The Development of CPLD-Based Ultrasonic Flowmeter

I. LIE, V. TIPONUȚ, I. BOGDANOV, S. IONEL, C.D. CĂLEANU
Applied Electronics Department, Faculty of Electronics and Telecomunications
"Politehnica" University of Timisoara
V. Parvan Av, no.2, 300223 Timisoara
ROMANIA
http://www.etc.upt.ro

Abstract: - The measurement principle of the transit time difference method of the ultrasonic flowmeter is presented. The hardware structure and realization method are introduced. The software function and work mode are overviewed. In order to enhancing flowmeter's precision and stability a Xilinx CoolRunner CPLD and a Texas Instruments microcontroller from MSP430 family are applied in high precision timing, complex logical control and communication. The result is a low cost portable solution working with a 3.3V supply and operating with ultrasonic transducers at 1MHz frequency.

Key-Words: - ultrasonic flowmeter, delay line, transit-time, CPLD, ultrasonic transducer

1 Introduction

The measurement of slow rate fluid flow velocity is one of the most actual problems of modern industry. It is concerned with the wide use of such fluid flows in various technological processes of industry and when creating the systems of maintenance of microclimate, ventilation and air heating. The control of such systems demands to measure small velocity ($v \leq 0.5$m/s) of fluid motion. All wide known methods, except laser based methods, are insensitive in the low velocity region ($v \leq 0.2 \ldots 0.3$m/s) and dos not ensure the required accuracy. Laser based methods for gas flow velocity measurements are distinguished by high accuracy, but they are very expensive and are hardly applied under industrial conditions [1, 2]. Ultrasonic methods due to their simplicity and cheapness are widely applied in the fluids flow velocity measurement, but in the range of slow rate flow they are investigated insufficiently. Therefore the aim of this investigation was to enhance flowmeter's precision and stability using CPLD and MSP microprocessor for high precision timing, complex logical control and communication.

2 Measurement Principle

Ultrasonic flowmeters measure the traveling times (transit time models) or the frequency shifts (Doppler models) of ultrasonic waves in a pre-configured acoustic field that the flow is passing through to determine the flow velocity [2]. Ultrasonic flowmeters can be categorized into two types based on the installation method: clamped-on and inline. The clamped-on type is located outside of the pipe and there are no wetted parts. It can easily be installed on existing piping systems without worrying about corrosion problems. Clamped-on designs also increase the portability of the flowmeter. The inline type, on the other hand, requires fitting flanges or wafers for installation. However, it usually offers better accuracy and its calibration procedures are more straightforward.

2.1 Transit Time Ultrasonic Flowmeter

A pair (or pairs) of transducers, each having its own transmitter and receiver, are placed on the pipe wall, one (set) on the upstream and the other (set) on the downstream - Fig.1.

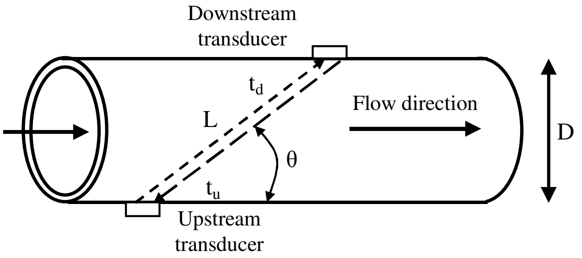

Fig.1. The transit time ultrasonic flowmeter setup

The time for acoustic waves to travel from the upstream transducer to the downstream transducer t_d is shorter than the time it requires for the same waves to travel from the downstream to the upstream t_u. The larger is the difference, the higher the flow velocity. t_d and t_u can be expressed in the following forms:

$$t_d = \frac{L}{c + v\cos\theta}; \quad t_u = \frac{L}{c - v\cos\theta} \qquad (1)$$

where c is the speed of sound in the fluid, v is the flow velocity, L is the distance between the

transducers and θ is the angle between the flow direction and the line formed by the transducers.
The difference of t_d and t_u is

$$\Delta t = t_u - t_d = \frac{L}{c - v\cdot\cos\theta} - \frac{L}{c + v\cdot\cos\theta} = \frac{2\cdot v\cdot L\cdot\cos\theta}{c^2 - v^2\cdot\cos^2\theta} = \frac{\frac{2\cdot v\cdot X}{c^2}}{1-(v/c)^2\cdot\cos^2\theta} \qquad (2)$$

where X is the projected length of the path along the pipe direction ($X = L\cos\theta$). To simplify, we assume that the flow velocity v is much smaller than the speed of sound c, that is, $v << c \Rightarrow (v/c)^2 \cong 0 << 1$

We then have $\Delta t \cong \frac{2\cdot v\cdot x}{c^2}$ or $v \cong \frac{\Delta t\cdot c^2}{2\cdot x}$ (3)

Note that the speed of sound c in the fluid is affected by many factors such as temperature and density. It is desirable to express c in terms of the transit times t_d and t_u to avoid frequent calibrations:

$$c + v\cdot\cos\theta = \frac{L}{t_d};\quad c - v\cdot\cos\theta = \frac{L}{t_u}$$

The speed of sound c becomes

$$c = \frac{1}{2}\cdot\left[L\cdot\left(\frac{1}{t_d}+\frac{1}{t_u}\right)\right] = \frac{(t_d+t_u)}{t_d\cdot t_u}\cdot\frac{L}{2}$$

The flow velocity is now only a function of the transducer layout (L, X) and the measured transit times t_u and t_d.

$$v = \frac{c^2\cdot\Delta t}{2\cdot X} = \left[\frac{(t_u+t_d)}{t_u\cdot t_d}\cdot\frac{L}{2}\right]^2\cdot\frac{\Delta t}{2\cdot X} =$$

$$\frac{L^2}{8\cdot X}\cdot\left[\frac{(t_u+t_d)}{t_u\cdot t_d}\right]^2\cdot\Delta t = \frac{L^2}{8\cdot X}\cdot\left[\frac{(t_u+t_d)^2\cdot(t_u-t_d)}{t_u^2\cdot t_d^2}\right]$$

The above formula can be further simplified by utilizing the following approximation:

$$(t_u+t_d)^2 = 4\cdot\left(\frac{t_u+t_d}{2}\right)\cdot\left(\frac{t_u+t_d}{2}\right) = 4\cdot\left(t_u-\frac{\Delta t}{2}\right)\cdot$$

$$\left(t_d+\frac{\Delta t}{2}\right) = 4\cdot\left[t_u\cdot t_d+\frac{\Delta t^2}{4}\right] \cong 4\cdot t_u\cdot t_d$$

The flow velocity can therefore be written as

$$v = \frac{L^2}{8\cdot X}\cdot\left[\frac{(t_u+t_d)^2\cdot(t_u-t_d)}{t_u^2\cdot t_d^2}\right] \cong \frac{L^2\cdot\Delta t}{2\cdot X\cdot t_u\cdot t_d} \qquad (4)$$

3 Flowmeter Implementation

The flowmeter is made up of the following parts:

- a calibrated measuring way, which contains two ultrasonic transducers and two mirrors by means of which the ultrasonic signal is transmitted between the two transducers.
- the circuit board which is supplied by a 3.3 V Li battery.

For a measuring way length of 8 cm, with a ultrasound velocity of c = 1450 m/s and a fluid velocity of v = 0,01 m/s, the measured time difference only amounts to Δt = 0.76 nanoseconds. With the transit-time method, the time measurement must be taken in hundred picoseconds in order for the smaller flow velocities to be resolved with the required exactness. The mirrors based measuring configuration maximizes the level of signal due to the fact that the propagation of the ultrasonic wave is on the flow direction.

3.1 Hardware Configuration

Regarding the electronic part, the main aim in implementing a transit time ultrasonic flowmeter was to obtain a low power, low cost solution. Following this aim was used a CPLD XC2C128 from Xilinx CoolRunner-II family, the industry's fastest low power CPLD and a Texas Instruments microcontroller MSP430F449.

The MSP430 microcontrollers incorporates a 16-bit RISC CPU, peripherals, and a flexible clock system that interconnects in a ultralow-power architecture which extends battery life The clock system is designed specifically for battery-powered applications. A low-frequency auxiliary clock (ACLK) is driven directly from a common 32-kHz watch crystal. The ACLK can be used for a background real-time clock self wake-up function. An integrated high-speed digitally controlled oscillator can source the master clock (MCLK) used by the CPU and high-speed peripherals [5].

This combination was chosen in order to accomplish the requirements for high frequency and low power. The CPLD will host the hardware support for the tasks which require high frequency and time resolution:

- Generation of the emitted burst for the 1MHz transducer's
- Measurement of the transit time.

The MSP430F449 microcontroller must solve the following:

- driving of the measurement cycle
- different parameters calculations based on the transit-time measurements results
- user interface through LCD display and keyboard
- Radio and RFID communications management

- calibration of the CPLD free running oscillator using the microcontroller clock generated with external quartz

The hardware diagram is as follows in Fig.1:

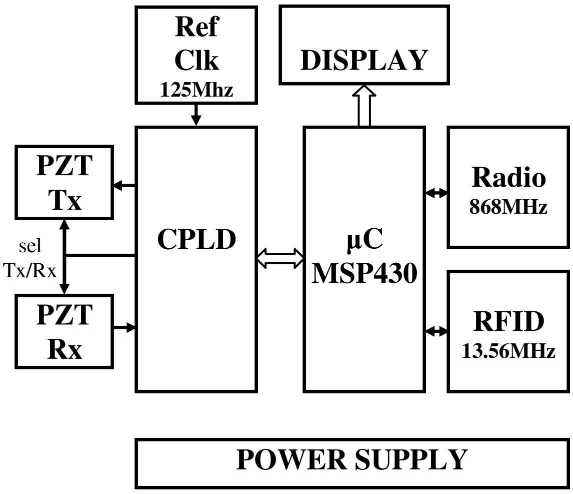

Fig.3. The hardware configuration

A specific interface with ultrasonic transducers is provided through the *PZT Tx* transmitter driver and the zero crossing detector based receiver stage *PZT Rx*. The data transfer to external world is realized with a 868MHz Radio module and a RFID 13.56MHz module. The reference clock is supplied by a 125MHz crystal oscillator.

3.2 CPLD-Hosted Arhitecture

In order to fulfill the tasks which require high frequency and time resolution was designed a CPLD based structure consisting of following blocks: Fire Pulse Generator, Transit Time Unit (TTU), Paralel to Serial Convertor (PSC), and Logic Control – Fig.4.

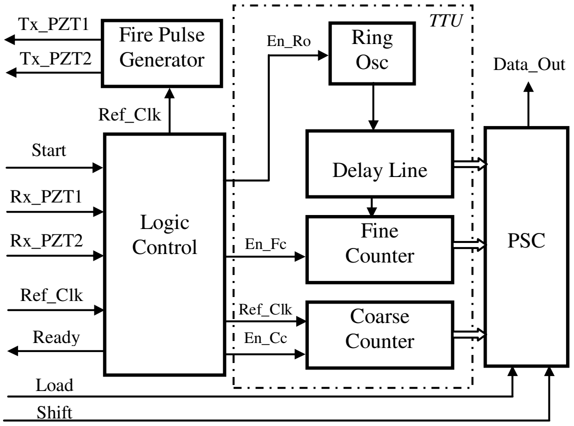

Fig.4. CPLD – based architecture

The *fire-pulse generator* generates a sequence of pulses which is programmable in frequency and number of pulses. The Ref Clk oscillator frequency (125MHz) divided by a factor selected is used as the basic frequency. A pulses counter shape the emitted burst for each START.

The digital *Transit Time Unit (TTU)* use internal propagation delays of signals through gates to measure time intervals with very high precision. It is composed of a high speed section and a coarse counter. The high speed unit contains the ring oscillator, a fine counter and the delay line. The high speed unit of the TDC does not measure the whole time interval but only time intervals from STOP to the next rising edge of the reference clock. This measured value is done by the content of fine counter and by the tape of delay line at which the rising edge appear. The internal START and the Fire Pulse Generator are synchronized with the rising edge of the external reference clock. In between START and STOP the coarse counter counts the number of periods of the reference clock (8 nS).

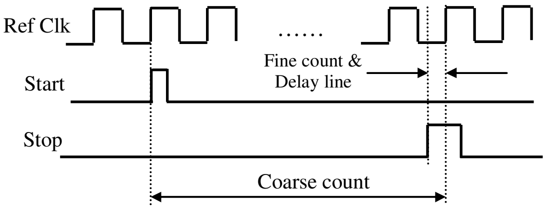

Fig.5. TTU operating diagram

The Delay Line – is based on Xilinx CoolRunner Timing Model [7]. We used combinatorial propagation delay T_{PD} with a single P-term and multiple P-terms. CoolRunner-II T_{PD} is separated into two individual timing parameters, T_{PD1} and T_{PD2}. T_{PD1} is calculated based on a single P-term path in the PLA structure. T_{PD2} is calculated based on more than one P-term existing in the data path. The CoolRunner-II architecture provides a fast path T_{PD} with a single product term logic equation. With a single P-term logic equation, the OR term can be bypassed, and the P-term is fed directly in the macrocell.

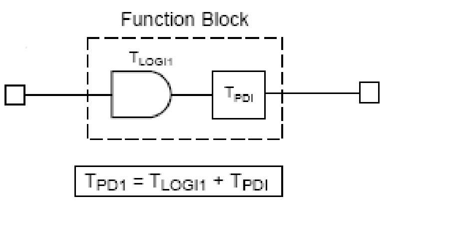

Fig.6. TPD1 with a Single Product Term

At function block level T_{PD1} is calculated as the sum of the single P-term logic time delay (T_{LOGI1}) and the bypass path of the macrocell (T_{PDI}).

With the addition of more product terms the time delay from input A is slightly altered with T_{PD2}, which accounts for additional product terms.

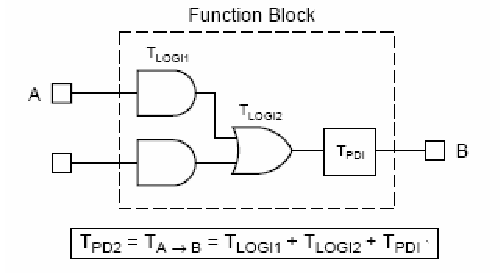

Fig.7. TPD2 with 2 Product Terms

T_{PD2} is calculated by adding to T_{PD1} the multiple P-term delay adder T_{LOGI2} which for XC2C128-6 is 300 picoseconds. This is the reachable tape resolution of the delay line built with a CoolRunner CPLD. The number of P-terms that must be inserted in the structure of the delay line results by dividing the period of fine counter to delay resolution. For download the measurement result the *PSC* build a serial string of bits which can be clocked out by a controller signal. The PSC consist of 2-input multiplexers and D-type flip-flops. The *Logic Control* implements the interface with the MSP and generates the command signals for CPLD blocks.

The CPLD section was tested and synthesized into a XC2C128 device using Integrated Software Environment ISE WebPACK. Table 1 summarizes the device utilization.

Table 1 Device utilization for XC2C128

Macrocells used	127/128 (100%)
Product Terms used	173/448 (39%)
Registers used	75/128 (59%)
Pins used	17/80 (22%)
Function Block Inputs Used	163/320 (51%)

The measurement result downloaded to MSP consists of a string of bits which must be separated into three sections representing:

- Cc – the number counted by the Coarse counter
- Fc - the number counted by the Fine counter
- Ds – the delay line's status

A dedicated routine running on MSP is used to calculate the transit time (T_T) with the following relation:

$$T_T = Cc \cdot T_{RClK} - Fc \cdot T_{Rosc} - N_{Tape} \cdot T_{Logi2}$$

- T_{RClk} is the reference clock period
- T_{ROsc} is the ring oscillator period
- N_{Tape} is the tape at which the rising edge appears

The result of implementation is a portable solution with a minimum number of discrete components, working with a 3V supply and operating with ultrasonic transducers at 1MHz frequency.

4 Conclusion

It is presented the measurement principles of the travel time difference method of the ultrasonic flowmeter. A common problem of flow meters is to obtain good accuracy when measure low flow velocities. The design method of the high precision measurement is analyzed. The hardware principles, the software function and design mode are described. The high - performance complex programmable logical device CPLD instead of normal discrete devices is utilized to realize high precision timer and complex logical control so as to develop the stability and reliability of the system It achieves on the transit time range control and reliability analysis through software and hardware.

Based on the above principle, a prototype model, using low power components (a CPLD and a MSP430 microcontroller) was then built and tested. It was found that the system operated as expected. The result confirms that the ultrasonic flowmeter has achieved the design objective. It was also noted that further improvement could be made by controlling the frequency of emitted signal when the temperature of the environment is changed. Work in progress includes further refinements to hardware and software for improving the accuracy and reliability of measurement.

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