XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6-11, 2009, Lisbon, Portugal

ADVANCED PHASOR CONTROL OF A CORIOLIS MASS FLOW METER (CMFM)

H. Röck, F. Koschmieder

Institute for Automation and Control Engineering, Christian-Albrechts-University of Kiel, Kiel, Germany, hr@tf.uni-kiel.de

Abstract– Advanced control of Coriolis Mass Flow Meters (CMFM) is crucial in situations with multiphase flow and absolutely necessary to prevent the meter from stalling [1]. A high dynamic response of the meter is also of great importance in order to realize advanced features s.a. parameter identification for self-diagnosis or detection of changes in sensitivity and zero. In [4] a cyclic stimulation of the coriolis-mode of the CMFM, representing a virtual mass flow, is presented for generating diagnostic data and marks a major step towards the realization of such features. The presented phasor control scheme for phasors with quasi stationary frequencies reduces the cycle time by a factor of two with respect to [6] and allows to handle situations with multiphase flow. The control performance is much better than reported before but can still be enhanced if the scheme is extended to time-varying frequencies.
In the paper only the drive-mode of the CMFM (single straight pipe) is investigated. The control objective is to stimulate the oscillation system in its a priori unknown eigenfrequency ω_{01} by phase control and to allow for phase and amplitude control simultaneously. This is different to conventional control schemes where phase- and amplitude control have to be separated in time in order to work properly. The control scheme is tested in simulation and realized in an experimental setup of a CMFM.

Keywords: Phasor Control, Coriolis Mass Flow Meter

1 INTRODUCTION / STATEMENT OF THE PROBLEM

According to the measurement principle, the accuracy of todays CMFM is very high. In addition to mass flow, measured by the phase difference of two electromagnetic sensors located at the up- and downstream part of the measuring pipe, it is also possible to exploit the change in eigenfrequency of the drive mode to measure fluid density. The principle element of the CMFM is a single straight pipe (fig. 1) rigidly connected to a supporting pipe. The oscillation of the pipe is stimulated via two actuators situated symmetrically to the middle of the pipe. Provided there is mass flow, the interaction of mass flow and stimulated oscillation of the pipe in its 1st eigenmode will induce Coriolis forces with opposite directions in the up- and downstream part of the pipe and thus stimulate the CMFM in its 2nd eigenmode. By addition and subtraction of the driving forces $\underline{F}_a$ and $\underline{F}_b$ together with the senor signals $\underline{V}_a$ and $\underline{V}_b$ we can derive a lumped parameter model of the CMFM [6] in which both of the eigenmodes are separated with input variables $\underline{U}_{1,2}$ and output variables $\underline{Y}_{1,2}$. In phasor notation we get:

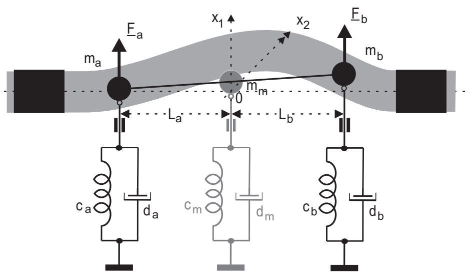

Figure 1: Equivalent mechanical oscillation system of the CMFM

$$\underline{U}_1 = \frac{1}{2}(\underline{F}_a + \underline{F}_b) \qquad \underline{Y}_1 = \frac{1}{2}(\underline{V}_a + \underline{V}_b) \tag{1}$$
$$\underline{U}_2 = \frac{1}{2}(\underline{F}_a - \underline{F}_b) \qquad \underline{Y}_2 = \frac{1}{2}(\underline{V}_a - \underline{V}_b)$$

The corresponding lumped parameter model and the block diagram of the CMFM are depicted in figs 1 and 2.
As the difference in phase between the phasors $\underline{V}_a$ and $\underline{V}_b$ is proportional to mass flow, the phasors $\underline{Y}_1$ and $\underline{Y}_2$ have to be orthogonal (fig. 3). Following [4] the control objectives that have to be met by the block-diagram of the CMFM are:

- Orthogonality of the phasors $\underline{Y}_1$ and $\underline{Y}_2$ by amplitude control of the corresponding real- and imaginary parts.
- Stimulation of the 1st mode (drive mode i.e. transfer function $G_1(s)$) in its eigenfrequency ω_{01} in order to enhance the SNR.
- Fast dynamic response when stimulating the 2nd mode (coriolis mode) with a virtual mass flow via $\mathrm{Re}\{\Delta U_2\}$ in order to gather diagnostic data.

To meet these control objectives in a first step only phase and amplitude control of the 1st eigenmode is investigated in this paper thus reducing the complexity of the problem substantially without loss of generality. As the eigenfrequency of the 1st mode ω_{01} is a priori unknown, the stimulating frequency has to be adjusted by phase control and the desired amplitude

ISBN 978-963-88410-0-1 © 2009 IMEKO

of the output has to be controlled to a specified set point simultaneously. This is different to conventional control schemes where phase- and amplitude control have to be separated in time in order to work properly.

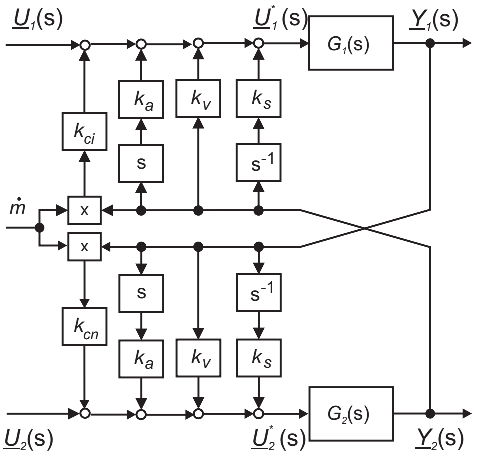

Figure 2: Block-Diagram of the CMFM

2 CONTROL SCHEME FOR THE 1st EIGENMODE

To realise phasor control for the 1st eigenmode of the CMFM represented by the transfer function

$$G_1(s) = \frac{\underline{Y}_1(s)}{\underline{U}_1^*(s)} = \frac{k_1 s}{s^2 + 2d_1\omega_{01}s + \omega_{01}^2} \tag{2}$$

the time signals have to be replaced by phasors. The phasor representation for G_1 has to allow for rapid changes in phasor length and momentary frequency $\dot{\Phi}$.
In two phase flow with variable gas void fraction the eigenfrequency of the CMD changes rapidly while the damping increases by an order of about 2 to 3 in magnitude.
In practice the computation of phasors from time domain signals is rather difficult. A widely used procedure is the method of quadrature demodulation where the time signal is multiplied by sine and cosine. The resultant dc components form the real- and imaginary part of the phasors. To get these dc components, the resultant signals have to be low pass filtered with high order filters that have proven inadequate for fast phase and amplitude control as they limit the bandwidth of the control loop substantially. The problem can be solved by using an extended Kalman Filter. Using a Kalman-Filter allows to generate the phasors without low pass filtering and thus provides a powerful tool to estimate the phasors much faster than with conventional quadrature demodulation.

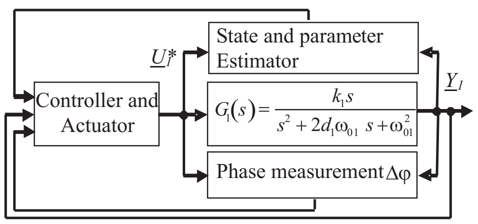

Figure 3: Scheme of the control system for the 1st eigenmode

The control objective for the 1st mode (fig. 3) can be summarized as follow:

- Simultaneous amplitude and phase control
- Stimulation of the CMFM in its 1st eigenmode
- Fast disturbance rejection and set point control to allow for cyclic operation
- Estimation of unknown parameters s.a. ω_{01}, d_1 and k_1

3 AMPLITUDE CONTROL

In steady state the control input and the controlled output are harmonic time signals, often represented by phasors with constant amplitude and constant rotating frequency $\dot{\Phi}$. If we extend this representation to time varying amplitude and frequency similar to applications in power electronics, where varying phasor amplitude with quasi stationary frequency is an established tool, we get

$$\begin{aligned}
x_1(t) &= \mathrm{Im}\{(X_{1R} + j\,X_{1I})\,e^{j\Phi(t)}\}\\
\dot{x}_1(t) &= \mathrm{Im}\{(\dot{X}_{1R} - \dot{\Phi}X_{1I})\,e^{j\Phi(t)} + j(\dot{X}_{1I} + \dot{\Phi}X_{1R})\,e^{j\Phi(t)}\}\\
\ddot{x}_1(t) &= \mathrm{Im}\{(\ddot{X}_{1R} - \ddot{\Phi}X_{1I} - 2\dot{\Phi}\dot{X}_{1I} - \dot{\Phi}^2X_{1R})\,e^{j\Phi(t)}\\
&\quad + j(\ddot{X}_{1I} - \ddot{\Phi}X_{1R} - 2\dot{\Phi}\dot{X}_{1R} - \dot{\Phi}^2X_{1I})\,e^{j\Phi(t)}\} \quad .
\end{aligned} \tag{3}$$

The differential equation for the oscillation of the 1st eigenmode

$$\begin{aligned}
\ddot{x}_1(t) + 2d_1\omega_{01}\dot{x}_1(t) + \omega_{01}^2 x_1(t) &= k_1 u_1^*(t)\\
y &= \dot{x}_1(t)
\end{aligned} \tag{4}$$

now reads

$$\begin{aligned}
&\underbrace{\begin{bmatrix}\ddot{X}_{1R}\\ \ddot{X}_{1I}\end{bmatrix}}_{\underline{\ddot{X}}_1} + \underbrace{\begin{bmatrix}2d_1\omega_{01} & -2\dot{\Phi}\\ 2\dot{\Phi} & 2d_1\omega_{01}\end{bmatrix}}_{A_1}\underbrace{\begin{bmatrix}\dot{X}_{1R}\\ \dot{X}_{1I}\end{bmatrix}}_{\underline{\dot{X}}_1}\\
&+ \underbrace{\begin{bmatrix}\omega_{01}^2 - \dot{\Phi}^2 & -(\ddot{\Phi} + 2d_1\omega_{01}\dot{\Phi})\\ \ddot{\Phi} + 2d_1\omega_{01}\dot{\Phi} & \omega_{01}^2 - \dot{\Phi}^2\end{bmatrix}}_{A_0}\underbrace{\begin{bmatrix}X_{1R}\\ X_{1I}\end{bmatrix}}_{\underline{X}_1}\\
&= k_1\underbrace{\begin{bmatrix}U_{1R}^*\\ U_{1I}^*\end{bmatrix}}_{\underline{U}_1^*}
\end{aligned} \tag{5}$$

with input

$$u_1^*(t) = \mathrm{Im}\{(U_{1R}^* + j\,U_{1I}^*)\,e^{j\Phi(t)}\} \quad . \tag{6}$$

Defining a reference model

$$\underline{\ddot{X}}_1 + A_1^*\underline{\dot{X}}_1 + A_0^*\underline{X}_1 = k_1^*\underline{U}_{1M} \quad \text{with} \quad \underline{U}_{1M} = \begin{bmatrix}U_{1MR}\\ U_{1MI}\end{bmatrix} \tag{7}$$

a reference model can be assigned to the system by the linearizing control

$$\underline{U}_1^* = \frac{1}{k_1}\{k_1^*\underline{U}_{1M} + (A_1 - A_1^*)\underline{\dot{X}}_1 + (A_0 - A_0^*)\underline{X}_1\} \tag{8}$$

As the matrices A_0 and A_1 depend on $\dot{\Phi}$ and $\ddot{\Phi}$, the control law is time variant. To account for model uncertainties and to guarantee unbiased control, an LQ-controller for $\underline{U}_{1M}$ with integral action (see fig. 4) is used.

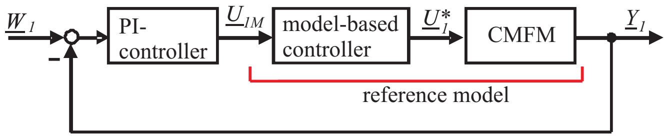

Figure 4: Schematic of amplitude control

4 PHASE CONTROL

As the damping $d_1 \approx 10^{-5}$ of the oscillation in 1st eigenmode is very low, the CMFM has to be operated in its eigenfrequency ω_{01} to maximize SNR. This is done if the input $\underline{U}_1^*$ and the output $\underline{Y}_1$ of the transfer function

$$G_1(s) = \frac{k_1 s}{s^2 + 2 d_1 \omega_{01} s + \omega_{01}^2} = \frac{\underline{Y}_1(s)}{\underline{U}_1^*(s)} \quad (9)$$

are in phase (see fig. 5), resulting in

$$\tan\gamma = \frac{Y_{1I}}{Y_{1R}} = \frac{U_{1I}^*}{U_{1R}^*} \quad (10)$$

or

$$U_{1I}^* Y_{1R} - U_{1R}^* Y_{1I} = 0 \quad (11)$$

For $\dot{\Phi} \neq \omega_{01}$ and during transients, eq. (11) will not hold, as the phase γ is only defined for stationary signals $\underline{U}_1^*$ and $\underline{Y}_1$. For that reason, an auxiliary measure $\varepsilon(t)$ of phase, derived from normalized phasors $\underline{Y}_{1n}$ and $\underline{U}_{1n}^*$

$$\varepsilon(t) = U_{1Rn}^* Y_{1In} - U_{1In}^* Y_{1Rn} \quad (12)$$

is defined, resulting in

$$-1 \leq \varepsilon(t) \leq 1 \quad . \quad (13)$$

Using simple integral control action

$$\ddot{\Phi}(t) = K_i \cdot \varepsilon(t) \quad (14)$$

the instantaneous frequency $\dot{\Phi}$ can be adjusted until $\varepsilon(t)$ – the error in phase – has vanished.

5 EXTENDED KALMAN-FILTER

The control scheme, as pointed out in figs 3 and 4, can only be realized, if the real- and imaginary parts and the related time derivatives of the phasors together with the a priori unknown parameters $X_{2d_1\omega_{01}} = 2\, d_1\, \omega_{01}$ and $X_{\omega_{01}^2} = \omega_{01}^2$ can directly be estimated from the time signal

$$y_1(t) = \dot{x}_1(t) = \mathrm{Im}\{(\dot{X}_{1R} - \dot{\Phi} X_{1I} + j(\dot{X}_{1I} + \dot{\Phi} X_{1R}))\, e^{j\Phi(t)}\} \quad (15)$$

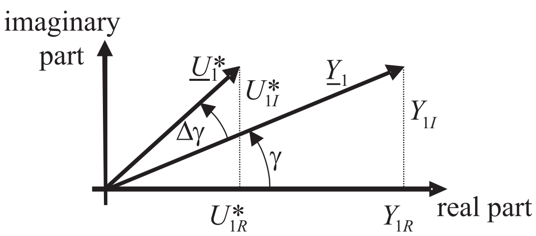

Figure 5: Phase shift $\Delta\gamma$ between the phasor signal $\underline{Y}_1$ and $\underline{U}_1^*$

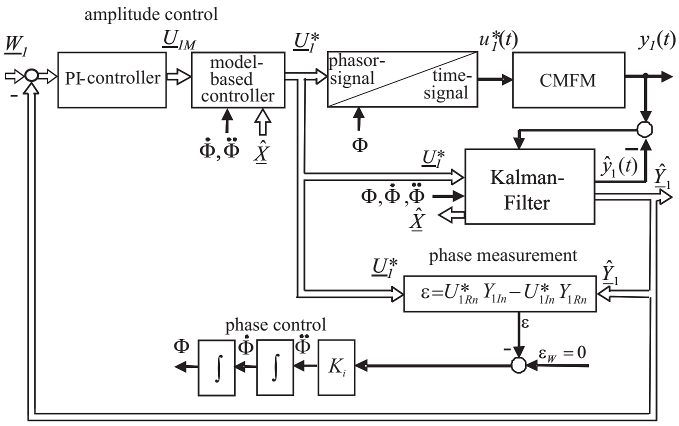

Figure 6: Model-based phasor control for the 1st eigenmode

From eq. (5) we derive

$$\begin{bmatrix} \dot{X}_{1R} \\ \dot{X}_{1I} \\ \ddot{X}_{1R} \\ \ddot{X}_{1I} \\ \dot{X}_{\omega_{01}^2} \\ \dot{X}_{2d_1\omega_{01}} \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \dot{\Phi}^2 - X_{\omega_{01}^2} & \ddot{\Phi} + X_{2d_1\omega_{01}}\dot{\Phi} \\ -(\ddot{\Phi} + X_{2d_1\omega_{01}}\dot{\Phi}) & \dot{\Phi}^2 - X_{\omega_{01}^2} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \cdots$$

$$\cdots \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ -X_{2d_1\omega_{01}} & 2\dot{\Phi} & 0 & 0 \\ -2\dot{\Phi} & -X_{2d_1\omega_{01}} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \underbrace{\begin{bmatrix} X_{1R} \\ X_{1I} \\ \dot{X}_{1R} \\ \dot{X}_{1I} \\ X_{\omega_{01}^2} \\ X_{2d_1\omega_{01}} \end{bmatrix}}_{\underline{X}}$$

$$+ \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ k_1 & 0 \\ 0 & k_1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} U_{1R}^* \\ U_{1I}^* \end{bmatrix} \quad (16)$$

and the measurement equation reads

$$y_1(t) = \begin{bmatrix} \dot{\Phi}\cos\Phi & -\dot{\Phi}\sin\Phi & \sin\Phi & \cos\Phi & 0 & 0 \end{bmatrix} \underline{X} \quad (17)$$

The detailed control scheme is given in fig. 6.

6 SIMULATION RESULTS (time varying excitation frequency)

The performance of phasor control has been tested using a 2nd order system (eq. (5)) with nominal parameters $\omega_{01} = 2$ rad/sec, $d_1 = 0{,}1$ and $k_1 = 1$. In fig. 7 the response of the output $y_1(t)$ to a step change in amplitude of $w_1(t)$ is shown. The step change in amplitude is translated into a step change of the corresponding real part of the phasor $\underline{Y}_1$. As can be seen, the settling time is reached after about one period of oscillation while during transients the input $u_1^*(t)$ is not a harmonic oscillation any more. The same applies for the momentary frequency $\dot{\Phi}$ of the input which also varies during the control process.

Simulation results based on a model for time varying excitation frequency

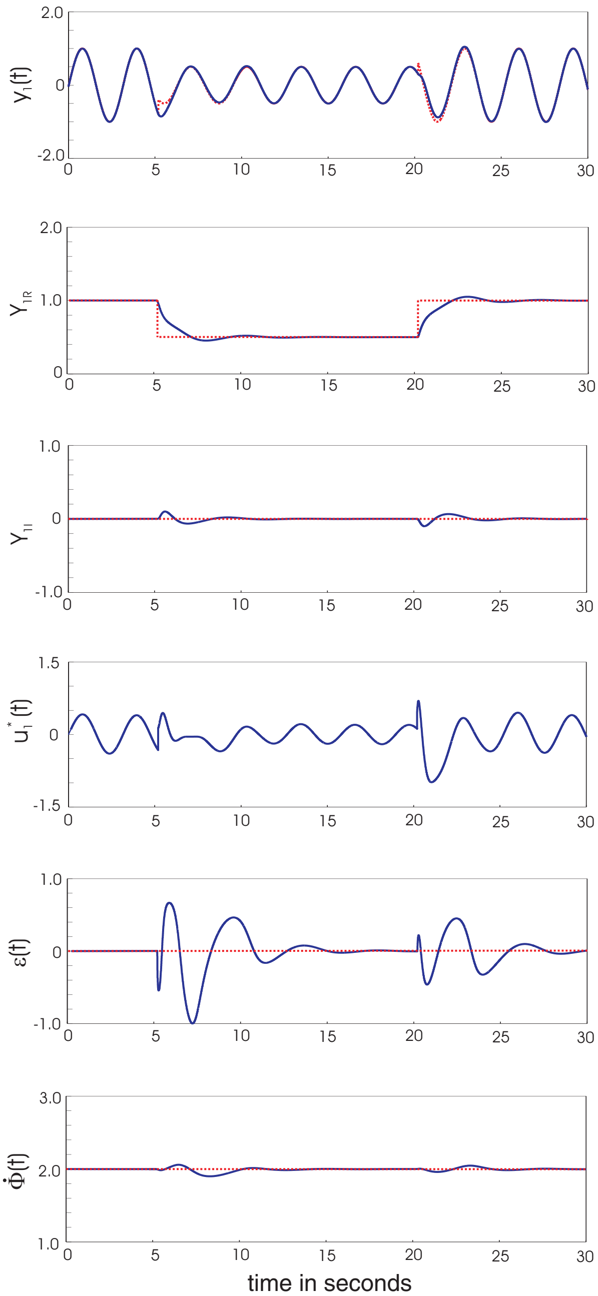

Figure 7: Response of $y_1(t)$ to a step change of the reference $w_1(t)$

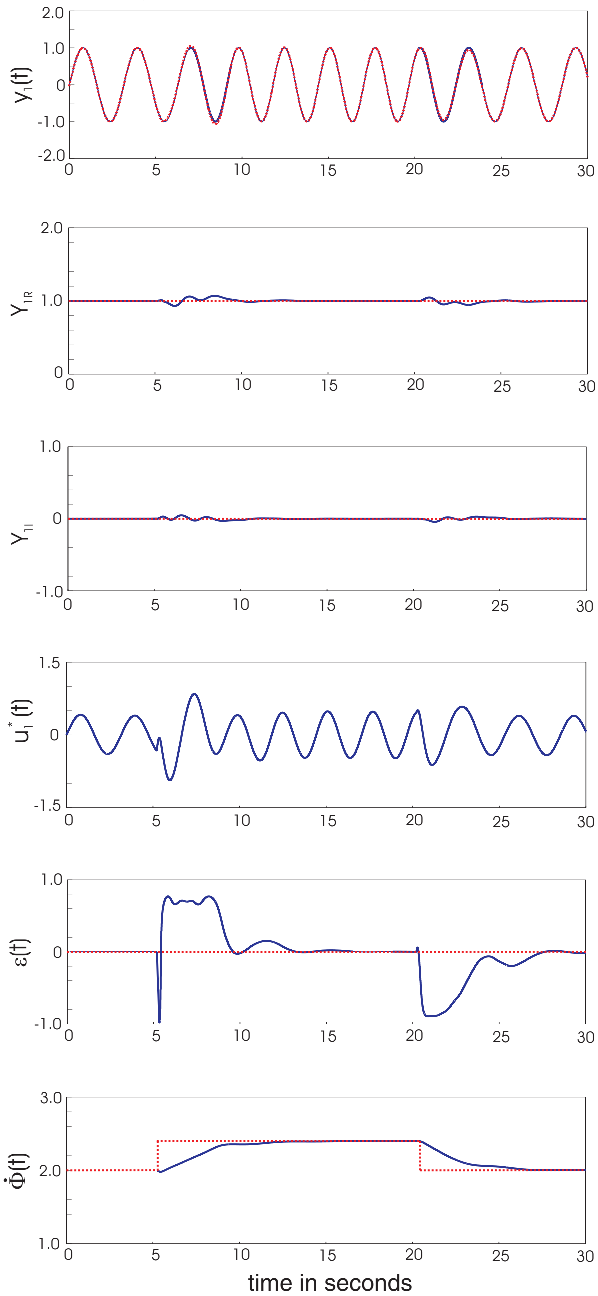

Figure 8: Response of $y_1(t)$ to a simulated step change in eigenfrequency ω_{01} about 20%

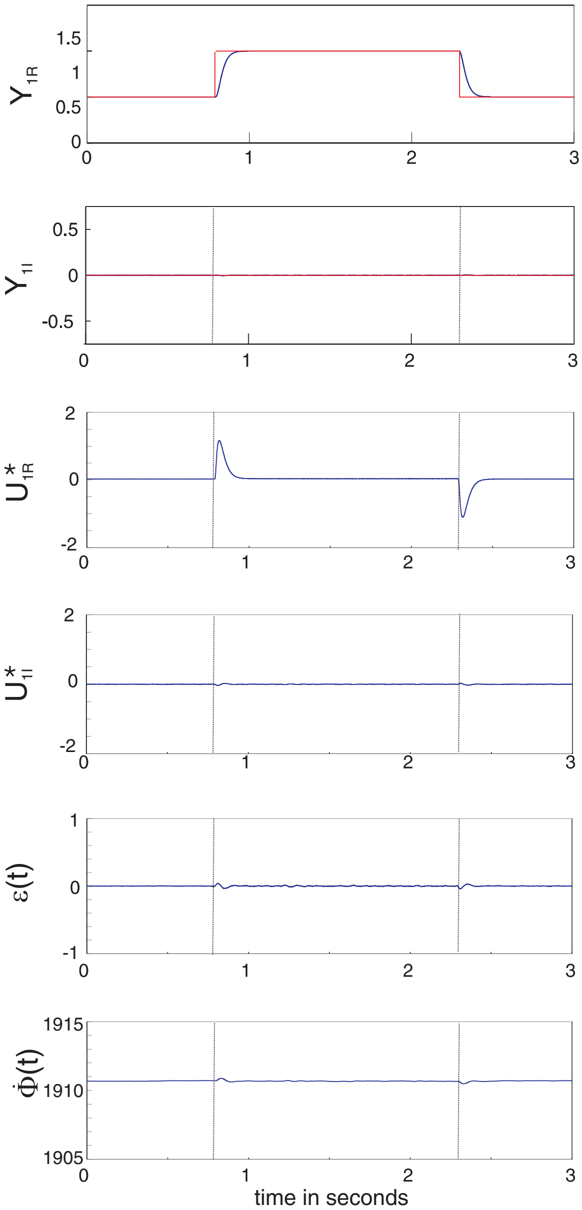

Figure 9: Response of the output $\underline{Y}_1$ to a step change of the reference $\underline{W}_1$ see fig. 7

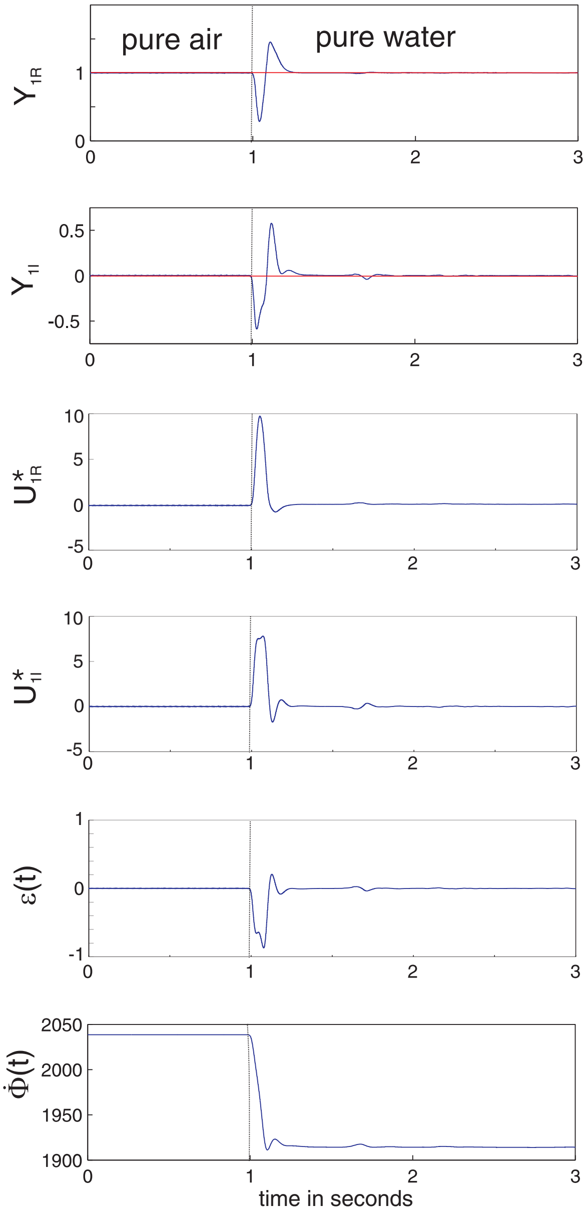

Figure 10: Response of the output $\underline{Y}_1$ to a change in eigenfrequency ω_{01} see. fig. 8

As often encountered in practical situations, the eigenfrequency of the 1st mode will change due to a change in fluid density. Fig. 8 shows the reaction of the control loop if a simulated step change in eigenfrequency ω_{01} of ca. 20% is induced. This change in eigenfrequency will occur, if in a batch experiment the CMFM will drain from full to empty and will be refilled again. As the control objective is to operate the CMFM in its 1st eigenmode with $\omega_{01} \sim \sqrt{1/\text{density}}$, the frequency of stimulation first increases until the eigenfrequency ω_{01} is reached and decreases again after the batching experiment has come to an end. During transients, the controlled output $y_1(t)$ and the corresponding real- and imaginary part of the phasor $\underline{Y}_1$ will exhibit only minor changes in amplitude, while the control input $u_1^*(t)$ is reacting to the error in phase. After about two periods of oscillation, steady state is reached again.

7 PRACTICAL RESULTS (quasi stationary excitation frequency)

In figs 9 and 10 the dynamics of the control for slowly varying stimulation frequencies is shown. In contrast to the previous simulation study, the momentary frequency is regarded as being quasi stationary. But instead of controlling only the 1st mode of the CMFM, both of the eigenmodes are controlled in order to orthogonalize the phasors $\underline{Y}_1$ and $\underline{Y}_2$.
Fig. 9 shows pure amplitude control of the 1st mode – for better comparison with fig. 7 the corresponding real and imaginary parts of the phasor representing the 2nd eigenmode are not shown. As can be seen, there are only minor changes in phase and momentary frequency $\dot{\Phi}$ during settling time. Fig. 10 reports a batch experiment where the measuring pipe is filled up with pure air at the beginning of the experiment. The eigenfrequency is $\omega_{01} \approx 2040$ rad/s. When the measuring pipe is being filled up, the eigenfrequency ω_{01} decreases and the stimulating frequency $\dot{\Phi}$ is adjusted by frequency control to the eigenfrequency ω_{01} in order to compensate the phase error $\varepsilon(t)$. Together with changes in eigenfrequency, the damping is also increasing and causes a decrease in the amplitude of the real- and imaginary part of the phasor $\underline{Y}_1$. Accordingly, by control action, the real- and imaginary part of the control input increases from nearly zero to an upper limit that will not damage the CMFM. As can be seen, the amplitude of $\underline{Y}_1$ exhibits a short break down, because the restrictions on amplitude for the control inputs U_{1R} and U_{1I} are temporarily violated.

8 SUMMARY / FUTURE WORK

In this paper a phasor control scheme for a 2nd order oscillation system with sinusoidal stimulation and time varying frequency of stimulation is presented and tested in simulation. The real- and imaginary parts of the phasors are estimated together with additional parameters s.a. damping and eigenfrequency by an extended Kalman-Filter. The linearizing control allows for rapid frequency and amplitude control. The extension of the existing phasor control scheme for quasi stationary frequencies of excitation to time varying frequencies for both of the outputs $\underline{Y}_1$ and $\underline{Y}_2$ of the CMFM is under work. It is hoped that the practical result gained so far with quasi stationary frequency of excitation and reported in this paper can still be outperformed by using a mathematical formulation with time varying frequencies as demonstrated in simulation.

References

[1] M. P. Henry, M. S. Tombs, and H. Yeung. Coriolis Meter in Two Phase Flows. *12th International Conference on Multiphase Production Technology, Barcelona, Spain*, 20.-27. May 2005.

[2] K. Kolahi and H. Röck. Density and Pressure Measurement with Coriolis Mass Flowmeters. *International Conference on Instrumentation, Communication and Information Technology (ICICI), Indonesia*, 3.-5. August 2005.

[3] K. Kolahi and R. Storm. Erkennung und Diagnose von Zweiphasenströmungen mit Coriolis-Massedurchflussmessern. *AUTOMATION 2008,Baden-Baden, Germany*, Vol. 2032:31 – 34, 3.6-4.6 2008.

[4] H. Röck and F. Koschmieder. A New Method to Detect Zero Drift and Sensitivity of a Coriolis Mass Flow Meter (CMFM) by Using Phasor Control. *3rd International Conference on Sensing Technology, Tainan, Taiwan*, pages 518 – 522, IEEE Explore No. 10415805, ISBN: 978–1–4244–2176–3, 30.11.-3.12 2008.

[5] H. Röck, T. Schröder, K. Kolahi, and F. Koschmieder. Flatness-Based Control of a Coriolis Mass Flowmeter. *ISMTII 2007, Sendai, Japan*, 24. -27. September 2007.

[6] T. Schröder. Model-Based Online-Self-Diagnosis of a Coriolis Mass Flowmeter with a Single Straight Pipe. Dissertation, Institute for Automation and Control Engineering, Christian-Albrechts-University of Kiel, 2006.

[7] R. Storm, K. Kolahi, and H. Röck. Detection of Zero Shift in Coriolis Mass Flowmeters. *Proceedings of the XVI IMEKO World Congress, Austria*, Vol. VI:61–66, 25.-28. September 2000.

[8] R. Storm, K. Kolahi, and H. Röck. Model-Based Correction of Coriolis Mass Flowmeters. *18th IEEE Instrumentation and Measurement Technology Conference, Budapest, Hungary*, Vol. 2:1231–1236, 21.-23. Mai 2001.