1997 ASME Fluids Engineering Division Summer Meeting
FEDSM'97
June 22 - 26, 1997

FEDSM97-3472

TORSIONAL CURRENT - METER FOR CHANNELS

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ABSTRACT

The main objective of this paper is to present the results of the experimental investigation of a Zarea-type torsional velocity-meter. For this, a torsional meter was designed, built and tested in the laboratory. The current meter consists of an axial rotor with blades fixed to a shaft which is in turn fixed to a rigid hub. The force of the water flow produces a torque which deforms the shaft. The current meter has been statically calibrated, thereby establishing the variational curve of the torsion angle as a function of the applied torque. A laboratory facility has been constructed in which tests were run for water speeds of up 3m/s. The torque measurements were taken by using strain gauges. The methodology and the equipment used for the experimental evaluation are shown. Additionally illustrated are the calibration curves, the analysis of obtained results, some advantages and disadvantages, and the range of application of the torsional current-meter are all discussed.

NOMENCLATURE

c	:airfoil chord
C_l	:corrected lift coefficient
d	:distance between magnetic cells
d_e	:external diameter of the sensor shaft
d_i	:internal diameter of the sensor shaft
g	:gravity acceleration (9.8 m/s^2)
h	:blade span
r_a	:hub radius
r_b	:radial distance from the meter hub to the blade tip
V	:volt
V_w	:towing car and modeled from velocity
V_c	:critical velocity ($\sqrt{g \cdot y}$)
V_e	:input voltage to Wheatstone bridge
V_s	:output voltage from Wheatstone bridge
y	:water depth within the channel
Z	:number of blades

Greek Symbols.

α	:attack angle
λ	:aspect ratio (h/c)
ρ	:water density at 21 °C

INTRODUCTION

The users of rivers and channels need to measure the available capacity and the used capacity. Because of this, various methods can be used as a function of the concrete and specific conditions of the free-surface flow in channels. Many methods and measuring devices permit to obtain the local velocity in a channel. The most appropriate current-meters for rivers and channels are: a) the helical type, also known as Ott mills; b) meters with rotors which have cup-shaped live elements, known as Price-type mills. These devices are mass-produced and subjected to rigorous finishing processes.

The common characteristics of these measuring devices are: a) the use of a rotor which is subject to erosion and marring due to solids dragged by the current; b) the need for expensive repair and periodic recalibrations; c) all this equipment is imported and relatively expensive. In order to minimize some of these design inconveniences, we constructed and experimentally evaluated (Rojas, 1992) a torsional velocity meter following a breakthrough design proposed by S. Zarea.

In this paper, a description of the Zarea-type torsional velocity current-meter, as well as of the Laboratory facility of two of the four constructive versions which were tested, the assay methodology and the obtained characteristics curves, are all presented. It is much more robust, versatile and requires a simpler construction process than a conventional current meter.

It requires cheaper materials, precludes less risk of damage, is much cheaper, and it can be made in this country.

DESCRIPTION OF THE TORSIONAL CURRENT-METER

Figures 1 and 2 show the developed Zarea-type current meter prototype. The device consists of 7 components and two different materials. The prototype dimensions as well as the materials, fit the strength, durability, portability and environmental constraints imposed at the beginning of the design. The sensor element is an aluminium hollow shaft with thin wall. The diameter and thickness are calculated to assure that the element always works in the elastic region of the deformation-stress curve of aluminium.

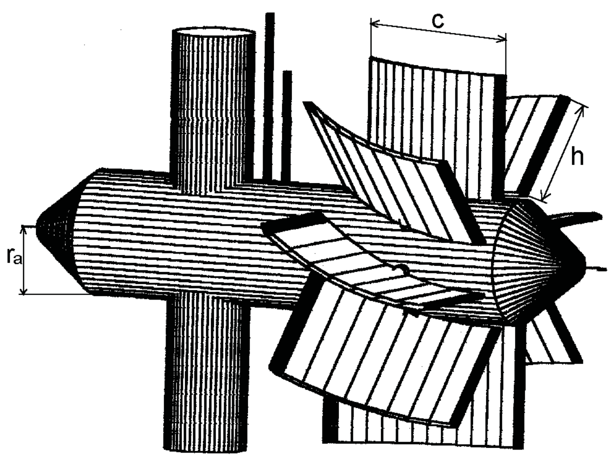

Figure 1. Zarea-type current-meter prototype with 8 curved blades (c=80 mm, h=45 mm, λ=0.5625).

The shaft torsional angle, is measured by a set of four strain gages fixed to the external surface of the shaft and connected in a Wheatstone bridge configuration. The shaft has internal and external diameters d_i and d_e of 6 mm and 6.6 mm, respectively along the sections of the region where the strain gauges are placed. Before the shaft is loaded, the Wheatstone bridge is excited and further balanced with an input voltage. The torsion of the shaft becomes a bridge unbalance and therefore an output voltage V_s.

The experimental prototype is designed to carry several combinations of blade arrangements. This special feature allows to explore the influence of the blade shape, number of blades and orientation of the blades on the instrument performance. In this investigation, two types of blade airfoils are explored : flat and Gö-417A (figures 3a and 3b). The current-meter is tested with 2, 4 and 8 blades, aspect ratio λ of 0.5625 and 1.125, and blade attack angle α between 5 to 25 degrees. Figures 1 and 2 show the current-meter with 8 curved blades and λ of 0.5625, and the current-meter with 4 flat blades and λ of 1.125, respectively.

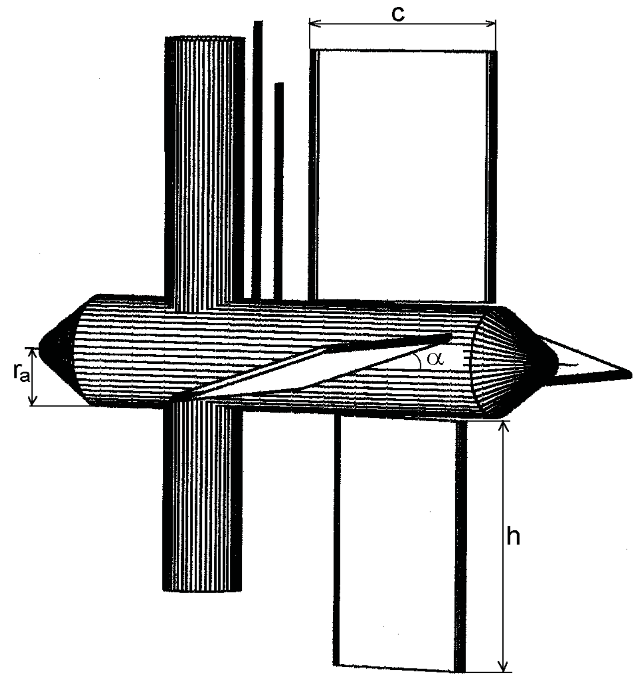

Figure 2. Zarea-type current-meter with 4 flat blades (c=80 mm, h=90 mm, λ=1.125).

The body and the blades of the current-meter are made of plexi-glass, which along with the aluminium for the shaft, give a light and durable instrument. These two materials are compatible with the chemical composition typically encountered in Venezuelan river waters, and allows a light-weight portable device. The frontal cone, covering the blade attaching mechanism, gives an hydrodynamic shape to the current-meter entrance, reducing the perturbation to the incoming flow.

The blades are designed using axial turbine design methodology along with other relevant mechanical considerations.

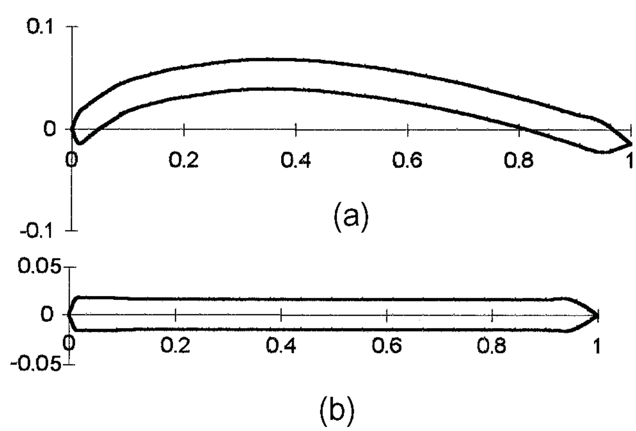

Figure 3. a) Hydrodynamic Profile Gö-417A. b) Symmetrical Profile.

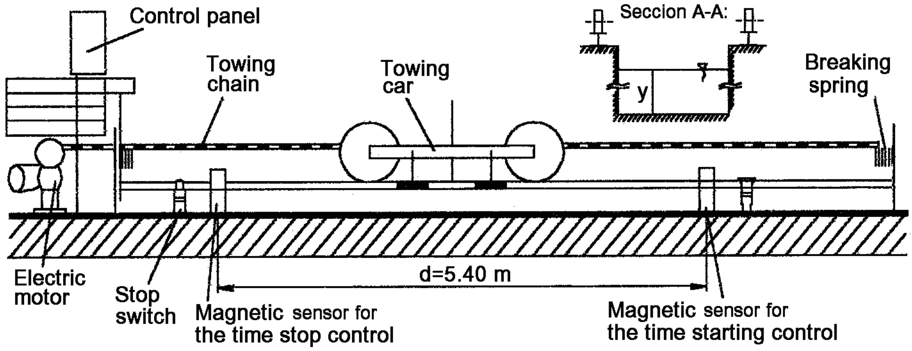

Figure 4. Towing car, car-to-instrument attachment and transmission system of USB calibration facility.

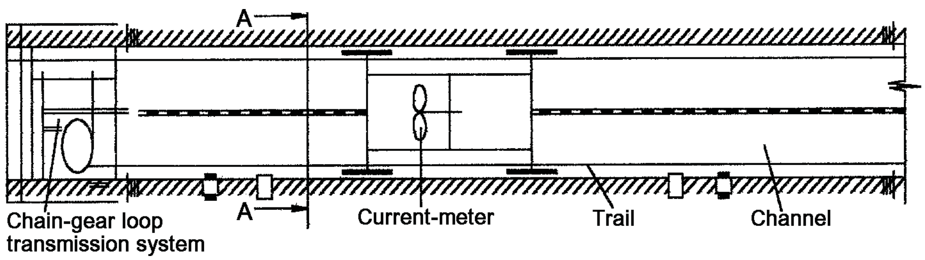

Figure 5. Top view of USB calibration facility.

LABORATORY FACILITY

The relationship between the flow velocity and the shaft torsional deformation is obtained through the current-meter calibration. The calibration consists in towing the instrument immersed in a channel full of water, along a well known length. Therefore, the towing velocity represents the flow velocity and the output signal is the time-averaged output voltage for one-way trip of the car. It is important to outline the absence of standards applicable to the torsional current-meter calibration, and therefore the provisions in standard ISO-3455 are not pertinent in this particular case.

An open channel which already existed in the Mechanical Energy Conversion Laboratory at Universidad Simon Bolivar (USB), is adapted to meet the special requirements of this investigation. This channel had been initially conceived to measure the flow of water feeding the connected turbomachinery (Kaplan and Francis turbines, centrifugal pumps, etc.) The main modification, for the purposes of the current-meter calibration, was the isolation of the channel by the use of two retractable doors located at the opposite ends. An Anderson-type car and screen were modified by removing the screen and using only the wheels and the chassis, to which a light structure was fixed in order to hold the current-meter rod.

Figures 4 and 5, show the modified channel, towing car, car-to-instrument attachment and transmission system, respectively.

The modified USB test facility observed in Figure 4, is a 10 m long, 1x1 m rectangular cross-section channel. The two trails along the channel edges guide the small towing car with the attached current-meter. The towing car transports the current-meter immersed in the water, from one side to the other side of the channel. The car-to-instrument attachment is the same used in the field measurements and permits the instrument immersion at different depths. An electric motor powers the chain-gear loop transmission system, allowing the smooth movement of the car in both directions of the channel at a constant velocity. More details of the towing car, current-meter attachments and transmission system design may be encountered in Rojas (1991).

MEASUREMENT PARAMETERS

The calibration of the current-meter is obtained through the accurate measurement of the distance d between two stations within the car trajectory, the time t taken for the car to go from one station to the other, and the instrument output signal Vs. The measurements are taken within a zone with an approximately constant car velocity v. Also, the current-meter output signal is obtained by averaging the signal along the two station trajectory.

GAUGING CONDITIONS

During the calibration process it is very important to guarantee the proper gauging. Some recommendations and requirements from the standard ISO-3455 and from our own criteria are followed. These are:

a) The error in the measurement parameters has to be smaller than 1 %.

b) Sufficient starting and braking distance out of the measurement zone have to be provided for the towing car. This condition assures an approximately constant car velocity, since a starting distance is required for the car to overcome the initial inertia. The braking distance guarantees a safe impact at the end of trip.

c) A vibration-free track has to be provided in order to reduce current-meter vibration to the minimum during the calibration.

d) The current-meter suspension system has to be the same as the one used during its actual application. The current-meter has to be immersed at such a depth as to render the influence of the wall and water surface effects negligible.

e) Before the calibration is performed, it is highly recommendable to bring the current-meter to the water temperature, since temperature variations affect the strain gauges output signal.

f) The water in the channel has to be at rest before each run. The recommended periods of time at rest after each run, previous to the next run, may be found within the standard ISO-3455.

VELOCITY RANGE IN THE LABORATORY FACILITY

The water depth in the tank might have a negative influence on test results which cannot be neglected. In particular, this is the case when the towing car velocity coincides with the wave propagation velocity on the water surface. This velocity is known as the critical velocity V_c (ISO-3455, 1976).

The wavecrest caused by the towed current-meter produces an increase in the height of the wet transversal section the meter is passing through. This effect causes a reduction in the relative velocity, according to the continuity equation. The phenomenon described before is known as the Epper effect. This effect might produce gauging errors within the velocity range 0.5 V_c to 1.5 V_c. Therefore, the channel maximum velocity was fixed at 1.6 m/s, which represents the lower value of this range.

ACCURACY AND RELIABILITY OF THE RESULTS

The towing car velocity is measured by using two magnetic cells separated 5.4 m (± 0.001m) from each other and located within the channel constant velocity zone at the previously mentioned measurement stations. These cells are connected to a DC wiring system and emit a pulse to start or to stop a digital time-counter when the ferromagnetic element, fixed to the car chassis, passes through them.

The relative error in the velocity calculation due to the instruments and distance measurements is 0.02 %. The error in the commercial voltmeter is smaller than 1 %. Details of the error calculations for the car velocity may be found in Rojas (1991).

The reliability of the measurements has been verified by calibrating two brand-new commercial Ott current-meters. The curves are in agreement within 2 %.

ANALYTICAL MODEL OF THE CURRENT-METER PERFORMANCE

The analytical model, developed in Rojas (1991), is based on the calculation of the torque exerted by the fluid flow passing through the blades onto the shaft.

$$T = \frac{1}{4} \cdot \rho \cdot V_\infty^2 \cdot Z \cdot C_L \cdot c \cdot (r_a^2 - r_c^2) \qquad (1)$$

For this, axial turbomachinery design concepts are used, along with experimental data available for the two selected airfoils. Then, the resultant angular deformation is calculated. Finally, the deformation is related to the electric output from the unbalanced Wheatstone bridge since the strain gauges electric resistance varies as a function of the mechanical deformation. The resultant expression for the output voltage as a function of the flow velocity is (Rojas, 1991) :

$$V_s = 0.000395.\rho.V^2.Z.C_L.c.(r_a{}^2 - r_b{}^2).V_e \qquad (2)$$

The meaning of each of the indicated parameters may be encountered within the nomenclature section of this paper. For all the results reported in this paper, the input voltage V_e was fixed at 4 Volts DC.

CURRENT-METER CALIBRATION

There is a minimum number of points required to obtain a representative calibration curve. The current practice in other current-meter test facilities recommends at least 10 different points for our range of velocities. Therefore, 20 velocities within the covered range are included in each calibration curve. 10 points are taken by testing the instrument from the lowest to the highest velocity and 10 points are taken in the opposite way.

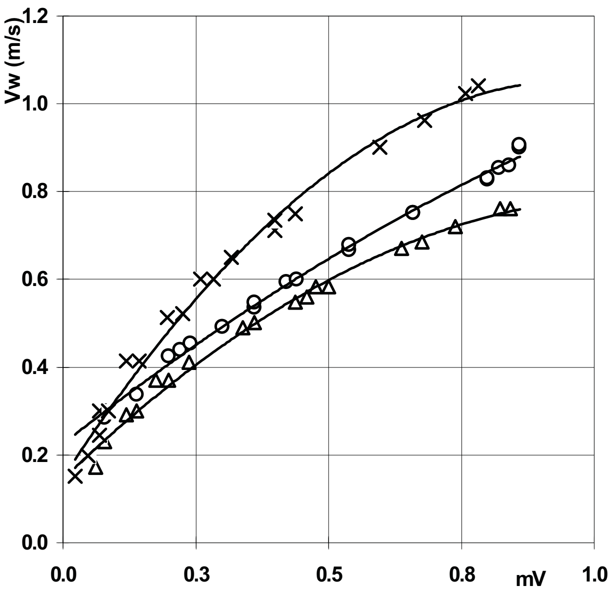

Figure 6. Calibration curves for 4 curved blades.
λ=0.5625; xxx α=5; ooo α=15°; ΔΔΔ α=25°

The calibration is performed for current-meters with 2, 4 and 8 blades, with flat and curved profiles (Gö-417A), installation angles of 5, 15 and 20 degrees, and aspect ratio λ of 0.5625 and 1.125.

Figures 6 to 9 depict the experimental calibration curves for 6 of the investigated configurations. It is notorious, for the cases explored, the parabolic relationship between the flow velocity and the output signal.

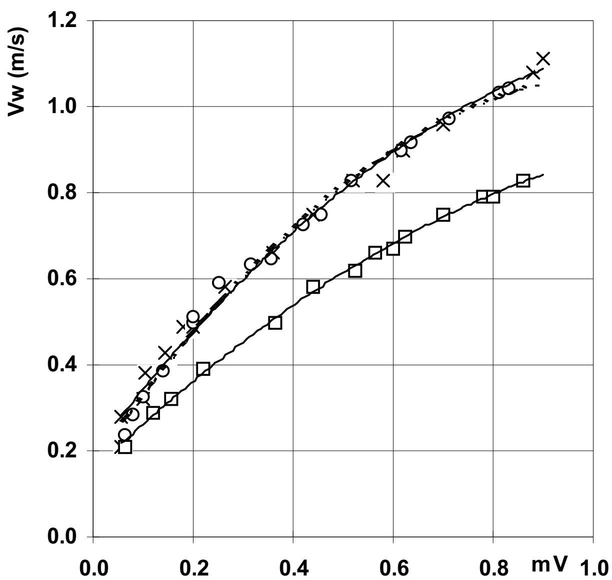

Figure 7. Calibration curves for 4 flat blades.
λ=0.5625; xxx α=5°; ooo α=15°; ΔΔΔ α=25°

The current-meter presents, as expected, a higher output signal with a higher number of blades and aspect ratio. It also has an output that is higher for the curved blades than for the flat blades. The strength of the signal is related to the lift force exerted for the fluid flow onto the blades. This force, through the blade-to-body connection, becomes a torsional moment on the instrument shaft.

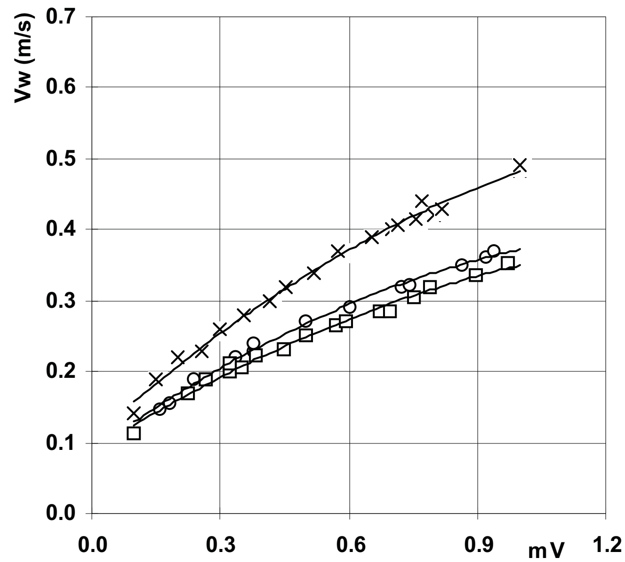

Figure 8. Calibration curves for 8 curved blades.
λ=1.125; xxx α=5°; ooo α=15° ; ΔΔΔ α=25°.

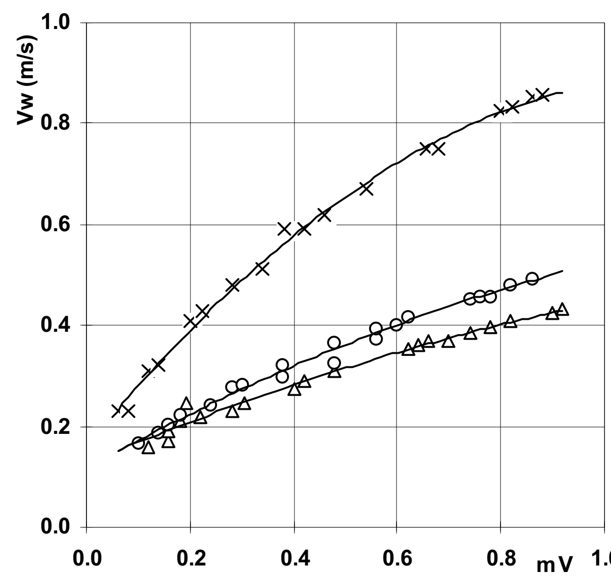

Figure 9. Calibration curves for 8 flat blades.
λ=1.125; xxx α=5°; ooo α=15°; ΔΔΔ α=25°

The results are in good consonance with the analytical model developed in Rojas (1991). In fact, the difference between the analytical predicted results and the experimental data is less than 10 % in all the cases. This difference may be attributed to the number of assumptions considered in the analytical model.

The torsional meter, although still in experimental phase, demonstrated high repeatability and excellent reliability and durability. However, it was noticed a high sensibility of the associated electric components to the external conditions.

CONCLUDING REMARKS

A prototype of a torsional current-meter has been designed, manufactured and experimentally calibrated. The conceptual design is taken from Stefan Zarea original idea.

The Zarea-type current-meter has a parabolic relationship between the flow velocity and the output signal. This performance resulted highly predictable, since the experimental results are in good agreement with a developed analytical model (Rojas, 1991). In particular, the quantitative agreement is observed to be within 10 %.

The strength of the instrument output signal is highly dependent on the blade lift force and the shaft geometry.

The results confirmed higher lift forces present on curved blades than on flat blades under the same flow field at the same attack angle and aspect ratio. It is also noticed a linear proportionality between the lift force and the number of blades, and the attack angle.

Also, as expected from strength of materials considerations, the stiffer the shaft the lower the torsional angle for a given flow-torque condition. In this paper, experimental data is reported for an unique shaft geometry. This unique shaft geometry was chosen to give the highest signal strength for the explored range of velocities, allowing the sensor shaft to work within the elastic range of the material. The elastic range of operation guaranteed the repeatability of the results since hysteresis effects are not present.

In comparison to the commercial units, the Zarea-type current-meter has a fundamental advantage due to the lack of moving parts. This advantage implies the reduction of the need for recalibration.

However, the deformation sensing system, demonstrated to be highly sensible to external conditions and requires further development to be commercially viable.

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