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A Smart Ultra-Sonic Water-Flow Meter with 180-nm CMOS Technology

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Abstract

A smart water-flow meter is proposed with ultra-sonic transducers and 180-nm standard CMOS technology. With the proposed corrections of offset and outlier removal, the flow rate can be measured accurately. A designed propagation time measurement also guarantees the accuracy of the measurements with the proposed time-zooming and precise crystal clock oscillator.

1. Introduction

In recent IoT world, every infrastructure is connected to the internet. A water-flow meter is no exception. A next-generation water-flow meter requires electrical measurement instead of current mechanics. Thus, in this paper, we propose a smart ultra-sonic water-flow meter system with integrated circuit technology.

2. Proposed Ultra-Sonic Water-Flow Meter System

Figure 1 depicts the block diagram of the proposed system. The proposed system consists of two major blocks; the first is the propagation-time (T_{meas}) measurement block and the second is a microprocessor, which transforms T_{meas} to amount of flow with the correction methods. First, T_{meas} block drives an ultra-sonic transducer (Tx) and detects the echo signal from another transducer (Rx) as shown in Fig. 2. T_{meas} block measures the period of T_{meas} from the transmission start time to the Rx zero-crossing time detected after threshold (V_{th}) exceeded [1,2]. After the T_{meas} measurement, it is corrected to T_{corr} in the microprocessor with two correction methods. *Correction1* removes the outlier which is an extraordinary value caused by unexpected babble or mechanical vibration and wait for the next measurement cycle. *Correction2* carry out the offset removal. As Fig. 2, T_{meas} has an offset because the path includes not only the distance between two reflectors (L =62 mm) but also two distances between the reflector and transducer. Here, D (=12 mm) is the diameter of the water pipe. Also, the T_{meas} contains the circuit delay and zero-crossing delay. Hence, *Correction2* calculates T_{corr} with T_{meas} and the correction table, which is created after the fabrication. The system measures two propagation times for the upstream (A to B) and downstream (B to A). Two propagation times T_{AB} and T_{BA}, which are the corrected propagation time (T_{corr}) for the upstream and downstream, respectively, are calculated by

$$T_{AB} = \frac{L}{C+V}\ ,\ T_{BA} = \frac{L}{C-V} \qquad (1)$$

, where C is the propagation speed of the ultra-sonic and V is the water flow speed. Therefore, the flow rate (Q) [m^3/h] is calculated by V [m/s] and the following equation [2].

$$Q = \frac{\pi D^2 V}{4}\ [\mathrm{m^3/s}] = 60^2 \frac{\pi D^2 L}{8}\left(\frac{1}{T_{AB}} - \frac{1}{T_{BA}}\right)\ [\mathrm{m^3/h}] \qquad (2)$$

Note that T_{AB} and T_{BA} are the corrected values by *Correction* 1 and 2. Figure 3 shows the measurement results by the proposed system and a water flow test equipment. Here, the number of the transmitted pulse of 1 MHz is changed from 30 pulses to 1 pulse. For low-power design, a pulse number reduction is essential. Thanks to the corrections, the variations of measurement are suppressed even under one shot pulse.

3. CMOS Circuit Design

Figure 4 illustrates the designed T_{meas} measurement block with a 180-nm CMOS technology and Figs. 5 and 6 give the operating sequence. Since the difference of T_{AB} and T_{BA} is only ns-order, a time-zooming technique is applied for low power operation. T_{meas} measurement block consists of four units. First, the controller unit switches upstream and downstream and transmission pulses are generated for Tx transducer. A zero-cross detect unit [3] detects the time of zero (V_{com})-crossing for the received echo signal and launches STOP signal and toggles SEL for switching Tx and Rx. To measure T_{meas}, two counters is used in the time-zooming unit and the controller unit. CNT_{Xtal} is counts N_{Xtal}, which is the number of the clock generated by the external crystal oscillator of 4 MHz from the falling edge of RST to the edge of SEL. Note that this is not overhead because the water flow meter requires a precise time to calculate the amount of water flow with time integration. On the other hand, CNT_{IntCLK} counts N_{IntCLK} and N'_{IntCLK} based on an internal fast oscillator. N_{IntCLK} is the number of the internal clock cycle during the falling edge of STOP and the edge of SEL. Although the period of > 500 MHz internal clock signal varies under PVT variation because a simple ring oscillator is used, a self-calibration is applied with N'_{IntCLK}, which is the internal clock cycle number during a period of the external crystal clock, T_{Xtal}. Here, the precise T_{meas} can be calculated by the following equation.

$$T_{meas} = (T_{Xtal} \times N_{Xtal}) - \left(T_{Xtal} \times \frac{N_{IntCLK}}{N'_{IntCLK}}\right) \qquad (3)$$

Since N'_{IntCLK} is renewed every measurement cycle, the accuracy of T_{meas} is guaranteed by the precise crystal oscillator. Figure 7 is T_{meas} measurement block layout and the fabricated chip microphotograph with a temperature sensor [4] that must be used for the calibration of C from the experimental formula [5] and Fig. 8 demonstrates a pair of T_{meas}'s for upstream (T_{ABmeas}) and downstream (T_{BAmeas}). From the serial outputs of the designed circuit, T_{ABmeas} and T_{BAmeas} are 58.932 µs and 59.280 µs, respectively. These results are approximately equal to the true value measured by an oscilloscope.

4. Conclusions

A water-flow meter with ultra-sonic transducer and 180-nm CMOS is designed. With the correction methods and time-zooming technique, it is successfully demonstrated that the flow rate is accurately measured.

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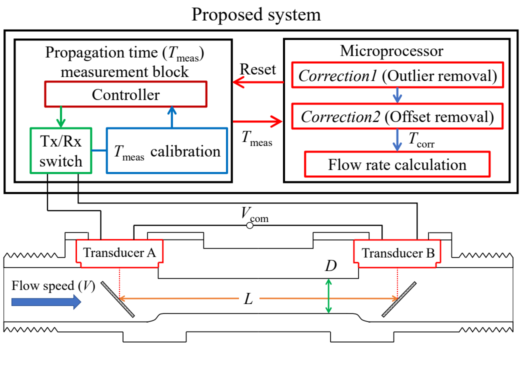

Fig. 1 Block diagram of the proposed system.

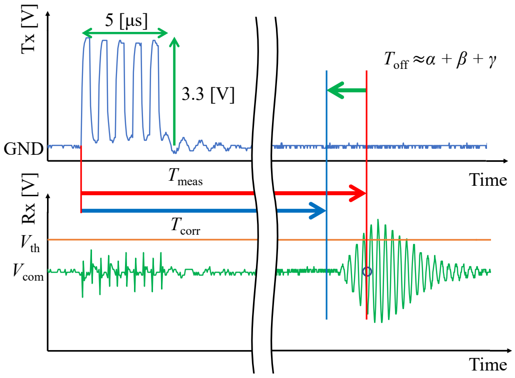

Fig. 2 Definition of T_{meas}, T_{corr} and T_{off}. The waveforms of transmitted and received echo signals are captured by oscilloscope. A discrete device and FPGA are used for this measurement. T_{off} contains the path between transducer and reflector (α), circuit delay (β) and the delay for zero-crossing (γ).

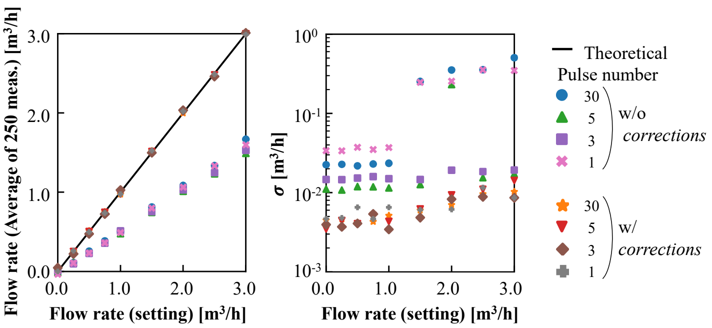

Fig. 3 Flow rate and its variation measurement results. The horizontal axis is the setting value. This measurement was carried out with flow rate test equipment. With the proposed correction methods, the standard deviation (σ) is effectively suppressed.

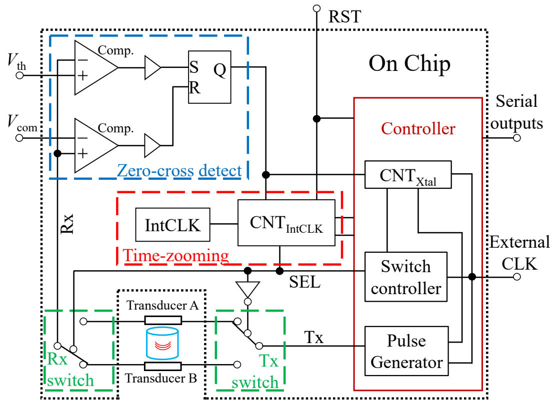

Fig. 4 Schematic of T_{meas} measurement block. This is designed with 180-nm standard CMOS technology.

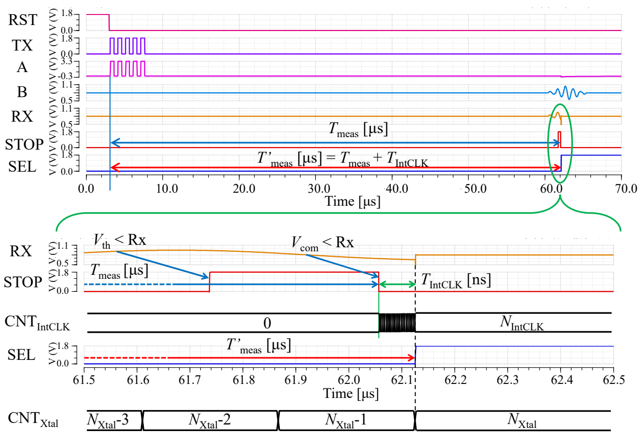

Fig. 5 Timing chart for the designed T_{meas} measurement block.

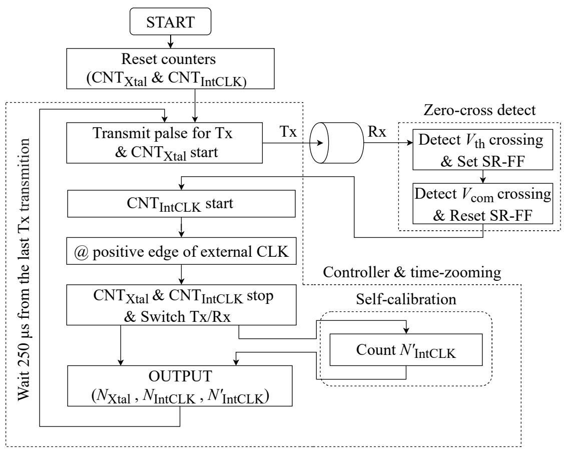

Fig. 6 Flowchart of T_{meas} measurement block operation.

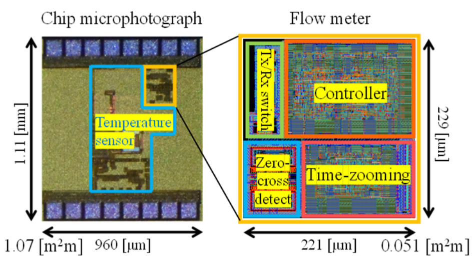

Fig. 7 Chip microphotograph and layout of the designed flowmeter.

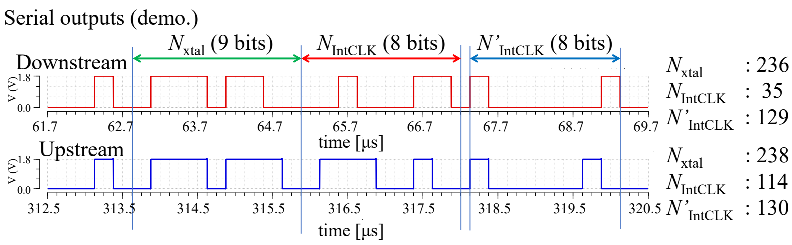

Fig. 8 Serial outputs for downstream (A to B) and upstream (B to A). With Eq. (3), T_{measAB} and T_{measBA} are 58.932 μs and 59.280 μs, respectively, due to T_{Xtal} = 250 ns (4 MHz). These are equivalent to the true value form an oscilloscope.