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Research Interests

Gas and Liquid Flows Through Microdevices

Interest in microelectromechanical systems (MEMS) has experienced explosive growth during the past few years. Such small devices typically have characteristic size ranging from 1 mm down to 1 micron, and may include sensors, actuators, motors, pumps, turbines, gears, ducts and valves. Microdevices often involve mass, momentum and energy transport. Modeling gas and liquid flows through MEMS may necessitate including slip, rarefaction, compressibility, intermolecular forces and other unconventional effects.

In this research, we provide a methodical approach to flow modeling for a broad variety of microdevices. The continuum-based Navier-Stokes equations---with either the traditional no-slip or slip-flow boundary conditions---work only for a limited range of Knudsen numbers above which alternative models must be sought. These include molecular dynamics (MD), Boltzmann equation, Direct Simulation Monte Carlo (DSMC), and other deterministic/probabilistic molecular models. The research broadly survey available methodologies to model and compute transport phenomena within microdevices.

Micropumps Smaller Than a Grain of Sand

For some medical and processing applications it might be desired to move gases and liquids using exceedingly small pumping devices. We introduce a novel approach for pumping fluids at extremely low Reynolds numbers. Presently the only mechanical pumps that can be used for microelectromechanical applications are of the positive-displacement type. The present pump is a much simpler alternative. Its operation is based on the rotation of a cylinder placed asymmetrically in a narrow duct, so that the differential viscous resistance between the small and large gaps causes a net flow along the channel.

Our version of a micropump is particularly suited for microelectromechanical system (MEMS) applications, and the concept has already been disclosed as a United States patent. To test the idea, two-dimensional, time-dependent Navier-Stokes calculations are carried out with Reynolds numbers in the range of 0-100. Questions related to the physics of the pumping mechanism, its efficiency, and parameter optimization are answered during this phase of the research. If the device shows promise, a subsequent phase will include experimental verification. Low-Reynolds number experiments will be carried out first using a viscous oil and a cm-scale polygon driven by a conventional electric motor, and then using air or water as the working fluid and a microfabricated cylinder and motor. Issues addressed during the latter experiment will include slip-flow and Knudsen number effects as well as the effect of interfacial forces.

Drag Reduction

Viscous or skin-friction drag accounts for about half of the total drag on modern aircraft at subsonic cruise conditions. A novel method to substantially reduce skin friction drag in a turbulent boundary layer is investigated. The technique combines the beneficial effects of a longitudinally ribbed surface and suction. The longitudinal roughness elements act as nucleation sites which cause the low-speed streaks to appear above them. Suction is then applied intermittently through longitudinal slots located at selected locations with respect to the roughness elements to alter the low-speed regions and to decrease the bursting. If proved successful, the application of the present innovation on commercial aircraft will result in annual fuel savings of several billion dollars.

Airborne Laser Platforms

An active flow control device to generate large-scale, periodic structures in a turbulent shear flow is developed. Together with adaptive optics, such a device could be used on airborne laser platforms to reduce or to eliminate optical distortion caused by the turbulence in the aircraft's boundary layer. The technique employs a cyclic jet issuing from a spanwise slot. A computer-controlled stepping motor drives a ball valve to provide temporal control of the secondary fluid issuing from the spanwise slot. When optimized for a given boundary layer, the cyclic jet produces periodic structures that are qualitatively similar to the random, naturally occurring ones.

Unsteady Separated Flows

Unsteady separation represents a domain of fluid mechanics that is presently beyond the reach of definitive theoretical or numerical analysis. A research program to study experimentally unsteady separated flows around rectangular wings of small aspect ratio, swept wings, delta wings, and bodies of revolution undergoing large-amplitude harmonic pitching motion has been initiated in the past few years. A model based on the mutual induction between leading edge and trailing edge vortices has been constructed to explain the experimental observations.

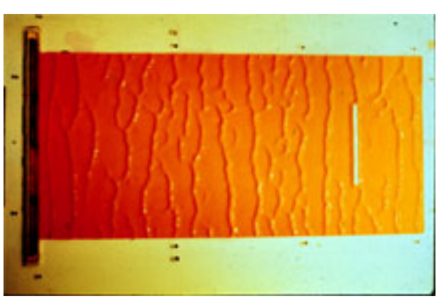
Control of Delta Wing Vortices

The classical leading edge vortices on delta wings have been shown to originate as a series of discrete vortices that are shed from the leading edge at a well-defined frequency. We are currently attempting to control these vortices, and hence the lift, by subharmonic impulsive perturbation at the leading edge. In an attempt to avert catastrophic stalling, the present work will be extended to higher angles of attack where vortex bursting is known to take place.

Compliant Coatings

The idea of using compliant coatings for drag reduction was first introduced 30 years ago based on observations of porpoises seeming to show off their speed by passing alongside a fast ocean liner in an effortless glide. The maximum observed swimming speed of dolphins and their known physiological propulsion efficiency prompted some biologists to speculate that the dolphin has some means of producing extensive regions of laminar flow. Aside from the issue of reducing the drag, compliant coatings are finding increasing use in sound absorption, vibration reduction, and noise shielding. The present research is aimed at gaining fundamental understanding of the complex interaction between a deformable structure and a boundary layer flow.

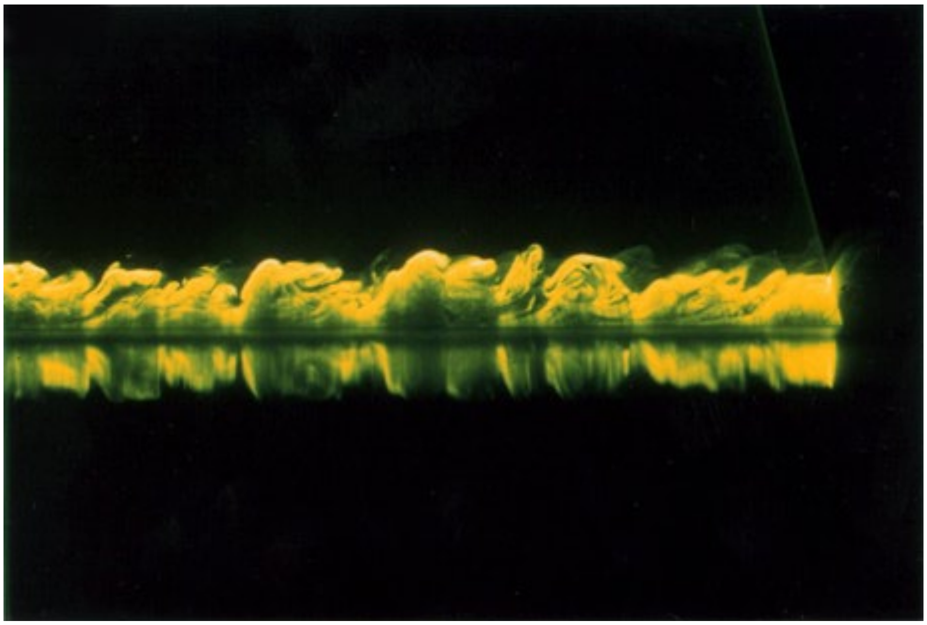
Laboratory simulation of compliant dolphin skin



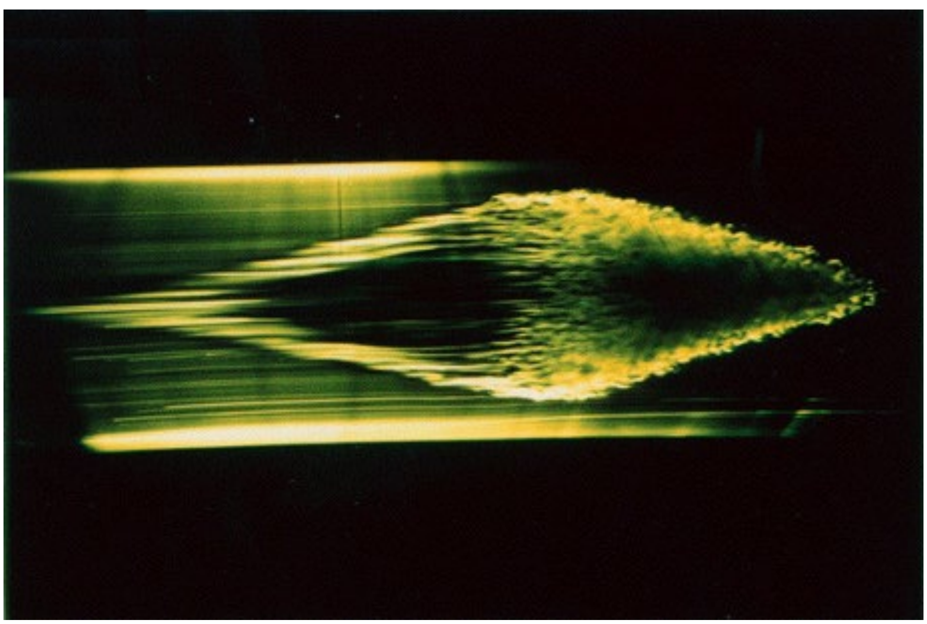
Boundary Layer Research

Laminar, transitional and turbulent boundary layers are studied. Among the particular issues investigated are the growth of turbulent spots, the stability of a decelerating Blasius layer, the physics and structure of coherent events in a turbulent boundary layer, analogies between transitional and turbulent boundary layers, boundary layer control, and the artificial generation of bursting events.

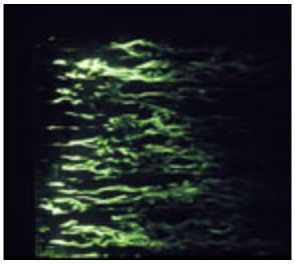
Large-eddy structures in a turbulent boundary layer



Turbulent spot embedded in a laminar boundary layer



Low-speed streaks in the near-wall region of a turbulent boundary layer



The Use of MEMS-Based Sensors for Measuring Wall-Shear Stress

In wall-bounded turbulent flows, the instantaneous wall-shear stress is an important quantity the measurement of which is notoriously difficult to make particularly at high Reynolds numbers. In this research, a MEMS-based sensor for measuring the wall-shear stress in a turbulent boundary layer is developed. The minute size of the typical microsensor allows better spatial as well as temporal resolutions than achieved in previous experiments. The probe is basically a heated element compensated for temperature fluctuations.

The principle of operation of the sensor is very similar to that of a constant-temperature hot-film; but instead of using a bridge balance, the present circuitry relies on a voltage difference which is formed between two temperature-sensitive PN-junction diodes, one at the higher temperature of the sensor and the other at the freestream temperature. The present wall-shear sensor is calibrated both statically and dynamically. The latter is done in a Blasius boundary layer with a known superposed disturbance. The issue of Reynolds analogy between heat and momentum transfers in an unsteady flow or in the presence of a pressure gradient is investigated. Limitations of the sensor due to a nonlinear or an unsteady velocity profile in the near-wall region are discussed through an analysis of the energy equation.

Separation Control Using Lorentz Forces

The flow around bodies moving in weakly electrically conducting fluids can be controlled by applying electromagnetic forces originating from electrodes and permanent magnets suitably placed on the surface of the body. Here we consider the possibility of separation control for a two-dimensional bluff body and an inclined flat plate by inducing Lorentz forces parallel to the surface. Physical and numerical experiments are carried out at diameter/chord Reynolds numbers in the range of 300-4,000 for the circular cylinder and 2,000-20,000 for the plate. Both steady and time-periodic forcing are applied.

The physical experiments are conducted in an open channel with sodium hydroxide as the working fluid. Dramatic separation delays are observed on both bodies for a modest expenditure of energy. Special attention is drawn to lift enhancement due to separation delay for the inclined plate. Direct numerical simulations at low Reynolds numbers confirm the physical tendencies of the experiments.

Selected Recent Publications

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