Flow Measurement and Instrumentation 44 (2015) 71–78

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Numerical analysis of installation effects in Coriolis flowmeters: Single and twin tube configurations

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ARTICLE INFO

Available online 24 December 2014

Keywords:
Coriolis flowmeters
Installation effects
Single and twin tube configurations
Numerical analysis
Coupled numerical model

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 modeled 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 modeled 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.

1. 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 analyzed 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 center-core velocities). The present paper also extends the findings for the single-straight full-bore flowmeter from our previous study [7] by studying

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http://dx.doi.org/10.1016/j.flowmeasinst.2014.10.001
0955-5986/

the influence of the axial placement of the sensors and exploring the possibility of using an additional sensor pair.

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 analyzed 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.

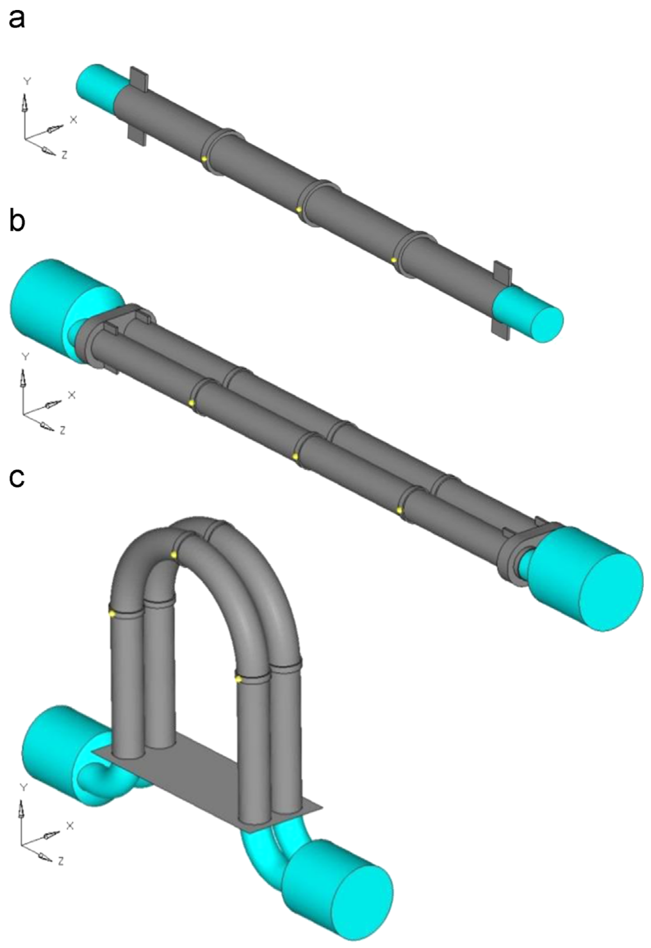

Fig. 1. Modeled configurations of Coriolis mass flowmeters.

2.1. Fluid domain

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

$$\frac{\partial}{\partial t}\int_{\Omega_F} \rho_F \, \mathrm{d}\Omega + \int_{\Gamma_F} \rho_F(\mathbf{v}_F - \mathbf{v}_S)\cdot \mathbf{n}\, \mathrm{d}\Gamma = 0, \quad (1)$$

$$\frac{\partial}{\partial t}\int_{\Omega_F} \rho_F \mathbf{v}_F \, \mathrm{d}\Omega + \int_{\Gamma_F} \rho_F \mathbf{v}_F(\mathbf{v}_F - \mathbf{v}_S)\cdot \mathbf{n}\mathrm{d}\Gamma = \int_{\Gamma_F} \boldsymbol{\sigma}_F \cdot \mathbf{n}\, \mathrm{d}\Gamma + \int_{\Omega_F} \mathbf{f}_F \, \mathrm{d}\Omega, \quad (2)$$

where Γ_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 Ω_F and $\boldsymbol{\sigma}_F$ 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–ε turbulence model [10].

The three different disturbance elements are modeled: 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.

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.

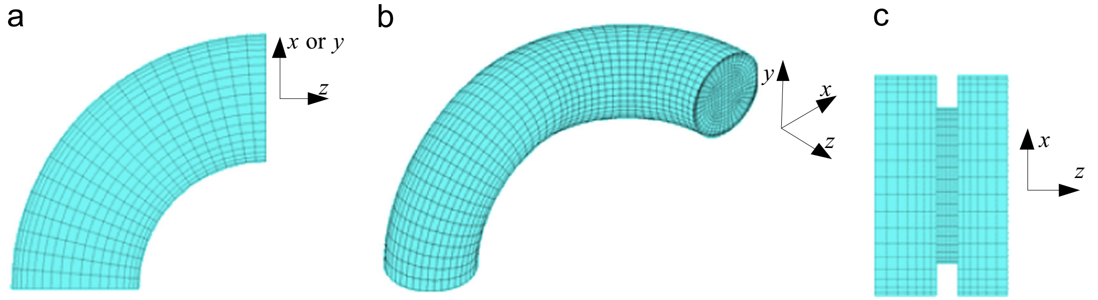

Fig. 2. Flow disturbance elements (fluid domain): (a) single elbow – SE, (b) double elbows out-of-plane – DE, and (c) orifice – OR.