Noise in Ice-Tethered Profiler and McLane Moored Profiler Velocity Measurements

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***Abstract*-In order to measure current profiles, and most recently, turbulent fluxes, moored profiling instrument have been equipped with acoustic travel-time current sensors. Noise in the measured currents has exceeded expectations. A customized Falmouth Scientific acoustic current sensor on a McLane Moored Profiler (MMP) has a standard deviation of measured velocity that is 4.4% of the profiler velocity in still water and a modified Modular Acoustic Velocity Sensor (MAVS) on an MMP and an Ice-Tethered Profiler (ITP) has a standard deviation of 4.6% of profiler velocity. Both of these sensors measure velocity along four acoustic paths and the water velocities were computed neglecting their downstream paths.**

The noise in measured velocity profiles from the ITP is more obvious because the relative ocean currents sampled by the ITP profiles were relatively weak. The ITP with the custom MAVS velocity sensor was investigated for a Strouhal resonance of the sensor structure, motor commutator noise, vibration from the profiler rolling up and down a mooring cable, and the Strouhal wake of the sensor itself. The noise was found to be dominated by the latter.

Acoustic travel-time current sensors do a good job of measuring a line integral of water velocity along their acoustic paths, but the presence of the acoustic transducers and their supporting structures may change the flow being measured. Some of the design tradeoffs of the sensor design are discussed. Two solutions to reduce velocity noise are described: over-sampling and averaging and design of a sensor optimized for profiling. Over-sampling and averaging is shown to significantly reduce noise deriving from the smaller eddies shed by the sensor structure while retaining signals due to eddies larger than the sampling volume. Over-sampling and averaging can be utilized by the existing profilers with a program change while the second option requires a new sensor head. In a tow tank test through still water, over-sampling and averaging from 16 Hz down to 2 Hz reduced the standard deviation of velocity of paths normal to the flow from 5.2% to 2.2% of the profiler velocity.

I. Introduction

The Ice Tethered Profiler (ITP) was developed at the Woods Hole Oceanographic Institution to measure profiles of water properties under the arctic icepack. The difficulty and cost of making year-round measurements in multiple places under the arctic ice have limited observations of the atmospheric-ice-ocean system. A wire-rope tether is suspended from a surface package deployed on a drifting ice floe; the ITP profiler vertically traverses this wire at nominally 0.25 m/s, down to 800 meters depth, while measuring ocean temperature, conductivity, and depth [1], [2], [3]. In this system, data collected by the profiler are telemetered up the mooring tether to the buoy on the surface with an inductive modem, after each profile. This buoy then telemeters the data back to land via an Iridium satellite link. The surface buoy also has a GPS to obtain locations and an irradiance sensor. The system was designed to fit through an 11 inch (0.28 m) diameter hole drilled through the ice. It is expensive to get to the arctic, expensive to ship the ice drilling equipment to the deployment site, and would be expensive to recover the system. Keeping the needed hole small reduces these deployment logistics costs, and telemetering the data to shore saves the cost of going back to recover the equipment to get the data. To date, forty-one ITPs have been deployed in the Arctic Ocean.

This present analysis resulted from the addition of current measurement to the ITP sensor suite to sample relative currents versus depth and in addition, measure vertical turbulent fluxes of momentum, heat and salinity a couple meters beneath the ice bottom between profile operations [4]. An acoustic travel-time current sensor was chosen because in the middle of the Arctic Ocean there are insufficient scatterers for a Doppler current measurement and to reduce power consumption. A modified Modular Acoustic Velocity Sensor (MAVS) was chosen. If a profiler only measures scalars, it does not need to measure its attitude in space, can wag in a current, and only needs to measure its depth. In order to measure the profiler's attitude, in addition to a three-axis current sensor, a three-axis magnetometer, a three-axis accelerometer, and a three-axis angle rate gyro were added. Near the magnetic North Pole, the magnetic lines of flux are very steep, making determination of instrument heading ill-conditioned. In addition, to make an accurate flow measurement, the current meter sensing volume needs to be in undisturbed flow requiring that the profiler orient into the current and not wag excessively.

The first ITP with a velocity sensor (ITPV) was deployed on October 8, 2009 on a 2.6 meter thick ice flow in the Beaufort Sea at 77° 45' N, 135° 25.8' W (Fig. 1).

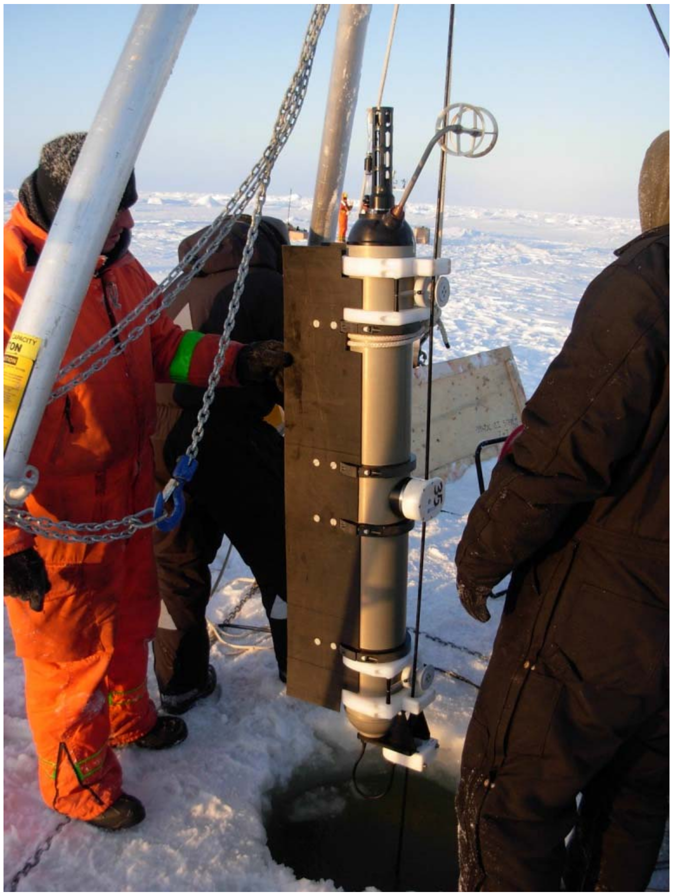

Fig. 1. Deployment of the first ITPV is shown. A tripod was used to support the wire tether and profiler during deployment. The MAVS acoustic current sensor supports are the circular rings extending up and to the right of the ITPV top end cap in this image. Black plastic tail fins extend off the trailing edge of the vehicle to orient the instrument into the relative horizontal flow.

The photo shows the fins added to keep the profiler pointed into the current and minimize Strouhal oscillation. The addition of the fins and current sensor increases the diameter of the required ice hole to 24 inches (0.61 m). The sensing volume of the current sensor was kept as close to the profiler as possible to minimize the needed hole diameter. The sensing volume also needs to be very close to the CTD to enable measurement of the turbulent temperature and conductivity fluxes. Due to a programming error, only the first two profiles were telemetered back to shore. However, the ITP data are stored internally in the underwater vehicle, and recovered one year later when the profiler was recovered. Since then, a second ITPV has been deployed.

The MAVS measures water velocity along four acoustic paths to form an over-determined three-axis water velocity measurement. The raw velocity measurements along each path from the initial down-going profile are shown in Figure 2. This profile occurred during a period with very little relative horizontal current which nicely illustrates the noise in the velocity measurement, especially when compared to the quiescent period before and after the profile. ITPs are typically programmed to sample for 2 minutes at rest before and after each profile operation. The sensing volume has a central ½ inch (1.27cm) tube and two streamlined rings holding the acoustic transducers. In this descending profile, the velocity path that lies above and downstream of the central sensor tube has the most noise (blue curve in Fig. 2). The path positioned below and upstream of the central sensor tube has the least noise (red curve). The other two velocity paths are situated diagonally in front of and behind the central sensor tube; both exhibit noise. The mean of the path standard deviations during the descent was 6.8% of profiler velocity. Due to the position of the sensors on the profiler body, the ascending profiles have less noise than the descending profiles because the sensor is in less disturbed water ascending. In the following ascending profile, the standard deviations of velocity path data were 0.53, 1.16, 2.76, and 1.99 cm/s, the first was the upstream path and the third was the downstream path. The mean of these was 5.45% of the profiling velocity. If the three-axis velocity is computed without the downstream path, the standard deviation of the derived relative velocity is 4.7% of the profiling velocity.

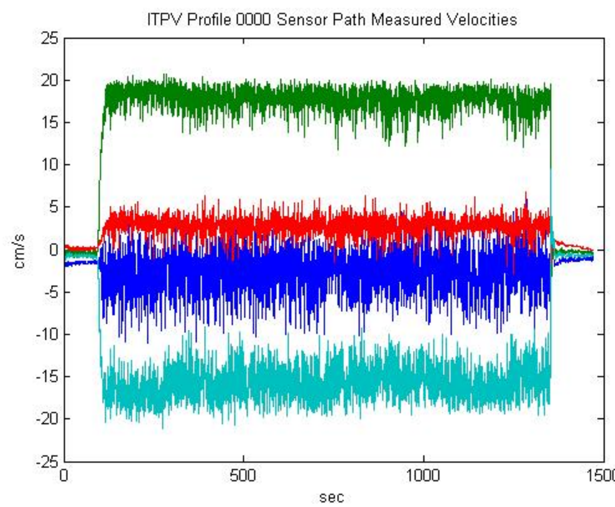

Fig. 2. Sensor path velocities from the first down-going profile of the ITPV deployment are plotted. The blue path is downstream of the sensor and has the most noise, and the red path is the upstream path with the least noise.

These noise issues are not restricted to the ITPVs; the current measurements from the McLane Moored Profilers (MMP) are also noisy [5]. To date, the majority of MMPs fielded have been equipped with Falmouth Scientific Instruments (FSI) acoustic current sensors installed with a special ACM configuration as in Fig. 3. Analyzing a representative set of MMP date, we find the standard deviation of the derived velocity when profiling through still water was 4.4% of profile speed when ignoring the downstream acoustic path. Recently, some of the MMPs have been fitted with modified MAVS acoustic current sensors and we have measured a standard deviation of 4.6% of profile speed through still water, again ignoring the downstream path.

Without the physical constraint of deploying through a hole in the ice, it is possible to place the ACM sensing volume a greater distance from the MMP body, in less disturbed water resulting in lower noise than the ITPVs.

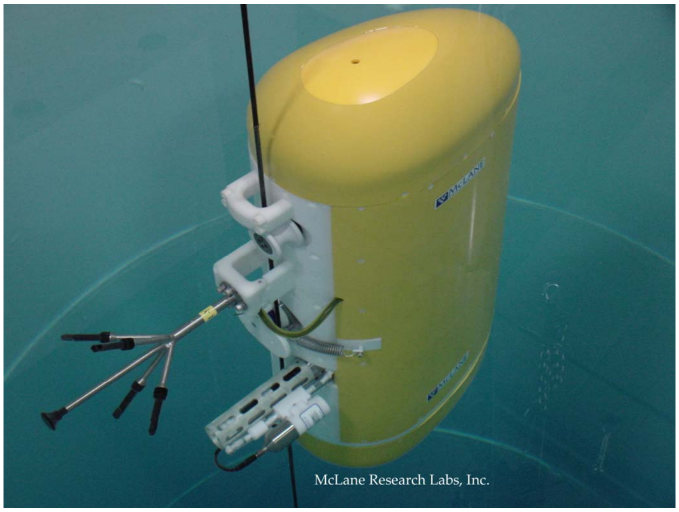

Fig. 3. McLane Moored Profiler with Falmouth Scientific Instruments acoustic current sensor in McLane test tank. Courtesy of McLane Research Inc.

These noise levels are larger than the author had expected/hoped for. During the development of the MAVS sensor, the prototype sensor was connected to a set of Benthic Acoustic Stress Sensor (BASS) electronics, literally off the shelf, and evaluated in a tow tank [6],[7]. While the investigation and resulting paper were primarily focused on measuring cosine response, the measured standard deviation of measured velocity towed through still water was 1.8% of tow carriage speed at moderate speeds. The present investigation tests five hypotheses for the increased velocity noise in Profiler applications over what was expected, and proposes two solutions to mitigate the problem. The five hypotheses are: 1) a Strouhal resonance of the sensor structure, 2) motor commutator noise, 3) climb and slip of the mooring cable on the rollers, 4) cable non-uniformity caused vibration increasing the correlation lengths of the vortices shed by the sensor, and 5) just the wake of the bluff sensor advecting through the acoustic paths. Lastly, two solutions are proposed; over-sampling and averaging of the velocity measurements, and/or a new sensor design.

II. Analysis

A. *Hypothesis 1, Strumming Resonance of the Sensor Structure*

The data plotted in Figure 2 suggest a strumming resonance of the sensor structure. Much of the initial analysis was done without a complete ITPV to test. When the vortex shedding frequency from flow over a lightly damped structure coincides with a resonant frequency of the structure, the flow-induced vibration can be large and vigorous [8]. Motion of a bluff body in a flow can organize the flow separation points and can increase the correlation lengths of the vortices along the object increasing the net oscillatory forces on the object. The sensor structure for the ITP is longer than the original MAVS sensor so it has lower resonant frequencies. The dominant excitation frequency of a flow normal to a tube is given by

$$f = \frac{0.2*U}{d}. \qquad (1)$$

In the equation, f is the frequency in Hz, U is the velocity of the flow, and d is the diameter of the tube. With a ½ inch (1.27 cm) tube profiling at 25 cm/s, the dominant excitation frequency is expected to be 3.9 Hz perpendicular to the flow and tube. There is also a smaller double frequency excitation parallel to the flow that can excite lightly damped structures for a possible 8 Hz excitation.

A finite element model of the sensor structure was created and the lowest normal mode calculated was 34 Hz. As shown in Fig. 4. This model included entrained and added masses. Given the factor of 4 ¼ difference between the lowest sensor structure resonance frequency and the vortex shedding forcing, we conclude that the strumming resonance hypothesis does not explain the measured flow noise.

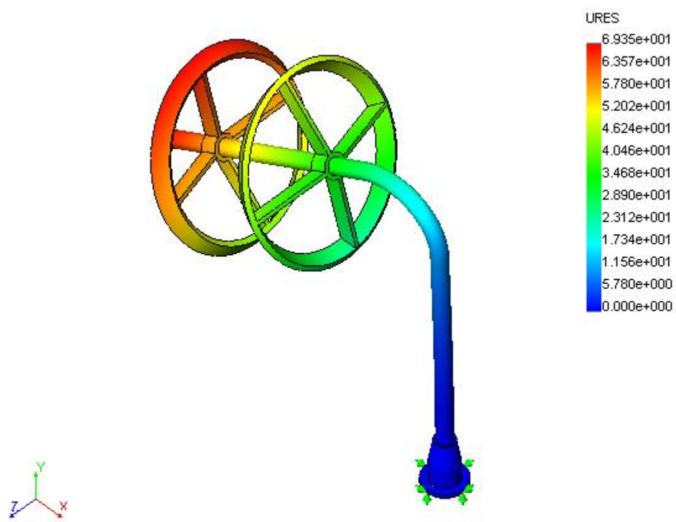

Fig. 4. Finite element vibration model of the sensor structure gave a lowest normal mode frequency of 34 Hz. The color shading indicates the amplitude of the resonant vibration.

B. *Hypothesis 2. Commutator Noise*

Electrical noise from the commutator was investigated as a cause of the velocity noise. During testing of the first ITPV in a tank, dropout of the ACM velocity was observed during the profiler's "soft start", Fig. 5. The profiler is driven by a brush DC motor through a magnetic coupling. The motor has a capacitor across its input leads to reduce noise from its brush commutation. To improve traction at the start of a profile and minimize drive wheel slipping on the cable, the motor is given a "soft start". The "soft start" slowly ramps up the speed of the motor by switching power to the motor rapidly with a fly-back diode and increasing the duty cycle until the profiler is up to speed. This switching causes significant electrical noise in the profiler as the switching was done from a circuit at the far end of the case, causing dropout in the MAVS sensor.

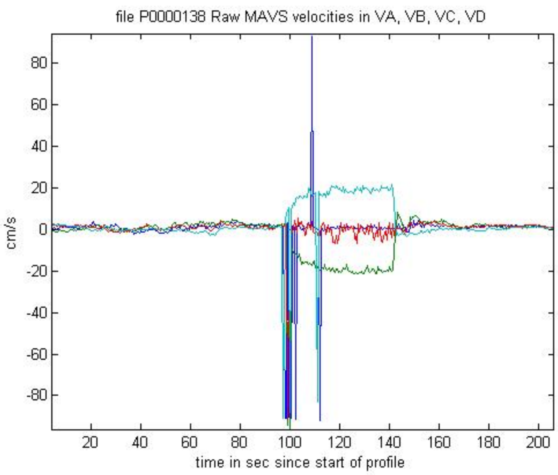

Fig. 5. An example is displayed of dropout in the measured path velocities during the switching "soft start" of the profiler. Shown are time series of the four MAVS velocity paths during a vertical profile in a test tank. The vehicle began to move around time 95 seconds and reached steady state profile speed around time 115 seconds. The vertical motion of the instrument ended around time 140 seconds, followed by a two minute sampling when the vehicle was stationary.

The MAVS measures the difference in arrival time of acoustic signals sent from the ends of each acoustic path. The MAVS measures the fourteenth zero crossing of a sine wave transmitted from each end as shown in Fig. 6. The Q of the acoustic transducer is about seven in water and the sine wave increases in size for several cycles. The fourteenth zero crossing is used since by this time the dv/dt of the signal is much larger than the zero crossings of the first one or two cycles and electronic Johnson noise present in the signal results in a smaller timing error. A dropout occurs if the first pulse is missed or if the circuit starts counting from a small precursor pulse. For the MAVS card used in the ITPV, it takes about a 50 millivolt noise pulse to cause the circuit to either start counting early or late. The result is a huge error in measured velocity and is called a dropout. Several shielding techniques were tried to reduce the dropout on "soft start".

By the fourteenth zero crossing, a 20 millivolt noise pulse on one side of the travel-time measuring circuit causes a 1 cm/s error in measured velocity. The second hypothesis is that noise from the brush commutation in the DC brush motor could cause noise on the order of 20 millivolts in the MAVS card. When we had a complete ITPV to test, with the sensor in still water, there was no measure-able increase in noise with the motor running (after the "soft start") with or without a load. Thus we reject commutator noise as cause of the excessive velocity noise.

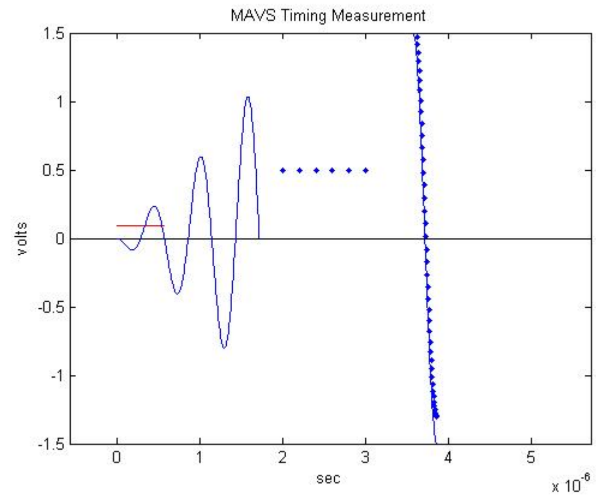

Fig. 6. MAVS measurement timing is shown. The time of the fourteenth zero crossing is used to reduce the effect of electrical noise. The red line is the Schmitt trigger threshold for detecting the first received cycle that starts the count. If the Schmitt trigger threshold is missed, or if the counter starts early from a noise spike, the resulting timing error is a whole cycle, termed dropout. The blue line on the left is a plot of the first three cycles received. The signal gets larger and the line on the right is the fourteenth cycle zero crossing. The dots are the same line with a DC voltage added. The steepness of the fourteenth zero crossing reduces the time error resulting from a noise voltage added to the signal voltage.

C. *Hypothesis 3. Cable Climbing and Slipping Down the Rollers*

Pulleys for belts to run on are crowned to keep the belts centered on the pulleys, Fig. 7. To effectively capture the mooring cable, the rollers on the ITPV and MMP are shaped in the opposite way. This shape can cause instability where the cable climbs up the side of the roller until the coefficient of friction no longer supports the surface shear stress and the cable jumps back down. If this occurs, the profiler will be repeatedly shaken when the profiler travels up and down the cable. Several empirical tests were performed to see whether this occurs. A 3/8 inch (0.95 cm) fiberglass rod was run on the ITPV pulleys with no climb and slip in evidence. In contrast, a 5/16 inch (0.79 cm) diameter magnesium rod was rolled on a single pulley and when rolled at a small angle did climb and jump back regularly. Observations of an ITP in the McLane tank did not show this climb and jump profiling on a wet polyethylene jacketed cable. While this behavior may happen occasionally on ITPVs and MMPs in the field, it does not explain the observed regular velocity noise.

D. Hypothesis 4. High frequency vibration from cable non-uniformity organizing the vortices from the profiler and sensor

Vibration of a bluff structure can increase the correlation lengths of the vortices shed by the structure [8]. Several sources of vibration exist. Every bluff body in a flow will have vortices shed at frequencies given by (1). In strong currents it is expected that the mooring cable will strum. Some of this strumming energy will be transmitted to the profiler through the rollers and drive wheel. Because this will only happen when the current is strong, the authors do not know how to unambiguously tease out this effect from the data.

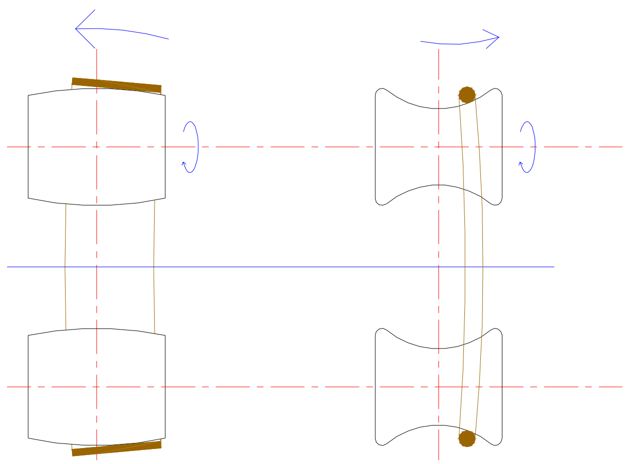

Fig. 7. Pulleys for belting are crowned to keep the belts centered on the pulleys. The shape of the ITPV guide rollers may cause the cable to climb out and then suddenly slide back shaking the profiler.

A source of vibration that exists when the mooring is in still water is vibration from the rollers and drive wheel rolling over imperfections in the mooring cable. The mooring cable is a 3 by 19 steel cable jacketed with polyethylene. The 3 by 19 structure has some print-through causing a 0.012 inch (0.3 mm) regular change in diameter. The inner steel cable has a full rotation in 2.6 inches (6.6 cm) with three bumps in that distance giving a 12 Hz vibration when a profiler travels the cable at 25 cm/s. This vibration of the cable is easily sensed in the McLane tank by touching the cable or from seeing the capillary waves created by the cable's vibration where the cable passes through the surface of the still water. A normal mode of the cable with a repeating length of ten feet (3.05 m) resonates at this frequency. A smooth 5/16 inch (0.79 cm) diameter stainless steel rod was made to form a smooth mooring cable and placed in the McLane tank to test this hypothesis. The vibration of the rod and profiler were measured and found to be significantly reduced, but the noise in the measured velocity was not measurably less. Thus we reject cable irregularities as a chief cause of the velocity noise.

E. Hypothesis 5. Vortex Wake of the Sensor Structure

When the wake of a bluff structure advects though a current sensing volume, a time varying signal will result as shown in Fig. 8. Acoustic travel-time current sensors measure an accurate line integral of water current along their acoustic paths, but the transducers and structure to hold the transducers change the flow being measured. The Reynolds number of the MAVS tube in cross-flow is about 2,100 putting it in the regime of a laminar boundary layer and organized vortex shedding. The magnitude of varying velocity measured in the wake of a bluff tube scales as

$$\Delta V \approx \frac{U*d}{L} \quad . \qquad (2)$$

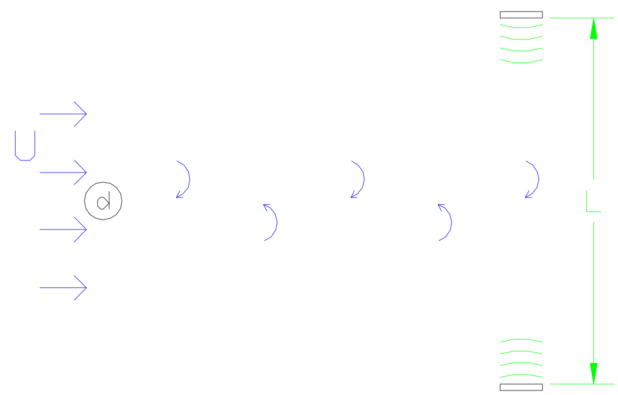

Fig. 8. A schematic of a vortex street in the wake of a bluff body advecting through the sensing volume of a travel-time current meter is shown.

This measured signal is real, but can be considered noise as it was not in the undisturbed flow. The ΔV is the varying measurement of the line integral of velocity along L, and is scaled by the product of the incident velocity U times the cylinder diameter d divided by L the length of the sensing volume. In the case of the MAVS sensor, the acoustic path in Figure 8 is 45 degrees out of the paper, but if the along-tube correlation lengths of the vortices shed by the tube are 2 or 3 diameters, the result is the same. There is a cos (45^o) over cos (45^o) multiplier resulting from the line integral measuring only cos (45^o) of the vortex velocity but over a path made longer by the inverse of cos (45^o). The expected frequency of the dominant shedding at 25 cm/s will be 3.94 Hz, a frequency aliased by the 2 Hz sampling. We conclude that eddy shedding from the transducer support structures is the principal source of noise in ITPV and MMP velocity measurements.

F. Discussion and confirmation

There are many tradeoffs in a design of a sensor for an acoustic travel-time current meter. If the diameters of the structure can be kept constant, increasing the acoustic path length will reduce this noise but increase the measurement volume. Many users of current meters want to measure turbulent transport in boundary layers. It is desirable to be able to measure a spectrum of the transport-containing eddies. Thus, if one wants to measure this transport one or two meters from a boundary, the measurement volume should not be larger than 10 or 20 cm. It is not possible to design an acoustic travel-time current sensor with no acoustic paths ever in the wake of the sensor itself with flow coming from any angle. The authors believe the slightly lower noise level of the FSI current meter on the MMP derives from its longer velocity path lengths.

In order to measure the flow measurement noise of the sensor itself, an ITPV and a MAVS were towed in the WHOI tow tank (Fig. 9). The MAVS, included in the testing to better compare with the original MAVS prototype tows, was programmed to sample at 16 Hz. There were some closed-loop oscillations in the speed control and carriage motion that were measured with a Gulf Coast Data Concepts model X6-2 three-axis accelerometer sampling at about 312 Hz, Fig. 10.

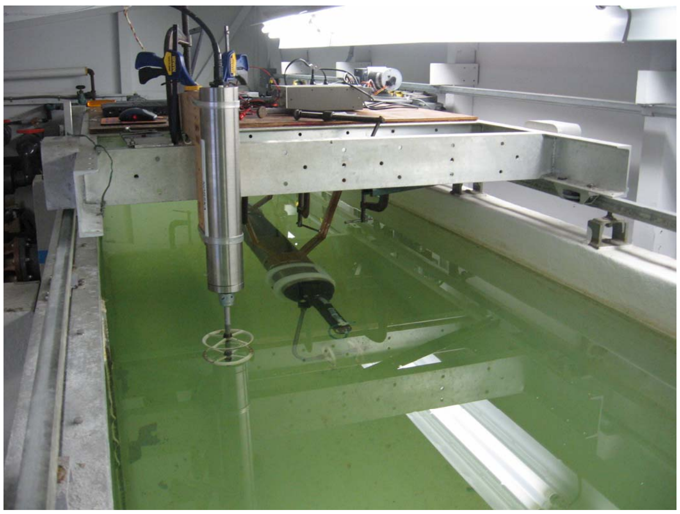

Fig. 9. ITPV and a MAVS are shown in the WHOI tow tank. The ITP is on the right and MAVS is on the left.

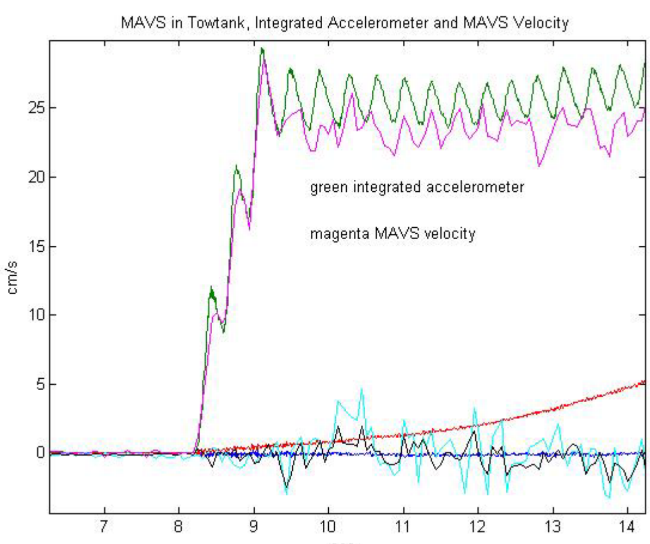

Fig. 10. Tow Tank velocity measured by a MAVS sampling at 16 Hz and deduced from time integration of data from a three-axis accelerometer is displayed. The along-carriage velocity estimates (green and magenta) show reasonable agreement. The blue, cyan, black, and red lines are velocities perpendicular to the carriage motion.

The carriage speed oscillation made sensitive measurements of current in the direction of the carriage motion impossible. However, the other two directions normal to carriage motion are useable. The measurement noise, in the directions normal to carriage motion, was still larger than the original MAVS prototype tows. In looking back at the previous laboratory records, it was seen that there were a set of BASS electronics on the shelf that had been programmed to sample fast and average down. The only way the first author could reproduce the original MAVS data was with over-sampling and averaging.

III. Solutions

Two solutions are proposed to ameliorate velocity noise in moored profiling instruments: over-sampling and averaging to average out the small vortices, and/or a new sensor design.

A. *Over-sampling and Averaging*

Over-sampling and averaging can be used to reduce the measurement noise of the ITPV and MMP. A sampling volume of diameter 10 cm can only spatially resolve a 20 cm diameter or larger eddy, Fig. 11. The small, order 2 cm, eddies from the sensor structure itself cannot be resolved by the 10 cm path length device. At a 25 cm/s profile speed in still water, the main tube wake should be shed at 3.9 Hz. and the 20 cm eddies to be resolved need to be sampled at 2.5 Hz. The 2 Hz sampling of the ITPV was a compromise to reduce the energy of transmitting data back to shore. The frequencies above 2.5 Hz are not resolved spatially so they are considered noise. The frequencies below 2.5 or 2 Hz should be retained. By sampling at 16 Hz or faster and averaging down to 2 or 2.5 Hz, much of the noise from the small shed vortices can be averaged out. For the MMP application, which does not telemeter data and with modern low-power flash memory, a much faster sampling rate can be accommodated, giving more flexibility in post processing.

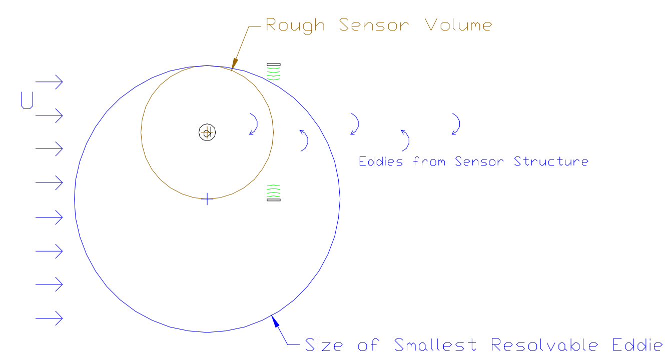

Fig. 11. The dominant eddies from the sensor structure are too small for the sensor to resolve. In this sketch, the small black circle can be thought of as the cross section of the sensor tube, the brown circle is a simplification of the sensing volume, and the blue circle is the size of the smallest eddy spatially resolvable with the sensing volume.

The tow-tank data were analyzed to quantify the benefits of over-sampling and averaging. The shed vortices that cause the measurement noise are not uncorrelated, Fig. 12. Because of the non-zero autocorrelation, the standard deviation of noise does not drop as one over the square root of the number of samples averaged. The 16 Hz velocity estimates normal to carriage motion were boxcar averaged to 2 Hz resulting in a reduction of the standard deviation of velocity from 5.2% of carriage velocity to 2.18% of carriage velocity. As a point of reference, 5.2% over the square root of eight is 1.84% so while the non-zero autocorrelation extends out quite far, the noise is significantly reduced by averaging.

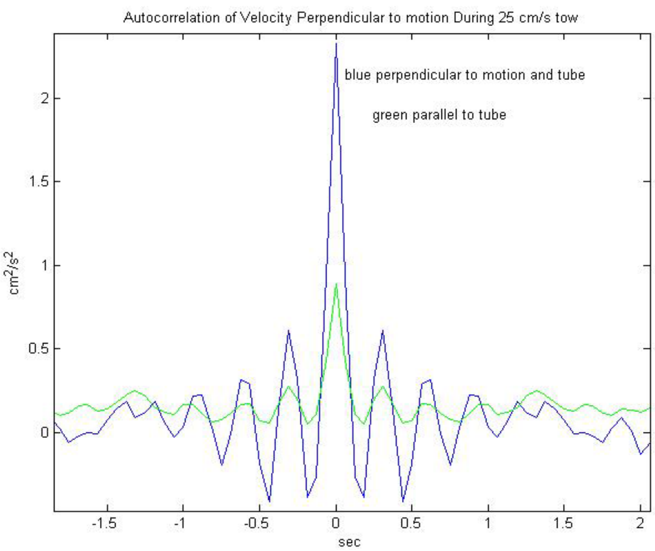

Fig. 12. The autocorrelation of 16 Hz velocity normal to carriage motion from tow-tank test is shown.

This same over-sample and average is shown in the time domain in Fig. 13, and in the frequency domain in Fig. 14. In the time domain graph, the green and blue lines are the 16 Hz samples temporally but not spatially resolving the vortex wake, and the red and cyan lines are the 2 Hz boxcar averages of the faster samples.

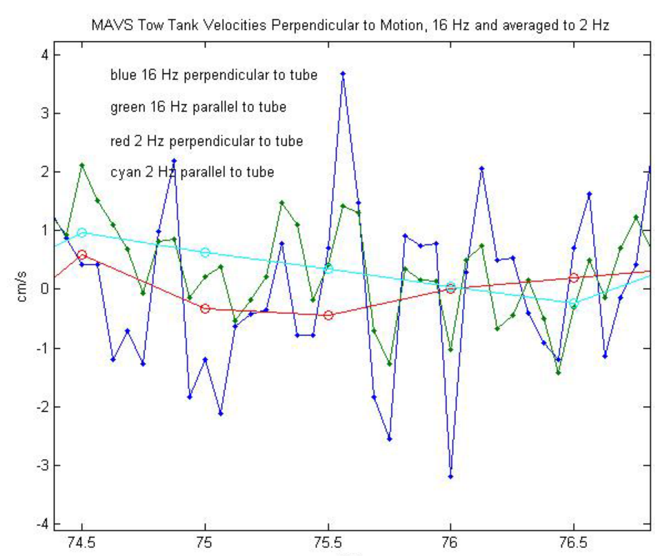

Fig. 13. Over-sampling and averaging in the time domain is demonstrated.

In the frequency domain the vortex wake frequencies above one Hertz (ideally 1.25 Hz.) should be averaged away and the energy below one Hertz (ideally 1.25 Hz.) should be kept.

B. Redesigned Sensor

A sensor optimized for profiling (as opposed to being equally sensitive to flow in all directions) would reduce noise in measured current. For an MMP that is not trying to sample near a boundary, the flow measurement would be less noisy if the acoustic path lengths were increased, to say 20 cm, while keeping the sensor structure diameters the same. For the ITPV and its need to fit down a small hole in the ice during deployment, a larger sensor is not appropriate. A sensor on a profiling vehicle that can turn into the current does not need to be free of disturbance from all angles of incident flow, only for headings of +/- 15° and elevations from +/- 90°, Fig. 15. With this geometry, no acoustic path will be downstream of a structural element from the angles encountered in profiling. There will still be some vortex shedding noise from the immediate vicinity of the transducer pods, which are bluff and will have their boundary layer separation points move about. But, this noise should be significantly less than a sensor designed to be reasonable from all angles. A custom ACM sensor was built for the Second Generation High Resolution Profiler and it measures a standard deviation of velocity through relatively quiescent seawater of 0.57 % of profiling speed [9]. Some of this 0.57% was signal and not noise.

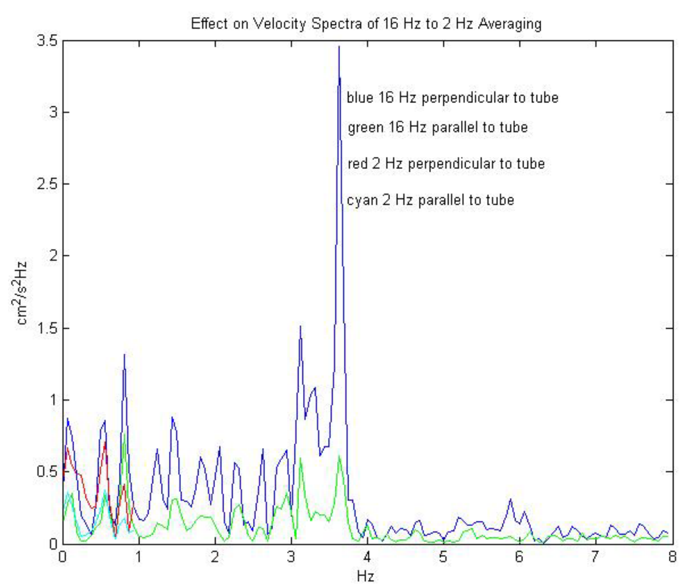

Fig. 14. Over-sampling and averaging in the frequency domain is illustrated in this figure. The blue and green lines are power spectra of the 16 Hz sampling and the cyan and red lines are spectra of the 2 Hz boxcar-averaged samples.

IV. Summary

Noise in velocity measurements from the ITPV was investigated by looking at five hypotheses: 1) strumming resonance of the sensor structure, 2) commutator noise, 3) cable instabilities in running over the ITPV sheaves, 4) vibration from cable non-uniformities organizing the vortices shed by the sensor, and 5) the vortex wake of the sensor structure. The last hypothesis was found to be the dominant source of measurement noise. Two solutions are proposed; over-sampling and averaging, and/or a sensor design optimized for profiling.

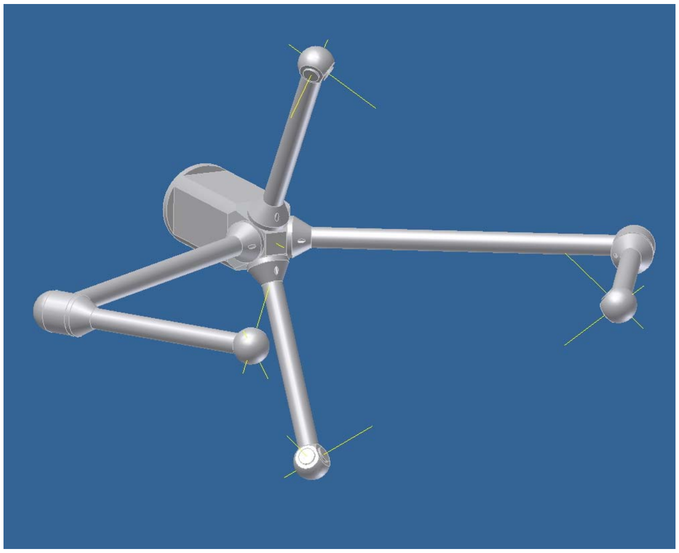

Fig. 15. Concept of an acoustic travel time sensor that is optimized for a profiler that orients into the incident horizontal flow is shown.

ACKNOWLEDGMENT

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