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EXPERIMENTAL MEASUREMENTS OF UNSTEADY TURBULENT BOUNDARY LAYERS NEAR SEPARATION

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INTRODUCTION

Unsteady turbulent boundary layers are of much interest because of unsteady aerodynamic phenomena associated with blades in compressors and with helicopter rotors in translating motion. While all turbulent flows are inherently unsteady, here the term "unsteady" means a periodic time dependent motion, in contrast to the relatively aperiodic motion of turbulence. The boundary layers cannot be ignored in unsteady flow analyses of these devices because there is considerable interaction between the boundary layer and the inviscid flow during high loading conditions. In such cases the relatively thick boundary layer on the suction side of the lifting body is near separation. "Separation" must mean the entire process of "departure" or "breakaway" or the breakdown of the boundary-layer concept. An abrupt thickening of the rotational flow region next to a wall and significant values of the normal-to-wall velocity component must accompany breakaway, else this region will not have any significant interaction with the free-stream inviscid flow [1].

Work supported by this grant is part of a program to document the behavior of turbulent boundary layers on flat surfaces that separate due to adverse pressure gradients. Simpson, Chew, and Shivaprasad [2,3] and Shiloh, Shivaprasad, and Simpson [4] reported extensive laser and hot-wire anemometer turbulence and flow structure measurements of a steady free-stream separating turbulent boundary layer produced on the floor of the SMU wind tunnel test section. The Reynolds number for that flow was 4.7×10^6, based on the entrance free-stream velocity $\overline{U}_{ei}$ of 15.06 mps and the 4.9 m length C of the converging-diverging section.

In work partially supported by this grant, Simpson, Shivaprasad and Chew [5] reported the effects of sinusoidal unsteadiness of the free-stream velocity on this separating turbulent boundary layer at a reduced frequency $k = \omega C/2\bar{U}_{ei}$ of 0.61. The oscillation amplitude to mean velocity ratio was about 0.3.

In work supported by this grant, Simpson and Shivaprasad [6] reported some effects of reduced frequency on the flow structure. Measurements were reported for the same oscillation frequency (0.596 Hz) as in [5] but with a mean entrance free-stream velocity $\bar{U}_{ei}$ of 10.18 mps. The oscillation amplitude to mean velocity ratio is about 1/3 and the reduced frequency $k = \omega C/2\bar{U}_{ei}$ is 0.90. Since the reduced frequencies based on the blade chord are of the order of 0.1 for helicopter blades and of the order of 1 for axial compressor blades, these data and those presented in [5] are within the range of practical reduced frequencies.

Since the detached flow behavior is dramatically affected by the unsteadiness at these practical reduced frequencies, some effects of the amplitude and waveform of the periodic unsteadiness were examined [7,8]. Measurements of surface skin friction and the near wall fraction of time the flow moves downstream were made for several cases using a Rubesin et.al. type [9] surface hot-wire anemometer and a thermal tuft [10] built at SMU. While the time-averaged free-stream velocity $\bar{U}$ was nearly the same in these cases as in the steady free-stream case [2-4], the surface skin-friction varies with $\overline{U_e^2}$ rather than $\bar{U}_e^2$ and the detached flow behavior is strongly affected by the unsteadiness waveform and amplitude [8].

SUMMARY OF ACCOMPLISHMENTS
DURING THIS GRANT PERIOD

During this grant period there were several significant achievements:

1. Detailed laser and hot-wire anemometer measurements of ensemble-averaged velocity and turbulence profiles were made for two moderate amplitude sinusoidal waveform unsteady separating turbulent boundary layers n the range of practical reduced frequencies [5,6].
2. A Rubesin et.al. type [9] of surface skin-friction gage was developed and used to measure the oscillatory surface shear stress.
3. Measurements and analysis of the viscous sublayer revealed that the large apparent ensemble-averaged phase shift can be due to the small relative motion between the measurement sensor and the test wall.
4. A thermal flow direction "thermal tuft" was developed [10] to determine the fraction of time that the flow moves downstream.
5. The "law of the backflow" that describes the near wall mean velocity profile for steady free-stream flows [11], holds for the unsteady flows examined here [5,6,8,12].
6. The skin friction gage and the thermal tuft were used to examine the effects of free-stream velocity waveform and amplitude on the skin-friction and the detached flow [8].
7. Laser and hot-wire anemometer measurements of ensemble-averaged velocity and turbulence profiles were obtained for a very large amplitude oscillatory flow, $(U_{emax} - U_{emin})/2\bar{U}_e \approx 0.75$, and are described in detail in ref. [8].

Abstracts of publications [5,6,7,10,11,12] are contained in the attached appendix. These articles discuss in detail the effects of periodic freestream unsteadiness on the structure of separating turbulent boundary layers.

FUTURE RESEARCH

It is clear from the work supported by this grant that unsteadiness markedly affects the behavior of a separating turbulent boundary layer. Further experiments are needed to relate the turbulent processes to the ensemble-averaged profiles in order to improve the modeling of this type of flow.

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4. Shiloh, K., Shivaprasad, B.G., and Simpson, R.L. (1981), "The Structure of a Separating Turbulent Boundary Layer: III, Transverse Velocity Measurements." J. Fluid Mechanics, 113, pp. 75-90.

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6. Simpson, R.L., and Shivaprasad, B.G. (1983), "The Structure of a Separating Turbulent Boundary Layer: V, Frequency Effects on Periodic Unsteady Freestream Flows." submitted to J. Fluid Mechanics.

7. Simpson, R.L., Shivaprasad, B.G., and Chew, Y.-T. (1981), "Some Features of Unsteady Separating Turbulent Boundary Layers." IUTAM Symposium on Unsteady Turbulent Shear Flows, Toulouse, France, May 5-8; pp. 109-119, Springer Verlag, ed. R. Michel, J. Cousteix, and R. Houdeville.

8. Simpson, R.L., and Shivaprasad, B.G. (1983), "The Structure of a Separating Turbulent Boundary Layer: VI, Some Amplitude and Waveform Effects on Periodic Unsteady Freestream Flows," to be submitted to J. Fluid Mechanics.

9. Rubesin, N.W., Okuno, A.F., Mateer, G.G., and Brosh, A., "A Hot-Wire Surface Gage for Skin Friction and Separation Detection Measurements," NASA TM X-62, 465 (1975).

10. Shivaprasad, B.G., and Simpson, R.L. (1982), "Evaluation of an Improved Wall-Flow-Direction Probe for Measurements in Separated Flows," TASME, J. Fluid Mechanics, 104, pp. 162-166.

11. Simpson, R.L. (1983), "A Model for the Backflow Mean Velocity Profile," AIAA Journal, Vol. 21.

12. Simpson, R.L., Chehroudi, B., and Shivaprasad, B.G. (1982), "Pointwise and Scanning Laser Anemometer Measurements in Steady and Unsteady Separated Turbulent Boundary Layers," International Symposium on Applications of LDA to Fluid Mechanics, Lisbon, Portugal, July 5-7.

PUBLICATIONS AND PRESENTATIONS DURING THIS PERIOD

1. References 5,6,7,10,11,12 were published or submitted for publication. Abstracts of these publications are in the appendix.

2. Simpson, R.L. (1981), von Karman Institute for Fluid Dynamics Lecture Series 1981-1, Separated Flows in Turbomachinery Components, Jan. 12-16, 1981 three lectures.

   A. Experimental Techniques for Separated Flows.

   B. Features of Separating and Reattaching Turbulent Shear Flows.

   C. Prediction Methods for Separated Turbulent Shear Flows.

3. Seminars on this work were held at:

   Max-Planck-Institut fur Stromungsforschung, FRG
   North Carolina State University, Raleigh, North Carolina
   University Tennessee Space Institute, Tullahoma, Tennessee
   Michigan Technological University, Houghton, Michigan
   Elliott Company, Jeannette, Pennsylvania
   Stanford University, Palo Alto, California
   NASA - Ames Research Center
   VPI and SU, Blacksburg, Virginia

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The structure of a separating turbulent boundary layer. Part 4. Effects of periodic free-stream unsteadiness

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(Received 17 February 1982)

Unsteady separating turbulent boundary layers are of practical interest because of unsteady aerodynamic phenomena associated with blades in compressors and with helicopter rotors in translating motion during high-loading conditions. Extensive measurements of a steady free-stream, nominally two-dimensional, separating turbulent boundary layer have been reported by Simpson, Chew & Shivaprasad (1981*a*, *b*) and Shiloh, Shivaprasad & Simpson (1981). Here measurements are reported that show the effects of sinusoidal unsteadiness of the free-stream velocity on this separating turbulent boundary layer at a practical reduced frequency of 0·61. The ratio of oscillation amplitude to mean velocity is about 0·3.

Upstream of flow detachment, single- and cross-wire, hot-wire anemometer measurements were obtained. A surface hot-wire anemometer was used to measure the phase-averaged skin friction. Measurements in the detached-flow zone of phase-averaged velocities and turbulence quantities were obtained with a directionally sensitive laser anemometer. The fraction of time that the flow moves downstream was measured by the LDV and by a thermal flow-direction probe.

Upstream of any flow reversal or backflow, the flow behaves in a quasisteady manner, i.e. the phase-averaged flow is described by the steady free-stream flow structure. The semilogarithmic law-of-the-wall velocity profile applies at each phase of the cycle. The Perry & Schofield (1973) velocity-profile correlations fit the mean and ensemble-averaged velocity profiles near detachment.

After the beginning of detachment, large amplitude and phase variations develop through the flow. Unsteady effects produce hysteresis in relationships between flow parameters. As the free-stream velocity during a cycle begins to increase, the Reynolds shearing stresses increase, the detached shear layer decreases in thickness, and the fraction of time $\tilde{\gamma}_{pu}$ that the flow moves downstream increases as backflow fluid is washed downstream. As the free-stream velocity nears the maximum value in a cycle, the increasingly adverse pressure gradient causes progressively greater near-wall backflow at downstream locations, while $\tilde{\gamma}_{pu}$ remains high at the upstream part of the detached flow. After the free-stream velocity begins to decelerate, the detached shear layer grows in thickness and the location where flow reversal begins moves upstream. This cycle is repeated as the free-stream velocity again increases.

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The structure of a separating turbulent boundary layer. Part 5. Frequency effects on periodic unsteady free-stream flows

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Measurements of a steady free-stream, nominally two-dimensional, separating turbulent boundary layer have been reported in earlier parts of this work. Here measurements are reported that show the effects of frequency on sinusoidal unsteadiness of the free-stream velocity on this separating turbulent boundary layer at reduced frequencies of 0.61 and 0.90. The ratio of oscillation amplitude to mean velocity is about $\frac{1}{3}$ for each flow.

Upstream of flow detachment, hot-wire anemometer measurements were obtained. A surface hot-wire anemometer was used to measure the phase-averaged skin friction. Measurements in the detached-flow zone of phase-averaged velocities and turbulence quantities were obtained with a directionally sensitive laser anemometer. The fraction of time that the flow moves downstream was measured by the LDV and by a thermal flow-direction probe.

Upstream of any flow reversal or backflow, each flow behaves in a quasisteady manner, i.e. the phase-averaged flow is described by the steady free-stream flow structure. The semilogarithmic law-of-the-wall velocity profiles applies at each phase of the cycle. The Perry & Schofield (1973) velocity-profile correlations fit the mean and ensemble-averaged velocity profiles near detachment.

After the beginning of detachment, large amplitude and phase variations develop through each flow. Unsteady effects produce hysteresis in relationships between flow parameters. As the free-stream velocity during a cycle begins to increase, the detached shear layer decreases in thickness, and the fraction of time $\tilde{\gamma}_{pu}$ that the flow moves downstream increases as backflow fluid is washed downstream. As the free-stream velocity nears the maximum value in a cycle, the increasingly adverse pressure gradient causes progressively greater near-wall backflow at downstream locations while $\tilde{\gamma}_{pu}$ remains high at the upstream part of the detached flow. After the free-stream velocity begins to decelerate, the detached shear layer grows in thickness, and the location where flow reversal begins moves upstream. This cycle is repeated as the free-stream velocity again increases.

In both unsteady flows, the ensemble-averaged detached-flow velocity profiles agree with steady free-stream profiles for the same $\tilde{\gamma}_{pu\,min}$ value near the wall when $\partial\tilde{\gamma}_{pu\,min}/\partial t < 0$. However, the reduced-frequency $k = 0.90$ flow has much larger hysteresis in ensemble-averaged velocity profile shapes when $\partial\tilde{\gamma}_{pu\,min}/\partial t \geqslant 0$. Larger and negative values of the profile shape factor $\tilde{H}$ occur for this flow during phases when the non-dimensional backflow is greater and $\tilde{\gamma}_{pu\,min} \rightarrow 0.01$.

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A MODEL FOR THE BACKFLOW MEAN VELOCITY PROFILE

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Introduction

Simpson, Chew, and Shivaprasad[1,2] and Shiloh, Shivaprasad and Simpson[3] presented detailed flow structure data obtained with a laser anemometer for the near wall backflow region of a separating turbulent boundary layer. Downstream of fully-developed separation[4] ($\tau_W = 0$ and the fraction of time that the flow moves downstream near the wall, $\gamma_{puw} = 1/2$), the mean backflow region appears to be divided into three layers: a viscous layer nearest the wall; an intermediate layer that seems to act as an overlap region between the viscous wall and outer regions; and the outer backflow region that is really part of the large-scaled outer region flow. Mixing-length and eddy-viscosity models are physically meaningless in the backflow near the wall, being imaginary and negative, respectively.

It was clear from these data, which are shown in Fig. 1, that the normal mean velocity $U/|U_N|$ was approximately a function of y/N, where U_N is the maximum streamwise backflow mean velocity and N is the distance from the wall to this maximum backflow velocity. At that time there was no obvious simple model equation that would fit the mean velocity profiles of the backflow region. Aside from the small amount of laser anemometer data of Hastings[5] and one pulsed-wire anemometer profile of Westphal[7], which are also shown on Fig. 1, no other investigators of separated flows have obtained measurements sufficiently close to the test wall to describe this backflow region.

The purpose of this paper is to present simple model equations for the mean backflow near the wall that are consistent with experimental observations. These equations satisfy the current need for a near wall mean backflow model for use in calculation methods[4].

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IUTAM Symposium on Unsteady Turbulent Shear Flows, Toulouse, France, May 5-8, 1981, Springer-Verlag.

Some Features of Unsteady Separating Turbulent Boundary Layers

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Abstract

A survey of the physical features of steady and unsteady separating turbulent boundary layers is presented for practical Reynolds numbers and reduced frequencies for helicopter and turbomachinery flows. Well upstream of separation there is little interaction between the periodic motions, so the flow away from the wall has little phase variation from the freestream. Near the wall between the viscous sublayer and the semi-logarithmic region, unexpected phase shifts of the velocity and turbulence oscillations occur.

Near separation and downstream more interaction occurs between the periodic and turbulent motions since the characteristic frequency of the large scale structures is much lower than upstream. Significant phase variations between the velocity and turbulence exist in the detached and back flows. For moderate oscillation amplitudes there is no effect of oscillation waveform on the mean flow features. Large amplitude oscillations affect the flow structure significantly.

TASME, J. Fluids Engineering, 104, pp. 162-166.

Evaluation of a Wall-Flow Direction Probe for Measurements in Separated Flows

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The upstream-downstream flow direction intermittency γ_{pu} is an important parameter that can quantitatively describe the stages of flow separation. This paper gives an improved design for a wall-flow-direction probe. Intermittency measurements made using this modified probe show agreement within experimental uncertainties with direct measurements made using a LDV, although both the unmodified and modified probe designs produce results that are consistently higher than those for the LDV.

International Symposium on Applications of LDA
to Fluid Mechanics, Lisbon, Portugal,
July 5-7, 1982.

POINTWISE AND SCANNING LASER ANEMOMETER MEASUREMENTS IN STEADY AND UNSTEADY SEPARATED TURBULENT BOUNDARY LAYERS

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ABSTRACT

A survey is presented of the physical features of steady and unsteady freestream separating turbulent boundary layers that have been determined by pointwise laser anemometer measurements. It appears that the large-scaled structures control the outer region backflow behavior. Near the wall the mean backflow velocity profile for both the steady and unsteady cases scales on the maximum negative mean velocity U_N and its distance from the wall N. A scanning laser anemometer is described that obtains almost instantaneous velocity profiles to examine the temporal features of these large-scaled structures. A "zero-wake" seeder is described that supplies particles to the outer shear layer and freestream flow with a minimal disturbance.