VELOCITY PROFILE EFFECTS IN CORIOLIS MASS FLOWMETERS: RECENT FINDINGS AND OPEN QUESTIONS

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ABSTRACT

The aim of this paper is to discuss velocity profile effects in Coriolis flowmeters and to review related research work. The measurements made by Coriolis flowmeters are dependent upon the steady flow velocity distribution within them whenever certain features of the fluid vibrational fields are not uniform inside the measuring tube. This dependence is confirmed by simulation results on two straight tube configurations, one operating in a beam-type mode and the other in a shell-type mode. Findings to date and open questions regarding velocity profile effects in Coriolis flowmeters are discussed for both fully developed and disturbed inlet flow conditions.

Keywords: Coriolis flowmeter; Velocity profile effect; Fluid vibrational field; Weight vector theory

NOMENCLATURE

- $A$: tube cross-section
- $D$: tube inner diameter
- $f$: fluid Coriolis-like body force
- $K_w$: weight function factor
- $L$: tube length
- $q_m$: fluid mass flowrate
- $R$: tube inner radius
- $Re$: Reynolds number
- $Re_{cr}$: critical Reynolds number $Re_{cr} \approx 2000$
- $s$: distance between the sensors
- $v_s(x)$: tube transverse velocity in the beam-type flowmeter
- $v_s(x, \theta)$: tube radial velocity in the shell-type flowmeter
- $v'_s$: derivative of the tube velocity with respect to $x$
- $\Delta v'_s$: net alteration of the tube velocities at the sensing points
- $v^{(1)}$: fluid vibrational velocity vector resulting from the tube no-flow drive mode
- $v^{(2)}$: fluid vibrational velocity vector resulting from the tube no-flow mode driven by unit forces at the sensing points
- $v_x, v_y, v_z$: fluid vibrational velocity components
- $V$: fluid steady velocity vector
1. INTRODUCTION

Velocity profile effects are variations in a flowmeter’s sensitivity arising from different velocity profiles of the measured flow. They may be divided into effects of fully developed and effects of disturbed velocity profiles. Fig. 1 shows some examples of fully developed velocity profiles in a straight, circular-section pipe of sufficient length. Because the form of these fully developed velocity profiles mainly depends on Reynolds number $Re = \frac{V_m D}{\nu}$ (but actually also on pipe roughness), this effect of variations in fully developed flow is usually termed Reynolds number effect. Reynolds number depends on the values of internal pipe diameter $D = 2R$, axial mean flow velocity $V_m$ and fluid kinematic viscosity $\nu$. The so-called critical Reynolds number $Re_{cr} \approx 2000$ represents the approximate boundary between laminar flow (for which $Re < Re_{cr}$) and turbulent flow (for which $Re > Re_{cr}$). Fully developed laminar flow in a circular pipe is described by a parabolic velocity profile, whereas fully developed turbulent velocity profiles at higher Reynolds numbers approach a flat distribution.

![Normalized fluid velocity vs. normalized coordinate](image)

**Fig. 1.** Fully developed velocity profiles in a circular tube for different Reynolds numbers.

The inconvenient velocity profiles encountered when installing a flowmeter downstream of pipe elements (bends, valves, etc.) are responsible for disturbed flow conditions within the flowmeter,
which differ from the calibration flow conditions with a fully developed flow at the inlet. Fig. 2 shows two examples of typical disturbance elements, where a single elbow leads to an asymmetric outflow, and an out-of-plane double elbow adds a swirl to the outflow. Flowmeters may be combined with flow straighteners and flow conditioners to reduce the disturbed flow effects and the required straight lengths in installation (see, for example, Baker [1]).

![Flow disturbance elements and their outflow fields.](image)

Different measuring principles and flowmeter configurations show different susceptibilities to velocity profile effects. Coriolis flowmeters are often (falsely) regarded as being immune to velocity profile effects. The aim of this paper is to discuss the background of velocity profile effects in Coriolis flowmeters and review the related research work. Velocity profile effects depend on many constructional and operational parameters of the flowmeter. That is why they can be small (and also negligible) for some configurations but also large for others. The required measurement accuracy of the flowmeter is certainly a decisive parameter in characterizing profile effects as negligible or significant. For example, a few effects of order 0.01% are not negligible for the new-generation devices trying to achieve accuracies better then ±0.1%. This should be borne in mind when evaluating the significance of particular effects.

In this paper a general discussion of velocity profile effects in Coriolis flowmeters is complemented with some illustrative results of calculations for the straight-tube configuration, vibrating in the fundamental beam-type mode and in the second circumferential shell-type mode. We should stress that there is (was?) only one commercially available shell-type flowmeter configuration, also known as the ‘radial mode flowmeter’. So the shell-type flowmeter is certainly not equal in importance to the beam-type flowmeter available in many straight and curved tube configurations. However, the case of the shell-type flowmeter represents a clear example of how the Coriolis measuring principle can be strongly influenced by velocity profile effects, and we can explain why. Section 2 gives an insight into the properties of the fluid vibrational fields in the flowmeter, which are then linked to results about Reynolds number effects and installation effects in Sections 3 and 4, respectively. The mathematical background of the weight vector approach and related analytical approximations used in this paper can be found in some recent references by Kutin at al. [2, 3].
2. PHYSICAL AND THEORETICAL BACKGROUND

The following discussion explains the primary Coriolis force measuring effect and the background of the related velocity profile effects. It neglects the higher-order flow effects (such as the centrifugal force or the higher-order Coriolis force effects), which could become important at larger flowrates. The assumption is quite reasonable since larger non-uniformities of the velocity profiles are expected at smaller flowrates (smaller Reynolds numbers). However, a reader should bear in mind possible mixing of different non-idealities in practical use of Coriolis flowmeters.

The primary mass flowrate measuring effect in Coriolis flowmeters arises from the fluid-structure interactions between the vibrating measuring tube and the fluid flowing in it. This is represented schematically as a block diagram in Fig. 3. A measuring tube vibrates at a defined driven mode frequency with a corresponding mode shape. The tube vibration causes a vibrational velocity field of the internal fluid (interaction (i)), which interacts with the measured fluid flow and gives rise to a Coriolis-like body force in the fluid. This body force acting on the fluid mass particles is transferred as a load back to the measuring tube (interaction (ii)) and that results in an alteration to the no-flow drive mode shape. On account of the properties of the Coriolis-like body force, this secondary tube motion has a phase lag of ninety degrees and opposite symmetry from the no-flow driven mode. The resulting asymmetry of the net tube mode shape is used as the basis of the mass flow measurement in a Coriolis flowmeter. Mass flow is usually measured from the phase or time difference between the output signals of two motion sensors, which are positioned symmetrically along the tube length.

![Fig. 3. Schematic view of the primary measuring effect in Coriolis mass flowmeters.](image)

A Coriolis flowmeter would certainly not show sensitivity to velocity profile effects if both fluid-structure interactions presented in Fig. 3 behaved ideally (as in the one-dimensional flow model of a beam-type meter). The causes of velocity profile effects are deviations from the ideal situation: (i) the fluid may not vibrate exactly as tube vibrates and (ii) the Coriolis-like body force may not be wholly transferred to tube loading.

The mathematical expression for the time or phase difference between sensors at measuring points in terms of the abovementioned body force in the three-dimensional fluid was derived by
Hemp [4, 5]. The Coriolis-like body force (per unit volume), which results from the coupling between the fluid vibrational velocity field $\mathbf{v}^{(1)}$ of the no-flow drive mode and the steady velocity field $\mathbf{V}$ of the measured flow, turns out to be:

$$
\mathbf{f} = -\rho \left[ \left( \mathbf{V} \cdot \nabla \right) \mathbf{v}^{(1)} - \left( \mathbf{v}^{(1)} \cdot \nabla \right) \mathbf{V} \right].
$$

(1)

It can be linked to the measuring effect by bringing into use the reciprocity principle of elastodynamic systems (see, for example, Achenbach [6]). The elementary reciprocity principle for two different loading cases 1 and 2 states roughly that the product of the loading in case 2 and the response in case 1 is equal to the product of the loading in case 1 and the response in case 2.

We consider a measuring tube with a symmetric no-flow drive mode shape, where the body force causes an anti-symmetric alteration of the tube velocities $v_{S1}^*$ and $v_{S2}^*$ at the sensing points. The net alteration $\Delta v_{S}^*$ (the sum of absolute values of $v_{S1}^*$ and $v_{S2}^*$) is linearly related to the phase difference between the sensing points due to the flow effect for small changes in the mode shape. We next consider a virtual loading case of the system, with unit external driving forces acting in opposite directions at the sensing points. These result in a vibrational velocity field $\mathbf{v}^{(2)}$ in the fluid. Under the assumption of inviscid vibrational flow, the net alteration of the tube velocities at the sensing points $\Delta v_{S}^*$ can be shown to be given by the following integral over the entire volume of the fluid:

$$
\Delta v_{S}^* = \int_{\Omega} \mathbf{f} \cdot \mathbf{v}^{(2)} d\Omega.
$$

(2)

Hence the Coriolis meter measurement result depends on the properties of the fluid vibrational fields $\mathbf{v}^{(1)}$ and $\mathbf{v}^{(2)}$, as well as on the measured flow field $\mathbf{V}$. (Bear in mind the symmetric alteration of the tube velocities at the sensing points for the anti-symmetric no-flow drive modes, and thus the symmetric virtual loading case 2).

Very helpful for evaluation of velocity profile effects in Coriolis flowmeters is a representation of the primary measuring effect in terms of weight vectors [4, 5]. Following from equations (1) and (2), $\Delta v_{S}^*$ can be expressed as a function of the measured flow field $\mathbf{V}$ (in the absence of tube vibration) and a weight vector $\mathbf{W}$, which depends on certain properties of the vibrational velocity fields $\mathbf{v}^{(1)}$ and $\mathbf{v}^{(2)}$ in the fluid (in the absence of the steady flow):

$$
\Delta v_{S}^* = \int_{\Omega} \mathbf{V} \cdot \mathbf{W} d\Omega,
$$

$$
\mathbf{W} = -\rho \left[ \left( \mathbf{v}^{(2)} \cdot \nabla \right) \mathbf{v}^{(1)} - \left( \mathbf{v}^{(1)} \cdot \nabla \right) \mathbf{v}^{(2)} \right].
$$

(3)

It is obvious that a Coriolis flowmeter’s reading depends linearly on the mass flowrate $q_m = \rho V_m A$ (i.e. is free of velocity profile effects) if the axial component of its weight vector does not vary over the tube cross-section $A$ (or if these variations are small enough). Furthermore, the transverse components of the measured flow field, which can occur in the case of disturbed flow conditions in the measuring tube, do not influence the flowmeter’s reading if the transverse components of the weight vector are zero (or small enough). A study of the fluid vibrational fields $\mathbf{v}^{(1)}$ and $\mathbf{v}^{(2)}$ that define the weight vector can help us to understand the causes of velocity profile effects in Coriolis flowmeters.
2.1 Fluid vibrational fields in the beam-type mode

As an illustration let us take a look at the properties of the fluid vibrational fields that arise in a straight tube vibrating in the fundamental bending, beam-type mode (schematically shown in Fig. 4). Fig. 5 presents variations of the $v_y$ component of the fluid vibrational velocity $v^{(1)}$, resulting from the no-flow drive mode, in the tube cross-section at the midpoint of the tube length. The scatter-plot results were obtained by CFD simulations of the viscous, water-like fluid at a vibration frequency of 100 Hz. The line-plot results represent the inviscid, potential flow approximation of the vibrational field (see Eq. (4)). The good agreement proves the applicability of the potential flow theory in such circumstances. (But it is to be expected that much higher fluid viscosities can have a significant influence on fluid vibrational fields, as also indicated by CFD simulations by Watt and Lu [7]. In such cases, the above expressions of the primary measuring effect should be also modified in accordance with Hemp and Hendry [8]. This extension could be important for modelling flowmeters that measure high viscous fluids and/or operate at small vibration frequencies.)

![Diagram](image)

Fig. 4. The fundamental beam-type mode of the straight measuring tube.

![Graph](image)

Fig. 5. Variations of the normalized $v_y$ component of the transverse vibrational velocity field on the centre plane of the beam-type tube along the $y$-axis for two values of the aspect ratio.
Fig. 5 shows that the $v_y$ component of the fluid vibrational velocity (in the direction of tube vibration) only approximately equals the tube transverse velocity $v_s$, with the largest deviation occurring at the tube centre. An important geometrical parameter affecting the fluid vibrational field is the tube aspect ratio, which is defined as the ratio of the tube length to the internal radius: $\alpha = L / R$. More slender measuring tubes contribute to more uniform transverse vibrational field.

We now study the three-dimensional form of the vibrational fields ($v^{(1)}$ and $v^{(2)}$) in a beam-type meter with a long straight tube. These fields can be expressed, inside a short length of the tube at position $x$ along the length of the tube, in terms of the local transverse tube velocity $v_s(x)$ and its first, second and third derivatives with respect to $x$. The potential flow approximation (as employed in Fig. 5) is derived, as in Appendix D of reference [2], by assuming the tube aspect ratio $\alpha$ large enough for terms of order $1/\alpha^4$ to be negligible in the expansion of the vibrational velocity field in powers of $1/\alpha$. We thus find for the velocity components in a Cartesian coordinate system the results

$$v_x \approx y \left( v'_s(x) + \frac{1}{8} \left( 3R^2 - y^2 - z^2 \right) v''_s(x) \right),$$
$$v_y \approx v_s(x) + \frac{1}{8} \left( 3R^2 - 3y^2 - z^2 \right) v'_s(x),$$
$$v_z \approx -\frac{1}{4} y z v'_s(x),$$

where the motion of the beam-type tube is described by the transverse velocity $v_s$ and the tube angular velocity is $v'_s$. The ideal fluid vibrational field distributions, which would ensure insensitivity to velocity profile effects, have the form of those inside a long straight tube vibrating as a rigid tube, that is when $v_x = y v'_s$, $v_y = v_s$ and $v_z = 0$, for both $v^{(1)}$ and $v^{(2)}$. However, Eq. (4) shows a secondary flow is generally present in the vibrational fluid. Its intensity has the inverse square dependence on the tube aspect ratio (i.e. it is of order $1/\alpha^2$) and is linked to the tube curvature $v'_s$ under the vibration. The secondary flow is mainly driven by the pressure gradient associated with variation of the local angular velocity of the tube. When this angular velocity is constant along the tube length, as in rotation of a straight rigid tube, there is no local velocity profile effect [4]. Therefore, it is the tube curvature during vibration that produces velocity profile effects in the beam-type flowmeter.

2.2 Fluid vibrational fields in the shell-type mode

A case of very intensive variations in the vibrational velocity field is represented in the shell-type Coriolis flowmeter. Its measuring tube vibrates in a higher circumferential mode, which does not preserve a constant cross-sectional shape. Fig. 6 shows schematically the second circumferential mode of a straight measuring tube. When the tube vibrates, opposite points in the cross-section move in the opposite directions. Therefore, it is anticipated that the vibrational velocity of the internal fluid changes its sign along a diameter.
That is verified by the numerical and the analytical calculations of the transverse components of the vibrational velocity field $v^{(1)}$ in the tube cross-section at the midpoint of the tube length. The results are shown in Fig. 7. CFD numerical simulations were performed for the same input data as in the beam-type case, only the mode shape was changed to the second circumferential form.

Fig. 6. The second circumferential shell-type mode of the straight measuring tube.

Fig. 7. Transverse vibrational velocity field on the centre plane of the shell-type tube.
Fig. 7(a) presents the vector plot of the transverse vibrational velocity field over the whole tube cross-section (plotted velocity vectors are positioned at cell centres of the finite-volume mesh). Fig. 7(b) presents variations of the $v_y$ velocity component, normalized on the tube radial velocity $v_S$ at $y = R$, along the $y$-axis. The transverse velocity distribution is approximately linear with a zero value at the tube centre. That is also confirmed by the potential flow approximation (as employed in Fig. 7(b)), derived as in Appendix D of reference [2], by neglecting terms of order $1/\alpha^2$:

$$
\begin{align*}
    v_x & \approx \frac{y^2 + z^2}{2R} v'_S(x, \theta), \\
    v_y & \approx \frac{y}{R} v_S(x, \theta), \\
    v_z & \approx \frac{z}{R} v_S(x, \theta),
\end{align*}
$$

where $v_S(x, \theta) = v_S(x) \cos \theta$ represents the radial velocity of the inner surface of the tube and $\theta$ is a circumferential coordinate (polar angle).

Let us make the point that a zero amplitude of the vibrational fields at the tube centre, for example, causes, from that locality, a zero contribution of the measured flow velocity to the meter reading. Therefore, the shell-type flowmeter is expected to be highly sensitive to velocity profile effects. The secondary flow of the $1/\alpha^2$ order, which determines the velocity profile effects in the beam-type measuring tube, is of marginal importance in the shell-type flowmeter. The non-uniformity of the fluid vibrational field in the circumferential mode is of the same order as the tube motion and does not significantly change with the length or radius of the measuring tube.

### 3. REYNOLDS NUMBER EFFECTS

Fig. 8 shows variations with Reynolds number of a beam-type flowmeter’s reading relative to that for uniform flow (flat profile). The results are calculated using the weight vector approach with CFD predicted fully developed velocity profiles of the measured flow (as presented in Fig. 10).
1), and a parabolic profile for the laminar flow case. The position of the motion sensors is selected at one quarter of the tube length from both ends. The flowmeter's sensitivity for these velocity profiles is found to be smaller than that for the uniform flow and it decreases in the direction of smaller Reynolds numbers. The largest non-linearity occurs at lower Reynolds numbers, where velocity profiles become intensively rounded. The tube aspect ratio $\alpha$ has an approximately inverse square influence on the Reynolds number effect in beam-type flowmeters, which is consistent with the findings about the intensity of the secondary flow in the corresponding vibrational fields (see Section 2).

Fig. 9. Variation of the weight function factor $K_w$ with the sensing distance $s$ for the lowest three modes of the beam-type flowmeter with the aspect ratio $\alpha = 30$.

In the case of fully developed flow, which has only an axial, axisymmetric velocity component $V(r)$, the weight vector equation (3) can be rewritten in terms of the axisymmetric weight function $W(r)$:

$$\Delta V_s^r = \int_0^R V(r) W(r) 2\pi r \, dr . \quad (6)$$

The analytical approximation of the weight function for the beam-type flowmeter is [2]

$$\bar{W}(r) \propto 1 - \frac{1}{\alpha^2} \left( \frac{3}{4} - \frac{r^2}{R^2} \right) K_w , \quad (7)$$

confirming the order $1/\alpha^2$ effect of the Reynolds number. The dimensionless factor $K_w$ can be understood as the integral contribution of the axial variations of the secondary flow in the fluid vibrational fields to the weight function non-uniformity. Fig. 9 shows the variation of $K_w$ with distance $s$ between symmetrically located sensing points. While $K_w$ is almost independent of the positions of the motion sensors when the measuring tube operates in the fundamental bending mode, this is not true for operation at higher frequency modes. The negative values of $K_w$ for sensing distances $s / L < 0.3$ in the third mode (even if such positions of motion sensors may not be practical) show that the non-linearity at low Reynolds numbers does not always take the form of a decrease in flowmeter sensitivity. The optimum sensing positions, which could be defined on
the basis of good sensitivity with satisfactory signal-to-noise ratio, are found to range from $s / L = 0.4$ to 0.7 [3]. Therefore velocity profile effects are expected to be larger for the higher modes (see Fig. 9). That there can be larger velocity profile effects in the higher modes is quite comprehensible, because more and more nodes cause shorter and shorter effective lengths of the tube. The curvature effects are therefore greater just as they are when the aspect ratio is reduced. The factor $K_n$ also includes the effect of boundary conditions at the ends of the measuring tube, which might also influence the sensitivity to velocity profile effects. For example, Hemp [9] predicted significant variations of flowmeter sensitivity in a tube configuration with unsupported ends.

Fig. 10 shows the Reynolds number effect for a shell-type flowmeter working in the second circumferential mode. The results are calculated in the same way as the results in Fig. 8 for the beam-type flowmeter, but they are only given for a single aspect ratio, because of its minor influence. The shell-type flowmeter shows huge velocity profile effects, which are up to two orders of magnitude larger than those in a beam-type flowmeter. That is consistent with the findings about the intense variations of the fluid vibrational fields in shell-type modes (see Section 2). For example, the weight function of the measuring tube with the second circumferential mode can be well approximated by $W(r) \propto r^2$ [2]. Such variation of the weight function in the tube cross-section comes from a superposition of linearly distributed properties of two vibrational fields (with a zero value at the tube centre).

Predictions of the Reynolds number effect by the weight vector approach have been confirmed by other methods in some cases. Bobovnik et al. [10, 11] calculated the integral Coriolis-like fluid body forces using CFD simulations of water-like fluid flow in a vibrating measuring tube. They computed integral reaction forces in beam-type and shell-type flowmeters with straight tubes and reached similar conclusions about their relative sensitivity variations with Reynolds number.
There are not many accessible results of experimental studies, which would reveal possible nonlinearities of Coriolis flowmeter measurements at low Reynolds numbers in the case of fully developed inlet flow conditions. Heywood [12] found significant errors in the water-based calibration for many commercial flowmeters applied to different slurries, also with high viscosity and non-Newtonian properties. Since the measurement errors are generally much higher below 40% of full-scale, they could be partially linked to velocity profile effects. However, it is hard to distinguish these from other possible (e.g. two-phase flow) effects on the mass flow measurement of slurries.

If one would like to quantitatively compare findings about velocity profile effects by theoretical and experimental approaches, the actual geometrical and operational properties of the flowmeter should be considered (and also its actual range of application with regard to fluid flow rates and fluid properties). There are still many parameters whose significance with regard to Reynolds number effects is not completely clear up till now; for example, possible peculiarities of curved measuring tubes, influences of inlet and outlet expansions and manifolds etc. In such cases, the measured flow is expected to vary along the measuring section although the inlet flow conditions are fully developed. We should be also aware that commercially available flowmeters may employ linearization of their measuring characteristic, so an experimental study does not necessarily show its inherent nonlinearity at low flow rates which may not be negligible. Bear in mind that the linearity of the flowmeter characteristic can be also influenced by other flow effects, such as the higher-order flow effects or the pressure effects.

4. DISTURBED INLET FLOW EFFECTS

Disturbed flow at the inlet of a flowmeter may cause a deviation of flow conditions in the measuring tube in comparison to the case of fully developed inlet flow. The intensity of such flow disturbances certainly depends on the type of the disturbance element and decreases downstream of it. If a flowmeter is found to be sensitive to Reynolds number effects, it is expected to be also sensitive to disturbed flow effects at the inlet. However, besides the axial velocity component, disturbed flow generally involves the transverse velocity components, which might make some additional contribution to the flowmeter’s reading. A more detailed study about installation effects in Coriolis flowmeters is just now in preparation by the authors. Table 1 presents some illustrative results of the influences of the two upstream elbow disturbance elements shown in Fig. 2. The beam-type measuring tube vibrates in the y direction and is positioned 2D or 10D, respectively, downstream of the disturbance element. Simulations are performed by the weight vector approach combined with the CFD predicted velocity fields of the measured flow. The results show some increase in the flowmeter sensitivity due to the disturbances in comparison with the fully developed flow conditions. As expected, a larger distance of the flowmeter from the flow disturbance assures a lower change in sensitivity. The out-of-plane double elbow leads to lower installation effects in comparison with the single elbow. Separate calculation of influences related to the transverse velocity components of the measured flow (such as a swirl motion from the out-of-plane double elbow) show their minor contribution to the total installation effect. Therefore, some lower distortion of the axial component of the measured flow from a double elbow is expected to be the reason for some lower installation effects in that case.
Table 1

<table>
<thead>
<tr>
<th>Flowmeter installation</th>
<th>Single elbow</th>
<th>Double elbow</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D downstream of the disturbance</td>
<td>0.11</td>
<td>0.04</td>
</tr>
<tr>
<td>10D downstream of the disturbance</td>
<td>0.06</td>
<td>0.02</td>
</tr>
</tbody>
</table>

A positive sensitivity error of the same order of magnitude as presented in Table 1 was also found by Bobovnik at al. [10] due to the influence of a hypothetical asymmetric, triangular inlet flow, calculated numerically using CFD simulations of integral fluid reaction forces. Their simulation of a hypothetical swirl flow at the inlet shows practically no sensitivity error at lower Reynolds numbers, but there is some rapid sensitivity change of 0.1 % at \( Re = 150000 \). The latter, a rather contradictory result, calls for further systematic study of swirl effects in Coriolis flowmeters.

There are also some published experimental studies about installation velocity profile effects in Coriolis flowmeters. Cheesewright et al. [13] tested three commercial beam-type Coriolis flowmeters with water flow under upstream disturbed flow conditions produced by a twisted strip (swirl flow) and by partial blockage plates (asymmetric flow). For two of the flowmeters, the relative change in calibration due to disturbances did not exceed a threshold of 0.25 %. As the authors of [13] explained, the effects of mounting and de-mounting the flowmeter, which might be necessary in the testing procedure, can influence reproducibility of testing results. One flowmeter showed ‘just detectable’ measurement errors in the presence of asymmetric disturbance which varied with the orientation of the asymmetry.

Grimely [14] tested three commercial flowmeters of beam and shell type with pressurized gas and upstream flow disturbances generated by a single elbow, a double elbow, a tee and a reducer. Two curved-tube beam-type flowmeters showed measurement errors due to installation effects well within the 0.2 % reproducibility of the baseline calibration, determined with 100 diameters of straight pipe upstream of the flowmeter. Beside smaller deviations from this threshold, a somewhat larger installation effect that exceeded 0.5 % at low flowrates was only observed in one of the beam-type flowmeters exposed to a reducer. The author of [14] suggests the repetition of tests with the reducer to check their validity.

Tests of the shell-type flowmeter in reference [14] were performed with an additional straight pipe of about 20 diameters between the disturbances and the flowmeter, and with an installed flow conditioner in the double-elbow tests. Irrespective of these smoothers at the inlet, the readings of the shell-type flowmeter were significantly affected by up to a few percent due to disturbances (from -1.5 % to 4 %). The largest positive errors were produced by a tee upstream, and the largest negative errors by the double elbow combinations. The increased level of turbulence downstream of a tee and the flow conditioner used in the double-elbow tests was also suggested as a possible source of these errors.

The above experimental findings agree with our physical/theoretical interpretations which suggest much smaller sensitivity to velocity profile effects in the beam-type flowmeters than in the shell-type flowmeters. The experimental results on the beam-type configurations in [13, 14]
showed installation effects, which ranged from undetectable magnitudes to a few tenths of a percent. If we look at the magnitudes of errors in Table 1, such conclusions are to be expected. The experimental results on the shell-type flowmeter [14] agree with the predicted large non-uniformities in its fluid vibrational fields (see Section 2) and the resulting high sensitivity to velocity profile effects. However, a more exhaustive comparison is not possible, partially because of the relatively simple flowmeter configuration (clamped single straight measuring tube) employed in the study of the physical background of velocity profile effects within this paper, but also because of the unknown constructional details of the tested flowmeter configurations. The velocity profile effects of the beam-type flowmeters are certainly sensitive to constructional parameters of the measuring tubes (such as the tube aspect ratio, possibly also the tube curvature), so the models built for their theoretical or numerical analysis should be close to their actual configurations to obtain quantitatively comparable results.

Further experimental and theoretical research work on Coriolis flowmeters is certainly needed to understand the relative importance of different disturbance elements, which are to be found in practical flow metering systems. The experimental identification of the installation effects relative to the fully developed flow conditions requires satisfactory repeatability and reproducibility of the measurement system in view of the required measurement accuracy of the tested flowmeter. At least in the beam-type devices with relatively shorter measuring tubes, which try to achieve accuracies of ±0.1 %, the installation effects are not expected to be negligible. Although the shell-type flowmeters are very rarely used, their further study is still interesting from the viewpoint of experimental verification of theoretical and numerical models, i.e. because of the essentially higher magnitudes of velocity profile effects and the possibility of their easier identification.

5. CONCLUSIONS

Coriolis flowmeters are found not to be generally insensitive to velocity profile effects. The reason can be related to the non-ideal fluid-structure interactions between the vibrating measuring tube and the measured fluid flow, which operate in the Coriolis measuring process. In the beam-type flowmeters with bending motion of the measuring tube, these non-idealities come from a secondary flow in the vibrational fluid, which is linked to the tube curvature during vibration. The velocity profile effects in beam-type configurations can become significant in shorter measuring tubes due to the inverse square dependence on the tube aspect ratio. They are also expected to be larger when higher frequency bending modes are employed and they depend on the clamping conditions at the tube ends. On the other hand, the shell-type Coriolis flowmeter exhibits much larger non-idealities which come from the properties of the circumferential vibration modes. The non-uniformities of the fluid vibrational fields in shell-type configurations are of the same order as the tube motion and do not significantly change with tube length or tube radius. Results show up to two orders of magnitude higher sensitivity to velocity profiles in comparison with beam-type flowmeters. Available experimental results support these conclusions.

Therefore, we can conclude that the magnitudes of velocity profile effects depend on many constructional and operational parameters of the Coriolis flowmeters. Questions remain regarding the understanding of velocity profile effects in flowmeters with curved measuring tubes, which
are very frequent in commercial configurations. For example, not only do curved tubes introduce some peculiarities in the fluid vibrational fields, they also lead to variable velocity distributions of the measured flow along the tube length, even if the inlet flow conditions are fully developed.

Beside depending on the configuration of the flowmeter, the magnitudes of velocity profile effects also depend on the measurement application. The range of flow rates and viscosities of the measured fluid defines the range of Reynolds numbers. Reynolds number is the key factor governing the velocity profile distribution in fully developed flow. As also shown in this paper, the more intensive changes in the form of velocity profiles at lower Reynolds numbers result in more intensive deviations in flowmeter sensitivity. There are some available results on flowmeter behaviour in the case of disturbed inlet flow conditions, but further systematic research is still needed to clarify the influence of different disturbance elements that appear in practical installations.

Fluid properties do not only affect the characteristics of the measured flow field, but also the fluid vibrational fields in the vibrating measuring tube defining the mass flow measuring effect. The simple physics employed in this paper was proved to be correct for low viscous incompressible fluids (e.g. water-like fluids). The peculiarities that might be introduced by (Newtonian or non-Newtonian) highly viscous or by compressible fluids remain an open question for further research work.

The modeling concepts, which have so far been applied for predictions of velocity profile effects in Coriolis flowmeters, can be classified as the weight vector approach and the direct numerical approach. The former is employed in some concrete calculations of this paper, where we combined the analytical models of the weight vector with the CFD-predicted velocity distributions of the measured flow. The analytical formulation of the weight vector approach is found helpful for physical insight into velocity profile effects in Coriolis flowmeters. But the analytical models in reasonably simple form are limited (so far at least) to flowmeters with simple geometry, such as straight-tube configurations. For that reason, the vibrational velocity fields and resulting weight vector might be calculated numerically (rather than analytically) and used in conjunction with CFD computation of steady flow velocity distributions to arrive, by integration, at the flowmeter sensitivity.

On the other hand, Bobovnik et al. [15] introduced a fully coupled three-dimensional numerical model of the Coriolis flowmeter, which includes coupled dynamics of the fluid flow domain and the solid domain. This can be used for predictions of the velocity profile and other effects in very general flowmeter configurations and applications. Such numerical modeling can overcome the restrictions of the (currently available) weight vector approach to the primary Coriolis force measuring effect. It can predict simultaneous influences of other non-idealities (such as the higher-order flow effects, the pressure effects etc.), which could be mixed/coupled with the primary effect in the practical use of Coriolis flowmeters.

6. REFERENCES


