Preliminary Tow Tank and Flume Tests of a Prototype BASS Rake Wave Bottom Boundary Layer Sensor

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Abstract - **The BASS Rake is an acoustic travel time current meter designed to make spatially and temporally dense velocity profile measurements in the continental shelf wave bottom boundary layer. The vertical extent of the WBBL is typically one to several centimeters, varying with water depth and wave conditions. The thinness of the layer is responsible for high levels of bottom shear stress which are important contributors to the sediment entrainment process and which enhance turbulent dissipation of flow energy. The BASS Rake is a modification of BASS, the Benthic Acoustic Stress Sensor, using a new geometry to image flow in the WBBL. An analysis of the flow distortion due to the sensor is presented suggesting some dependence of the gain on flow speed. Tow tank tests demonstrate the suggested dependence and are used to calibrate the sensor. In flume tests, the horizontal velocity vector is measured at $0.5\,cm$, $2.4\,cm$, and $5.0\,cm$ above a sand bottom at nominal flow speeds of $10\,cm/s$, $20\,cm/s$, and $34\,cm/s$ and a depth of $8.6\,cm$. The $34\,cm/s$ test included a significant bedload with no observed degradation of sensor performance. Velocity profiles are acquired within a $4\,ms$ window at a $1\,Hz$ rate. The flume measurements are compared to concurrent measurements made with an LDV.**

I. INTRODUCTION

Surface swell over the continental shelf generates a thin sheet of oscillatory shear flow called the wave bottom boundary layer. Large bottom stresses generated within the layer are an important element of the sediment entrainment and transport process. Additionally, high levels of turbulent dissipation within the layer have a strong effect on the mean flow over the continental margins. The thickness of the layer is typically one to several centimeters, varying with water depth and wave conditions [2, 3, 4].

To instrument this region, the BASS Rake, an acoustic current meter based on the Benthic Acoustic Stress Sensor differential travel time technique [11], is being developed here at the Woods Hole Oceanographic Institution (WHOI). A discussion of the characteristic scales of the wave boundary layer and the preliminary mechanical design of the sensor can be found in [7]. Supporting the mechanical design required a flexible electronic interface between the transducer array and the BASS transmitter/receiver. This circuit, a layered multiplexer, is described in [8].

This paper documents the initial tow tank and flume tests of a working, laboratory capable, BASS Rake. Section II describes the prototype, some lessons from the prototyping process, and the test conditions common to both the tow tank and the flume. An analysis of the flow distortion caused by the sensor and its effect on the gain is presented in Section III. Calibration of the instrument in a tow tank and boundary layer measurements in a flume are described in Sections IV and V. The results are summarized and a few caveats are attached in Section VI.

II. DESCRIPTION OF THE PROTOTYPE

The original Rake design used $2.5\,mm$ transducers in three offset columns. The goal was $1\,mm$ vertical resolution of the horizontal velocity profile. Experience and some additional analysis during the prototyping process have led to the use of $6\,mm$ transducers in a single column along the sensor tines.

The small transducers presented a number of technical challenges. Their small diameter to thickness ratio shifted their resonant frequency down from $1.75\,MHz$ to $0.85\,MHz$. The impedance at this frequency was highly reactive resulting in very weak dissipation of electrical energy as sound energy in the water. This was compensated for by inserting an inductor in the signal path to balance the capacitive reactance. The increase in coupling efficiency was augmented by a 3:1 gain in voltage across the transducer due to the LC resonance. However, the $2.5\,mm$ transducer still produced an exceedingly small received signal. This was extracted using two wide band, high gain amplifier stages and a narrow band, 6-pole, filter of the linear phase (flat delay) Bessel type, built with passive LC components. The signal to noise ratio at the filter output to the detector stage was in excess of $50\,dB$. In terms of velocity, this represents a single measurement accuracy of $3\,mm/s$. This success notwithstanding, the lower frequency and small diameter produced a wide beam pattern, $\approx 60°$ to the first null. This characteristic was expected to permit the measurement of vertical velocities by selection through the layered multiplexer of two transducers at different heights. Unfortunately, whenever the ends of the tines were placed closer than $4\,cm$ to $6\,cm$ above a sand bottom in the laboratory tank or the flume, the received signal was heavily corrupted by reflections and velocity measurements were impossible.

The solution is higher signal frequency to produce a narrower beam. Given the success of the $6\,mm$ transducers (9.5° to the first null), a frequency of at least $5\,MHz$ is indicated. There are difficulties associated with in-

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creasing the frequency. For example, some of the components currently used in BASS have effective operational limits between $5\,MHz$ and $10\,MHz$. Similarly, $10\,MHz$ is a practical limit for the bulk manufacture of piezoelectric transducers [9]. Therefore, somewhat higher frequency is not being pursued now, but it is considered a direction for future development.

It is worth noting here that, because of Fresnel zone averaging, the increase in tranducer size may not mean a reduction in the vertical resolution of the flow. For practical purposes the Fresnel zone can be thought of as the physical volume through which the acoustic pulse travels between two transducers [5]. The radius of the zone is inversely related to the acoustic frequency and is, for the transducers considered here, larger than the radius of the cylinder defined by a transducer pair. At $0.85\,MHz$ the Fresnel radius is approximately $8\,mm$. At $1.85\,MHz$, the resonant frequency of the $6\,mm$ transducers when mounted in a tine, the radius is approximately $5\,mm$. The original goal of $1\,mm$ vertical resolution would not have been reached with the $2.5\,mm$ transducers, because the measured velocity "along an acoustic axis" is actually a weighted average over the Fresnel zone. The $6\,mm$ transducers may actually have the finer resolution of the two. Accuracy depends on the weighting (a function of beam pattern) and the degree to which the velocity profile is nonlinear over the zone. The higher frequencies suggested above to reduce beam width would also reduce the size of the Fresnel zone. Unfortunately, a $1\,mm$ Fresnel radius requires a $30\,MHz$ operating frequency. This would be an enormously difficult undertaking and is not being seriously considered at this time.

The development of the $2.5\,mm$ prototype did demonstrate the capabilities of the layered multiplexer [8]. The interface allows flexible selection of transducer pairs, extremely low through resistance ($< 1\,\Omega$), and good cross-talk isolation ($30\,dB$). Capacitive shunt loading is optimized for a given level of measurement flexibility and, as designed, over 90 % of the transducer current is delivered to the receiver load. The multiplexer is part of the $6\,mm$ prototype used in the tests presented here.

The prototype is assembled on two chassis. The first is a standard BASS backplane with the transmit/receive (T/R) card removed. A jumper carrying power, logic, and analog signals on twisted pairs connects the T/R slot to the Rake backplane. Mounted there are the T/R card, the multiplexer and its address sequencer, and connections to the transducers in two tines. A braided ground strap also joins the two chassis to provide a low resistance ground path. This reduces high frequency noise between the chassis that would otherwise be coupled to the signal path through the multiplexer.

The prototype has four $6\,mm$ transducers in each of two tines spaced a nominal $15\,cm$ apart. Transducers are mounted with their centers $0.5\,cm$, $1.2\,cm$, $2.4\,cm$, and $5.0\,cm$ from the bottom of each tine. The pair at $1.2\,cm$ operated only intermittently; those measurements are not reported here. The tines are $1\,cm$ diameter, half-round cylinders (Figure 1), rather than the fully round shape described in [7]. The urethane originally used to fill out the tine attenuated the acoustic signal by $\approx 10\,dB$. The attenuation was initially overcome with a single amplifier stage and a passive LC band pass filter, a reprise of the technique used to boost the received signal of the $2.5\,mm$ transducers. This increased the measurement noise from $< 1\,mm/s$ to $\approx 3\,mm/s$. While this is certainly tolerable, we opted for the simpler circuit during this phase of the development and removed both the urethane and the amplifier/filter.

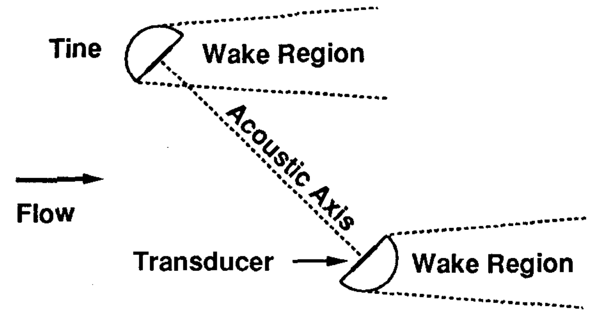

Figure 1. Plan View of Tines - The two half round tines of the prototype are shown here in plan view from above. Note that this sketch is not drawn to scale. The acoustic axis is oriented at 45° to the direction of flow. The tines are $1\,cm$ across the flat face and their separation is nominally $15\,cm$. Rough approximations to the downstream wake regions are indicated.

During the tow tank and flume tests described here the tines were rigidly mounted to a horizontal bar attached to a light rectangular frame. The bar was oriented at an angle of 45° to the sides of the frame and the sides of the frame were oriented parallel to the flow during tests. Components of the frame that enter the water are sufficiently small and far away that they do not distort flow in the neighborhood of the tines. The vertical position of the bar relative to the frame can be adjusted along sliders. During tow tank tests the height was adjusted to keep the tine mounting blocks above the water surface. In the flume the bottom of the tines was in contact with a sand bottom. The water depth of $8.6\,cm$ kept the mounting blocks above the water surface. In all tests there was some vibration of the tines leading to elevated noise levels in the measurement. The Rake backplane was mounted to the tine bar to fix the zero offsets [6] and the BASS chassis was attached to the frame.

The velocity measurement at each level requires $320\,\mu s$ [11]. A software delay of $1\,ms$ between measurements eliminates echos from the sidewalls of the tow tank and flume. A complete profile requires $4\,ms$. Profiles were obtained at a $1\,Hz$ rate over a $6\,min$ period. Historically, a $6\,min$ average has been necessary to supress most flow variations in the flume [10].

A nanosecond delay circuit [12] was used to precisely calibrate the BASS receiver's conversion from differential arrival time to measured voltage. Measurements of transducer separation and an accurate knowledge of the sound speed determined the conversion from along axis fluid velocity to differential arrival time [11]. A geometric correction for the 45° orientation of the acoustic axis to the flow is straightforward. This three part calibration constant, hereinafter "the standard calibration", was applied to all velocities reported here. A flow dependent correction to this constant will be discussed in subsequent sections.

III. FLOW DISTORTION BY THE SENSOR

Consider a simplified situation, modeling the tines as circular cylinders in a uniform, two dimensional, potential (irrotational, inviscid) flow, u. u is oriented at 45° to the line connecting the cylinders as in Figure 1. Let r_o be the radius of the tines and L be the separation of their centers. For $(r_o/L)^2 \ll 1$ (10^{-3} in this case), the two flow distortions interact only weakly and the along axis velocity, $u_a(r)$, where r runs from 0 at one tine to L at the other, can be written down by inspection [1].

$$u_a(r) = \frac{u}{\sqrt{2}}\left[1 - \frac{r_o^2}{r^2} - \frac{r_o^2}{(L-r)^2}\right] \tag{1}$$

The integral of $u_a(r)$ averaged over the path length is u_m, the measured velocity reported by BASS. Note particularly that the transducer separation, L, is assumed to define the path length even though there are regions of known zero flow at each end of the path in this model.

$$\begin{aligned} u_m &= \frac{1}{L}\int_{r_o}^{L-r_o} u_a(r)\, dr \\ &= \frac{u}{\sqrt{2}L}\int_{r_o}^{L-r_o} 1 - \frac{r_o^2}{r^2} - \frac{r_o^2}{(L-r)^2}\, dr \\ &= \frac{u}{\sqrt{2}}\left[1 - \frac{4r_o}{L} + \frac{2r_o^2}{L(L-r_o)}\right] \end{aligned} \tag{2}$$

The third term in this solution is small compared to the others and can be ignored. The leading term, $u/\sqrt{2}$, is the accurate, undisturbed flow along the axis. $4r_o/L$ is the expected error, more than 13 %, in the reported along axis velocity. Half of this, $2r_o/L$, is due to distortions in the flow outside the idealized cylinders and on the acoustic axis. The cylinders turn the on-axis portion of the undisturbed flow field towards the cross-axis direction, reducing both the actual and measured along axis flows. The addition of two tines forming a crossing measurement axis [7] will tend to rotate the field back towards the direction of undisturbed flow and reduce this error. The balance of the expected error is due to the regions of zero flow within the cylinders at each end of the path.

Is this model reasonable? Potential flow is a good approximation outside of boundary layers so one may expect a measurement using only the standard calibration to be at least 7 % low. Referring to Figure 1, the flow near the face of the downstream tine must be parallel to the face and thus makes no contribution to the average along axis velocity. The thickness of the face parallel region will depend on the flow, but there is a reasonable expectation that it is of order r_o. The sharp edge of the upstream tine causes flow separation and a vortex or series of vortices immediately in front of the face. A small vortex also makes no contribution to the average along axis velocity and there is a reasonable expectation that its size will scale with r_o. This line of reasoning should not be taken as a quantitative description of the flow. It is a qualitative model that provides a simple but reasonable structure for testing and calibration of this instrument. Based on this argument, an additive flow dependent gain correction of 5 % to 15 % is expected. Expressed as a multiplicative correction to the measured velocity after the standard calibration is applied, this range is 1.05 to 1.18.

IV. TOW TANK CALIBRATION

To determine the flow dependent gain correction the prototype was towed at speeds of $10\,cm/s$, $20\,cm/s$, and $30\,cm/s$ in the WHOI tow tank. The tank is approximately $1.5\,m$ wide, $1\,m$ deep, and $20\,m$ long. The tow carriage is controlled by a PC and has a maximum speed of $90\,cm/s$. The tow speeds were verified using a stopwatch over $10\,m$ of each $16\,m$ run. The error in the stated speed was always below 1 %. The tank was allowed to settle between runs, however, localized, unsteady currents of order $1\,cm/s$ are plainly visible in the tow record. Additional test conditions were given in Section II. The velocity record for the $10\,cm/s$ tow, after application of the standard calibration, is shown in Figure 2. The $20\,cm/s$ and $30\,cm/s$ tows exhibited similar characteristics.

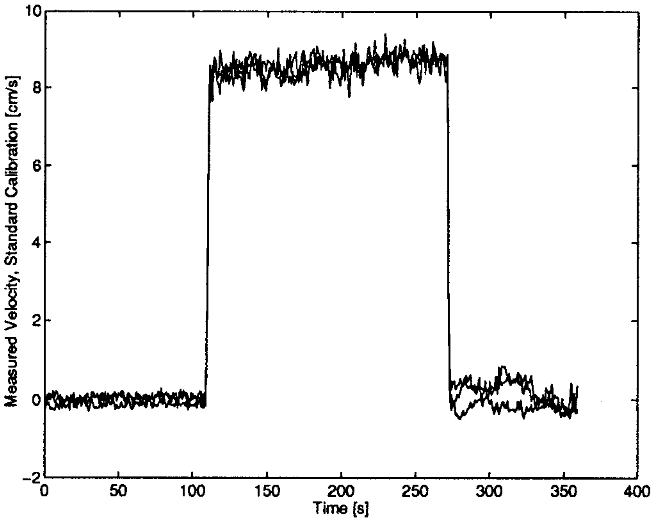

Figure 2. VELOCITY RECORD FOR 10 CM/S TOW - The velocity records of the $0.5\,cm$, $2.4\,cm$, and $5.0\,cm$ axes are shown after multiplication by the standard calibration. Note that the measured velocity is well below the actual velocity. Zero offsets were determined from averages over the first $100\,s$. The gain correction was determined using the first half of the $10\,cm/s$ transit, before a backflow in the tow tank increased the relative velocity.

During processing the records were first multiplied by the standard calibration. Zero offsets were determined from the data obtained before the cart was commanded to move. The gain correction for the tow speed is then simply the ratio of the tow speed to the measured velocity. A plot of the gain corrections versus Reynolds number for the three velocities is shown in Figure 3.

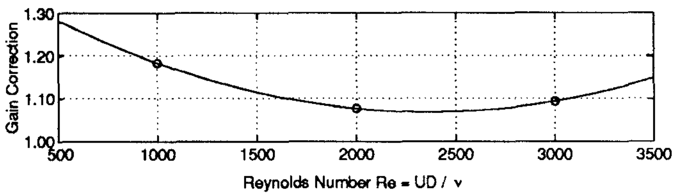

Figure 3. FLOW DEPENDENT GAIN CORRECTION - The circles (o) mark the empirically determined, multiplicative corrections to the standard calibration. The solid line (-) is a spline fit to the three points over the plotted range.

Note that the gain corrections are all in the anticipated range, based on the qualitative model of Section III. More interestingly, the smooth spline fitted to the gain corrections is strongly reminiscent of the curve for the drag coefficient of a cylinder in steady flow in the given range of Reynolds number. Below $Re = 10^5$, flow in the boundary layer around a cylinder is both stable and laminar. Drag changes with velocity as the angular position of the separation point changes. Drag increases as the separation point moves toward the upstream stagnation point. The wake widens around the cylinder as this happens, wake vortices grow larger, and a greater fraction of the acoustic axis makes a reduced contribution to the along axis velocity [1]. One can reasonably expect the gain correction to increase under these conditions and that is, in fact, the observed behavior.

This interpretation supports using the qualitative model as a reasonable guide. We recognize, however, that three points do not generally qualify as revealed truth and further tests are planned. One point in particular that must be settled is the best shape for the tines. Conceivably, a fully round tine would stabilize the gain by removing the path length ambiguity. Alternatively, fixing the location of one of the separation points with the sharp edge of a half round tine may prove more advantageous.

V. FLUME TESTS

The flume tests were conducted in the WHOI $17\,m$ flume [10]. The flume is $60\,cm$ wide with smooth walls. Tests were conducted at three velocities, nominally $10\,cm/s$, $20\,cm/s$, and $34\,cm/s$. Water depth above a $6\,cm$ thick sand bottom was kept near $8.6\,cm$ at all speeds. The sand was obtained from a local beach and had a median grain size of $\approx 250\,\mu m$. The Rake was positioned $12\,m$ from the flume entrance. Comparison measurements were made with a nonintrusive LDV $1.25\,m$ upstream of the Rake. Both instruments were in the region of fully developed flow.

The bed remained flat and there was no observable motion of the sand during the $10\,cm/s$ runs. With the nominal velocity at $20\,cm/s$, small pits, $1\,mm$ to $2\,mm$ deep, formed in the sand under the tines. No other bedforms were present and no organized motion of the bed was observed. During the $34\,cm/s$ runs, a speed chosen to induce bedload transport, large scale motion of sand grains over the bed occurred. Larger pits, $1\,cm$ deep, formed beneath the tines and a field of disorganized mounds and pits occupying the full width of the flume eventually formed downstream of the tines and supporting frame. Changes of elevation in this field were commonly $5\,cm$ over $15\,cm$ to $20\,cm$ horizontally.

During each $6\,min$ run the LDV sampled a single height at $25\,Hz$ while the BASS Rake obtained three level profiles at $1\,Hz$. The LDV height was then adjusted for the next run, leaving the flume speed constant until the LDV had built up a complete four level profile (the failure of the transducers at $1.2\,cmab$ only became apparent part way through the tests). We believe the LDV and transducer heights above the local bottoms were matched within $1\,mm$ for the $10\,cm/s$ runs. The transducers were $1\,mm$ to $2\,mm$ below the LDV during the initial $20\,cm/s$ runs ($0.5\,cmab$ and $1.2\,cmab$ measurements) and lower by up to $1\,cm$ during the final runs ($2.4\,cmab$ and $5.0\,cmab$ measurements). The frame supporting the tines was moved and reset in the sand bed during the acquisition of the $20\,cm/s$ profile when it became apparent that the $1.2\,cmab$ transducers were returning intermittently anomalous data. The heights were matched again for the $34\,cm/s$ runs, but that measure is somewhat fuzzy given the bedload and eventual pitting.

The flume speed is known to fluctuate over short periods ($< 1\,min$), particularly at slow nominal velocities [10]. These fluctuations can be seen in the data record. During these tests, the "steady" flume speed also changed, slowing down nearly $1.5\,cm/s$ between two supposedly stationary runs at one point. The more glaring examples of this behavior were not used in this data set, however, there remains some potential error in the LDV "profiles". The advantage of simultaneous measurements at multiple heights is obvious.

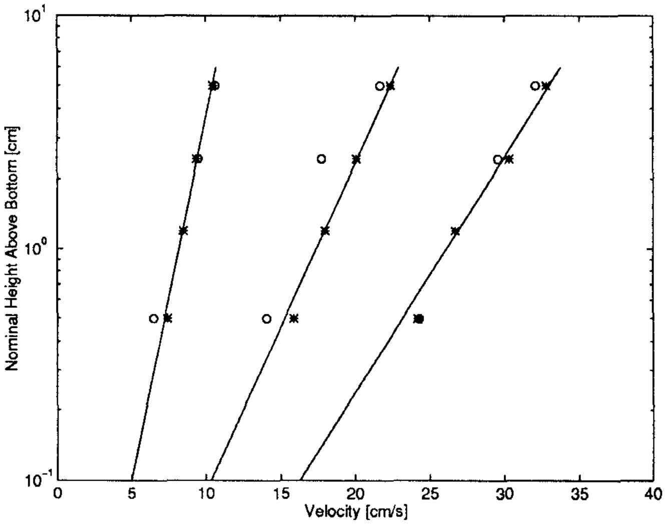

Figure 4. $6\,min$ BASS RAKE AND LDV AVERAGES AT 3 VELOCITIES - The asterisks (*) are $6\,min$ LDV averages. The circles (o) are gain corrected Rake velocities also averaged over $6\,min$. Each pair of averages was obtained over the same time interval. The solid lines (-) are logarithmic profiles based on the upper three LDV points for each velocity.

Figure 4 shows a comparison of $6\,min$ LDV and gain corrected Rake averages. Paired averages were taken over the same time period. The standard deviation of the LDV measurements was approximately twice that of the

Rake measurements at all speeds. The $10\,cm/s$ gain correction from the tow tank calibration was applied to the $10\,cm/s$ BASS Rake profile. No correction was made for the variation of fluid velocity with depth. Similarly, the $20\,cm/s$ and $30\,cm/s$ corrections were applied uniformly to the $20\,cm/s$ and $34\,cm/s$ Rake profiles.

The largest errors occur in the $20\,cm/s$ run during which the BASS Rake is known to have been below the nominal heights. A $1.5\,mm$ downward shift of the $0.5\,cmab$ measurement and an $1\,cm$ downward shift of the $2.4\,cmab$ and $5.0\,cmab$ measurements eliminate all three errors, placing the Rake measurements on the calculated LDV profile. Those offsets are entirely consistent with our records of the test, which are described above. The remaining errors are all below 2 %, with the exception of the $0.5\,cmab$ measurement at $10\,cm/s$. A portion of that time series is shown in Figure 5.

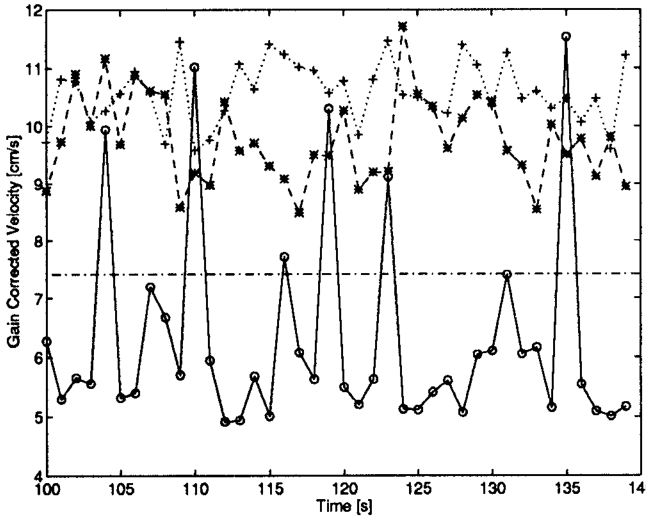

Figure 5. BASS Rake Velocity Record - The velocities at $0.5\,cmab$ (o), $2.4\,cmab$ (*), and $5.0\,cmab$ (+) were recorded simultaneously. This was a nominally $10\,cm/s$ run concurrent in time with the $0.5\,cmab$ LDV measurement (— · —). The spikes and low average of the $0.5\,cmab$ Rake measurement may indicate a thin layer of air bubbles on the tine.

The velocity spikes in this record are not present in the concurrent LDV record, nor do they occur in any of the subsequent Rake measurements at that level. This implies they do not represent the actual flow. We conclude, based on previous experience, that a thin layer of air bubbles may have formed on the tine. This phenomenon is common when urethane coated transducers are first placed in water less than a meter in depth. This was the first recording run of the day and the tines had been in the water less than five minutes at the time. The air bubbles attenuate the acoustic signal and can produce odd results. It is also possible that the signal indicates an acoustic interaction with the bottom. However, there is no repeat of the behavior in the immediately following runs and the tines were not moved relative to the bottom during that period. The bubbles, or some similarly obscuring, transient phenomenon, are more consistent with the observed behavior.

If the $0.5\,cmab$ Rake average taken during any of the subsequent $10\,cm/s$ runs is used, the error is eliminated. A portion of a $10\,cm/s$ Rake profile concurrent in time with the $2.4\,cmab$ LDV measurement is shown in Figure 6. The LDV averages at $0.5\,cmab$ and $2.4\,cmab$ are shown for comparison.

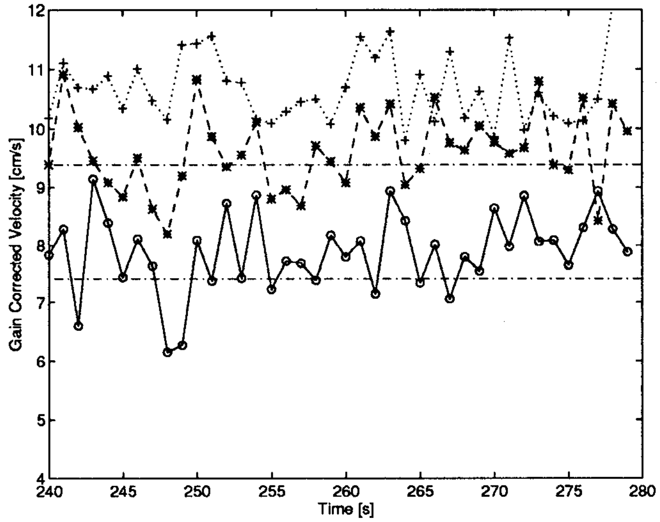

Figure 6. BASS Rake Velocity Record - The velocities at $0.5\,cmab$ (o), $2.4\,cmab$ (*), and $5.0\,cmab$ (+) were recorded simultaneously. This was a nominally $10\,cm/s$ run concurrent in time with the $2.4\,cmab$ LDV measurement. The $0.5\,cmab$ and $2.4\,cmab$ LDV measurements are both shown (—·—). The records show no evidence of anomalous behavior. The simultaneous nature of the profile reveals some coherent structures and a possible turbulent instability.

Figure 6 also demonstrates the value of essentially instantaneous profiles. Several vertically coherent structures are clearly evident in the record. Note the below average velocities at all three levels from $245\,s$ to $250\,s$. The trough appears to arrive later in time in the slower flow near the bed. Above average velocities with a similar time structure follow at $253\,s$ and $263\,s$. The behavior near $273\,s$ may indicate a turbulent instability.

VI. CONCLUSIONS

On the whole, we were quite satisfied with the performance of the BASS Rake during this first set of measurements. Accuracy appears to be quite high, but this is a very limited and preliminary data set. The results need to be confirmed and extended under much more tightly controlled conditions. That work will be guided by the framework established in these early measurements.

The dependence of gain on the ambient flow is disturbing. Reshaping the tines, including the tines of the crossing acoustic axis, and increasing the path length may all mitigate the effect. Additionally, the smooth shape of the gain correction curve (Figure 3) would support a rapidly converging iterative loop during post processing. We stipulate again, for the record, that three points do not generally qualify as revealed truth. More investigation is needed.

On the positive side, the flume tests demonstrate the ability of this technique to obtain near instantaneous velocity profiles in a boundary layer. Accurate measurements were made beginning less than 1 *cm* above a sand bed. A strong bedload transport of sand did not interfere with the near bed measurements. The prototype appeared to image several vertically coherent structures in the flow and possible turbulent instabilities.

Further tests with the prototype are planned. The gain correction curve for steady flow will be filled in and extended in the tow tank. The response to oscillatory flows will be similarly studied. The flume tests will be repeated, with more care, at a higher sampling rate, and for a greater selection of nominal speeds. Eventually, we intend to follow the prototype with a 16 level, field capable instrument.

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