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DSP-based Electromagnetic Flowmeter with Sinusoidal Excitation

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Abstract – *A digital signal processor (DSP) based electromagnetic flowmeter is presented. Our development has been focused on the hardware design and signal processing problems, rather than improving or investigating the measurement principle itself. The system is able to measure the flowrate also in partially filled pipes, since it contains 4 pairs of electrodes and a pressure sensor for level measurement. The magnetic induction has sinusoidal waveform, and the coils are driven by class-D amplifiers minimizing the power consumption of the module. A resonator-based controller ensures the automatic and effective suppression of parasitic electrode voltages. The module measures the flowrate as function of time and the raw data can be further processed on a PC connected to the module by RS-485 bus.*

Keywords – *magnetic flowmeter, sinusoidal excitation, class-D amplifier, floating-point DSP, Hilbert transform, resonator-based controller, RS-485 bus*

I. INTRODUCTION

Electromagnetic flowmeters are widely used for flowrate measurement of fluids. Such flowmeters do not have moving parts, and do not require special tube geometry, so the measurement does not obstruct the liquid flow and the maintenance costs are minimized. The method can be used for measurement of corrosive or slurry fluids, as well. Magnetic flowmeters show high accuracy, especially high linearity. The only disadvantage is that they cannot be used for non-conductive fluids.

The measurement is based on the phenomenon that a voltage is induced in a conductor moving relative to the magnetic field. It can be expressed by the following vectorial product:

$$\mathbf{E} = \mathbf{v} \times \mathbf{B} \tag{1}$$

where $\mathbf{E}$ denotes the induced electric intensity in the conductor; $\mathbf{v}$ and $\mathbf{B}$ stand for the velocity and the magnetic induction. The magnetic field is considered to be spatially uniform. If the velocity is also uniform (which is mainly the case), furthermore $\mathbf{v}$ and $\mathbf{B}$ are perpendicular to each other, the induced voltage can be expressed in a simple way:

$$U = v\,B\,l \tag{2}$$

where l is the distance between the electrodes sensing the electric field; v and B denote the absolute value of the velocity and the magnetic induction.

Although the above principle was described at the beginning of the last century [1], its wider application became possible just by the spreading of electronic instrumentation (see e.g. [2]). The theory of the operation is well developed, the induced voltage can be calculated even for non-uniform velocity and induction distribution [3].

In magnetic flowmeters the electromagnetic coils are located outside of the pipe. The material of the tube must be nonmagnetic to allow admission of the induction into the fluid, and the inside of the tube must be non-conductive to avoid shortening the induced voltage. Most flowmeters have just one pair of electrodes, and the measurement is correct only if the tube is filled. For partially filled tubes a few pairs of electrodes are placed in the tube. More than one pair of electrodes can also be used to measure the flow profile [4].

At the end the induced voltage is proportional to the current excitation of the coils, therefore the excitation is of key importance in magnetic flowmeters. A straightforward choice is a DC excitation. However, the measured and amplified voltage has a significant offset error, and, in addition, the constant voltage can start galvanic processes. To overcome such problems, a rectangular signal can be used, and the average of the two amplitudes of the gained induced voltages can supply the measurement result. Such excitation is used e.g. in [5]. The flowrate is calculated from DC measurement results, when the settling of the current in the coils is complete. Since the coils have a large time constant, it takes a long time (typically hundreds of milliseconds) to get one sample from the flowrate. Sinusoidal excitation is a much better solution, since in steady-state of the coils' current the flowrate can be calculated at any sampling frequency. However, the sinusoidal magnetic field can induce additive voltage in the sensing circuit, which must be compensated.

The novelty of our recently developed flowmeter is that it uses sinusoidal excitation and can measure the flowrate in partially filled pipes. The measurement and the necessary compensation tasks are done by a floating point digital signal pro-

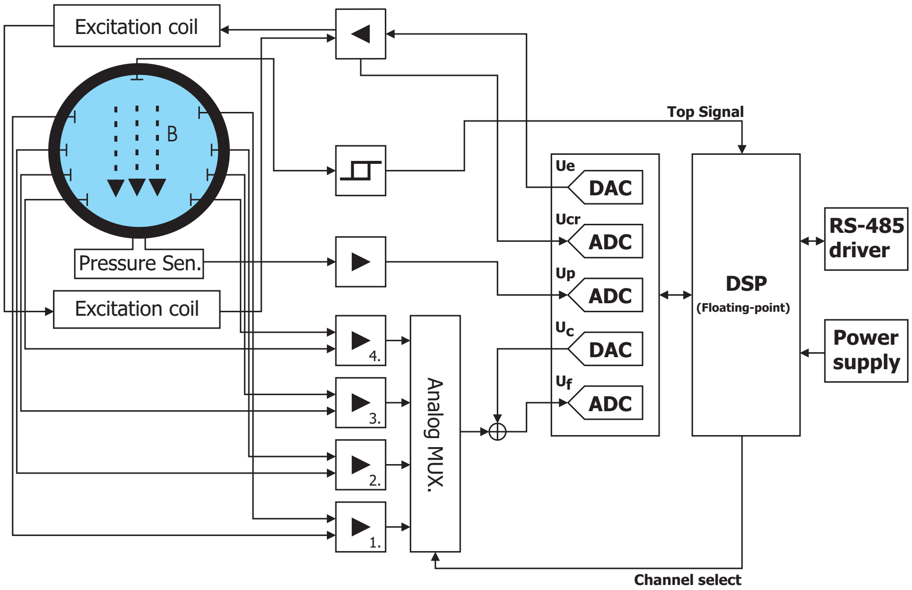

Fig. 1. Block diagram of the flowmeter

cessor (DSP). The module is connected to a PC by an RS-485 bus.

Section II. introduces the flowmeter itself, and section III. deals with signal processing details. Section IV. presents measurement results, while section V. is the conclusion.

II. SYSTEM DESCRIPTION

The block diagram of our system can be seen in Fig. 1. As the figure shows, there are 4 pairs of electrodes in the tube. The electrode on the top is built for the indication whether the tube is filled. The pressure sensor provides signal proportional to the level of the fluid for partially filled measurements. One pair of electrodes is used at a time and it is selected by an analog multiplexer.

A stereo sigma-delta codec (AD73322) serves for signal conversion. The two output signals are the excitation and the compensation voltages (U_e and U_c in the figure). The first input signal is the amplified and compensated electrode voltage (U_f), the second one is the voltage proportional to the real current in the coils (U_{cr}). There is an additional AD-converter which receives the signal from the pressure sensor.

The input signals are amplified by instrumentation amplifiers. The coils are driven by a class-D amplifier which converts the output voltage of the DA-converter into current. Class-D amplifier minimizes the dissipation at current generation. The coils' current is observed by a resistor, and its voltage is fed back into the DSP.

Signal processing and communication is provided by a floating point DSP (ADSP 21065L). Next section deals with signal processing details. The DSP board communicates with the PC via the RS-485 bus. The software running on the PC allows supervising the module: it can be tested, calibrated from the PC, the measured parameters can be seen in real-time. The flowrate as the function of the time is also plotted in real-time. After calibration, the module calculates the flowrate stand alone.

III. SIGNAL PROCESSING

The signal processing system of the measurement module can be seen in Fig. 2. The main task of the DSP is to generate sinusoidal excitation voltage for the coils and measure the level of the voltage coming from the electrodes. Theoretically the electrodes derive sinusoidal voltage proportional to the flowrate, and the voltage level measurement is simply the determination of the amplitude of the received sinusoidal waveform. In reality, however, the generated voltage is gained and transformed into current, so the magnetic induction is only nearly constant and the waveform is distorted, as well. In addition, the electrode circuit receives parasitic voltages and noise. Partially filled pipes require the measurement of the fluid level, and in certain cases the flow direction should also be measured. Therefore, many auxiliary signal processing tasks are required.

A. *Electrode voltage measurement*

The sinusoidal excitation signal $U_e(t)$ is generated using a look-up table downloaded into the DSP's memory. The physical sampling frequency is $f_s = 7320$ Hz, the frequency of the sinusoidal is approximately $f_0 = 5$ Hz. The operating frequency f_0 does not require such high sampling frequency, but the codec cannot work at lower physical sampling frequency. Hence, input signals are decimated by FIR filters. The final sampling frequency is $f'_s = 34$ Hz.

The signal which is proportional to the flowrate is the envelope of the electrode signal $U_f(t)$. In order to get its envelope, it must be demodulated. The envelope is calculated by the Hilbert transform of the signal [6] as it is depicted in Fig. 3.

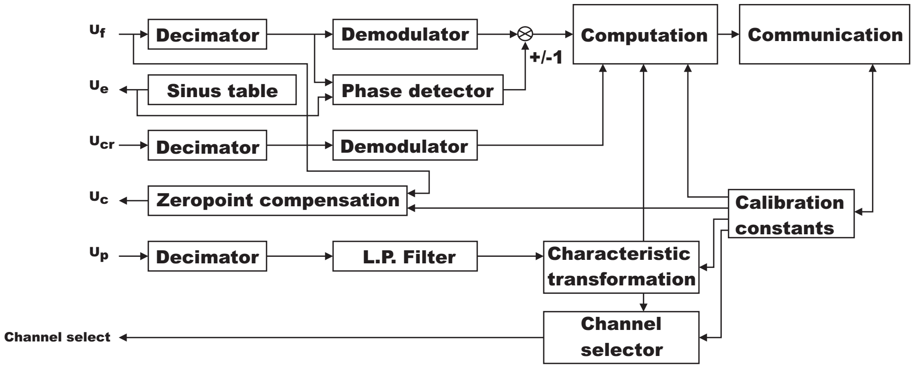

Fig. 2. On-line signal processing in the DSP

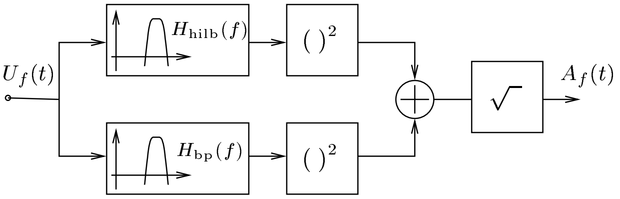

Fig. 3. Envelope calculation of the electrode signal

The envelope is the absolute value of the analytical signal as it follows:

$$A(t) = \sqrt{U_f^2(t) + H_f^2(t)} \tag{3}$$

where $H_f(t)$ is the Hilbert transform of $U_f(t)$:

$$H_f(t) = \mathcal{H}\left\{U_f(t)\right\} \tag{4}$$

In Fig. 3 the Hilbert transform is calculated by $H_{\mathrm{hilb}}(f)$, which has a bandpass magnitude response around f_0. Its reason is twofold: the theoretical Hilbert transformer cannot be realized (its frequency response has disruption at $f = 0$); on the other hand, bandpass filtering suppresses the measurement noise.

The evaluation of (3) needs also $U_f(t)$ as is. On the contrary, it is filtered by $H_{\mathrm{bp}}(f)$. Its reason is twofold again: since the group delay of $H_{\mathrm{hilb}}(f)$ is nonzero, $U_f(t)$ have to be delayed to the same extent, and the measurement noise have to be suppressed, as well. So $U_f(t)$ is also filtered by a bandpass filter having the same magnitude response as the Hilbert filter.

Both filters are linear phase finite impulse response (FIR) filters of equal number of coefficients, so their group delay is equal, as well. Linear phase filtering allows to measure flowrate waveform without any distortion.

B. *Auxiliary signal processing*

The above procedure ensures accurate and efficient measurement of the flowrate, but the direction of the flow cannot be determined. The 'phase detector' block in Fig. 2 solves this problem. The phase of $U_f(t)$ changes by 180 degrees if the flow direction changes. A sinusoidal signal synchronized to the excitation is added to the electrode voltage, and the direction can be determined by comparing the amplitude of the sum to $U_f(t)$.

The electrode voltage depends not only on the flowrate v, but on the induction B according to (2). It is assumed that the induction is proportional to the excitation current of the coils. However, it cannot be assumed that this current is proportional to the voltage $U_e(t)$, so it has to be measured. In the amplifier, the transistors are grounded by a resistor ($R = 1\ \Omega$), and its voltage is proportional to the real current. The only problem is that the this current consists of positive half-sines, according to the class-D operation. Theoretically this current is the absolute value of the real coils' current, so the voltage through the resistor $U_{cr}(t)$ is proportional to the absolute value of the coils' current. In our system this is measured similarly to $U_f(t)$, the only difference is that the filters (see Fig. 3) are tuned to $2f_0$, since the sine-absolute has a fundamental frequency of $2f_0 = 10$ Hz.

If the pipe is only partially filled, the flowrate is not proportional to the velocity v any more, the effective area of the flow is to be calculated. To do this, the liquid level has measured by a pressure sensor, and its signal is processed. The pressure signal is filtered by a lowpass filter for noise suppression. Since the filled area is not proportional to the level of the liquid, level must be transformed into area. It is done by the 'characteristic transformation' block. The actually active channels are selected by the level information.

C. *Compensation of parasitic electrode voltage*

Unfortunately, the electrode signal is nonzero, even if the flowrate is zero. The reason of this disturbance is the capacitive coupling between the cables and the induced voltage in the electrode circuit. (The latter one is different from the induced voltage due to the liquid flow.) This voltage is also sinusoidal of the same frequency as the useful signal, so it cannot be removed by filtering.

A compensating signal $U_c(t)$ is generated and added to the electrode signal. The amplitude and the phase of $U_c(t)$ is set so that it cancels the disturbance. The setting of $U_c(t)$ is done off-line, in the calibration phase. During the measurement $U_c(t)$ does not change. The compensation path can be seen in Fig. 1 or separately in Fig. 4. The compensation signal $U_c(t)$ is added to the electrode voltage as an analog signal, although it would be much more simple in the DSP. Its reason is the following.

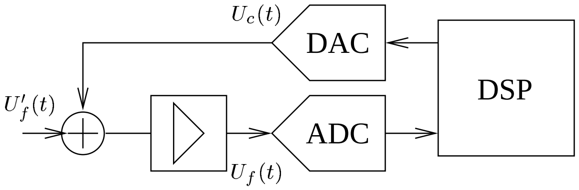

Fig. 4. Signal path for compensation of electrode disturbance

The range of the useful electrode voltage and that of the AD-converter requires high gain. If the electrode signal is burdened by disturbance, the input voltage can saturate the instrumentation amplifier. If $U_c(t)$ is added before amplifying the electrode signal, the saturation can be avoided. As a consequence, however, the compensation signal in the DSP cannot be determined precisely, since the converters and the amplifier have uncertain transfer function.

In our system the compensation signal is set automatically. The signal path in Fig. 4 is a control loop if a controller is run in the DSP. The control problem is very similar to those of periodic acoustic noise [7], [8] or distortion cancelation [9]. In these problems unwanted spectral components (acoustic noise or spectral artifacts) are canceled by generating a periodic signal (e.g., acoustic noise), the components of which have the same amplitudes as those of the signal to be canceled, but the phases are opposite. For periodic disturbances the resonator-based controller [8] ensures significant suppression. Here a resonator is implemented at the excitation frequency ($f_0 = 5$ Hz) and its output (phase and amplitude) automatically set to the proper value. In calibration phase the control loop is active, while it is inactive during the measurement.

IV. RESULTS

Our flowmeter module was tested in filled mode. The diameter of the tube was 50 mm, the excitation current was about 100 mA. The reference meter was a 'Promag 53' type magnetic flowmeter produced by Endress+Hauser [10]. Fig. 5 shows our measurement results versus the reference data. Calibration points were in the range of 0.36..74 m^3/h. This range covers the usual industrial flowrate values at such diameter. The reference points are plotted with a solid line while the test module's points are plotted by crosses. The maximum error of our module was less than 0.4% of range, including offset and non-linearity errors. Now the tests are going on in partially filled mode. The calibration is more complicated than in filled mode, since the fluid (water) with open surface swings and the flowrate in a time different at the reference and the test flowmeter.

V. CONCLUSION, FUTURE WORK

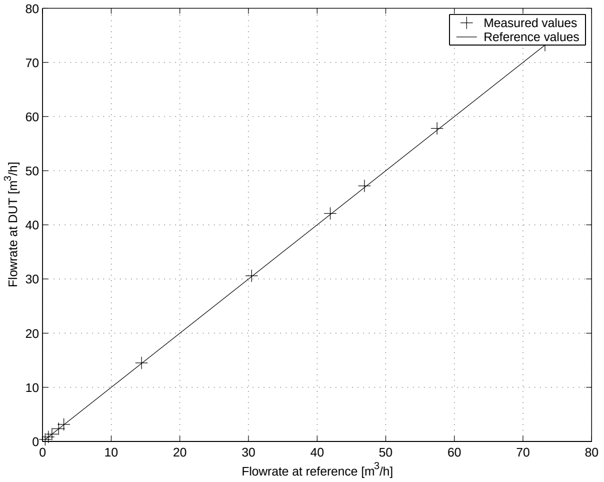

Fig. 5. Result of the calibration

The paper presented a DSP-based electromagnetic flowmeter. There are 4 pairs of electrodes and a pressure sensor for effective flowrate measurement in partially filled pipes. Although this setup is able to measure different flow profiles, our development focused on the improvement of measurement accuracy by signal processing methods. A sinusoidal excitation is used allowing fast sampling of the flowrate. The coils are driven by class-D amplifiers minimizing the power consumption of the module. The demodulation of the electrode voltage is carried out by a linear phase Hilbert transformer. Linear phase filters guarantee that the flowrate waveform is preserved. Resonator-based controller ensures the automatic and effective suppression of disturbing electrode voltages. Measurement results clearly confirmed the expectations: tests in filled mode have shown high accuracy and reliability. Our ongoing task is testing the flowmeter in partially filled mode, while new developments can aim the exploitation of the electrode pairs for flow profile measurement.

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