AFOSR-TR-95-0493 Rec'd 1 June 95

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
5/24/95

3. REPORT TYPE AND DATES COVERED
FINAL TECHNICAL REPORT 11/1/90 - 2/28/95

4. TITLE AND SUBTITLE
Turbulent Flow Control

5. FUNDING NUMBERS
AFOSR-91-0072

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NA
110 Duncan Avenue, Suite B115
Bolling Air Force Base
Washington, DC 20332-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release
Distribution is limited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The primary purpose of this project was to explore actuators, sensors, and control strategies for active control of turbulent jets and boundary layers. Potential applications of this work are to boundary layer control in aircraft and propulsion systems, which should be enabled by concurrent developments in MEMS fabrication technology. The present experiments were performed in a low-speed water flow, where the turbulence is large scale and slow, allowing easy measurement of flow properties and use of actuators and sensors that could be fabricated individually. A zero net mass flow actuator was developed and used in conjunction with wall stress sensors to demonstrate control of laminar flows containing steady and unstead streamwise vorticies similar to those found in the near-wall region of turbulent boundary layers. Various closed loop control schemes, including an adaptive inverse neural net control, were explored. An early phase of the project was devoted to extension of work on control of round jets by acoustic excitation. It was shown that the jet direction and mixing can be strongly influenced by acoustic and fluidic actuation.

14. SUBJECT TERMS
Active Flow Control, Turbulence Control, Actuator, Neural Networks, Vortex Generator

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
unclassified

20. LIMITATION OF ABSTRACT
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DTIC QUALITY

Final Technical Report
Turbulent Flow Control
AFOSR-91-0072

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1. Objectives

The ability to control turbulence in boundary layers would enable new technologies for drag reduction, aerodynamic control, heat transfer reduction, and noise control in aircraft and other systems where turbulent boundary layers cause problems. As a result of many years of research on the structure of turbulent boundary layers and the underlying stochastic field dynamics (much of it supported by the AFOSR), the basic understanding of boundary layer turbulence is now sufficient that the possibilities of control can be investigated. Numerical simulations of boundary layers has progressed to the point where hypothetical control schemes can be explored in the simulations. These have indicated that significant control could actually be achieved if one could sense the distribution of wall shear stress over the surface and respond injecting or removing fluid appropriately through the surface (with no average mass flow).

This project was an attempt to address wall turbulence control using discretely fabricated hardware and design concepts that could be applied to large arrays using microfabrication techniques. The objectives were as follows:

- To develop an actuator capable of affecting near-wall turbulence on demand with no net transpiration flow.
- To combine a small array of actuators with a small array of shear stress sensors and demonstrate control of unsteady three-dimensional laminar flows simulating near-wall turbulence.
- To investigate various control stategies, including neural networks, as applied to turbulent boundary layer control.

Early in the project, some effort was also devoted to extension of previous work on control of round jets. In the earlier work we showed that one could make a round jet explode into a shower of vortex rings (bloom), or split into two or three jets (bifurcate or trifurcate), by using appropriate combinations of axial and azimuthal acoustic forcing (dual-mode excitation). This previous work led to improved understanding of the flow physics. It was clear that the entrainment by the jet could be significantly increased with judicious unsteady forcing, but the levels of increase were not known. Moreover, stronger forcing was found necessary at higher Reynolds numbers. The objectives of this phase were as follows:

- To determine the additional entrainment associated with blooming jets at moderately high Reynolds numbers ($Re_D = 10^6$).

- To explore nozzle lip geometrical modifications seeking configurations that enable control with weaker forcing.

2. Accomplishments

A. Boundary layer control

The boundary layer research was performed in an existing low-speed water channel at Stanford University, using a steady flat-plate laminar boundary layer as the basic test flow, with imposed unsteady streamwise vortices. The low speed provided large-scale, slowly evolving turbulence, which was easily visualized and measured using a two-component laser anemometer. Commercially available small hot-film sensors were used to measure the local instantaneous wall shear stress. The large scale of the flow permitted a number of concept actuators to be fabricated and explored rather easily, and out of this work emerged an effective actuator concept.

The actuator, which is the principal device contributed by this program, is shown schematically in Fig. 1. It consists of a cantilever mounted flush with the surface over a cavity, and resembles a springboard with its mounting point upstream. The cantilever consists of a stainless steel sheet bonded to a piezoelectric material (PZT). It is driven close to its resonance frequency using a sinusoidal applied voltage. The cantilever is mounted so that along one side there is a narrow gap and along the other side a wider gap. When the cantilever moves into the surface, there is a directed outflow from the cavity, with the velocity emerging from the narrow gap much larger than that from the wide gap. When the cantilever moves out into the flow, there is an inflow into the cavity that is diffuse. The net effect is the formation of a streamwise vortex pair over each gap, with the stronger pair over the narrow gap. The common flow of these vortex pairs is away from the surface, and this can be used to impede the turbulent motion of fluid towards the surface associated with streamwise vortices in the near-wall region. By modulating the amplitude of the driving voltage, the strength of the induced vortices can be varied. The resonant frequency of the actuator must be high compared to the frequency of change in the wall flow to be controlled, and that was the situation in the low-speed water flow.

A small array of up to four actuators was used in conjunction with up to six wall stress sensors to explore various concepts for control of steady and unsteady streamwise vortices in a laminar boundary layer, and to explore control of a turbulent wedge produced by a small cylinder protruding into the laminar boundary layer.

A number of control experiments were completed. In experiments on transition delay in a turbulent wedge, it was found that active control by a single actuator positioned just downstream of the disturbance point could extend the transition region downstream by approximately 40 boundary layer displacement thicknesses ($40\delta_*$).

The most complex experiments involved control of streamwise vortices introduced randomly in time by applying suction to four holes upstream of the actuator sensor array. Three sensors were located upstream of the array of four actuators, and three downstream. Only two of the actuators were used in these experiments (the two positioned so as to oppose the flow towards the wall produced by the streamwise vortices). Fig. 2

shows a schematic of the experiment and the key result. Note that the mean shear stress m_S indicated by the three downstream sensors is reduced by about 10% by application of control, and the standard deviation σ_S of the three downstream sensors is reduced by approximately 80%, indicating that the actuator is indeed effective in removing spanwise variations. This is important because the spanwise variations in wall stress are believed to result in instabilities that help renew the turbulence in a turbulent boundary layer.

The results in Fig. 2 used a fast-feedforward slow-feedback closed loop control scheme. The use of neural networks was also explored, using both simple compuational models and the hardware in Fig. 2. Forward model and adaptive inverse control architectures were studied. In the experiments, the neural net controller learned to control the flow to a degree comparable with that shown in Fig. 2, but the learning period was disappointingly long. The field of neural net control is developing rapidly, and as improvements are made it should be possible to do better and learn faster.

This project is described in detail in the companion report by Jacobson and Reynolds (1995), filed separately with the AFOSR and available from the DOD or Stanford University.

B. Jet control

The incremental entrainment by a blooming jet was measured by shrouding the jet and measuring the shroud exit profiles using hot wire anemometry. At a point eight nozzle diameters downstream of the nozzle, the total flow exiting the shroud was measured to be as much as 4.5 times that of the primary jet. This compares to the value of 2.5 obtained at this distance using an elliptical jet. It clear that proper dual-mode forcing could be very useful in practical devices, if it can be achieved with disturbances of reasonable magnitude.

A number of geometrical modifications of the nozzle exit configuration thought to be useful for obtaining control with weaker forcing amplitudes were explored. The most interesting efffects were obtained by rounding the jet lip and using tangential wall-jet blowing at the start of the rounded section (Coanda blowing). With a blowing flow equivalent to 12% of the primary jet flow, the jet could be completely turned to flow *radially* outward, inducing a strong flow on the jet axis from the free stream *towards the nozzle*! This provided an important indication that thrust vectoring might be possible by fluidic control of an aircraft engine jet at its exit plane. The possibility of complete jet reversal is also suggested.

This project is described in detail in the companion report by Juvet and Reynolds (1993), filed separately with the AFOSR and available from the DOD or Stanford University.

3. Personnel

The boundary layer research formed the basis for the PhD dissertation of S. A. Jacobson. The jet work formed the basis for the PhD dissertation of P. J. D. Juvet. Both were conducted under the guidance of Professor W. C. Reynolds.

4. Transitioning

The actuator developed under this program has been adapted by K. Breuer at MIT for use in air. The actuator concept is being explored by P. Bradshaw at Stanford for use at larger scale in air as on-demand vortex generators for aircraft applications, where no drag penalty would be incurred when they are inactive. N. Mansour at NASA/Ames is conducting direct numerical simulations of the actuators in order to provide insight into their operation and a design optimization tool. The adaptive neural network control ideas have influenced the neural network development for MEMS flow control at UCLA. Dr. S. A. Jacobson is now on the Research Staff at MIT, where he is engaged in a project to develop microscale turbines and consulting on neural networks and turbulent flow control. Two journal articles on this work are now being prepared.

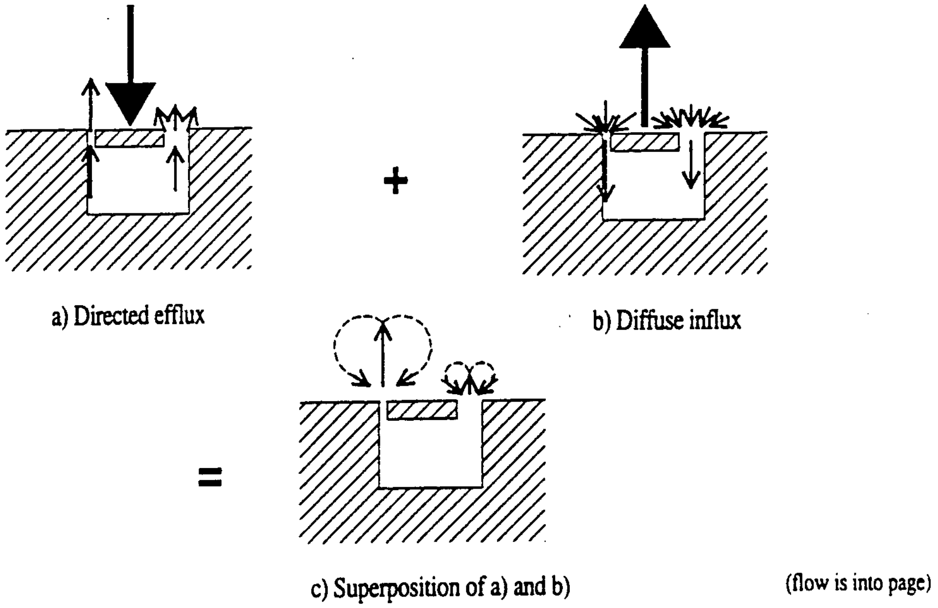
The jet control work has not been continued at Stanford because we believe that it is ready for transitioning to applications and that is best done by companies and government laboratories. However, it is clear that it has influenced the work at McDonnell-Douglas by David Parekh (a previous PhD student in this program), by Ari Glezer at Georgia Tech, and through them work in Air Force Laboratories, where there are rich opportunities for exploitation of jet flow control. Two journal articles on the work now in preparation.

5. Publications

Juvet, P. J. D. & Reynolds, W. C. 1993 Control of High Reynolds Number Round Jets. *Report TF-59*, Thermosciences Division, Department of Mechanical Engineering, Stanford University, March.

Jacobson, S. A. & Reynolds, W. C. 1993 Active control of boundary layer wall shear stress using self-learning neural networks. *AIAA Paper 93-3272*, AIAA Shear Flow Control Conference, July 6-9.

Jacobson, S. A. & Reynolds, W. C. 1995 An experimental investigation towards the active control of turbulent boundary layers. *Report TF-64*, Thermosciences Division, Department of Mechanical Engineering, Stanford University, March.



Above: Actuator concept

Below: Actuator details

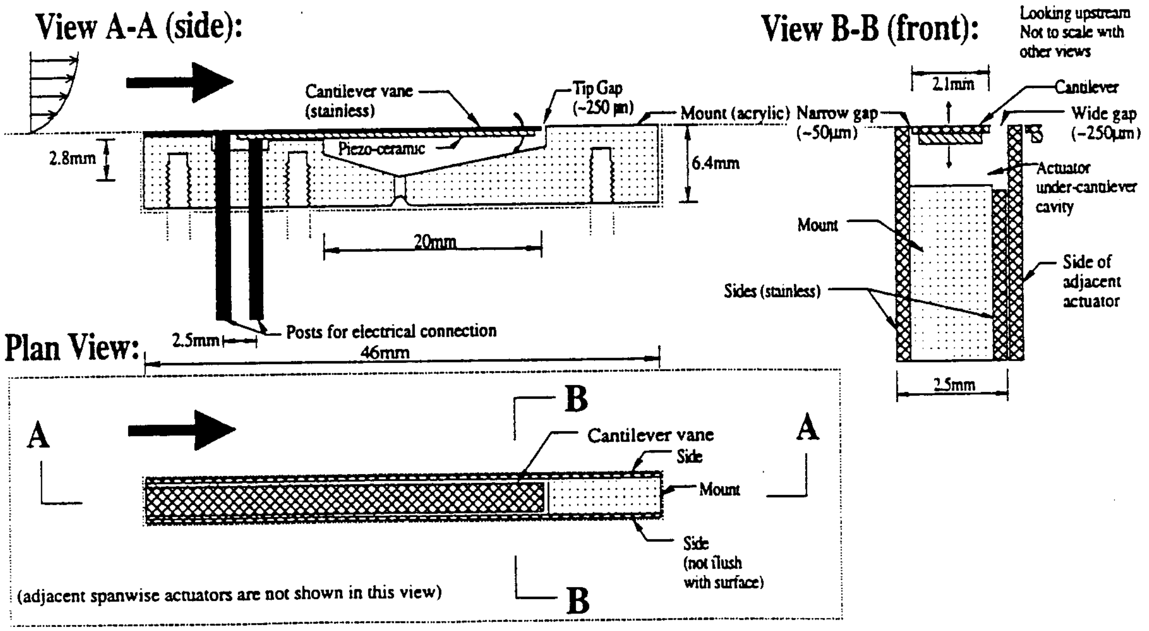
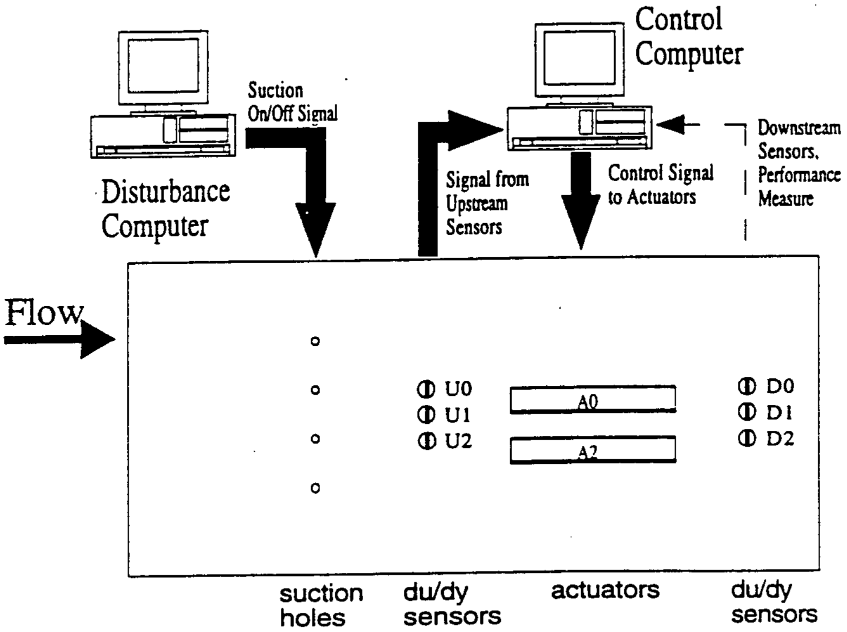


Figure 1. Actuator concept and construction details



Above: Experiment configuration

Below: Results

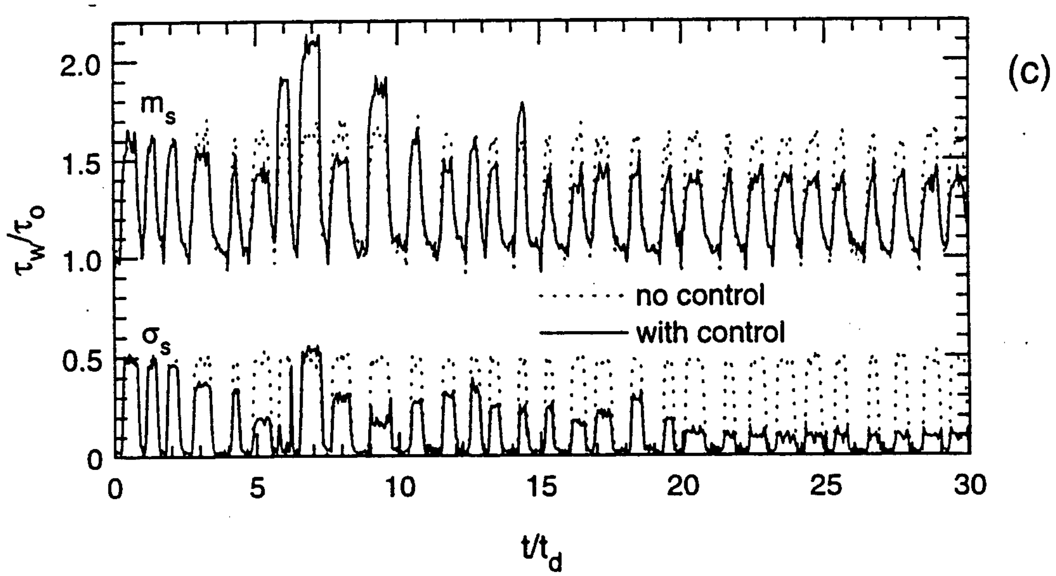


Figure 2. Control of random streamwise vortices in a laminar boundary layer.