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Quantification of the influence of external vibrations on the measurement error of a Coriolis mass-flow meter

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ABSTRACT

In this paper the influence of external vibrations on the measurement value of a Coriolis mass-flow meter (CMFM) for low flows is investigated and quantified. Model results are compared with experimental results to improve the knowledge on how external vibrations affect the mass-flow measurement value. A flexible multi-body model is built and the working principle of a CMFM is explained. Some special properties of the model are evaluated to get insight into the dynamic behaviour of the CMFM. Using the model, the transfer functions between external vibrations (e.g. floor vibrations) and the flow error are derived. The external vibrations are characterised with a PSD. Integrating the squared transfer function times the PSD over the whole frequency range results in an RMS flow error estimate. In an experiment predefined vibrations are applied on the casing of the CMFM and the error is determined. The experimental results show that the transfer functions and the estimated measurement error correspond with the model results.

The agreement between model and measurements implies that the influence of external vibrations on the measurement is fully understood. This result can be applied in two ways; firstly that the influence of any external vibration spectrum on the flow error can be estimated and secondly that the performance of different CMFM designs can be compared and optimised by shaping their respective transfer functions.

1. Introduction

A Coriolis mass-flow meter (CMFM) is an active device based on the Coriolis force principle for direct mass-flow measurements with a high accuracy, range-ability and repeatability [1]. The working principle of a CMFM is as follows: a fluid conveying tube is actuated to oscillate with a low amplitude at a resonance frequency in order to minimise the amount of supplied energy. A fluid flow in the vibrating tube induces Coriolis forces, proportional to the mass-flow, which affect the tube motion and change the mode shape. Measuring the tube displacement, such that the change of its mode shape is determined, allows calculating the mass-flow.

Besides the sensitivity for a mass-flow, there are many factors influencing the measurement value. Anklin et al. [1] mentioned several factors: the effect of temperature and flow profiles on the sensitivity and measurement value, external vibrations and flow pulsations. More factors are investigated by Enz et al. [2]: Flow pulsations, asymmetrical actuator and detector positions and structural non-uniformities. And more recent also by Kazahaya [3]: uneven flow rates in two flow tubes, vibration effects, temperature effects and the inner pressure effects. Further Bobovnik et al. [4] studied the effect of disturbed velocity profiles due to installation effects and other influencing factors like two-phase or even three-phase flow effects were studied by Henry et al. [5].

In our research we focus mainly on the effect of floor/mechanical/external vibrations. These vibrations create additional components in the CMFM sensor signals [6], those additional components can introduce a measurement error. The effect of mechanical vibrations on the sensor response of a CMFM is also studied by Cheesewright [7,8]. The analytical study showed that external vibrations at the meter's drive frequency produces a measurement error, regardless of the flow measurement algorithm. There is no attempt made to quantify the error in any particular meter, since such an error depends on dimensions, type of actuators and sensors and the used flow measurement algorithm.

A solution to reduce the influence of external vibrations is to apply a robust balancing system. (e.g. a twin tube configuration) [1,3]. There are many types of CMFMs available, whereby the size depends on the flow range. One category is the CMFM for low

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flows [9]. For low flows, the Coriolis force induced motion is relatively small compared to external vibrations induced motions, thus CMFM's designed to be sensitive to low flows is rather sensitive to external vibrations. Applying a twin tube configuration is not an option, because some structural non-uniformities [2] can lead to large differences between the two tubes, due to their small dimensions. This has a negative impact on the measurement sensitivity of the instrument and reduces the decoupling of external vibrations to the internal measurement system.

A quantitative model of the influence of external vibrations is not yet available. In this study the effect of external vibrations on the measurement error is quantified using an experimentally validated model. The results presented in this study are an extension of previous work [10]. First, a model of a CMFM is derived, using the multi-body package SPACAR [11] resulting in a linear state space representation [12]. In the modelling, a tube-element [13] is used to model the inertial interaction between flow and the tube dynamics. Secondly, the model is extended to be able to predict the influence of external vibrations, with the eventual goal to find and test designs that reduce the influence of external vibrations on an erroneous mass-flow reading.

2. Modelling method

In this section, the Finite Element Method (FEM) model is explained. Subsequently, the system equations are derived and the inputs and outputs are defined to derive the input–output relations. This results in a state space representation of a CMFM in the final subsection.

2.1. Coriolis mass-flow meter

For this research a functional model of the patented design [9,14] (see Fig. 1) is used. First, a FEM model is derived, using the multi-body package SPACAR [11]. The graphical representation of the model is shown in Fig. 2. The model consists of a tube-window, conveying the fluid flow, which is actuated by two actuators act_1 and act_2. The displacements of the flexible tube-window are measured by two displacements sensors s_1 and s_2. On the casing a vector $\boldsymbol{a}_0$, representing the external vibrations and consisting of three translation and three rotational movements, is imposed. The model is made out of multi-body beam, truss and tube elements. The beam elements are used to model the rigid casing and the truss elements to measure relative displacements and to apply a force on the tube-window. Further, a tube-element [13] is used to model the inertial interaction between flow and the tube dynamics.

2.2. System equations

The linearised system equations of the FEM model, with n degrees of freedom of tube deformations $\boldsymbol{q}$ and the imposed casing movements (rheonomic degrees of freedom: $\boldsymbol{x}_0, \boldsymbol{v}_0 = \dot{\boldsymbol{x}}_0, \boldsymbol{a}_0 = \ddot{\boldsymbol{x}}_0$), can be written as [12]:

$$\begin{bmatrix} \boldsymbol{M}_{11} & \boldsymbol{M}_{12} \\ \boldsymbol{M}_{21} & \boldsymbol{M}_{22} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}} \\ \boldsymbol{a}_0 \end{bmatrix} + \left[\boldsymbol{C}(\dot{\Phi}) + \boldsymbol{D} \right] \begin{bmatrix} \dot{\boldsymbol{q}} \\ \boldsymbol{v}_0 \end{bmatrix} + \left[\boldsymbol{K} + \boldsymbol{N}(\dot{\Phi}^2) \right] \begin{bmatrix} \boldsymbol{q} \\ \boldsymbol{x}_0 \end{bmatrix} = \begin{bmatrix} \boldsymbol{f} \\ \boldsymbol{F}_0 \end{bmatrix} \tag{1}$$

The other terms are the mass matrix $\boldsymbol{M}$, stiffness matrix $\boldsymbol{K}$, damping matrix $\boldsymbol{D}$, the velocity sensitive matrix $\boldsymbol{C}$, the dynamic stiffness matrix $\boldsymbol{N}$, the actuation input vector $\boldsymbol{f}$ and the reaction force $\boldsymbol{F}_0$. The matrices $\boldsymbol{C}$ and $\boldsymbol{N}$ depend linear and quadratic on the mass-flow $\dot{\Phi}$ respectively, and are representing the forces induced by respectively the Coriolis and centrifugal acceleration of the flow. The matrices $\boldsymbol{C}$, $\boldsymbol{D}$, $\boldsymbol{K}$ and $\boldsymbol{N}$ can be divided into the same parts as the mass matrix $\boldsymbol{M}$. Using the multi-body package SPACAR

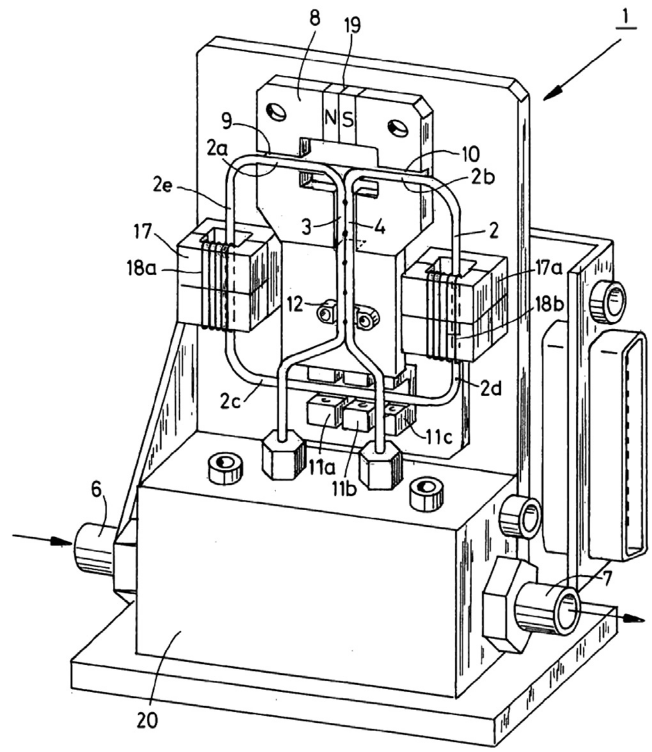

Fig. 1. Coriolis mass-flow meter, used as a reference instrument in this study. Details on the patented design are given in [9,14]. The instrument is connected to a pipeline; a fluid flow enters the instrument (6), flows trough the tube-window (2) and exits the instrument (7). The flexible tube-window (2) is actuated in resonance by an Lorentz actuator (8) and the displacements are measured by optical displacements sensors (11abc) [15].

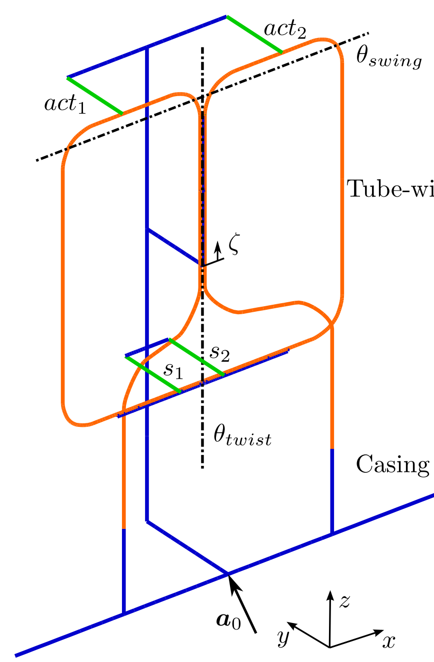

Fig. 2. CMFM multi-body model, the flexible tube-window is actuated by two Lorentz actuators act_1 and act_2. The trajectory of the curved tube-window is parametrised by ζ, starting at the fixation point of the tube-window to the casing. The displacement are measured by two displacements sensors s_1 and s_2. On the casing a vector $\boldsymbol{a}_0$ with floor movements is imposed.