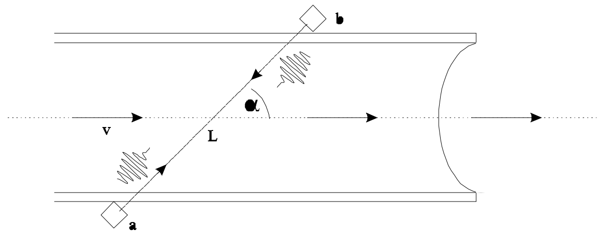
Ultrasonic Flowmetering with TDCs

Flow measurement is one of the most important functions in modern process control, wether in the chemical and petrochemical industries or in food and pharmaceutical industries. Due to their advantages the use of non-invasive flowmetering technologies increased strongly over the years. There are no mechanically moved parts, that are sensitive to dirt and corrosion. They reduce the maintenance costs and increase the life time of equipment considerably. The popularity and use of ultrasonic and electromagnetic flowmeters have steadily increased. The ultrasonic method has the advantage, that also fluids without self-conductivity can be measured. The current consumption is much less than for electromagnetic flowmeters.

There are three principle methods to realize ultrasonic flowmeters:



- direct time-of-flight measurement: the transit time of an acoustic pulse along a known path is altered by the fluid velocity. By accurately measuring the transit times of signals sent in both directions, the average velocity can be calculated.

- „Sing-Around"-type: In a closed loop a signal travels partly as electrical, partly as acoustic signal and passes several times the fluid of interest. The acoustic wave is under the influence of the fluid for an arbitrarily long time.

- Doppler-type: acoustic signals of known frequency are transmitted, reflected from particels in the fluid and picked up. The received signals show a frequency shift proportional to the velocity of the particles moving with the fluid.

Flowmeters using the time-of-flight method compute the average axial velocity unlike doppler-type flowmeters. The measurent time is much smaller than for "sing-arround"-type flowmeters, so that the conditions during measurement can be regarded as constant.

The main problem with transit-time flowmeters is to measure the quite long time-of-flight of the acoustic signal with a sufficiently high resolution. For large diameters the time-of-flight can be up to 50ms. Regarding small flow values the difference in time-of-flight for upstream and downstream measurement is so small however, that a resolution of less than 1ns is necessary to achieve an acceptable precission.

This task can be solved most elegantly with single-chip time-to-digital-converters (TDC's).

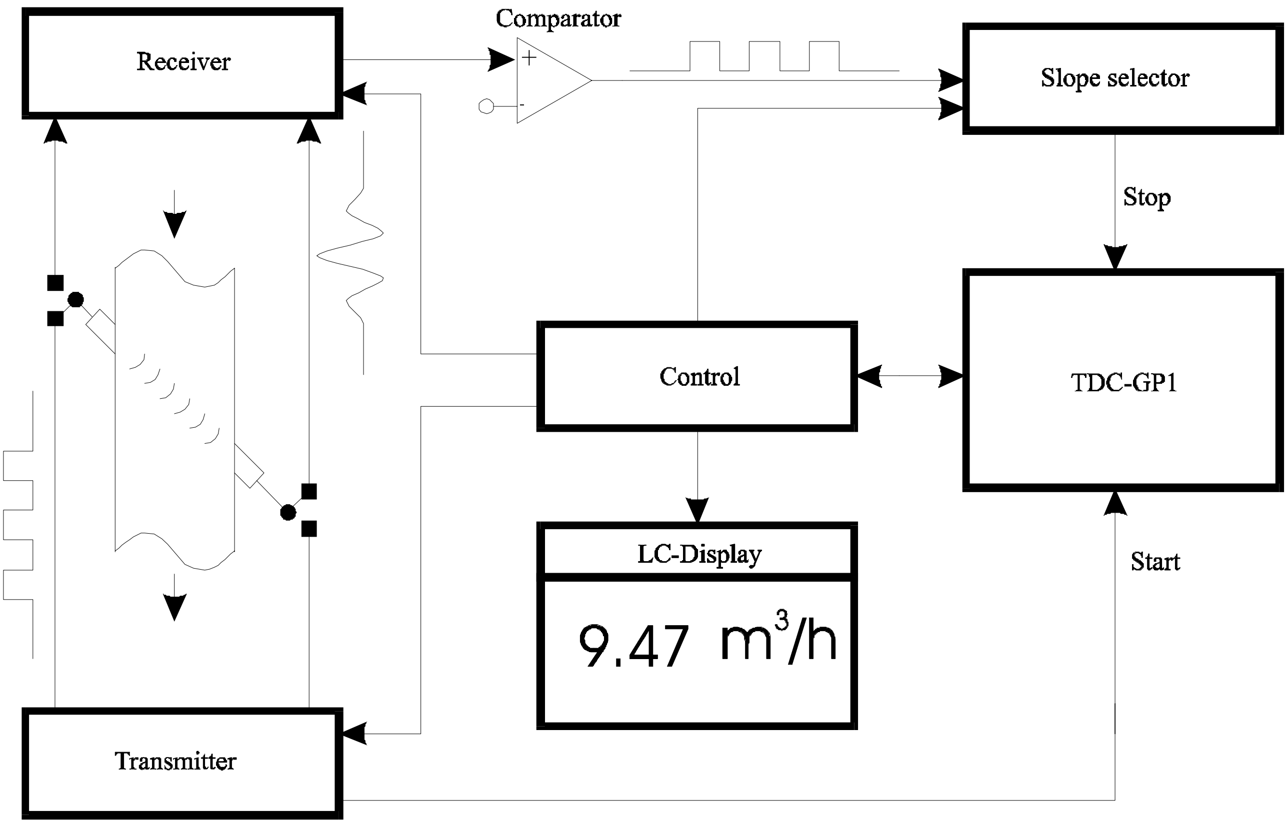
Two examples for illustration:

For a given average fluid velocity v, a measurement path L and a sound veocity C_0 in the fluid, an acoustic signal needs the time t_{ab} for the upstream path:

$$t_{ab} = \frac{L}{C_0 + v \cdot \cos\alpha}$$

For the downstream path the time is:

$$t_{ba} = \frac{L}{C_0 - v \cdot \cos\alpha}$$



The time difference caused by the fluid is therefore:

$$\Delta t = t_{ba} - t_{ab} = \frac{2 \cdot L \cdot v \cdot \cos\alpha}{C_0^2 - v^2 \cdot \cos^2\alpha} \approx \frac{2 \cdot L \cdot \cos\alpha}{C_0^2} \cdot v$$

Example 1:

In a pipe of 100mm diameter a water based solution is flowing with **70 l/min**. With an angle of 45° the following values are given:

v = 0.1485 m/s

L = 0.1414 m

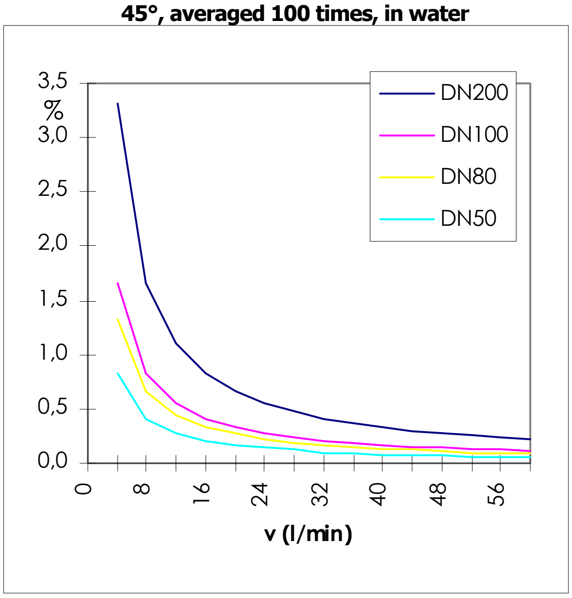
C_0 = 1500 m/s

Δt $\approx$ 13.2 ns

Using the TDC-GP1 with it's 130ps „Single-Shot"-resolution this time difference can be measured with a resolution better than **1%**.

The TDC-GP1 has very good statistical properties. An averaging over several measurements is recommend, if no high measurement rate is needed. The resolution of the averaged value is decreased with the squareroot of the averaging rate. Taking example 1 together with an averaging over 100 measurements it would be possible to measure even a flow of **7 l/min** with a accuracy of **1%**. The transit time of the acoustic signal in this example would be less than 100µs. Adding the times that are necessary for the measurement in both directions, including the time for signal preparation in the electronics, the total time for a single measuremnt will take less than 1ms. With an averaging rate of 100 the measurement rate still would be 10 measurements per second.

Calculated resolution in % with TDC-GP1 45°, averaged 100 times, in water



Example 2:

In a pipe of 20mm diameter a water based fluid is flowing with **5l/min**. The following values are given (α=45°):

v = 0.2652 m/s

L = 0.0283 m

C_0 = 1500 m/s

Δt $\approx$ 4.7 ns

This time difference can be measured with the TDC-GP1 (130ps „Single-Shot"-resolution) to a precision of **2.7%**.

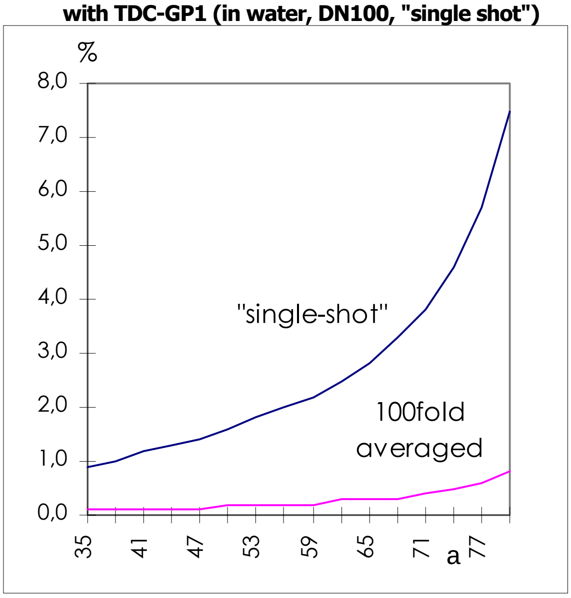
Again averaging is recommended. Averaging over 500 single measurements would increase the precision by a factor of √500 = 22.36. Regarding example 2 and taking in account an averaging rate of 500 it would be possible to measure a flow of **0.5 l/min** with a precision of **1.2%**. The transit time for the acoustic signal in example 2 is less than 20µs. Adding the times that are necessary for the measurement in both directions including the time for signal preparation in the electronics, the total time for a single measuremnt will take not more than 100µs. The measurement rate still would be 20 measurements per second

For small pipes the time difference Δt decreases linearly with the diameter. In the same way the precision of the single measurement is reduced. Investing the time, that is won from the smaller transit time, into a higher averaging rate, the precision of the flow measurement can almost be kept the same with smaller diameters.

As the time for a single measurement is very small, changes in temperature or pressure can be neglected.

An increase in acoustic path angle will give a worse precision. This too can be compensated by a higher averaging rate. A reduction in the lenght of the system can be achieved without a loss in quality of measurement.

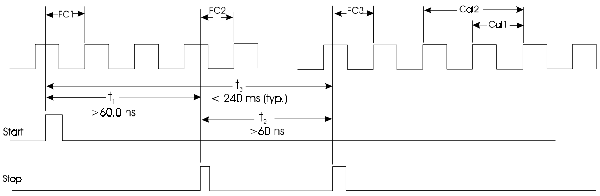
Calculated resolution (in %) against angle (degree) with TDC-GP1 (in water, DN100, "single shot")



The TDC-GP1 is a very general purpose circuit, that offers many measurement modes and programmable features. The next section will deal with the mode that is of interest for ultrasonic flowmetering.

Measurement range 2, High Resolution

In this mode the TDC-GP1 is working with a predivider. There are one start input and one stop input available.



$$time = period*(CC + \frac{FC1-FC2}{Cal2-Cal1})$$

CC = value of the precounter

The minimum measurement time is given as two cycles of the reference clock. The maximum measurement time is given as 2^{16} times the cycle of the refence clock and can reach 200ms.

The following list of numerical values refers to TDC-GP1 in combination with a 1MHz reference clock, and water as fluid. For reference clock a stantdard quartz oscillator can be used.

Measurement range:	**3µs - 65ms**
Acoustic path:	**5mm - 97m**
Resolution:	**130ps**
Standarddeviation:	**110ps**
distance passed by the acoutic signal in 130ps:	**0.2µm**

What has to be regarded?

- The pulse width of start and stop must be more than 2.5ns.

- The first stop will be accepted at the earliest 2 periods of reference clock after the start.

- To measure two stops following each other, the time difference between them has to be more than 2 reference clock periods + 3ns.

- The GP1 has to be calibrated. To do this, the autocalibration function of the TDC-GP1 can be used. After each measurement the values are automatically calibrated. As an alternative the TDC-GP1 can be calibrated independently from the measurement in a separate run.

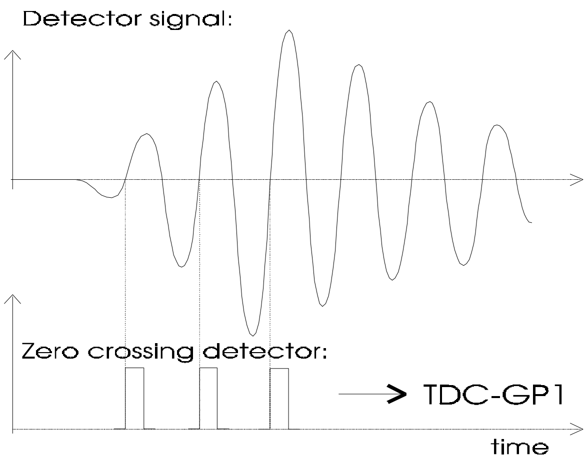
- if averaging is done, it has to be respected, that the clock for the acoustic transmitter and the reference clock for the TDC-GP1 are not in a fixed phase relationship. Otherwise the good statistical properties of the TDC-GP1 are lost.

Which are the advantages of the GP1 in this application?

- In the example shown the TDC-GP1 has a dynamic range of 29 bit. This is enough for direct measurement of the transist time in pipes with largest diameters.

- There is a pin to disable the stop-input of the TDC-GP1. This allows to select the optimum part of the received wave package. The detection of the zero crossing can be of much higher precision.

- In this mode the TDC-GP1 can measure directly 3 stops according to one start signal. This offers the opportunity to average over 3 values with only a small increase in measurement time. The time between succeeding stop-signals has to be more than 2 reference clock periods + 3ns. In the example given this means, that the frequency of the acoustic signal has to be less than <480KHz. Otherwise on has to ommit some oscillations.



- In spite of it's high resolution the TDC- GP1 has no need for a high frequency reference clock.

- Since it is a purely digital CMOS device, it consumes current only during measurement. The current consumption is calculated the following way: If the reference clock is attached permanently this needs 200µA per MHz. Independent of the duration of the measurement the GP1 needs 100nAs per measurement (calibration included). The ALU takes 10nAs each calculation.

With 1000 measurements per second the result is:

Reference clock	200µA
Measurement	100µA
ALU	10µA
Total	310µA

With a just as current saving design of the other electronic components one can develop equipment that is suitable for battery driven operation.

- The result is given as a 32 bit fixed point number in multiples of the reference clock.

Typical register content with one stop (reference clock 1MHz):

Reg 0:	0x54	Auto_Cal + Calibrate + Meas.range 2
Reg 1:	0x4D	HighRes, Adjust value
Reg 2:	0x21	Finecount 1 - Finecount 2
Reg 3:	0xXX	Default
Reg 4:	0x00	(1MHz(RefClk) corresp. 1000ns)
Reg 5:	0xXX	Default
Reg 6:	0x02	Default
Reg 7:	0x02	Enable 2 Hits onStop 1
Reg 8:	0x00	Default
Reg 9:	0x00	Default
Reg 10:	0x80	Default

Multifunctional instruments for process control

TDC's are used not only in ultrasonic flowmeters. The principle of measuring the time-of-flight of acoustic signals can also be used to measure the density or the concentration of a substance as the velocity of sound is changing also with these parameters.

In most applications temperature has to be measured too. This can be done with a TDC in a very current saving manner. Highest precision can be achieved, when the frequency change of a temperature dependend quartz is measured. With TDC's this method reaches a precision of a hundredth degree with only a few µA current consumption.

The TDC as an interface between sensors and processor is a powerful tool to improve the capabilities of non-invasive process control technologies.

1st Release February 1999