A Low Cost CPLD-Based Ultrasonic Flowmeter

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Abstract: - Based on the characteristics of ultrasonic non-contact measurement and the combination of temperature measurement with ultrasonic flow measurement, a flowmeter was designed. The structure of the ultrasonic flowmeter and the circuits of temperature and flow measurement were described. The design method of the meter with low power consumption was given by selecting MSP430 single chip microcomputer. In order to enhance flowmeter's precision and stability a Xilinx CoolRunner CPLD was applied in high precision timing. 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 in-line 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.

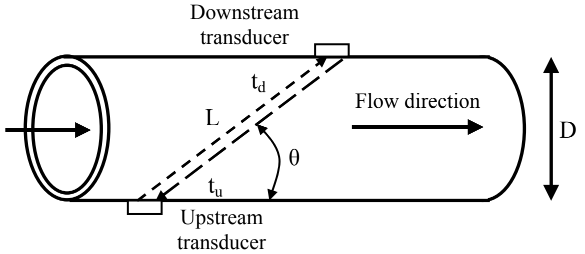

Fig.1. The transit time ultrasonic flowmeter setup

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:

$$t_d = \frac{L}{c + v\cos\theta}; \quad t_u = \frac{L}{c - v\cos\theta}, \tag{1}$$

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 time's 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

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

It should be mentioned that the actual implementation of the above principle is much more complex than what it looks like. The challenges include:

- how to accurately measure the transit-time,
- how to reduce the discrepancy between the upstream and the downstream signal paths,
- how to treat the short-circuit wave (or pipe-wall born wave),
- how to reduce installation-induced errors, how to make the installation easy and reliable,
- for high temperature application, how to design a high temperature transducer and how to compensate the temperature influence,
- how to provide a user-friendly operation interface, how to provide more functionalities,
- and, of course, how to reduce the cost.

A low-cost, high accuracy, reliable and easy to use ultrasonic flowmeter is always the pursuing goal of all ultrasonic flowmeter designers.

3 Flowmeter Implementation

The flowmeter is made up of the following parts:

- a calibrated measuring way, which contains two ultrasonic transducers and two ultrasound reflector, by means of which the ultrasonic signal is transmitted between the two transducers – figure 2 ;
- a temperature sensor for offset compensation and heating evaluation in heat-metering arrangements;
- a circuit board supplied by a 3.3 V 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 45^0 reflector's based measuring configuration maximizes the level of signal due to the fact that the propagation of the ultrasonic wave is on the flow direction.

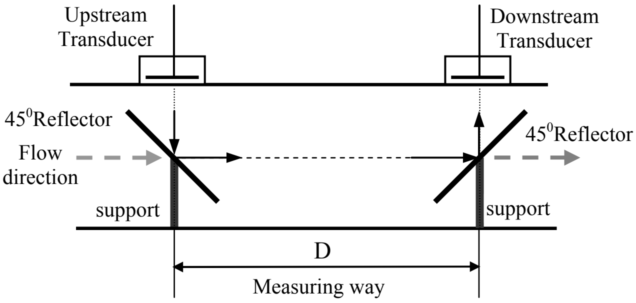

Fig.2. The measuring configuration setup

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 ultra low-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. The MSP430x4xx family contains also a high-performance analog, ideal for precision measurement, including converters, comparators and comparator-gated timers for measuring resistive elements. [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
- timing the temperature measurement sequence
- different parameters calculations based on the transit-time value received from CPLD and temperature 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
- flow rate calculation as a frequency output

The hardware diagram is as follows in Fig.3:

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.

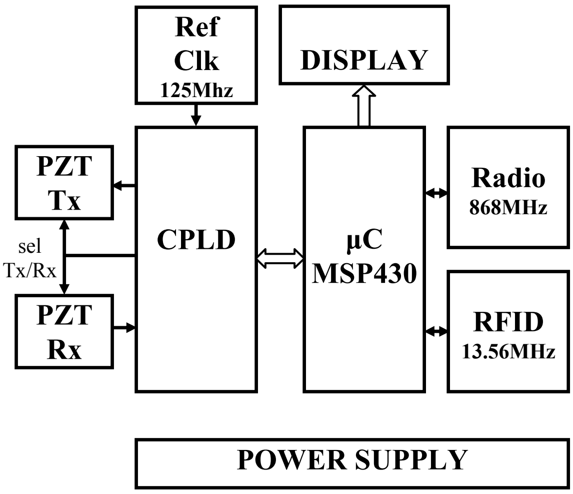

Fig.3. The hardware configuration

3.2 Temperature Measurement

The MSP430 Comparator can be optimized to precisely measure resistive elements using single slope analog-to-digital conversion. For temperature measurement, this can be converted into digital data using a thermistor, by comparing the thermistor's capacitor discharge time to that of a reference resistor as shown in Fig. 4. A reference resistor Rref is compared to sensor value Rmeas.

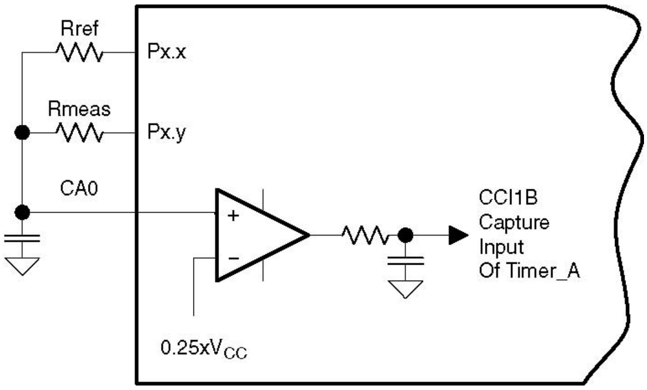

Fig.4. Temperature measurement setup

The MSP430 resources used to calculate the temperature sensed by Rmeas are:

- Two digital I/O pins to charge and discharge the capacitor, the comparator and a timer operating in Capture Mode activated by the comparator's edge. Each I/O is set to output high (VCC) to charge capacitor, is reset to discharge and is switched to high-impedance input when not in use.

- One output charges and discharges the capacitor via Rref, the other output discharges capacitor via Rmeas.

- The comparator's + terminal is connected to the positive terminal of the capacitor and the – terminal is connected to a reference level, 0.25 x VCC.

- The comparator output is used to gate Timer, which capture the capacitor discharge time.

The thermistor measurement is based on a ratio metric conversion principle. The ratio of two capacitor discharge times is calculated as shown in Fig.5. The V_{CC} voltage and the capacitor value should remain constant during the conversion, but are not critical since they cancel in the ratio:

$$\frac{N_{meas}}{N_{ref}} = \frac{-R_{meas} * C * \ln\frac{V_{ref}}{V_{CC}}}{-R_{ref} * C * \ln\frac{V_{ref}}{V_{CC}}} \qquad R_{meas} = R_{ref} * \frac{N_{meas}}{N_{ref}}$$

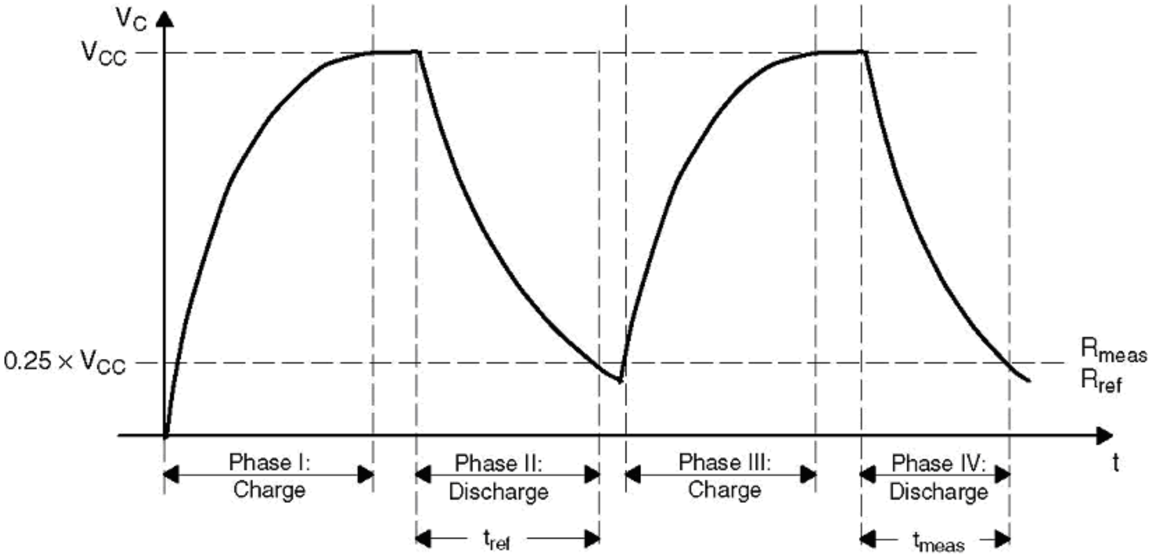

Fig.4. Timing for temperature measurement

3.3 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.6.

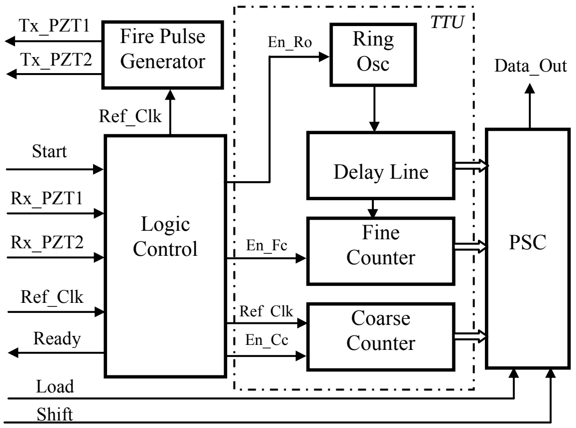

Fig.6. CPLD – based architecture

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).

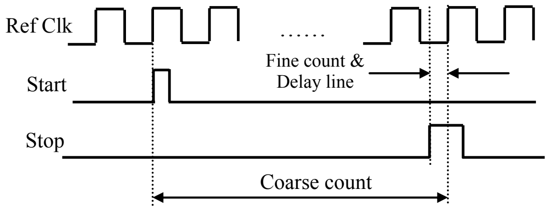

Fig.7. TTU operating diagram

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.

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}).

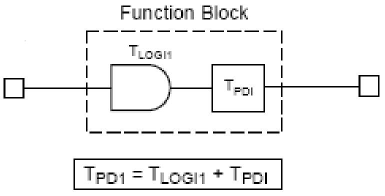

Fig.8. TPD1 with a Single Product Term

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.

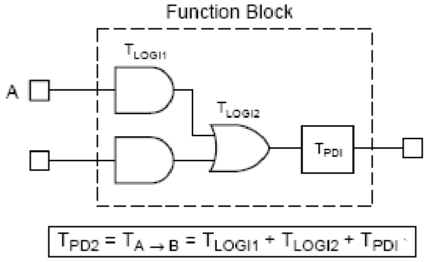

Fig.9. TPD2 with 2 Product Terms

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.

A special function of the logic block is to set time-based masking windows for raising edge on Stop input when no events are accepted. The masking refers to the start event and has an accuracy of 8 ns. Because the measuring way length is known this windowing feature allows canceling the effect of short-circuit wave and/or pipe-wall born wave.

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 position of the tape at which the rising edge appears

Based on the transit time value and measuring way parameters another routine synthesize a pulsed signal output with the frequency proportional with the measured flow value.

Finally the solution was a portable, low cost implementation with a minimum number of discrete components, working with a 3V supply and operating with ultrasonic transducers at 1MHz frequency. For mass production the minimal microprocessor architecture and the high speed section hosted in CPLD may be integrated on the same chip in a dedicated circuit.

4 Experimental Results

The design was tested especially for low values of flow between 10 l/h and 200 l/h at different temperatures from ambient – 23 ^{o}C to 70 ^{o}C. For each flow value a number of 100 pairs of measurements upstream and downstream were averaged to increase the precision. The flow range was swept from small to great values and back.

The results presented in fig. 10 and separated in fig. 11 a-d, show a temperature dependent offset.

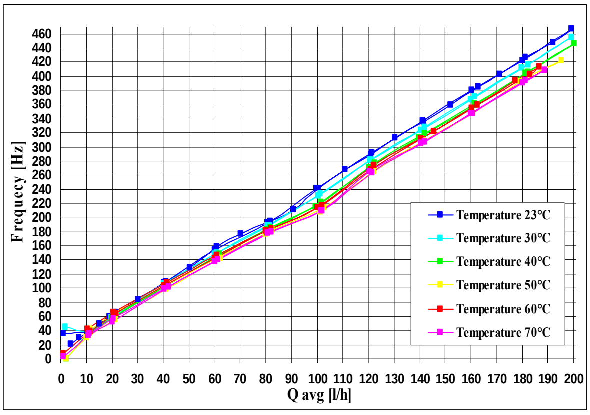

Fig.10. The dependence output frequency – flow

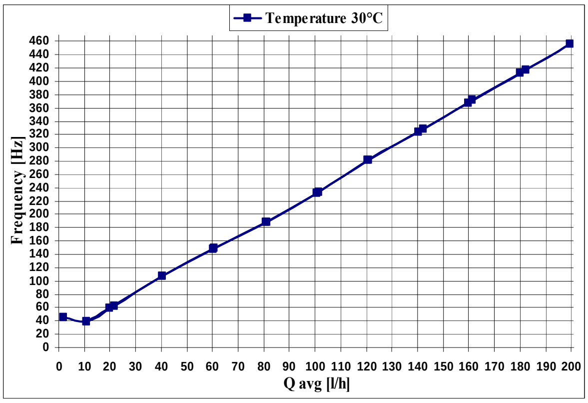

Fig.11-a. The dependence frequency – flow at 30°C

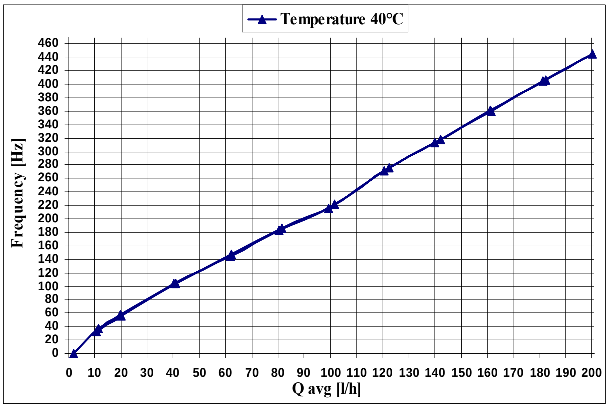

Fig.11-b. The dependence frequency – flow at 40°C

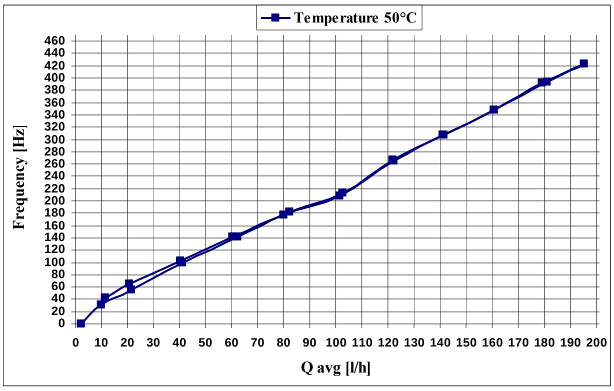

Fig. 11-c. The dependence frequency – flow at 50°C

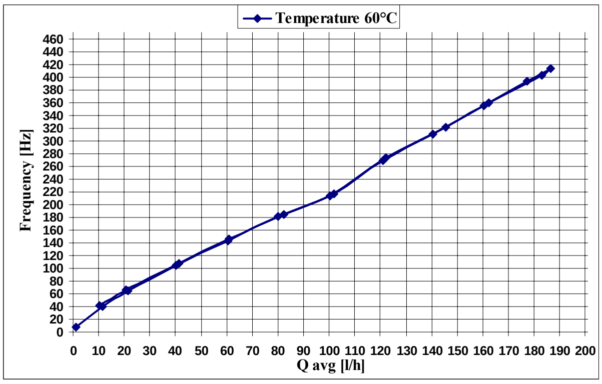

Fig. 11-d. The dependence frequency – flow at 60°C

Between the causes of offset appearance are the temperature dependence of sound propagation and the dilatation of measurement path.

The compensation was done using a look-up table with a number of predetermined values for different temperatures. Following o linear compensation, a range of errors between +-10 % was obtained for values of flow greater than 1 l/minut. The flow dependence of error is presented in figures 12a-d. The diagrams for 40^{0}C, 50^{0}C and 60^{0}C presents an uncompensated version obtained for offset values for ambient temperature (28^{0}C) followed by a compensated version. The last diagrams include the temperature dependent values in each case.

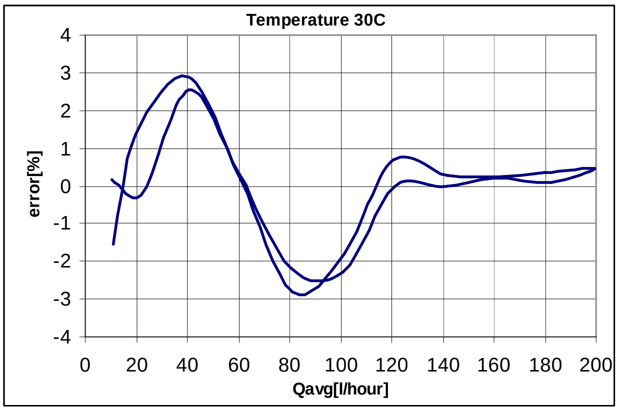

Fig.12-a. Measurement error at 30°C

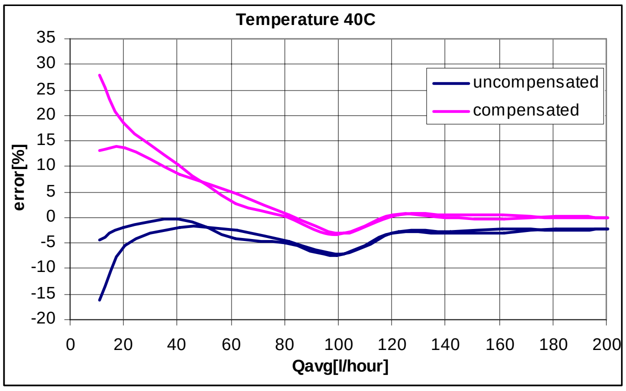

Fig.12-b. Measurement error at 40°C

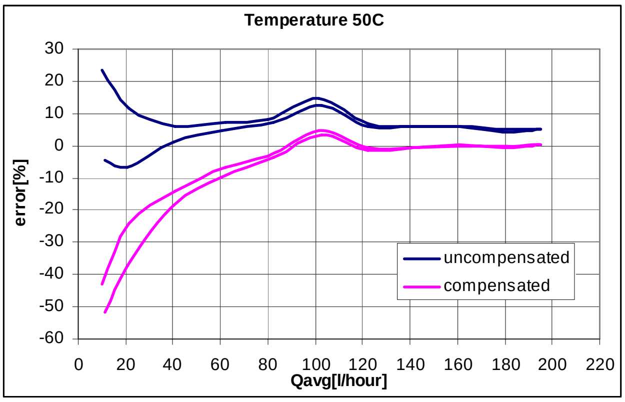

Fig.12-c. Measurement error at 50°C

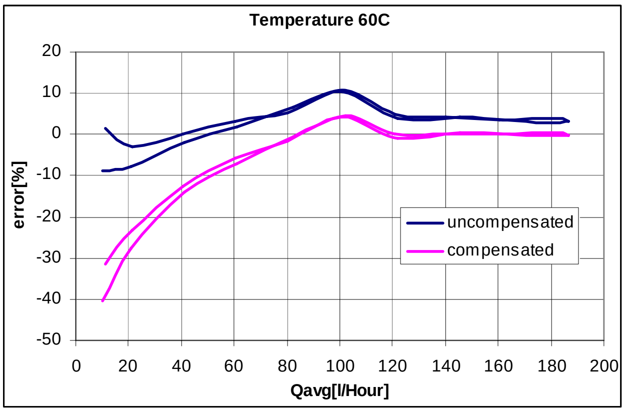

Fig.12-d. Measurement error at 60°C

5 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 functions 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 especially at low values of flow. The result confirms that the ultrasonic flowmeter has achieved the design objective. Further refinements to hardware and software for improving the accuracy and reliability of measurement are still possible. The design is suitable in prototyping stage for checking measurement algorithms. For mass production the minimal microprocessor architecture and the high speed section hosted in CPLD may be interconnected on the same chip in a dedicated integrated circuit.

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