NEW ACOUSTIC METER FOR MEASURING 3D LABORATORY FLOWS

By Nicholas C. Kraus,[1] Member, ASCE, Atle Lohrmann,[2] and Ramon Cabrera[3]

INTRODUCTION

The U.S. Army Engineer Waterways Experiment Station (WES) operates a large number of physical-model facilities, encompassing several thousand square meters of water surface. These facilities, used in support of both engineering and basic hydraulic and wave research studies, encompass a broad range of applications, including tidal and river flow, spillway design, ship navigability, breakwater stability and riprap protection, movable bed modeling, spectral coastal wave modeling, and wave-generated currents. Two- and three-dimensional, steady and unsteady, and laminar and turbulent water flows are generated in these facilities that range in size from laboratory scale to near-prototype scale. Also, although many models are housed in enclosed shelters, others stand open to weather. Most models in shelters are exposed to ambient atmosphere temperature and humidity fluctuations.

Under these different physical and flow conditions, and with different requirements for accuracy, point flow measurements are made with a wide variety of custom-made and commercial devices. Such devices include laser-Doppler velocimeters (LDVs), micropropellers, time-of-flight acoustic-type current meters, electromagnetic current meters, and Pitot tubes. A new research initiative to study the hydrodynamics at inlets and entrances, which involves tidal flow, wave transformation, wave-induced currents, and wave-current interaction, prompted formation of an interlaboratory committee at WES to determine technical specifications for a new three-dimensional (3D) current meter. The objective was to develop a current meter that could be deployed on most facilities, while meeting technical specifications of the users and reducing requirements of support staff in maintaining several types of meters.

This note introduces main requirements for the new current meter, the 3D acoustic-Doppler velocimeter (ADV) developed, and selected results of performance tests.

REQUIREMENTS

The requirements for the new current meter can be divided into two categories, practical operation and technical specifications. Main require-

---

[1] Dir., Conrad Blucher Inst. for Surv. and Sci., Texas A&M Univ.-Corpus Christi, 6300 Ocean Dr., Corpus Christi, TX 78412-5599; formerly, Sr. Sci., U.S. Army Engr. Wtrwys. Experiment Station, Coast. Engrg. Res. Center, Vicksburg, MS.

[2] Sr. Oceanographer, SonTek, Inc., 7940 Silverton Ave., Ste. 105, San Diego, CA 92126.

[3] Sr. Engr., SonTek, Inc., 7940 Silverton Ave., Ste. 105, San Diego, CA.

Note. Discussion open until August 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this technical note was submitted for review and possible publication on May 26, 1993. This technical note is part of the ***Journal of Hydraulic Engineering***, Vol. 120, No. 3, March, 1994. ©ASCE, ISSN 0733-9429/94/0003-0406/$2.00 + $.25 per page. Technical note No. 6249.

ments for practical operation were relatively modest cost (less than approximately $10,000, including hardware and software) so that a wide-area model project could afford several devices; easy portability; mechanical ruggedness to withstand normal activity and frequent relocation on large physical models; environmental ruggedness to withstand changes in temperature and humidity; sufficiently small size so as not to disturb the flow; stability over long time periods to eliminate frequent calibration; use of normal power with standard electrical component safety; and interface capability with common personal computers and mainframe data-acquisition systems.

The operations requirements suggested investigation and development of an acoustic-type device based on the Doppler-shift velocity-measurement principle. Such devices are relatively insensitive to drift due to aging components and environmental factors, and they have seen routine use in oceanographic applications. The main question was whether a miniature Doppler-type 3D current meter could be developed to satisfy the technical requirements. Another general conclusion was that a point-type current meter, as opposed to an instrument that can profile through the water column, would satisfy the majority of present needs for flow measurements at WES.

Not all the technical requirements can be described here, but several basic ones are as follows.

- Measurement of 3D current with resolution 0.1 mm/s over the range 0 to 2.5 m/s.
- Accuracy better than ±0.25% or ±0.25 cm/s, whichever is greater.
- Controllable sampling rate up to 25 Hz.
- Operating depths: minimum depth 20–30 mm for horizontal velocity only, and 55–70 mm for 3D velocity; maximum depth 5 m.
- Minimum distance from sampling volume to boundary of 5 mm.
- Operating temperature range 0°C to 40°C.
- Minimum flow disturbance, to be evaluated in performance tests.

DESCRIPTION OF CURRENT METER

A six-month development project, including two sets of tests at WES in several different model facilities, as well as calibration tests in a tow channel, led to final design and fabrication of the 3D ADV. In a typical configuration, the system consists of a probe attached to a 7-mm thick, 40-cm-long stem that is easily attachable to and detachable from a signal conditioning module. A cable of up to 30-m length connects this assembly to the signal processing module, installed in a 386/486 personal computer, which also serves as the power supply. The signal processing is controlled by a menu-driven interface in which data-collection parameters, such as sampling frequency and duration, and signal graphical display in engineering units and at various scales can be controlled. Ready detachability of the probe and stem from the conditioning module allows interchange of stems of different lengths and configurations as, for example, stems with right angles for reaching around model structures.

Fig. 1 shows the prototype probe and stem, and Fig. 2 shows details of the probe. To meet the requirement for minimum operation depth, the sampling volume is located 50 mm from the probe. This distance is commensurable with an operating frequency of 10 MHz and permits use of

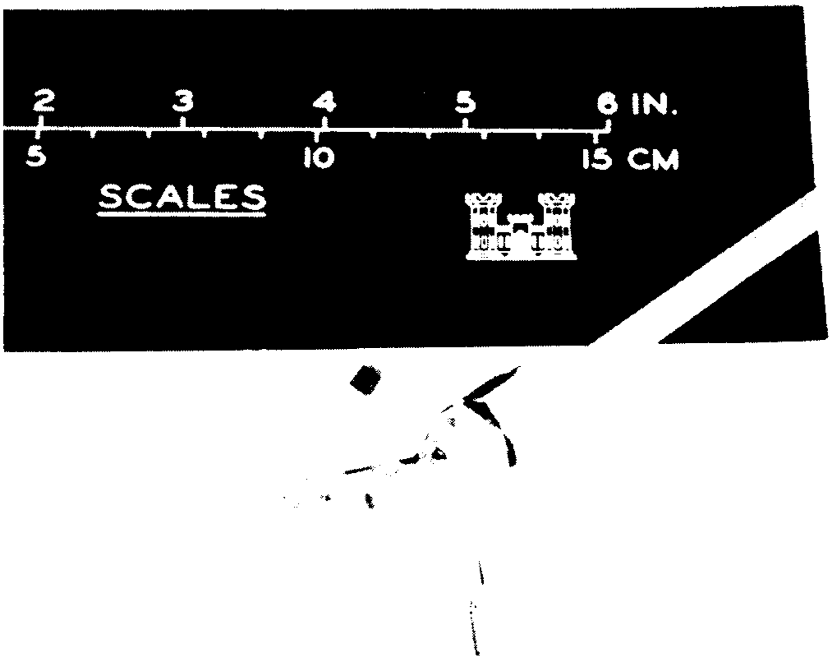

FIG. 1. Measurement Probe and Stem

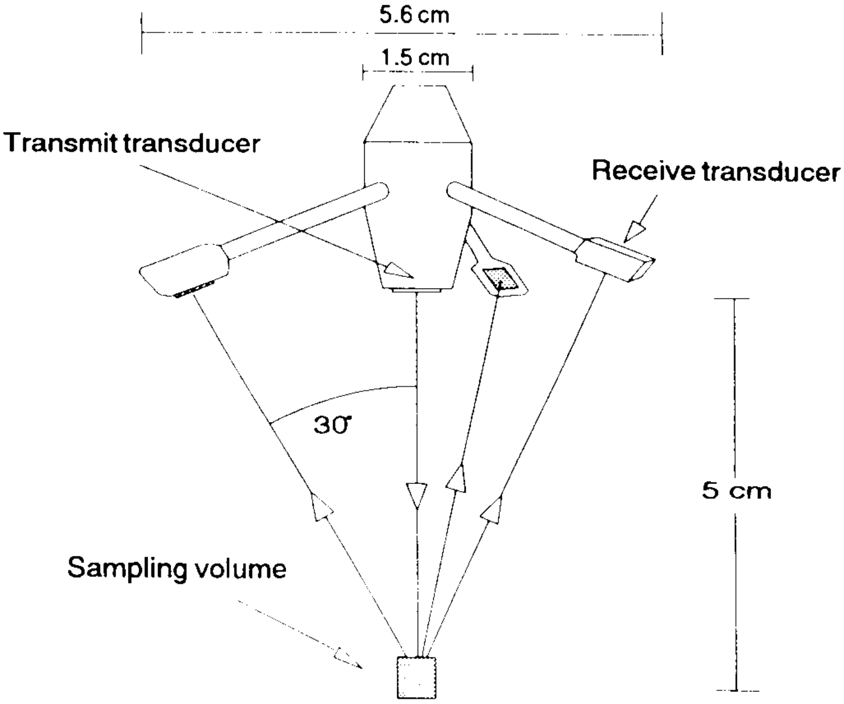

FIG. 2. Measurement Probe

small, narrow-beam, ceramic elements, giving subcentimeter spatial resolution. Three receivers are placed at 120° azimuth angles. The angle between each receiver, sampling volume, and transmitter is 30°. This angle was determined through a balance between probe size and statistically induced variance in the horizontal velocity components. In the present configuration,

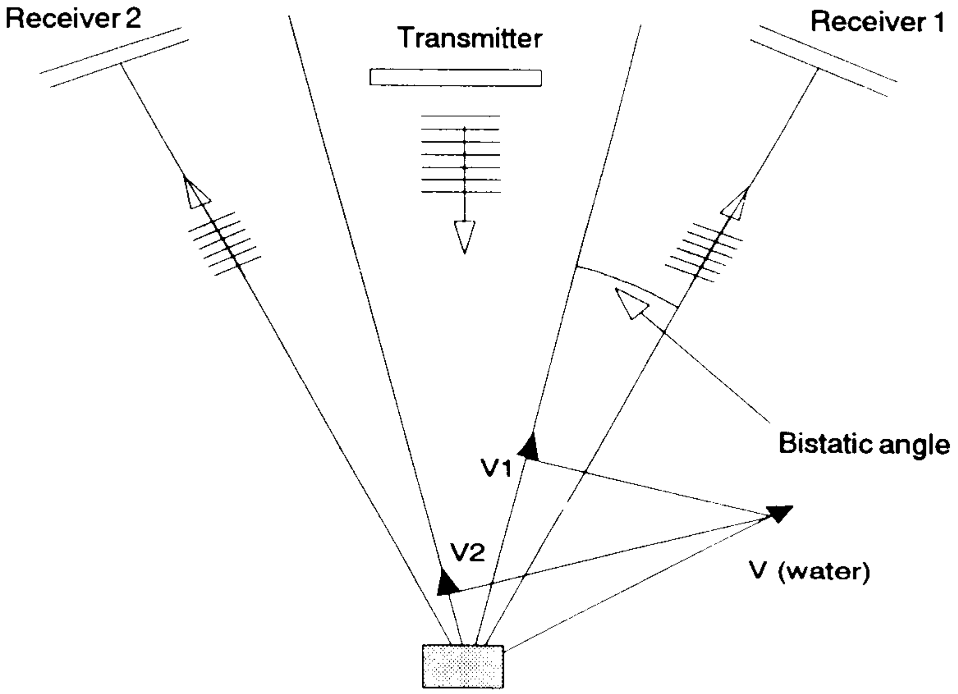

FIG. 3. Acoustic Beam Configuration

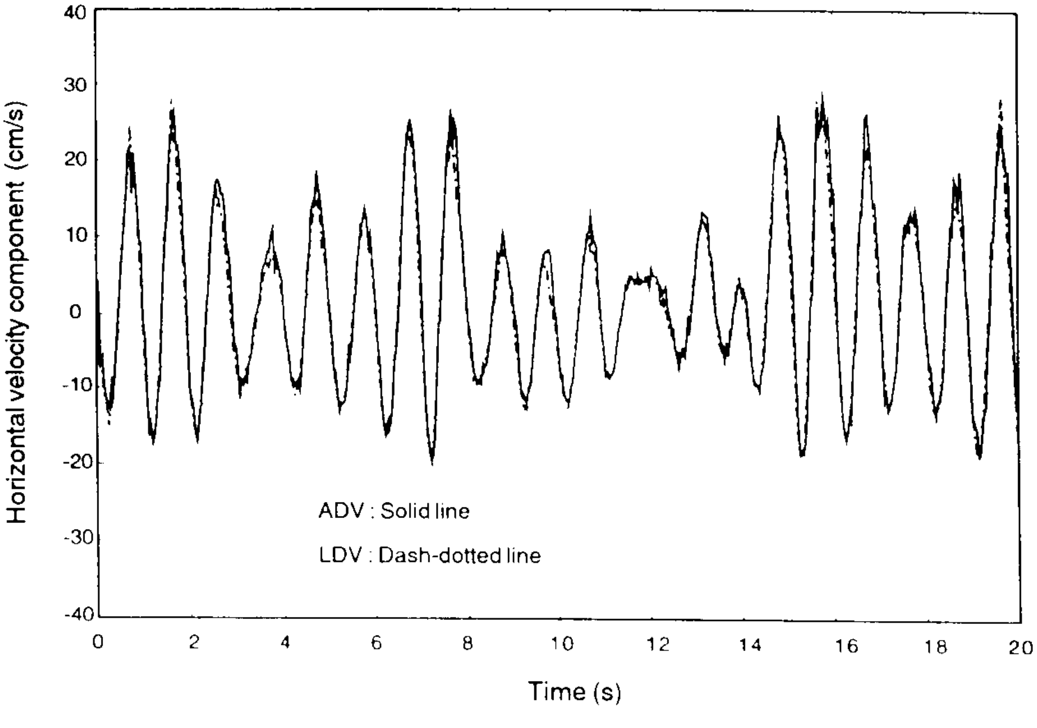

FIG. 4. ADV and LDV Comparison

each receiver arm is 27 mm long, and the variance is typically less than 1 $(cm/s)^2$.

Fig. 3 shows the operation principle of the Doppler measurement technique. The transmit transducer produces periodic short acoustic pulses. As the pulses travel along the beam, ambient scatterers such as microbubbles, suspended sediments, or seeding material, scatter a tiny fraction of the acoustic energy. These acoustic echoes are detected by the receive transducers if they originate at the sampling volume defined by the intersection of the transmit and receive beams. The frequency of the echo is Doppler shifted according to the relative motion of the scatterers, assumed to be traveling with the velocity of the fluid flow. Orthogonal components, such as the indicated v_1 and v_2, of the total velocity vector **V** can be computed by knowledge of the geometry of the beams.

The velocity vector obtained from the ADV is determined by the three measured velocity projections and a transformation matrix that incorporates the relative position of the three receiver arms and transmit transducer. The transformation matrix can be determined empirically by calibrating the system at one speed and will remain constant if the physical dimensions or geometry of the probe remain unchanged. Given a correct transformation matrix, a highly accurate 3D velocity measurement system is assured if the Doppler output is linear over the full velocity range.

The strength of the echo relative to the electronic noise level can be expressed as a signal-to-noise ratio (SNR). The SNR is a central parameter in ADV operation and is a measure of the scattering strength. The ADV interface reports this quantity, and it has been found that a 20-dB SNR assures reliable velocity measurement. Microscale and larger air bubbles serve as excellent natural seeding for achieving a high SNR.

EXAMPLE RESULTS

As part of the ADV evaluation, tests were conducted in a spillway model, two-dimensional (2D) wave channel, 3D wave basin, ship navigation model, a near-prototype scale rip-rap test circular channel, and a precision tow channel. Three example results are presented.

Fig. 4 compares concurrent measurements of the horizontal component of the wave orbital velocity under random surface waves made with a 2D Dantec Corporation LDV and the 3D ADV. The still-water depth in the wave channel was 0.3 m, and the sampling volume of both instruments, aligned visually, was located approximately 0.15 m below the water surface. The broadband random waves had mean period of 1.0 s and root-mean-square wave height of 0.15 m. The LDV sampled at 50 Hz and the ADV at 25 Hz. Fig. 4 shows good visual agreement in shape and peak of the oscillatory signals from the two instruments. Linear regression was performed on the data sets, giving a slope of 1.03 and offset of 0.11 cm/s. Similar good agreement was obtained for the much weaker vertical velocity component despite the configuration of the ADV probe and stem being aligned vertically in the wave channel.

The second example gives a result from a test in a 3D directional wave basin. The ADV was placed just seaward of the predominant zone of broadband random breaking waves of zero-moment spectral wave height of 15.0 cm and spectral peak period of 1 s. The waves arrived obliquely at a fixed initial angle of 30° on a horizontal bottom that joined to a 1/30 slope. The ADV was in water depth of 32 cm and sampled at 16-cm depth. Fig. 5 shows a 9-s segment of the record. The x-axis pointed positive onshore, the y-axis alongshore, and the z-axis positive upward. The y-component of velocity has a mean of -2.2 cm/s and represents the weak seaward tail in the wave-induced longshore current; the x-component of velocity had a mean of -0.8 cm/s and represents the undertow, and, possibly, a spurious basin circulation; the z-component has a mean of 0.08 cm/s, which is below the estimate of statistical variance for this short record. The horizontal flow pattern

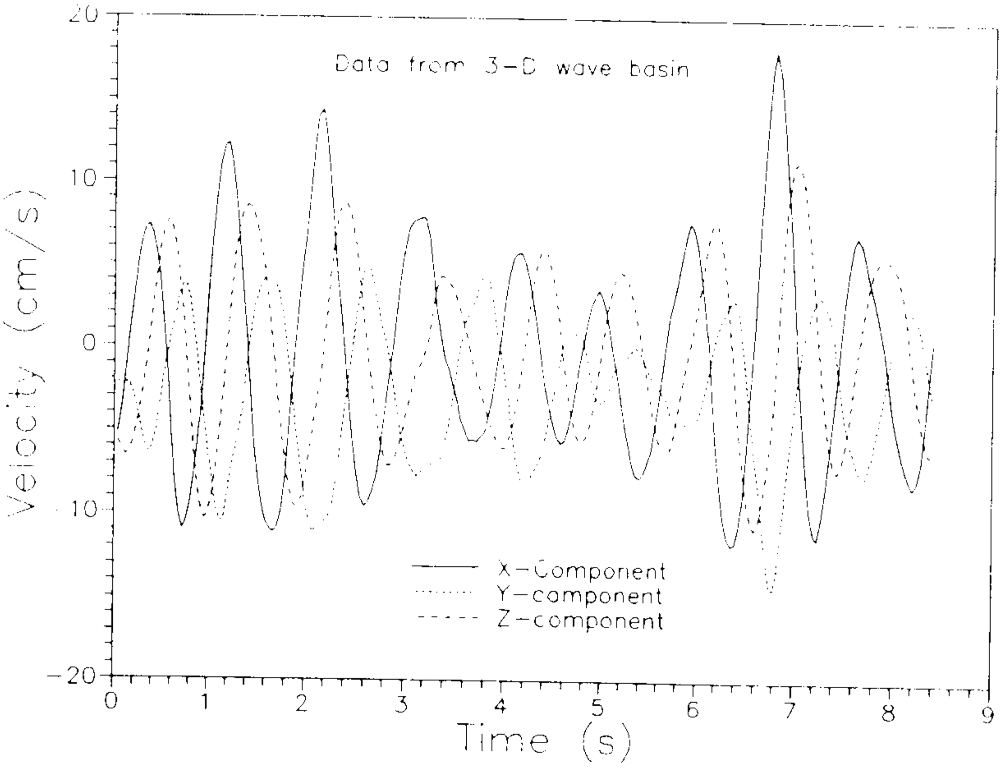

FIG. 5. Example Result in 3D Wave Basin

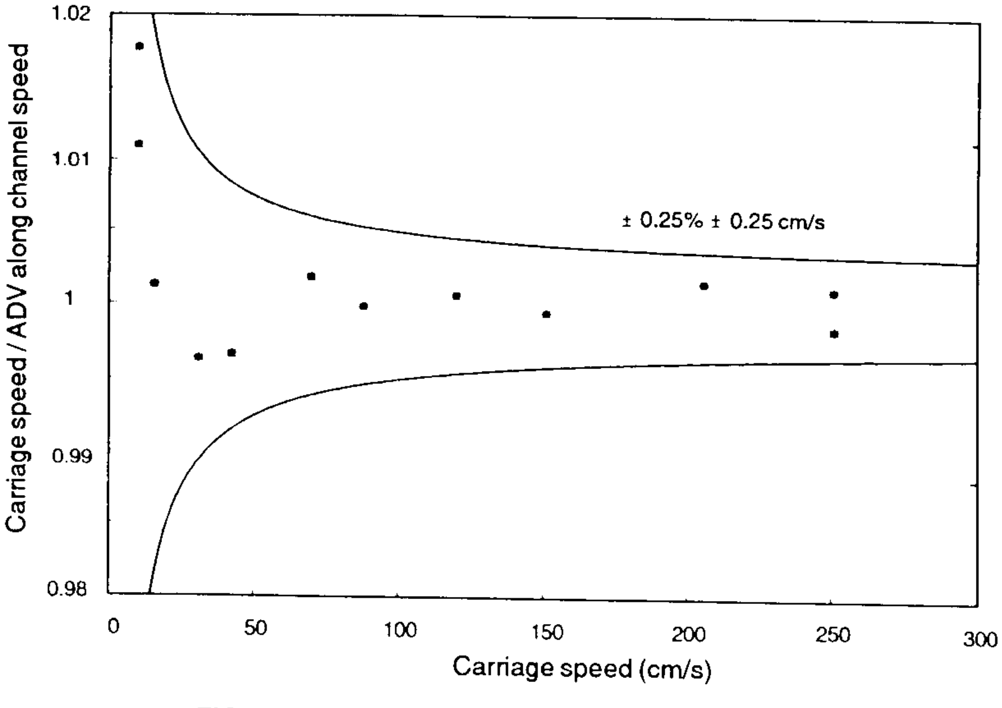

FIG. 6. Example Result of Tow-Channel Test

determined by the ADV agreed with qualitative observations of the movement of dye injected near the meter.

The final example pertains to tow-channel tests conducted at NorthWest Research Associates, Inc. (NWRA), in Bellevue, Wash. The NWRA channel is 9.75 m long and 0.91 m wide, and the test condition water depth was

0.91 m. The ADV probe was attached to a tow carriage mounted on top of the channel that is driven by an electrical motor. The carriage speed is determined both by tachometer and by elapsed time for the carriage to pass three optical sensors located on the channel wall. The standard deviation of these four speed estimates was 0.2% over the range of 1 to 250 cm/s.

Fig. 6 shows the ratio between carriage speed and along-channel velocity component over carriage speeds from 10 to 250 cm/s. The output is linear with ±0.25% over a range of 15 to 250 cm/s. To assure complete satisfaction of the accuracy requirements, calibration in a single-speed tow channel accurate to ±0.1%, is required. A tow channel that meets this specification is under construction. Rotation of the probe around the vertical axis in the tow-channel test minimally changed the measurement. The difference between a worst-case configuration (one probe aligned directly into the flow) and the best-case configuration (flow between two receivers) was less than 0.5%.

CONCLUSIONS

A new 3D ADV has been designed and successfully tested in a variety of engineering physical-model settings involving oscillatory flow and uniform flow. The current meter showed good linearity in magnitude and direction in uniform-flow tow-channel tests. The ADV is rugged and can be deployed and relocated easily to measure 3D water velocity in facilities and flow regimes encountered in most hydraulic laboratory situations. Future developments of ADV technology include a field version and a profiling version.

ACKNOWLEDGMENTS

Numerous WES staff members assisted in the requirements analysis and tests of the ADV, and their efforts are acknowledged: Coastal Engineering Research Center—Michael Briggs, Dr. Steven Hughes, Dennis Markle, Trapier Puckette, William Seabergh, and Ernest Smith; and Hydraulics Laboratory—Sandra Martin and Dr. Stephen Maynord. The assistance of Dr. Yogesh Agrawal and Lee Piper at the NWRA is acknowledged. Permission was granted by the Chief of Engineers to publish this information.