Flow and efficiency measurements with clamp-on ultrasonic equipment

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Abstract. There are several efficiency measurement methods to determine the performance of hydraulic turbines under various circumstances in hydropower plants. To do this, most of the measurement methods require precise determination of discharge. Any hydropower plant with complex pipe geometry and short water inlet near discharge measurement section complicates the use of traditional measuring techniques. Clamp-on ultrasonic flowmeter (USM) can be a good alternative in this situation as it is easy to install at very low cost compared to most of the volumetric flowmeters. Clamp-on USM can be used as index testing method that provides relative values of hydraulic efficiency by measuring the discharge.

In this study, discharge measurements with a clamp-on USM were performed at three different positions away from a valve which was partially opened. The main objective was to study the repeatability of the measurements in each position.

1. Introduction

1.1. Background

The knowledge of turbine efficiency and performance is necessary to know how a turbine is operating, to determine if the guarantees given by turbine manufacturer are fulfilled and for optimizing operation [1]. Efficiency tests are also useful to confirm the efficiency gain after upgrading the old powerplants.

There are several methods for determining the efficiency of a turbine. The choice of the methods depends on factors like available pressure head and discharge, costs associated with the measuring equipment, its installation and implementation, design and geometry of the conduits in powerplants and operative conditions.

Hydraulic efficiency, $\eta_h$, is found by dividing the mechanical power by the hydraulic power [4]:

$$\eta_h = \frac{P_m}{P_h}$$  \hspace{1cm} (1)

where $P_m$ is the mechanical power delivered by the turbine shaft and $P_h$ is the hydraulic power available for the turbine to produce power.
Before one can determine hydraulic power, $P_h$, available, the discharge, $Q$, should be known, which is the most challenging parameter to measure precisely.

$$P_h = \rho Q g H_n$$  \hspace{1cm} (2)

where $g$ is the local value of gravitational acceleration, $\rho$ is the density of water and $H_n$ is the net head available.

For discharge measurement, either absolute method or relative method can be used. Absolute methods are considered as the fundamental methods for determining the absolute values of both discharge and hydraulic efficiency. Relative measurements, commonly referred as index tests are usually performed either to gain supplementary information or as alternatives when absolute methods are difficult to implement [4]. Winter Kennedy (WK) method is still a very popular relative discharge measurement method, although results with this method have shown discrepancies [1]. An alternative measurement method, clamp-on ultrasonic flowmeter (USM) will be presented in this paper.

1.2. Previous studies

Discharge measurements with clamp-on USM do not fulfill the accuracy and reliability requirements of IEC standard. However, the method can be used as relative flow measurement method under mutual agreement [4]. The accuracy of clamp-on USM using single path was studied in 2008, and it was found that the repeatability of the flow measurements was within $\pm 0.15\%$ of the flow rate [6]. Most of the investigations so far have considered only favourable situations such as long and straight pipe geometry to find the repeatability of the clamp-on USM [6][9][10]. However, this paper will mainly focus on the repeatability of the clamp-on USM downstream of a partially opened gate valve.

1.3. Uncertainty analysis

Three different types of errors that must be considered in statistical analysis of flow measurements are spurious errors, systematic errors and random errors. Spurious errors occur because of human and instrumental failure and these should be avoided and corrected if discovered. Systematic errors are caused by the equipment errors, and these errors cannot be removed by calibration or by increasing the number of measurements. Random errors on the other hand are caused by numerous, small and independent influences which are unpredictable. The parameters like variable water temperature and density and noises in the electrical installation can lead to random errors while measuring the velocity of the flow.

Repeatability is a measure of the ability to provide repeatable measurements under the same conditions. It is determined by measuring random uncertainties of the measurements [9], whereas systematic uncertainties do not affect the repeatability of the measurements during a test [4]. For the precise estimation of a true value it is important
to calculate a mean value from the measurements. For \( n \) number of measurements, \( X_1, X_2, X_3, \ldots, X_n \), the arithmetic mean, \( \overline{X} \) is found by using equation 3.

\[
\overline{X} = \frac{1}{n} \sum_{i=1}^{n} X_i
\]  

(3)

where \( X_i \) is the value of the \( i \)th measurement. It is necessary to calculate standard deviation \( (\sigma) \) and decide the confidence level to determine the random uncertainties of the measurements. The exact \( \sigma \) of any measured parameter is rarely known, but its estimate \( \text{Std}_x \) can be calculated using equation 4.

\[
\text{Std}_x = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (X_i - \overline{X})^2}.
\]  

(4)

The requirement made by IEC41 [4] is that the random uncertainties should lie within a 95% confidence level. For relating the required confidence level to the interval, the Student’s \( t \) distribution can be used. For doing this, the number of degrees of freedom, \( \nu \) is defined as \( (n - 1) \), where \( n \) is the number of measurements. The value of \( t \) for corresponding number of degrees of freedom can be calculated using equation 5 [4].

\[
t = 1.96 + \frac{2.36}{\nu} + \frac{3.2}{\nu^2} + \frac{5.2}{\nu^{3.84}}
\]  

(5)

Using equation 6, the random uncertainties of the measurements can be calculated.

\[
\text{u}_r = \pm \frac{t \cdot \text{Std}_x}{\sqrt{n}}
\]  

(6)

The corresponding percentage error is equal to

\[
\text{u}_r(\%) = \frac{\text{u}_r}{\overline{X}} \cdot 100
\]  

(7)

2. Clamp-on ultrasonic equipment as a flowmeter

Unlike inline flowmeters, clamp-on USM has its transducers and sensors externally mounted on a measuring tube. The discharge measurement with this equipment is made without interrupting the flow or draining the pipe. Clamp-on USMs use either

![Figure 1. Clamp-on USM with V-configuration](Image)
transit-time or Doppler technology to measure the velocity of the fluid, while in some cases both of them are used. This study will only focus on the clamp-on transit time ultrasonic flowmeter (TTUF) using a single path system. It includes transducers externally mounted in a measuring section of the pipe, an electric equipment to operate the transducers which take the flow measurements and process the measured data and a display window where the recorded data will be displayed. The transducers are piezoelectric elements which generate ultrasonic pulses that penetrate through the pipewall and are transmitted along the path as shown in figure 1. The theory of operation of ultrasonic flowmeter is based on the fact that the sound wave or ultrasonic wave traveling in the same direction as the fluid has bigger absolute velocity than a wave traveling in the opposite direction. The flowmeter calculates the average fluid velocity based on the difference in time required for the waves to travel between the upstream and downstream transducer. It can be shown that for a uniform velocity in a pipe, an expression for the average fluid velocity, $V$, can be obtained in terms of the transit times of upstream, $t_u$, and downstream, $t_d$, wave pulses and the time difference, $\Delta t$.

$$V = \frac{L^2 \Delta t}{2X t_u t_d} = \frac{L \Delta t}{2 \cos \theta t_u t_d}$$

where $X$ is the axial spacing between transducers and $L$ is the path length [5] as shown in figure 2. The average fluid velocity can be used to measure discharge, $Q$, by taking into account that the pipe internal diameter, $D$, is known. Using equation 8 and assuming that $V$ is constant across the pipe, $Q$ can be determined.

$$Q = \frac{\pi D^2 V}{4} = \frac{\pi D^2 L \Delta t}{8 \cos \theta t_u t_d}$$

It is obvious that the expressions given for $V$ and $Q$ when dealing with a clamp-on flowmeter will be different. $t_u$ and $t_d$ will be different now because the time taken by the pulses through transducers wedge and pipe wall should be considered in this case [5].

3. Installation effects on Clamp-on USM

The algorithms used by clamp-on USM to determine the velocity of the fluid assumes an “ideal” flow stream where the flowmeter is placed. The “ideal” flow stream can be
intercepted as fully developed, symmetric, swirl-free turbulent flow profile as shown in figure 3.

![Figure 3. Fully-developed turbulent velocity profile](image)

The velocity profile which is not ideal is distorted in some way. For example, a 90° bend or a valve will change fully-developed, symmetric, swirl-free velocity profile passing through it to one that has counter-rotating vortices and an asymmetric profile. This type of flow distortion affects the clamp-on USM measurements using single beam as it is very sensitive to the velocity profile. A distorted flow requires relatively long length of straight pipe to re-establish their characteristics of a fully developed flow profile [8].

4. Experimental setup

In order to study the repeatability of the clamp-on USM, discharge measurements with this flowmeter were carried out at three different distances away from a partially opened gate valve. The water was led down from a tank to a long, straight pipe arranged with an electromagnetic flowmeter and the gate valve as shown in figure 4. The tank was constantly filled with water with the help of a pump. The test pipe was of stainless steel with inner and outer diameter of 150 mm and 154 mm respectively. The pipe wall thickness was 2.0 mm.

The electromagnetic flowmeter was used as the reference flowmeter in order to validate the measurements obtained with the clamp-on USM.
5. Measurement procedure

The repeatabilities of the clamp-on USM were studied for three different cases as given in table 1. These cases were based on how far the clamp-on meter was placed from the valve which can also be seen in figure 4.

Table 1. Distance between the valve and the clamp-on USM.

| Case | Distance from the valve |
|------|-------------------------|
| 1    | 3.70 m = 24.7 D         |
| 2    | 1.47 m = 9.80 D         |
| 3    | 0.59 m = 3.93 D         |

6. Results

The discharge measurements obtained by the reference flowmeter and the clamp-on USM along with other parameters that were taken in account to find the random uncertainties of the clamp-on USM are given in table 2. Equations 3, 4 and 6 are used to calculate the mean values, standard deviations and random uncertainties respectively for all the cases. Determining hydraulic efficiency in a hydropower plant is not a complex task once discharge is determined, as other parameters given in equation 1 and 2 are not difficult to find. As a result no any effort was made to perform efficiency measurement in this study.
Table 2. Random uncertainties for all three cases together with other parameters.

|                  | Case 1  | Case 2   | Case 3  |
|------------------|---------|----------|---------|
| Q<sub>ref</sub>  | 0.0112  | 0.0112   | 0.0112  |
| Q<sub>mean</sub> | 0.0108  | 0.0107   | 0.0118  |
| Number of repetitions, n | 30     | 30       | 30      |
| Standard deviation, SD<sub>Σ</sub> | 6.02 · 10<sup>-5</sup> | 1.04 · 10<sup>-4</sup> | 2.22 · 10<sup>-4</sup> |
| Random uncertainty, u<sub>r</sub> | 2.25 · 10<sup>-5</sup> | 3.90 · 10<sup>-5</sup> | 8.30 · 10<sup>-5</sup> |
| u<sub>r</sub> in percentage of mean value, X | 0.208% | 0.365% | 0.712% |

Q<sub>ref</sub> is the discharge measurement obtained by the reference flowmeter. Q<sub>mean</sub> given in the table is the average of 30 repetitions of measurements taken by the clamp-on USM in each cases. The Q<sub>ref</sub> value is only given to figure out how far the Q<sub>mean</sub> values are from it. As the main objective of this paper is to find the random uncertainties and the repeatabilities of the measurements obtained by the clamp-on USM, the Q<sub>ref</sub> values are not given importance.

6.1. Case 1

In Case 1, the clamp-on USM was placed 24.7 D away from the valve in which random uncertainty, u<sub>r</sub>, was calculated to be 0.208%. Q<sub>ref</sub> values taken at the same time as

![Figure 5. Discharge measurements taken in 30 repetitions in case 1.](image)

Q<sub>clamp-on</sub> values, were around 0.0112 m<sup>3</sup>/s and seem to be steadier than Q<sub>clamp-on</sub>. Each of these 30 Q<sub>clamp-on</sub> values obtained represents the average of more than 600 measurements.

6.2. Case 2

In Case 2, where the clamp-on USM was placed 9.80 D away from the valve, u<sub>r</sub> was found to be 0.365%. Q<sub>mean</sub> was 0.0107 m<sup>3</sup>/s, and Q<sub>ref</sub> were as in the first case. The random uncertainty of the measurements in this case was bigger than that of Case 1.
This can also be seen in figure 6 as \( Q_{\text{clamp-on}} \) values are more spread out from the mean line here than in Case 1.

![Figure 6. Discharge measurements taken with 30 repetitions in case 2.](image)

### 6.3. Case 3

The random uncertainty of the measurements was even bigger in Case 3 which was 0.712\%. In this case, the clamp-on USM was placed just 3.93 D away from the valve. \( Q_{\text{clamp-on}} \) values are even more spread out in this case which can also be seen in figure 7.

![Figure 7. Discharge measurements taken with 30 repetitions in case 3.](image)

Unlike the first two cases, in this case, \( Q_{\text{clamp-on}} \) values for all 30 repetitions were bigger than \( Q_{\text{ref}} \).

### 6.4. Error bar

Error bars of the standard deviation of all the cases is shown in figure 8. The error bar is small for case 1 when the clamp-on was placed far away from the valve representing
a very high repeatability. The error bars get bigger as the clamp-on USM gets closer to the valve.

7. Discussion

The upstream pipe configuration in all three cases was the partially opened gate valve. The phenomena such as swirling eddies and asymmetric velocity profile mentioned above, which develop after the valve could have made impacts on the discharge measurements obtained by the clamp-on USM. The measurements repeatability of case 1 when the flowmeter was placed 24.7 D away from the valve was expected to be higher than of two other cases. This was logical assumption as the intensity of the most of the installation effects would have gradually decreased before this point. The confirmation for this was calculated and the size of the error bar for this case.

The measurements repeatability got lower as the clamp-on USM was placed closer to the valve. For case 3, installation effects were considered to be very severe as the flowmeter here was positioned nearby the valve. The random uncertainty of the measurements and the size of the error bar obtained verified the severity of installation effects in this case.

The total uncertainties of the measurements were neglected, as the main objective of this paper was to study the repeatability of the clamp-on ultrasonic equipment. The results in case 1 and case 2 give confidence that the equipment can be used for comparative flow efficiency measurements in hydropower plants. Obviously, two parties should determine themselves the acceptable value of the repeatability of the equipment.
8. Further work

Pipe configurations like bends and valves are difficult to ignore in hydropower plants. Further investigations will be carried out in attempt to obtain more reliable discharge measurements using clamp-on USM with single paths system near a double bend. A clamp-on USM with several paths system is less sensitive to the velocity profile. One approach to get similar characteristic with clamp-on USM with single path could be determining the mean velocity by systematically rotating the flowmeter around the pipe. This might give a precise value of mean velocity. CFD simulations are required to get the knowledge of appropriate angles where the flowmeter should be placed to obtain reliable mean velocity right after the double bend.

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