Discussion on Acoustic Flow Measurement Method

By		
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Abstract

In the following paper an attempt is made to theoretically analyse the uncertainty of acoustic flow measurement method. The analysis covers different basic aspects such as possible errors in the zones near the penstock wall and also deals with the integration method.

1. Introduction

The use of sound for measurement of flow in hydro power stations has become very popular over the last decades. This acceptance is mainly based on the improved technology of acoustic sensors. Therefore acoustic flow measurement is widely used in the hydro industry although it is not officially accepted as a full measurement in the relevant IEC Testing Code 60041. The reason for certain reluctance by industry to fully accept the acoustic method can be found in the suspicion that particularly at unfavourable flow fields some error is contained in this measurement method.

Basically this method offers a lot of advantages. For example the costs involved do not depend on the size of a penstock or intake. Furthermore a continuous measurement is possible. Also the measurement equipment easily can be transported and mounted on different locations.

The acceptance would be even higher if some doubts on the accuracy can be eliminated. In order to improve the acceptance of above method particularly under difficult test conditions an attempt is made to analyse some possible reasons for the pretended overestimating of flow.

2. Testing Code IEC 60041

The existing Code IEC 60041 is using the classical Gauss-Jacobi integration method, to get the volumetric flow rate from the measured velocities. It is essential for this method that for a given number of nodes the node position is fixed by the method leading to the fact that with n nodes one can interpolate polynomials of order (2n-1). But as a disadvantage an error in positioning leads consequently to an error in integration.

Secondly this method does not have any interpolation points at the walls and therefore it does not account for the zero velocities there. This can lead to overestimating the flow, as demonstrated in this paper. Figure 1 gives a graphic representation of Gauss-Jacobi integration points and weighting factors.

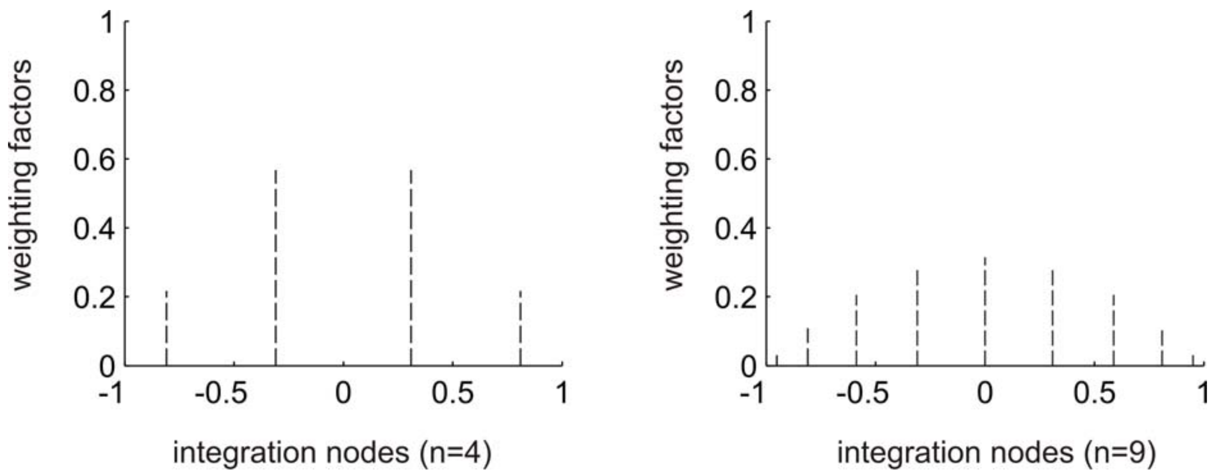


Figure 1 Integration nodes and weighting factors of Gauss-Jacobi polynomials

3. Discussion on Influencing Effects

In order to improve the integration method three different items will be discussed in the following.

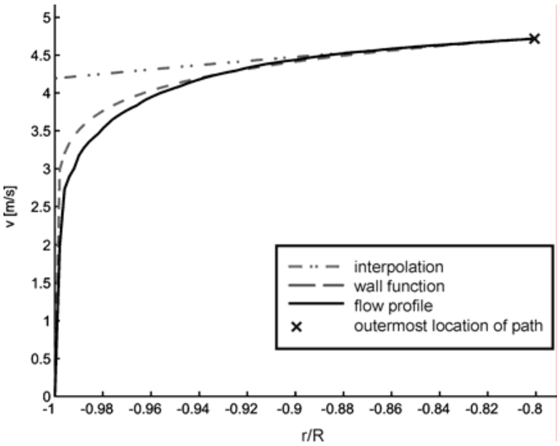
- It is assumed that the so called protrusion effect has some effect to the uncertainty of acoustic method.
- Secondly it seems to be important to improve the integration of the flow profiles near the walls.
- Finally this paper proposes a new interpolation method for the main flow.

3.1 Near-wall Flow

An important topic of an acoustic measurement is the integration of flow velocities in the boundary regions. As already mentioned the Gauss-Jacobi integration method does not account for the fact that the velocity is zero near the wall. Basically it would be possible to include the values $v = 0$ for the wall, by changing the integration method.

But such an approach would be too simple because from a mathematical point of view this will not lead to a better interpolation in general, since the advantage of Gauss-Jacobi method will be lost - we need additional interpolation points to reach the same order of accuracy - and we will not overcome the (wrong) assumption that flow profiles are polynomials.

It seems to be much better to incorporate theoretical information on the flow profiles near the wall. It is well known that an exponential function as shown in Figure 2 describes quite well the near-wall flow, whereby an exponent n in the order of 10 represents best the pipe flow in penstocks. More details on how to choose n can be found in relevant literature. This function now is linked with the outer point in such a way that the first derivation of this function matches with the interpolation curve in the outer point of function.



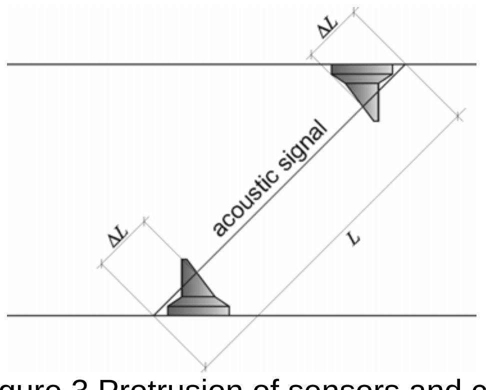
$$v(x,y) = v_{max}\left(1-\frac{\sqrt{x^2+y^2}}{R}\right)^{1/n}$$

Figure 2 Improved approximation of near-wall flow profile

3.2 Protrusion Effect

An important effect to be considered is the so-called protrusion effect. In order to measure the mean velocity along a path the sensors ideally should be flush with the wall, but practically sensors protrude some distance into the penstock (Figure 3). Consequently, a small portion at the beginning and at the end of a path is not included in the measurement. The portions not considered by the sensors are areas of small velocities with zero velocity right at the wall.

The result is that the measured mean velocity is higher than the real one. In other words there is a systematic over-estimating of the discharge resulting in lower efficiencies to the disadvantage of a manufacturer. In order to account for this so-called protrusion effect a special correction factor is included in the Japanese Standard JEC 4002.



$$\overline{v}_c = \frac{1-\frac{2\Delta L}{L}}{1-\left(\frac{2\Delta L}{L}\right)^{1+1/n}}\overline{v}_m$$

Figure 3 Protrusion of sensors and correction factor of Standard JEC 4002

The magnitude of effect depends very much on the length and shape of the protruding sensor, on the penstock diameter but also on surface roughness or more general on the near wall flow. The above correction factor allows easily estimating the error introduced by neglecting the protrusion effect. It was found that protruding sensors have a secondary effect by influencing the flow field. Protruding sensors reduce the flow velocity near the sensors and therefore reduce the negative effect as described before.

3.3 Interpolation Method

The classical integration method is compared with a new approach using a PCHIP interpolation. PCHIP stands for “**P**iecewise **C**ubic **H**ermite **I**nterpolation **P**olynomial”. The advantages/disadvantages of the PCHIP integration method are the following:

- It is less suitable for polynomial functions but it is superior for data like the ones from flow profiles
- PCHIP interpolation conserves monotony. If measuring data are increasing monotonously, the interpolating function is doing the same way
- there is no overshooting, extreme values of the measuring data remain extreme values also in the interpolation function (Figure 4)

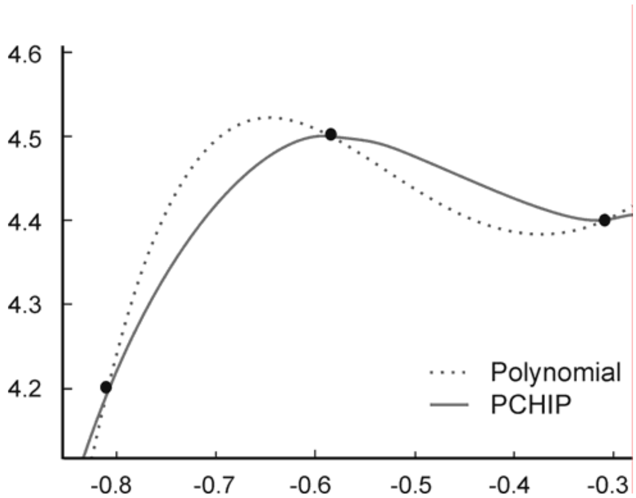


Figure 4 Comparison of polynomial interpolation and PCHIP

4. Analysis of Error Quantities

After having discussed some principles and new ideas like the protrusion effect, consideration of near-wall flow and PCHIP interpolation, we can start to analyse the systematic uncertainty of different test cases. It will be shown that under insufficient flow profiles the error using the classical method as described by IEC can be significant. The cumulated error arising from above noted effects can reach magnitudes of 1%. In the following paragraphs we will analyse the magnitudes of the different effects by comparing measurements with virtual measurements.

This analysis is based on so-called “virtual” measurements. The practical examples were taken from a power station with a penstock delivering very typical distorted flow profiles due to bends in front of the area where the sensors for acoustic measurement were installed. For a given discharge the flow fields were calculated by CFD. Once the flow field is defined, virtual measurements can be done, using an in-house developed tool.

In the following the tool “virtual measurement” is applied on the example of a penstock configuration. This penstock has a bend in a rather small distance to the spiral inlet with the measuring section in between. The flow field was calculated and the velocity distribution in the measurement section is shown in Figure 5.

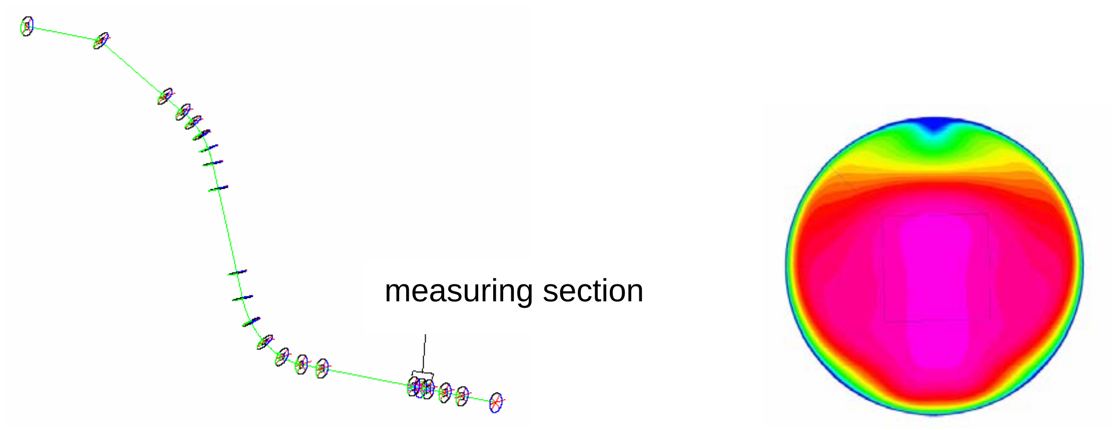


Figure 5 Penstock configuration and flow field

The method applied in the test case consists of the following elements:

- Four paths measurement
- Classical Gauss-Jacobi interpolation
- No correction of protrusion effect
- No correction of near-wall flow

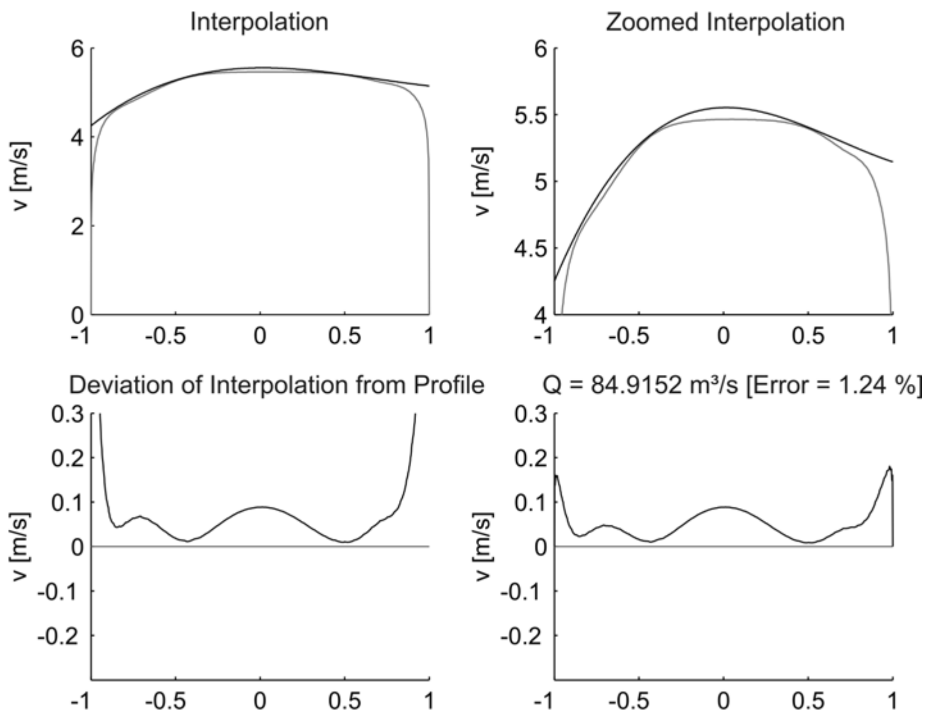


Figure 6 Comparison of calculated versus measured profile (classical method)

Above figure is split into four smaller diagrams (Figure 6). In the upper left diagram the interpolated profile is compared with the calculated one. In the upper right graph one can see a zoomed representation of it. The lower diagrams show how the interpolation fits to the theoretical profile, whereby in the chart to the right the deviations are area weighted finally resulting in a smaller discharge by 1.24%.

For a more detailed discussion the error of 1.24% can be split into three elements:

Cause	Error	Correction
Protrusion effect	0.69	no
Interpolation	0.26	no
Near-wall flow	0.29	no
Total	1.24%	

In order to reduce this error we can apply now alternative methods of integration. One obvious idea is to increase the number of paths and to correct the negative effect of protruding sensors. The following approach consists of the elements:

- Nine paths measurement
- Classical Gauss-Jacobi interpolation
- Correction of protrusion effect
- No correction for near-wall flow

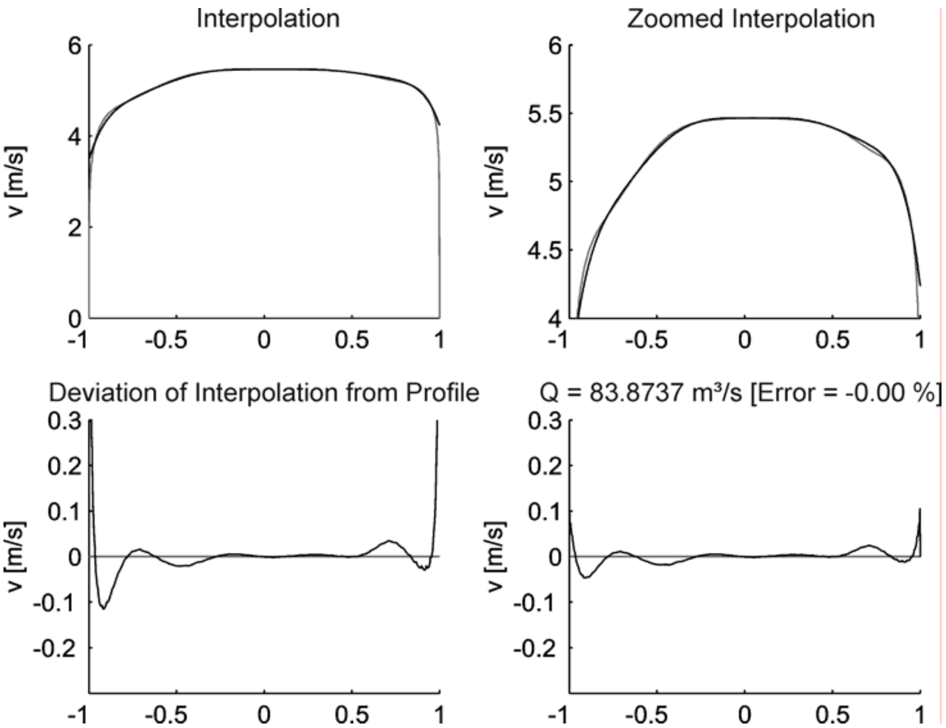


Figure 7 Comparison of calculated versus measured flow profile

By this approach the theoretical flow profile is perfectly approximated (Figure 7), and hence the introduced error by integration is only 0.05%. The overall error was calculated to be zero. Using nine paths and additional correction for the near-wall flow does not seem to be necessary.

Also here a study on the composition of error and the influence of the various correction terms was made. The big disadvantage of above approach obviously is the high number of sensors necessary for this measurement.

Cause	Error	Correction	after correction
Protrusion effect	0.71	- 0.89	- 0.18
Interpolation	0.05	no	0.05
Near-wall flow	0.13	no	0.13
Total	0.89	- 0.89	0.00 %

Another reasonable approach consists of the following elements:

- Four paths measurement
- PCHIP interpolation
- Correction of protrusion effect
- Correction for near-wall flow

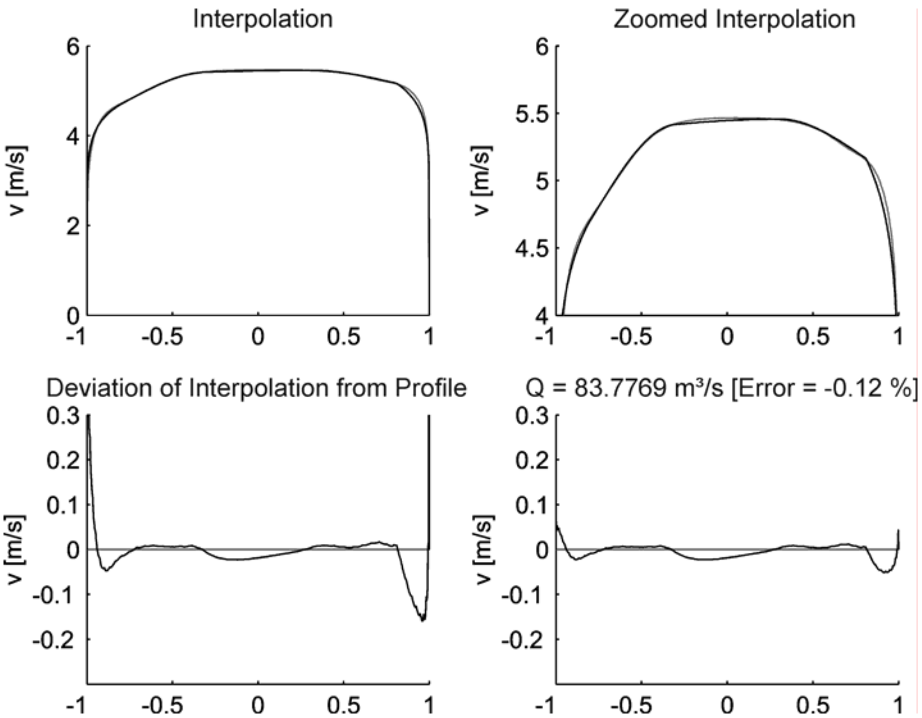


Fig. 8 Comparison of calculated versus measured flow profile

The results of analysis are plotted in Figure 8. An analysis of the errors and corrective terms is plotted in below table, note that the interpolation error is relatively close to Gauss Jacobi with nine paths:

Cause	Error	Correction	after correction
Protrusion effect	0.69	- 0.85	- 0.16
Interpolation	0.26	- 0.17	0.09
Near-wall flow	0.29	- 0.34	- 0.05
Total	1.24	- 1.36	- 0.12 %

5. Conclusion

Differences up to 1% (!) could be found whereby there was a clear tendency that the classical method as per Code IEC 60041 is overestimating the flow finally resulting in lower turbine efficiencies. The proposals given in this paper lead to measurements in good agreement with the real discharge.

Basically there are two approaches recommended in this paper. The first one consists of the following elements:

- Nine paths
- Correction for protrusion effect
- Interpolation by Gauss-Jacobi polynomials

The advantages of this proposal are improved accuracy by increasing the number of paths, whereby four out of nine locations are identical to the four-path method. Secondly the use of the classical Gauss-Jacobi interpolation as it gives the opportunity to easily improve the existing Code IEC 60041 just by coupling with the Japanese Standard JEC - 4002. A disadvantage is certainly the high number of sensors needed.

The second proposal includes the following elements:

- Four paths
- Correction of protrusion effect
- Correction for near-wall flow
- Interpolation by PCHIP

This method has shown for the given test case to be equally accurate compared to the first proposal with nine paths although a smaller number of sensors are used. This method is also advantageous because it is less sensitive on the exact position of sensors. In case of significantly disturbed flow profiles an increased number of sensors together with a PCHIP interpolation seem to be an adequate approach.

6. Literature

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