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DETECTION OF ZERO SHIFT IN CORIOLIS MASS FLOWMETERS

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Abstract: Coriolis mass flowmeters (CMF) are claimed to be not affected by the properties of the liquid such as heat conductivity, heat capacity and viscosity. They are direct mass flowmeters and form a real mean along the flow profile. However, there is some evidence from field applications that the devices, in particular with single straight pipe, suffer under the null drift. Therefore, the zero shift must be adjusted to the properties of liquid, installation site and operating conditions. The zero shift is caused by asymmetry of the oscillating system. A change in the asymmetry leads to the zero shift. This paper presents two methods to determine the zero shift: a sensor and a model based approach. The first uses additional acceleration sensors to measure the vibration of the straight pipe's mounting. The motion of the mounting represents asymmetries in dissipation. The second method utilizes a model which includes the asymmetries as parameters. These can be detected by auxiliary exitation of the oscillating system.
Keywords: Coriolis mass flowmeter, accuracy, zero shift

1 INTRODUCTION

Coriolis mass flowmeters have wide acceptance in industry based on high accuracy and good repeatability and the ability to measure mass flow directly. The straight pipe type has shown excellent performance measuring mass flow as well as measuring fluid density.

The basic element of the examined commercial flowmeter is a straight tube with rigid supports at both ends (fig. 1). It oscillates at its fundamental eigenfrequency (first mode) with an amplitude controlled by a digital signal processor (DSP) and two drivers. At zero flow all parts of the metering pipe will vibrate synchronously. When mass flow is introduced in the pipe, Coriolis forces are caused by two orthogonal velocities, one representing the velocity of the fluid and the other the velocity of the pipe.

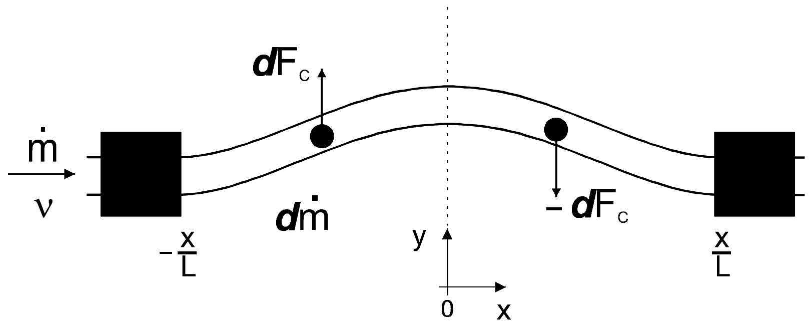

Figure 1. Coriolis forces effected by two orthogonal velocities

The reaction forces on the pipe's wall have opposite directions in the upstream and downstream side. In the resultant oscillation, the upstream side will lag and the downstream side will lead the center (second mode). The oscillation of the pipe is no more synchronous. The symmetry is broken. Formally, the CMF can be viewed as an instrument that measures some kind of „non symmetries“. The delay in time, between the movement of two given points (velocity sensors) along the length of the metering pipe, is a measure of the mass flow.

2 STATEMENT OF THE PROBLEM

The actual commercial straight pipe CMF give compact and slim designs. However, there are some limitations in their application due to fluid properties and/or the installation. These are so-called „zero-stability problems“ [1].

Up to now the end-supports are assumed as being perfectly rigid. In practice, they are neither of the clamped-type nor of the pinned-type. There exists a coupling of the metering pipe to the environment. This coupling is unavoidable because in practice the ends of the metering pipe do not correspond to two perfect nodes. The unperfect nodes cause dissipation that is certainly not symmetrical since in general the boundary conditions are not symmetrical. The asymmetrical dissipation leads to zero shift and can falsify the result of the measurement.

Different methods are used to decouple the measuring pipe's motions from the environment. One possibility consists of preventing the motion of pipe's mountings by means of a massy foundation for the measuring device. As this method is applicable only in very small size of CMF, the decoupling is done by using an additional vibration system, which can compensate the reaction forces and momenta in the end-supports, enabling a node of oscillation for the measuring pipe. This method is used in most commercial CMF also with a single straight measuring pipe:

- STmass of the company OVAL
- PROM ASS I of the company Endress+Hauser
- Corimass G+ of the company Krohne Meßtechnik
- T-Series of the company Micro Motions (Fisher-Rosemount)

Despite the complex mechanics, the decoupling of the CMF from the environment is unperfect. This is due to the fact that the characteristics of the supplementary vibration system can not be adapted to the current vibration behavior of the measuring pipe. Therefore, the zero shift changes during operation. Supplementary information has to be provided in order to detect the change of the zero shift.

The supplementary information can be divided into a priori information and online information. A priori information is information about the measurement procedure which can be provided before measuring. It is structure information about the internal representation of the characteristic properties (zero shift and sensitivity) as well as information about the known limiting conditions under which the measurement procedure should progress (parameter). This a priori information has to be acquired by theoretical modeling and experimental identification and is filed in the CMF. The online information can be acquired sensor or model based by suitable stimulation of the CMF.

3 PROTOTYPE SYSTEM

The prototype comprises the mechanical part of a commercial CMF (figure 2) that was extended by two electromagnetical actuators and two micro mechanical acceleration sensors with capacitive tap. The entire signal processing and control is completly digital and is implemented on a digital signal processor (DSP). After passing a wideband amplifier, the sensor signals are digitized immediately,. The drive signals generated by DSP only pass a voltage current converter.

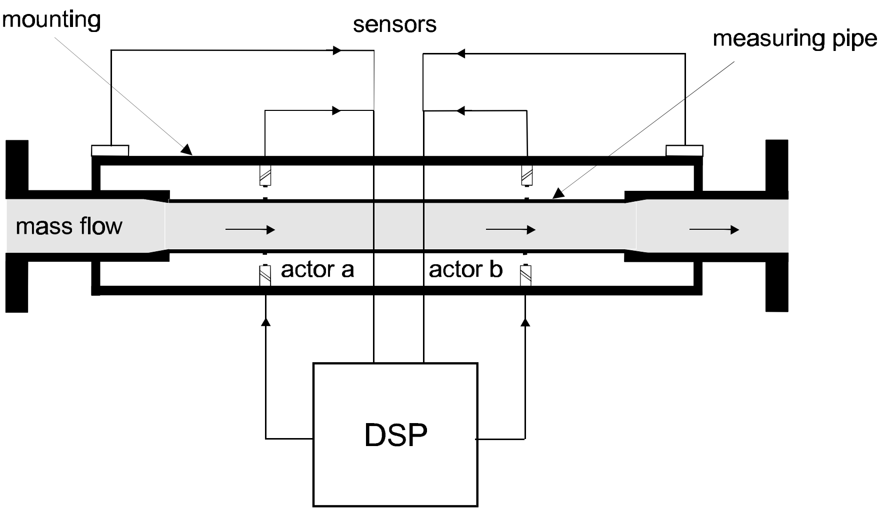

Figure 2. Schematic of a commercial mass flowmeter with additional actuators and sensors

4 PHYSICAL-MATHEMATICAL-MODELLING

The basic mathematical derivation of interactions between a vibrating straight measuring pipe and a flowing fluid was derived by numerous authors in different ways using different simplifying assumptions [2]. The resulting continuous models serve as a very useful means to calculate the natural frequencies and the sensitivity of CMF. Unfortunately, they can not describe some phenomena, in particular the phenomenon of the zero shift, the essential problem of present CMF with a single straight measuring pipe.

CMF are assumed to be ideally symmetric with regard to dimensions, mounting and material properties. This is to be abandoned if the changes of the characteristics of the CMF are to be described, because the causes of these changes are asymmetries. Sources of such asymmetries are manufacturing and assembly inaccuracies in the structure (measuring pipe, sensors, actuators, mounting), density and viscosity variations as well as temperature and pressure gradients along the measuring pipe, etc. A distributed analytical description of these imbalances and their effect on the mass flow measurement is costly and can not contribute to the practical solution of the problem i.e. for the online determination of the characteristics of CMF. Therefore, the behavior of the CMF is modeled as a condensed parameter system.

The essential characteristics of the present discrete model [3,4] is represented by its two eigenmodes. The first eigenmode corresponds to the synchronously oscillation of the measuring pipe's halves (translation) and the second eigenmode to the antiphased oscillation (rotation).

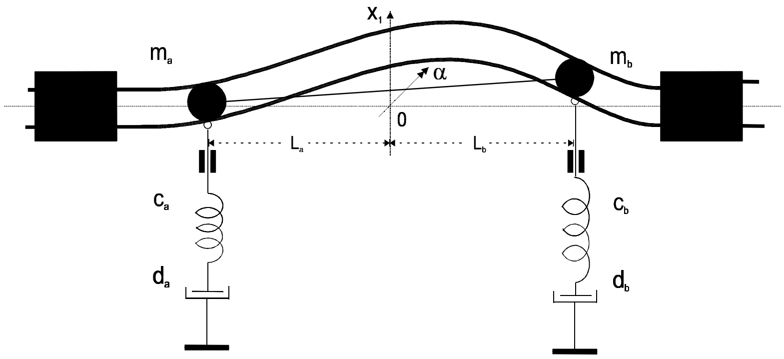

Figure 3. Condensed parameter model

The effective vibrating mass of the left half of the measuring pipe is supposed to be an ideal condensed mass m_a at the left sensor position L_a. Correspondingly, the mass of the right half of the measuring pipe m_b is placed on the right sensor position L_b. A condensed mass m_m takes into account the masses which are involved only during translation of the measuring pipe however not during rotation. The masses m_a, m_m and m_b are connected by a mass free, radially rigid and axially flexible bar. Internal and external forces act on these masses. The same applies to the springs substitute c_a, c_m and c_b as well as to the dampers d_a, d_m and d_b. With respect to presentiveness, the mean mass spring damper system is not drawn in Fig. 3.

Figure 4 shows the essential internal structure of the CMF with all possible couplings. The Normal operating mode is highlighted by thick lines. The dynamics of the measuring system can be expressed in a simplified way by two vibrating systems $G_1(s)$ and $G_2(s)$,

$$G_1(s) = \frac{V_1(s)}{F_1(s)} = \frac{K_1 s}{s^2 + 2 d_1 w_{01} s + w_{01}^2} \quad (1)$$

$$G_2(s) = \frac{V_2(s)}{F_2(s)} = \frac{K_2 s}{s^2 + 2 d_2 w_{02} s + w_{02}^2} \quad (2)$$

that are coupled with each other in 6 different ways. These couplings describe the asymmetries in the CMF:

1. The acceleration coupling k_b is caused by differences of the vibrating masses of the measuring pipe's halves ($m_a \neq m_b$).
2. The displacement coupling k_s is caused by differences in potential energy storage of the measuring pipe's halves ($c_a \neq c_b$).
3. The velocity coupling k_v is caused by different dissipation in the measuring pipe's halves ($d_a \neq d_b$).
4. The drive coupling ε_A describes the difference of the statical characteristics of the actuators.
5. The sensor coupling ε_S represents the different statical characteristics of the electro-magnetic sensors.
6. The couplings k_{CN} and k_{CI} allow for the measurement of mass flow.

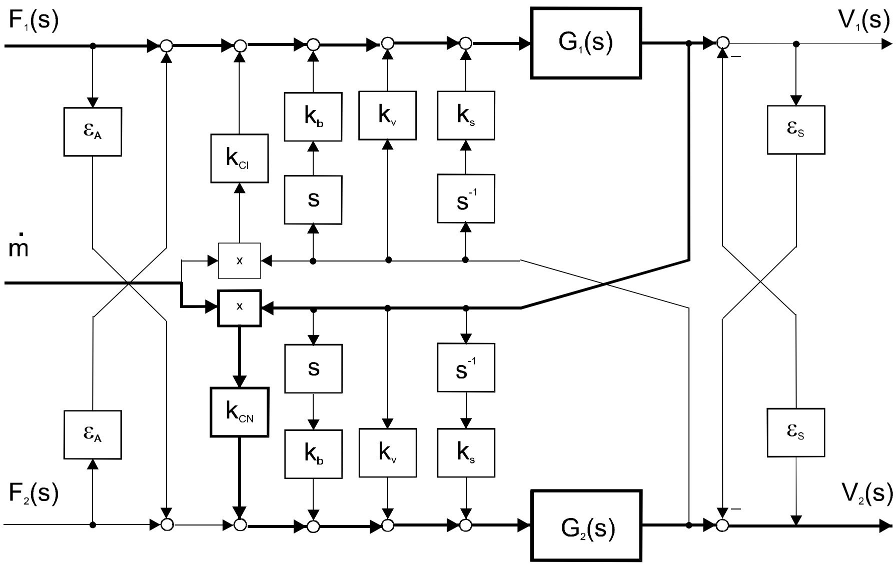

Figure 4. Structure of the condensed parameter model

5 EXPERIMENTAL IDENTIFICATION

Because of the extremely poor attenuation of the eigenmodes, the identification of the parameters of the mathematical model in the time domain is not feasible because the PRBS's response of CMF shows spectral fractions measurable only in a very narrow-band range around the natural frequencies. Therefore, an identification of the parameters can only be carried out in the frequency domain.

The transfer functions between excitation in the mode i={1,2} and measurement of mode j={1,2} can be represented by

$$G_{ij}(s) = \frac{Z_{ij}(s)}{N_{ij}(s)} = \frac{\sum_{\ell=0}^{m} b_{ijl}\, s^{l}}{\sum_{n=0}^{n} a_{ijn}\, s^{n}} \qquad (3)$$

The denominator polynomials $N_{ij}(s)$ are identical for all four transfer functions $G_{ij}(s)$.

The coefficients of the transfer functions $\underline{\theta}=\{a_{ij\nu}, b_{ij\iota}\}$ are linked with the physical system parameters $\underline{p}=\{\omega_{01}, \omega_{02}, d_{01}, d_{02}, ...\}$ via non-linear relations:

$$\underline{q} = \underline{f}(\underline{p}) \qquad (4)$$

This function is complicated and in general, its reverse function can not be determined. Additionally, the number of the unknown physical parameters is larger than the number of the coefficients. Hence an unique determination of the physical parameters is not feasible. Therefore, a specific approach is practised.

First the input/output couplings, i.e. the differences of the actuators ε_A and the sensors ε_S, were experimentally determined and eliminated. Then the couplings due to acceleration coupling and velocity were put together at the frequency ω_{01}. This is allowed since only the difference of the two couplings becomes effective (quasi stationary operating mode). Subsequently the remaining model coefficients were estimated in the frequency domain by means of a Maximum-Likelihood-Method. Afterwards the unknown physical parameters were computed.

6 SUPPLEMENTARY ONLINE INFORMATION

To determine the characteristics of a CMF during normal operation, supplementary online information is necessary in addition to the a priori information provided in the previous sections. It can be acquired by further sensors or a suitable supplementary excitation of the CMF and a model based evaluation of their response. In the following sections, a sensor based approach and a model based approach are presented.

6.1 SENSOR BASED APPROACH

The fundamental idea of the sensor based approach is the measuring of the motions of the pipe's mounting (fig. 2) in order to get additional information about the CMF. The motions are measured using acceleration sensors whose electrical signals are fed to the digitial signal processor (DSP). These signals are processed and evaluated in the DSP by different estimation techniques. The relationship between the acceleration signals and the zero shift of the CMF are formulated heuristically as follows.

Permanently the actuators feed energy into the oscillating system. This excitation energy is dissipated in the clamped halves of the measuring pipe. In general the energy dissipation is different in the halves. This leads to the fact that additionally to the forced oscillations of the measuring pipe in the first mode an oscillation in the second mode develops, which causes a delay in time between the motions of two given points along the length of the metering pipe. The mass flow influences the time shift between the velocity sensor's signals Dt_v however not the time shift between the acceleration sensor's signals Dt_b. The lastly specified correlates with the zero shift and can serve as a measure of the zero shift.

Finally, the relationship between Dt_b and the zero shift N is determined experimentally for numerous operating conditions. It is stated that a linear relationship can be established for different clamping conditions.

$$N = \Delta t_v \big|_{\dot{m}=0} = K \Delta t_b, \text{ with K} = 0.0034 \qquad (5)$$

With the available supplementary acceleration sensors, the accuracy of the zero shift is improved by a factor of 3. The general applicability of equation (5) has to be examined by integrating the pipe's mountings into the mathematical model.

6.2 MODEL BASED APPROACH

The main idea of the model based approach is to stimulate the measuring pipe not only in its first eigenmode but also in its second eigenmode, in order to obtain supplementary information about the behavior of the CMF.

Velocity responses of the eigenmodes can be obtained directly from figure 4:

$$V_1(s) = G_1(s)\left[F_1(s) + V_2(s)\left(s\,k_b + k_{CI}\,\dot{\mathrm{m}} + k_{\mathrm{v}} + \frac{k_s}{s}\right)\right] \qquad (6)$$

$$V_2(s) = G_2(s)\left[F_2(s) + V_1(s)\left(s\,k_b + k_{CN}\,\dot{\mathrm{m}} + k_{\mathrm{v}} + \frac{k_s}{s}\right)\right] \qquad (7)$$

In the normal operating mode of the CMF, only the first eigenmode is stimulated externally.
This operating mode is characterized by:

$$w = w_{01};\ F_{1N}(w) = 0;\ F_{1N} = \text{const.};\ \angle(F_{1N} V_{1N}) = 0;\ w_{02} > w_{01}$$

Additionally we suppose that the couplings due to acceleration and displacement are compensated. These specifications yield

$$\mathrm{Im}\{V_{1N}\} = 0 \qquad (8)$$

$$\mathrm{Re}\{V_{1N}\} = \mathrm{Re}\{G_1\}\mathrm{Re}\{F_{1N}\} \qquad (9)$$

$$\mathrm{Re}\{V_{2N}\} = 0 \qquad (10)$$

$$\mathrm{Im}\{V_{2N}\} = \mathrm{Im}\{G_2\}\mathrm{Re}\{V_{1N}\}(k_{CN}\,\dot{m} + k_v) \qquad (11)$$

The delay in time between the signals of the velocity sensors is

$$y_{MN} := \Delta t = \frac{1}{w_{01}}\Delta j \approx \frac{1}{w_{01}}\frac{\mathrm{Im}\{V_{2N}\}}{\mathrm{Re}\{V_{1N}\}} \qquad (12)$$

With (11) and (12), the static characteristic curve of the CMF in normal operating mode results in:

$$y_{MN} = \underbrace{\frac{1}{w_{01}} \mathrm{Im}\{G_2\} k_{CN}}_{E} \dot{\mathrm{m}} + \underbrace{\frac{1}{w_{01}} \mathrm{Im}\{G_2\} k_v}_{N} \tag{13}$$

The sensitivity E and the zero shift N can be determined by calibration of the CMF. However, they are dependent on time since they are influenced by conditions of use.

To determinate the sensitivity and the zero shift during the operating mode, the second eigenmode is incited with a force F_{2M} orthogonal to F_{1N}. Now the responses V_{1M} and V_{2M} are

$$\mathrm{Im}\{V_{1M}\} = 0 \tag{14}$$

$$\mathrm{Re}\{V_{1M}\} = \mathrm{Re}\{G_1\}[\mathrm{Re}\{F_{1N}\} + \mathrm{Re}\{V_{2M}\}(k_{CI}\dot{m} + k_v)] \tag{15}$$

$$\mathrm{Re}\{V_{2M}\} = \mathrm{Im}\{G_2\}\mathrm{Im}\{F_{2M}\} \tag{16}$$

$$\mathrm{Im}\{V_{2M}\} = \mathrm{Im}\{G_2\}\mathrm{Re}\{V_{1M}\}(k_{CN}\dot{m} + k_v) \tag{17}$$

According to eq. (13), the sensitivity E contains three parameters. The first parameter k_{CN} describes the conversion of the distributed Coriolis forces along the measuring pipe into located forces. Therefore, it is taken to be constant. The second parameter ω_{01} is the manipulated variable for $\angle(F_1, V_1) = 0$ and can be regarded as a known quantity. The third parameter $\mathrm{Im}\{G_2\}$ has to be identified by means of eq. (16). Thus the sensitivity is

$$E = k_{CN} \frac{1}{w_{01}} \frac{\mathrm{Re}\{V_{2M}\}}{\mathrm{Im}\{F_{2M}\}} \tag{18}$$

To compute the zero shift (eq. (13)), only velocity coupling k_v has to be determined. For this purpose, $\dot{m}$ is eliminated in equations (15) and (17). This, and some algebra, yields

$$N = \frac{k_{CN}\mathrm{Re}\{F_{1N}\}\mathrm{Re}\{V_{1M}\}[\mathrm{Re}\{V_{1M}\} - \mathrm{Re}\{V_{1N}\}] - k_{CI}\mathrm{Im}\{F_{2M}\}\mathrm{Re}\{V_{1N}\}\mathrm{Im}\{V_{2M}\}}{(k_{CN} - k_{CI})\mathrm{Re}\{V_{1M}\}\mathrm{Re}\{V_{2M}\}\mathrm{Im}\{V_{1N}\}} \tag{19}$$

Thus, utilizing eq. (18) and (19), the sensitivity and the zero shift can be determined.

7 CONCLUSIONS

The accuracy of Coriolis mass flowmeters can be affected more or less seriously by changes of boundary conditions and/or changes of fluid properties. Consequently the zero shift has to be detected online during operation. This can be realized in a simple way with additional sensors which directly measure the movement of the metering pipe’s mounting. With this sensor based approach, improvement in the accuracy of a factor of 3 can be reached. The model based approach also permits the determination of the zero shift. It improves the accuracy of the zero shift in simulation by a factor of 8. This approach is of high performance but costly and still has to be tested in practice.

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