2nd International Symposium on Seawater Drag Reduction
Busan, Korea, 23-26 MAY 2005

Micro-Optical Sensor Use in Boundary Layer Flows with Polymers and Bubbles

D. Modarress, P. Svitek (Measurement Science Enterprise, USA),
D. Wilson (Jet Propulsion Laboratory, USA)

ABSTRACT

Recent advancements in the design and development of small optical sensors have made it possible to investigate complex flows. These include flows with bubbles and polymers at high Reynolds numbers which are present in drag reduction experiments. We have developed optical sensors for use in scaled and full-scale experiments, both in laboratory and at sea conditions.

These sensors have been tested in water tunnels and at sea, with and without polymer injection. The presence of polymers and/or bubbles in the flow did not degrade their performance. The sensors also performed well in full-scale at-sea tests.

Recently, we have fabricated a total of 37 optical sensors packaged for installation on the surface of a lifting body hydrofoil of a full-scale, vessel and scheduled to be tested soon.

This paper describes the individual sensors and sensor suites that have demonstrated their capability to provide reliable flow velocity data throughout the boundary layer under a variety of flow conditions. These non-intrusive sensors are appropriate for single-phase and multi-phase flows present in drag reduction related experiments. They do not require on-site calibration, and are not affected by environmental parameters such as pressure, density, temperature, salinity, or index of refraction.

INTRODUCTION

It is generally accepted that the injection of polymers and/or bubbles in the boundary layer of a flow will result in a "substantial change in the character of the turbulence within the boundary layer" (Kowalski 1974). This may result in the modification of the mean flow and turbulence intensity profiles compared to the profiles of single-phase flows. Understanding of the modification of the boundary layers in the presence of polymers and/or bubbles may lead to a better understanding of the role of these additives in the reduction of the friction drag. This requires reliable experimental data for the near surface region of the boundary layer, including the mean and rms flow velocity, the concentration profile of the polymer at different locations over the hydrofoil, or concentration and size distribution of micro-bubbles. Due to the extreme flow scales, to-date it has not been possible to accurately characterize boundary layer flows in the presence of polymer or bubbles at high Reynolds numbers.

In this paper, an optical instrument, called Multi-location Velocimeter, for on-board measurement near surface boundary layer is presented. The instrument consists of three individual micro-optical sensors providing flow velocity data at 100 microns from the surface with a spatial resolution in the direction normal to the surface of approximately 20 microns. It also is capable of measuring flow velocities up to 4 mm from the surface. The watertight instrument was designed to be surface mounted over nearly flat surfaces. The individual micro-optical sensors have been used in a number of flow facilities and "at-sea" tests and the sample results along with the description of the instruments are presented here. Finally, twelve sensor packages along with a number of pressure, temperature, and wall shear sensors have been fabricated and are scheduled to be used in a series of at sea tests.

MULTI-LOCATION VELOCIMETER

An integrated optical flow velocity sensor package (called Multi-location Velocimeter or **MV3**) was developed for the measurement of the boundary layer profile close to the surface. The MV3 package has two fixed sensors measuring the flow velocities at 100 and 180 microns from the surface. The diverging fringe sensors used here have a spatial resolution of 20 and 30 microns in the normal direction to the surface respectively. The MV3 is designed to be self-contained and water tight. A conceptual drawing of the MV3 developed for the drag reduction experiments is shown in Figure 1.

The MV3 sensor package consisting of three optical sensors was designed to be completely sealed and flush mounted to the hydrofoil. The package included a traversing mechanism and three diode lasers with power supplies. Two of the optical sensors were fixed location "diverging fringe velocity sensors" and one sensor was a cross-correlation time-of-flight sensor attached to a traverse mechanism. The two diverging fringe Doppler sensors were designed to measure the flow velocity at the heights of 100 and 180 microns in water. The time-of-flight cross-correlation sensor was designed to measure the flow velocity from 300 microns to approximately 4 mm from the surface.

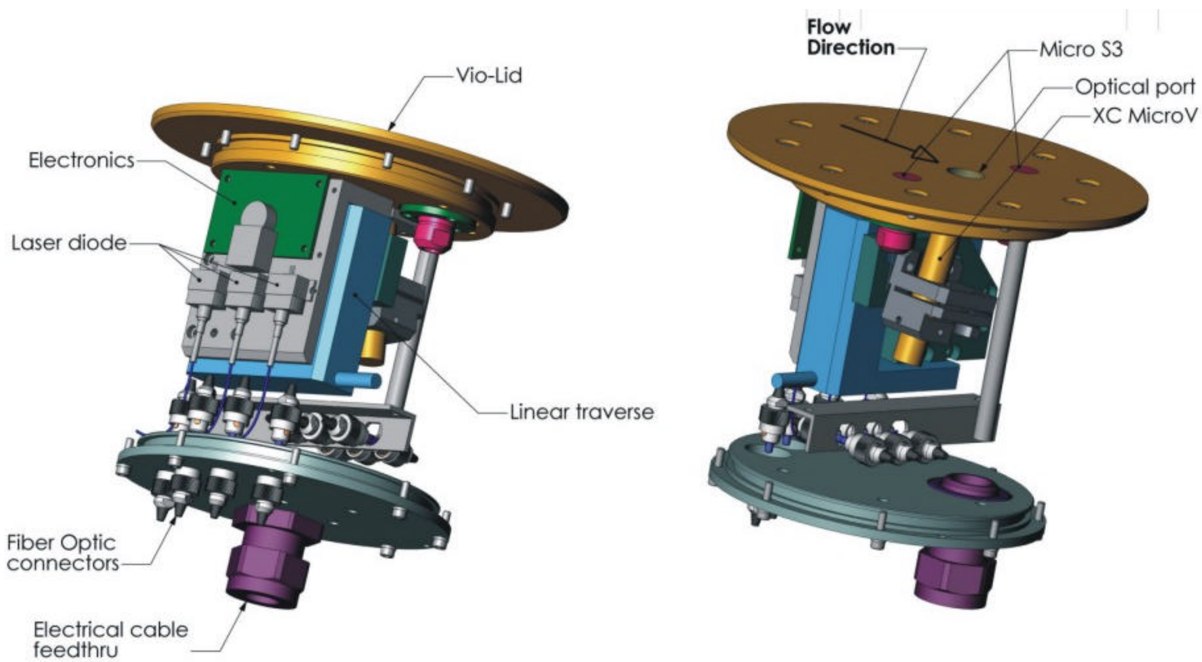

Figure 1 Multi-location Velocimeter Package-

The MV3 sensor package was designed to detect the presence of polymers or micro-bubbles and to provide an indication of the changes of the polymer or bubble concentration across the boundary layer. This is extremely important since the extent by which the polymer or bubbles remain in the boundary layer has a direct bearing to the overall drag reduction over the entire vessel.

In the following sections, sensors are briefly described and sample results are presented.

Diverging Fringe Near Wall Velocity Sensor

The diverging fringe Doppler velocimeter (dfv), originally proposed by Naqwi and Reynolds (1987) as a shear stress sensor, has been described in detail in Modarress (2000). The sensor projects a set of diverging fringe patterns with their origin located at the wall. The Doppler shifted frequency of the scattered light (from particles) passing through the fringes near the wall is directly proportional to the velocity gradient at the wall. The sensor consists of a specially designed double-sided micro-optical device with a transmitter diffractive optic element (DOE) illuminated by a laser light from a single-mode fiber. The scattered light is collected through a receiving doe and onto a multi-mode fiber. The fibers and the micro-optical device are packaged into a permanent housing for flush mounting to flow models. The optical arrangement of the diverging fringe Doppler sensor is shown in Figure 2.

The dfv sensor, in addition to its use in measuring the velocity gradient at the wall, may also be used as a velocity sensor at a fixed location (as low as 70 microns from the wall in air, and 100 microns in water) for direct measurements of the flow velocity mean and RMS values. The sensor, due to its linearity, does not need calibration and operates at various temperatures, pressures, and salinities of ocean water). A photograph of the diverging fringe velocimeter is shown in Figure 3.

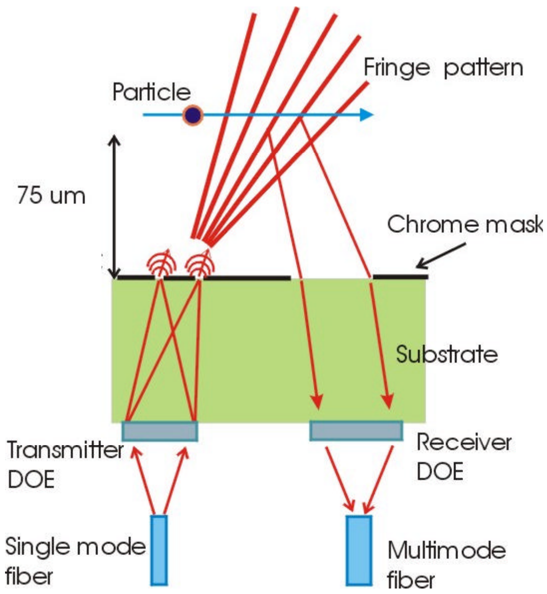

Figure 2 - Diverging Fringe Velocity (dfv) Sensor

Figure 3 - Photograph of a Diverging Fringe (df) Doppler Velocity Sensor

Particles passing through the interference fringes shown in Figures 2 and 3 generate Doppler signals, similar to a classical Laser Doppler system. A sample signal (red: unfiltered, black: high pass filtered) is shown in Figure 4. The instantaneous velocity is calculated from the frequency of the Doppler signal.

The dfv sensors have been used in a number of different experiments. Figure 5 shows the shear data obtained from a dfv sensor imbedded in an infinitely long circular cylinder.

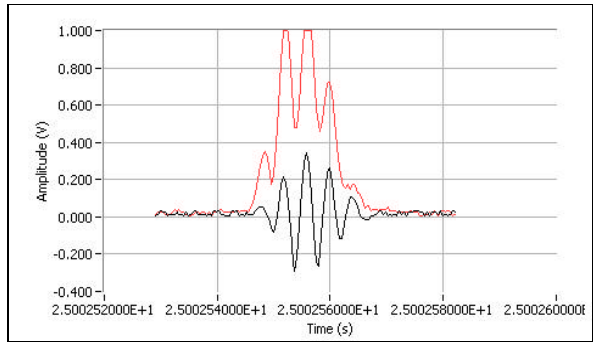

Figure 4 - Typical Doppler signal for diverging fringe velocimeter

The cylinder was rotated around its axis, positioning the dfv sensor at different locations over the circumference of the cylinder relative to the stagnation point. The experimental data compares well with theoretical (Twaites Method) values of the wall shear over an infinitely long circular cylinder. The accuracy of the dfv sensor has been experimentally demonstrated to be better than 95% for flow Reynolds number of up to 2.0E+6. More detailed description of this and other experiments is provided in Fourguette et. al. (2004).

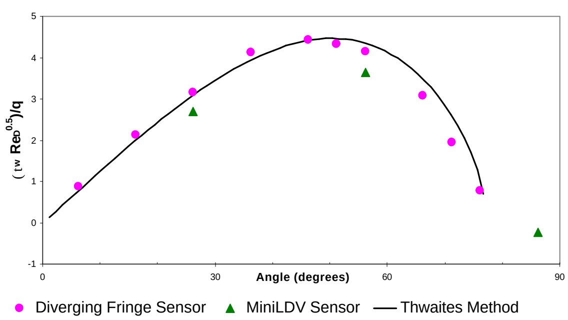

Figure 5 - Measured Wall Shear around a Circular Cylinder

Time-of-Flight Cross-Correlation Velocimeter

The third sensor integrated into the MV3 package is a Cross-correlation velocimeter (CCV) that uses the time of flight between two sheets of light approximately 50 microns apart. A photograph of the sensor and its detector electronics is shown in Figure 6. Here, the measurement location was designed to be 10 mm from the end of the probe with all of the active components located in the detector box.

Figure 6 - Cross-Correlation Velocimeter Probe and Power Supply

Particles passing through the two sheets generate signals similar to Figure 7. The cross-correlation of the two signals provides the time-of-flight between the two sheets of known distance. The instantaneous velocity is then calculated.

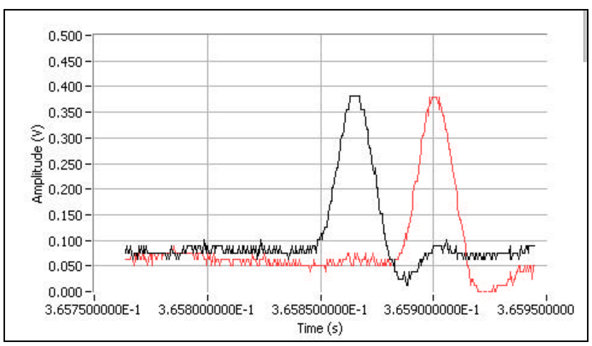

Figure 7 - Output signal from the Cross-Correlation Velocimeter

EXPERIMENTAL RESULTS

The above-described sensor suits have been used in a number of experiments and "at-sea" tests with positive results. Representative results of these experiments are presented here to demonstrate the accuracy and range of applications of these sensors.

Polymer added Experiments at ARL

The performance of the dfv sensors in the presence of polymer was evaluated at the 12-inch water tunnel at the Applied Research Laboratory at Penn State University. The sensors were attached downstream of the polymer injection slots on the bottom surface of the tunnel test section. The tests were carried out to investigate the performance of optical sensors in the presence of polymer and bubbles.

The velocity data from two sensors for clean flows and for polymer-laden flows are shown in Figure 8. Here, the measured flow velocities at a fixed distance of 150 microns from the surface (in water) are plotted against the tunnel velocity. The data for no polymer flow agreed well with the ARL flow data (not shown here). The data for the polymer flows were recorded at two tunnel speeds. In both cases the local mean flow velocity was reduced with the increase in polymer flow rate.

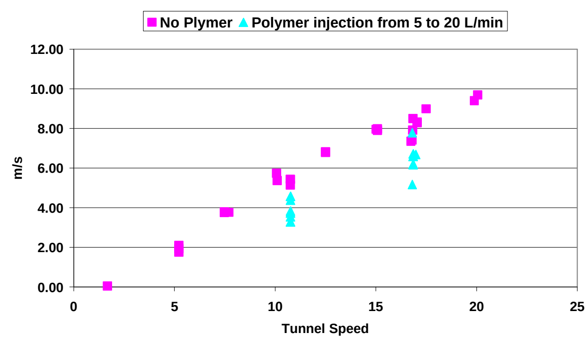

Figure 8 - Variations of flow velocity with Polymer flow rate (at Z = 150 microns)

This short experiment also verified that optical sensors are appropriate for the flows with polymer. The polymers acted as additional scattering canters and the data rate was increased with the concentration of the polymer present at the probe volume.

At sea experiments (SDV45)

The SDV45 test conducted by Cortana Corporation was designed to provide a realistic environment for the initial shake down of the test equipment and sensors. An MV3 sensor package shown in Figure 9 was used for this test. As shown, the two diverging fringe velocimeter sensors were located on the sides of an optical window used for the cross-correlation velocimeter.

Figure 9 - Multi-location Velocimeter Package used at SDV45

The MV3 sensor along with a number of wall shear sensors and a pitot tube was installed at the lower side of a hydrofoil attached to the bottom of a 45 ft boat. The boat and the hydrofoil are shown in Figure 10, and a picture of the plate assembly located at the bottom of the hydrofoil is shown in Figure 11.

Figure 10 - SDV 45 ft boat with the attached hydrofoil

Figure 11 – SDV45 Sensor Assembly plate

Interceptor Base Line Velocity Data

Initially, velocity profiles of the flow at the bottom of the lifting body were obtained without the injection of polymers and using the particles present in the seawater. The data were collected for a nominal boat speed of 9 knots. The profiles are shown in Figure 12. For reference, a theoretical velocity profile obtained for a fully developed turbulent boundary layer over a flat plate at zero pressure gradient for 9 knots is also shown. The velocity data were obtained at two different runs shown with separate colors. The scatter of the velocity data was attributed to the variation of the boat speed (approximately 20% of the mean boat speed) and changes of the boat heading during the data acquisition period.

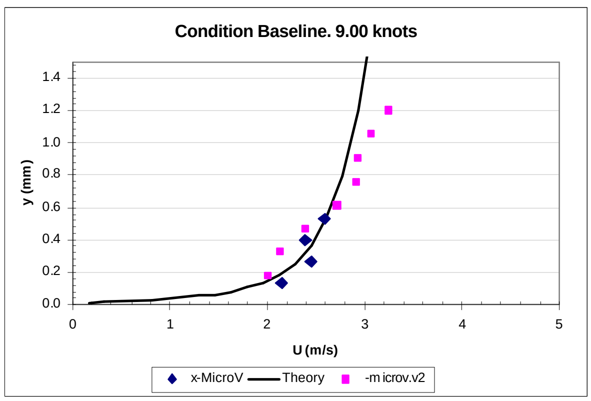

Figure 12 - Velocity data obtained with no polymer injection

Similar velocity data obtained with polymer injections and a plot of sample results are shown in Figure 13. It should be noted that not all the data were consistent with the results shown here, and these data are shown to represent the spatial resolution that were obtained with the instrument.

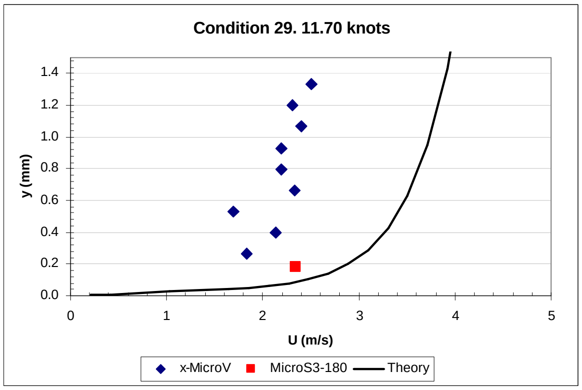

Figure 13 - Measured flow velocity with polymer injection

CONCLUSIONS AND SUMMARY

A suit of sensors appropriate for experiments related to drag reduction are developed. The sensors are non-intrusive and operate in water with added polymer and/or micro-bubbles. Due to the linear response of the sensors, they do not require on-site calibration and are invariant to the flow pressure, temperature, salinity or other additives. The Micro-optical sensors are designed to have extremely small spatial resolution in the wall normal direction.

A watertight and relatively small integrated sensor package has been developed where a combination of micro-optical sensors are used for in-situ measurement of the flow boundary layer. These sensor packages have been successfully tested at sea and will be used in a series of drag-reduction tests.

ACKNOWLEDGMENT

The authors wish to acknowledge the useful discussions with Dr. k.j. Moore and Mr. Christopher Moore of Cortana Corporation, Dr. Ki-Han Kim of ONR, Dr. David Hess and Dr. P. Atsavapranee of NSWC CD. The reported research was supported by Cortana Corporation under a contract to ONR, and a Phase II SBIR project with ONR, Contract number N00014-03-C-0375 with Dr. Ki-Han Kim as the Contract Technical Monitor.

REFERENCES

Cortana Corporation Sea Lift tests scheduled for May 2005.

Fourguette, D., Modarress, D., “Optical Measurement of Wall Shear Stress With Emphasis on Flows Near Separation,” 24th AIAA Aerodynamic Measurement Technology and Ground Testing Conference June-2004.

Kowalski, T., “Macromolecular Entanglement Hypothesis in Drag Reduction Flows,” Proceedings of the international Conference on Drag Reduction, Cambridge, England, September 1974.

Modarress, D., “Design and development of miniature and micro-Doppler sensors,” Proceedings of ASME FEDSM 2000-11096, June 2000.

Modarress, D., VioSense Corporation Note, ITN.V520.011. MicroS3.ARL, Dec. 2003

Naqwi, A. A., Reynolds, W.C., “Dual cylindrical wave laser-Doppler method for measurement of skin friction in fluid flow,” Report No. TF-28, Stanford University. 1987.