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New advances in the calibration of Doppler current-meters and current profilers

M. Le Menn[1], S. Morvan [2], A. Lusven [1]

[1] *SHOM, 13 rue du Chatellier, CS 92803 29228 Brest Cedex, marc.lemenn@shom.fr*
[2] *Ecole Nationale Supérieure de d'Électrotechnique, d'Électronique, d'Informatique, d'Hydraulique et des Télécommunications (ENSEEIHT)*

***Abstract* – Doppler current profilers are used in oceanography to measure oceanic circulation, but also in hydrology to calculate the flow of rivers. They allow the retrieval of water masses profiles in terms of velocity and direction. Direction is obtained via an electronic compass and tilt sensors, while velocity is obtained by measuring Doppler pulses shifts back scattered by particles located in water cells allocated along the instrument's measurement range. For current-meters and low range current profilers, calibrations are possible in towing tanks. But, these calibrations are limited in maximum velocity and they are not applicable for long range profilers. In the last years, new techniques were developed to calibrate compass and tilt sensors of current-meters and current profilers in their mooring cages and to obtain in the laboratory the deviations in velocity of these instruments. This paper presents the existing methods and the new advances in the metrological mastering of these devices.**

I. INTRODUCTION

Oceans control a big part of earth climate through ocean – atmosphere exchanges, phenomena such as El-Niño or great cycles and oceanic currents. Measuring current is essential to build current charts useful for navigation, 3D models of oceanic circulation, or more recently, to improve the efficiency of submarine tidal turbines.

Some ten years ago, rotor current-meters were replaced by Doppler effect acoustic current-meters. As the marine environment is favourable to acoustic wave's propagation, the arrival time of pulses reflected by particles, led to the creation of Doppler current profilers. Placed under the hull of oceanographic boats and directed toward the seabed, in cages deposited on the seabed or on mooring cables, and directed toward the surface, water column velocity profiles can be obtained. Their range, which depends on their wavelength, extends from a few metres to several hundreds of metres, according to the particles concentrations.

These profiles are artificially divided into cells by the instrument's software, which gives average velocity values per cell, in relation with the measured Doppler shifts.

Following what was made for rotor current-meters, in the field of river hydrology, quality assurance tests [1], laboratory inter-comparisons [2] or validation by bottom track in towing basins [3-4] have been proposed. In oceanography, Doppler profiler ranges often extend from ten to hundreds of metres, making controls in towing basins impossible. Moreover, the number of stand-alone instruments used in hydrographic and oceanographic centres makes this technique difficult to implement. Thus, over the past years, calibrating or simply testing these instruments has been an untreated problem.

At SHOM, a platform has been built and brought into service in 2012, to calibrate within their instrumental usage configuration, the electronic compasses and the tilt sensors they are equipped with [5-7]. These compasses are used to retrieve the directions of profilers relative to magnetic North, their three transducers being used to retrieve the direction of currents in the instrument referential.

There remained to find a method to calibrate the velocity measurements made by profilers. The solution found was of using an acoustic transducer attached successively to the device under test (DUT) transducers. Linked to a frequency generator, this allows the simulation of echoes received by the DUT. The exploitation of the Doppler effect formula and of the speeds sensed by the instrument, has allowed a test method of the DUT's measurement channels to be perfected [8].

With these last advances, all the quantities measured by current profilers can actually be controlled and calibrated.

II. OPERATING PRINCIPLES OF DOPPLER CURRENT PROFILERS

Current profilers measure velocities (V_1, V_2, V_3) in their beams axes. The transducers are tilted by 20 °, 25 ° or 30 ° (angle β). It is thus possible to calculate velocities (V_x, V_y, V_z) in their own referential [9]:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} \frac{2}{3\sin(\beta)} & \frac{-1}{3\sin(\beta)} & \frac{-1}{3\sin(\beta)} \\ 0 & \frac{-1}{\sqrt{2}\sin(\beta)} & \frac{1}{\sqrt{2}\sin(\beta)} \\ \frac{1}{3\cos(\beta)} & \frac{1}{3\cos(\beta)} & \frac{1}{3\cos(\beta)} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} \tag{1}$$

They are equipped of ‘flux-gate’ compasses to retrieve the amplitude of currents components (U, V, W) in reference to magnetic North (angle Ω), and considering the magnetic declination, in relation to true North (2). Moreover, their inclination can be corrected thanks to a tilt sensor measuring roll and pitch angles Ψ and θ (in equation (2), C = cos and S = sin) [10]:

$$\begin{bmatrix} U \\ V \\ W \end{bmatrix} = \begin{bmatrix} C_\psi C_\Omega & (-S_\psi S_\theta C_\Omega + C_\theta S_\Omega) & (S_\psi C_\theta C_\Omega + S_\theta S_\Omega) \\ -C_\psi C_\Omega & (S_\psi S_\theta S_\Omega + C_\theta S_\Omega) & (-S_\psi C_\theta S_\Omega + S_\theta C_\Omega) \\ -S_\psi & -C_\psi S_\theta & C_\psi C_\theta \end{bmatrix} \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} \quad (2)$$

Speeds (V_1, V_2, V_3) are obtained by measuring the Doppler effect from the detection of echoes resulting of the reflection of pulses on the successive layers of particles. To improve measurements trueness, pulses are repeated at a frequency f_r. The maximum measurable speed V_{max} depends on f_r and on the wavelength λ:

$$\pm V_{max} = f_r \, \lambda / 4 \qquad (3)$$

f_r determines also the maximum profiling range r_{max}, at which a target can be detected without ambiguity concerning its position:

$$r_{max} = c / 2 f_r \qquad (4)$$

c is the speed of sound. Relationships (3) and (4) lead to express the range – velocity ambiguity relationship [11] as follow:

$$V_{max} \, r_{max} = \pm \, c \, \lambda / 8 \qquad (5)$$

To overcome the limits imposed by equation (5), various techniques have been developed, based on the processing of emitted and received signals.

Thus, conventional profilers are called ‘incoherent’ or ‘narrowband’ because the received echoes from two different pulses are not correlated. The lowest uncertainty that can be obtained for the measurements of (V_1, V_2, V_3) is limited by the variance of the Doppler noise σ_δ, which is inversely proportional to the duration of pulses t_p. This noise is generated by the random displacement of particles. To decrease the uncertainty, it is necessary to multiply the number of pulses n. The uncertainty on V_i's, $i \in \{1, 2, 3\}$, can be reduced statistically:

$$\sigma_V = \frac{\sigma_\delta}{\sqrt{n}} \qquad (6)$$

Another solution rests on the increase of the value of t_p, but it leads a reduction in spatial resolution. In order to overcome this ambiguity, ‘pulse-to-pulse coherent’ or ‘pulse coherent’ profilers were created. Their measurement principle relies on working on series of coherent pulses coded in phase. In order to extract the signal from the noise, an auto-covariance function $R(\tau)$ of these pulses is calculated [12]. To improve the extraction, the auto-covariance is assessed from the reception of M sequences of two pulses and of the average of M functions $R(\tau)$ [13]. Most often, the average Doppler frequency characterizing the Doppler shift δf, is extracted from the phase $\phi \in [-\pi, +\pi]$ of this average auto-covariance function. Finally, if f_0 is the emitted frequency, the measured radial velocity is obtained by the relationship:

$$V_i = \pm \, \delta f_i \, c / 2 f_0 \qquad (7)$$

If t_l is the time corresponding to pulses going there and back, we have $2\pi\delta f = \phi / t_l$. The expression of the velocity becomes:

$$V_i = \pm \, \phi \, c / 4 \, \pi f_0 \, t_l \qquad (8)$$

III. THE ‘TRADITIONAL’ CALIBRATION METHODS

For rotor current-meters, this calibration was made in test open channels [14–15] or hydrodynamic channels [16]. The ISO 3455:2007 standard [15] applied in hydrology, specifies the calibration procedure of current-meters equipped with rotating-element or stationary sensors in straight open tanks.

The DUT is fixed on a mobile trolley. A speed sensor often composed of an optical coded rotation sensor, is mounted on the trolley and is used as a reference to control the speed of the trolley and to calibrate the current-meters. If the DUT is a profiler, it can be used in bottom-track mode or in water-track. In bottom-track, the velocity is obtained over the bed. It is representative of the trolley's speed. Basins length and time needed to obtain a constant speed and to slow down, limit the maximum rating carriage to a speed between 1 and 3 m/s.

In the case of hydrodynamic channels, the DUT is in a static position and a turbine allows the variation of the water's circulation speed in the circular channel. A Laser velocimeter or an electromagnetic flow meter, like in ref. [16], gives the reference speed. In this publication, the speed is generated by gravity from a tank and a valve regulates it. A pump allows the reloading of the tank.

These facilities present the advantage to test instruments in hydrodynamic conditions close to usage conditions but with some differences [3]: there is no turbulence, the backscatter material is artificial, the bed is smooth, and there are negligible or zero-velocity gradients in the sample volume.

Their measurement uncertainty is principally limited by the time during which the speed can be keep constant to be considered as a reference and by the reading uncertainty of the reference sensor. Acoustic reflections on bed and sidewall can increase also the measurement uncertainty of the DUT, and acoustic interferences can introduce negatives bias [3]. Because of these side effects, when deviations are calculated, it remains difficult to determine if they come from the instrument or from experimental bias. The direction of the DUT versus the flow can also leads measurement errors.

These facilities cannot be used in the case of long-range profilers whose size of the first measurement cell is superior to the depth of the channel of water. The cleanness of the water is also an obstacle to make measurements with low noise. Doppler current-meters need particles to detect echoes. The lack of particles increases their measurement uncertainties.

Lastly, these facilities do not allow the calibration of compass and tilt sensors. Generally magnetic interferences lead systematic errors on compass readings and they cannot be used.

IV. THE NEW ADVANCES IN CALIBRATION METHODS

In order to overcome the previous problems and to address the needs met in oceanography, a calibration platform for compass and tilt sensors and a velocity calibration bed have been built in SHOM.

A. The compass calibration platform

References [5] to [7] describe in details the techniques used to built the platform and the results obtained on a stock of instruments. Fig. 1 shows the platform with a DORA cage. Compass and tilt sensors are used to retrieve the amplitude and the direction of currents components relative to true North, thanks to relation (2). Tilt sensors are necessary also to retrieve the cells true depth.

Fig. 1. DORA cage on the calibration platform.

Profilers are often installed in mooring cages equipped with launcher, battery packs, flash lamps or tide recorders. The cage and its components can have a strong influence on the local magnetic field. The mapped magnetic field of the platform allows the measurement of induced errors which can be corrected thanks to polynomial relations. If the DUT is in a non-magnetic cage, its instrumental errors can be corrected. Fig. 2 shows an exemple of error function (blue dots) obtained with an AQD mounted in a DORA cage, and the residuals after applying the polynomial (purple squares).

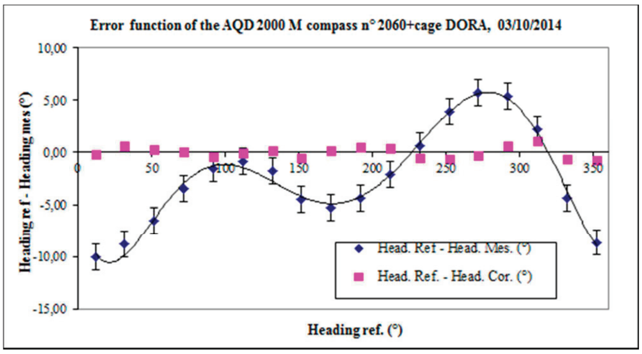

Fig. 2. Error curb of a current-meter's compass installed in a DORA cage.

B. The calibration of transducers

The necessary number of current-meters and current profilers in oceanographic centres (more than 110 units in SHOM) makes inter-comparisons at sea or calibrations in towing basins hardly realisable.

A method, described in details in ref. [8] was perfected, based on fitting a plane hydrophone attached successively on the transducers of the DUT. This hydrophone is used as a receiver, at first, and connected to a numerical oscilloscope. In order to warrant its stability and accuracy in frequency, it is linked to an external Epsilon clock, synchronised to a GPS signal which is a reference for Time and frequencies [17].

A Fast Fourier Transform (FFT) of the digitised signal allows the accurate measurement of pulses frequencies emitted by the profilers. Thereafter from the relation (7) it is possible to determine a frequency variation range corresponding to its variation range in velocity. It is also possible to determine an increment step δf_s, knowing the resolution in velocity δv of the instrument. A frequency generator is therefore adjusted to transmit a variable sinusoidal frequency $f_0 \pm k\delta f_s$, the value of k being used to explore the velocity range. Therefore, in a second step, the hydrophone is used as a transmitter.

All this equipment is remote controlled by a program developed using LabVIEW© software. It automates testing by decoding the messages from different profilers models, to determine and change their configuration, to extract speed values and to drive the frequency generator.

The calibration consists in calculating a speed deviation δv such that:

$$\delta v = V_{ref} - V_i = \frac{c}{2}\left(\frac{\delta f_{ref} - \delta f_i}{f_0}\right) \qquad (9)$$

with $\delta f_{ref} = k\delta f_s$. δf_i is defined by relationship (7), i being the index of the instrument's transducer. c is fixed to

1525 m/s to obtain profilers responses in the range ± 6 m/s (except for the Nortek DeepWater where f_r is different and leads phase wrapping). This value is programmed in the instrument and in the Labview program to calculate a reference velocity V_{ref}.

Most of the instruments tested had errors of less than a few mm/s, but this test bed allowed also to detect defaults on some of them: noisy transducers, small offsets, small non-linearity's and one with a response completely out of tolerances. Fig. 3 shows an example of a noisy transducer on a 1 MHz profiler. The Y-axis represents the measured velocity errors.

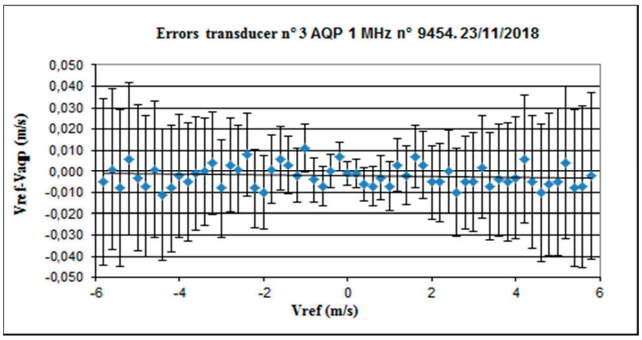

Fig. 3. Example of velocity response curb of a noisy transducer. Error dashes represent the expanded uncertainty of the calibration.

V. CONCLUSION

The new calibration techniques developed for compass, tilt sensors and velocity measurements, allows the test in large number of Doppler current-meter and current profilers. It allows also a calibration in velocity whatever is the range of the instrument. Compared to the 'traditional' calibration techniques, the errors generated by the instrument can be measured and separated of errors in relation with its environment. The uncertainty of the calibration can be also evaluated enough easily.

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