An integrated MEMS based system for multiscale surface measurements

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1 Project summary

The measurement of shear- and normal-stress on a surface is of outstanding practical importance across a vast range of scales. On the macroscale, these quantities account for the surface drag on transportation vehicles, thereby affecting maneuverability and fuel efficiency. In such environments a detailed knowledge of the surface shear-stress (skin-friction) and pressure can be used to characterize near-surface fluid flows, such as turbulent boundary layers and separating structures, with applications in design and the emerging field of flow control[2]. On the microscale, shear- and normal-stress can be used to characterize the low Reynolds number flow of complex fluids; their measurement permits quantitative assessment of both the first and the second normal stress difference of fluids such as wormlike micellar solutions and biopolymer solutions, and the normal-stress properties of physically-crosslinked gel networks in biofluid systems. The goal of this proposal is to develop an integrated system for measuring surface shear-stress and pressure, in collaboration with industrial partners, to address the combined research and teaching needs of the newly merged Mechanical and Ocean Engineering departments.

In February 2004 a workshop on shear-stress measurement techniques held at CALTECH [1] concluded that no measurement approach existed that is free from significant limitations. Recently, however, a new technology for measuring shear-stress, using state-of-the-art optical MEMS processing, has been developed by VioSense. Their MicroS3 shear-stress sensor is capable of instantaneous measurement of the velocity gradient and flow direction in a region 30 microns high, located 75 microns above the sensor surface. The sensor, shown in figure 1, measures the velocity gradient at the wall using a fan-fringe technique [6]. The sensor is flush-mounted at the position of interest, and particulates, which either exist naturally in the flow or are introduced, create frequency modulated bursts proportional to the velocity gradient as they cross the fringe. The sensor, which is non contact and requires no calibration, has been successfully tested in air and water flows at velocities as low as 1mm/s [8] and Reynolds numbers as high as 10^8 [3].

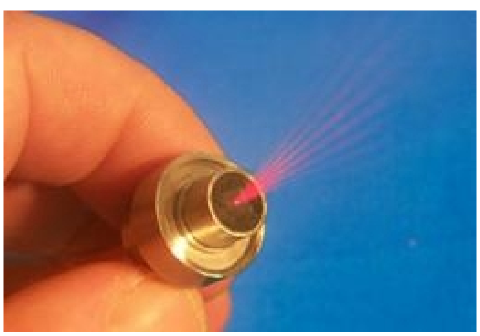

Figure1 : Image of the MicroS3 shear-stress sensor.

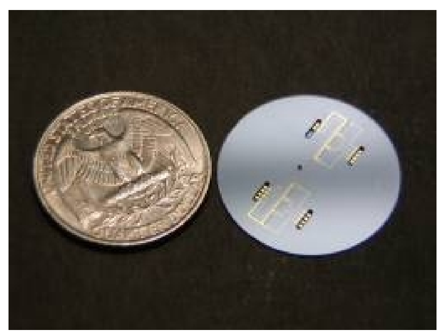

Figure 2 : Array of pressure sensors fabricated by Rheosense Inc.

MEMS fabrication techniques have also enabled the development of high-performance microscale pressure sensors. Foremost amongst these are the pressure sensors developed by RheoSense Inc., using an NSF SBIR grant. An image of an array of the sensors is shown in figure 2. The sensors are capacitive type, with a silicon membrane that deflects less than 0.5 microns for the pressure ranges under investigation (0-50,000Pa). The highly sensitive sensors can be closely packaged, with separations on the order of 100 microns, and have been demonstrated to accurately measure first and second normal stress differences in a cone and plate rheometer[1].

We propose to develop an integrated system for measuring skin-friction and surface pressure utilizing these recent advances in MEMS technology. At present, no commercial product exists for their localized simultaneous measurement. The system will comprise an array of five closely spaced shear-stress sensors, with a spacing of 2mm. This close packing will require product development by VioSense. The purpose of this arrangement is to locally measure the skin-friction gradient along a boundary. Integrated with this will be an array of pressure sensors. The integration will be modular, to allow positioning of one of three pressure sensor arrays adjacent to the shear-stress sensors; the choice of pressure sensor array being determined by the operating conditions. In addition we shall obtain three individual shear-stress sensors, to be used for widely distributed surface measurements on a variety of experimental geometries. Again, modular packaging

[1] Shear stress sensing technqiues and measurement results, CALTECH, February 5-6, Caltech, USA.

developed collaboratively by MIT, VioSense and RheoSense will allow suitable pressure sensors to be positioned adjacent to the shear-stress sensor. Finally, we shall incorporate a near wall MicroV velocimeter, manufactured by VioSense. This is a time-of-flight velocity sensor, also utilizing optical MEMS technology, capable of measuring flow velocities up to 15 mm away from the sensor surface. The sensor can be used for detailed boundary layer characterization in its own right, as well as for quantitative checks of the shear stress sensors. A National Instruments based system will be used for data acquisition and processing.

The facility will be widely used for research and teaching purposes by faculty in the newly merged Mechanical and Ocean Engineering Departments. By virtue of it's modularity, the apparatus may be dedicated to one experiment, or simultaneously distributed amongst two or three research and teaching projects.

2 Impact of Infrastructure Project

The existence of this facility will have a significant impact on research and education in fluid dynamics at MIT. The only other institutions possessing assemblies of MicroS3 sensors are the Navy - which recently commissioned an array of 32 sensors for implementation in the hulls of ocean going vehicles - NASA Langley, Bechtel Bettis Laboratory and Stanford University. Non of these institutions have such a closely packaged array of shear-stress sensors or integration with pressure sensors, which we propose to develop with VioSense and RheoSense. The apparatus will attract researchers throughout the field, for whom this capability does not exist anywhere else. This will put MIT at the forefront of surface-force measurement and strengthen MIT's existing close connection with Naval Education.

A schematic of the infrastructure surrounding the facility is presented in figure 3; incorporating research, education and product development. The team of faculty involved comprises equal amounts of senior and junior faculty from Mechanical and Ocean Engineering. Two of the junior faculty are women, and all members have a strong record of advising under-represented groups and women. More details on the infrastructure are presented throughout this section.

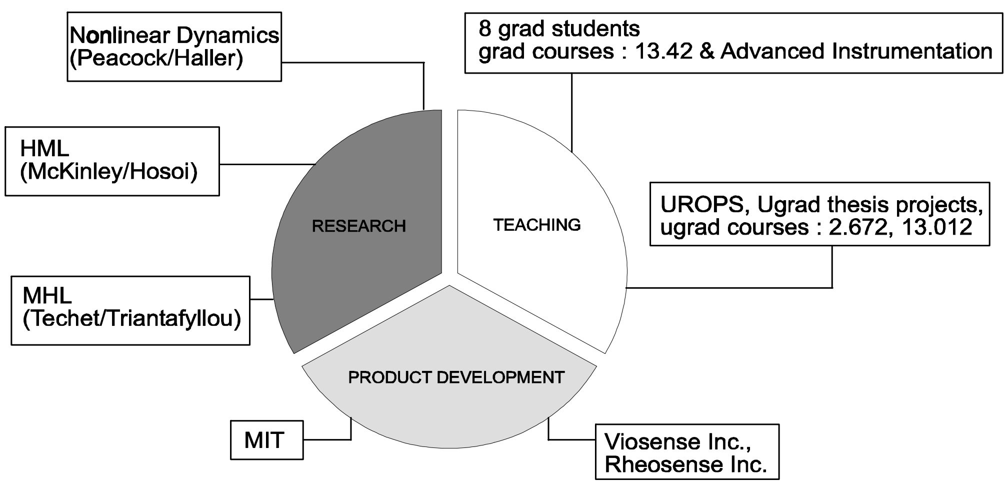

Figure 3 : Schematic of project infrastructure.

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The sensors will be used to demonstrate a new approach to unsteady separation in the Nonlinear Dynamics Laboratory. This has long been an outstanding issue in fluid mechanics, addressed in a recent theoretical publication by Haller[4]. The method uses advanced concepts from nonlinear dynamical systems theory, in which one seeks a time-dependent material curve, the separation profile, along which material is ejected from the vicinity of the fluid boundary The approach yields expressions for the location and angle of separation based on distributed unsteady surface shear-stress and pressure measurements, making it a practical tool for maneuvering aerospace vehicles, where surface information is the only quantitative data realistically attainable. Initial experiments in the nonlinear dynamics lab by the Peacock have demonstrated this to be the case, although current efforts are hindered by characteristic difficulties with traditional shear-stress measurement techniques..

Ongoing work in the Ocean Engineering Marine Hydrodynamics Laboratory (MHL) will benefit from distributed shear and pressure sensors in applications to ship hydrodynamics and underwater vehicle control. Recent studies of unsteady flow control and boundary layers have shown that near-body turbulence levels are significantly modified by imposed fish-like swimming motions. Experiments by Techet reveal that the local turbulence levels are significantly reduced and the boundary layer profile is altered[9]. The goal is to implement the sensors in this experiment to observe both spanwise and longitudinal shear-stress and pressure fluctuations over the cycle of the swimming motion. Traditional measurement techniques such as Laser Doppler Velocimetry and Particle Image velocimetry have not provided sufficient resolution in the very near boundary layer to resolve shear-stress accurately. Ultimately these experiments will serve as a test bed for evaluating their use on an the flapping foil vehicle, built by Triantafyllou's group[5], to facilitate real-time flow control of the vehicle propulsion and maneuvering.

In the Hatsopolous Microfluids Laboratory (HML) these novel shear stress and normal stress sensors will be used to characterize the low Reynolds number flow of complex fluids on the microscale. Quantitative study of non-Newtonian fluids requires the use of non-invasive optical sensors because the presence of a conventional velocimetric sensor such as a 'hot-wire' disrupts the flow field. Similarly flush-mounted pressure sensors are required to avoid the 'hole pressure' error that plagued early normal stress measurements in complex fluids. The sensor arrays will be employed in the McKinley lab for quantitative assessment of both the first and the second normal stress difference of fluids such as wormlike micellar solutions and biopolymer solutions. Furthermore, the close spacing and high sensitivity of the flush-mounted pressure sensors will be used in the construction of a novel microfluidic rheometer, based on the extensional flow of complex fluids in a microfabricated converging nozzle of hyperbolic cross section[7]. In the Hosoi lab, the equipment will be used characterize the normal- and shear-stress properties of physically-crosslinked gel networks, secreted as a thinlayer of mucus in gastropod locomotion. The proposed sensors are unique in their ability to make these measurements, because of their small scale and non-invasive principles - a very important factor for biological systems.

The apparatus will support the research work of 8 graduate students. The graduate course 13.42 (Design Principles of Ocean Going Vehicles - to become 2.22), taught by Techet, will incorporate these state-of-the-art flow diagnostic tools into the laboratory section of the course. This course has a strong practical focus and is geared to the 13A Navy students. There are 30-35 students in the course with about 5-10 women per year. The equipment will also be a focus of a new graduate level course in ME on advanced instrumentation, to be proposed for the academic year 2006/07.

At the undergraduate level, the apparatus will be incorporated as a new experiment in course 2.672, and in existing experiments in 13.012. The latter focuses on basic hydrodynamics for ocean systems. Weekly laboratory assignments incorporate current research into the curriculum, introducing modern flow diagnostic tools and involving undergraduates in ongoing research projects. The current enrollment is 12 students, of which 6 come from Ocean Engineering and 4 are women. UROPS will be involved in experimental design processes, data acquisition and data processing for all the described research.

Product development will incorporate both academia and industry, involving a three-way collaboration between MIT, VioSense Inc. and Rheosense Inc. The faculty at MIT will generate design concepts and specifications for manufacturing a modular system capable of integrated skin-friction and pressure measurements. RheoSense Inc will develop the arrays of pressure sensors. VioSense Inc., working closely with the faculty at MIT, will package the pressure sensors with their shear-stress sensors.

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