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PLL CONTROL OF THE CORIOLIS METER RESONANCE FREQUENCY

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Abstract: The Coriolis meter is used for direct measurements of fluid density and mass flowrate. Its regular operation is conditional on the vibration of its measuring tube at the resonance frequency. The accuracy and quickness of the resonance control have an impact on static and dynamic meter characteristics. In the paper, results of using a phase-locked loop (PLL) control system are presented. The measurements were performed on a straight-tube meter with an electromagnetic exciter and piezoelectric accelerometers.
Keywords: Coriolis flowmeter, tube resonance frequency, phase-locked loop.

1 INTRODUCTION

The Coriolis meter is one of the most important techniques for direct measurement of the mass flowrate [1, 2]. Moreover, it measures fluid density independently. Its basic sensing element is a vibrating measuring tube, usually clamped at both ends, conveying the measured fluid. The interaction between tube motion and fluid flow leads to additional forces on the tube. The Coriolis force alters the symmetry of the fundamental mode shape, which is used for determining the mass flowrate. However, the measurement of fluid density results from the change in the tube resonance frequency due to fluid added mass.

Components, usually used for vibration excitation and detection, are based on the electromagnetic and piezoelectric principle. The exciter is located at the midpoint and the detectors symmetrically with regard to the midpoint of the tube length (if only fluid density is of interest, only one vibration detector is required). An independent and continuous measurement of the mass flowrate and fluid density is conditional on continuous vibration of the tube at its resonance. The measuring tube can be observed as a mechanical resonator and the Coriolis meter as a resonant sensor [3]. The resonance frequency of the tube has to be controlled by a suitable feedback loop [4]. The accuracy and quickness of the control system affect static and dynamic meter characteristics.

This paper presents results of resonance control using a phase-locked loop (PLL). The PLL control system maintains a proper phase difference between the excitation and detection signal of the oscillator. Our measurements were performed on an experimental model of the straight-tube Coriolis meter with an electromagnetic exciter and piezoelectric acceleration detectors. The PLL controller was implemented at the LabVIEW programming system.

2 THEORETICAL BACKGROUND

2.1 Linear mechanical oscillator

The equation of motion of a single degree of freedom linear mechanical oscillator is (see, e.g., reference [5])

$$m\frac{\mathrm{d}^2u_o}{\mathrm{d}t^2}+c\frac{\mathrm{d}u_o}{\mathrm{d}t}+ku_o=u_i\,, \tag{1}$$

where m is mass, c damping constant and k spring constant. Considering the harmonic exciting force

$$u_i=U_i\cos(\omega t)\,, \tag{2}$$

the steady-state solution for displacement results in the form

$$u_o=U_o\cos(\omega t-\phi)\,. \tag{3}$$

Let us use the definitions $\omega_n^2 = k/m$ and $\zeta = c/(2m\omega_n)$, where $\omega_n = 2\pi f_n$ is the natural frequency of the undamped system and ζ the damping factor. So the amplitude ratio U_o/U_i and the phase angle ϕ can be expressed as

$$\frac{U_o}{U_i} = \frac{1/k}{\sqrt{\left(1-\omega^2/\omega_n{}^2\right)^2 + \left(2\zeta\omega/\omega_n\right)^2}}\,,\ \phi = \arctan\left(\frac{2\zeta\omega/\omega_n}{1-\omega^2/\omega_n{}^2}\right). \tag{4}$$

The condition $\omega/\omega_n = 1$, so that the exciting frequency ω equals the oscillator natural frequency ω_n, is known as resonance. It results in amplitude ratio $(U_o/U_i k)_n = 1/(2\zeta)$ and phase angle $\phi_n = 90°$. If $\omega/\omega_n < 1$, then $0° < \phi < 90°$, and if $\omega/\omega_n > 1$, then $90° < \phi < 180°$.

2.2 Phase comparator

Let us suppose two sinusoidal signals, u_i and u_o, with equal frequencies ω and phase difference ϕ (see, e.g., reference [6]):

$$u_i = U_i \cos(\omega t)\,,\ u_o = U_o \cos(\omega t - \phi)\,, \tag{5}$$

where U_i and U_o are their amplitudes. Multiplying both signals, the result can be presented as

$$u = u_i u_o = U + u'\,, \tag{6}$$

where U is a time-independent, DC component:

$$U = \tfrac{1}{2} U_i U_o \cos(\phi) \tag{7}$$

and u' is a time-dependent, AC component:

$$u' = \tfrac{1}{2} U_i U_o \cos(2\omega t - \phi)\,. \tag{8}$$

The DC component U is a function of phase difference ϕ: $U > 0$ for $0° < \phi < 90°$, $U = 0$ for $\phi = 90°$ and $U < 0$ for $90° < \phi < 180°$ (identical for negative values of ϕ). In the systems, where ϕ between the output and input is 90° or –90° in the resonance, U can be used as a deviation from this condition.

3 EXPERIMENTS

3.1 Measuring system

The measuring system of the experimental model of the Coriolis meter is schematically presented in Figure 1. The measuring tube is straight and clamped at both ends (material: stainless steel DIN 1.4571, dimensions: length 1 m, outside diameter 17,2 mm and wall thickness 1,5 mm).

The tube vibration is excited by an electromagnetic exciter, located at the middle of the tube length (a permanent magnet is fixed on the tube and coil on the base). An electrical current through the coil, which is proportional to the exciting force, is measured as the voltage drop on a known resistor. The coil is supplied alternately using a function generator (Goldstar, type FG-8002, voltage range ±10 V, sine wave distortion <1 %). Its frequency can be controlled by the input voltage ±10 V.

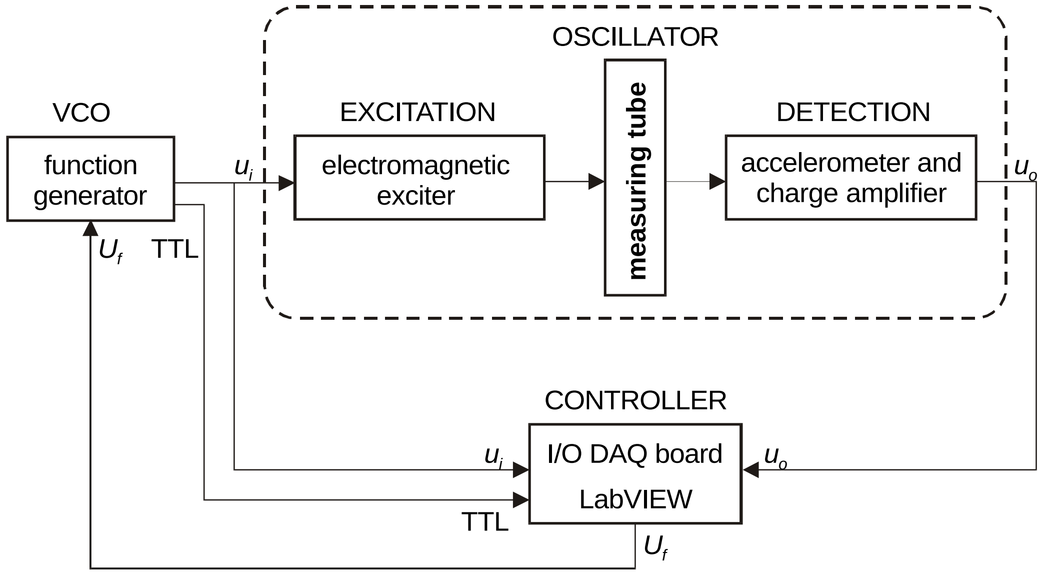

Figure 1. Block diagram of the measuring system.

The tube vibration is detected by a piezoelectric accelerometer, located at the middle of the tube length (Kistler, type 8044, sensitivity 0,278 pC/*g*, acceleration range ±10 *g*, linearity 1 %, resonance 60 kHz). Generally, two detectors are required to determine the mass flowrate effect in the Coriolis meter. However, the described configuration satisfies the purpose of this paper. The accelerometer charge output is converted to the voltage signal by a charge amplifier (Dewetron, type DAQ-CHARGE, gain 1 V/pC, voltage range ±5 V, input noise <0,01 pC, pass filter between 0,3 Hz and 20 kHz).

Computer control of the measuring system was realized by the National Instruments DAQ board (type PCI-6031E) and graphical programming system LabVIEW for DAQ board control and data processing (see, e.g., reference [7]). We used analog voltage inputs and outputs (resolution 16 bit, max scan and update rate 100 kHz, max voltage range ±10 V, accuracy ±1,5 LSB) and timing input to measure the period of the TTL signal from function generator (resolution 24 bit, base clock 20 MHz, time base accuracy ±0,01 %).

3.2 PLL controller

Figure 2 presents the measured amplitude and phase frequency characteristics of the measuring tube in the region of the first resonance frequency. (The resonance frequency decrease, shown in the below figure, is the effect of the fluid density increase.) The voltage proportional to excitation current u_i and the voltage from charge amplifier u_o were used as the input and output signal respectively. Being

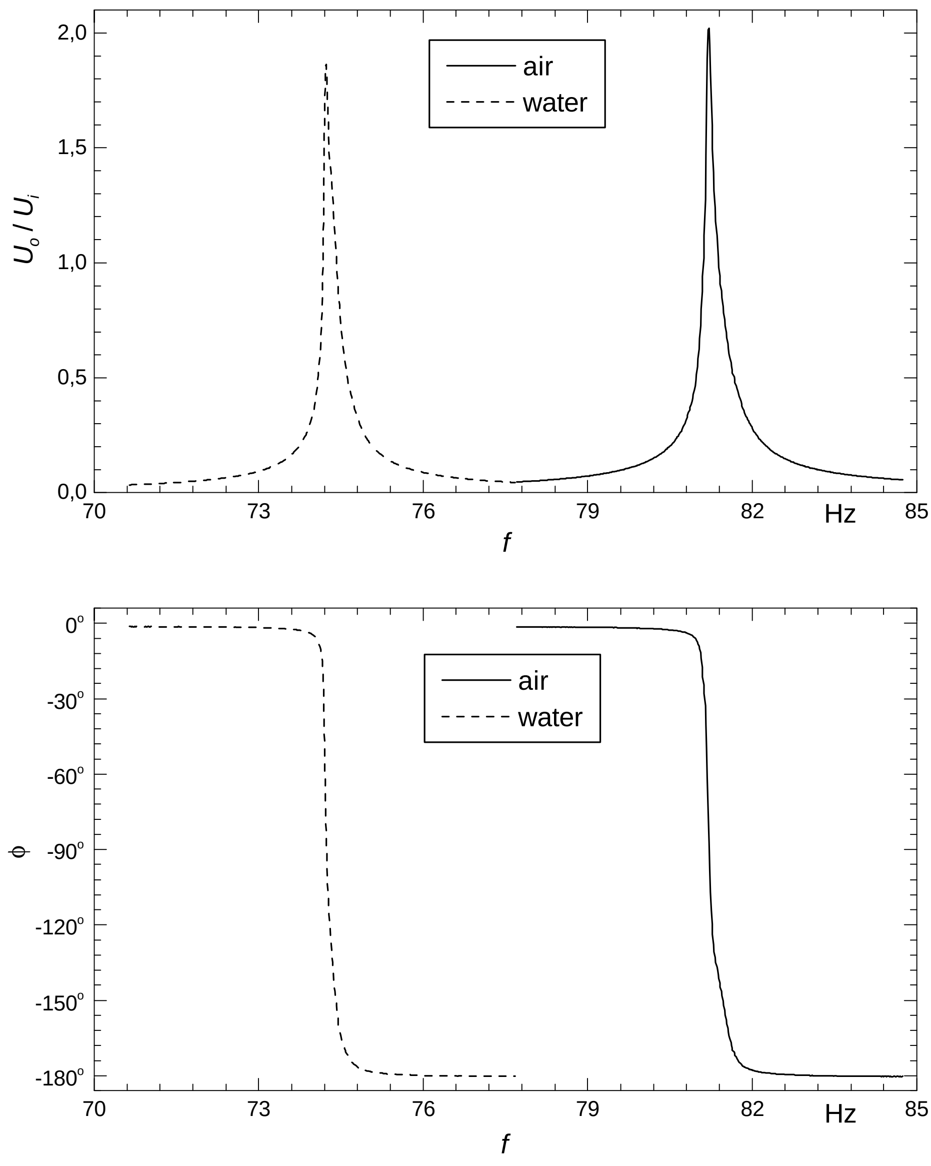

Figure 2. Amplitude and phase frequency characteristics of the measuring tube in the region of the first resonance frequency.

conscious of acceleration detection, the results match with findings in Section 2.1. The phase –90° has to be maintained to control vibration in the resonance.

The PLL controller, based on findings in Section 2.2 and programmed by LabVIEW, is schematically presented in Figure 3. The DC content U of the product $u = u_i u_o$ is computed by the DC estimator which uses the Hanning window before averaging. The value of U has the proper sign for controlling the excitation frequency to the desired resonance frequency: $U > 0$ for $f < f_n$ and $U < 0$ for $f > f_n$. With the intention of improving the controller quickness and stability, U is multiplied by

$$K = \frac{K_0}{U_o^{\ 2}}. \tag{9}$$

Therefore, the control action is theoretically of the form (see equation (7)):

$$\Delta U_f = KU = \tfrac{1}{2} K_0 \frac{U_i}{U_o} \cos(\phi). \tag{10}$$

The control-action dependence on U_i / U_o makes the frequency control quick far from the resonance (U_i/U_o is large) and stable near the resonance (U_i/U_o is small).

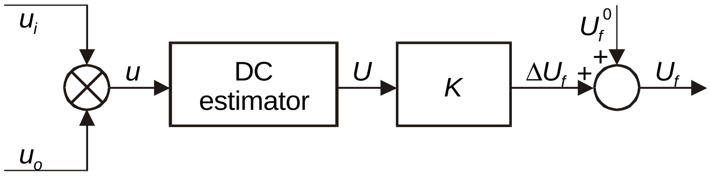

Figure 3. Block diagram of the PLL controller.

3.3 PLL control system performance

Figures 4 and 5 show the control system response to the first resonance frequency of the water-filled measuring tube for two different constants K_0 (initial frequency is about 27 Hz larger than f_n). Besides the frequency, the diagram shows the response of the normalized control signal $\Delta U = 2U/(U_i U_o)$ which depends on the phase difference ϕ ($\Delta U = \cos(\phi)$ for ideal sine waves). Owing to the considerable changes of ϕ near the resonance, ΔU gives a better insight into the control behavior.

For small enough K_0 (see, e.g., Figure 4 for $K_0 = 0{,}02$), there is a negligible overshoot, but rise time is relatively long. Larger K_0 (see, e.g., Figure 5 for $K_0 = 0{,}08$) gives a shorter rise time, but the oscillation becomes significant. If K_0 exceeds some critical value (0,2 in our case), the control system becomes unstable and the steady-state value is not attainable. It could be expected that an optimal constant K_0 for using PLL in the Coriolis meter lies at some value between 0,02 in 0,08.

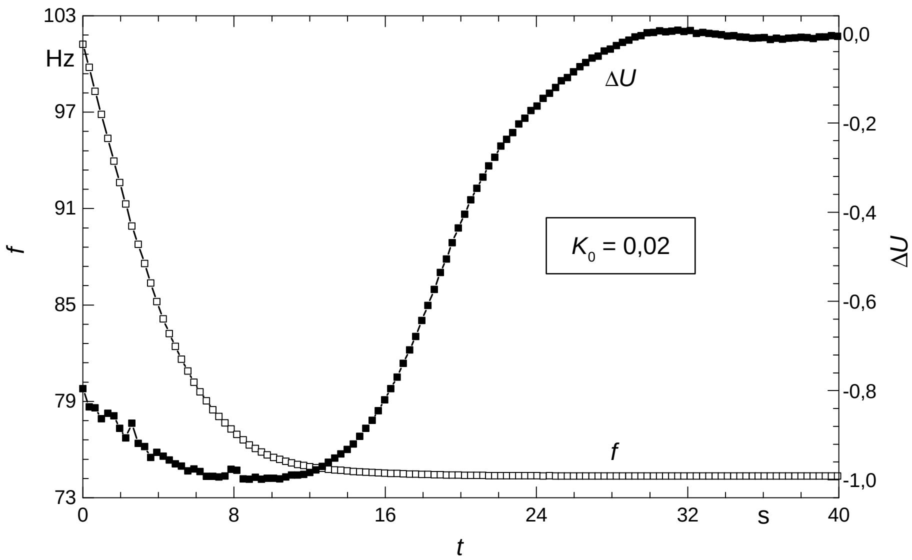

Figure 4. Response of the PLL control system to the first resonance frequency for $K_0 = 0{,}02$ (water in the tube, initial frequency ~101 Hz).

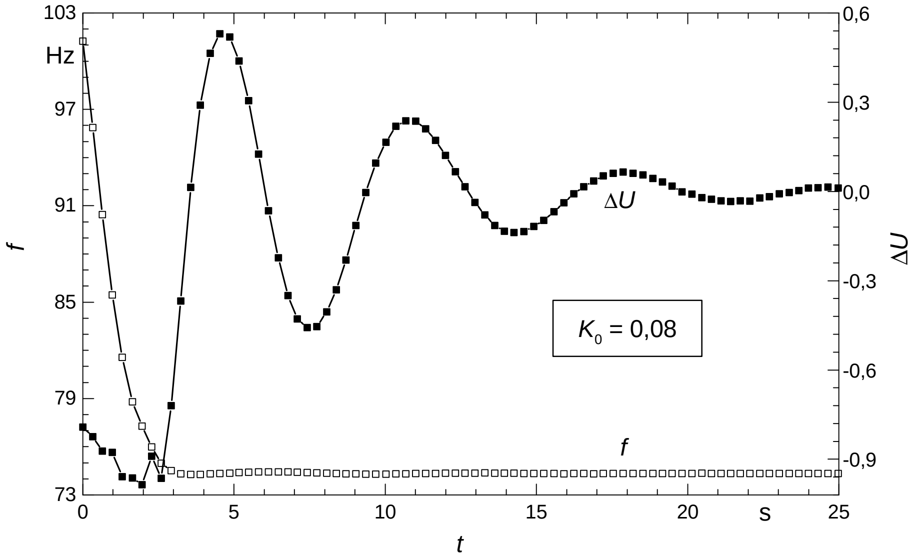

Figure 5. Response of the PLL control system to the first resonance frequency for K_0 = 0,08 (water in the tube, initial frequency ~101 Hz).

Figure 6 shows results of the next experiment. The measuring tube was emptied at moment t = 0 and the vibration frequency changed from its resonance value for the water-filled tube to the resonance value for air in the tube. The vibration amplitude has to be reduced in the first part of the response and is than set up and stabilized at the new resonance condition.

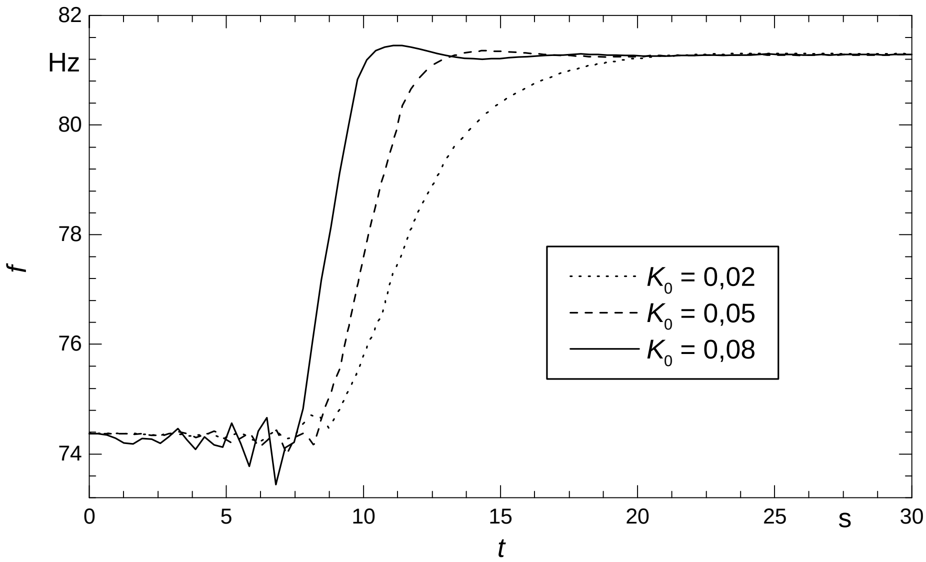

Figure 6. Response of the PLL control system from one (water in tube) to another resonance condition (air in tube) for K_0 = 0,02, 0,05 and 0,08.

4 CONCLUSION

Control of the resonance frequency of the measuring tube is one of significant demands for quality operation of the Coriolis meter. It is a prerequisite for independent measurement of fluid density and mass flowrate. The accuracy and quickness of this control affect static and dynamic meter characteristics.

In the paper, the results of using a phase-locked loop (PLL) for maintaining the tube resonance is presented. The rise time of about 2 s, as needed to reach 90 % of the desired resonance frequency, is attained. The steady-state error (standard deviation) of the frequency is about ±0,003 Hz for a stable operation. Such characteristics of the control system enable the meter to do applicable measurements [8].

Certainly, some aspects of the presented control system could be optimized. Divisioning of the control action by the vibration amplitude (equation (10)) was chosen based on the system response observation. Combining experimental results with a theoretical analysis could be appropriate for finding possible better solutions.

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