
University of California
Berkeley, Ca.

An approximation formula for slightly viscous flow near a boundary is presented. It is used as a basis for two approximate treatments of a boundary layer. In the first treatment, a random-number generator is used to approximate diffusion; the resulting method is valid in a laminar regime, and possibly during transition. In the second treatment, the flow field is viewed as random, and a statistical (non-Monte-Carlo) analysis of the structure of the boundary layer is given. The second method is applicable in a turbulent regime. Sample calculations will be exhibited.

A NEW SEMI-RATIONAL MODEL FOR TRANSITION OF INCOMPRESSIBLE BOUNDARY LAYERS*

R. E. Kaplan

Department of Aerospace Engineering
University of Southern California
Los Angeles, Ca.

By an ad hoc application of a critical disturbance level criterion, transition predictions can be made for:

1. free-stream turbulance spectra,
2. transition velocities,
3. transition Reynolds numbers for "frozen" free-stream turbulance, and
4. wall roughness correlations.

The criterion invclves a literal interpretation of Reynolds stress, knowledge of the eigenfunctions of the Orr-Sommerfeld equation, and a model for the coupling of free-stream turbulence to Tollmien-Schlicting waves and their growth when randomly driven.

One elementary consequence is that much larger free-stream turbulence levels are needed to induce turbulence for adverse pressure gradients than one would expect from the results of a linear stability analysis.

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*This research was partially supported by the National Science Foundation under Grant GK-35800X.

NUMERICAL SIMULATION OF INSTABILITY AND TRANSITION

Chester E. Grosch

Institute of Oceanography
Old Dominion University
Norfolk, Va.

"Exact" numerical simulations of the instability and transition due to both two- and three-dimensional disturbances in two-dimensional laminar boundary layers (Falkner-Shan profiles) are being carried out. The Navier-Stokes equations are solved using finite-difference techniques as a marching problem in time. The pressure field is determined by a direct method. The classes of disturbances being modeled in these calculations are: small and large amplitude disturbances of fixed frequency, free-stream disturbances with a spectrum characteristic of free-stream turbulence, acoustic disturbances, and wall vibrations. Details of the calculation scheme, including the variable-sized spatial mesh, the spatial and temporal differencing scheme, the direct method used to solve for the pressure field, and the details of the modeling of the disturbances will be discussed. Available results of the calculation will also be discussed.

EXPERIMENTAL SESSION

STABILITY OF A HEATED WATER BOUNDARY LAYER: THEORY

R. L. Lowell and E. Reshotko

Department of Fluid, Thermal and Aerospace Sciences
Case Western Reserve University
Cleveland, Ohio

Solutions have been obtained to the sixth-order system of disturbance equations describing the hydrodynamic stability of a heated flat-plate water boundary layer including all mean and disturbance property variations. The results are compared with those calculated using the fourth-order constant density system of Wazzan, Okamura, and Smith that assume variation only of the mean viscosity. Over the normal temperature range of water, the results of the sixth-order calculations show a slight enhancement of stability over those of the fourth-order system. Gains in stability due to inclusion of disturbance viscosity terms in the calculations are offset by the effects of including density fluctuations in the problem. Results will be presented that are pertinent to the experiment reported by Strazisar, Nice, and Prahl.

STABILITY OF A HEATED WATER BOUNDARY LAYER: EXPERIMENT

A. Strazisar, M. Nice and J. M. Prahl

Department of Fluid, Thermal and Aerospace Sciences
Case Western Reserve University
Cleveland, Ohio

The stability of a heated boundary layer in water is being studied experimentally in a closed-circuit water tunnel. The test section is 6 × 9 in. in cross section and is about 12 in. long. The free-stream turbulence level is about 0.25 percent. The test plate is mounted as the top wall of the test section. The boundary layer ahead of the test plate is removed through a slot that spans the tunnel. Disturbances of prescribed frequency are introduced in the boundary layer by means of a vibrating ribbon. There are heating coils in the plate so that it may be run either with or without heating.

Measurements taken on unheated boundary layers show that both the mean and disturbance flows are in good agreement with respective theoretical expectations. A preliminary test with heating indicated decay of the imposed disturbance for a Reynolds number and frequency that had yielded amplification in the absence of plate heating. More complete results on the effect of plate heating will be presented, including comparison with the calculations of Lowell and Reshotko.

THE EFFECT OF SOUND UPON BOUNDARY-LAYER TRANSITION

Patrick Leehey

Acoustics and Vibration Laboratory
Massachusetts Institute of Technology
Cambridge, Mass.

There is some experimental evidence that both discrete tone and broad-band sound cause premature boundary-layer transition. This evidence is reviewed and related to current state of knowledge of the transition process. An outline of a proposed experimental program to explore this effect is presented and speculations are offered as to the probable outcome of these experiments.

A CURIOUS MECHANISM OF TRANSITION TO TURBULENCE DOWNSTREAM OF AN ISOLATED THREE-DIMENSIONAL ROUGHNESS

M. V. Morkovin and R. S. Norman
Illinois Institute of Technology
Chicago, Ill.

When the locally separated shear layer downstream of a rectangular obstacle, buried in a laminar boundary layer (height $\sim 0.2\delta$), was excited by a forcing acoustic frequency f_1 in the precritical regime, the nonlinear Gregory-Walker-Mochizuki vortex loops were formed. However, they moved out to the top of the boundary layer and decayed without onset of turbulence. When simultaneously a second sound frequency f_2 excited the shear layer, hot-wire anemometers disclosed vorticity waves not only with frequencies f_1 and f_2, but also with combination frequencies $f_1 + f_2$, $2f_1 + f_2$, etc. and harmonics $2f_1$, $2f_2$, $3f_1$, etc. Again the vortex formations moved out of the boundary layer and had apparently nothing to do with the transition which then took place. This transition was traced to the amplification of the lowest combination frequency $f_1 - f_2$ deep in the reattached boundary layer. ($f_1 - f_2$ was below the noise level in the separated shear layer!) Direct, strong acoustic excitation in the $f_1 - f_2$ frequency caused no detectable waves in the reattached boundary layer. Speculations are offered on the possible generality of this nonlinear modulation phenomenon. Information on the locale of the onset of turbulence and on some structural features of the ensuing turbulent wedge are also included.

A NOTE ON THE TRANSITION OBSERVATIONS ON AN AXISYMMETRIC BODY AND SOME RELATED FLUCTUATING WALL PRESSURE MEASUREMENTS*

Vijay H. Arakeri
Research Fellow

Division of Engineering and Applied Science
California Institute of Technology
Pasadena, Ca.

Boundary-layer transition on an axisymmetric body up to Reynolds number 1.26×10^6 was observed by schlieren method of flow visualization developed for water tunnel use. The spectrum of the flush-mounted pressure transducer signal showed a dominant frequency to exist at transition; further, this frequency was in close agreement with the predicted critical frequency by Smith's approximate method of transition calculation based on linear stability theory.

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*This research was carried out under the Naval Ship Systems Command, General Hydromechanics Research Program, Subproject SR 023 01 01, administered by the Naval Ship Research and Development Center, Contract N00014-67-A-9984-0023.

TENTATIVE PREDICTION OF THE BOUNDARY-LAYER DEVELOPMENT IN A TRANSITION REGION

R. Michel
ONERA-CERT-DERAT
Complexe Aerospatial
France

Important efforts have been made at ONERA in studying the effects of viscosity upon turbulence in turbulent boundary layers. It is believed that the same ideas and hypotheses also could be helpful in the search for prediction methods for the boundary-layer transition phenomenon.

The research is being developed on one hand with the help of transport equations for the different turbulence quantities. It makes use on the other hand of an improved mixing length model, involving, for example, the hypothesis of a universal mixing length curve and a corrector function applied to the classical expression of turbulent shear stress. This corrector function depends on the ratio of the turbulent to the laminar shear stress. It appeared at first that the model leads to a theoretical solution which passes progressively from a laminar to a turbulent profile when the Reynolds number is increasing from 0 to infinity. Some kind of intermittency factor has then been defined, which permits the mixing length to be zero at a given beginning of transition, and tends to the turbulent level when the turbulent flow is established.

The velocity profiles measured in a transition region and the corresponding boundary-layer parameters are well represented by a calculation method based on these assumptions. Interesting results also have been obtained on the extent of the transition region and the influence of positive and negative pressure gradients upon the development of transition.

SOME OBSERVATIONS ON THE GROWTH OF TURBULENCE IN A LAMINAR BOUNDARY LAYER

I. Wygnanski, M. Sokolov, and D. Friedman

School of Engineering
Tel-Aviv University
Tel-Aviv, Israel

Some exploratory measurements have been made of the properties of a single turbulent spot and the properties of a turbulent cone which are embedded in a laminar boundary layer in the absence of pressure gradient. The spot was initiated artificially by an electric discharge while the cone was initiated by a permanent spherical protrusion. Conditional sampling techniques were used to determine the character of the two turbulent regions in detail and to study the process of entrainment.

All data recording and analysis were done digitally using a small Varian 620i computer connected on-line to the experiment. Considerable effort was made to synchronize the acquisition properly in order to have a good resolution of the flow around the turbulent/nonturbulent interface.

SOME EXPERIMENTAL INVESTIGATIONS IN THE GARFIELD THOMAS WATER TUNNEL

Blaine R. Parkin

Applied Research Laboratory
Pennsylvania State University
University Park, Pa.

Some measurements of suction slot flows in air and glycerine are reported briefly. These data were obtained at the Garfield Thomas Water Tunnel because of their possible application for boundary-layer control on marine vehicles. A progress report on wind tunnel experiments on transition in the boundary layer of a blunt-nosed body of revolution forms the main topic of discussion. Systematic hot-wire measurements are being made in the transition region in the presence of an adversed pressure gradient. Because the experiments are still in progress, preliminary data are presented and present plans for completing the current phase of the work are discussed.

AN EXPERIMENTAL STUDY OF THE WALL PRESSURE BURSTS DURING BOUNDARY-LAYER TRANSITION

Fred C. DeMetz

Naval Ship Research and Development Center
Code 1942
Bethesda, Md.

The properties of the intermittent wall pressure field have been measured in the transition boundary layer on a large flat plate and a body of revolution in the subsonic Anechoic Flow Facility at the Naval Ship Research and Development Center. Natural transition was achieved on the flat plate with a mild favorable pressure gradient at Reynolds numbers, based on downstream distance from the plate's leading edge, in excess of 7×10^6. The development of the laminar boundary layer prior to transition was in agreement with numerical solutions to the laminar boundary-layer equations and with stability criteria for pressure gradient effects. The temporal, spatial, and spectral properties of the transition wall pressure field associated with the natural transition process occurring on the plate were obtained as a function of the intermittency factor and compared with those of the fully turbulent pressure field. Specifically, the mean-square pressure, spectral densities, convection velocities, distributions of burst periods, and burst rates of the intermittent pressure field are computed from the data. The effects of randomly distributed sand roughness on the transition pressure field were also determined.

Transition was obtained on the nose of a conventionally shaped body of revolution model by tripping the boundary layer with discrete and distributed roughnesses. The presence of a random sand grain roughness downstream of the point of tripping was seen to have a pronounced effect on the fully turbulent wall pressure field. Measurements were also made of the properties of the intermittent pressure field when transition was caused by the two-dimensional and distributed tripping devices.

THE TURBULENT SPOT AS A LARGE VORTEX

D. Coles and S. Barker
California Institute of Technology
Pasadena, Ca.

Some exploratory measurements have been made of the properties of a single turbulent spot in a laminar boundary layer. The measurements were made in water, using one channel of laser-doppler-anemometer instrumentation to observe the streamwise component of velocity at a fixed point. The spots were generated at regular intervals by an intermittent jet disturbance at a surface orifice. The anemometer signal was demodulated and sampled at various delay times, using an integrating voltmeter to remove most of the high frequencies. Data were then ensemble-averaged in a computer for a large number of repetitions.

The experiments with a single spot, including flow visualization with dye, showed that the spot had the expected arrowhead shape. Viewed in a coordinate system moving at the characteristic spot velocity, the spot is a large U-shaped vortex structure which grows nearly linearly in time or distance. Much of the entrainment occurs as the spot overruns vorticity-bearing fluid in the laminar boundary layer and lifts this fluid away from the surface inside the loop of the vortex.

EXPERIMENTAL STUDIES OF NATURAL TRANSITION

C. S. Wells, Jr.
Advanced Technology Center, Inc.
Dallas, Texas

An experimental facility designed for the investigation of natural transition from laminar to turbulent flow is described. High values of zero pressure gradient transition Reynolds number ($R_{e_x} \approx 5 \times 10^6$) were obtained in the facility through control of external disturbances such as free-stream turbulence, mechanical vibrations, and pressure variations from the air handling equipment. Hot wire studies confirmed the existence of amplified boundary-layer disturbances typical of natural transition.

The effects of two types of free-stream disturbance--grid-produced turbulence and acoustic noise at discrete frequencies--were investigated separately. The grid turbulence produced higher transition Reynolds numbers at the low turbulence levels than published results from other facilities for natural transition. This is discussed in terms of the ability to control disturbances which may affect transition in various types of facilities.

The acoustical disturbances produced effects on transition which generally agreed with the predictions of small disturbance theory; i.e., transition Reynolds number was observed to decrease more rapidly for acoustical disturbances in the critical range of frequencies for amplification of small disturbances than for those that did not fall in the critical range. These results are also discussed in terms of previously published data.

DESIGN SESSION

THE PREDICTION OF TRANSITION FROM LAMINAR TO TURBULENT FLOW IN BOUNDARY LAYERS ON BODIES OF REVOLUTION

Paul S. Granville
Naval Ship Research and Development Center
Bethesda, Md.

A new correlation of experimental data is developed for predicting transition from laminar to turbulent flow in boundary layers on smooth bodies of revolution immersed in axisymmetric flows with very low background turbulence. The correlation incorporates not only the usual effect of pressure gradients but the effect of axisymmetric spreading of the boundary layer on the location of transition. Existing methods are also examined critically.

THE "e^9" METHOD WITH SPECIAL REFERENCE TO BODIES OF REVOLUTION

A.M.O. Smith and Kalle Kaups

Douglas Aircraft Company
Long Beach, Ca.

Most people do not know about the "e^9" method except in broad principles. Certainly very few have truly applied it. Therefore, the method is described, including the basic hypothesis. Stability charts are explained and a step-by-step trace-through of the method is made. To illustrate, wave growth on a wedge and its equivalent cone are traced in detail. One important contribution is formulas that show why the "e^9" method predicts transition relatively early even though the point of neutral stability is three times as far down in terms of R_x on a matched cone as it is on a wedge.

The talk closes with some mention of studies done for the Naval Undersea Center on transition on bodies of revolution. The work is described in Douglas Report MDC J6530, "Transition Prediction on Bodies of Revolution," by K. Kaups. It is also available as AD 778 045.

ON AN EXTENSION OF THE TWO-DIMENSIONAL MICHEL-SMITH CORRELATION TO AXISYMMETRIC BODIES

E. Van Driest and J. Aroesty
The Rand Corporation
Santa Monica, Ca.

There are few experiments and little theoretical guidance for the prediction of transition on bodies of revolution. However, there are more data available for flow over two-dimensional bodies than for axisymmetric ones, and it would be desirable to use these data to develop a transition criteria for bodies of revolution. The Mangler transformation provides the theoretical means to correlate laminar boundary-layer flow over a body of revolution and the corresponding flows over an entire family of related two-dimensional bodies, where each of these two-dimensional flows has a different length scale. Out of this infinite family of two-dimensional flows, the particular length is chosen such that at transition the boundary-layer momentum thicknesses at corresponding points on the two-dimensional and axisymmetric surfaces are equal. This is equivalent to choosing the length scale of the Mangler transformation to correspond to the radial distance of the transition location of the axisymmetric flow. We have used the two-dimensional transition data collected by Michel, and by Smith and Gamberoni, to develop a form of the Michel-Smith curve based primarily on two-dimensional data. The criteria are sensitive to the choice of a particular representation of the Michel-Smith line (Re_θ vs Re at transition), but we have selected a representation which is consistent with the two-dimensional data, and which then gives reasonable agreement with the limited experimental data for bodies of revolution. The Douglas-Neumann program, the method of Thwaites for the calculation of boundary-layer parameters, the Mangler transformation for correlation of axisymmetric and two-dimensional flows, the prescription for the arbitrary length scale given above, and a representation of the Michel-Smith transition curve for two-dimensional data are the ingredients in this particularly simple approach. A similar approach could be used to extend other two-dimensional transition criteria (Hall-Gibbings, Granville) to axisymmetric flow.

SUBSONIC, AXISYMMETRIC BOUNDARY-LAYER TRANSITION PREDICTIONS VERSUS EXPERIMENTS

George H. Christoph
Naval Underwater Systems Center
Newport, R.I.

One of the possible sources of transducer self-noise is flow or flow-induced noise arising from the transition of the boundary layer from laminar to turbulent flow. The location of transition and the abruptness of the transition region are strongly dependent on the pressure distribution along the torpedo head (i.e., the head geometry). Very little is known about the relationship of pressure distribution, transition region location or extent, or the resultant array self-noise for torpedo-shaped bodies.

Presently, NUSC, Newport, is undertaking a program with the National Bureau of Standards (NBS) which will study the flow around blunt noses and its relation to self-noise. This paper briefly reviews the factors affecting transition and the existing methods of predicting transition, with emphasis on the types of flow related to the NUSC/NBS study. It also reports on the experimental work being conducted in the NBS subsonic wind tunnel. The following experimental data are being taken:

1. Static pressure profiles (to be compared with computer predictions).
2. Dependence of transition region and intermittency profile on Reynolds number.
3. Influence of free-stream turbulence on transition region and intermittency profile.
4. Frequency content of turbulent bursts.
5. Spatial uniformity of the transition characteristics around the nose.
6. Effect of angle-of-attack on the above mentioned items.

Three torpedo nose contours (8-in. diameter models) are being tested at NBS. The first nose has a broad pressure minimum, the second nose has a sharper pressure minimum, and the third nose has two pressure minima. Transition is predicted analytically on these noses for several speeds in water and in air by seven prediction methods. Predictions are compared to NBS experimental data. It is hoped that some flow visualization will also be done.

AXISYMMETRIC TRANSITION: CORRELATION OF THE MAXIMUM REYNOLDS NUMBER LIMITING APPLICABILITY OF THE TWO-DIMENSIONAL MICHEL-SMITH CRITERION TO AN ARBITRARY BODY

F. R. Goldschmied

Westinghouse Research Laboratories
Pittsburgh, Pa.

The first successful correlation has been developed to predict the maximum Reynolds number limiting the applicability of the two-dimensional Michel-Smith transition criterion to any given axisymmetric body, and therefore limiting its low-drag range.

The physical basis of the method is given by three correlation plots with concomitant mathematical functions, comprising the test data of eight different bodies with fineness ratios from 15 to 3.3.

The "switchover" point has been recognized as the key feature in the axisymmetric transition plot as against two-dimensional performance. A "crossover" point has been defined as the intersection of the experimental curve with the Michel-Smith prediction.

Four parameters are involved in the prediction of the switchover and crossover points, i.e., body longitudinal slope and curvature, body transverse curvature, and a multiplier to be applied to the Michel-Smith momentum Reynolds number. The Jaffe-Okamura-Smith spatial amplification theory has been reviewed and it has been concluded that it can be "calibrated" by the switchover prediction which would then yield the correct amplification factor to be used for any given body.

A STUDY OF THE TRANSITION AND DRAG CHARACTERISTICS OF A FAMILY OF THREE AXISYMMETRIC BODIES

R. Gulino and R. F. Mons

Westinghouse Underseas Division
Annapolis, Md.

Tow tank experiments have been performed on three 14.5-cu-ft axisymmetric bodies with fineness ratios of 7.731:1, 4.45:1, and 3.9:1. Measurements of the axial location of transition and of drag were made over a range of unit Reynolds number from 0.5×10^6 to 6.5×10^6 and the results compared to transition predictions based on (a) two-dimensional Michel-Smith criteria, (b) two-dimensional Michel-Smith criteria with Mangler transformation, (c) two-dimensional Michel-Smith criteria with local slope and curvature corrections, (d) Hall-Gibbings criteria based on Pohlhausen parameters, and (e) Smith-Gamberoni "e^9" criteria based on spatial amplification calculations.

MEASUREMENT OF BOUNDARY-LAYER TRANSITION ON A HEMISPHERICAL BOW OF THE SUBMARINE DOLPHIN

Brian E. Bowers

Naval Ship Research and Development Center
Code 1942
Bethesda, Md.

To gain insight into the extent of turbulence on a large hemispherical bow, small flush-mounted hydrophones were utilized to determine the position of transition from a laminar to a turbulent boundary layer on USS DOLPHIN (AGSS-555). The end objective was to develop submarine sonar dome shapes that would minimize the extent of turbulent flow over the dome, i.e., postpone transition and thus reduce flow-induced self-noise. The measured transition region on the bow, as it varied with speed and pitch angle, was shown to be well forward of that calculated, using currently accepted theoretical methods. This finding pointed to the need for improved transition-prediction techniques which would take into account realistic values of dome-surface imperfections, ambient turbulence intensity, and other major transition-inducing parameters.

EXPERIMENTAL INVESTIGATION OF BOUNDARY-LAYER TRANSITION ON A LARGE SUBMARINE MODEL: KAMLOOPS

John T.C. Shen
Naval Ship Research and Development Center
Code 1942
Bethesda, Md.

Experimental investigations of boundary-layer transition on a large submarine model, KAMLOOPS, have been conducted at Lake Pend Oreille, Idaho. For this purpose, KAMLOOPS is utilized as a rising body propelled by its own buoyancy. To insure a low-turbulence environment, the data were taken below the thermal layer of the lake--usually at a depth greater than 300 ft. Whereas it is well known that boundary-layer transition is dependent upon Reynolds number as well as on pressure gradient, experimental evidence indicates that, for large Reynolds numbers, the position of transition is largely influenced by the rate of change in pressure gradient. In such cases, the transition is primarily controlled by the geometrical shape of the bow when the surface is hydraulically smooth.