REYNOLDS STRESS RESOLUTION FROM A MODULAR ACOUSTIC VELOCITY SENSOR

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***Abstract* - Correlation of fluctuations in velocity components in a boundary layer flow represents turbulent exchange of momentum across streamlines. Averaged over many burst and sweep events, the correlation of velocity fluctuations normal to the boundary with streamwise velocity fluctuations is Reynolds stress. Exchange of fluid is the dominant stress carrying process from the viscous sublayer to the outer boundary layer. In this region, millimeters to meters, the stress is constant and a single measurement of Reynolds stress represents the shear stress at the boundary. The Modular Acoustic Velocity Sensor, MAVS, measures the 3-D vector velocity in a 10-cm diameter volume, a size suitable for resolving Reynolds stress. Such a measurement is valuable for studies of sediment transport in which the shear stress on the bottom is the forcing function for erosion and a barrier to deposition. Noise level in still fluid, correlations of velocity while towed in unsheared fluid, and comparison with BASS (Benthic Acoustic Stress Sensor) in an inertial sublayer test whether MAVS can measure Reynolds stress.**

Flow distortion by the transducer supports and correlation of fluctuations in velocity components in the wake are the potential limits on MAVS for Reynolds stress sensing. Electronic noise and drift are not a problem. If one assumes 1/3 of the fluctuations in the wake correlate (downstream with vertical) then the limit for rms flow noise in the wake is about 3% of the flow velocity. Experimental verification shows the Modular Acoustic Velocity Sensor, MAVS, does meet the noise criteria for measuring Reynolds stress. The rms flow noise is 1.5% at 40 cm/s and is 2.5% at 80 cm/s. Electronic noise is equivalent to 0.5 mm/s rms flow noise. The deviation from ideal vertical cosine response at 15˚ elevation is 5% or 2.8˚ while the limit would be 9% or 5°. These noise limits should permit MAVS to resolve Reynolds stress.

Towing in a tank provides noise figures for unsheared flow (no Reynolds stress). Deployment with BASS on a tripod in a boundary layer flow in a tidal channel gives a comparison of Reynolds stress between a known sensor and MAVS. The results from the towing tests and the tidal channel can be compared to give a lower limit of Reynolds stress that MAVS can detect and the expected error in stress as a function of speed.

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I. INTRODUCTION

The Modular Acoustic Velocity Sensor, MAVS [1], measures the instantaneous flow velocity vector along four acoustic paths resolved into Cartesian earth coordinates [2]. All paths are contained in a cylindrical volume 10 cm in diameter and 9.5 cm high. This small region can be assumed to be uniform in velocity for purposes of resolving Reynolds stress down to a scale of 20 cm although there are certainly turbulent fluctuations down to the dissipation scale of millimeters that are not resolved by the 10 cm acoustic paths in MAVS. In fact, the wavenumber resolution of MAVS and its related velocity sensor, BASS [3] is order 100 m^{-1} due to near field acoustic caustics. The energy content of the fluctuations is less at the 1cm scale than at the 10 cm scale of the sensor if the boundary that generates the Reynolds stress is several sensor diameters away.

Sediment transport and boundary layer mixing require estimates of the bottom shear stress. Reynolds stress measured within the inertial sublayer represents the boundary layer shear stress because within this region, stress is carried by turbulent exchange of momentum. In stationary, homogeneous flow, the stress in this region is constant so a measurement at one height represents the stress at the boundary, even if the boundary is rough. If MAVS can measure this turbulent exchange of momentum, it will be a useful tool for boundary layer research. This study set limits on the ability of MAVS to measure Reynolds stress.

II. NOISE IN STILL FLUID

A. Bucket Zero

MAVS is calibrated for zero velocity offset in a bucket of still fluid, generally water but sometimes gelatin [4]. This presents a test of electronic noise, including cross talk between acoustic axes, when the Cartesian earth coordinates are processed for Reynolds stress. Over short periods, the typical least bit fluctuations of MAVS velocities of 0.1 cm/s give instantaneous correlations of 0.01 dy/cm^2 or 0.01 gm/cm $s^{2.}$ This does not adequately represent the short-term drift and offsets from standing acoustic waves that might contribute to the apparent Reynolds stress in a small bucket. To better represent the longer-term effects, averages of 10 instantaneous correlations are plotted in Fig. 1 along with one of the velocity components, a horizontal component, averaged over 10 samples. In the bucket, it doesn't matter very much how rapidly these samples were taken because there is no actual flow, but the samples were every 700 ms and the record length is 10 minutes. The apparent horizontal velocity is about 0.5 cm/s. The correlations are positive and negative but average to –0.007 gm/cm s^2 where the density of fresh water has been used to put the correlation of velocities into the units for stress.

The actual computation for this plot and this result was the one used for Reynolds stress in general. The sample interval over which stationarity is assumed is the block that will give a single Reynolds stress. The mean of each component of flow is subtracted from the instantaneous velocities and the vertical and horizontal fluctuations are multiplied together and averaged. The plot is the running 10-point average of both the horizontal velocity and the product of the instantaneous horizontal and vertical velocities.

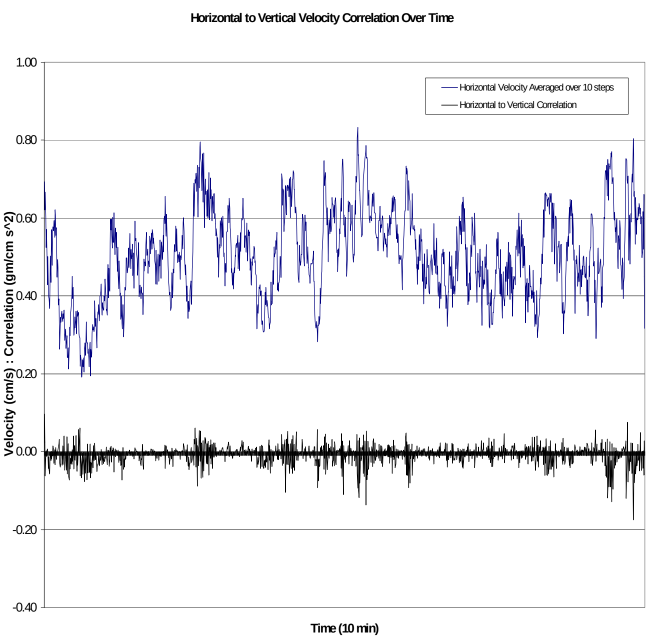

Fig. 1. Bucket zero velocity correlations expressed as Reynolds stress. 10-point averages of horizontal velocity component and correlated horizontal and vertical fluctuations are plotted.

It appears that the electronic noise limit for MAVS is less than 0.01 dy/cm^2 from the bucket zero test.

B. Large Tank

Echoes and changes in these echoes with temperature change in the bucket cause drift of apparent velocity. The effect is only a few mm/s but in a large tank, the arrival of echoes from the walls of the tank are outside the receive window and negligible. Although echoes are suppressed, in a large tank convection can create real currents that change with heating and cooling of the walls. If the water in the large tank stratifies, convection is inhibited. Internal waves are supported in a stratified tank and seiches are generally observed in large tanks. Still, the zero experiment was repeated in a 1-meter cube tank and the results were improved from the bucket zero. The average stress in the large tank was less than 0.001 dy/cm^2.

III. Tow Tank Tests

A. Tow Tank

Still water in a tow tank is free of Reynolds stress or at least the shear associated with convection and internal waves is low enough that the Reynolds stress should be very low. So if the MAVS sensor is towed through such still water, any correlations between vertical and horizontal velocities are instrumental and thus a limit to measurements of Reynolds stress in a real flow. The tow tank we used is 1.2 m deep, 1.2 m wide and 21 m long. The carriage can travel smoothly at speeds as low as 5 cm/s and as high as 70 cm/s. At the higher speeds, the runs are short. Fig. 2 shows the set of runs performed and the shortness of the higher speed runs can be seen. The tank is not still after the first run. Each run reversed the direction of the previous run so the initial part of each run after the first was through the wake from the previous run. This added turbulence to the measurement, which can be seen in the Reynolds stress records.

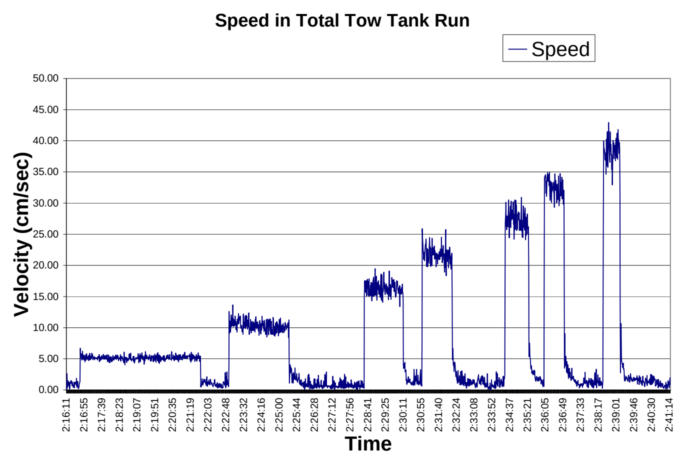

Fig. 2. Tow tank runs at 5, 10, 15, 20, 25, 30, and 35 cm/s, each reversing direction to the one before. Only the first has still water, the others are towed through the wake of the run before.

Note that the 10 cm/s run starts at 12 cm/s and finishes at 10 cm/s, showing the wake most at the beginning of the run. Horizontal speed is plotted rather than velocity because a large steel valve halfway down the tank distorted the earth coordinate velocities badly. The stationary period after the 5 cm/s run shows 2 cm/s as the wake overruns the stopped sensor. Because speed is absolute value, the speed is positive even though the velocity was negative.

B. Towed Reynolds Stress

At 5 cm/s, the water was still and the 10-point average of the correlation of vertical velocity with speed was –0.05 dy/cm^2. This is a very acceptable result. It is shown in Fig. 3.

Fig. 4 shows the 10-cm/s tow with an average correlation of –0.28 dy/cm^2. This increases in the 15 cm/s tow to –0.72 dy/cm^2, in the 20 cm/s tow to 0.21 dy/cm^2, and in the 30 cm/s tow to –0.37 dy/cm^2. The 30 cm/s tow is shown in Fig. 5. In Figs. 4 and 5, the individual correlation peaks are as likely to be positive as negative although there is a net apparent stress.

We believe there is a true stress but that it is not momentum transport in a vertical direction. Rather, it is the decay of the wake by momentum exchange from the core of the wake to the surrounding water. This is a correlation of velocity fluctuations in all directions, only the vertical and horizontal being plotted.

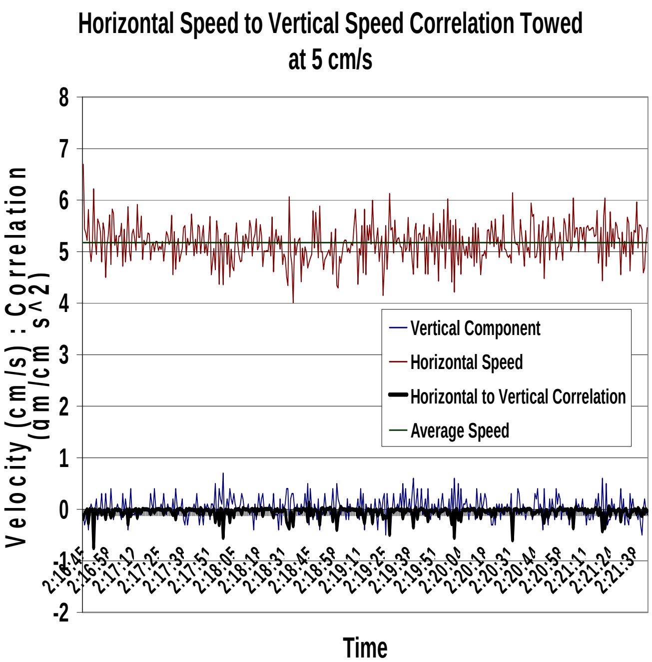

Fig. 3. 5 cm/s tow in still water. Average correlation of vertical velocity fluctuations with horizontal speed fluctuations is –0.05 dy/cm^2.

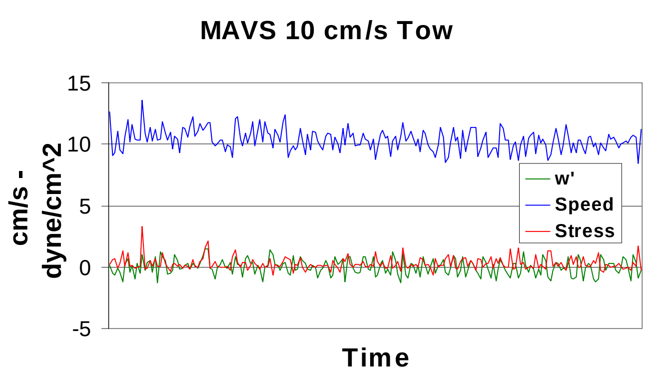

Fig. 4. 10 cm/s tow in tank back through wake of 5 cm/s tow. The average stress is –0.28 dy/cm^2.

IV. Intercomparison With BASS

A. BASS and MAVS on the CMO Tripod

For intercomparing BASS and MAVS, a tripod supporting both was deployed off the Woods Hole Oceanographic pier. BASS measures the vector velocity components in a cage 10 cm in diameter, the same as MAVS. The acoustic paths of BASS cross the center of the measurement volume while the acoustic paths of MAVS are on chords surrounding a central support. BASS has been used to measure benthic boundary layer flow for many years [5,6,7] and obtains reliable Reynolds stress estimates within the inertial sublayer in stationary, homogeneous flow.

Three BASS sensors were mounted on the CMO SuperBASS tripod [8] where they had been compared to ADV (Acoustic Doppler Velocimeter) probes. The MAVS was substituted for one of the ADVs and the tripod was redeployed in 22 meters depth in Great Harbor within reach of a crane on the dock. BASS sampled every 850 ms while MAVS sampled every 700 ms. The ADV mount was very convenient, the same diameter as the MAVS, but the ADV was designed to point up and the MAVS to have its sensing volume below the housing. To fit in the mount, MAVS was inverted. This placed the sensing volume of MAVS at 110 cm above the bottom. The BASS sensors were at 39 cm above bottom and 74 cm above bottom with a third sensor also 74 cm above bottom but mounted horizontally instead of vertically. (The purpose of the two BASS orientations was to explore the effect of the support rings on BASS. The horizontal mounting has minimal cosine error for flows out of the horizontal plane as long as the plane of the support rings is parallel to the flow.) The two BASS sensors at 74 cm above bottom were 66 cm apart. MAVS was an additional 55 cm from the horizontal BASS sensor.

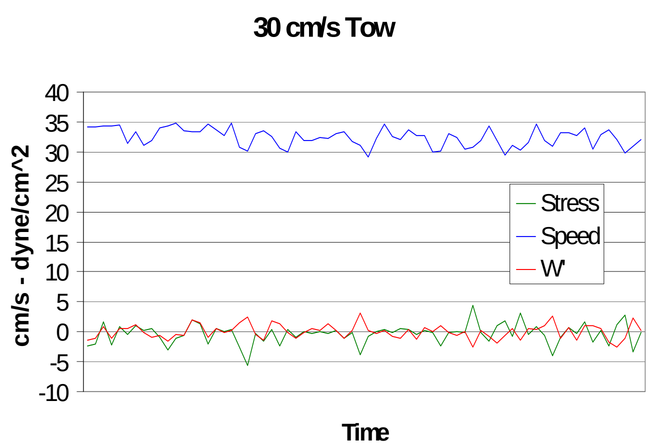

Fig. 5. 30 cm/s tow in tank back through the 25 cm/s wake. The average stress is –0.37 dy/cm^2.

The shape of Great Harbor rectifies the tidal flow. It does not reverse. Near the bottom, the flow must be sheared by the no slip condition on the bottom and thus a boundary layer exists with an inertial sublayer where the stress is constant. We had hoped that this region would be thick enough to provide uniform Reynolds stress to all the sensors of BASS and to MAVS. Unfortunately, the BASS sensors did not experience the same stress, or even similar current. However MAVS did measure the same mean current as the closest BASS sensor. BASS sensor speed is shown in Fig. 6. The current is only 4 cm/s over the 10 minute interval of the plot.

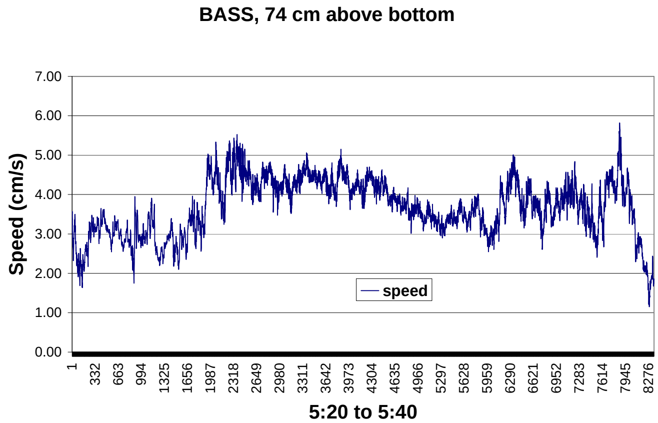

Fig. 6. The speed measured by the BASS sensor 74 cm above the bottom in Great Harbor. This modest velocity is the least variable period of 10 minute duration that was observed in 30 hours.

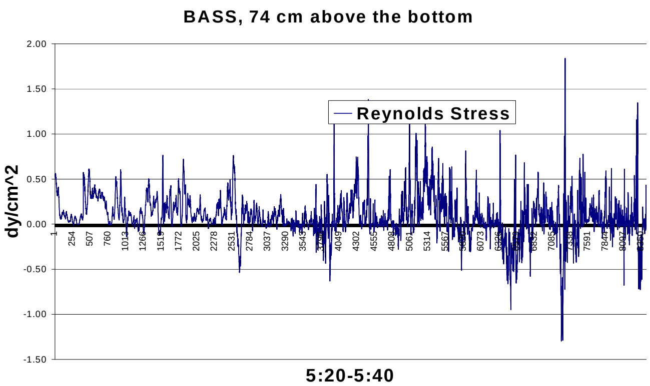

Fig. 7. The Reynolds stress measured by the BASS sensor 74 cm above the bottom in Great Harbor. The stress is highly variable and when averaged over the entire period is only 0.06 dy/cm^2

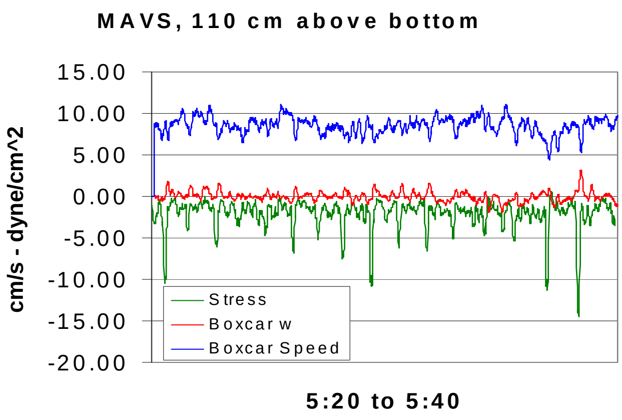

Fig. 8. The speed measured by MAVS 110 cm above the bottom in Great Harbor. Stress is presented with a 10-point running boxcar average. Mean Reynolds stress is –2.12 dy/cm^2 and exhibits intense bursts with stress exceeding –10 dy/cm^2.

BASS stress is shown in Fig. 7 and will be commented upon below. MAVS velocity is shown in Fig. 8. Note that the MAVS velocity is twice that measured by BASS. It is possible that there was some flow blockage at BASS due to Eel grass that was present in great abundance. In any case, the velocity at MAVS is more reasonable than that at BASS during the peak current of the tidal period, even in a neap portion of the tidal cycle.

B. Stress from BASS and from MAVS

BASS stress results are displayed in Fig. 7. MAVS stress results are displayed in Fig. 8. Fluctuations in the stress measured at the BASS sensor are not unreasonable except that true Reynolds stress is negative and only in the last few minutes of this period is the stress negative. In fact it averages slightly positive over the entire period, 0.06 dy/cm^2.

The MAVS stress time series is highly irregular and the stress is substantially greater than that measured by BASS. This deserves discussion but for the moment, MAVS appears to be measuring stress at a level much greater than in the tow tank at a similar speed. We believe this implies that fluctuations in velocity in the vertical are correlated with fluctuations of velocity in the horizontal. The boundary layer near the bottom in Great Harbor, for all its peculiarities, does carry turbulent eddies that transport momentum and exhibit Reynolds stress. The normal constraints of the Reynolds decomposition that allows the stress to be extracted are that the flow be stationary and homogeneous. It is neither in this case. Most seriously, it is not homogeneous.

C. Great Harbor Flow

The current in Great Harbor is driven by the current running across the mouth of the harbor through Woods Hole Passage from Vineyard Sound to Buzzards Bay. When the current runs SE from Buzzards Bay to Vineyard Sound, it runs SE past the end of the Woods Hole Oceanographic pier. This makes Great Harbor part of the flow. The current sweeps through the harbor driven by flow through several guts in its western end. When the current runs NW through Woods Hole Passage, it divides at the southern entrance to Great Harbor and a filament swirls through Great Harbor in the same direction that it did during the SE flow. The current near the pier is curving strongly right in either case and passes by the pilings of the pier before reaching the measurement location. We postulate that the curvature in the flow is supported by horizontal, cross flow Reynolds stress that steers the flow to the right. Also, the pilings shed a vortex sheet that narrowly misses the tripod. Or more precisely, it misses the MAVS sensor except for brief instants when an eddy passes through the MAVS sensor volume. At those moments the stress is very great; it is the cross flow stress associated with the vortex.

V. Conclusions

MAVS has an electronic noise level below 0.01 dy/cm^2 apparent Reynolds stress. In still water, this will permit real stress to be measured slightly greater than this. The distortion of flow around the sensor when towed through still water gives rise to an apparent Reynolds stress below 0.1 dy/cm^2 at a tow speed of 5 cm/s. Our tests at higher tow speeds revealed that MAVS does measure the real Reynolds stress present in the wake from the previous tow but that even at speeds as high as 30 cm/s, the self generated apparent Reynolds stress is below 0.4 dy/cm^2.

The attempt to measure real boundary layer stress was complicated by the geometry of the harbor, by the location of the sensors near the vortex street of a piling, and by possible obstruction with eel grass. Stress was present as expected and MAVS did measure Reynolds stress. It requires a lot of power to produce a thick turbulent boundary layer and tidal forces are competent to do this work. Unfortunately the natural flumes driven by tidal power are not simple and the flow is rarely homogeneous and may be unsteady. Tidal flow does produce turbulence and this was measured by MAVS.

References

[1] Thwaites, F.T., and A.J. Williams 3rd, 1996. Development of a Modular Acoustic Velocity Sensor, Oceans 96, pp. 607-612.

[2] Williams, A.J.3rd, and F.T. Thwaites, 1998. Earth coordinate 3-D currents from a Modular Acoustic Velocity Sensor, Oceans 98, IEEE Catalog Number 98CH36259, pp. 244-247.

[3] Williams, A.J. 3rd, J.S. Tochko, R.L. Koehler, W.D. Grant, T.E. Gross, and C.V.R. Dunn, 1987. Measurement of turbulence in the oceanic bottom boundary layer with an acoustic current meter array, J. Atmos. and Oceanic Tech., 4(2), pp. 312-327.

[4] Morrison, A.T., A.J. Williams 3rd, and M. Martini, 1993. Calibration of the BASS acoustic current meter with carrageenan agar, Oceans 93, pp. 143-148.

[5] Gross, T.F., A.J. Williams 3rd, and W.D. Grant, 1986. Long-term in situ calculations of kinetic energy and Reynolds stress in a deep sea boundary layer, J. Geophys. Res., 91(C7), July 15, pp. 8461-8646.

[6] Gross, T.F., A.J. Williams 3rd, and E.A. Terray, 1994. Bottom boundary layer spectral dissipation estimates in the presence of wave motions, Cont'l. Shelf Res., (10/11), pp. 1239-1256.

[7] Grant, W.D., A.J. Williams 3rd, and T.F. Gross, 1985. A description of the bottom boundary layer at the HEBBLE site: Low frequency forcing, bottom stress and temperature structure, Marine Geology, 66, pp. 219-241.

[8] Williams, A.J. 3rd, D.B. Peters, A.G. Gordon, and J.H. Trowbridge, 1997. SuperBASS Tripod for Benthic Turbulence Measurement, Oceans 97, IEEE Catalog Number 97CH36105, pp. 524-527.