ACOUSTIC DOPPLER VELOCIMETER EVALUATION IN STRATIFIED TOWING TANK

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ABSTRACT: The performance of an acoustic Doppler velocimeter (ADV) was evaluated using a towing tank. Rudimentary tests of the speed response were followed by tests of yaw and pitch response. Because only a few published (and inconsistent) values of sound speed as a function of saltwater concentration were found, a simple scheme was devised using the boundary-detection feature of the ADV to obtain such values. Tests were also run in the stratified tank to verify the usability of the ADV there. The accuracy of the probe to horizontal flow fields is generally within the range of ±0.25% ± 0.25 cm/s, and the yaw response is very nearly sinusoidal. Limited pitch-response tests suggested an indicated overspeed of some 5–10% for horizontal velocities and an indicated underspeed of 5–15% for vertical velocities. A correction scheme was developed to allow the ADV to be used in high-concentration saltwater, and its suitability was verified in homogeneous saltwater solutions. When the same scheme was used in a strongly stratified tank, however, a small overcorrection was indicated. Tests on a new probe design suggested much improved pitch response.

INTRODUCTION

The acoustic Doppler velocimeter (ADV) was developed to measure three-dimensional velocity components in laboratory and field situations, but it has undergone only limited testing of its performance (Kraus et al. 1994; Bowles et al. 1997). Its use in a stratified tank where the density of the saltwater may vary significantly over the transmit/receive path of the probe has not been assessed. The present evaluation began with rudimentary testing of the speed response over its specified range in freshwater. This was followed by tests of yaw and pitch response, as no published results of such tests could be found. Also, because only a few published (and inconsistent) values of sound speed as a function of saltwater concentration were found, a simple scheme was devised using the boundary-detection feature of the ADV to obtain such values. Subsequently, tests were run in the stratified tank to verify the usability of the ADV there. Finally, the prototype of a new probe design was evaluated, primarily with respect to its pitch-response characteristics.

DESCRIPTION OF EXPERIMENTS

ADV Instrument

The unit evaluated contained a 5-cm, downward-looking, three-dimensional probe as sketched in Fig. 1. It was a standard system (supplied by Nortek, although virtually identical units are available from Sontek) except that the probe was attached to the conditioning module through a 1.5-m flexible cable (in the standard package, this linkage is rigid). The stem length of the probe was 17.5 cm, including a 10-cm-long rubberized handgrip. A sacrificial zinc anode (for corrosion protection), 2.3 cm in diameter and 3 cm long, was attached to the stem as close as possible to the handgrip. The unit was dubbed a "field system" by the manufacturer, primarily because the electronic processing module is packaged as a self-contained unit rather than as a PC board (as in the "lab system"). The processor output was RS-422–compatible, and the software used for the data acquisition was version ADF 2.6 (Nortek). Much of the signal processing was done with very convenient freeware (WinADV, ver. 1.034) obtained through the Internet. Note that we use the same coordinate system and notation as does the manufacturer (V_x, V_y, and V_z) to denote the longitudinal, cross-stream, and vertical components, respectively.

The operator must choose one of five software-selectable range settings prior to data collection. These settings, which range from ±3 to ±250 cm/s, represent nominal values. The permissible maximum velocities may exceed these nominal values by large amounts, especially on the lower ranges. Because the inherent instrument noise increases with increasing range, the operator is advised to select the smallest range consistent with the expected maximum velocity. If the actual velocity exceeds that allowable on a given range, aliasing occurs, and a false (and not necessarily obvious) velocity indication is obtained.

Subsequent to the testing of the above probe, Nortek provided a probe with a new design, and additional tests were conducted, primarily on pitch response. The new probe, like the older one, was a 5-cm, downward-looking, three-dimensional probe, but the new probe had a more streamlined design. Whereas the transmitter and receivers of both probes

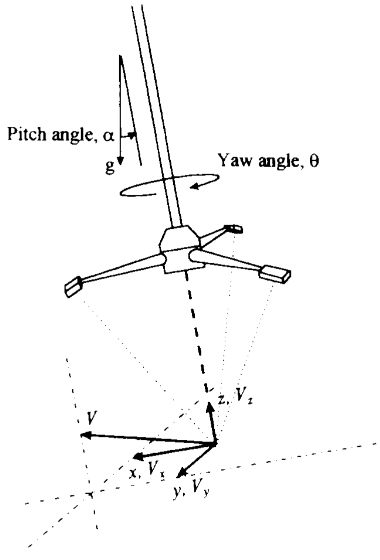

FIG. 1. Sketch of ADV Probe and Its Coordinate System

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were the same size and had the same geometry, the encasing and supporting structures of the new probe were smaller. The support arms of the receivers of the new probe were cylindrical and straight and were attached to the probe support stem farther from the transmitter. The sacrificial anode was absent. The new probe used the same signal conditioning module and processor electronics as the original one. We will refer to the original and new probes as probes 1 and 2, respectively.

Experimental Setup

The towing tank is 125 cm wide and 12 m long and may be filled to a maximum depth of 100 cm. The tank has an automated filling system that allows specified density profiles of virtually any shape with neutral or stable saltwater density gradients. A towing carriage is capable of speeds from 1 to 35 cm/s. A mount was constructed to clamp the probes rigidly to the carriage, yet allowing vertical and angular positioning for testing of the yaw and pitch response of the probe. Scales permitted angle measurements to an estimated relative accuracy of 1° and an absolute accuracy of 2°. A stopwatch was generally used to check the carriage speed over a specified distance, and recording of the ADV signal was begun after a steady-state carriage speed had been attained.

The sampling rate was fixed at its maximum of 25 Hz, and block averaging of the entire record (or selected portions) was done using WinADV. The signal-to-noise ratio (SNR), which provides an indication of the sufficiency of seeding material, exceeded the manufacturer's recommended value of 15 db for high-resolution measurements (25 Hz) in the vast majority of the measurements. A correlation coefficient, output with each ADV sample, is a quality parameter that indicates the degree to which all particles within the sampling volume are moving in precisely the same manner. Low values may result from high turbulence, the presence of large individual particles or bubbles, a low SNR, or interference from boundaries. WinADV was used to filter out samples with correlation coefficients less than 70%, but very few samples were in fact rejected.

Seeding Material

In our clean, freshwater tank, the addition of particles was essential to provide sufficient scatterers for satisfactory operation of the ADV. The suspension of hollow glass spheres (HGS, supplied by Nortek) clearly fractionated rather quickly in its storage container, with approximately a third of the HGS going to the top and two thirds settling to the bottom, with clear water between. These particles are not ideally suited for use in a towing tank, as they settle out rather quickly (half-life of about 2 1/2 hours). In freshwater, they can be resuspended to some extent with vigorous stirring, but considerable time must then be allowed for the turbulence and secondary flows to disappear. In the case of the stratified tank, stirring to distribute the HGS would have tended to destroy the stratification. We hoped that the HGS would have a distribution of densities such that the end result (after the HGS had found their equilibrium levels) would be a continuous distribution of seeding material over the entire depth of the tank, but complete fractionation seemed to occur just as in freshwater. A workable solution, which was also frequently used in the nonstratified, freshwater tank, used a "squirt bottle" to spray a diluted mixture of HGS with an oscillating motion onto the water surface. Within a few minutes, the SNR would increase to the vicinity of 15–20 db at depths of 10 cm below the surface, and within approximately 30 min, the SNR would increase to usable levels even near the bottom of the tank (1-m depth).

RESULTS

Basic Response of ADV

As the ADV was turned on in still water, the indicated horizontal velocity components were zero, but a downward velocity was observed to increase from zero to a steady-state value that was dependent upon the range setting of the instrument. This indicated velocity ranged from approximately 0.7 cm/s on a range setting of 3 cm/s to nearly 2 cm/s on a range setting of 250 cm/s. This range in indicated velocity is due to the energy output by the transmitter; a net downward force is exerted on the fluid because of nonlinear effects of the acoustic (pressure) field. The steady-state flow field was established in approximately 5 s. It is suppressed by rather slight motions of the carriage (or fluid motions orthogonal to the axis of sound transmission), as new fluid is encountered continuously; because of erratic motion of the carriage at speeds less than 2 cm/s, it was difficult to examine this aspect in more detail, but the indicated velocity was substantially reduced at 0.9 cm/s (on the 3-cm/s range) and was clearly absent with horizontal velocities above 2 cm/s. This induced motion may also be suppressed by the stratification and was absent in the strongly stratified tank. The signals indicated some "turbulence" owing to Doppler noise, related to the random distribution of particles that contribute to the back-scattered echo. In still water, the fluctuations amounted to about 1 cm/s (peak to peak) for the horizontal components and about 0.3 cm/s for the vertical component.

As the carriage was started, the vertical velocity was observed to return quickly to zero, then increase (negatively) to another steady-state value, with the magnitude being dependent on the towing speed, and it was downward regardless of the direction of motion (Fig. 2). This is evidently due to the influence of the probe itself on the flow field; the streamlines would appear to be deflected by about 1°, which is conceivable given the dimensions of the probe (7.7 cm dia.) and the distance to the sampling volume (5 cm). The probe is nonsymmetrical in the fore and aft directions, and the figure does indicate nonsymmetrical behavior, but the differences are smaller than our ability to align the probe would allow. Straight lines have been fitted to the data as a rough guide only. Because the best-fit lines would not appear to be straight, Reynolds number effects are indicated (i.e., streamline deflections are dependent upon the flow speed or, nondimensionally speaking, upon the Reynolds number, R = UD/ν, where U is the flow speed, D is a characteristic dimension such as the probe diameter, and ν is the kinematic viscosity of the fluid). Also, the slopes of the best-fit straight lines appear to change with range setting, suggesting range dependence as well. Although this aspect of the new probe was not tested, in view of its improved pitch response (see later discussion), the streamline deflections and, hence, the indicated vertical velocities in purely horizontal flow might be expected to be smaller than those indicated here.

Fig. 3 shows the results of the basic calibration check of the ADV, where we have plotted the ratios of the indicated to

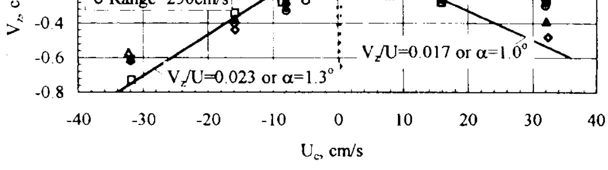

FIG. 2. Indicated Vertical Velocity with Horizontal Flow

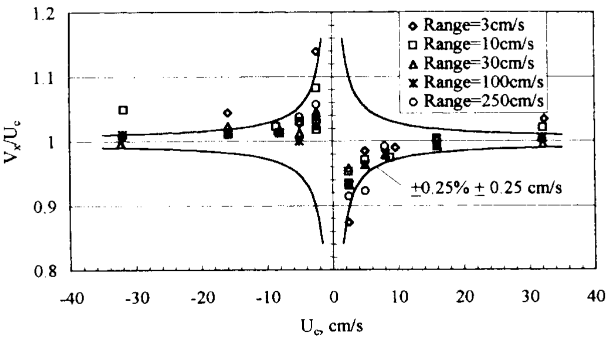

FIG. 3. Linearity Check of ADV with Horizontal Flow

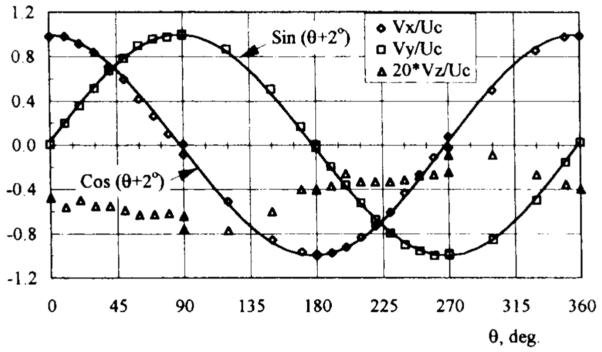

FIG. 4. Yaw Response of ADV

actual speeds versus the carriage speed. The negative velocities were obtained, of course, by reversing the direction of the carriage. For comparison, we have added lines representing accuracies of ±0.25% ± 0.25 cm/s, as suggested by Kraus et al. (1994). Note that the first figure (0.25%) is a relative accuracy, being a percentage of the value indicated, and the second (0.25 cm/s) is an absolute accuracy, providing a lower limit or minimum resolution related to the inherent Doppler noise. The majority of points lie within the envelope created by these curves. Some of the outliers may be explained, others not. It would appear that the points just outside the envelope at carriage speeds of ±2 cm/s may have been biased because of exceptionally high initial turbulence and concomitant secondary flows caused by vigorous stirring shortly beforehand. Three sets of points were repeated at the same carriage speeds of ±2 cm/s after the turbulence had dissipated ($t > 20$ min), and all those points were within the envelope. The outlying point at a carriage speed of −16 cm/s is inexplicable, as all other indications regarding data quality were good; the SNR was 24 db and the correlation parameter was 90%. These tows of the probe were done about 1 1/2 hours after stirring, so turbulence and secondary flows should have been negligible. Timing by the stopwatch, believed to be accurate to 0.2 s, could account for an error of about 0.7%, which is not enough to move the point to within the envelope. Similar remarks can be made concerning the outlying points at carriage speeds of ±32 cm/s and a range of 10 cm/s. The outlier at the speed of 32 cm/s with the ADV on the 3-cm/s range may be excused, as it is outside the limits specified by the manufacturer (±30 cm/s can be measured on the 3-cm/s range). Note that all three unexplained outliers are cases where the actual velocity exceeded the nominal "range setting," although they are well within the stated maximum velocities. This may suggest that the maximum velocity limits should be lower.

Indicated lateral velocities during this series of tows were quite small, were independent of range setting, and were within our ability to align the probe (~0.5°).

Yaw Response

Yaw is defined here as a rotation of the probe about its vertical axis or stem (Fig. 1). The yaw angle θ is measured between the mean velocity vector and the downstream-pointing arm of the ADV, and thus the ideal response of the instrument is $V_x = U_c \cos\theta$, $V_y = U_c \sin\theta$, and $V_z = 0$. Yaw-response measurements were undertaken at a nominal carriage speed of 10 cm/s and at a range setting of 3 cm/s. By rotating the probe in ±10° increments and towing it in both directions, the full 360° response was obtained. The results are shown in Fig. 4. The horizontal velocity components are fit very well by sinusoids after allowance for a 2° angle shift; this shift is possibly due to an initial misalignment of the probe. The indicated vertical velocity, also shown in Fig. 4, is always negative and shows some variability with yaw angle, but it is generally within the range shown in the previous section, i.e., due to probe self-interference and indicating streamline deflections of about 1°.

Pitch Response

Pitch is defined as a rotation about the lateral or y-axis. The pitch angle α is measured between the probe axis and the vertical, positive when rotated such that the indicated vertical component of velocity is positive when the mean horizontal component is positive (forward direction of tow; Fig. 1). Thus, the ideal instrument response is $V_x = U_c \cos\alpha$, $V_z = U_c \sin\alpha$. Pitch-response measurements were undertaken at a nominal carriage speed of 9 cm/s and at a range setting of 3 cm/s (except as indicated). The probe was rotated in ±5° or ±10° increments and was towed in both directions. The results are shown in Fig. 5(a), where the data from both probes are compared with sinusoids. These sinusoids have been shifted by 1°, consistent with a possible initial misalignment.

For probe 1, the horizontal velocity component displays a near-cosine response when the pitch angle is positive and the probe is towed in the reverse direction or when the pitch angle is negative and the probe is towed in the forward direction. Otherwise, its cosine response is rather poor; indeed, when the pitch angles are as large as ±20°, the indicated speeds are larger than those with zero pitch angle. Fig. 5(b), which displays the actual responses normalized by the ideal responses, shows that the errors in the indicated horizontal velocity component may be as large as 10% when the vertical velocity is positive and the magnitude of the pitch angle exceeds 20°. When the vertical velocity is negative, the error in the indicated horizontal velocity is considerably smaller, reaching only 4–6% when the pitch angle is ±30 and ±40°. Inexplicably, the indicated errors at ±50° appear to be somewhat smaller than those at ±30 and ±40°. Finally, one pair of tows (forward and reverse) was done at pitch angles of ±50° with a different range setting of 10 cm/s; the indicated errors in the horizontal velocity component are significantly larger, 15–20%. This finding was pursued somewhat further and is discussed in the next section.

Also for probe 1, the indicated vertical component of velocity appears to be closely sinusoidal [Fig. 5(a)], but the best fit was obtained when the amplitude of the sine function was adjusted downward by 7% to 0.93. The differences between ideal and actual responses are made clearer in Fig. 5(b). The points at pitch angles near zero may be anomalous because the values of V_z/U_c have been divided by a very small number (sin 1°). To a first approximation, the response for positive pitch angles is nearly constant around 0.9, and that for negative angles is constant around 0.95. The differences would appear to be consistent with our intuitive notions of probe interference, i.e., the tendency to push fluid ahead with positive

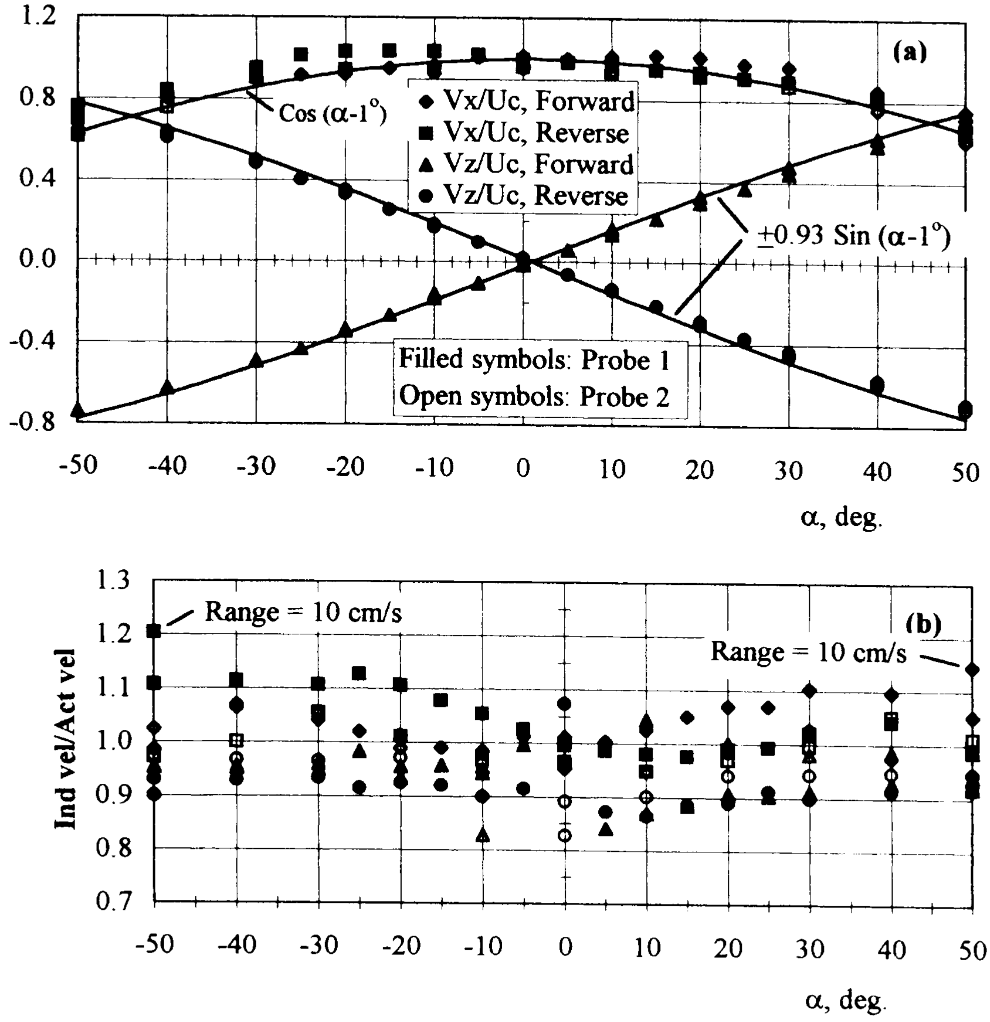

FIG. 5. Pitch Response of Two ADV Probes (Range = 3 cm/s, U_c = 9 cm/s)

angles, thus reducing the vertical component, and to drag fluid behind with negative angles, thus increasing the vertical component.

Although explicit tests were not conducted, these pitch-response tests suggest that the indicated vertical turbulence intensities may be in error by typically 7% as they should be directly related to the error in mean velocities.

Probe 2 (the new probe) was tested in like manner, but because of some contamination with saltwater, the fluid density was 1.022 g/cm^3; this value was input to the ADV acquisition program. The probe 2 results are included for comparison with those of probe 1 and with sinusoids in Fig. 5(a). These data again suggest a possible misalignment of 1°. Unlike the original probe, probe 2 displays a near-cosine response of the horizontal velocity component regardless of the direction of the tow, and speeds larger than the carriage speed at any pitch angle are not indicated. Fig. 5(b) shows that the errors in the indicated horizontal velocity component are significantly reduced; they are all within 7% of the true values and are generally much smaller, although at 0° they are in the range of 3–4%.

Fig. 5(a) also includes the indicated vertical component of velocity of probe 2, and it appears to be closely sinusoidal. Note that the amplitude of the best-fit sine function need not be adjusted downward by 7%, as was the case with the original probe. Again, in comparison with the original, the errors [Fig. 5(b)] are substantially reduced. Outside the range of ±10°, the errors are all within 7% and are generally much smaller than that. The large errors indicated within the ±10° range should perhaps be disregarded, as the actual values have been divided by quite small numbers (sin 10°); an error in this quantity (ratio of indicated velocity to actual velocity) of 10% would be equivalent to an absolute error in V_z of less than 2% of the carriage speed.

One pair of tows (forward and reverse) was done with the original probe held at a compound angle $\theta = 30°$ and $\alpha = 30°$). The ideal response should have been $V_x/U_c = \cos\theta \cos\alpha = 0.75$, $V_y/U_c = \sin\theta = 0.5$, and $V_z/U_c = \cos\theta \sin\alpha = 0.43$. The actual values were 0.73, 0.57, and 0.41, with ratios (actual to ideal) of 0.97, 1.14, and 0.95, respectively. It is perhaps at first surprising that the largest error resulted in the component V_y, which theoretically does not involve the pitch angle α, but this clearly results from the large overspeed caused by probe interference at pitch angles greater than about 20°.

Effects of Range Setting

An exploratory series of tests was conducted using the original probe, at the fixed pitch angle of −30° and a nominal carriage speed of 9 cm/s, to examine several aspects of the pitch response of the ADV on different range settings. Initially, hollow glass spheres were added to the tank, and the water was stirred vigorously with a paddle. After approximately 15 min, measurements were begun, and they were continued at intervals over a total period exceeding 6 h, so that both the SNR and the turbulence decreased during this series. This process also permitted some examination of the effects of the SNR and turbulence.

For the sake of brevity, the results are summarized here; further details may be found in Snyder (1997). First, as the turbulence dissipated completely within about 20 min, the variations in indicated turbulence intensity thereafter were related to the SNR, and they clearly increased on each range as the SNR decreased (time increased). Second, with this range of SNR (10–30 db), the inherent Doppler noise restricted the minimum levels of turbulence that could be detected by the ADV, and these levels were range dependent; on the 3-cm/s range, the minimum levels for the horizontal components were 2–4%; for the vertical components, they were around 1%. On the 30-cm/s range, minimum levels were 6–10% for the horizontal components and 1–2% for the vertical components. The "half-life" of the particles in the tank, defined as the time during which the SNR is reduced by a factor of 2, was approximately 2 1/2 h.

Rather unexpectedly, we found that the indicated mean velocity depended on the range setting, so we conducted two further series of tests, one with each probe, to better quantify these effects. The probes were tilted at 30° and towed forward and backward on the carriage at a fixed speed of 10 cm/s. The results are shown in Fig. 6, where the data obtained at negative pitch angles are indicated on the negative range axes. For probe 1, the horizontal velocity is overestimated by 4–12%, with the larger values occurring on the smaller range settings and the errors being roughly independent of the sign of the pitch angle ($\alpha = \pm 30°$). The vertical velocity is underestimated by 5–16%; in this case, the results are practically independent of range, but they are quite strongly dependent on the sign of the pitch angle. To a first approximation, the error in vertical velocity is −15% when $\alpha = +30°$ and is −6% when $\alpha = -30°$.

For the series with probe 2, the salt-water density of 1.022 g/cm^3 was input to the ADV software. The results from this probe are also shown in Fig. 6, which shows that the errors are clearly and substantially reduced with the new probe design. For the horizontal velocity, the errors range from ±2 to −6%. The smaller values are on the lowest range, which is opposite to the behavior probe 1. These errors are practically independent of the tow direction (or of sign of the pitch angle). The slightly larger errors indicated for the vertical velocity range from +1 to −7%; the larger errors are all associated with positive pitch angles, as was the case with probe 1. As a rough overall indication, we may say that the new probe design has reduced the indicated errors by a factor of at least 2.

Reynolds Number Effects

The previous pitch-response tests had mostly been conducted at one mean velocity (Reynolds number). As the fluid medium and the size and geometry of the probe were fixed, Reynolds number effects of the probe could be tested only by towing it at different speeds. Because a full three-dimensional matrix to examine effects of pitch angle, speed, and range setting was beyond the scope of the present study, we fixed the pitch angle at ±30°, and conducted a series of measurements where the response over the full range of velocities was explored on a range setting of 10 cm/s. The results, shown in Fig. 7, suggest that Reynolds number independence is obtained with the original probe at a pitch angle of ±30° when $|U_c| >$ 5 cm/s. At the smaller velocities ($|U_c| <$ 5 cm/s), the errors become quite large and even change sign. Note that in the Reynolds number–independent regime, errors in the indicated horizontal velocity are in the neighborhood of 10%, regardless of direction. These errors far exceed the values observed with purely horizontal flow; the error bounds of ±0.25% ± 0.25 cm/s would allow a maximum error of only 3% (with $|U_c|$ = 10 cm/s). Again in the Reynolds number–independent regime, errors in the indicated vertical velocity range from 5 to 15%, with the smaller values being associated with the negative pitch angle.

The results for probe 2 are also shown in Fig. 7, where it is again clear that the new design is a substantial improvement. With the smallness of the errors and the scatter in the results, it is difficult to ascribe Reynolds number effects per se at any particular velocity, but it is clearly no more Reynolds number–dependent than was the original probe. It is also clear that the errors with the new probe are much closer to the error bounds of ±0.25% ± 0.25 cm/s, particularly for the negative pitch angles.

We offer a final comment on the range settings. The manufacturer provides a table listing the maximum velocities measurable on the various range settings. For a range setting of 10 cm/s, the table shows maximum horizontal and vertical velocities of ±60 and ±15 cm/s, respectively. However, in the above tests, when the original probe was inclined at 30° and was towed at speeds exceeding ±22 cm/s, aliasing was observed (and indicated horizontal velocities of ±58 cm/s), even though both components were well within the stated limits (V_x = 22 cos 30° = 19 cm/s and V_z = 22 sin 30° = 11 cm/s). It thus appears that the limits should be more restrictive than stated.

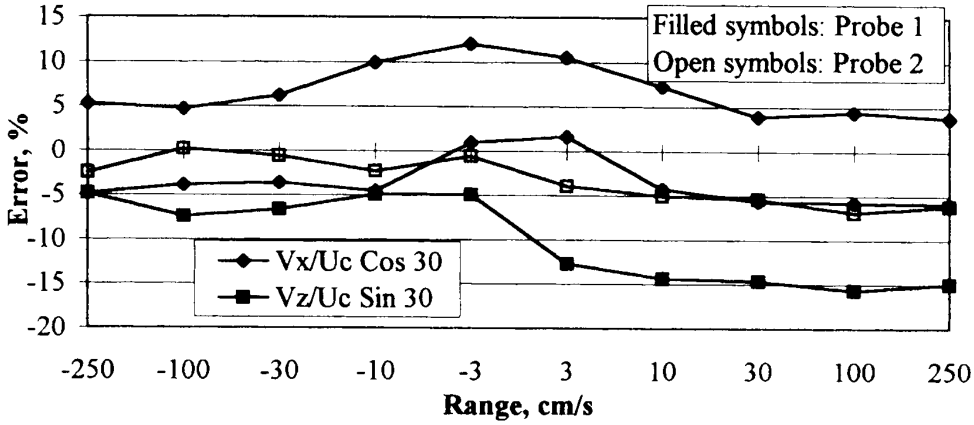

FIG. 6. ADV Errors on Different Range Settings (U_c = 10 cm/s, $\alpha = \pm 30°$; Negative Values Correspond to Negative Pitch Angles)

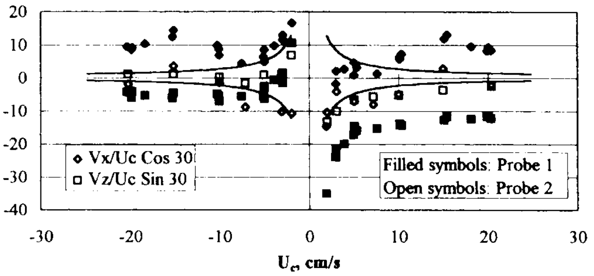

FIG. 7. Reynolds Number Independence Tests of ADV Probes at 30° Pitch Angle

Resonance over Hard Surfaces

For various reasons, we chose, when stratifying the tank, to fill it with only a relatively shallow depth of water and thus to attempt measurements with the ADV sampling volume relatively close to the floor. Our first experiences were bewildering. Large amplitude noise was observed sporadically. At times the noise was seemingly related to the SNR; at other times it seemed to be related to the distance between the probe and the floor of the tank, to the type of underlying surface, or to the pitch angle of the probe. In some cases the trace was reasonably noise-free; in others, intermittent noise appeared on the signal for the duration of the tow; and in still others, the signal was excessively noisy over the stainless-steel section of floor at one end of the tank, yet relatively quiet over the remaining glass section.

Considerable experimentation suggested that a resonance occurred with the ADV at certain distances from the floor of the tank and, in those instances, extremely large turbulence intensities were indicated. The distances at which resonance was observed were dependent on the type of surface and also, we believe, on the stratification in the tank. Fig. 8 shows results of one set of measurements made in freshwater at various elevations above the normal floor of the tank as well as another set where, in an effort to reduce the resonance, one section of the floor was covered with a thin rubber mat. The signals were recorded over the entire floor, but analysis was undertaken on the separate sections. Two spikes with very large indicated turbulence intensities are observed over the glass floor with the probe sampling volume 3.3 and 5.3 cm above it. We refer to these as resonance points, as the high turbulence values are clearly not real, but are related to interference from the sound pulses reflected from the floor of the tank. The widths of the resonance regions were quite small—less than 1 cm in each case. No other resonance points were found over a 33-cm depth, but because of the narrowness of the regions and the density of sampling points, additional ones could have been missed. Note that at the resonance points, the indicated lateral turbulence intensity is nearly double the longitudinal one, and the vertical intensity displays a much smaller peak (albeit, on a relative basis, quite distinct). In spite of the excessive noise, the mean velocities were hardly affected. Some very limited testing suggested that the locations of the resonance points may be dependent upon range setting.

The rubber mat was clearly effective in eliminating the resonance points (Fig. 8), so for subsequent tests, a 60-cm-wide swath of rubber was used to cover the entire length of the floor; no further resonance problems were observed. The mat was common corrugated flooring material, about 2 mm thick. It was placed upside down in the tank so that the surface facing the probe was not the normal corrugations but was the slightly textured side.

Another interesting point is that in one instance, the sampling volume was only 0.04 cm from the floor (as indicated by the ADV itself) when the probe was at its initial (parked) position above the rubber-covered floor. In spite of its close proximity to the floor, it gave a surprisingly good indication of the mean velocity, only some 6.5% low. Over the glass floor, the actual distance from the sampling volume to the floor increased perhaps 0.3–1 cm due to the absence of the mat and to some unevenness in the floor itself. In spite of this, the ADV provided an estimate of mean velocity that was just as accurate as at other positions. The turbulence (noise) levels indicated here also appeared quite reasonable.

Speed of Sound in Saltwater

Literature distributed by the manufacturer states that if the speed of sound used by the ADV is in error by 1%, the resulting measured velocity will be in error by about 2%. This error is due in part to the simple scaling relationship between the Doppler shift and the sound velocity and in part to a change in the timing in the "receive" window by the software in order to maintain a constant position of the sampling volume (per A. Lohrman, personal communication). A set of tests was conducted to ascertain this relationship. The probe was towed repetitively through the tank, changing only the indicated temperature (a user input to the software) and thus the indicated sound speed. The results were contrary to our expectations: The best-fit line suggested that a change of 1% in the speed of sound used by the ADV resulted in a change of approximately 1% in the resulting velocity measurement, with

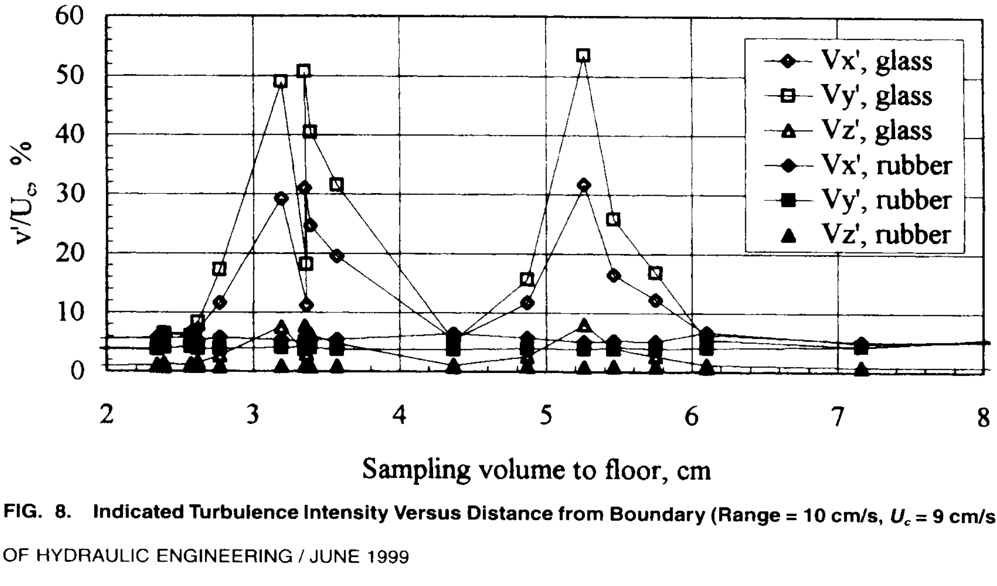

FIG. 8. Indicated Turbulence Intensity Versus Distance from Boundary (Range = 10 cm/s, U_c = 9 cm/s)

very little scatter. A similar set of measurements for which the indicated salinity was varied in order to vary the indicated sound speed showed virtually identical results.

The density gradients used in stratified towing tanks are generally quite strong, with the salinity commonly varying from freshwater at the surface to saturated brine at the bottom of the tank (1-m depth). Even stronger gradients may be used, particularly if an atmospheric inversion is being simulated in which case the density may vary from 1.0 to 1.2 over a distance of perhaps 10 cm. In all such cases, the water density may vary substantially over the path length of the ADV, 5 cm in the present case. Thus, the objective here was to investigate the suitability of the ADV for use in this type of environment.

Because the ADV was designed primarily for use in natural environments, its software handles salinity values of up to only 60 ppt, whereas the density of saturated brine is approximately 260 ppt (26% NaCl, or density of 1.2 g/L). Hence, the first task was to establish the speed of sound in saltwater of varying concentrations. A literature search showed very limited and highly inconsistent values [Fig. 9(a)]. Whereas the values derived from the Nortek software are in reasonable agreement with the one value from the AIP Handbook (1972), the data from Kaufman (1968) for higher concentrations appear widely scattered and do not fit the trend at all well. (The original sources of the Kaufman data, in fact, trace to the mid-nineteenth and early twentieth centuries!)

However, a built-in feature of the ADV that allows it to be used to determine the speed of sound, at least in a relative sense, is its boundary-detection ability; this instrument accurately measures the distance to a boundary by effectively measuring the transit time of the sound pulses from the transmitter to the receiver. The operator does not have direct access to this time interval, but instead a distance to the boundary is displayed. If the speed of sound of the medium increases, the time interval will decrease, and the apparent boundary distance will be proportionately smaller. Provided the speed of sound in one medium (say, freshwater) is known, then the speed of sound in another medium may be determined through the ratio of the indicated boundary distances in the two media.

A rather rudimentary apparatus was set up to establish the speed of sound using the ADV. It consisted of a small cylinder of water with a rubber mat lining the bottom. The ADV probe was supported just below the water surface, pointing downward. The temperature and salinity settings used in the ADV software were held constant (at 20°C and 0 ppt, respectively). Saltwater mixtures in the tank were exchanged, and each time, measurements were taken of the density and temperature of the mixture and the apparent (per the ADV) as well as the actual boundary distances. In freshwater, these latter two distances generally agreed within 0.3 cm out of an actual distance of around 20 cm, and this "offset" was accounted for in the computations. The densities were measured in two ways: with

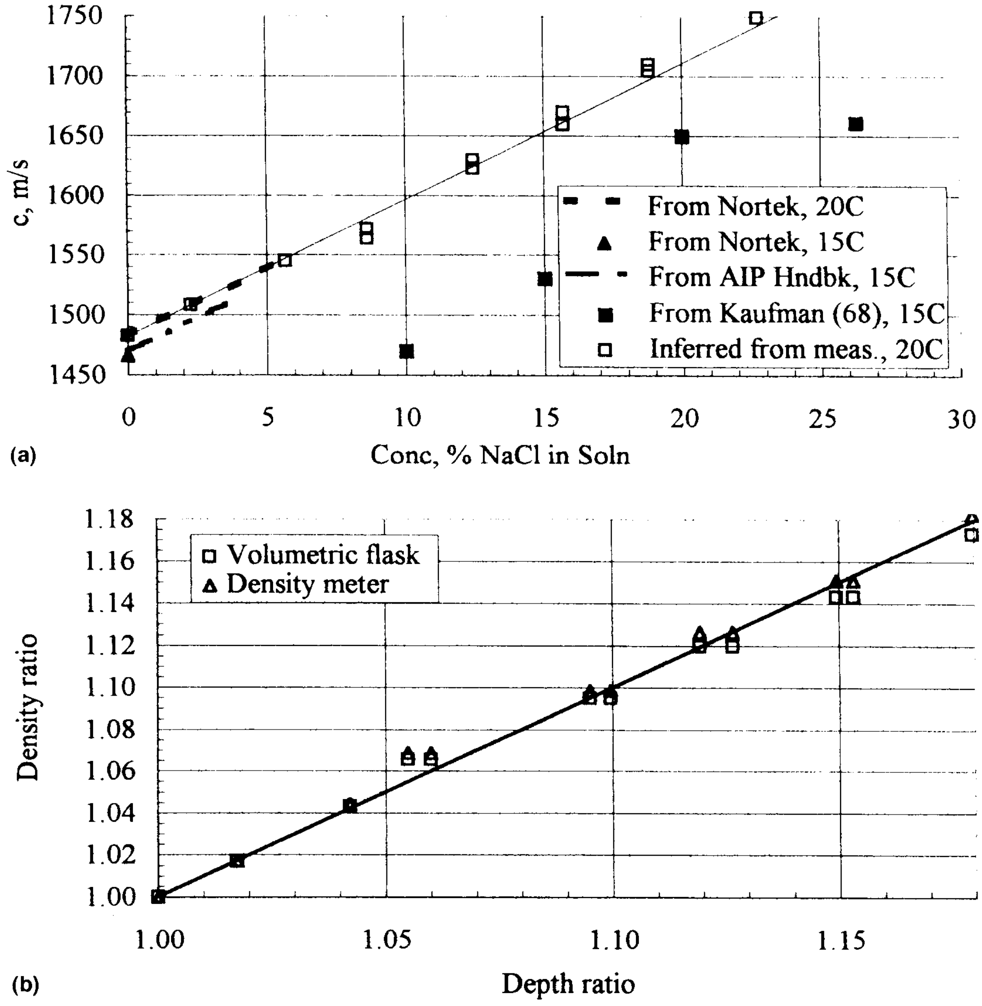

FIG. 9. Speed of Sound Determined Through Boundary Detection Feature of ADV: (a) Sound Speed Versus Concentration; (b) Density Ratio Versus Depth Ratio

a handheld density meter (Paar DMA 35) and weighing a volumetric flask using an electronic balance.

The basic results of density ratio (ratio of solution density to freshwater density) versus the ratio of apparent to real boundary distance are shown in Fig. 9(b), where a linear trend is quite clear. Indeed, a line with slope of 1.00 appears to provide an excellent fit. These results were transformed into sound speed versus salt concentration in Fig. 9(a), where they are compared with previous results from the literature. The linearity and the virtually perfect agreement with the trend of the existing ADV software are regarded as excellent.

After the above tests, the towing tank was filled with a homogeneous solution of nearly saturated brine, then with roughly half-saturated saltwater, and the ADV was towed through these solutions. From the results of the above tests, we may deduce that the ratio of the actual to indicated velocities should be equal to the specific gravity of the solution (with the reference density being that of freshwater at 20°C). The ADV response showed the following results:

Salt-water specific gravity	U_t/V_x
1.173	1.172
1.093	1.093

The exceptionally good agreement between the two quantities is perhaps fortuitous but it is indicative of the efficacy of the method.

Response Tests in Stratified Tank

To test the response of the probe under typically stratified conditions, the tank was stratified with saltwater to a depth of 79 cm, providing a closely linear gradient of 0.002 $\mathrm{g/cm^4}$ (Brunt-Väisälä frequency $N = [(-g/\rho)d\rho/dz]^{1/2} = 1.44$ rad/s). Over the 5-cm path length of the ADV probe, the density change was 1% or less, depending slightly upon the depth of immersion. The combined effects of the change in the speed of sound and ray bending tend to cancel one another, so that only the speed of sound at the level of the face of the transmitter (and receivers) need be known in order to measure the horizontal velocity accurately (A. Lohrman, personal communication). The probe was towed at various depths in the tank, and corrections were made as indicated. The corrected and uncorrected velocities are shown in Fig. 10, which shows that multiplication of the indicated velocities by the specific gravity at the transmitter results in an overestimate of the true velocity by typically 2–4%. This correction provides an improved velocity estimate, as the uncorrected values range to 8% below the true values.

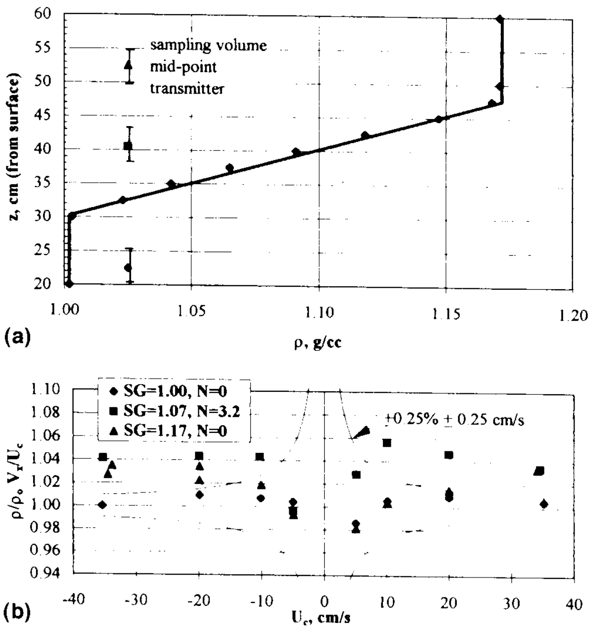

FIG. 11. ADV Response in Strongly Stratified Fluid (Range = 30 cm/s): (a) Density Profile, $N = 3.2$ rad/s; (b) Ratio of Actual Response to Ideal Response

The reason for the overcorrection of the indicated velocities in the stratified flows is clearly not the 1% variation in density over the path length of the probe per se and additional tests were conducted to examine whether an induced flow may have resulted at the sampling volume because of internal-wave effects. In general terms, in a strongly stratified flow, we may expect vertical displacements of approximately U/N, which in the present case is about 7 cm. The relevant nondimensional parameter is the Froude number, $\mathsf{F} = U/NL$, where L is a characteristic length such as the probe diameter. In the present case, F was about 1, so that vertical displacements may have been of the same order as the path length of the probe, and it was conceivable that the probe itself was inducing wave motions at the sampling volume. We tested this hypothesis with additional measurements in the stratified tank. These measurements also allowed us to examine the performance of the probe in a much stronger density gradient of 0.01 $\mathrm{g/cm^4}$, in which case the density varied by 5% over the path length of the probe.

The tank was filled as shown in Fig. 11(a), where the top

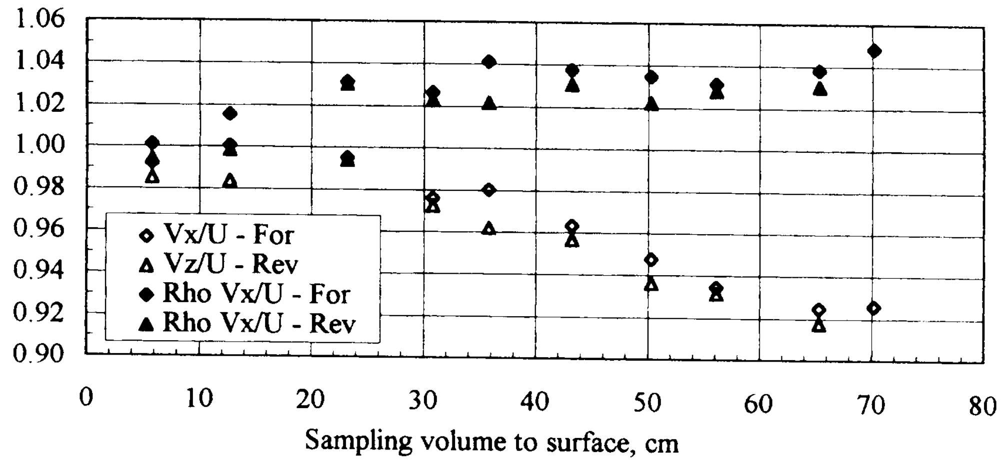

FIG. 10. Comparison of Corrected and Uncorrected Velocities in Stratified Tank

and bottom regions were fresh and nearly saturated saltwater mixtures with densities of 1.00 and 1.17 g/cm^3, respectively, each with a 30-cm depth, and the middle region was a 17-cm-deep stratified layer with constant gradient and Brunt–Väisälä frequency of 3.2 rad/s. The probe was then towed at various speeds through the middle of each region (pitch angle = 0°).

The results [Fig. 11(b)] show that in the freshwater region, the response was within the error bounds suggested by Kraus et al. (1994). In the homogeneous saltwater region, application of the correction procedure (multiplying the indicated velocity by the solution specific gravity) provides estimates of the true velocities, with errors somewhat outside these bounds but still within 2–3%. In the strongly stratified layer, the correction procedure applied using the specific gravity at the transmitter level resulted in slightly larger errors, with overestimates of approximately 3–5%. When $|U_c| < 10$ cm/s, the errors are somewhat smaller, but this is evidently due to Reynolds number effects, discussed earlier. When $|U_c| > 10$ cm/s, the results are virtually independent of speed, which suggests that Froude number effects are unimportant (U/N, a measure of possible vertical deflections in a stratified flow, ranged from 3 to 11 cm).

The reason for the overcorrection in the stratified layers must be related to the detailed physics of the sound-transmission process, although we have no satisfactory explanation for this discrepancy.

CONCLUSIONS

Generally speaking, from our basic calibration checks, we found the response of the ADV to a horizontal velocity to be accurate to within the stated bounds of ±0.25% ± 0.25 cm/s. A few points were inexplicably well outside this range, but the maximum error observed with speeds exceeding 2 cm/s was approximately 5%. For many purposes, this range of accuracy is quite acceptable, as the instrument does not need calibration and is not subject to drift.

The downward velocity observed with the ADV when it was sitting still was due to the effects of the nonlinear pressure field generated by the transmitter. The magnitude of the downward velocity increases with range setting, from about 0.7 cm/s on the 3-cm/s range to 1.8 cm/s on the 250-cm/s range; this induced velocity is virtually erased with horizontal flows above about 1 cm/s (and may disappear at even lower speeds).

More serious was an apparent downward motion induced by the probe itself. This vertical velocity was always negative and had a value of approximately 2% of the horizontal speed, indicating a streamline deflection of approximately 1°.

The inherent Doppler noise of the ADV limits the minimum turbulence levels that may be observed. In one set of tests, the indicated vertical component of turbulence (rms) was about 0.15 cm/s; this value was basically independent of the actual speed of flow, but it increased somewhat with a lowering of the SNR and with increasing range setting of the instrument.

Yaw- and pitch-response tests were conducted at nominal speeds of 10 cm/s. The yaw tests showed excellent cosine response, but the pitch tests displayed rather more serious limitations of the ADV. For the original probe, the indicated horizontal velocity components were generally within 5% (and usually within 2%) of the actual ones out to pitch angles of ±50° if the vertical velocities were negative. Otherwise, the errors increased with pitch angle to ±30°, leveling off to an error of about +10% between 30° and 50°. The indicated vertical velocities were generally 5–15% lower than the actual ones.

Series of tests undertaken to examine effects of range-setting, all at a carriage speed of 10 cm/s and pitch angle of ±30°, showed errors of 5–15% in indicated horizontal and vertical velocities; errors in the horizontal velocities were positive, were dependent on range setting, and were independent of the sign of the pitch angle; errors in the vertical velocity were negative, were roughly independent of range setting, and were strongly dependent on the sign of the pitch angle.

Reynolds number–independence tests on the original probe showed that errors were virtually independent of speed when $|U_c| > 5$ cm/s. In the Reynolds number–independent regime, both the range-setting and speed tests at pitch angles of ±30° showed errors in indicated horizontal velocity in the vicinity of 5–15%; these magnitudes are well outside the range of ±0.25% ± 0.25 cm/s; errors in vertical velocities were generally 5% with negative pitch angle and 15% with positive pitch angle.

The ADV displayed extremely noisy signals at certain distances above the floor of the tank. These resonance points were less than 1 cm in width, and their locations were found to depend on several factors, but mainly on the type of surface. They were effectively eliminated by covering the floor of the tank with a thin rubber mat.

One series of tests showed that the ADV responded linearly to changes in the input speed of sound, i.e., that a 1% input error in the sound speed will result in 1% error in the indicated speed (contrary to the 2% error quoted elsewhere).

The speed of sound in saltwater was determined using the boundary-detection feature of the ADV. This set of tests showed that the indicated distance to the boundary was directly proportional to the specific gravity of the saltwater, with a proportionality constant of 1.00. Hence, in a homogeneous saltwater solution, the true velocity may be determined from $V_s\rho/\rho_o$, where V_s is the velocity indicated by the ADV (with the salinity parameter input as 0), ρ is the density of the solution, and ρ_o is the density of freshwater.

Whereas tests of this correction procedure ($V_s\rho/\rho_o$) in homogeneous saltwater solutions showed resulting errors of generally less than 2%, testing in stratified solutions showed this procedure to overcorrect the indicated velocities to values typically 2–5% above the actual values. The errors appear to be independent of Froude number per se.

The newer probe provides substantially improved performance over the original one. The smaller support features and more streamlined design reduce the errors by roughly a factor of 2 or more. The pitch response of the new probe is much more closely sinusoidal for both horizontal and vertical velocity components, with errors typically less than ±5% out to pitch angles of ±50°. It displays results that are practically independent of range setting and errors that are more nearly independent of the sign of the pitch angle. Finally, its absolute accuracy, whereas not generally within the error envelope of ±0.25% ± 0.25 cm/s suggested by Kraus et al. (1994), appears to be much closer to it, for both the horizontal and vertical velocity components.

ACKNOWLEDGMENTS

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