

## UNCERTAINTIES FOR PRESSURE-TIME EFFICIENCY MEASUREMENTS

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### ABSTRACT

In connection with the pressure-time project at the Norwegian University of Science and Technology and Luleå University of Technology, a number of tests with the pressure-time method have been performed at the Waterpower Laboratory in Trondheim, Norway. The aim is to lower the uncertainty and improve usability of the method. Also a field test at the Anundsjoe power plant in Sweden has been performed.

The pressure-time measurement is affected by random uncertainty. To minimize the effect of the random behavior it is found that a correct integration end limit in the integration of the differential pressure is essential. An analysis using 100 different end points for integration show a possible random error as large as 0.6%. A filtration method for finding an appropriate end point is developed and presented.

In laboratory, the random behavior of the method can be described since many tests can be performed. During field measurements, this may not be feasible. However, the random uncertainty can be included if the efficiency curve can be described by polynomial regression curves. This method is presented with the Anundsjoe Power Plant measurements.

### 1. INTRODUCTION

In all experimental work it is important to know the limits and capabilities of the method and equipment. This includes all the uncertainties that arises during measurements. It is essential to know how the method performs relative to the actual conditions, e.g., actual flow, fluctuations etc. Therefore, finding a flow matching a reference flow is not the only goal. Consistency in the measurements is essential to give a statistically good foundation for research. There is therefore a need for a statistical foundation to describe influence from e.g. distance between measurement cross sections, flow velocity, bends and so forth. Efficiency tests on hydro power plants are usually made with few repetitions at each operational point. This restricts the possibility for finding random behavior and uncertainties. To investigate the uncertainties, at a detailed level and with well controlled conditions, a pressure-time measurement test rig was built in the Waterpower Laboratory at NTNU in Trondheim. Performing pressure-time measurements in a laboratory has some disadvantages:

- joints and pipes not directly involved in the test can give pressure pulse reflections and hence noise in the measurements
- limitations in
  - pipe diameter
  - length of pipes
  - maximum flow

But there are also advantages which make laboratory tests very valuable:

- good reference of real flow
- high accuracy test geometry specification
- high accuracy and control of test conditions
- possibility to perform a large number of tests

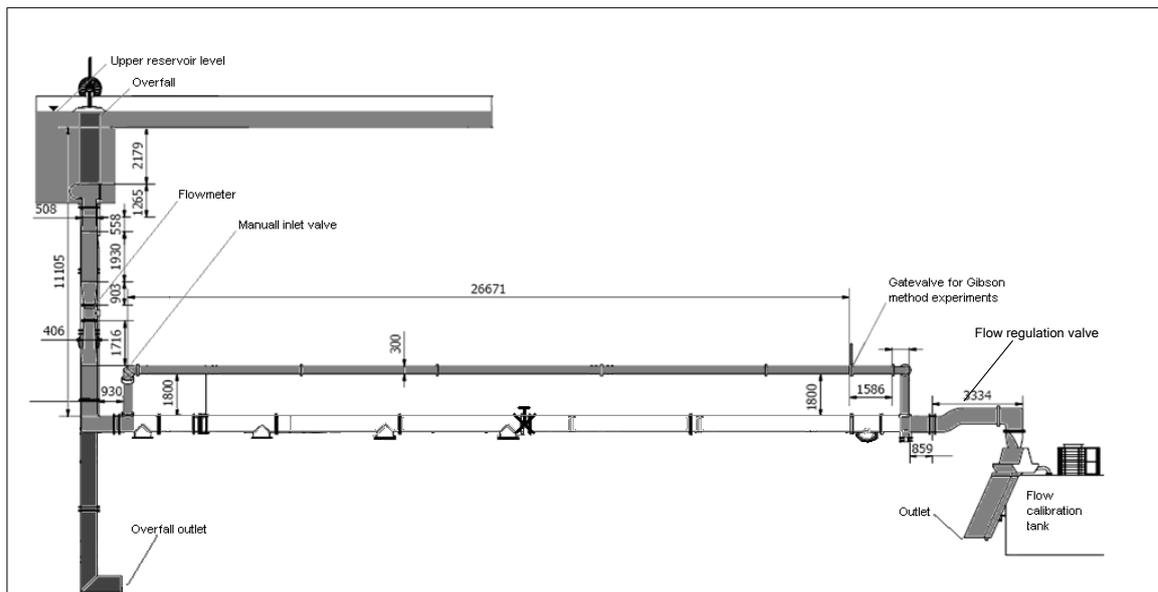
Especially the last point is convenient as the tests are not subject to economy or power production for a company, which is usually rather common during site efficiency test.

This paper evaluates the main uncertainties for a pressure-time method in the laboratory. Developments of different methods to improve pressure-time calculations on noisy signals are also discussed.

For a field test at Anundsjo power plant in Sweden it is shown how the uncertainties that originates from the efficiency curve, and/or the random behavior of the test points can be implemented in the total uncertainty.

## 2. THE LABORATORY SET UP

Figure 10 shows a schematic overview of the test rig. The pressure-time test section consists of a stainless steel pipe with 300 mm diameter and 26.7 m long. The valve is operated by a hydraulic aggregate and actuator.



**Figure 10: Schematic of the laboratory test rig.**

The pressure sensors used in this project are Honeywell FP2000/FDW differential pressure transducers (DPT) with a range from -0.5 to 0.5 bars. Four sensors connected to the pipe by tubing have been distributed around the pipe with an even angle of  $90^\circ$  between them. Calibration was done using a Procurements P3023-6-P dead weight manometer system, and based on this the specific uncertainty was determined. The specific uncertainties of the sensors obtained by calibration vary from 0.06% to 0.12%, the manufacturers specification is 0.25%. In lack of better ways to combine uncertainties from several sensors it is chosen to use the mean of all specific uncertainties as the specific uncertainty for the system as a whole. The reference flow is determined by an electro-magnetic flux flow meter, calibrated with the laboratory's flow calibration system. The overall uncertainty for the reference flow is approximately 0.3% according to the manufacturer.

The test cases have been performed on three approximate flows, 400, 300 and 170 l/s, and variable distance between measurement cross-sections. The distances have been 3, 4, 6, 9 and 17 m. Results for a flow of 400 l/s with measurement cross-sections distance 9 m are mainly used for illustration in the uncertainty analysis. For the end point discussion measurements at 6 m and a flow of 170 l/s is used since it is graphically good as an example.

## 3. CALCULATION AND UNCERTAINTY

Calculation of flow rate is done using equation 2.1

$$Q = \frac{A_{\text{int}} \cdot A_{\text{pipe}}}{l \cdot \rho} \quad [\text{m}^3/\text{s}] \quad (2.1)$$

where

$$A_{\text{int}} = \int_{t_1}^{t_2} (\Delta p + \xi) \cdot dt \quad [\text{kg/ms}] \quad (2.2)$$

This gives the uncertainty equation

$$f_Q = \sqrt{f_{A_{\text{int}}}^2 + f_{A_{\text{pipe}}}^2 + f_l^2 + f_\rho^2} \quad [-] \quad (2.3)$$

For values of the parameters see Table 1.

Furthermore, the spread of the measurements are evaluated relative to the mentioned EMF flow meter which also has an uncertainty  $f_{EMF}$ . This uncertainty is calculated from the uncertainty given in calibration and the random uncertainties during tests. The final uncertainty equation for the measurements becomes

$$f_Q = \sqrt{f_{A_{\text{int}}}^2 + f_{A_{\text{pipe}}}^2 + f_l^2 + f_\rho^2 + f_{EMF}^2} \quad [-] \quad (2.3b)$$

In this equation the parameter  $f_{A_{\text{int}}}$  is calculated by

$$f_{A_{\text{int}}} = \sqrt{\frac{\sum_i^n (e_{(\Delta p + \xi)_i})^2}{\sum_i^n (\Delta p + \xi)_i^2} + f_t^2 + f_{Q_{t=zero}}^2} \quad [-] \quad (2.4)$$

where  $e_{(\Delta p + \xi)_i}$  shall consist of both a specific and a random uncertainty, but since the water hammer is a transient phenomenon, the random uncertainty is difficult to evaluate. Values based on experience can be used, but here it is chosen to use the same random uncertainty for the water hammer as for the stationary mean before the valve closure. Further

$$\begin{aligned} f_{Q_{t=zero}} &= \sqrt{\left(\frac{0.5 \cdot e_{r_{start-1}} \cdot \Delta t}{A_{\text{int}}}\right)^2 + \left(\frac{0.5 \cdot e_{r_{2-end}} \cdot \Delta t}{A_{\text{int}}}\right)^2 + \left(\frac{e_{\Delta p_{spec}} \cdot \Delta t}{A_{\text{int}}}\right)^2} \quad [-] \\ &= \frac{\Delta t}{A_{\text{int}}} \cdot \sqrt{(0.5 \cdot e_{\Delta p_{start-1}})^2 + (0.5 \cdot e_{\Delta p_{2-end}})^2 + (e_{\Delta p_{spec}})^2} \end{aligned} \quad (2.5)$$

$f_{Q_{t=zero}}$  is the uncertainty in the determination of pressure lines or the uncertainty in the mean of the stationary values before and after the valve closure. It is based on the strategy presented by Hulås and Dahlhaug [2] in Portland 2006, but with some changes. In the original method this uncertainty was, easily explained, based on variations in calculated flow from different samples of start and end points. Here the basis for the parameter is the random and specific uncertainty in the averages of the pressures before and after the valve closure, and the influence this uncertainty has on the integrated area.

The valve used in the laboratory measurements is absolutely tight; hence there is no uncertainty contribution from leakage.

Table 1 shows the uncertainty for the different parameters represented in the uncertainty calculations. Some uncertainties are individual for each test, e.g., random uncertainties. To describe these, the span of uncertainty is showed.

**Table 3: Parameter uncertainties.**

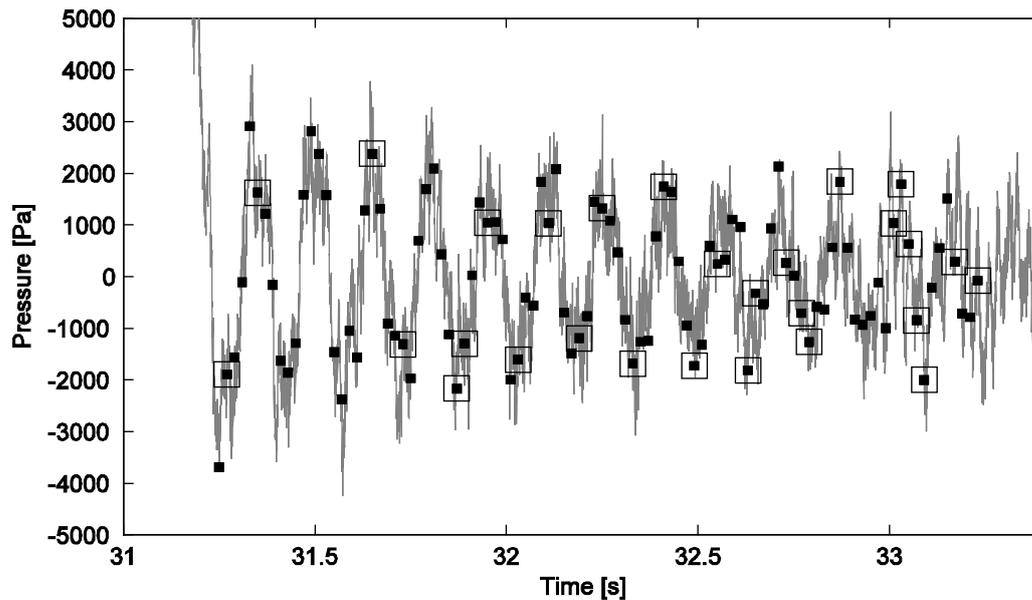
Label	Explanation	Value	Unit	Comment
$e_{\Delta p_{spec}}$	Specific uncertainty differential pressure transducers	9.25	[Pa]	Mean of the specific uncertainties
$f_t$	Uncertainty in time logging	0.01	[%]	
$f_{Q_{t=zero}}$	Uncertainty in the mean of the stationary values before and after the valve closure	0.16-0.26	[%]	
$f_{A_{pipe}}$	Uncertainty in pipe area	0.167	[%]	
$f_{\rho}$	Uncertainty in water density	0.01	[%]	
$f_l$	Uncertainty in length between measurement cross sections	0.011	[%]	
$e_{\Delta p_{start-1}}$	Random uncertainty in average pressure before valve closure	13.78-16.54	[Pa]	
$e_{\Delta p_{2-end}}$	Random uncertainty in mean pressure after valve closure	6.88-14	[Pa]	
$f_{EMF}$	Uncertainty in reference flow	0.3	[%]	

Using the values given in the table the uncertainties for measurements with 9 meters distance and 400 l/s becomes  $\pm 0.38\%$  -  $0.44\%$ . A large contribution to the uncertainty is due to the electromagnetic flow meter: 0.3%. The uncertainty decreases to  $\pm 0.23\%$  -  $0.32\%$  without taking it into account. The spread of the measurements are 0.55% ( $\pm 0.275$ ) which means that the spread is within the calculated uncertainties.

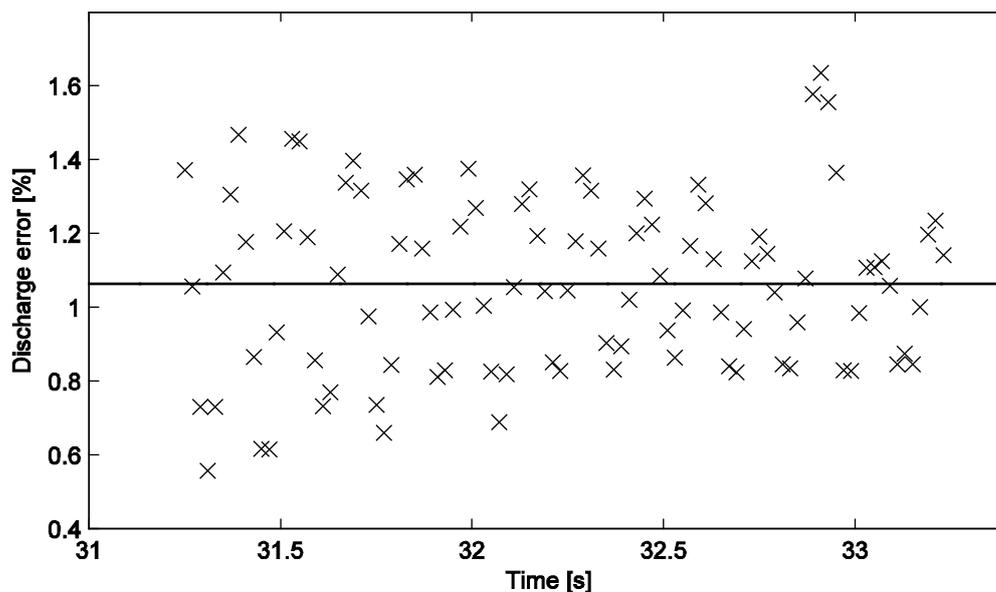
Hulås and Dahlhaug [2] also implemented friction line uncertainty. This parameter is not implemented here as one of the goals for the work in a long horizon is to find whether any adjustments, and what kind of adjustments, should be done to the friction line equation, see Jonsson *et al* [3].

#### 4. THE END POINT DISCUSSION

In the process of analyzing the data, it was discovered that the position of the start and end point for the water hammer integral influences significantly the calculated flow. An article by S. Mollicone from Hydro Quebec [3] states that the end point should be picked such as the resulting integral after the end point is zero. This gives in general an end point located a small distance after the top or bottom of a peak. The IEC 41 [2] has adopted the same principle. Finding suitable end points have however proved to be more problematic in the laboratory measurements. The main reason is attributed to noise from reflections from joints and pipes connected to the system without flow. Similar phenomenon can occur in field measurements where bends, surge tanks, etc. can cause noise and disturbances in the measurements. Using randomly distributed end points for the case with 6 m distance and 170 l/s, has shown that the difference in calculated flow can be as large as 0.6%. To investigate this discrepancy two different methods have been tested. One is to filter the signal in order to find the correct pressure peaks to use, i.e., zero-passages and peak amplitudes. The method will be presented in the next chapter. The other method consists in using several end points, and find a mean based on these. Using this method, it also became possible to determine the most appropriate integration points for the conditions set for the test. In present case, 100 end points equally distributed in time were used, and the flow was calculated for each one of them. Thereafter the flow was determined as the mean of the calculated flows. Figure 11 shows the end points distribution after the valve closure and ahead in time.



**Figure 11: 100 end points, equally spaced in time. The points with an extra square are within 0.1% of the mean flow calculated**



**Figure 12: Discharge error for the different end points shown in Figure 11.**

The points with an extra square in Figure 11 are points within 0.1% of the mean flow calculated. They are mainly located close to the peaks, but there are also points close to peaks that are not within the 0.1% span. Therefore, there is no guarantee to get consistent results from measurements by picking peaks randomly. There are also more frequent points within the 0.1% span as the points are coming further out on the time abscissa. This is expected as the area under/over each peak becomes smaller and hence less significant in the integration. Figure 12 shows the error for all tested points shown in Figure 11. The spread seems to be randomly distributed with a maximum deviation away from the mean around 0.6%. The importance of an appropriate end point for integration is again pointed out.

The integration start point is also of importance to determine the flow. An analysis using several integration start points similarly to the end points previously described point out that the difference in calculated flow can be as large as 0.6%. The standard states that the integration start point shall be at the start of the valve closure. Neither is the flow before the closing of valve affected by pressure pulsations with regular frequencies in the same manner as after the closure. In other words; the calculation of flow based on different start points can not be expected to have a cyclic behavior in the same manner as the end

points. Therefore to perform an analysis of where to set the start point is not considered correct. However it introduces an uncertainty and it becomes a question of how to include this in the results. Moreover, in some cases a relaxation time between the actual valve closure and the signal may exist; hence, this uncertainty should be included in the results.

## 5. FILTRATION OF THE MEASUREMENT SIGNALS TO FIND CORRECT END POINT.

In order to find the peaks representing the physics of the test cases, signal filtering may be used. This may save time in the calculation process since filtration makes it possible to, in a noisy signal, automatically calculate several end points which take much shorter time than manually calculating the flow for several points. It also gives the advantage to easily find calculation errors and corrupted data series.

As mentioned in chapter 4, it can be hard to find and locate the correct end point in laboratory measurements, i.e., locate the zero-passage and peak value which are needed to calculate the end point according to IEC 41 [1].

In case of a pressure signal with significant noise having higher frequencies than the swinging in the penstock, the signal can be low pass filtered. This gives a clear signal in which the zero-passage and peak values easily can be located. Thus, the appropriate end point can be determined. The attained end point is thereafter used in the integration of the original signal. This gives a correct integration limit without losing information due to filtration. Since calculation procedure is made by script it is easy and preferable to calculate the flow for a couple of subsequent end points. By doing that it is possible to view part of the uncertainties in the integration.

Figure 13 shows an example of a filtered (black) and original (grey) signal with the calculated end points. The signal is obtained at a measuring length of 6 m and a discharge of 170 l/s. It is not that noisy, but still it is difficult to determine the exact peak amplitudes and zero-passages.

The calculated discharge error corresponding to each stop point is shown in Figure 14. The mean error is slightly lower compared to the mean in Figure 12 (just above 1%). This is, as well, near the mean error (mean of 6 runs) shown in Jonsson *et al* [3]. The spread is below  $\pm 0.1\%$  from the mean for all tested points and hence confirms the results from chapter 4.

However, the influence of the end points gets more significant in cases with high amplitude pressure traces after valve closure. If these high amplitudes appear in a truly noisy signal, the filtering method works well and is both fast and simple to use.

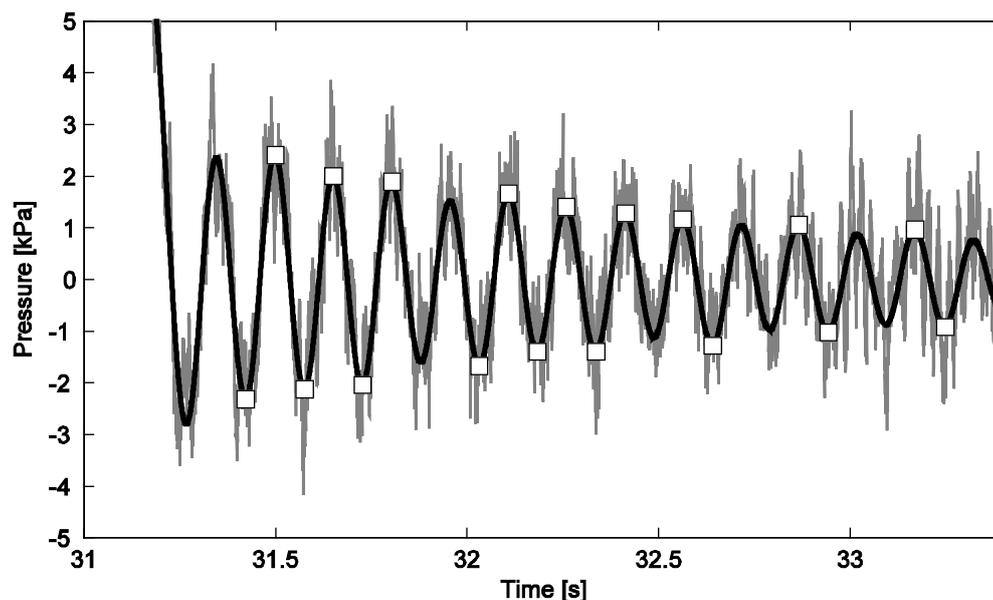


Figure 13: Filtered (black) and original (grey) signals and calculated end points (white squares).

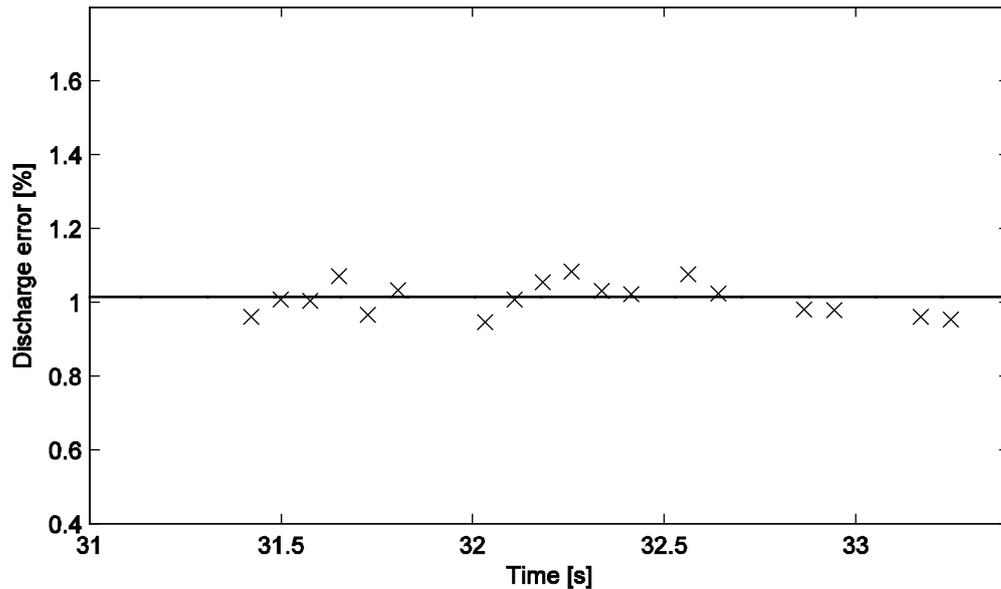


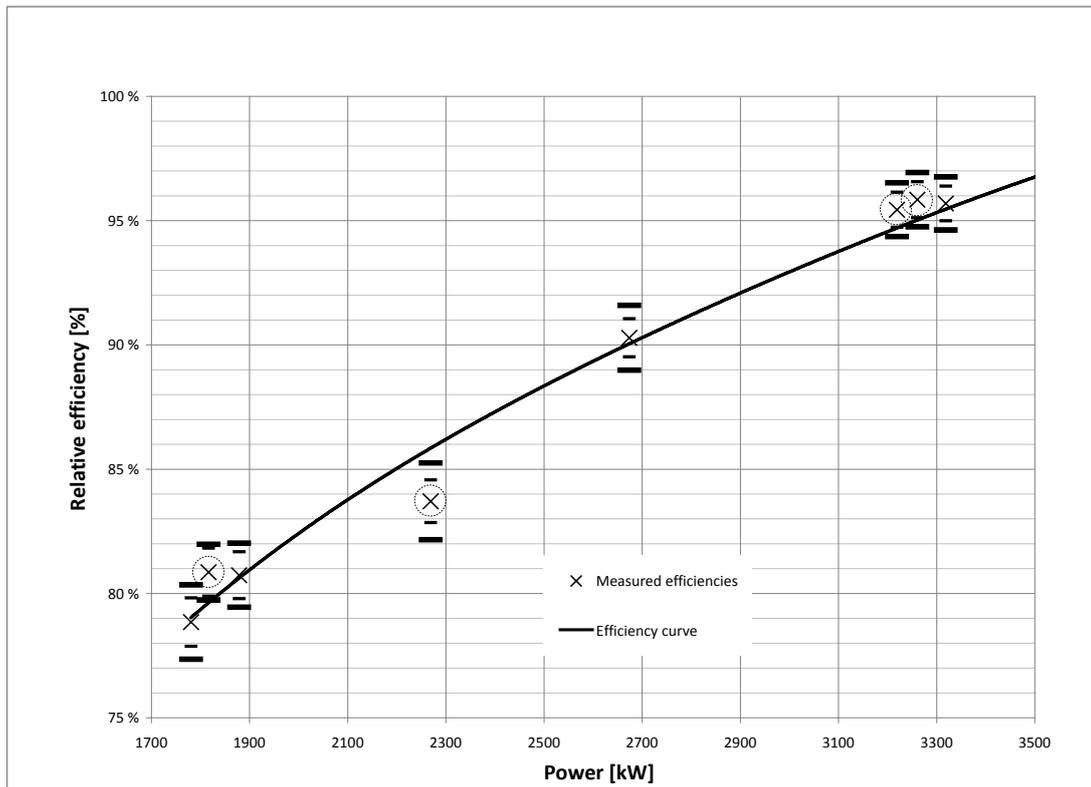
Figure 14: Discharge error for the different end points shown in Figure 13.

## 6. IMPLEMENTING UNCERTAINTY IN REGRESSION CURVE

As stated in chapter 3, there was a spread in the calculated flows. Even though the spread is within the calculated uncertainty, there is still reason to believe that there is a significant random uncertainty in the transient pressure (in the water hammer). Since this is a transient phenomenon it is almost impossible to find the random uncertainty for it. In the laboratory, a large number of test points at approximately the same flow are taken. Based on the measurements, an expectation for random behavior of the method under certain conditions is determined. In the field, the power plant owner will usually demand as short down time as possible, and in order to cover the whole range of the turbine, running on several flows will also be prioritized contrary to running on the same flow several times. This excludes the possibility to find the random behavior of the method at the specific site for a certain flow. In order to express an expectation for the spread in field measurements a choice can be to find the uncertainty for points around a higher order regression curve. This is described in the IEC 41 [1] (APPENDIX D), but it seems as though this analysis is often skipped in the final uncertainty calculations.

This method was used for the Anundsjoe efficiency measurements. The Anundsjoe Power Plant consist of one 5 MW francis unit with nominal head 58.5 m and a flow of  $10 \text{ m}^3/\text{s}$ . Altogether 19 test points were measured with the pressure time method. For more details see Jonsson *et al* [3]

To estimate the efficiency curve through the measured points, a higher order equation for the efficiency curve was found. This was made by a 4<sup>th</sup> order polynomial regression based on the points taken in the measurement. (It is as a start assumed that this represents the efficiency curve. However, an efficiency curve can not always get a good representation by a higher order equation.) When having plotted the curve and the measured points with uncertainties, it could be seen that the curve did not lie within the uncertainties for some of the points. Hence, either the curve mismatched the true efficiency curve, or the random behavior of the measured points was larger than so far calculated uncertainty. Therefore the uncertainty for the regression curve was added to the uncertainty calculation. After this the estimated efficiency curve came within the uncertainty for all measured points but one. This is illustrated in Figure 15. (It will be a question whether the calculated uncertainty for the regression curve represents the uncertainty of the regression curve itself, or the variation in measured points. Whether it is the one or the other becomes more clear with an increasing number of test points) The efficiency curve is made up by altogether 19 points, but only the efficiency curve at part load is shown in order to get a better view. Points with estimated curve not within uncertainty are marked with a dotted circle. The ranges of the first calculated uncertainties are marked with a “-“, and the ranges of the uncertainties after added regression uncertainty is marked with a bold “-“.



**Figure 15: Relative efficiency with regression curve (4th order polynomial), measured points and uncertainties (- represents uncertainty without regression uncertainty and bold - represents total uncertainty with regression uncertainty)**

There are some challenges to the use of uncertainty for regression curves. One is that the efficiency curve can not necessarily be expressed by a higher order equation. This can in some cases be solved by splitting the efficiency curve into several lines with different equations. Another is that few measured points will give a high uncertainty due to the fact that it is based on Student t distribution, and the nature of this distribution will give high uncertainty if few points are measured. However, to get consistent results and low uncertainty as many points as possible should be taken. If the measurement is done under good conditions with good repeatability and the efficiency curve has a good match with a higher order polynomial, adding the regression uncertainty will not give a large contribution to the total uncertainty. If the case is the opposite, a more correct uncertainty will be obtained by adding the regression uncertainty.

## 7. COMMENTS

In the measurements nylon tubes were used for their easily mounted and allowing monitoring the presence of air bubbles. To state whether nylon tubing was acceptable, 30 tests were performed where simultaneous measurements with both steel pipes and nylon tubes were performed. The mean difference in calculated flow with nylon tubes versus steel pipes was 0.08%, a negligible difference.

Absolute pressure transmitters (APT) have also been used. Being mounted directly to the pipe wall using absolute measurements should avoid uncertainties related in connection tubing effects. Both the calculated instrument uncertainty and the spread have proved to be larger for the APTs, but the mean of the results is approximately the same for both kinds of sensors. However, the DPTs were preferred for research evaluations due to their lower spread and uncertainty compared to APTs. A difference in the behavior of the pressure pulsations in the APTs compared to the DPTs was registered. The reason for this may be that the absolute sensors are subjected to larger pressure peaks that will influence the result, while these peaks are damped out in the connection tubing of the differential pressure transducers.

## 8. CONCLUSION

This paper presents an uncertainty analysis of the pressure-time method. It also presents suggestions how to make the post processing more easy to use and accurate.

The integration end point is in many cases easy to find as well as difficult due to the presence of noise and/or interaction of different pressure waves in the signal. Noisy signal can result in poor calculations and, thus, give an inaccurate result. The mean of 100 end points and its variation shows that the deviation can be rather high for randomly selected points; up to  $\approx 0.6\%$  in the present case. Filtration of the signal makes it easy and straight forward to calculate the correct end points, and thus reduce the uncertainty in the results.

If not having several measurement points to describe random behavior of a measurement, e.g., in field tests, some of this random behavior can be described by using uncertainty of a polynomial regression curve.

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