Advanced phase- and amplitude control of a coriolis mass flow meter (CMFM)

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Abstract

The operation of a Coriolis Mass Flow Meter (CMFM) is dependent upon the proper oscillation of the flow tube controlled by drive signals generated by a transmitter. Commonly used techniques for controlling Coriolis meters are analogue positive feedback which has proved adequate in conventional applications. In difficult situations however as batching to/from empty, two phase flow or when changes in set point are injected to gather diagnostic information [2-8], more elaborate control strategies are necessary to prevent the meter from stalling. The approach presented in the paper uses a time variant phasor representation of a 2nd order oscillation system, allowing for simultaneously controlling amplitude and phase without the necessity to chronologically separate both of these control tasks.

Keywords: Coriolis mass flow meter, phasor control

1. Introduction

Commonly used techniques for controlling Coriolis meters are analogue positive feedback which has proved adequate in conventional applications. In difficult situations however [1] more elaborate control strategies are necessary to prevent the meter from stalling.

In Fig. 1 the Coriolis Mass Flow Meter CMFM and the associated mathematical model in terms of lumped parameters are shown.

Fig. 1. Coriolis Mass Flow Meter CMFM and associated mathematical model.

In what follows, only the stimulation of the CMFM in its 1st eigenmode (transfer function $G_1$) is investigated, corresponding to a common mode stimulation via the actuators $F_a$ and $F_b$. The corresponding velocity signals can be measured via the sensors $S_1$ and $S_2$. It is well known, that the mass flow is proportional to the phase-shift or more precisely the time-shift between these harmonic velocity signals.
2. Phasor approach for amplitude control

The input \( u_1(t) \) and the output \( y_1(t) \) are both modeled as harmonic signals that can be derived from a phasor representation as harmonic signals with time varying amplitude and phase. From the phasor representation we get:

\[
y_1(t) = \text{Im}\left\{ (Y_{1R} + j Y_{1I}) e^{j \phi(t)} \right\}
\]

(1a)

\[
\dot{y}_1(t) = \text{Im}\left\{ (\dot{Y}_{1R} - \dot{\phi} Y_{1I}) e^{j \phi(t)} + j(\dot{Y}_{1I} + \dot{\phi} Y_{1R}) e^{j \phi(t)} \right\}
\]

(1b)

\[
\ddot{y}_1(t) = \text{Im}\left\{ (\ddot{Y}_{1R} - 2\dot{\phi} \dot{Y}_{1I} - \dot{\phi}^2 Y_{1R}) e^{j \phi(t)} + j(\ddot{Y}_{1I} - \dot{\phi} \dot{Y}_{1R} - 2\dot{\phi} Y_{1R} - \dot{\phi}^2 Y_{1I}) e^{j \phi(t)} \right\}
\]

(1c)

Using the phasor representation

\[
u_1(t) = \text{Im}\left\{ (U_{1R} + j U_{1I}) e^{j \phi(t)} \right\}
\]

(2)

for the system input, we can transform the differential equation of the oscillation system

\[
\ddot{y}_1(t) + 2d_i \omega_{01} \dot{y}_1 + \alpha_{01}^2 y_1(t) = k_1 u_1(t)
\]

(3)

into an equivalent phasor representation given by

\[
\begin{bmatrix}
\dot{Y}_{1R} \\
\dot{Y}_{1I} \\
\ddot{Y}_{1R} \\
\ddot{Y}_{1I}
\end{bmatrix}
+
\begin{bmatrix}
2d_i \omega_{01} & -2\dot{\phi} & \dot{\phi}^2 & \alpha_{01}^2 - \dot{\phi}^2 \\
\dot{\phi} & 2d_i \omega_{01} & \dot{\phi}^2 & \alpha_{01}^2 - \dot{\phi}^2 \\
\alpha_{01}^2 & \dot{\phi} & 2d_i \omega_{01} & \dot{\phi}^2 \\
\dot{\phi} & \alpha_{01}^2 & \dot{\phi} & 2d_i \omega_{01}
\end{bmatrix}
\begin{bmatrix}
Y_{1R} \\
Y_{1I} \\
\dot{Y}_{1R} \\
\dot{Y}_{1I}
\end{bmatrix}
= k_1 \begin{bmatrix}
U_{1R} \\
U_{1I}
\end{bmatrix}
\]

(4)

Now it is easy to control the phasor amplitude with a predescribed dynamics (trajectory control)

\[
\ddot{Y}_M + A_1 \dot{Y}_M + A_0 Y_M = k_1 W_1
\]

with

\[
W = \begin{bmatrix}
W_{1R} \\
W_{1I}
\end{bmatrix}
\]

(6)
representing the reference for the real- and imaginary part of the phasor output. The implementation is done using a 2DOF-Structure [7].

As \( A_I \) and \( A_0 \) are depending on \( \phi \) and \( \dot{\phi} \), the control is time variant.

3. Phase and frequency control

To meet the control objective, i.e. stimulation of the oscillation system in its eigenfrequency \( \omega_{o1} \), we have to measure the phase shift between input and output and set up a control law for the momentary frequency \( \dot{\phi} \). Using a simple PI-Controller, we get:

\[
\dot{\phi} = K_p \left[ \varepsilon + \frac{1}{T_i} \int \varepsilon(t) \, dt \right]
\]

(7a)

where \( \varepsilon(t) \) represents a normalized phase-shift. As the phase-shift is only defined in steady state and not during transients, we have to derive an equivalent measurement (cf. 5).

The oscillation system is operated in its eigenfrequency \( \omega_{o1} \), when \( \Delta \phi \equiv 0 \). For \( \Delta \phi \equiv 0 \) we get the relation

\[
U_{i1} Y_{i1} - U_{i1} Y_{i1} = 0
\]

(8)

Using normalized signals \( \frac{U_{i1}}{U_{i1}} = U_{i1}^* \); \( \frac{U_{i1}}{U_{i1}} = U_{i1}^* \); \( \frac{Y_{i1}}{Y_{i1}} = Y_{i1}^* \); \( \frac{Y_{i1}}{Y_{i1}} = Y_{i1}^* \) we define the normalized phase shift \( \varepsilon(t) \) as follows

\[
U_{i1}^* Y_{i1}^* - U_{i1}^* Y_{i1}^* = \varepsilon(t)
\]

(9)

4. Kalman-filter

The 2DOF control can only be implemented if estimates of the real- and imaginary parts of the phasors together with their derivatives are provided. Using an extended Kalman-Filter for the 2nd order time varying system \( G_1(s) \)

\[
\begin{bmatrix}
X_{i1r} \\
\dot{X}_{i1r} \\
X_{i1f} \\
\dot{X}_{i1f}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\phi^2 - \omega_{o1}^2 & \phi + 2d_t \omega_{o1} \phi & -2d_t \omega_{o1} & 2\phi \\
\phi + 2d_t \omega_{o1} \phi & \phi^2 - \omega_{o1}^2 & -2\phi & -2d_t \omega_{o1}
\end{bmatrix} \begin{bmatrix}
X_{i1r} \\
\dot{X}_{i1r} \\
X_{i1f} \\
\dot{X}_{i1f}
\end{bmatrix} + \begin{bmatrix}
U_{i1r} \\
0 \\
1 \\
0
\end{bmatrix}
\]

(10)

together with the measurement equation

\[
y_M(t) = \begin{bmatrix}
\sin \phi & \cos \phi & 0 & 0
\end{bmatrix} \begin{bmatrix}
X_{i1r} \\
X_{i1f} \\
\dot{X}_{i1r} \\
\dot{X}_{i1f}
\end{bmatrix}
\]

we can estimate both the states i.e. the real- and imaginary parts of the phasors and their derivatives as well as the model parameters \( k_i, d_t, \omega_{o1} \).
5. Simulation

To show the performance of the proposed control scheme, a 2nd order oscillation system (Fig. 2) is simulated (nominal parameters $\omega_0 = 2.2$, $d_1 = 10^{-1}$, $k_1 = 1$). At start-up there is a difference of about 20% in the actual parameters compared to the nominal parameters. Figs. 7

Fig. 7. Start-up and step change in amplitude.

Fig. 8. Phasor description of $y_1(t)$.

Fig. 9. Adjusting the drive frequency $\omega_B$ from start-up.

Fig. 10. Output with/without 41% gas void fraction (GVF).

Fig. 11. Two phase flow (Batch experiment empty to full).
and 8 show the performance of amplitude control in terms of time signals as well as phasor signals. As the oscillation system has to be operated in its eigenfrequency \(\omega_{01}\), i.e. \(\Delta \phi = 0\), the frequency of the harmonic drive signal \(\omega_b\) has to be adjusted to the a priori unknown frequency \(\omega_{01}\). Figure 9 shows the performance of phase/frequency control.

The control of a real CMFM according to the proposed control scheme is given in Figs. 10 and 11. As commercial meters often stall in situations with two phase flow, the transition from water to two phase flow is investigated. Due to the increased damping during two phase flow, the drive amplitude shows dramatic changes in amplitude, whereas the amplitude of the output is constant if we neglect the small steady state error that will disappear if integral action is provided. The adjustment of the drive frequency \(\omega_b\) to the eigenfrequency \(\omega_{01}\) in case of two phase flow is also very fast.

In a further batch experiment the transition from empty to full is investigated. During the transition the damping increases rapidly if flow enters the empty tube and decreases if the tube is filled up. As the driver output is bounded the amplitude of oscillation decreases as well, but reaches its set-point again when the meter is filled up.

Further investigations, regarding the accuracy of the meter with the proposed control scheme in situations with two phase flow have to be carried out.

References