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# CALIBRATION OF A DRAG TILT CURRENT VELOCIMETER FOR AN OPEN CHANNEL APPLICATION

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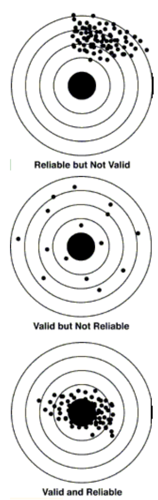
**Graphical abstract**




**Abstract**

Water is one of the prime elements responsible for life on earth with two thirds of the earth's surface covered by it. Managing water resources effectively can promote conservation and make the best use of our limited water resources. Having knowledge about flow information on the river networks can be very beneficial for applications such as hydropower, transportation, irrigation, flood mitigation, water treatment, industrial and domestic needs. The development of simple and inexpensive instrument (<RM500) is to help researchers to produce and measure flows on spatial river at a very low cost. The analytic approximation was derived for giving relationship of the instrument's tilting behavior on water velocity. Calibration process was held and the data are used to investigate the relationship between the measurement collected from the experiment and the known values. Analyzing the experiment results, it was concluded that the instrument tilting in response to the water velocities but not up to the expected known values. Random and systematic errors arise during calibration processes which contribute to the high uncertainties of the instrument. The documented experiments, procedure and facility used for the calibration are given in this paper. It is shown that the accuracy relationship of this instrument against the analytic approximation identified is 66.45%.

*Keywords*: Low cost; flow meter; calibration



## 1.0 INTRODUCTION

The development of Drag Tilt Velocimeter (DTV) has brought in the simplest technology and hydrological concepts into measuring the velocity of water at the river and streams. This innovative approach in developing an electronic flow meter is based on the drag force that a body will experience when immersed in a fluid stream and has proven excellent in measuring flow in the ocean for aquatic study [1]. This DTV is meant to be deployed in the river as it is required for measuring water velocity in field for the mini hydro project. It will serve the purpose of judging the river conditions to locate river flows which will suit the turbine placement in order to assure a highly profit and low risk project development as well as boosting the investor's confidence [2].

There are many flow measurement techniques as well as different types of flow meter to measure the river flow but these all are too costly and require extra effort to monitor and additional safety measures to figure in as well as the maintenance itself. Various types of flow meters are available in the market and Table 1 below lists out the different types of flow meter based on various principles [3].

**Table 1** Flow meter category based on various principles

| Principle | Types |
|---|---|
| Differential Pressure | Orifice Plate type of meter, Rota Meter, Flow Nozzle, Pitot type Tube, Elbow Tap, Venturi Tube |
| Positive Displacement | Oval Gear type, Rotating Disc type, Rotary Vane type, Reciprocating Piston |
| Velocity | Turbine type, Vortex Shedding Electro-magnetic, Ultrasonic Doppler type, Ultrasonic Transit Time type. |
| Mass | Coriolis, Thermal |
| Open Channel | Weir, Flume |

The sensor used to measure velocity can be either contactable type with water or non-contactable. Despite the ability to give highly accurate and precise water velocity, the technology of ultrasonic and acoustic Doppler comes with a price where their deployments at site are limited. The deployment of low cost, robust, user friendly and accurate instrument can be beneficial for the spatial dense of river study. The accuracy of the measurement is an essential step for the qualitative and economic points of view. This paper will observe the behavior of the drag-tilt velocimeter during calibration process and analyze the error made by it.

# 2.0 METHOD OF APPROACH

## 2.1 The Fundamentals of Drag Tilt Velocimeter

Our design of drag tilt velocimeter uses a negatively buoyant object which is mounted under the pontoon or any rigid structure. This technique is not new, but our approach of measuring the tilt angle using a cheap and low power sensing devices is much more accurate than any of the previous systems which manually estimated the angle by visual, which will cause uncontrolled random error and low range of measurement [4]. The measurement range of DTV which relies on tilt angle also increases. There are possibilities for communication through wireless sensor network [5] or cabling direct to the console. The assembly of fittings is also different from others where we introduced a simple and commercially available part made by galvanized iron tube as the drag tilt object where an accelerometer is attached at the bottom of the tube.

Figure 1 below shows the schematic of the Shre Drag Tilt Current Velocimeter (DTCV).The self-weight of the tube should be more than the buoyancy force to act as a restoring force when there is no current and the tilt angle is zero. A downward 'zero' position kept by the negative buoyancy of the tube in a situation of no current.

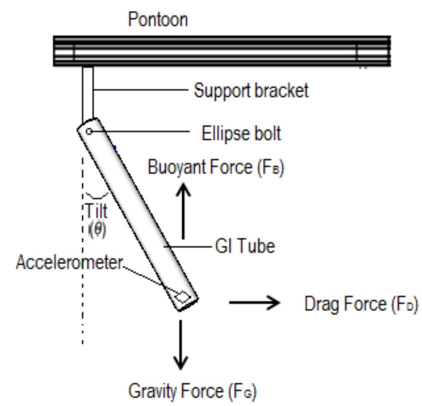



**Figure 1** Shre DTCV Concept

## 2.2 The Analytic Approximation

The technique's principle is that, a drag force will make the submerged tube deviate from the vertical line. An analytic approximation of the system of forces was performed to relate tilt, current velocity, tube size and buoyancy. We consider a simplified static solution with the assumption of horizontal flow than a dynamic solution which is more complicated and nonlinear with flow from various angles.

From energy conservation, the drag force, $F_D$equals to:

$$F_D = \frac{1}{2} v^2 \rho \, C_D A \quad (1)$$

where,

$F_D$ is drag force, (N)
$v$ is current velocity, (ms$^{-1}$)
$\rho$ is water density, (kgm$^{-3}$)
$C_D$ is the drag coefficient, (Unitless) and
$A$ is the cross sectional area of the tube, (m$^2$).

The drag coefficient, $C_D$ varies with the various body size of tube [6], [7].

By equating the drag and restoring forces [4], it follows that:

$$v = k\left(\sqrt{\tan\theta}\right) \quad (2)$$

where,

$k$ is sensitivity factor, (Unitless)
$\theta$ is the tilt angle, (radian)

while,

$$k = \sqrt{\frac{2\, m_{sub} g}{\rho \, C_D \, A}} \quad (3)$$

where,

$v$ is current velocity, (ms$^{-1}$)
$m_{sub}$ is the submerge tube mass, (kg)
$g$ is the gravity coefficient, (9.81 ms$^{-2}$)
$\rho$ is water density, (kgm$^{-3}$)
$C_D$ is the drag coefficient, (Unitless) and
$A$ is the cross sectional area of the tube, (m$^2$)

$m_{sub}$, the submerged mass of the tube assembly is calculated by

$$m_{sub} = m_{tube} - \rho V \quad (4)$$

where,

$m_{tube}$ is the mass of the tube , (kg)
$\rho$ is water density, (kgm$^{-3}$)
$V$ is the volume of the tube, (m$^3$)

### 2.3 The Instrument Setup

The Shre DTCV was manufactured using commercially available materials. We used a bracket as the upper body and ellipse bolt as the swivelled connector for the lower body. The bolt will also prevent the tube from rotating about its longitudinal axis. The dimension of lower body made by galvanized iron is 25mm diameter and 400mm length. The 25mm diameter of pipe allows the insertion of the accelerometer sensor to the bottom of it for data logging. The tube allows the measurement of tilt direction.

### 2.4 Automated Data Collection

The ability to collect useful measurement information on water flow is dependent on the timing and frequency of data collection over time. A very quick response on water flow measurement is a benefit of automated and real time data collection. The installation of the drag-tilt velocimeter under the pontoon based will support the quick and real time collection of the data at any weather condition as the controller and cabling systems of the sensors can be done on the surface of the pontoon. The tilt was measured with an ADXL335 triple axis accelerometer by Analog Devices and supported by Arduino microcontroller.

### 2.5 Selection of Sensor

The main electronic device that detects and measures water velocity through drag and tilt pipe is an accelerometer. It acts as a sensory organ for the brain in the controller, giving its information to make calculation. As the water flows through the tube, it tilts and the accelerometer inside the tube will also be displaced according to the tilt movement. The ADXL335 is a triple axis accelerometer with extremely low noise and low power consumptions shown at Figure 2 below.

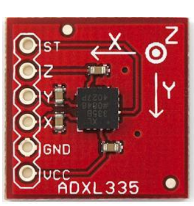



**Figure 2** Accelerometer

Even though this sensor is called accelerometer, we use it as a tilt sensor. The reason why we just do not simply get the acceleration output is because we want the reading in velocity but it is hard to convert acceleration to velocity. That is why we use the formula to get the velocity output by using the formula given by Eq. (2). The reading will be much more accurate based on the object mass and volume, cross-sectional area, water density, coefficient of drag and gravity. We will use the output angle from the ADXL335 into the formula to calculate the velocity of the water in ms$^{-1}$.

The operating voltage range is only 1.6V - 3.6V. Oversupply of the voltage will spoil the sensor. The ADXL335 will connect to the 3.3V on the Arduino UNO board. The most important thing is, when we attach ADXL335 to something, when it is at rest or static, the velocity or angle reading must be zero. Otherwise, the rest of the reading will not be accurate.

Table 2 below lists the absolute maximum ratings of the accelerometer sensor.

**Table 2** Absolute maximum rating of accelerometer

| Parameter | Rating |
|---|---|
| Acceleration (Any Axis, Unpowered) | 10,000g |
| Acceleration (Any Axis, Powered) | 10,000g |
| $V_s$ | -0.3 V to +3.6 V |
| All Other Pins | (COM -0.3V) to ($V_s$ + 0.3V) |
| Temperature Range (Powered) | -55˚C to +125˚C |
| Temperature Range (Storage) | -65˚C to +150˚C |

## 3.0 ASSOCIATED ERRORS

An error in the scientific context is a point to the uncertainty that affects all the measurement. Errors are inevitable. The best one can do is ensuring the errors are as small as reasonably possible and how large they can go could be estimated [8]. For every new instrument, it would be recommended to be calibrated to make sure the instrument accuracy indicated achieved. Occurrences of error in instrument may cause by many factors such as drift, environmental, electrical supply, addition component to the output loop, type of material used, mechanical wear and tear, process changes, etc.[9].

Experimental error can be classified into two categories; namely random and systematic errors. Random Error results from unknown or unpredictable variations during experiment such as temperature or in-line voltage fluctuations. These accidental errors can be reduced by repeating the measurement, taking average value or improving the experimental technique [10]. Systematic Errors are associated with particular instruments or techniques. Reducing the systematic errors always depends on the skill of the experimenter to detect, prevent and correct them since improperly calibrating the instruments are the sources of this error [10]. Measurements with relatively small determinate error are of high accuracy.

Fitting experimental data using the least square method are mostly chosen. The $n$ experimental data points $(x_i, y_i)$, where$i$=1, 2,……., $n$,.. can be modeled by the function $f(x_i, p_m)$ with $m$ adjustable coefficients. The "best" of least square method is defined when the sum of squared residual, $SS_{res}$ is minimal. Given by [8], the $SS_{res}$ is computed as:

$$SS_{res} = \sum_{i=1}^{n} (y_i - f(x_i, p_m))^2 \tag{5}$$

It is defined as the difference values of the dependent variables $y_i$ and the predicted values from the estimated model $f(x_i, p_m)$.

The goodness of the fit statistical model is typically reported as R-square either it is a line or a curve. An $R^2$ closer to 1 indicates a better fit where the regression line perfectly fits the data. If $\bar{y}$ is the mean of observed data, given by [8],

$$\bar{y} = \sum_{i=1}^{n} y_i \tag{6}$$

The variability of the data set can be measured using this sum of squares formula;

$$SS_{tot} = \sum_{i=1}^{n} (y_i - \bar{y})^2 \tag{7}$$

and $R^2$ is computed by;

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{8}$$

## 4.0 EXPERIMENTAL SETUP

### 4.1 Measurement Facility

Most of the time, current meter calibration is carried out by towing instrument meters along a tank at a series of predetermined speed. At National Hydraulic Research Institute Malaysia (NAHRIM), Seri Kembangan, Selangor there are only 60m long flume which can operate reliably at lower speed over a velocity range of 0-0.7ms$^{-1}$. The flume section is 60 meters long, 2 meters deep and 1.2 meters wide. It has a combination of concrete walls and glass side wall. Figure 3 below shows the plan view diagram of the experimental set up for this calibration process.

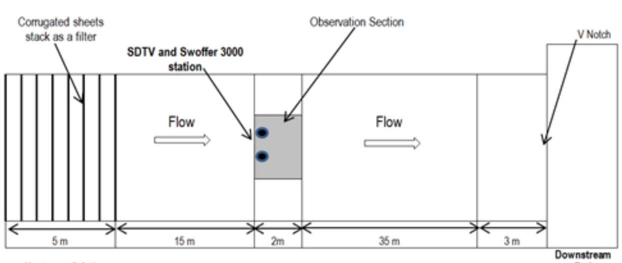



**Figure 3** Plan view of the experimental set up

The width result is dimensionally stable and repeatable. Figure 4 below shows the general view of the flume.

**Figure 4** Flume facilities at NAHRIM

To perform the experiment, the flume was filled with water up to 1.2 meters deep. The flow was generated by circulating the flow from the holding pond at the downstream end of the flume back to the upstream end of the flume. To accomplish the process, 2 units of variable heavy duty electrical powered 4hp pump was installed to force the water up with the pump inlet connected to the downstream holding pond then the pump outlet was connected to an inlet of the upstream flume structure which goes through a series of filters. The entrance to the flume was designed to give disturbance free uniform velocities by series of filters so fairly uniform laminar flows go through the flume.

### 4.2 Calibration Procedure

At the early stage, the water left stagnant and stable without any flow to locate a downward 'zero' position kept by negative buoyance of the drag tilt tube. In this no current situation, a tilt reading was recorded digitally by accelerometer to the computer and the real flow reading recorded visually by Swoffer 3000, a propeller type current meter.

To measure the response to differing flow rate, water velocity was varied from 0 ms$^{-1}$ to 0.7 ms$^{-1}$. It was done by running the water through the flume by controlling the water pump power switch to get variations of speed. Until the flow becomes perfectly stable at the location identified, the flow readings were recorded.

The drag tilt velocimeter was steadily installed about 15 meters from the upstream end, while the Swoffer 3000 was attached adjacent to it as per Figure 5 below.

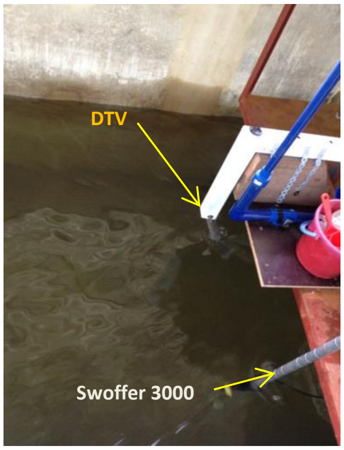



**Figure 5** Arrangement of DTV and Swoffer 3000 current meter at Flume

Three series of flow run were conducted at different constant velocities. The data of calibration curve of three series of run was analyzed on the basis of analytic approximation curve as described in Section 2.2 above. The three run of calibration data was combined to check the overall performance of the Shre DTCV.

## 5.0 RESULTS AND DISCUSSIONS

The behavior and performance of the Shre DTCV are interpreted in the following graphs.

### 5.1 Analysis of calibration curves:

From the experiment, the variations in the value of velocities were observed. The graph was drawn for the variations in the value of velocities, $v$ against the tube tilt inside the water, *rad*.

The graphs of runs no. 1-3 (Figures 6, 7, 8) show that the tube continuously tilts from 0-0.7 radian as velocities increase

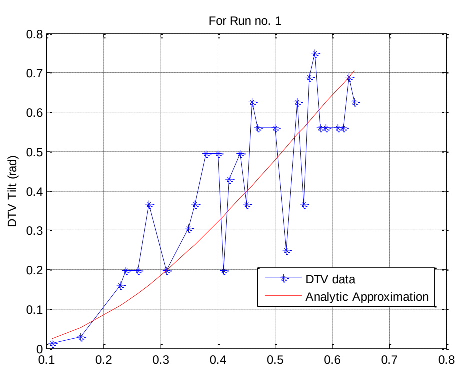



**Figure 6** Graph for Run no. 1

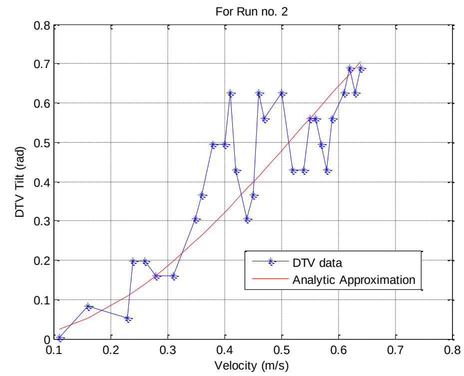



**Figure 7** Graph for Run no. 2

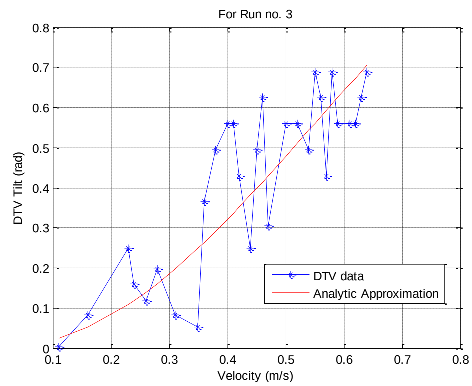



**Figure 8** Graph for Run no. 3

As per Table 3 below, the fluctuations of radian tilt shows that the tube tilting is not 100% following the preset value of analytic approximation curve as there are random and systematic type of errors during the calibration process. Only 62.36% of calibration data fitted the analytic curve for test run 1. While for test run 2 it is 68.99% and test run 3 is 67.80%. Standard deviation for run 1 and 2 is similar which is 0.041, while run 3 is 0.047

**Table 3** Details of calibration results

| Test Run | Standard deviation | R-Squared |
|---|---|---|
| No. 1 | 0.041 | 62.36% |
| No. 2 | 0.041 | 68.99% |
| No. 3 | 0.047 | 67.80% |

### 5.2 Analysis of Combining All Calibration Curves:

All the three sets of the calibration data were combined to discover more information when the data was fitted into the analytic curve. The graph is as shown at Figure 9 and the details calibration results as per Table 4 below. It was found that the R-squared and standard deviations were not much change compared to the individual run test with 66.45% and 0.042 values each. Points that fall off the trend lines decreased the R-squared value.

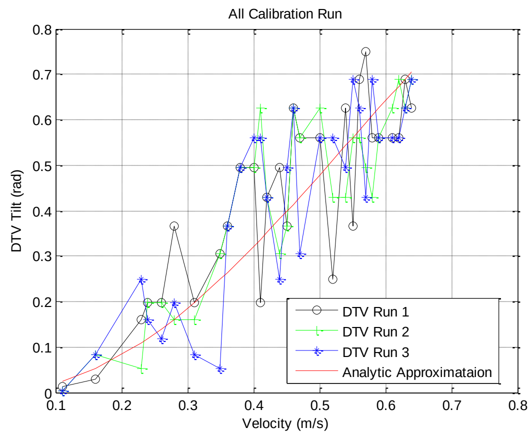



**Figure 9** Graph for combination run

**Table 4** Details of combine calibration results

| Test Run | Standard deviation | R-Squared |
|---|---|---|
| Combine Test Run | 0.042 | 66.45% |

The low accuracy points means that the calibration process and procedure is less accurate or not properly done. It happened consistently at all three sets of calibration data and exists either at low flow or high flow region. The increase of error may be associated with the procedure or the instrument itself.

## 6.0 CONCLUSIONS

The root cause of wide spread variations on the data calibration values can be the instrument configuration systems and calibration process. Thus, a detail configuration of system needs to be executed on the Shre DTCV in order to increase the accuracy of the instrument. Furthermore, a proper calibration technique and procedures can be conducted at an accredited lab and performed by skilled control system technician where their equipment, standard and procedure are traceable to a national or international standard. Calibration or zeroing a flow meter instrument in flow meter measurement is critical and should be done properly to avoid a systematic offset introduced into the system. The technique of using the drag-tilt principle in measuring water velocity is still reliable. Their low cost, rugged, attractive and user friendly system require much more effort on research in order to increase the accuracy of the instrument. Analytic approximation can be made as a guideline in designing the instrument. At the same time, introducing an artificial intelligence technique or modeling can be beneficial to increase the instrument's accuracy. As there is no instrument which has 100% accuracy, as yet the drag-tilt instrument can help researchers to get spatial dense of river study at a very low cost.

## Acknowledgement

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