Estimation of installation errors in acoustic flowrate measurements by CFD-modeling

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Introduction

The results of investigation concerned with the development of new computer-based models for ultrasonic multipath time-of-flight measurements of perturbed flows as well as the data of corresponding numerical modeling are presented. It is shown that effective CFD-modeling of fluid or gaseous media is an additional powerful tool allowing to obtain high-precision estimations of both averaged flow velocities and flowrates (volumetric or mass) even in the case when ultrasonic measurements are carried out at unstable or perturbed flow conditions, i.e., $v=v(x,y)$ where (x,y) are Cartesian coordinates in a normal channel's cross-section.

Evaluation of volumetric flowrate

Up-to-date strategies of both diametral and chord acoustical measurements enable to obtain with high precision (in actual practice about 1,5 ÷ 2%) an axisymmetric flow velocity profile $v(r)$ at steady-state flow conditions in an arbitrary cross-section on the basis of differential time-of-flight data [1, 2]. Thereby, a set of high-precision estimations of the averaged flow velocities $v(i)$, $i=1 \ldots I$ in I measuring planes is provided with and high-quality determinating on it's basis the total flowrate.

A volumetric flowrate Q of liquid or gas being transported in the pipeline is defined as an amount of liquid or gas flowing through cross-section S of the spoolpiece per unit time. For steady flow, the flowrate is determined as

$$Q = \iint_S v_z(x,y)dxdy\,, \tag{1}$$

or can be rewritten as

$$Q = 2\int_{-R}^{R} \sqrt{R^2-\xi^2}\,\overline{v}_Z(\xi)d\xi, \tag{2}$$

where $\overline{v}_z(\xi)$ is an average flow velocity in the measuring section of the channel and

$$\overline{v}_z(\xi) = \frac{c^2}{2L}\Delta t\,. \tag{3}$$

Here c is the velocity of sound in motionless medium, L is a distance between ultrasonic transducers, Δt is a time difference for propagation of ultrasonic pulse between pair transducers in direct and opposite direction.

The calculation of integral (2) for a fixed number of the estimations of the integrand is more effective by using a theory of quadrature integration where three settings of the problem are possible [3].

Newton's problem. For a given set of abscissas (path locations) ξ_j find the best values of the coefficients λ_j; the best-known problem of this class is the problem with equidistant abscissas ξ_j, i.e., the Newton-Cotes quadrature integration.

Chebyshev's problem. For given set of the coefficients λ_j find the best values of the abscissas ξ_j. The best-known problem of this class is the problem with equal, constant coefficients $\lambda_j = 2/n$, i.e. Chebyshev approach to quadrature integration.

Gauss's problem. Find the best positions for the abscissas ξ_j and corresponding to them values of the coefficients λ_j.

Modeling of perturbed flows

The estimation of the flow velocity profiles nearby hydraulic resistances of different kinds is carried out on first step by using set of Salami basis functions [4]. Numerical modeling include, in particular, three interrelated stages: a) flow profile assignment; b) making up set of projections of time-of-flight data for an arbitrary rotation angle of the measuring system; c) obtaining direct and quadrature volumetric/mass flowrate estimations.

For model representation of perturbed flow velocity vector profiles, the following types of functions are used

in radial form

$$U = (1-\rho)^{1/n} + m\rho(1-\rho)^{1/k} f(\theta), \tag{4}$$

and in trigonometric form

$$U = \sin\left(\frac{\pi}{2}(1-\rho)^{1/n}\right) + m\sin\left(\pi(1-\rho)^{1/k}\right) f(\theta), \tag{5}$$

which correspond to basic kinds of the hydrodynamic flows in transport channels having some geometrical changes.

Broad variety of spatial variations of velocity field profiles can be derived by variation of n, m, k and $f(\theta)$ values in (4) and (5), in particular, axisymmetric test profile:

$$U = (1-\rho)^{1/9}, \tag{6}$$

profile P9 (Fig. 1):

$$U = (1-\rho)^{1/9} + \frac{2}{\pi^5}\rho(1-\rho)^{1/4}\theta^2(2\pi-\theta)^2, \tag{7}$$

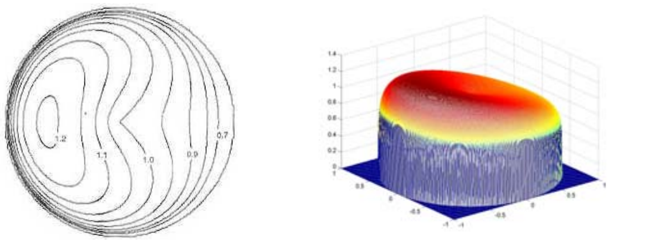

Figure 1: Contour representation and central projection of the axial flow velocity profile calculated by using (7)

profile P10 (Fig. 2):

$$U = (1-\rho)^{1/9} + \frac{2}{\pi^3}\rho(1-\rho)^{1/4}\theta(2\pi-\theta)\sin^2\theta, \qquad (8)$$

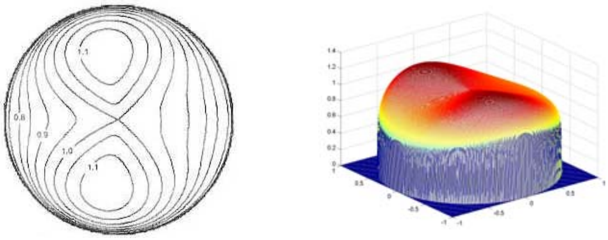

Figure 2: Contour representation and central projection of the axial flow velocity profile calculated by using (8)

Estimation of installation errors

Appropriate installation errors in ultrasonic multipath measurements are represented in Table 1. The designations denote the following: nn – order of discretisation (discretization dimension is 2^{nn}); pp – number of measuring planes; θ - angle of plane's tuning; dn – relative error of flowrate estimation by cross-section integration; dq - relative error of quadrature flowrate measurements estimation.

Table 1: Installation errors

nn	pp	θ	dn0	dq0	dn9	dq9	dn10	dq10
4			2,9	7,5	2,7896	4,2	0,9	14,2
5			0,84	6,7	0,8187	3,6	0,83	13,7
6			0,2215	6,2	0,21	3,2	0,22	13,1
7			0,0804	5,9	0,07	2,9	0,07	12,9
8			0,042	5,8	0,0401	2,8	0,04	12,8
	2			0,92		0,91		1,7
	3			0,8		0,88		1,37
	4			0,85		0,67		1,2
	5			0,67		0,75		0,59
	6			0,59		0,55		0,66
	7			0,51		0,54		0,44
	8			0,3		0,28		0,33
8	1	20		5,7501		2,6603		10,1635
		40		5,7656		2,3059		4,4587
		60		5,7501		1,818		1,5404
		80		5,7656		1,4567		4,9323
		100		5,7656		1,4567		4,9323
		120		5,7656		1,8312		1,5265
		140		5,7501		2,2927		4,4447
		160		5,7656		2,6735		10,1775
		180		5,7501		2,7967		12,5116

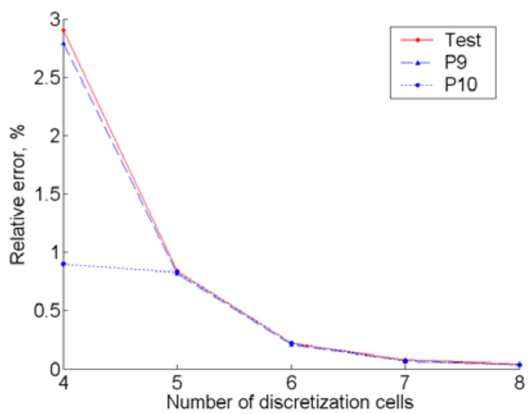

Figure 3: Relative errors of flowrate measurements for trapezoidal integration

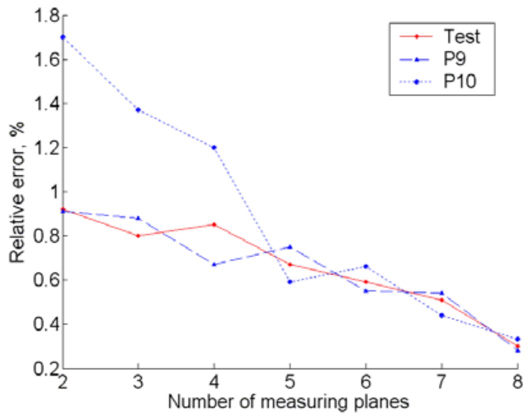

Figure 4: Relative errors of flowrate measurements by using qudrature integration (more than one measurement plane)

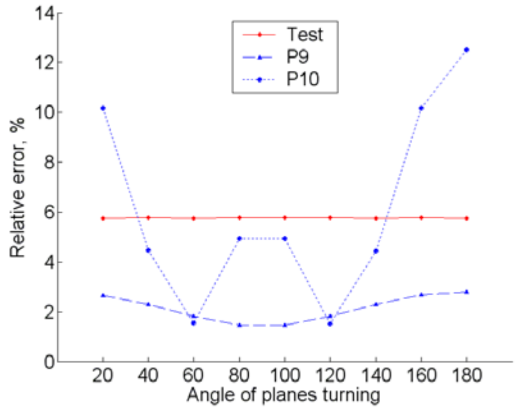

Figure 5: Relative errors of flowrate measurements for the case of plane rotation

Some results on numerical estimation of installation errors occurring in ultrasonic multipath flowcells are depicted in Figs. 3-5. Additional data can be also found in [5, 6].

References

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