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NUMERICAL ANALYSIS OF INSTALLATION EFFECTS IN CORIOLIS FLOWMETERS: SINGLE AND TWIN TUBE CONFIGURATIONS

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ABSTRACT:
A fully coupled, partitioned, numerical model that accounts for fluid-structure interaction is applied for a study of the installation effects of Coriolis flowmeters. The modelled configurations include a single straight-tube full-bore flowmeter and two different twin tube flowmeters with straight and U-shaped measuring tubes. Three different flow disturbance elements positioned upstream of the flowmeter are considered in the study, as well as two different types of flow splitters in the case of the twin tube configurations. The installation effects are estimated by comparing the mass-flow sensitivities under the disturbed and fully developed flow conditions at the inlet of the flowmeter. For the modelled twin tube flowmeters they are found to be of the order of one-tenth of a per cent. These relatively small values of the installation effects are related to the presence of flow splitters and to the averaging of the motion of both measuring tubes in the twin tube configurations. Similarly, averaging the response from two sensor pairs instead of only a single sensor pair reduces the circumferential variations and the peak values of the installation effects for asymmetric flows in the single straight-tube flowmeter.

KEYWORDS:
Coriolis flowmeters, installation effects, single and twin tube configurations, numerical analysis, coupled numerical model
INTRODUCTION

The installation effects in Coriolis flowmeters are in general assumed to be relatively small. However, there are only a limited number of published experimental studies dealing with this subject [1-4]. In some cases the installation effects were identified, but the repeatability of the performed experiments was, in most cases, to excessive for positive identification of the installation effects of the order of magnitude of tenths of a per cent (or even smaller), which would be relevant for the latest generation Coriolis flowmeters.

Our research group has already studied the installation effects in the single straight-tube Coriolis flowmeters analytically using the weight vector theory [5] as well as numerically [6, 7]. The latest paper [7] employed a fully coupled three-dimensional numerical model that accounts for the fluid-solid interaction in the measuring tubes of the flowmeters. The installation effects were identified and explained using a model of a short straight single-tube full-bore flowmeter without considering any attachments fixed to the measuring tube. The results showed that the magnitude of the installation effects under asymmetric flow conditions depends on the circumferential position of the sensors, while remaining unaffected under axisymmetric flow conditions. The installation effects could be of an order of magnitude of 1 % if the sensors were positioned in the plane of the greatest velocity profile asymmetry. However, the installation effects and their variations around the circumference are reduced by increasing the length-to-diameter ratio or the wall thickness of the measuring tube.

The main objective of this paper is to use the above-mentioned, three-dimensional, coupled numerical model for an investigation of the installation effects in more realistic configurations of Coriolis flowmeters. The considered configurations are shown in Fig. 1 and include a single straight-tube full-bore flowmeter and two different twin tube flowmeters with
straight and U-shaped measuring tubes. The different attachments as well as added masses of the motion sensors and the exciters are taken into account. In the twin tube configurations two different types of flow splitters, which divide the flow into two measuring tubes and merge it back at the outlet, are also studied. The installation effects are analysed for three different disturbance elements that are upstream of the flowmeter: a single elbow (producing a high asymmetry axial velocity profile), closely coupled double elbows out-of-plane (producing an asymmetrical axial velocity profile with intense swirl) and an orifice (producing a distorted axisymmetric velocity profile with increased centre-core velocities). The present paper also extends the findings for the single-straight full-bore flowmeter from our previous study [7] by studying the influence of the axial placement of the sensors and exploring the possibility of using an additional sensor pair.

Fig. 1. Modelled configurations of Coriolis mass flowmeters
2 NUMERICAL MODEL

The fluid-structure interaction in the measuring tube of the Coriolis flowmeter is simulated using a partitioned numerical model, which means that the fluid and the structure are computationally treated as two isolated domains interacting in each time step of the simulation. The turbulent fluid flow is analysed by the finite-volume code and the deformable shell structure by the finite-element code. The solution procedure is characterized by an alternative exchange of data between the two computational codes, where the data computed within one code provide the information to be used in the subsequent numerical step in the other code. The model adopts a conventional serial staggered procedure with a three-point fluid predictor for the fluid stress tensor and the additional inner iterations in each time step. A more detailed description of the simulation procedure, its validation and an analysis of the different coupling scenarios can be found in [8,9]. This section presents the governing equations of the problem, the boundary and initial conditions, defines the computational domain and the material properties of the fluid and the structure, the method for the estimation of the measuring effect and the temporal and spatial discretization of the model.

2.1 Fluid domain

Based on the assumption of a Newtonian, turbulent, isothermal and weakly compressible fluid flow with a density $\rho_F$, a fluid velocity vector $\mathbf{v}_F$ and a boundary velocity $\mathbf{v}_S$ of the fluid domain $\Omega_F$, the conservation of mass and momentum principles can be written in the following form

$$\frac{\partial}{\partial t} \int_{\Omega_F} \rho_F \, d\Omega + \int_{\Gamma_F} \rho_F \left( \mathbf{v}_F - \mathbf{v}_S \right) \cdot \mathbf{n} \, d\Gamma = 0,$$

(1)
\[
\frac{\partial}{\partial t} \int_{\Omega_F} \rho_F v_F \, d\Omega + \int_{\Gamma_F} \rho_F v_F (v_F - v_S) \cdot \mathbf{n} \, d\Gamma = \int_{\Omega_F} \sigma_F \cdot \mathbf{n} \, d\Gamma + \int_{\Omega_F} \mathbf{f_F} \, d\Omega , \quad (2)
\]

where \( \Gamma_F \) is the boundary of the fluid domain, \( \mathbf{n} \) is the normal vector to the boundary, the vector \( \mathbf{f_F} \) stands for the volume forces acting inside the fluid domain \( \Omega_F \) and \( \sigma_F \) is the fluid stress tensor combining the viscous stresses and the pressure. The stresses due to turbulent motion are resolved by employing the standard \( k-\varepsilon \) turbulence model [10].

The three different disturbance elements are modelled: the single elbow (SE), the closely coupled double elbows out-of-plane (DE) and the orifice-like constriction (OR) (see Fig. 2). The single elbow is assumed to be positioned in the \( x-z \) plane (SE-X; in the plane of the tube vibration) or in the \( y-z \) plane (SE-Y; perpendicular to the plane of the tube vibration). The downstream elbow of the double-elbows configuration is always positioned in the \( x-z \) plane.

![Flow disturbance elements](Fig. 2. Flow disturbance elements (fluid domain):

a) single elbow – SE, b) double elbows out-of-plane – DE, c) orifice – OR.)

The computational fluid domain is schematically presented in Fig. 3 for the single straight-tube flowmeter positioned downstream of the single elbow in the \( x-z \) plane and the twin U-tube meter positioned downstream of the double elbows out-of-plane. The fluid domain
consists of the flow disturbance section (a straight tube run of $10D_{in}$ and the disturbance element), the inlet section, which in all cases has a fixed length of $5D_{in}$, the flowmeter, and the outlet section of length $10D_{in}$, where $D_{in}$ is the inner diameter of the connecting tubing. All the elbows have a centreline curvature radius of $1.5D_{in}$, and the inner diameter and the thickness of the orifice equal $D_{in}/\sqrt{2}$ and $0.1D_{in}$, respectively. The fluid domain of the flowmeters consists of the flow splitters and the measuring tubes (please note that no flow splitters are needed in the single tube full-bore flowmeter design). In the reference case, with the fully developed (FD) flow conditions at the inlet of the flowmeter, only the straight inlet section of length $10D_{in}$ was assumed upstream of the measuring tube.

Fig. 3. Scheme of the computational fluid domain for the single straight-tube flowmeter downstream of the single elbow (SE-X) and the twin U-tube flowmeter downstream of the double elbows out-of-plane (DE)
In the modelled twin tube designs the flow is divided into two measuring tubes at the inlet and then merged back at the outlet using the flow splitters. We considered the two different flow splitter designs shown in Fig. 4. The type A flow splitter is characterized by a longer and smoother transition between the external tubing and the measuring tubes and therefore has a considerably smaller pressure loss compared to the type B flow splitter. The pressure loss in the twin straight-tube meter equipped with the type A flow splitters is about 30% smaller than when using the type B flow splitters. Similar configurations of flow splitters were, in terms of minimizing the pressure loss, also thoroughly studied in [11].

Fig. 4. Flow splitters: a) type A, b) type B
The initial fluid velocities in the fluid domain correspond to the steady-state field of the fluid flow in the tube at rest. The fully developed velocity profile is set at the inlet boundary of the fluid domain, while the constant pressure boundary is imposed at the outlet. The domain wall velocities are only prescribed for the surface of the measuring tube section (elsewhere they equal zero), according to the results of the solid domain analysis. A moving grid simulation is performed to capture the motion according to the results of the solid domain analysis. The finite volumes’ boundary velocities are calculated by obeying the so-called space-conservation law [12].

The numerical solution to the fluid problem is obtained by employing the CFD code Star-CD v4.18. The unsteady terms are discretized in accordance with the first-order, implicit Euler scheme, while the convective and diffusive terms are approximated using the upwind differencing scheme.

The inner diameter of the measuring tubes for all the modelled cases equals $D = 20$ mm, which is clearly also the inner diameter of the connecting tubing for the single straight-tube flowmeter, whereas for the twin-tube flowmeter the inner diameter of the connecting tubing equals $D_{in} = 50$ mm. A water-like fluid is assumed with a density of 1000 kg/m$^3$ and a viscosity of 0.001 Pa·s. For all the simulated cases, the inlet mass flow rate in the single straight-tube flowmeter is equal to $q_{in} = 1.56$ kg/s (Reynolds number of $10^5$), and it is twice as large in the twin tube flowmeters, with the aim being to obtain comparable flow velocities and Reynolds numbers in the measuring tubes.
2.2 Solid domain

The three-dimensional spatial distribution and time evolution of the tube’s dynamic response are governed by the conservation of momentum principles. The associated equation of motion can be derived using Hamilton's variational principle

\[ \int_{t_1}^{t_2} \delta (E_p - E_k) \, dt = 0 \, , \]  

(3)

where \( E_p \) and \( E_k \) are, respectively, the total potential energy and the total kinetic energy of the moving solid structure. The total potential energy \( E_p \) is the sum of the strain energy corresponding to the actual deformation of the tube, and the load's potential corresponding to the actually applied conservative external forces. Considering the nature of the investigated case, the surface tractions \( p_s \) acting on the moving tube boundary through the respective displacement field \( u_s \), and the concentrated force \( F \) at points \( P_i \), where the forced vibration is generated, are taken into account. These loads yield the following integral expression for the total potential energy

\[ E_p = \frac{1}{2} \int_{\Omega_s} \sigma_s : \varepsilon_s \, d\Omega - \int_{\Gamma_s} p_s \cdot u_s \, d\Gamma - \sum_i F \cdot r_i \, , \]  

(4)

where \( \Omega_s \) is the tube domain and \( \Gamma_s \) is its boundary, \( \varepsilon_s \) and \( \sigma_s \) are, respectively, the strain and the stress tensors in the tube, and \( r_i \) is the position vector of the point \( P_i \) where the force \( F \) is applied. The total kinetic energy \( E_k \) of the tube can be written as

\[ E_k = \frac{1}{2} \int_{\Omega_s} \rho_s (v_s \cdot v_s) \, d\Omega \, , \]  

(5)

where \( \rho_s \) is the density of the tube material and \( v_s \) is the tube velocity field.
The computational domain for the structural dynamic analysis consists of the vibrating measuring tubes and the additional elements attached to it. The details of the considered geometries are shown in Fig. 1 (the fluid domain (blue) is included for a clearer representation). The rings, which represent the local reinforcements caused by the different means of attaching the exciters or the sensors to the measuring tube, are positioned at equal distances from each other. The masses of the exciters and the sensors are represented by the discrete mass elements (yellow points). In the twin tube configurations they are positioned on the outer sides of the tube. In straight-tube configurations the fins are also considered at the ends of the measuring tubes. They are used to enforce the desired direction of the tube vibration by increasing the stiffness of the tube in the direction perpendicular to it.

The initial velocity, corresponding to the first natural lateral vibration mode, is prescribed as the initial condition of the simulation. The measuring tube at rest is assumed to be both unstressed and unstrained. The imposed boundary conditions are the clamped ends of the measuring tubes, the time-varying pressure load of the fluid on the inner side obtained with the fluid analysis, and the time-varying excitation forces on the outer side of the measuring tube. In all cases the excitation forces are applied in the \( x \)-direction at the middle of the measuring tubes at the positions of the exciters. The measuring tubes in the twin tube meters are excited in anti-phase to each other.

In the numerical model the vibrating measuring tubes are modelled as a deformable shell structure with isotropic, linear elastic, material properties, and the attachments are modelled as solids and as discrete mass elements. The simulation is realised using the commercial code Abaqus 6.10, which solves the dynamics problem in accordance with the finite-element method.
The Newmark formulae are used for the implicit displacement and the integration of the velocity over time.

The effective length of the measuring tubes is equal to $L_m = 20D$ and the wall thickness is equal to $s = 1$ mm (if not explicitly stated otherwise). The sensors are positioned symmetrically with respect to the centre of the tube length with the distance $L_s$ apart (measured along the length of the measuring tube). The ratio $L_s/L_m$ equals 0.5. The sensors’ masses are assumed to be equal to 1 g, and the rings’ rectangular cross-section is 1 mm thick and 4 mm wide (their mass equals approximately 1.25 g). The measuring tube and the attachments are assumed to be made of titanium with a density of 4510 kg/m$^3$, a Young’s modulus of 102.7 GPa and a Poisson’s ratio of 0.34.

### 2.3 Estimation of the installation effect

The mass-flow sensitivity of the Coriolis meter can be defined by the ratio between the time difference $\Delta t_S$ of the responses from the motion sensors along the length of the measuring tube and the inlet mass flow rate $q_m$. $K_{\Delta \phi} = \Delta t_S / q_m$. The time difference is calculated as $\Delta t_S = \Delta \phi / 2\pi f_0$, where $\Delta \phi$ is the phase difference between the response of the motion sensors and $f_0$ is the natural frequency. When four sensors are used the time difference is calculated between the signals that are generated by combining the responses of the sensors at the same axial position. The frequency $f_0$ and the phase $\phi$ at $f_0$ of each individual response (signal) are obtained using a DFT (discrete Fourier transform) algorithm and the phase difference $\Delta \phi$ was calculated as the difference between the phase values of the sensors’ responses (signals). The values used in the calculation of the mass-flow sensitivity are obtained from the last 10 oscillation periods.
The values of $f_0$ and $K_{\Delta t}$ for the single straight-tube flowmeter are about 500 Hz and $1.3 \times 10^{-6} \text{ s}^2/\text{kg}$, respectively. For the twin straight-tube flowmeter $f_0$ is about the same, whereas $K_{\Delta t}$ is approximately half the size due to the two-times-larger inlet mass flow rate. For the twin U-tubes flowmeter $f_0$ and $K_{\Delta t}$ are about 350 Hz and $2.0 \times 10^{-6} \text{ s}^2/\text{kg}$, respectively.

The installation effects are estimated as the relative change of the mass-flow sensitivities under the disturbed flow conditions with respect to the fully developed (FD) flow conditions upstream of the flowmeter

$$ \varepsilon_K = \left( \frac{K_{\Delta t}}{K_{\Delta t,\text{FD}}} - 1 \right) \cdot 100\% . $$

(6)

### 2.4 Temporal and spatial discretization effects

The measuring tube is discretized using the structured mesh of shell finite elements, which divide the circumference of the tube into 40 segments and have an axial length of about 4 mm (their length is reduced at the positions of the attachments and in their vicinity). The surface of the fluid in the measuring tube has the same discretization as in the solid model, so a perfect match on the fluid-structure interface is ensured. The cross-section of the tube is discretized using 441 cells. The same cross-sectional pattern of the finite volumes is used for the discretization of the entire fluid domain. The approximate number of cells is about $1 \times 10^5$ for the single straight-tube model and about $2 \times 10^5$ for the twin tube models.

The time step of the simulation is set to $1/70$ of the oscillation period of the measuring tube. All the simulation results were conducted for 3000 time steps, which equals approximately 43 oscillation periods of the measuring tube, and were run on a PC with four 3.5 GHz cores and
with 16 Gbyte of RAM, operating under the Windows 7 OS. Each simulation required about 2 to 4 days of wall clock time. The repeatability (i.e., the scatter) of $\varepsilon_K$ is less than 0.015 % for all the simulated cases. A longer computer simulation did not improve the estimated repeatability.

The influence of the selected spatial and temporal discretizations on the computed installation effects was estimated for the single straight-tube as well as for the twin straight-tube meters positioned downstream of the single elbow (SE-X case), which produces pronounced asymmetry of the velocity profile. To estimate the effect of the selected grid size the models for both flowmeter configurations with axial length of elements reduced by a factor of 2 were prepared and to evaluate the effect of the selected temporal discretization the time step size was decreased for a factor of 2 in the original numerical models. The mass-flow sensitivities ($K_M$) and the installation effects ($\varepsilon_K$) were the observed parameters. For the single straight-tube flowmeter they were observed at different circumferential positions and in the case of the twin-tube flowmeter both parameters were analysed for the entire flowmeter and also for each measuring tube separately (see Section 3 for more details). It was found that either space or time refined numerical models produced up to 0.25 % higher mass-flow sensitivities compared to the original numerical models. However, their influence on the estimated magnitude of the installation effect was found to be insignificant for the purposes of the current study, i.e., the values of $\varepsilon_K$ differed less than 0.01 % in all the investigated cases for the single and twin straight-tube flowmeters.
3 RESULTS

3.1 Straight-tube full-bore design

The effect of the axial position of the sensors on the installation effects is studied on a simplified “bare” model of the single straight-tube full-bore flowmeter, which does not account for any attachments or added masses on the measuring tube that are shown in Fig.1. Using such a model we can simultaneously monitor the simulation responses of multiple sensing points positioned on the measuring tube. The axial distance between the sensing points is given by the ratio $L_s/L_m$, which changes from 0.2 to 0.8 (if $L_s/L_m$ was zero, both sensing points would be positioned at the centre of the tube, i.e. at the driver position). In addition, four different circumferential positions of the sensor pairs at $\theta = 0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ were observed (see Fig. 3 for the definition of $\theta$).

Fig. 5 shows the relative change of $\varepsilon_K$ as a function of the ratio $L_s/L_m$ for different circumferential positions $\theta$ of the sensor pairs on the measuring tube. For the single elbow (SE-X) case shown in Fig 5a, the installation effects significantly increase by placing the sensors at a greater distance apart, if the sensors are positioned in the plane of the velocity profile’s greatest asymmetry (at $\theta = 0^\circ$ and $180^\circ$). In that case the absolute value of $\varepsilon_K$ increases from 0.26% at $L_s/L_m = 0.2$ to 0.48% at $L_s/L_m = 0.8$. On the other hand, the estimated installation effects at $\theta = 90^\circ$ and $270^\circ$ are practically not influenced by the axial distance between the sensors. Such observations can be partly attributed to the fact that the velocity profile changes significantly in the x-z plane ($\theta = 0^\circ$ and $180^\circ$), but remains symmetrical in the y-z plane (see Fig. 5 in Ref. [7]).
The variations of $\varepsilon_K$ with the ratio $L_s/L_m$ are more complex when the measuring tube is positioned downstream of the double elbows (Fig. 5b). At all circumferential positions the
installation effect is significantly altered for different axial distances between the sensing points and also changes sign for three of the four observed circumferential positions.

In contrast to the results presented in Fig. 5, we can mention the findings obtained by the simulations of the flowmeter downstream of the orifice. The results show that the values of $\varepsilon_K$ remain almost independent of the ratio $L_s/L_m$ ($\varepsilon_K$ varies between 0.16 % and 0.18 %), which is probably due to the constant recovery of the fully developed velocity profile along the length of the measuring tube.

The results for the asymmetrical flow conditions downstream of the single elbows (see Fig. 5a) show that if the value of $\varepsilon_K$ is positive at a certain circumferential position $\theta$ then its value will be negative on the opposite side at $\theta + 180^\circ$. Such observations led us to investigate the estimated installation effects when using four sensing points (two sensor pairs) instead of two sensing points (one sensor pair) for the estimation of the mass-flow sensitivity. In the first case the two sensors pairs were positioned in the $x$-$z$ plane at $\theta = 0^\circ$ and $180^\circ$ and in the other one they were positioned in the $y$-$z$ plane at $\theta = 90^\circ$ and $270^\circ$. Fig. 6 presents the results of simulations that were conducted on the “bare” model with the identical upstream disturbance elements as shown in Fig. 5. A comparison of these two figures shows that the values of $\varepsilon_K$ obtained using two sensor pairs positioned at opposite sides of the circumference equal the mean of the values obtained for each sensor pair individually. Using the two sensor pairs positioned in the $x$-$z$ plane, the installation effect in the single elbow case is therefore reduced by at least one order of magnitude; the values of $\varepsilon_K$ are reduced to 0.02 % or even less. Similarly, the installation effects in the case of the double elbows also decrease when two sensor pairs were used. On the other hand, it is obvious that such a measure cannot reduce the installation effects if the plane of the flow symmetry coincides with the plane in which the sensors are positioned.
(e.g., in any axisymmetrically distorted flows caused by the orifice or similar concentric flow disturbance elements, in the y-z plane downstream of the single elbow).

Fig. 6. Variations of $\varepsilon_K$ with the ratio $L_s/L_m$ for a measuring tube downstream of a) the single elbow (SE-X) and b) the double out-of-plane elbows (DE) using two sensor pairs.

Next, we want to demonstrate how the circular stiffness and the added masses influence the installation effect of the single tube flowmeter. The following cases were compared: the “bare” measuring tube with wall thicknesses of $s = 1$ mm and $s = 1.5$ mm and a more realistic model of the measuring tube accounting for the different attachments and added masses of the exciters and the sensors (see Fig. 1a). In the “bare” tube model the circumferential stiffness is uniformly increased by increasing the tube wall thickness, whereas in the latter model the tube is reinforced only locally with rings at the positions of the sensors and the exciter. In all three cases the measuring tube was assumed to be positioned downstream of the single elbow (SE-X) and the distance between the sensors equals $L_s/L_m = 0.5$. The calculated results are shown in the polar
diagram in Fig. 7, in which the magnitude of the installation effect is represented by the radial distance from the zero value, which is marked by the circular border between the yellow/brighter (negative) and the blue/darker (positive) regions. The values of $\varepsilon_K$ have the same trend along the circumference for all three cases; however, the values at $\theta = 0^\circ$ and $90^\circ$ are reduced by about 50% when the thickness of the measuring tube is increased by a factor of 2, and by about 20% for the model including the attachments and added masses. Next, we prepared an additional model, including only rings (no other attachments), and almost identical results compared with the model including attachments and added masses were obtained. This shows that the fins modelled at the tube endings, enforcing the desired direction of the tube vibration, and the masses of the sensors and the exciters, do not contribute to the decrease of the installation effect.

Fig. 7. Variation of $\varepsilon_K$ as a function of the sensors’ circumferential position for different models of the single straight-tube flowmeter positioned downstream of the single elbow (SE-X).
3.2 Twin tube designs

The simulations were performed for the twin tube flowmeters with two different shapes of the measuring tubes (straight and U-tubes – see Figure 1b and 1c) and two different types of flow splitters, which are shown in Fig. 4. The attachments, the added masses of the sensors and the exciters, and the other design features of the investigated configurations of the flowmeters were taken into account in all cases. The mass-flow sensitivity is calculated by considering the motion of four sensors: two on each measuring tube. The simulations were performed for four different upstream configurations: the single elbow positioned in the x-z plane (SE-X) or in the y-z plane (SE-Y), the double out-of-plane elbows (DE) and the orifice-like constriction (OR). The results are presented in Fig. 8. It is evident that the predicted installation effects are affected by the shape of the measuring tubes as well as by the type of flow splitter. Observing the absolute values of $\varepsilon_K$, it is clear that their average value is approximately two-times larger for the straight-tube flowmeters (about 0.08%) than for the U-tube flowmeters (about 0.04%). The results indicate that the U-tube flowmeters might be, in general, less prone to the installation effects than the straight-tube ones. This could be explained by the fact that the flow in the curved measuring tube is primarily governed by the curvature of the tube and not by the shape of the velocity profiles entering the measuring tube. In favour of the latter is also the observation made by comparing the values of mass-flow sensitivities $K_M$ of the particular flowmeter configuration in fully developed upstream flow conditions obtained for the two modelled flow splitters. It was established that $K_M$ changes by about 0.6% for the straight-tube flowmeter, whereas a difference of less than 0.1% is predicted for the U-tube flowmeter. Thus, it is evident that particularly for the straight-tube configuration the design of the flow splitter alone can have a considerably larger effect on the sensitivity than any of the upstream modelled disturbance elements (the installation effects of which in combinations with flow splitters are shown in Fig. 8).

Fig. 8. Values of $\varepsilon_K$ for different upstream disturbance elements for the modelled configurations of the twin tube flowmeters (■ – straight-tube flowmeter & type A flow splitter, □ – straight-tube flowmeter & type B flow splitter, ● – U-tube flowmeter & type A flow splitter, ○ – U-tube flowmeter & type B flow splitter)

It is clear from Fig. 8 that the installation effects for the twin tube configurations exceed 0.1\% in only two out of sixteen simulated cases. One of the reasons for such a relatively small installation effect is shown in Fig. 9, which presents the integral value (using four sensors) of the installation effects of the twin straight-tube flowmeter as well as the separate installation effects for the sensor pairs on each measuring tube, 1 and 2 (viewed in the $x$-direction the measuring tube 2 lies behind the measuring tube 1). The installation effects for the SE-X single elbow and the double elbows cases differ for each measuring tube, whereas in the case of the symmetric flow conditions in both measuring tubes, as for the SE-Y single elbow and the orifice upstream of the flowmeter, they remain practically equal. In all cases the integral value of the flowmeter’s
installation effect (sensitivity) is the average of the individual installation effects (sensitivities) of both measuring tubes. This observation is analogous to the averaging of the response of two sensor pairs in the single straight-tube flowmeter discussed in the previous subsection.

Fig. 9. Variations of $\varepsilon_K$ for different upstream disturbance elements for the twin straight-tube flowmeter in combination with the type A flow splitter

The other important parameter influencing the magnitude of the installation effect is the shape of the velocity profiles entering the measuring tubes. In Fig. 10 the axial velocity profiles 0.5$D$ downstream of the flow splitter’s outlet are shown for both planes of the measuring tubes for the same cases as in Fig. 9. It is evident that the flow splitter causes a significant alteration of the axial flow that enters the measuring tubes, regardless of the disturbance element, and that the resulting velocity profiles observed in the $x$-$z$ plane are relatively flat. Regarding the results presented in Fig. 9, it is evident that the different installation effects in each measuring tube for the single elbow (SE-X) case are caused by the inlet velocity profiles not being symmetric in the
x-z plane and that the highest installation effect observed in the orifice case is related to the largest alteration of the inlet velocity profile among the observed cases. However, the differences in the resulting axial velocity profiles are rather small, irrespective of the upstream perturbation element, which explains the relatively small installation effects. Besides, it is reasonable to expect that if the sensors were to be placed on the opposite sides of the measuring tubes’ circumference (on the inside), the sign of the estimated installation effects would change, due to an almost symmetric flow alteration in the measuring tubes (with respect to their midline) in most of the cases.

Fig. 10. The axial velocity profiles downstream of the type A flow splitter in the measuring tubes of the twin straight-tube meter
4 CONCLUSIONS

A study of the installation effects is presented for the single tube and twin tube Coriolis flowmeters with straight and U-shaped measuring tubes using a fully coupled numerical model. The installation effects were observed for the flowmeters positioned downstream of a single elbow, a closely coupled double elbows out-of-plane and an orifice.

Simulations of the single straight-tube flowmeter show that the magnitude of the installation effects can be affected by the axial distance between the sensors, especially in asymmetrically distorted flows such as downstream of the single elbow. For the asymmetric flows the installation effects can be significantly reduced by using two pairs of sensors positioned at the opposite sides of the circumference, instead of only one. The simulations also demonstrate that the local reinforcements of the measuring tube, for instance caused by the fastening of any attachments to the measuring tube, like the increased thickness, reduce the circumferential variations of the installation effect in asymmetric flow conditions.

The installation effects of the modelled twin tube flowmeters using straight or curved U-tubes are found to be relatively small: of the order of one-tenth of a per cent. This is related to the averaging of the motion of both measuring tubes and to the usage of flow splitters in the twin tube configurations. Namely, the flow splitters represent an additional perturbation of the flow, which causes the axial velocity profiles entering the measuring tubes to be more comparable, regardless of the upstream disturbance element. However, it was shown that the actual values of the installation effect for any specific configuration of the flowmeter depend on its actual design features, such as the shape of the measuring tube, the position of the sensors, the flow splitter design, etc. The obtained results also indicate why the identification of the installation effects proved to be difficult in earlier published experimental studies [e.g. 2, 3]. An estimated
reproducibility for the experiments of about 0.25% was reported, which is of about the same order of magnitude (or even larger) as the magnitudes of the installation effects in the twin tube flowmeters predicted in this paper.

The reader should be aware that the obtained values of the installation effects for the considered types of flowmeters are also dependent on the quality of the numerical model, especially the quality of the turbulence model. However, even if we used a more complete numerical model that could describe the nature of the flow more precisely, we would still not be able to predict the exact flow conditions found in the operational environment of the flowmeter. In addition to the modelled disturbance elements, there are other details affecting the actual flow conditions in the measuring tubes: non-smooth passages, misalignment of the connecting flanges, actual wall roughness of the tubes, reducers that are often installed upstream (downstream) of the flowmeter, etc. Nevertheless, we believe that even if we used an enhanced numerical model this would not change the general conclusions of the presented study.
5 REFERENCES


