MODULAR ACOUSTIC VELOCITY SENSOR:
A GENERAL-PURPOSE FLOW METER

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ABSTRACT

This paper evaluates the accuracy of a new acoustic current meter. The instrument under development (MAVS), or Modular Acoustic Velocity Sensor, will be based on BASS (Benthic Acoustic Stress Sensor), taking advantage of developments in electronics, transducers, and manufacturing.

The MAVS is intended to be an extremely accurate, general-purpose current meter with the capability to measure acoustic sound speed as well as flow speed. It will be ideally suited to low velocity flow such as experienced by an AUV or ROV, or to studies of oceanic turbulence and mixing. It will be very inexpensive for the user, and it will be designed as a component in a measuring system, rather than as a stand-alone current meter. Description of the system components will be the subject of a separate paper.

The sources of error addressed in this paper include flow disturbance from potential flow around the sensor cage, wake effects from support structure and transducers, vortex shedding from the cage, and electronic zero-point offsets. The electronic error dominates at velocities less than 5-10 cm/s, while flow disturbance dominates at higher speeds. The estimated RMS error of the MAVS will be on the order of 3.7% of the mean flow, with a low velocity error floor of 0.1 cm/s. The accuracy estimate is based on calibrations and experience with the BASS instrument.

INTRODUCTION

The majority of oceanographic measurements are made using custom instrument packages. As a result, sensors are expensive, and require an experienced engineer to deploy them. A standard current meter which can measure both low-velocity mean current in a moored application, and turbulent fluctuations in other applications would allow scientists to have an off-the-shelf general-purpose flow sensor. Add to this the almost free bonus of acoustic speed of sound measurement, and the sensor becomes extremely attractive. If the sensor were modular, it could be plugged into a variety of measurement systems. We are presently designing and testing a prototype MAVS (Modular Acoustic Velocity Sensor) which will incorporate these features. A pictorial sketch of the MAVS is shown in figure 1. This paper will discuss the accuracy of an acoustic sensor for flow, with specific application to MAVS.

MAVS must be inherently calibrated, able to endure ocean pressures, impervious to marine fouling, resistant to corrosion, and manufactured in large numbers with as little hand assembly as possible. The acoustic measurement technique is a logical choice since calibration depends on transducer positioning and electronic component stability, both easily maintained to 1%. Piezo-ceramic transducers are easily mounted on a substrate, and much of the sensor electronics can be adapted to surface mount and VLSI technology. Measurement of velocity by acoustic travel-time requires no moving parts, so failure due to fouling and corrosion are drastically reduced, if not eliminated entirely.

The velocity sensor in MAVS consists of eight high frequency acoustic transducers. They are arranged in four pairs. Each pair of transducers face each other and form one axis along which we wish to measure a component of velocity. Only three axes are needed for a vector measurement, but four are used for redundancy. When a measure of velocity is requested, both transducers of a pair ping at the same time, then both listen. When one return is detected, an electric current source is steered to an integrating capacitor. When the second return is detected, another current source is steered to a different capacitor. After a set interval, the voltage across both capacitors is compared. This voltage difference is proportional to the difference in travel time between two directions of propagation along an acoustic path. Differential travel-time is proportional to the component of fluid velocity along the path. Four such measurements allow a vector velocity to be constructed. The basic relations for acoustic travel-time measurement of velocity are presented in figure 2.

The salient aspects presented in figure 2 are: 1) The difference between the acoustic travel-time in opposite directions between two transducers is **linearly** proportional to the flow velocity. The error in this approximation is on the order of $1/c^4$. 2) The absolute travel-time between the same two transducers is proportional to the inverse of the speed of sound. Thus, by measuring the acoustic travel-time in two directions, we get two independent parameters for calculating flow speed and acoustic speed. These are obtained from the exact same sound pulses in the water, so the traditional sampling problem of velocity and temperature lacking correlation is avoided, and we can use the V and C estimates to calculate a function proportional to convective heat flux, or simply use the C estimate to give a better prediction of velocity if the heat flux is not desired.

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Measurement of travel times to a precision of 40 pico-seconds is practical in a direct time-measurement system [1] and that phase-measurement techniques also exist which may be comparable . Flow disturbances created by struts and supports which position the acoustic transducers exceed other sources of error for velocities greater than 5cm/s. We will address the issues of flow disturbance, and strategy for reducing its effect in the next section. This will be followed by discussion of other error sources, a description of the prototype MAVS, and finally an evaluation of the ultimate accuracy expected from the MAVS sensor.

FLOW DISTURBANCE

When considering a new flow sensor, we first list where the main sources of error are likely to be found. Using a moored application as an example, the mooring cable has the potential to destroy the measurement from an otherwise accurate current meter. The cable may shed vortices in its wake, strum, or move the sensor around in such a way as to obscure the desired measurement. Two problems are apparent in a moored application; avoidance or minimization of the cable wake; and minimization of self-induced wake from a sensor head which is moving through the water in an oscillatory manner. Other flow disturbances, such as the wake from the electronics housing must be kept out of the measurement volume. We will address the flow disturbance from MAVS itself, and leave the topic of support structure flow disturbance for future papers.

There are three sources for self-induced flow disturbance: 1) Potential flow effects 2) Wake effects 3) Strumming. Each of these will be addressed in turn.

Potential Flow Effects

An object introduced into a flow will perturb that flow in proportion to its size. The precise shape of the object may reduce the effect, but it cannot be eliminated. Figure 3 shows the streamlines around the cross-section of a right circular cylinder. The velocity at any point in the flow is given by:

$$U_r=U(1-a^2/r^2)\cos\vartheta$$

$$U_\vartheta=-U(1+a^2/r^2)\sin\vartheta$$

The magnitude of velocity will be:

$$U_m=U(1-2a^2/r^2\cos2\vartheta+a^4/r^4)^{1/2}$$

In order for the velocity magnitude error to be less than 1%, we must look at least 10 diameters away from the center of a cylinder. [2] reviewed the flow disturbance around a circular cylinder, but we chose to use a simpler approach in the design of MAVS. Given the approximate nature of the calculations, our approach is appropriate.

Since acoustic measurement of velocity is an integrated measurement of the flow speed along an acoustic path, the portion of that path within ten diameters of a strut will be strongly influenced by the object. Using the typical case of 15 cm acoustic paths, and a 1cm diameter object, we could expect to influence 67% of the measurement path by potential flow disturbance from a single strut. This will occur even at low velocities, neglecting turbulence or wake effects.

Wake Effects

The self-induced wake from cylinders supporting transducers has been studied by other investigators. As a rough guide, it has been found that the measurement error scales with the ratio of acoustic path length to strut diameter. The strut produces a shadow zone in which the velocity is less than that in the surrounding flow. The zone occupies a region roughly as shown in figure 4. Equations for the velocity in the wake are also presented in the figure. The restrictions on this equation are that the velocity defect in the wake be small compared to the free-stream velocity, and that it only be applied in the far field downstream where pressure fluctuations due to the body are negligible (100 diameters according to [3]).

Keeping these restrictions in mind, we can use the relation to indicate that the velocity defect is linearly proportional to strut diameter, and the width of the shadow zone is independent of diameter. If we consider a 1cm diameter strut, the distance downstream where the velocity defect will recover to 10% of the free-stream value is more than 125cm. A 3mm diameter strut will recover to 10% of free-stream in only 37cm. The two options we have for reducing wake effects on flow measurement are to use small diameter struts, and to keep the wake away from acoustic axes as much as possible.

One technique for reducing the amount of error due to wake defect is to make the acoustic path length much longer than the

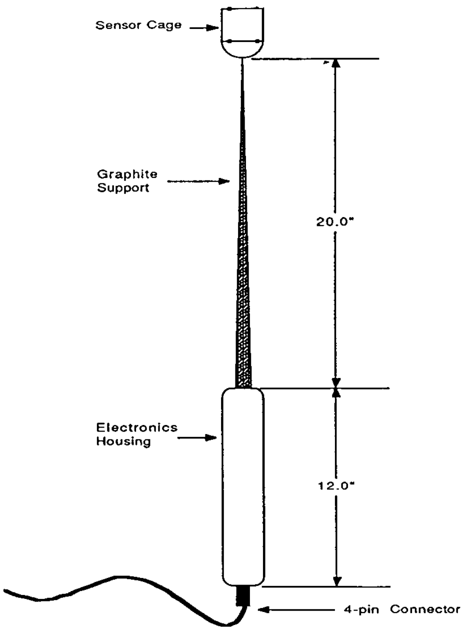
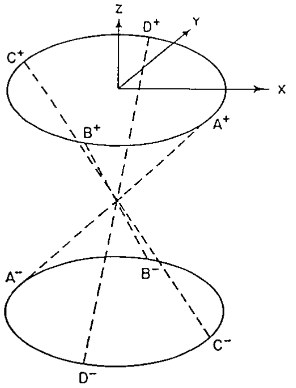


Figure 1: MAVS General Configuration



$R = path\ length$

$c = speed\ of\ sound$

$u = flow\ speed$

$TT = acoustic\ travel - time$

$$(TT)_{12} = \int_{A^-}^{A^+} \frac{dr}{c(T,r) + u(r)} \approx \frac{R}{c} - \frac{uR}{c^2} + o(\frac{u^2R}{c^3})$$

$$(TT)_{21} = \int_{A^+}^{A^-} \frac{dr}{c(T,r) - u(r)} \approx \frac{R}{c} + \frac{uR}{c^2} + o(\frac{u^2R}{c^3})$$

$$(TT)_{12} + (TT)_{21} \approx \frac{2R}{c} + o(\frac{u^2R}{c^3})$$

$$(TT)_{21} - (TT)_{12} \approx \frac{2uR}{c^2} + o(\frac{u^3R}{c^4})$$

$$where\ u(r) \ll c(T,r)$$

Figure 2: Acoustic Velocity Measurement

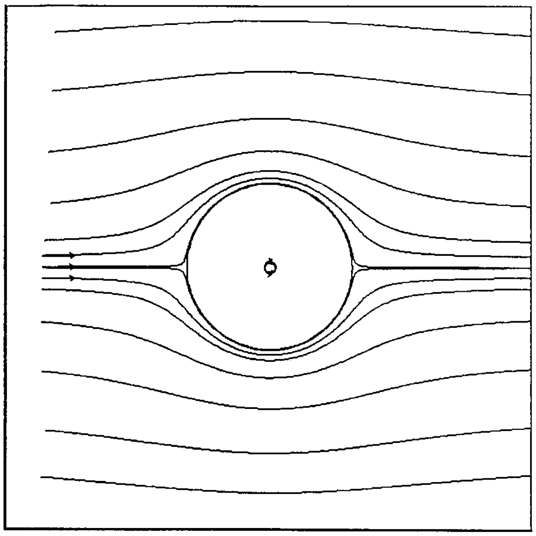
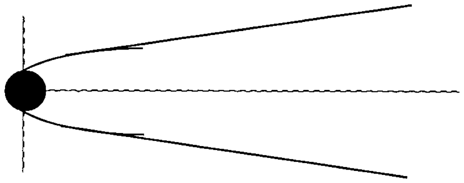


Figure 3: Potential Flow Around a Cylinder



$$\delta = 1.675 \left(\frac{\nu_T x}{U}\right)^{1/2}$$

$$\frac{U_1}{U} = 0.141 C_D a \left(\frac{U}{\nu_T x}\right)^{1/2}$$

Figure 4: Shadow Effect of a Cylinder Wake

scale of strut diameter. An L/D ratio on the order of 50 is a reasonable design goal. For such slender struts, the wake would only influence 2-10% of a measurement path intersected at an angle as shown in figure 10. The Williams' Benthic Acoustic Stress Sensor (BASS) cage minimizes the intersection of strut wake with acoustic paths [4]. Despite an L/D ratio of 15 based on transducer diameter and path length for BASS, calibrations show that the BASS cage achieves better than 5% accuracy over all flow directions (figure 5).

There are other configurations which may or may not be superior to BASS. We plan to test several in the development of MAVS to determine the advantages and disadvantages of each. BASS will be used as a standard of comparison, since it has undergone extensive tow-tank and flume tests. It is accessible, and simple to setup in a tow-tank with equipment we have on hand.

Vortex Shedding Effects

Figure 6 shows frequency components from BASS records of tow-tank runs at six sets of velocities. The data is a sample of more than 300 separate tows conducted in a calibration facility at the Canada Centre for Inland Waters in Burlington, Ontario. The first spectra shows fluctuations in recorded velocity at a tow speed of 1 cm/s. The spectra is extremely flat out to the Nyquist frequency of 2.5 Hz. The peak observed at .1 Hz is evident in all tow data at all speeds and is the result of the sampling and windowing used. On each spectrum, the four spearate curves represent four acoustic axes in a single BASS pod. At 2 cm/s a spectral peak appears centered on 0.5 Hz. In the subsequent spectra, this peak is seen to move higher in frequency until it is beyond the cut-off frequency, and begins to alias the data, eventually raising the apparent noise floor. Figure 7 shows the mean energy of each spectra plotted against tow speed. This plot an be interpretted as the energy present in frequencies higher than DC for each tow speed. The second plot in figure 7 shows the variability in the spectra as a function of speed. This indicates that the non-DC components of the flow measurement get more complicated as speed goes up. It is worth remembering that a perfect velocity sensor would see only DC for all of these tow-tank runs. Vibration of the carriage and tank are not a concern due to the large masses involved driving their resonant frequencies very low..

When the strumming frequencies are calculated using [5]:

$$f_s=0.2U/D$$

The resulting shedding frequency from a 1cm diameter object corresponds exactly with the observed peaks up to 10cm/s , which is the point where the sampling rate was no longer sufficient to resolve the phenomena. The BASS sensor cage contains 1cm diameter acoustic transducers which are cased in polyurethane. It is from these objects that the shedding most likely occurred (figure 8).

The solutions to velocity errors due to strumming are to reduce the strut size, and to modify the cross-section taking advantage of separation locking-points and elimination of length correlation [6]. Strut size must be chosen carefully to avoid structural resonances in the frequency bands of interest. This may be a very restrictive condition, forcing an extremely stiff structure with resonances higher than perhaps a few hundred Hertz. Particular sensor cage designs will be discussed in a later section.

NON-HYDRODYNAMIC SOURCES OF ERROR

Other error sources can be the result of electronic effects in the measurement technique, sampling errors due to the sensor geometry, and errors in referencing the velocity data to earth coordinates using a compass and tilt-meters.

Zero Offset

At low velocity, the zero offset of the electronics dominates error. In BASS, errors in velocity prediction at tow-speeds of 1cm/s are on the order of 10%, due entirely to the uncertainty in zero velocity offset. This comes about because of small differences in the electrical properties of the signal path between one direction versus the other. In BASS, this error may be due to the fact that the sensor cages are separated from signal generation and reception electronics through 18 feet of coaxial cable which is constantly being flexed and stretched. This mechanical deformation changes the capacitance of the cables enough to skew the zero measurement by up to .3 cm/s.Transducers themselves may also change the zero offset through aging, and moisture absoption [1]. The effects can be reduced in BASS by careful *in situ* zero calibration. In MAVS, the electronics will be much closer to the transducers, so the relative capacitance of the conductors between sensor and electronics will only be a minor part of the circuit. In addition, the conductors will be fixed in a rigid support, and will not be subjected to flexing and stretching. Thus, the zero offset of MAVS is expected to be substantially better than .3cm/s.

It has been suggested that phase-measurement techniques rather than time-measurement techniques do not suffer from this zero offset . Comparison testing will be done in the course of the MAVS development to determine if this is so.

Spatial Sampling Error

The volume of fluid which is sampled by an acoustic current meter such as MAVS resembles an intersecting group of cylinders with the long dimension of each cylinder equal to the path length, and the diameter equal to the transducer diameter. Thus, there are at least two length scales important in any discussion of spatial sampling. A mechanical flowmeter averages over a large area, benefiting from inertial effects to minimize aliasing due to high frequency fluctuations. An acoustic current meter is a truly discrete sampling device where each measurement is independent of the previous one, thus temporal and spatial sampling issues are more critical. In effect, the

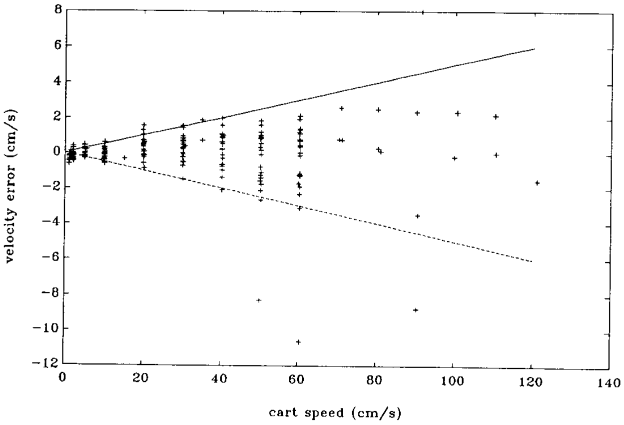


Figure 5: BASS Tow-Tank Accuracy

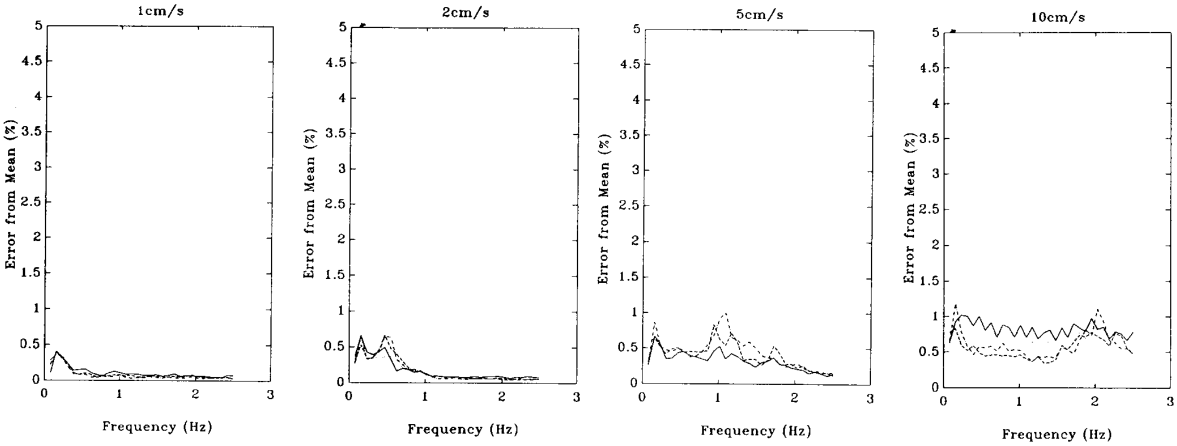


Figure 6: Frequency Components of Velocity Measurements from Tow Data

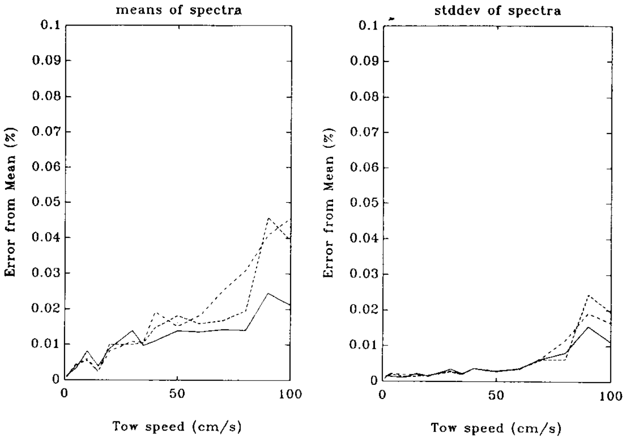


Figure 7: Mean Energy and Variability in Frequency Estimates

resolvable eddy scale based on acoustic path-length is on the order of 30 cm, while the scale based on cross dimension is substantially smaller. This may contribute to the overall instrument noise floor. Since the noise floor observed in BASS is already extremely low (less than 1% of mean flow from figure 7, assuming this source of noise is the part which is independent from tow-speed, and the strumming contributes all of the dependent part), the sampling volume errors are not expected to be a major concern in MAVS.

The path length of MAVS will have a large impact on the resolvable eddy scales . For greater velocity sensitivity, we tend to demand longer paths. Greater spatial and temporal resolution of small eddies demand shorter paths. The minimum resolvable travel-time difference in BASS is 40 pico-seconds. Using the relation :

$$\Delta t=\frac{2UL}{c^2}$$

path lengths on the order of 15cm give velocity sensitivity of 0.3mm/s.

Spatial resolution is governed by:

$$U=2Lf_s$$

Where f_s is the sampling frequency required to avoid aliasing, and U is the mean flow velocity. For mean flow on the order of 100 cm/s, the sampling frequency required for a 10 cm path sensor is 5 Hz, while for a 5 cm path sensor it is 10Hz. This only takes into acount scales based on the acoustic path length. There are two length scales of importance in an acoustic current meter; the path length ; and the beam diameter. To avoid aliasing from eddies the size of the transducer diameter (in effect , the cross-beam dimension) then we must sample significantly faster. For applications where the noise floor mentioned above is low enough, this will not be an issue. For measurements of turbulent properties [7], this may be an important effect.

The desire for good spatial resolution drives design toward smaller size, as does ease of handling and ruggedness. Reducing flow disturbance due to relative strut size drives the design to larger path lengths. The MAVS development will determine a sensor size which can accommodate users interested in both mean flow measurement, and in small-scale or high velocity fluctuations.

Compass and Tilt-sensor errors

Current measurements must be referenced to earth coordinates to be useful. This is done using a compass and tilt-sensors. Typical compasses have minimum errors on the order of 1-3 degrees. The performance is degraded if the compass platform is subjected to motions, so gimballing has traditionally been important. This has led to mechanically complex and expensive compasses. A new compass is being developed in parallel with the MAVS program by Neil Brown which will be less expensive, more accurate, and will consume less power than currently available hardware.

This aspect of the MAVS development is extremely important since it has been seen from data recorded using BASS on a floating platform that compass errors are a large fraction of the total measurement uncertainty [8].

MAVS SENSOR CONFIGURATION

The error sources discussed above have been considered in the preliminary design of a sensor head for MAVS. The design includes construction of a new support cage, new transducers, new instrument housing and mounting, and redesigned electronics. The development and testing of this sensor will be the subject of a doctoral thesis in engineering. We will outline some of the crucial aspects of the MAVS preliminary design.

Transducers

The operating frequency for the acoustic transducers (1.75 MHz) has been chosen based on attenuation range, noise levels, and beam pattern. This is the same as used in BASS, so for initial prototypes we can test sensor cages using existing electronics.

The 1cm diameter piezo-ceramic transducers in BASS gave sufficient signal to noise ratio that we could reduce the transducer size. This will provide several advantages including low flow disturbance due to the transducers, a wider beam pattern allowing greater alignment tolerance, and a simple mounting configuration. In the prototype MAVS, we will use 3mm diameter piezo-ceramic disks which vibrate in the thickness mode. Tests will be done with impedance matching layers to optimize the acoustic coupling between ceramic and water. Alternate acoustic paths, such as the path through the cage structure will be investigated to minimize confounding effects on signal detection. Such paths were not a problem in BASS.

Cage Design

The tow-tank data from the BASS sensor cage have given us an initial guide in the design of the MAVS sensor head. It was clear from the data discussed in a preceding section that the main error source at low speed was zero offset, and at high speed it was

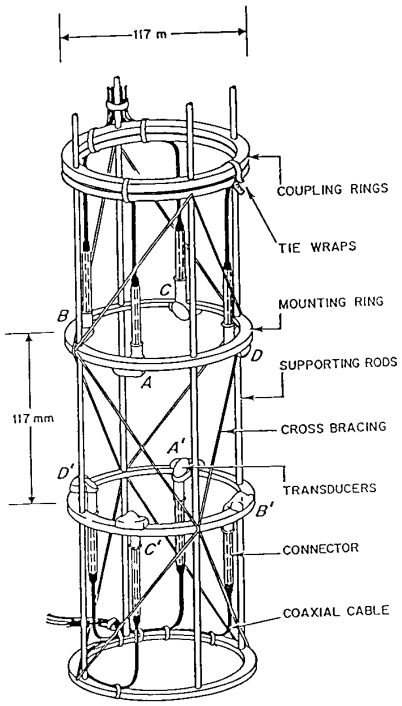


Figure 8: BASS Sensor Cage Configuration

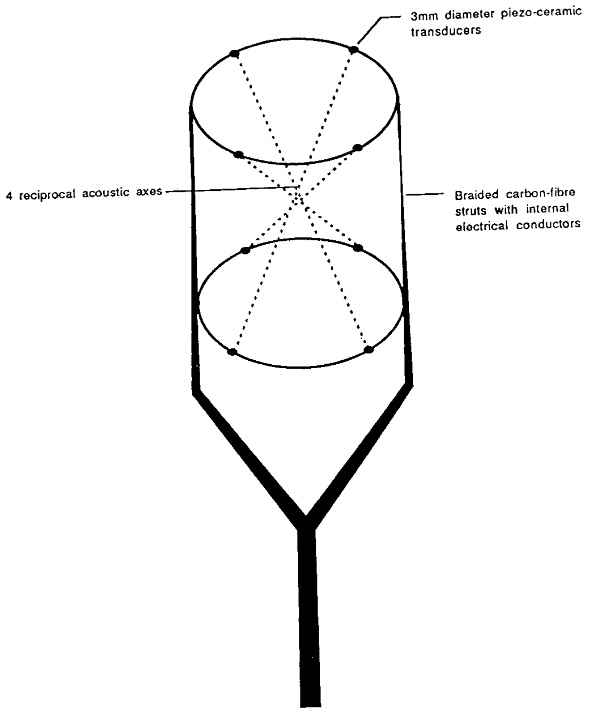


Figure 9: Prototype of the MAVS Sensor Cage

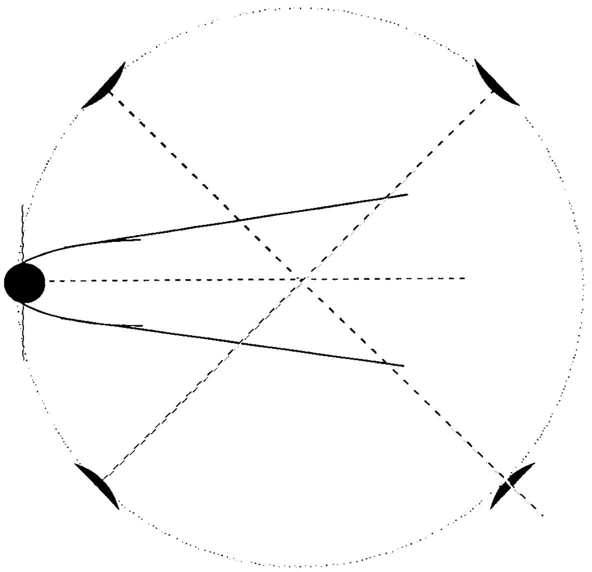


Figure 10: Wake Interaction with Acoustic Measurements

strumming flow disturbance.

We have attempted to minimize the zero offset error by incorporating two features in the new sensor: 1) the cables between electronics and transducers will be shorter than 1meter; 2) the cables will be housed in a rigid strut. The former will reduce the impact of the cables on measurements since the equivalent circuit of the transmitting and receiving system will not be dominated by the cable capacitance, as it is with BASS [1]. Likewise, the transmitted waveform will not be distorted before reaching the transducer. The latter design feature will prevent the cables from being flexed, and having their already lowered capacitance changed by mechanical action. It has been observed in BASS that cable flexing can change the zero calibration by a significant fraction of the total.

In addition to the above measures, the MAVS cage is being designed to allow simple and repeatable zero calibration by placing the sensor head in as small a container as possible to limit the large scale fluid motion while performing a calibration.

Flow disturbance at higher speed is a more complex problem than zero offset. A compromise must be struck between competing demands on strut diameter and structural stiffness. To lower the impact of both strumming and wake velocity defects, we want to use very small diameter struts. To prevent low frequency structural modes from being excited, we want to use large diameter struts having high stiffness.

One option involves the use of carbon fibre struts molded into a cage structure. 3mm diameter struts have been tested with magnet-wire core conductors which will be connected to the transducers. The carbon fibre has the advantage of high stiffness, low weight, ease of fabrication using molding procedures, plus the option to tailor the thermal expansion coefficient by adding other types of fibres to the matrix. It may be possible to manufacture a composite strut with nearly zero thermal expansion. Tests of this technology will be conducted in the near future. A sketch of the prototype sensor cage is shown in figure 9.

Additional design considerations for the sensor are for ease of manufacture, ruggedness, and resistance to fouling. The ruggedness of MAVS will be determined both by the scantlings of the sensor cage, and by its mounting. A semi-rigid mounting may be practical which will keep the cage fixed under normal use, but if the cage were slammed hard, its support strut would bend to absorb impact energy.

The sensor cage will be only minimally effected by marine fouling if the surface area of the support struts is kept small. By minimizing the surface area, two effects will be seen; organisms will have only small area for colonization; and the strut which has a clean diameter less than 1/50 of the sensor path length will have to be thickened a great deal by marine growth in order to seriously impact flow measurement. Transducers themselves are impervious to marine growth. BASS has been tested in very soft bottom sediments where the measurement, although effectively zero, was still made with few signal dropouts.

The cage geometry has been addressed by numerous authors (reviewed by [9]). There is no clear consensus as to which best combines structural stiffness, low flow disturbance, and manufacturability. We will be building prototype cages in several of the standard geometries for comparative testing in this development. Some of the geometries to be considered in addition to the BASS-like one shown already are presented in figure 9.

Many support cages used in previous instruments had mooring stress carried through the sensor cage itself. This had an impact on the cage design. In MAVS, we are designing a cage which will not carry any foreign loads, which makes it possible to use very small diameter structural elements, as well as optimizing the geometry for the single purpose of minimum flow disturbance.

CONCLUSION : AN ERROR BUDGET FOR MAVS

The discussion above regarding first the sources of error in an acoustic current meter, and the subsequent section on design of the MAVS leads us to estimate the magnitudes of error in MAVS. There have been two types of errors mentioned so far: those which scale with mean velocity, and those which are constant in magnitude regardless of flow speed. First, we will address the latter.

In BASS, there is a zero offset which was due to both the cable capacitance, and transducer electrical properties. This offset was observed to change up to 0.3 cm/s between experiments [10]. The drift is thought to be due to mechanical changes in the cables, aging and moisture absorption of the transducers. Recent calibrations done by Santala show an average change of .11 cm/s from *in situ* zeros between two deployments spaced three months apart. The two calibrations were made too close together for transducer aging to have been a factor. Thus, the cable capacitance fluctuations, and transducer aging are considered to have roughly equal impact on zero drift.

Using the equivalent circuit model proposed by [1]), we can estimate the offset sensitivity of MAVS relative to BASS. The crucial point in the above reference was that the source and load impedance should be much less than the transducer and cable impedance. Using estimated circuit values for MAVS, it was calculated that MAVS will be half as sensitive to capacitance changes in the cables and transducer as BASS. This can be simplified to the conclusion that MAVS will have a zero offset drift on the order of 0.05 to 0.15 cm/s. If we recognize that the MAVS will not allow flexing of the connections between electronics and transducers, this drift will be reduced by approximately half, assuming that half the error is caused by transducer aging, and half by mechanical stresses on the cables. The capacitance changes in the cable will be effectively eliminated by preventing them from flexing. The error due to offset drift will thus be on the order of 0.03-0.07 cm/s.

The second non-velocity dependent error is due to time resolution in the detection electronics. If we assume that MAVS will do no better than BASS in this regard, we can state with confidence that this error will be on the order of 0.03 cm/s, given a time resolution of 40 ps.

All other major sources of error scale with the mean flow velocity. One error present in any acoustic current meter arises from unmeasured changes in the speed of sound. Since the speed of sound is used to convert time difference to velocity as shown in a previous section, and the velocity is proportional to c^2, errors in c are significant. If the true and assumed speed of sound differ by 4 m/s (equivalent to a 1°C change in temperature), the calculated velocity will be in error by 0.6 %. By measuring the speed of sound, we can minimize the effect of this source of error. The accuracy to which the speed of sound can be measured is unclear at this time, but it is reasonable to expect it will be better than 1°C (corresponding to a time accuracy of 300 nanoseconds over a 15cm path).

It was shown that the potential flow disturbance from an infinite cylinder reduces to 1% beyond 10 diameters away. If we assume that MAVS will use 3mm diameter struts, and the acoustic axes will be 15cm long, we can estimate that 30mm of the acoustic path will be effected. If the integrated velocity along that 30mm is different from the mean flow by 10%, we can conclude that the error will be:

$$U' = (15U-(12U+3(0.9U)))/15$$

$$U'/U=2.0\%$$

This crude estimate assumes that the potential flow from a single strut interferes with an acoustic axis. All axes actually are influenced by at least two struts, however one will be upstream and one downstream. The downstream one will influence the measurement axis through potential flow. The upstream one will influence it through wake effects, since potential flow solutions are not valid in a wake of a cylinder in real flow.

Wake effects can be estimated in a similar way as potential flow. The difficulty lies in the condition on wake similarity solutions that they are only valid far downstream. The sensor volume for MAVS includes only the near-field wake. Since the analytical solution quoted in [3] is not valid, we must make a broad assumption regarding the wake velocity defect. Tochko [4] gives velocity defect measured by a single BASS axis as 20% of the free-stream.

Since MAVS, like BASS will have a redundant axis to allow the user to throw out any which is seeing only the wake of an upstream strut, it can be asserted that the condition where all of a measured axis is obscured is irrelevant. We assume the maximum fraction of a path which will be obscured is 10 diameters. This comes from estimating the spreading effect of a 20 degree wake which intersects an acoustic axis 25 diameters downstream. Because the L/D ratio of MAVS will be 50, as opposed to 15-20 for BASS (depending on which structural element is used in the calculation), the wake velocity defect for MAVS is assumed to be 15%, rather than 20%. The velocity error from such a situation will be on the order of:

$$U'' = (15U-(12U+3(.85U)))/15$$

$$U''/U=3.0\%$$

The situation above corresponds to the wake sketch of figure 10.

Strumming errors will not have a major impact on the mean flow error, but it will have an effect on the noise level measurements. Thus we can use strumming estimates to predict the variance in velocity measurement. The spectral plots presented in figures 6-7 show that the strumming noise level in BASS is on the order of 1-4% of the mean flow. The MAVS sensor cage will have only one principle strut dimension, nominally chosen as 3mm. Thus, the shedding will be constrained to distinct harmonics of a very narrow-band process which will move in frequency with change in velocity. As a result, the aliasing error will be reduced since fewer high frequency components will be folded into the sample window. If we implement a strum-preventing structure similar to the SAIC Quiet Cable [6], this source of measurement noise may be reduced by an indeterminate amount. Tests will be required to evaluate the utility of this added complication.

In summary, the MAVS will be subject to the errors listed above, the RMS sum of which give us an overall error for the sensor on the order of 3.7%. This neglects errors from the compass, since no technology has yet been chosen for this component.

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