INTEGRATION OF CURRENT METER MEASUREMENTS IN GENERAL FLOW CROSS SECTIONS

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ABSTRACT

A novel method for evaluation of current meter measurements is presented. This method is especially suited for generally shaped flow cross sections, where the application of procedures described in the international standards are not suitable. The proposed procedure bases on numerical flow simulation with exactly known flow rate and a subtraction of simulated velocities from the measured velocities. The integration of differences and the known reference flow rate allow determining the actual flow rate accurately and reduce the integration uncertainty. This method avoids the difficulties of flow field integration in the peripheral zone of the measuring section.
Validation of the method was performed for selected field tests in a circular cross section and in a rectangular cross section. The case study presented for a generally shaped cross section bases on current meter measurements carried out in the tidal hydro power station of La Rance.

1 INTRODUCTION

ISO 3354:2008 [1] specifies the widely used methods for the determination of the flow rate in closed conduits by means of the velocity-area method using propeller-type current-meters. Assumption for use of the method are that the velocity distribution is more or less regular, that the conduits are completely filled, that the flow is steady and swirl free. Integration bases on cubic interpolation in between local measuring points and on the assumption of an exponential decay of the velocity in the peripheral zones of the flow field (Kármán's conventional law).
In ISO 3354:2008 integration procedures are described for circular and rectangular cross sections. In annex A, also measuring sections other than circular or rectangular sections are considered. However, the proposed procedures are limited in use, since non-circular sections (e.g. horseshoe like sections) are not incorporated and the procedures described for rectangular cross sections with corners cut-off or rounded do not respect the altered flow fields and will increase the uncertainty of integration.
The standard IEC60041 [2] refers to ISO 3354 and expands the method to open channels and trapezoidal sections. Typical uncertainties that have to be expected are quoted for closed conduits, intakes, and for open channels with rectangular or trapezoidal sections.
In practice one is often confronted with non-ideal cross section and a method for integration is needed, which can handle generally shaped cross sections and also non-regular velocity distributions.
The basic concept of the here proposed method is that the integration error can be reduced by integrating differences of the measured data and a given velocity distribution for which the flow rate is known. Integration of differences results always in smaller integration errors, especially if the velocities in the peripheral zones are correctly predicted, compared to a direct integration of measured data.

For rectangular and circular cross section the reference velocity distribution and the reference flow rate can be determined e.g. from a power law distribution (Nikuradse velocity profile). Another possibility is the numerical simulation of the flow field (CFD).

For general cross section shapes the power law method is not practicable, accordingly only the CFD method can be applied.

With the proposed method the flow rate is determined as follows:

$$Q = Q_{ref} - Q_{diff} \tag{1}$$

where: Q = final flow rate, Q_{ref} = reference flow rate (from power law or CFD), Q_{diff} = result of the integration of velocity differences.

2 CIRCULAR CROSS SECTION

During the acceptance test of hydro power plant (HPP) of Antuco, Chile, current meter measurements were performed in a circular cross section of a diameter of 5m [3]. The 29 current meters were installed on a cross, with one, specially calibrated, current meter in the center. Due to an upstream bifurcation and an upstream bend the velocity distribution was slightly irregular.

The selected operating point was at that time evaluated with the graphical method proposed in IEC60041 to have a flow rate of $Q = 92.84\text{m}^3/\text{s}$. The recalculation according to the ISO 3354 procedure resulted in $Q = 92.74\text{m}^3/\text{s}$.

In order to compare the previous evaluations with the new method the velocity distribution was approximated in a first step with the power law:

$$v(r) = v_{\max}\left(1 - \frac{r}{R}\right)^{1/n} \tag{2}$$

where: r = variable radius, R = conduit radius ($R = 2.499\text{m}$), v_{max} = center velocity ($v_{max} = 5.8\text{m/s}$), n = exponent of power law ($n = 9$).

The formula given in eq. (2) can be analytically integrated and the reference flow rate results from eq. (3). The result of this integration can then be used in equation (1) as reference flow rate.

$$Q_{ref} = v_{max} \cdot \pi \cdot R^2 \frac{2 \cdot n^2}{(n+1)(2n+1)} \tag{3}$$

A plot of the velocity difference of measured points and the velocities calculated with the power law is depicted in Fig. 1. The plotted surface connecting the point is created by bi-cubic interpolation. The integration of such determined differences results in Q_{diff}, which can be used in eq. (1).

All results of integration and deviations are summarized in Table 1.

Table 1: Comparison of different integration methods for the circular cross section.

circular cross section	IEC60041 graphical method	ISO3354 recalculation	Integration of differences to power law	Integration of differences to CFD
flow rate [m³/s]	92.84	92.74	92.70	92.64
difference to the CFD method [%]	0.21	0.10	0.05	0

Both the method of the graphical and the ISO3354 procedure result in a slightly higher flow rate compared the difference integration methods.
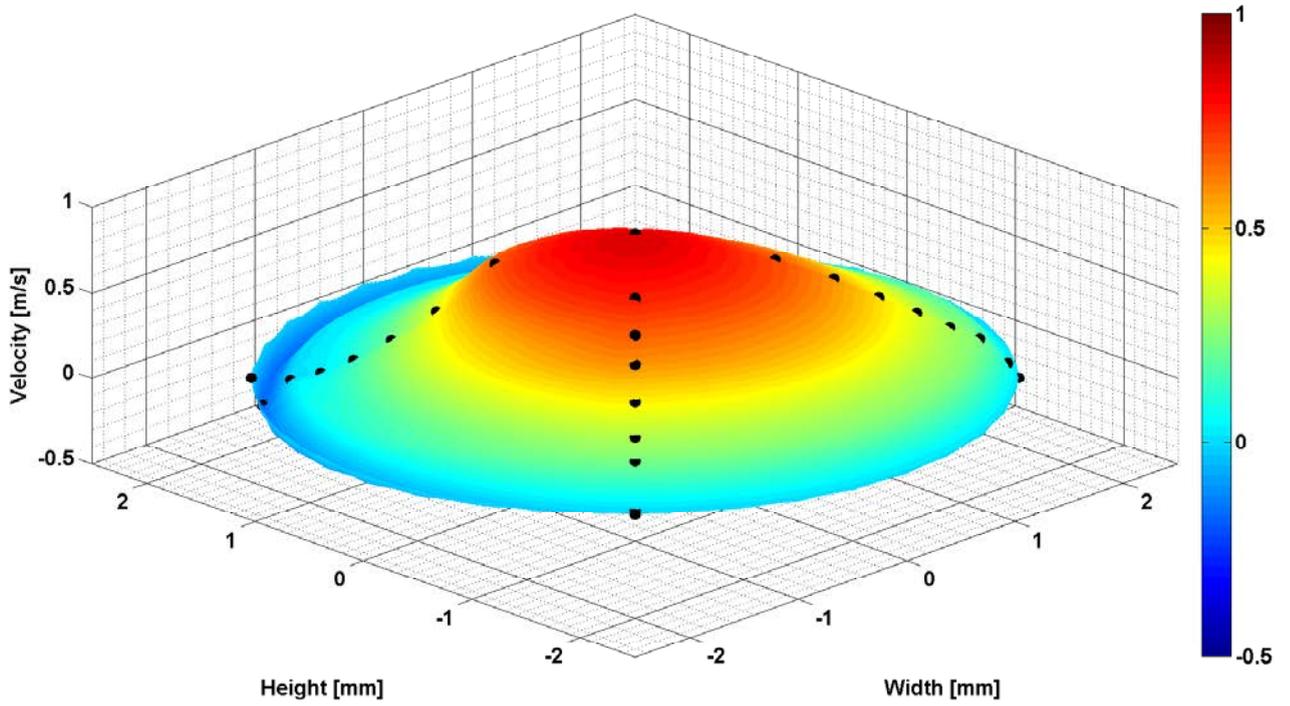
Figure 1 - Plot of the velocity difference of measured velocities minus power law velocities.
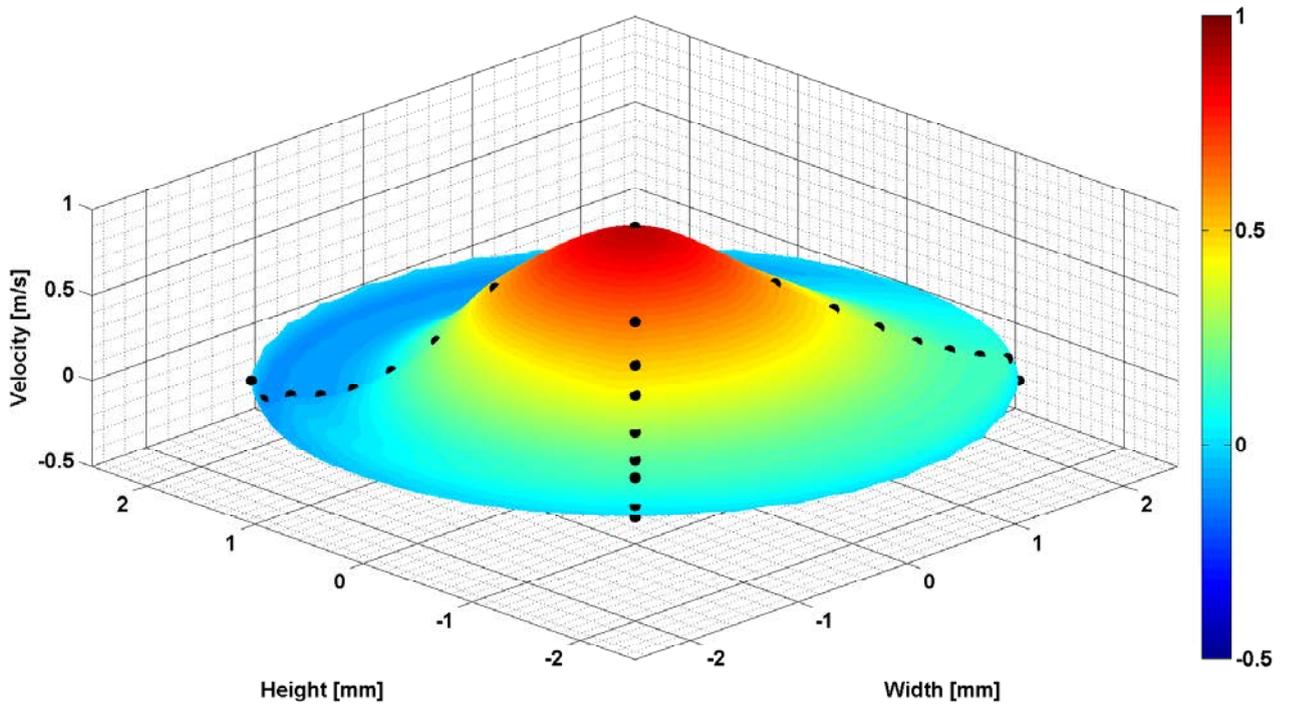
Figure 2 - Plot of the velocity difference of measured velocity minus CFD velocities.

3   RECTANGULAR CROSS SECTION

Almquist [4] describes comparative field tests in the short intake of the HPP Kootenay Canal, Canada. Current meter measurements were performed by Hydro Québec. Velocity data measured with current meters are presented here with the kind permission by Gilles Proulx, Hydro Quebec, who reports on details of the current meter measurements in [5]. The measurements were performed in the bulkhead gate slots and the cross section was rectangular.

Also in the case of the rectangular cross section the velocity distribution can be approximated with the power law:

$$v(x, y) = v_{max} \left(1 - \frac{2x}{W}\right)^{1/n} \left(1 - \frac{2y}{H}\right)^{1/m} \tag{4}$$

where: x, y = coordinates, W = cross section width (W = 4.875m), H = cross section height (H = 7.437m),

v_{max} = center velocity (v_{max} = 3.44m/s), n = exponent in x direction (n= 80), m = exponent in y direction (m = 80).

The exponents were chosen exceptionally large because the flow was accelerated in the converging section of the measurements and accordingly the boundary layers are small.

Also the formula given in eq. (4) can be analytically integrated and the reference flow rate for the rectangular section results in eq. (5). Again, the result of this integration can then be used in eq. (1).

$$Q_{ref} = v_{max} \cdot W \cdot H \frac{m \cdot n}{(1+m)(1+n)} \tag{5}$$

A plot of the velocity difference of measured points and the velocities calculated with the power law is depicted in Fig. 3. The plotted surface connecting the point is created by cubic interpolation. All results of integration and deviations are summarized in Table 2.

Table 2: Comparison of different integration methods for the rectangular cross section.

rectangular cross section	Evaluation HydroQuébec	ISO3354 recalculation	Integration of differences to power law	Integration of differences to CFD
flow rate [m³/s]	107.47	106.90	107.23	107.03
difference to the CFD method [%]	0.41	-0.12	0.19	0

Locally, at the upper end of the rectangular cross section, large discrepancies between simulation and measurement are evident. The reason for this discrepancy lies in the fact that there is in reality a flow into the bulkhead slots leading to locally lower velocities in comparison to the simulated velocities, where the bulkhead slots were not modelled. Nevertheless, since the integration of the differences amounted to only 7.97 m³/s, the increased local integration uncertainty has only a minor influence on the flow rate determination as the results summarized in Table 2 show.

The reason for the increased flow rate evaluated by Hydro Québec lies in the fact that in this evaluation it has been taken into account that the velocities do not go down to zero at the upper end of the flow cross section.
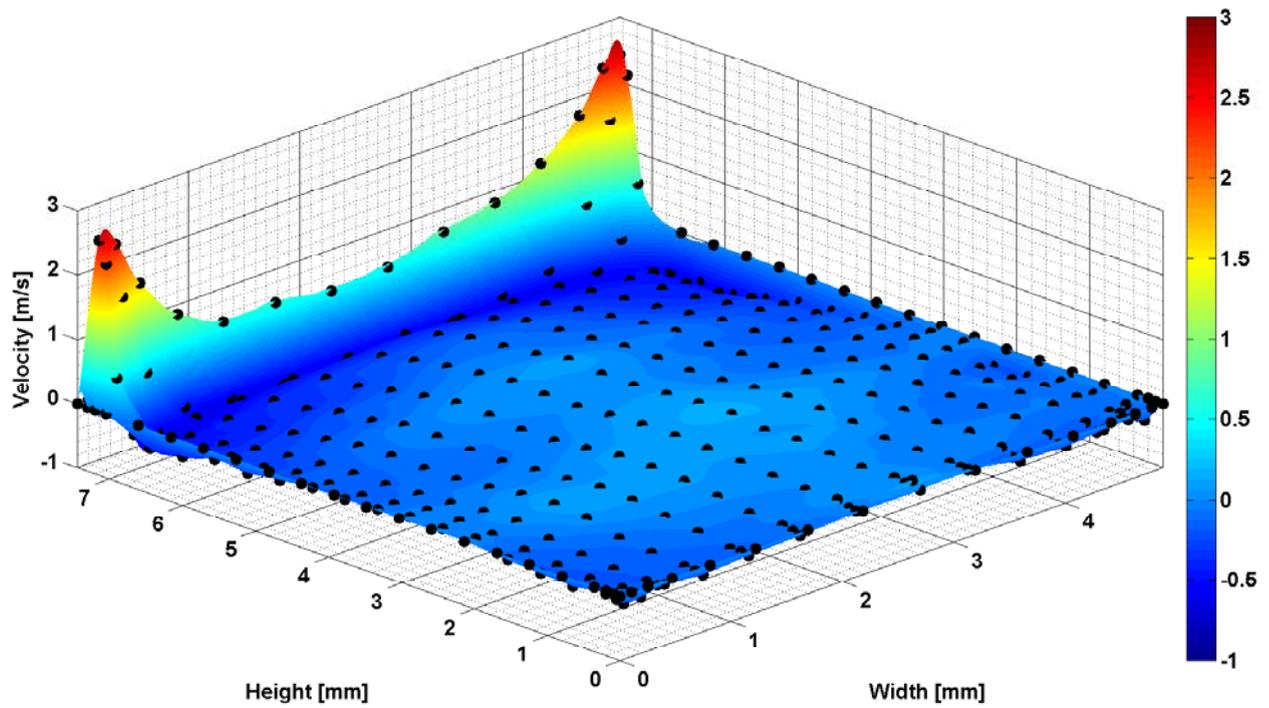
Figure 3 - Plot of the velocity difference of measurement minus power law velocities.
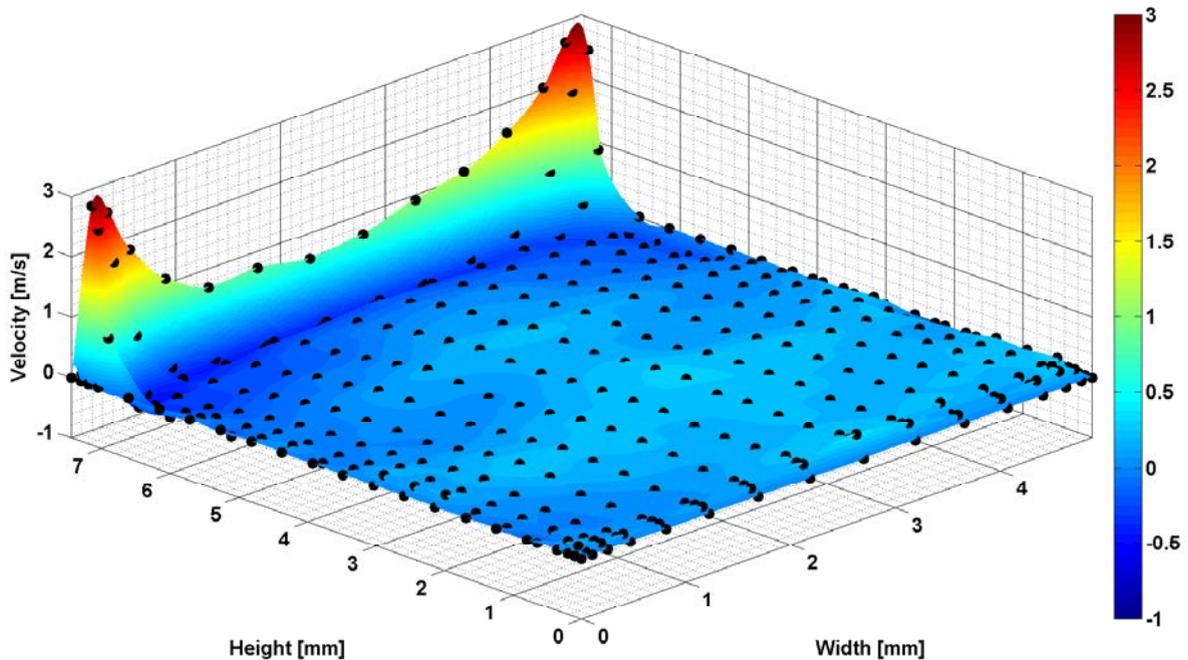
Figure 4 - Plot of the velocity difference of CFD minus measurement.

4   GENERAL CROSS SECTION

Rolandez [6] describes measurements in the tidal HPP of La Rance, France. In the following the flow rate determination for one selected operating point is demonstrated. Since the flow cross section is of general shape only the method based on the integration of the differences of measurement and CFD simulation was applicable.

The simulations were performed with the commercial CFD software package ANSYS CFX

14.5.7. This CFD code solves the conservation equations for mass, momentum and energy in all three dimensions and the discretisation is performed applying the Finite Volume method. The computational grid was manually generated with the program ANSYS ICEM CFD 14.5.7 resulting in a pure hexahedral mesh. To get a higher resolution, mesh refinements were carried out at the boundary layer resulting in a mean y+ value of 45. The simulations were performed in steady state. This means, that all transient effects are ignored and time averaged velocity distributions result. The Reynolds number based on the hydraulic diameter and the mean velocity is Re = $30.6 \cdot 10^{6}$. The solutions are based on the shear stress transport (SST) turbulence model. The near wall behaviour of the flow has been considered applying automatic wall functions. The presented results have been solved with the high resolution advection scheme.

The Fig. 6 shows the differences between the CFD velocities and the measured velocities at the measurement points for the turbine mode. The differences can reach locally in the peripheral zone values of up to ± 0.5 m/s. Fig. 5 shows the velocity distribution that was simulated in the cross section of the measurements.
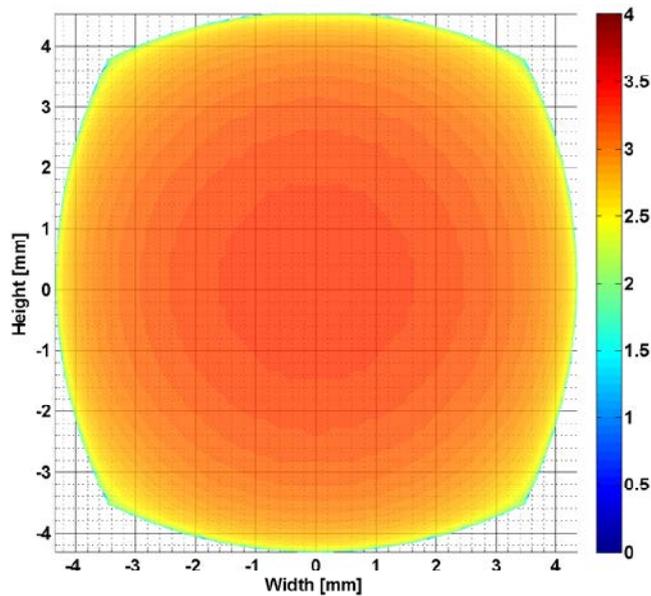
Figure 5 - Simulated velocity distribution in the measuring section.
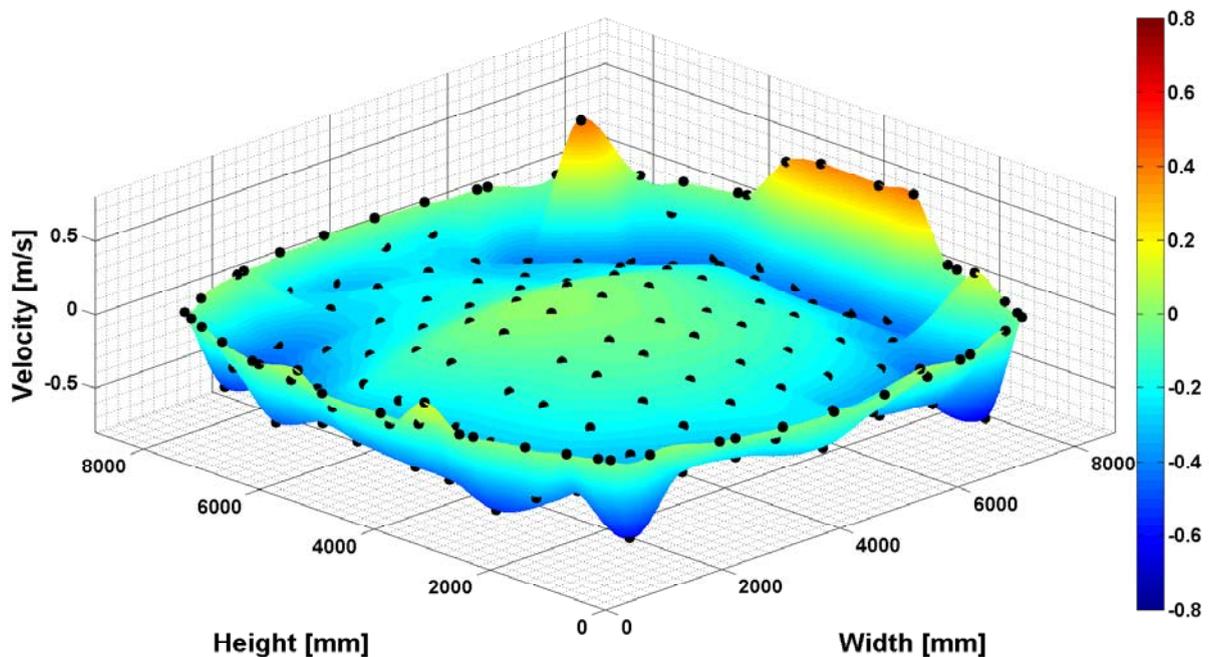
Figure 6 - Plot of the velocity difference of measurement and CFD.

From Fig. 6 can be concluded that the near wall slope is in parts along the circumference underestimated and in other parts overestimated. But the problem of the integration of an exponential velocity decay in the peripheral zone is avoided.

For the shown example, the final flow rate was evaluated to be $Q = 213.52$ m^3/s, the reference flow from CFD was $Q_{ref} = 200$ m^3/s and the integrated difference $Q_{diff} = -13.52$ m^3/s.

5 DISCUSSION

A procedure is introduced in which velocity differences are integrated and not the measured velocities distribution itself. These differences result from measured velocities minus analytically determined velocities or simulated velocities. Condition for the validity of the procedure is that the reference flow rate associated with the analytical velocity distribution or the simulated flow field is exactly known.

For circular or rectangular cross sections both methods could be successfully applied, as the two validation examples showed. Based on the simulations in a circular and in a rectangular cross section and comparison with conventional integration methods the correctness of the procedure could be confirmed. In a cross section of general shape only the procedure of integration of the differences of measurements velocity is applicable.

A direct integration using numerical methods is not recommended for general cross sections because interpolation tool are not able to predict the exponential decay of the velocities in the near wall zone. Furthermore the interpolation in between the near wall measuring points is not correctly done with conventional tools for the generally shaped cross section.

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