DEVELOPMENT OF TWO NEW VELOCITY SENSORS WITH PARTICULAR APPLICATION TO TURBULENCE MEASUREMENTS

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Abstract - We are developing two sensors for measuring velocity and turbulence in the bottom boundary layer under breaking waves in a beach environment. This paper outlines the initial tests and design of a simple, rugged strain-gage probe, and a more complex, and more accurate acoustic velocity sensor.

1. INTRODUCTION

We are currently developing two very different velocity sensors for measurement of fluid flow under breaking waves, and above moving sediment beds. This environment imposes severe demands on any structures that are unfortunate enough to find themselves in the path of a breaker.

Measurement requirements dictate that the sensors be relatively small, and unaffected by proximity to the sediment bottom, which can and will move relative to the sensor location. Marsh-McBirney electro-magnetic sensors have been used in this application, but in high-precision applications, their response is confounded by the presence of the sediment boundary.

Useful sensors for wave boundary layers must have reasonably good sensitivity in calm periods (say accuracies better than 1cm/s), but must operate in very high velocity flows periodically (up to 300cm/s).

The two devices we are testing are: 1) a strain-gage sensor which measures the drag on a small cylinder, and 2) an acoustic velocity sensor based on the Benthic Acoustic Stress Sensor [1]. The first device shows promise for its simplicity and small size, while the second one shows promise for its potential sensitivity and high accuracy. We will discuss our progess to date with the ongoing development of both sensors.

2. THE BLCP

Initial tank tests of the Boundary Layer Current Probe (BLCP) were conducted in the Bedford Institute of Oceanography (BIO) towing tank, and at the National Research Council (NRC) Hydraulics Laboratory high-discharge flume, and wave basin. The tests were performed in November-December 1991.

The BLCP is a flow sensor that can be used to measure velocity within 20cm above a moving sediment bed. It will be used in beach environments where the orbital velocities of breaking waves are large, and there is significant sediment in suspension.

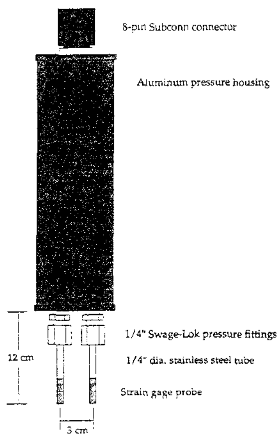

Figure 1: *General configuration of the first BLCP sensor. The grey ends of the probes at the bottom of the figure represent the strain gage probes potted in silicone rubber compound. An eight pin connector at the top of this figure provided + and -12V power, and 3-wire serial data communications to and from the data logger inside the pressure housing.*

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The first prototype of the BLCP consists of two strain gage bridge circuits that are cemented to two thin stainless steel beams. The beams are oriented orthogonal to each other in order to measure two components of velocity. Figure 1 shows a schematic of the sensor. Slight bending of the beam is detected by the strain gages. An analog circuit was built to amplify the signal for analog-digital conversion. Our first prototype of the BLCP includes a data acquisition and storage computer (TattleTale Lite 512F, made by Onset Computers) inside the waterproof housing. A block diagram of the instrument is shown in figure 2.

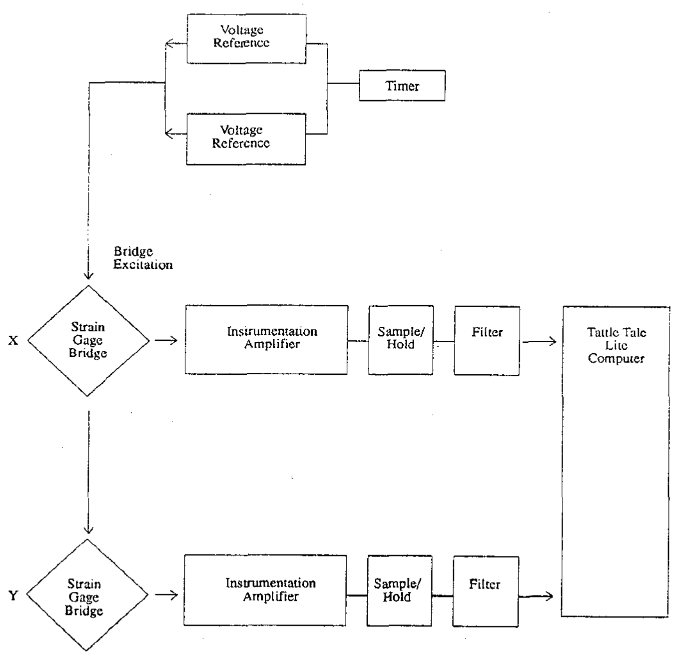

Figure 2: *A block diagram of the BLCP. The timer at the top of the figure provided a signal to cycle power from the + and - voltage references to the strain gage bridges (on for 15 micro-seconds, off for 100 milli-seconds). The voltage offset produced by strain on the beams is amplified by an instrumentation amplifier, and the sample/hold holds the signal over the 100 msec when the bridge is not active. The signal is filtered, and digitized by the TattleTale Lite computer. Data is stored (up to 512 kbytes) for later retrieval through the serial data lines.*

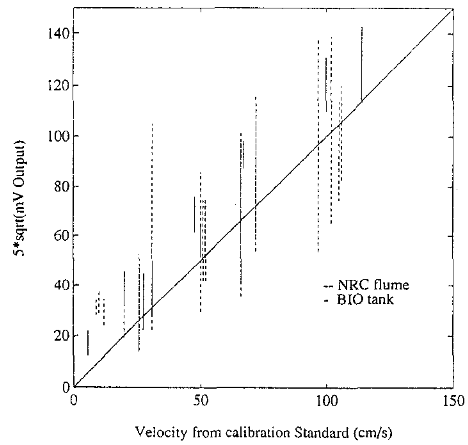

Figure 3: *Summary of calibration curves for the BLCP from tests in the BIO tow tank and the NRC flume. The vertical lines represent the standard deviation of the measurements. Much of this standard deviation is due to physical fluctuations in the velocities, and in the structure supporting the instrument housing.*

Figure 3 shows a summary plot of the relationship between the flow speed measured with a calibrated electro-magnetic flowmeter, and the square root of the BLCP output. Data in this plot was obtained from a series of runs in a tow tank at the Bedford Institute of Oceanography, and a series of runs in a flume at the National Research Council of Canada, Institute for Mechanical Engineering Hydraulics Lab. The variance on this calibration curve is indicated by the height of the error bars at each measured velocity. Much of the variance in the signal was due to fluctuations in the flow (and vibration of the carriage in the BIO tow-tank). A time-series of one calibration run is shown in figure 4.

The signal that the BLCP detects is caused by fluid drag acting on the cylinder in which the gages are potted. A typical relation for drag of a cylinder in turbulent flow is;

$$Fd = 0.5 C_d \rho U^2 L D \qquad (1)$$

where drag coefficient (C_d) is approximately 1.0. The measured force is proportional to the square of the flow velocity (U). The results plotted in figure 3 and 4 take the square law relationship into account by subtracting the mean zero-velocity offset from the data, then calculating the square root of the output magnitude.

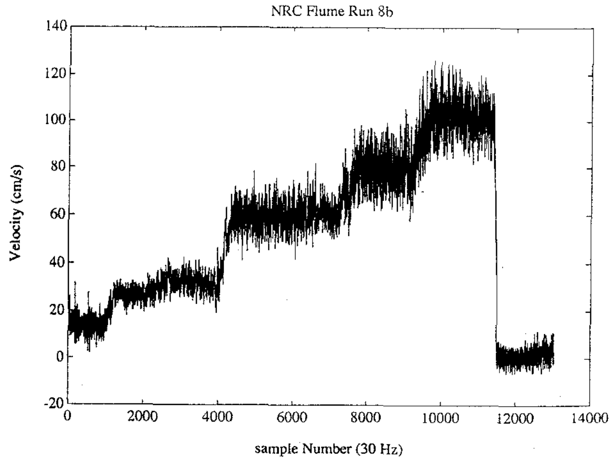

Figure 4: *A calibration run in the NRC flume. The tests began at a velocity of 20cm/s, and stepped up to 105 cm/s. The final segment of the data shows the signal at zero velocity. The fluctuation levels are clearly shown as the velocity changes.*

To give an intuitive idea for the size of the forces being measured, consider the drag force in a flow of 10 cm/s. The density of water (ρ) can be assumed to be 1000 kg/m^3, the length of the cylinder over which the strain gauge measures forces (L) is around 2.5 cm, and the diameter (D) is 0.7cm. Thus, the drag force at this speed will be 0.000875 N , or in terms of mass, it is equivalent to less than 0.1 grams.

Figure 5 shows spectra of the output of the strain gage probes at three different speeds in the NRC high discharge flume. The significant peaks at 18.4 Hz, 13.9 Hz, and 5.9 Hz that occur at the three velocities shown are probably due to vortex induced oscillations from the cylindrical supports in which the strain gages are housed. The frequency of vortex shedding is given by [2] as;

$$f_s = S\frac{U}{D} \quad (2)$$

where U is the free stream velocity, D is the cylinder diameter, S is the critical Strouhal number for vortex shedding , and fs is the shedding frequency (Hz). The measured velocity, frequency, and cylinder diameter for the laboratory runs represented in figure 6 indicate the coefficient S would be between 0.12 and 0.20. This is sufficiently close to the published value for S = 0.2 that I assert this peak is due to the strumming of the cylindrical probes.

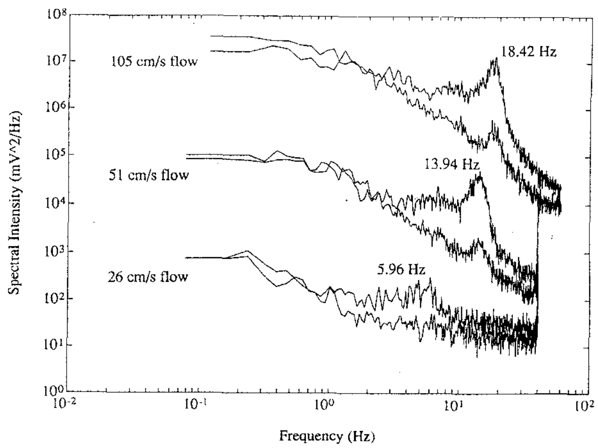

Figure 5: *Power spectra from three calibration tests in the NRC flume. The probe was mounted rigidly on a frame that was bolted to the tank, and stayed with taught lines to four corners. Only a small part of the structure was in the flow. The spectral peaks in this figure correspond to the strumming frequencies for a .7cm diameter cylinder in the flows at the velocities shown. At each velocity, the spectra for x and y velocity is shown. The spectrum with the higher peak is that from the gage oriented to measure cross-flow fluctuations. The two lower spectra were sampled at 80Hz, and the top ones were sampled at 120Hz.*

The magnitude of the vortex shedding force scales with the square of velocity. This force is typically represented by oscillating lift and drag coefficients (reviewed by [2,3]]). The largest force due to the shedding is directed perpendicular to the direction of mean flow. Observe the radio antenna on an automobile at highway speed. It will remain bent from the mean drag, but at some speed it will begin to strum with remarkable determination. The amplitude of the strumming peak is higher for the cross-flow axis in all spectra shown in figure 5, indicating that the oscillating motion is much larger when the strain gage is oriented perpendicular to the flow (and thus the thin dimension of the beam on which the gages are mounted is parallel to the direction of flow).

The spectral peaks shown in figure 5 were not seen the tow tank, or wave tank test runs. The velocity fluctuations introduced by the tow carriage, and probe support in the BIO tow tank prevented observation of the shedding frequencies.

3. The VDV

Acoustic current meters, such as BASS [1], and the new "VDV" sensor (Figure 6), measure 3-dimensional velocity in a single sensor. Flows where turbulent fluctuations are large compared to the mean flow (as in boundary layers, or under waves) are situations where a 3-dimensional sensor will help resolve features of the flow. Nadaoka et al. [6] showed the importance of 3-dimensional flow and vorticity induced by breaking waves in a laboratory study. The VDV will provide an extremely useful measure of 3-dimensional velocity in situations where the flow direction is constantly changing, such as under breaking waves. Likewise, any deployment where the sensor orientation is unknown, uncertain, or variable would be well served by a 3-dimensional velocity sensor.

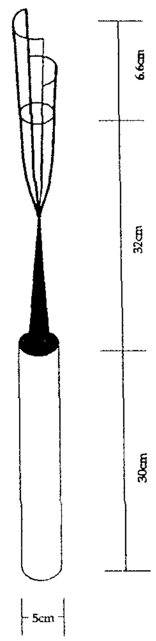

Figure 6: ***A preliminary sketch of the VDV sensor package is shown. The cage to the right will support the acoustic transducers with an epoxy-composite cage structure. Structural elements of the cage are 3mm in diameter. The electrical conductors for signals are led along the fiber struts into the pressure housing.***

Our design of the VDV will permit resolution of velocity in 3-dimensions from a large number of components, permitting the formation of closed loops of acoustic axes that allow us to calculate a 3-dimensional vorticity vector. Vorticity is the vector curl of velocity, and can be measured by sensing the net circulation around a closed path. It may be an important parameter in turbulence research, since turbulent vortices are the principle vehicle for diffusion and dissipation of flow energy. Microscale vorticity in the ocean has not been measured to date, yet much unexplained microscale turbulence data in the deep ocean may be due to small horizontal or vertical vortices [7]. Thwaites and Terray [8], backed by previous demonstrations [9], have demonstrated that vorticity measurements are possible with a reorganization of the geometry of acoustic axes in the BASS sensor cage.

Velocity measurement in an acoustic current meter is made by an array of high frequency acoustic transducers. The straight-line path between transducers form axes along which components of velocity are measured. When a measure of velocity is required, the transducers at both ends of an acoustic path transmit a pulse of sound at some high-frequency carrier (5MHz in the VDV). The component of flow parallel to the acoustic axis adds to the acoustic propagation speed for a pulse going in one direction along the acoustic path, and it subtracts from the propagation speed of the pulse going in the other direction. The difference in the time of arrival of these two pulses (typically, tens of nanoseconds) at either ends of the acoustic path is directly proportional to the flow velocity component. It is important to note that the velocity measurement is not made by subtracting two travel-times from each other. This would require extremely high resolution over a large timing interval. Instead, a timing circuit is started upon detecting the first received pulse, and an identical circuit is started when the pulse from the opposite transducer is detected. Both timing circuits are stopped at the same time, and their results are compared. Thus, we get a direct analog measure of the difference in sound propagation time in one direction versus the other. In the BASS instrument [1], differential travel-time has been measured using this technique to a sensitivity of 40pS over a 15cm path. This translates into velocity sensitivity of 0.03 cm/s. Performance of the VDV will meet or exceed this specification (after [5]).

The time between sound transmission and the first detected arrival (tens of microseconds) is independent from the differential travel-time measurement described above. It is purely a function of acoustic sound speed and the length of the acoustic path. In the BASS instrument [1], absolute travel-time was measured with a sensitivity of 7nS. This translates into a sound speed sensitivity of 0.1 m/s [10]. By measuring both the one-way travel-time, and the difference in travel-time in one direction versus its reciprocal, we can get both flow velocity, and acoustic sound speed from the same volume of water, and from the same acoustic pulse.

We have formulated a design for the VDV where all the acoustic transducers will transmit simultaneously. The measurements along each individual path connecting transducers will be distinguished in time due to a careful design of the placement of transducers in a cage so that each path has a significantly different length from all other paths. This permits us to make a complete velocity, vorticity, and travel-time measurement within the travel-time along the longest path (8.5 cm, or less than 60 microseconds). This development will make the travel-time and velocity measurements extremely well correlated in time and space, which is a major advantage when measuring rapidly varying turbulent velocities .

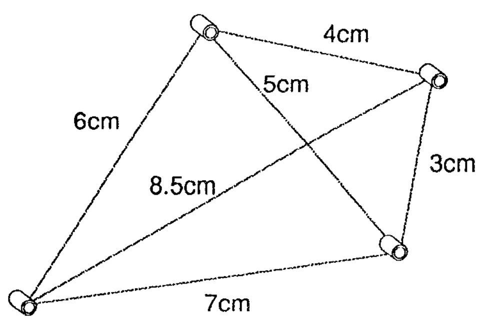

Figure 7: *A two dimensional geometry of transducers is shown where all the acoustic paths are more than 1cm different in length. The length of a pulse during the measurement sequence will be approximately 0.5cm, so this difference in path lengths will permit the sound arrivals corresponding to each path to be distinguished from one another. Two orthogonal planes identical to the one shown above will be formed by the VDV sensor cage, thus permitting three-dimensional velocity measurements, and two components of vorticity. A fully three-dimensional array has been designed that will also give 3-dimensional vorticity vector, but it cannot be clearly represented in a two-dimensional or perspective drawing.*

Vorticity measurement is dependent on the sum of velocity around a closed path. For the VDV, each acoustic path will measure velocity to an accuracy of $\pm$0.1cm/s. The sensor geometry will permit vortices of different scales to be compared, depending upon which set of velocity measurements are used to calculate vorticity. If a closed path consists of four independent velocity axes, then the approximate vorticity error will be the root-mean-square of the error from each path. This accuracy will be 0.2cm/s over a characteristic scale of 5-7cm, implying vorticity sensitivity of 0.08-0.06 rad/s (0.013 revolutions per second). This level of vorticity sensitivity can be realized from a single measurement taken in less than 60 microseconds (the time sound takes to travel the longest path, 8.5cm).

Practical concerns such as fouling often dominate current meter performance. Williams has deployed BASS in a variety of sites, including the deep-sea benthic boundary layer, the coastal boundary layer, under breaking surface waves, and in the shear field of internal waves. Despite deployments from a month to a year in duration, only minimal effects from fouling were encountered. Certainly, the VDV would be difficult in deployments where kelp or eel grass become entangled in the sensor cage. Such conditions destroy the performance of all types of velocity sensors (for example, [4]). The actual measurement of velocity from an acoustic current meter is not affected by surface properties, so the only impact of fouling is to increase the flow blockage near an acoustic path. We are minimizing the fouling effects by presenting as little surface for colonization of organisms as possible. Fortunately, this goal fits very well with the desire to minimize flow disturbance by reducing the sensor support structure.

4. CONCLUSIONS

Initial tests of the prototype BLCP show that it is possible to use a simple strain gage bridge to measure flow velocity at speeds relevant in boundary layer research. It will take a design iteration to give measurements of practical quality. With some added development, particularly involving clever mechanical and electronic design, we may build a unique micro-scale boundary layer velocity probe for use in coastal waters.

The VDV is still in the initial prototype stage, and no test data is yet available. We expect that this sensor will compliment the BLCP in that it will have significantly greater accuracy and resolution, but will not be appropriate within the boundary layer, 10-20cm above a sediment bed. The parallel development of the two sensors gives us the potential for a unique measurement capability in the beach environment.

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