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NASA Ames Fluid Mechanics Laboratory Research Briefs

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NASA Ames Fluid Mechanics Laboratory Research Briefs

FLUID MECHANICS LABORATORY BRANCH, SANFORD DAVIS, EDITOR

Ames Research Center

Summary

The Ames Fluid Mechanics Laboratory research program is presented in a series of research briefs. Nineteen projects covering aeronautical fluid mechanics and related areas are discussed and augmented with the publication and presentation output of the Branch for the period 1990–1993.

Introduction

Our research program can be traced to the late 1970s when we were named the Aerodynamics Research Branch and served as a research arm for the Unitary and other large high speed wind tunnels at NASA Ames Research Center. Due to limited access to large tunnels, plans were drawn up for a new laboratory to satisfy a need for dedicated small-scale wind tunnels. These facilities, augmented with modern data systems were to be used for research studies on work already underway. A reorganization in 1985 placed the Branch in a newly formed Fluid Mechanics Division and it was renamed the Fluid Dynamics Research Branch. At that point, certain applied aerodynamics activities such as wing optimization, rotor analysis, and high angle-of-attack aerodynamics were moved to other organizations. The present Fluid Mechanics Laboratory building was dedicated in 1986 and now contains a wide range of test facilities, instrumentation systems, and computer networks to support diverse investigations. (An indication of the Branch activities to 1986 may be found in the NASA publications "A Collection of Flow Visualization Techniques Used in the Aerodynamics Research Branch," NASA TM-85998, Dec. 1984 and "Vortical Flow Research Program of the Fluid Dynamics Research Branch," NASA TM-88332, Aug 1986.) During the period 1986-1992 the Branch

completed a number of investigations including an adaptive wall wind tunnel demonstrator, a novel circulation control airfoil for helicopter rotors, and an extensive investigation of vortex asymmetries and shear layer control.

In 1992 the Branch was again renamed as the Fluid Mechanics Laboratory Branch. Recently, emphasis has shifted from basic fluid physics to increased support of NASA focused programs, and, in a sense, back to our roots as an aerodynamics facility. We now contribute to the NASA High Speed Research Program with an extensive effort to develop and use a new generation of supersonic, quiet, low disturbance wind tunnels. This research is augmented with advanced sensor concepts to aid in flow diagnostics and external support to other Ames facilities. Branch programs in fluid physics continue and are concerned with developing the physical understanding required to model and control flows of technological importance. In particular, active research is underway in transitional boundary layers and adaptive aerodynamic flow control.

The enclosed Research Briefs give a snapshot view of current and selected past programs. Our work supports both NASA aeronautics and the larger NASA mission concerning educational outreach and technology transfer.

Each brief is identified with a point of contact (P.O.C.) for identification purposes, but most areas require a team effort. An indication of the wide participation and cross-fertilization is apparent from the citation list following each brief. These citations constitute a portion of the publications output from the Fluid Mechanics Laboratory Branch for the past four fiscal years. A complete publication and presentations list is included in a section following the briefs.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



Aerial view of the NASA Ames Fluid Mechanics Laboratory. Front to back: office wing, stand-alone wind tunnels, indraft wind tunnels, and compressor building.

Research Briefs

1. **Boundary Layer Transition Research on Swept Wings at Low Supersonic Mach Numbers** *Point of Contact: Daniel C. Reda*

A national effort is underway to develop and market the next-generation commercial aircraft, the High Speed Civil Transport. Environmental-acceptability and economic-viability issues dictate that this supersonic plane be designed to minimize drag. Maintaining the boundary layers on the wing surfaces in a low-drag, laminar state would have a major positive influence on drag reduction. As a consequence, NASA and the U.S. aerospace industry are actively involved in Laminar Flow Control research. A flighttest program is underway using F-16XL aircraft to investigate boundary layer transition on swept wings at low supersonic Mach numbers.

Attainment of laminar flow control via distributed suction through the porous wing surface is the primary objective of these experiments. Extensive computational fluid dynamics research and controlled experiments in newly-created quiet supersonic wind tunnels play major roles in supporting the flight-test program. These research activities should ultimately yield validated design codes for industry's use.

The NASA Ames Quiet Supersonic Wind Tunnel will be utilized to support this overall research program. Full-scale replicas of the F-16XL swept wing leading edge will be tested at Mach 1.6 over a unit Reynolds number range matching that of the flight tests.

Pressure distributions will be measured and compared to both predictions and flight-test data. The influence of angle of attack, radiated noise, attachment line lateral contamination, surface roughness, and surface suction on boundary layer stability and transition will be studied. Advanced diagnostic techniques such as surface-mounted hot-film arrays and liquid crystals for transition visualization will be employed.

The schedule calls for passive leading edge models to be tested in FY94, followed by suction models in FY95.

Aeronautical applications areas:

This activity forms a part of the NASA focused program on Technology Development for the next generation supersonic transport.

Citations: 95, 127-129, 135

2. **Experiments on the response of a Perturbed Boundary Layer to Acoustic Excitation** *Point of Contact: Mehran Tadjfar*

This study is concerned with the effect of receptivity mechanisms on boundary layer transition. Receptivity refers to the response of a laminar boundary layer to an imposed disturbance. Parallel numerical/theoretical and experimental research are being conducted to better understand this phenomenon. The goal is to understand the environmental influence on the boundary layer transition in order to control the process.

In the experimental part, the 15 × 15 in. subsonic tunnel at FML has been dedicated to this study. Appropriate model and instruments are designed to isolate the initial Tollmien-Schlichting (T-S) waves from the rest of the spectra in the flow. The boundary layer is perturbed with small, three-dimensional roughness elements. Then the boundary layer is subjected to harmonic disturbances using acoustic speakers. The interaction of the perturbed boundary layer with the acoustic excitation initiates T-S waves inside the boundary layer which are later amplified or damped according to the flow conditions. Extensive software has been developed to isolate and separate the much smaller T-S wave components from the acoustic mode and the rest of the spectra. The T-S profiles are extracted from the flow at many locations in the interaction zone. The growth or decay of these waves are studied in relation to other experiments parameters.

Aeronautical applications areas:

The experimental results can be used to validate transition theories and numerical codes. Receptivity mechanisms must be accounted for in any numerical code written to study transition. For example, the Parabolized-Equations codes require an initial state to start. This initial state will be provided by the receptivity codes once the important factors are identified and evaluated. New design tools will be used to analyze the onset of transition on swept wings, nacelles, and other aircraft components.

Citations: 103-105

3. **Experimental Investigation of Disturbances Generated by Suction Holes for Laminar Flow Control** *Point of Contact: Jonathan H. Watmuff*

The beneficial effects of suction for delaying transition to turbulence have been known for some time but it is only

recently that technology has become available to produce large sheets of perforated material for use in aircraft wings at reasonable cost. Flight tests have been conducted using porous surfaces containing around 109 0.002 in. diam. laser drilled holes. The drag reduction obtained by maintaining laminar flow over a substantial portion of the wing surface potentially offers considerable fuel savings. Suction, as a means for Laminar Flow Control (LFC), is being seriously considered for production aircraft in the near future.

Even the most sophisticated engineering design tools for predicting the transition location assume that the suction is uniform. However there is evidence to suggest that local 3-D disturbances are generated by the discrete holes which could defeat the purpose of the suction, i.e., cause premature transition. Much attention has been given to the cross-stream layout of suction holes to minimize cross-stream interaction. However almost nothing is known about streamwise interactions. The objective of this project is to determine the characteristics of suction hole disturbances, whether they decay or amplify with streamwise distance, and whether there are interactions between disturbances generated by different holes, which are aligned, but displaced in the streamwise direction.

A small scale facility has been modified to create a laminar boundary layer in a zero pressure gradient (ZPG) to provide the undisturbed base flow. A sophisticated high-speed computer-controlled 3-D probe positioning system is integrated into the wind tunnel test section. The traverse is synchronized with a high-speed data acquisition and processing capability and all experimental procedures are totally automated under computer control. Disturbances are introduced by perturbing the suction either harmonically or impulsively and averaging the data on the basis of the phase of the disturbance. Complex 3-D grids containing tens of thousands of data points can be created and experiments performed continuously (24 hours a day) over several weeks without manual supervision. These techniques have recently been enhanced with multiple probes to reduce experimental run-time by an order of magnitude. Post-experimental processing schemes are used to transform the raw data into the form required to produce animations on a dedicated workstation using the same software tools developed for examining numerical calculations.

The evolution of Tollmein-Schlichting (TS) waves downstream of an isolated hole, both with and without suction, was demonstrated using harmonic disturbances. With suction, vortices are generated by the holes and measurements indicate that they are subject to a secondary instability mechanism. The stability of suction hole vortices is currently being investigated. Impulsive disturbances may

be used since multiple instability modes are excited (i.e., a wave packet). The impulsive disturbances may also excite the secondary suction hole vortex instability.

In other work, disturbances have been generated at two holes, aligned, but displaced in the streamwise direction. The results obtained when disturbances are applied to each hole independently compare favorably to the case when the disturbances are applied simultaneously. The linearity implied by these observations suggests that an optimal streamwise hole spacing may exist to provide maximal cancellation of TS waves, dependent on the wavelength of the most unstable mode, i.e., the streamwise spacing for optimal cancellation may depend on flight speed.

Aeronautical applications areas:

The data base generated from these experiments will be used to develop better design tools for the selection and application of porous surfaces for laminar flow control devices on future aircraft.

4. Coherent Structures in a Shear Layer Flow Point of Contact: Richard L. LeBoeuf

The objective of this study is to investigate the development of three-dimensionality and transition to turbulence in a forced plane two-stream mixing layer. Acoustic forcing is used to generate specific pairing mechanisms which would otherwise occur randomly. Phase-averaged measurements are used to quantify coherent vorticity development and interaction. These measurements, coupled with previous direct numerical simulation results, should shed new light on the development of spatially evolving mixing layers. In particular, the relationship between time-averaged measurements and the three-dimensional structure will be clarified.

Measurements of the streamwise development including the initial roll-up and first pairing have shown that the mean streamwise vorticity in the near-field characterizes the instantaneous streamwise vorticity resident in the spanwise rollers. Further downstream, the mean streamwise vorticity was found to be more representative of the rib vorticity found in the braid region (between adjacent spanwise rollers). Future work will examine vorticity development and interaction during the second and possibly third pairing of spanwise rollers as well as more infrequent pairing mechanisms such as tripling. The natural occurrence of tripling in which two out of three first generation vortices pair and the resulting second generation spanwise roller combines with the remaining first generation vortex has been shown experimentally.

By enhancing understanding of mixing layer transition, it is hoped that this study will help guide turbulence model development in the quest to incorporate more physics into this heretofore mostly empirical work area. This, of course, should lead to more general purpose closures which may be appropriate for complex flows. Additionally, since mixing layers are technologically significant flows, an increased understanding of their structure and control may lead to better mixing in industrial chemical processes, reduced jet engine noise, etc. This work is coordinated with and partially supported by the Center for Turbulence Research.

Aeronautical applications areas:

These investigations will aid in the development of better turbulence models which, in turn, will enable CFD-aided aircraft designers to better simulate a real-fluid flow.

Citations: 69, 70, 74-79, 83-89

5. Measurements of Surface Shear Stress Vector Fields Using Liquid Crystal Coatings *Point of Contact: Daniel C. Reda*

The objective of the present research is to develop a technique for the areal measurement of the surface shear stress distribution on any test surface immersed in a three-dimensional flow field. Full-surface measurements of both magnitude and direction of such skin-friction forces would provide designers with detailed data sets for code validation and advanced design tools. Once proven, the application of such measurement capability to the prototype test of advanced aerodynamic configurations could greatly increase the productivity of ground-based facilities.

Cholesteric liquid crystals reside in a highly anisotropic mesophase that exists between the solid and isotropic-liquid phases of some organic compounds. Such materials can exhibit optical properties characteristic of a crystalline solid. Once aligned by shear, molecules within a thin liquid crystal coating scatter incident white light as a spectrum of colors, with each color at a different orientation relative to the surface. Shear-stress-sensitive and temperature-insensitive compounds now exist. For such coatings, "color play," i.e., discerned color changes at a fixed angle of observation for a fixed angle of illumination, results solely from the application of shear stress. Such color changes are continuous and reversible, with time response of order milliseconds. Based on these characteristics, liquid crystal coatings have been used to visualize shear patterns on aerodynamic surfaces in both laboratory and flight-test applications.

Research conducted in the Fluid Mechanics Laboratory has recently shown that liquid crystal coating (LCC) color-change response to shear depends on both shear stress magnitude and direction. Additional studies extended the LCC method to a quantitative surface shear stress vector measurement technique. In this recent study, a shear sensitive LCC was applied to a planar test surface and illuminated by white light from the normal direction. A fiber optic probe was used to capture light scattered by the LCC from a point on the centerline of a turbulent, tangential-jet flow. Based on these tests, a vector measurement methodology, involving multiple oblique-view observations of the test surface, was formulated. Under present test conditions, the measurement resolution of this technique was found to be $\pm 1^\circ$ for vector orientations and $\pm 5\%$ for vector magnitudes.

Efforts are currently underway to extend this measurement methodology to full-surface applications using a color video camera, a frame grabbing system, and supporting data-reduction software.

Aeronautical applications areas:

This new sensor concept will have a major impact on wind tunnel testing. In conjunction with recently developed pressure sensitive paint technology, it will be possible to measure complete surface pressures and shear stresses for the first time.

Citations: 90-92, 94-98

6. Application of Luminescent Paint to Aeronautical Fluid Dynamics *Point of Contact: Rabindra D. Mehta*

Pressure sensitive luminescent paints have emerged as a viable technique for measuring surface pressures on wind tunnel models. The method utilizes a surface coating containing fluorescent or phosphorescent materials, the brightness of which varies with the local air pressure on the model surface. In current practice, a wind tunnel model is coated with the luminescent material, which is then illuminated with light of an appropriate wavelength to excite the material. The illuminated model is imaged with a conventional video camera during the wind tunnel test. The images are then computer processed in order to obtain a map of the surface pressure distribution. The relationship between surface brightness and pressure is generally determined by comparison with a few existing pressure taps on the model.

Pressure sensitive paints have some important advantages in comparison to the pressure taps currently used for surface models. First, the paint provides a measurement over the entire model surface, as opposed to taps which provide

data only at preselected, discrete points. Second, since the response time of the luminescent materials is relatively short, there is the potential of obtaining time-dependent pressure measurements; this would be particularly useful for the study of unsteady aerodynamics. Third, measurements with pressure sensitive paint hold the potential of being more cost effective (over time) than those with pressure taps.

The overall program objective is to apply the luminescent paint technology to study flows of interest to the aeronautical industry. Some examples are the shock/boundary layer interaction, separation and reattachment (2-D and 3-D) and wing/body junction flows. It is extremely desirable to obtain quantitative pressure measurements on the whole model surface in any type of wind tunnel test. However, apart from the most obvious applications to airplane components (where the pressures can be integrated directly to give the aerodynamic forces) there are more fundamental applications. The basic physics of the flow over complex airplane geometries cannot be usually studied directly. More often than not, a simplified version of the geometry is designed and tested in the wind tunnel so that the flow features may be studied in sufficient detail. The simplification of the experiment not only helps to optimize instrumentation usage, but also makes it easier to fully understand the flow physics, since individual effects can often be isolated and studied separately. The understanding of the flow physics is essential if adequate computational models and successful flow control mechanisms are to be developed.

Aeronautical applications areas:

Pressure sensitive paint technology will be used to expand the domain of aeronautical component testing to full spatial measurements. Emphasis will be on using these spatial sensors to ascertain methods for flow control and subsequent drag reduction on model configurations.

Citations: 2, 72

7. Computer Code Validation and Flow Physics of a Subsonic Wing-Tip Flow

Point of Contact: Greg G. Zilliac

The performance of virtually every fluid dynamic machine, from the household fan to the space shuttle is, to some degree, affected by the flow over wings. In the past, typically, the approach to wing design has included costly parametric studies of wing contours and wingtip shapes in wind tunnels. With the emergence of computational fluid dynamics as a design tool, the amount of wind tunnel testing required to design an efficient wing has been reduced, yet questions remain concerning the accuracy of the computer-generated flowfields.

The flow in the vicinity of a wingtip is a fairly difficult test case for a Navier–Stokes code. Under typical flight conditions, highly skewed turbulent boundary layers detach from the surface of a wingtip and roll up into a tightly wound vortex. The mean velocity in the vortex core has been found to be almost twice the freestream velocity and the turbulence levels in the core are much higher than previously thought.

The emphasis of this study is to compare a measured and computed wingtip flowfield and to identify the shortcomings of the computational techniques. An extensive database of measured and computed results, for the flow over a rectangular wing with rounded tip, has been analyzed. The Reynolds number based on chord was 4.6 million and the angle-of-attack was 10° . The results show that the Navier–Stokes predictions are a close approximation of the flowfield everywhere with the exception of the vortex core. In the vortex core, the peak axial velocity is underpredicted by approximately four percent. The probable cause of the core-velocity underprediction is a deficiency in the capability of the turbulence model used in the computations.

Aeronautical applications areas:

The flow over a wing tip is a critically important area for efficient flight. New devices are constantly being applied to guide the swirling flow, mostly with cut-and-dry techniques. The current research is aimed at developing a rational design procedure to choose and apply these devices.

Citations: 45-48, 143

8. Development of a Laminar Flow Supersonic Wind Tunnel

Point of Contact: James A. Laub

Over the past two decades, all significant laminar flow control research was conducted in flight. It is recognized by aeronautical engineers that flight testing, especially in the field of transition to turbulence research, is of higher cost and greater risk than in a reliable, controlled ground test facility. For this reason, there is a need for a new generation of efficient quiet supersonic wind tunnels for investigation, prediction, and control of transition on supersonic wings and other components.

A research project team was assembled in January, 1989. The goal of the team was to develop a laminar flow supersonic wind tunnel (LFSWT) in which laminar flow control devices and related instrumentation could be studied. The new facility was to have an approximate one square foot test section with complete visual access and operate continuously at $1.6 \leq M \leq 2.5$ using the available FML

240,000 ICFM indraft compressor. The LFSWT was scheduled to be operational by December 1993.

With these parameters in mind, the project team decided that the best approach was to develop a proof-of-concept (PoC) one eighth scale model of the proposed LFSWT. Proof-of-concept testing proved that use of a unique injector drive system, Ames dry high pressure air system, and the FML compressor could power the new full scale LFSWT. A laminar boundary layer was documented over 84% of the test section floor at Mach 2.5 and 1.6 over a Reynolds (Re) range of one to two million per foot.

Based on these preliminary investigations a complete Design Requirements Document was prepared. In February 1993, the LFSWT design was complete and fabrication underway. The LFSWT was installed in the FML on July 11, 1993. The first data acquisition run at Mach 1.6 and the integrated systems test (were also completed in July.

The first model, a 70° swept wing for supersonic testing at $M = 1.6$, is scheduled for tunnel entry in FY94. Considering the tight schedule and need for rapid use of this new resource, It is noteworthy that the LFSWT was fabricated and installed on schedule. The total cost of the project including infrastructure modifications, design, fabrication, and installation was \$1.5 million.

Citations: 126-129, 131, 132, 134, 135

9. Supersonic Quiet Tunnel Facility Envelope Expansion

Point of Contact: Stephen W. D. Wolf

The research is an ongoing study to develop design principles for a new generation of national low-disturbance (or “quiet”) supersonic wind tunnels, more capable of meeting the needs of future transition research. Studies involve both theoretical and experimental efforts to identify critical factors governing quiet tunnel operations. The goal is to better understand these factors, so that this knowledge can be applied to wind tunnel designs to either introduce or expand (maximize) the quiet test envelope for new or existing wind tunnels.

Two supersonic wind tunnels have been built in the FML to study quiet design features for low-supersonic testing up to Mach 2.5 (see Research Brief 8). The initial design concept for these FML tunnels was based on the only previously documented quiet low-supersonic tunnel (the Jet Propulsion Laboratory 20-in. tunnel operated in the 1950s and 1960s), and modern CFD analysis of tunnel flows. The passive quiet design features attributed to the JPL tunnel were a large low-disturbance settling chamber and a long, low-curvature nozzle geometry. However, the

quiet test envelope of the JPL tunnel was limited to Reynolds numbers of about one million per foot at Mach 2 and above; this is insufficient to meet the needs of the HSR program today.

The factors affecting the quiet test envelope at low-supersonic speeds are free stream disturbances in the settling chamber, the extent of laminar boundary layers on the nozzle and test section walls, nozzle and test section vibration, and stability of the supersonic diffuser flow. Our wind tunnel testing has proven (for the first time) quiet design principles for the settling chamber and a Mach 1.6 nozzle, for Reynolds numbers up to two million per foot. We are also in the process of making detailed measurements of the tunnel test cores to identify sources of flow disturbances, which currently limit the quiet test envelope. These measurements will provide feedback to our CFD effort (see Research Brief 10), to hopefully provide our analyses with some capability to predict transi

In the future, we intend to examine quiet design features at higher Mach and Reynolds numbers, both by modifying our existing quiet tunnels and building a new high Reynolds number quiet tunnel. We will expand the quiet test envelope by actively delaying boundary layer transition on the nozzle and test section walls. One technique will be to heat and cool the tunnel walls relative to the flow. (FML funded research is already underway at Montana State University using a Mach 3 quiet wind tunnel to support this effort.) Another technique will be to optimize the nozzle geometry to minimize instabilities fed into the boundary layers. This research will be a joint experimental and computational effort to identify tunnel design features necessary to expand the quiet test envelope.

Aeronautical applications areas:

This research is immediately applicable to the HSR program in the area of Supersonic Laminar Flow Control (SLFC) ground testing. Furthermore, this research will help develop better national facilities, which are more capable of meeting the needs of the aerospace industry in the future.

Citations: 67, 126-129, 134, 135

10. High Speed Transition Prediction on Wings and Wind Tunnel Nozzles Using Navier–Stokes Technology

Point of Contact: Lyndell S. King

The ability to control the extent of laminar flow on swept wings at supersonic speeds may be a critical element in developing the enabling technology for a High Speed Civil Transport (HSCT). Laminar boundary layers are less

resistive to forward flight than their turbulent counterparts. The farther downstream that transition from laminar to turbulence in the wing boundary layer is extended can be of significant engineering and economic impact for the HSCT.

Experimental studies of boundary layer stability and transition are needed for understanding of the flow physics and for validation of computational tools. These studies are performed in "quiet" tunnels which are capable of simulating the low-disturbance environment of free flight. In turn, to develop a quiet tunnel it is necessary to study the boundary layer and transition characteristics of the tunnel's supersonic nozzle, and this involves in large measure the use of computational techniques for boundary layer stability and transition prediction.

Current state-of-the-art computational techniques for transition prediction on swept wings consists of three elements: (1) an Euler or Navier-Stokes (NS) code to predict the three-dimensional pressure distribution on the wing; (2) a quasi-3-D boundary layer (BL) calculation to obtain the mean flow profiles in the wing boundary layer; and (3) a linear stability code utilizing the so-called $\exp(N)$ method for transition prediction. Efforts are now being concentrated on developing methods with less restrictive assumptions than conventional approaches. A fully 3-D BL code has recently been obtained to replace the BL code of the hierarchy above. An interface technique is being developed so that the solution from the 3-D NS code can be employed for the mean flow profiles in the wing boundary layer, obviating the need for a BL code. Under a SBIR contract, a parabolized stability equation (PSE) code (which can account for nonlinear as well as linear stability), is being developed for swept wing flows. These codes will be used to predict the mean flow and transition due to attachment line and crossflow instabilities for a swept wing to be tested in the Ames quiet tunnel as described in Research Brief 8.

Regarding the Ames Laminar Flow Supersonic Wind Tunnel, two-dimensional NS and BL calculations were made for the 2-D nozzle of the tunnel. Stability calculations along the upper and lower surfaces indicated that Gortler and TS instabilities were insufficient, by themselves, to produce transition in the nozzle. Three-dimensional NS calculations, however, have shown corner vortices and cross-flow along the sidewall due to secondary flow in the nozzle. Possibilities thus exist for transition originating from the corner vortices, from secondary instabilities and from nonlinear interactions. Work will continue in complement with experimental flow surveys in the LFSWT to identify the processes involved leading to transition in the tunnel.

Aeronautical applications areas:

First, to aid in the design and development of a quiet supersonic flow tunnel at Ames for transition testing. Second, to provide computational tools for transition prediction on supersonic swept wings and for the aerospace industry to use in design/development of the HSCT.

Citations: 67

11. Compressibility Effects and Control of Dynamic Stall on Oscillating Airfoils

Point of Contact: M. S. Chandrasekhara

This research in the FML is an ongoing study to determine the onset of dynamic stall over oscillating airfoils under compressibility conditions using non-intrusive laser-based optical techniques. The goal is to obtain the necessary understanding of the flow for developing dynamic stall control concepts. The research is jointly funded by the U.S. Army Research Office, Air Force Office of Scientific Research, and other agencies.

One of the main accomplishments of the study is the development of a new real-time interferometry technique called point diffraction interferometry (PDI). This permits obtaining large amounts of flow field data in real-time. A comprehensive software package was developed for analysis of the interferograms. In its present mode of operation, it has been partially automated. Extremely high resolution instantaneous pressure distributions (15-20 pressure values in the first 1.5% of the airfoil chord) are then generated. Large density variations around the leading edge causes the light beams to deflect out of the region resulting in some loss of information. A correction scheme is being devised using ray theory to account for this effect.

More conventional laser velocimetry data of the flow over the airfoil oscillating at 2° amplitude revealed that the airfoil could stall at angles of attack *lower* than the static stall angle. The vorticity field information derived from the measured velocities indicated that this was due to the rapid release of the vorticity in the flow, which cannot occur by simple diffusion of vorticity through the airfoil boundary layer at high oscillation rates. Support for this result was found from the PDI studies as well.

Aeronautical applications areas:

The primary customer for this research is the Army in view of its need for maneuverable helicopters. A similar effort on transiently pitching airfoils/wings is being supported by the Air Force Office of Scientific Research which is interested in enhancing the maneuverability of fighter aircraft. Other Department of Defense agencies (NAVAIR Systems Command and the Navy) are also

co-sponsoring the effort. These various customers are awaiting the development of stall control concepts from this research for use in flight systems.

Citations: 1, 11-17, 20-24, 26-39, 63, 65, 82, 108, 117

12. Innovative Aerodynamic Flow Control Using Deforming Airfoils and Smart Structures Concepts

Point of Contact: Lawrence W. Carr

Aeronautical engineering is at an exciting stage—new technologies are becoming available that offer the opportunity to fundamentally affect the flow of air on the aerodynamic surfaces of airplanes and helicopters. For example, Micro-Electro-Mechanical Systems (MEMS) are being developed that can directly influence the flow over control surfaces at the same time that they measure the result of such influence; flow control technologies such as neural networks open new possibilities for aerodynamic control; computational fluid dynamics methodologies are rapidly reaching the stage where accurate representation of complex flows is becoming a reality.

The present boundaries of aircraft flight are due to limitations based on aeroelastic behavior of wings, and on avoidance of nonlinear flow regimes such as separation and stall. Active control of aerodynamic flows offers the opportunity to directly modify the way air behaves as it passes over the aircraft. For example, aeroelastic effects (“flutter” or “buffet”) restrict the flight envelope of aircraft, and “dynamic stall” limits the usefulness of helicopters. However, modern control and aerodynamic techniques can “decouple” the airframe from the aerodynamics—the aircraft can then fly into regimes that formerly were prohibited.

Research is now underway at the Fluid Mechanics Laboratory into the interaction between rapidly deforming airfoil surfaces and the surrounding flow field. Dynamic motion of airfoil surfaces has not been quantitatively analyzed in the past, and therefore has only been used in “ad hoc” conditions. However, new technologies developed at the FML offer the possibility for quantitative study of the behavior of aerodynamic flows over surfaces which are deformed in ways designed to suppress unwanted flow behavior such as separation. This task now is focused on the suppression of compressibility effects (see previous Research Brief) that normally cause premature separation on airfoils operating at high angles of attack—this flow control technology will be directly useful in suppression of buffet loads on control surfaces, as well as alleviation of gust-induced loads on aircraft wings.

13. Computer Algorithms for Numerical Wave Propagation

Point of Contact: Sanford S. Davis

High order compact algorithms are developed for the numerical simulation of propagating waves using the concept of a discrete dispersion relation. The dispersion relation is the unique imprint of any linear operator in spacetime. The discrete dispersion relation is derived from the continuous dispersion relation by examining the process by which locally plane waves propagate through a chosen grid. The exponential structure of the discrete dispersion relation suggests an efficient splitting of convective and diffusive terms for dissipative waves. Fourth- and eighth-order convection schemes are examined that involve only three or five spatial grid points. These algorithms are subject to the same restrictions that govern the use of dispersion relations in the construction of asymptotic expansions to nonlinear evolution equations. A new eighth-order scheme is developed that is exact for Courant numbers of 1–4.

Applications areas:

Much of aerodynamics and fluid mechanics depends on signal propagation. These high resolution schemes are applicable to aeroacoustic propagation, flow stability, and the simulation of unsteady flows in general.

Citations: 49-52, 54-57, 59, 60, 80, 81

14. Advanced Acoustics Sensors for Wind Tunnel Applications

Point of Contact: Y. C. Cho

Acoustic measurements in wind tunnels are subject to certain interference effects such as wind noise, flow induced sensor vibration, reflections from facility and sensor support components, and noise due to temperature fluctuation. Furthermore, it is often desirable to investigate specific source regions on the models being studied. Existing acoustic sensor techniques are not adequate to cope with these problems. Fluid Mechanics Laboratory jointly with Full-Scale Aerodynamics Research Division embarked on a program to develop advanced acoustic sensors to eliminate or minimize these interference restrictions. The program involves development of adaptive arrays using fiberoptic sensors as transducers. The technology of fiber-optic interferometric sensors has matured in underwater acoustics and is adapted to aeroacoustics. Fiber-optic acoustic sensors offer a number of advantages: High sensitivity, wide dynamic range, high temperature tolerance, compact sensor package, geometric versatility,

superb telemetry capability, immunity to electromagnetic interferences, etc. The compact size of sensors can be utilized to reduce the flow-sensor interactions. Owing to its geometric versatility, the optical fibers can be configured with great flexibility as extended sensor elements or sensor arrays. Such configurations would generate a great variety of array sensitivity patterns. Furthermore, the optical fibers can be implanted on the surface of a solid body. With the sensor elements implanted on an aerodynamically smooth body, the flow-interaction can be made negligible, the aerodynamically induced vibration will be minimized, and effects of the boundary layer will be more tractable.

Mach Zehnder interferometry was employed to develop and fabricate the first fiber-optic microphone. Extensive laboratory tests are in progress for evaluation of its acoustic characteristics including acoustic sensitivity, dynamic range, frequency response, etc. The test results thus far demonstrated successfully its feasibility as aeroacoustic sensors.

Customers:

One of the immediate customers is the large 40- x 80-Foot Wind Tunnel. This technology has potential for aerospace industry applications such as measurements of pressure fluctuation associated with laminar and turbulent boundary layers.

Citations: 43-45

15. Facility Automation using Off-the-Shelf Hardware and Graphical User Interface Software

Point of Contact: David Yaste

There is an ongoing need to improve information to the users of complex equipment such as the FML Compressor system. In 1989/90 we began researching hardware and software packages that would allow us to utilize the increasing power of micro computer technology to monitor and eventually control the compressor system along with our small-scale wind tunnels. We eventually settled on a PC-Windows based system that allows a certain level of hardware independence, a reliable performance based upgrade path, near real time data acquisition, and a user friendly interface to the process.

The installed software is capable of acquiring, displaying and storing approximately 200 discrete references and 120 analog values at 1 second intervals. The software also contains a near-real-time strip chart display, historical trending, and export capability for more cause and effect determination if the compressor fails. The software is also now being, used in conjunction with a programmable

logic controller in totally automated operation of the High Pressure Air System and the Laminar Flow Supersonic Wind Tunnel (Research Brief 8). Future additions to the system will be to post data on our PC network as part of our growing MIS/Groupware thrust at the FML.

Customers:

Several operations on the center have been moved (or are being moved) to a Windows based Graphical User Interface. Most notable among these are three separate systems at the 40- x 80- x 120-Foot Wind Tunnel that are being handled by the same software first used at the FML. As more users of complex research facilities become aware of the increased diagnostic and efficiency gains of low-cost interfaces, more implementations are certain to follow.

Citations: 138

16. Predictive and Preventive Maintenance in the FML

Point of Contact: James A. Laub

Maintenance in NASA's R&D facilities has traditionally been schedule-driven and very labor intensive. With today's declining resources, it is important to conduct maintenance in a more efficient manner without compromising dependability and availability. With this in mind, we have developed a computer-based Predictive and Preventive Maintenance Program (PPM). The PPM is designed to compare near real time data against historical data from which trending analysis can be performed. Upon completion, PPM software and hardware will be capable of detecting compressor drive train anomalies and make projections of time to catastrophic failure. This capability will allow scheduling of an orderly facility shutdown, acquisition of parts, and human resource planning.

Off-the-shelf software and hardware was purchased for the PPM. The software resides in an IBM-compatible host computer. Communication with the FML automated compressor control system occurs through a commercial Genius bus. The Genius system acquires analog vibration data from 19 locations, pressure and temperature data, and power consumption and operating times. All this data is automatically stored in a database from which real time data trending can be performed against history using available software (Research Brief 15).

Also residing in the host computer are pop-up windows from which a display of the entire drive system can be viewed. The mimic displays real time valve movement, manifold pressure, compressor data, and power

consumption information. Other windows can display up to 158 different parameters, either alone or up to four simultaneously. Should an out of tolerance parameter be detected by PPM, the information is fed to the automated compressor control system where the appropriate warning or shutdown command is given. The PPM can then be called upon to graphically display the events that preceded the detected anomaly. The historical graphics window will also display the time the anomaly occurred and the duration of the event.

The information provided by this state-of-the-art program has been proven very reliable. The compressor is now continuously available for research in multiple test cells. Operations require no monitoring personnel and all maintenance is based on PPM data.

Customers:

This technology is applicable to a wide variety of research and production facilities. It will enable facility managers to plan a rational maintenance program for equipment required to operate continuously on a three-shift schedule.

**17. Industrial Aerodynamics in the FML
32" × 48" Wind Tunnel**

Point of Contact: Greg G. Zilliac

The 32" × 48" wind tunnel in the Fluid Mechanics Lab at NASA Ames has been used for several applied research studies. The most interesting of these studies was an investigation of the effect of winds on telescope observatory domes. The prevailing winds at most observatory dome sites are often high enough to cause flow induced vibration of the telescope, thus greatly reducing useful viewing hours. A new concept in dome design (developed by MONOPTEC, Inc.) involved implementation of a circular dome-aperture of greatly reduced area in comparison to the rectangular openings used in conventional dome designs. Hot-wire anemometry was used to measure the flowfield in the interior of several dome configurations. Results showed that the flow environment of the dome with the circular aperture was the most favorable.

In addition to the basic and applied fluid mechanics research which has been carried out in the 32" × 48" wind tunnel, a few measurement techniques have been developed to the point where they should be of use to industrial aerodynamicist. The low turbulence and low freestream angularity of the 32" × 48" tunnel proved to be indispensable in the development and evaluation of a seven-hole pressure probe measurement technique. This particular pressure probe allows the measurement of the

mean velocity in a turbulent flow-field to within one percent accuracy and is a very robust technique.

Citations: 139, 140, 144

18. Computational Support for Space Life Sciences Activities

Point of Contact: Sanford S. Davis

The unsteady transport of a reacting permeant diffusing through thin membranes and modeled red cells was investigated using a new nonlinear analysis of the reaction-diffusion equations. This model is adapted from similar problems in fluid mechanics. Implicit finite difference methods and a matrix formulation are used to study deviations from equilibrium-based theories and the transient behavior of facilitated oxygen transport across cell membranes. The loading and unloading of oxygen from an erythrocyte model is computed and contrasted with the diffusion of oxygen across hemoglobin-saturated membranes.

In another application, unsteady facilitated transport of nitric oxide across a thin liquid membrane containing ferrous chloride as a facilitator is investigated experimentally and computationally. Predicted nitric oxide transport and flux are compared with experiments first reported by Ward in 1968. Unsteady transport is predicted qualitatively quite well, but precise quantitative agreement between the differential equation model and experiment depends on an accurate determination of the transport coefficients, especially the diffusion constants.

Citations: 53, 57, 58

19. Advanced Training Activities in Cooperation with the Naval Postgraduate School, Monterey
Point of Contact: M. S. Chandrasekhara

FML facilities are also being used by graduate students at the Naval Postgraduate School (NPS) through the Navy-NASA Joint Institute of Aeronautics. Presently, a Ph.D. student is involved in experimental and computational studies of dynamic stall over oscillating airfoils. Further, graduate students in the NPS Aeronautics and Astronautics department have used experimental data generated in FML experiments to compare and validate CFD codes developed as part of their Master's and Engineer's theses. A graduate course AE 3802: Advanced Aeronautical Measurement Techniques, is offered twice a year at NPS and uses FML facilities for presentations and field trips. Lectures on specific research topics and measurement techniques are routinely given by FML staff members

(Dr. S. S. Davis: Overview of the branch research, Dr. L. W. Carr: Dynamic stall of airfoils, Dr. D. C. Reda: Use of liquid crystals in aerodynamic measurements, Dr. B. G. McLachlan: Use of pressure sensitive paint for aerodynamic measurements, Dr. R. D. Mehta: Hot-wire laboratory classes). This constant interaction between FML scientists and NPS faculty and students is one of the hallmarks of the research program at FML and the Joint Institute.

20. Ph.D. Training Activities in Cooperation with Stanford University

Point of Contact: Rabindra D. Mehta

Two Stanford University graduate students (James H. Bell and James H. Weygandt) were supported by the Fluid Mechanics Laboratory. Both students conducted their experimental research work in facilities located within the FML under the training and supervision of Dr. Mehta. Both students graduated with Ph.D. degrees from the Department of Aeronautics and Astronautics at Stanford University.

James Bell graduated in 1989 with a thesis entitled: "Three-Dimensional Structure of Plane Mixing Layers." His research project dealt with direct measurements of the streamwise vortical structures in mixing layers which were recently observed riding over the familiar spanwise vortices. A special purpose wind tunnel was designed and built for this study. The results indicated that the instability, leading to the formation of streamwise vortices, was initially amplified just downstream of the first spanwise roll-up. The streamwise vortices first appeared in clusters, but soon realigned to form counter-rotating pairs. The streamwise vortex spacing increased in a stepwise fashion while the peak mean streamwise vorticity decayed with downstream distance. The streamwise structures persisted through to what would normally be considered the self-similar region, although they were very weak and the mixing layer otherwise appeared to be two-dimensional.

James Weygandt graduated in 1993 with a thesis entitled: "Three-Dimensional Structure of Straight and Curved Wakes." He investigated the effects of initial conditions on straight and mildly curved plane wakes. The curved wake is particularly interesting since the inside half of the wake is unstable, whereas the outside half is stable. In both untripped wakes, well-organized streamwise vorticity was generated in the form of quadrupoles which had a significant effect on the wake growth and defect-decay rates. In the straight wake, the mean streamwise vorticity decayed on both sides of the wake at approximately the same rate. However, in the curved case, the mean streamwise vorticity on the unstable side decayed at a significantly lower rate than that on the stable side. Despite the

decay of mean streamwise vorticity, the spanwise variations persisted into the far-wake in both cases. The effects of curvature were also apparent in the Reynolds stress results which showed that the levels on the unstable side were increased significantly compared to those on the stable side.

The results from both investigations revealed many important details regarding the three-dimensional structure of free-shear flows. Results are presently being compared to direct numerical simulation data so that a better understanding of the flow physics may be obtained. The present results also inspired further studies where mechanisms for free-shear flow control were investigated with a view towards practical applications in aeronautics, (Research Brief 4).

Citations: 3-9, 74, 75, 118-122

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