ISSN 1392-2114 ULTRAGARSAS, Nr.1(34). 2000.

Measurement ultra slow dynamic flow

G. Poviliūnas, R. Kažys

Kaunas University of Technology, Ultrasound Research Center

Studentu 50, 3031 Kaunas, Lithuania

Introduction

Modern industry uses a lot of high viscous liquids that in production process have to be dosed. The quantity dosed may be calculated directly from the flow rate of such a liquid in the pipe used for the dosing. As liquid is dosed, the flow is dynamic and includes some fast changing parts and some semi-steady zone. It had been established in [1] and [2] that the flow profile of a high viscous liquid would be laminar and the flow velocity may not be increased in order to avoid not desirable high hydraulic losses in the pipeline. Therefore, the part of the pipe used for the ultrasonic flowmeter should be of the same diameter as a pipeline. As the application is industrial, the temperature of the liquid dosed may change in a wide range and comparably fast. Temperature influences the ultrasound speed in the liquid quite a lot. Experimental results presented in [3] show ultrasound speed dependencies upon temperature and their approximations in three viscous liquids: the sunflower oil, the emulsifier lecithin E322 and the palm oil. The ultrasonic flowmeter design overview in [3] shows that the only one acceptable design of ultrasonic flowmeter for viscous liquids in a dosing regime is the transit time flowmeter with angular installation of the ultrasound path.

The aim of this work is to define the acceptable flow measurement method for viscous liquids in a dosing regime in a wide temperature range. In order to reach the aim some particular analysis has to be done, that include:

- the practical range of duration of component parts of the dosing pulse;
- the time distribution of sent – received signals against the flow and along it;
- the temperature and flow velocity influence on component parts of the ultrasonic signals;
- the duration of informative signal and technical capability to measure it with acceptable accuracy, when one or other measurement method is used.

Duration of component parts of the dosing pulse

The dosing pulse (Fig. 1.) may be divided into three parts: the rising front A, that lasts $t_{f1}=t_2-t_1$, the top or the zone of semi-steady flow B, that lasts $t_t=t_3-t_2$ and the end slope C, that lasts $t_{f2}=t_4-t_3$. As the flow in a dosing regime is dynamic, the speed of change of the flow rate in zones A, B and C is of a high importance.

The duration of the part B may vary from some seconds up to tenths of minutes, depending on an application. The duration of zones A and C is much shorter than B, it depends on the way of realization of a dosing. In dosing tasks it is aimed to make these fronts as short as possible. However, duration of front A is limited by technical capabilities and liquid hammer effect. Duration of the front C is even more limited by liquid hammer effect. Thus in a reality the duration of an end slope would be the same or shorter than duration of the rising front.

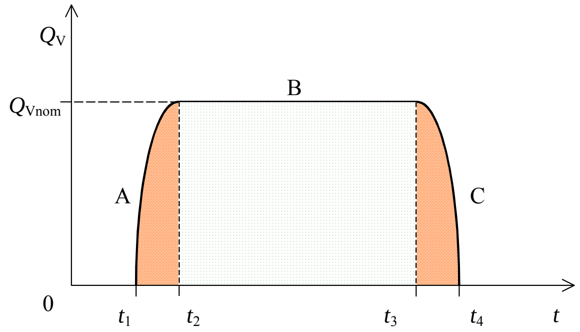


Fig. 1. **The simplified dozing pulse**.

The dosing regime may be organized in two ways: as gravitational flow or as forced flow. Gravitational flow is started and stopped by means of a valve as shown in Fig. 2.

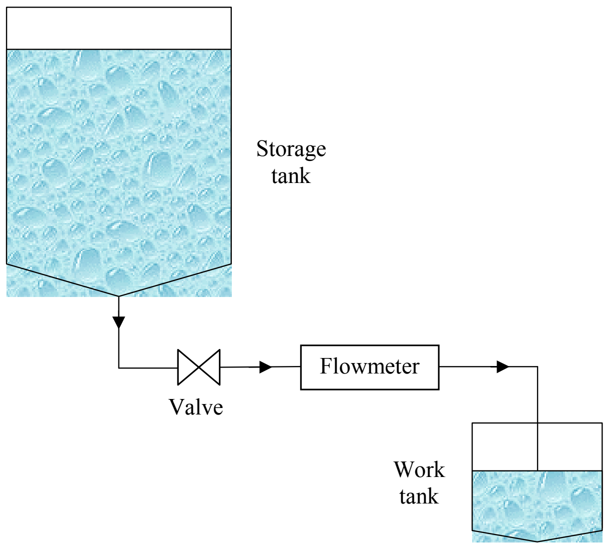


Fig. 2. **Dosing by means of a gravitational flow**

The duration of the front A mainly depends on the valve opening time, while duration of C depends on its closing time. The valve may be actuated automatically (pneumatic, hydraulic or electric), or it may be operated by hand. If the valve is actuated automatically, its opening time won't be shorter than 0.1s. The closing time would be even longer. If the valve is operated by hand, its opening and closing time would hardly be shorter than 0.1s just because of a human capability to do that.

The forced flow is started and stopped by means of a pump, as shown in Fig. 3.

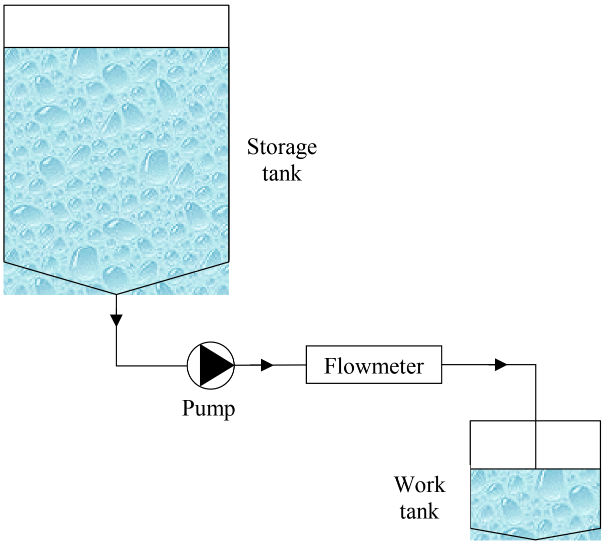


Fig. 3. **Dosing by means of a forced flow**

In such an installation, duration of the rising front depends on time needed for the pump to reach its full capacity from zero. The duration of end slope depends on the time needed for the pump to stop from its full capacity. In reality, these fronts last for several seconds. In extreme situations with the pipeline of a small diameter and low flow rate, it is possible to reach as short fronts as 0.2s.

Summarizing, it would be correct to state that in practice duration of either rising or falling front of the dosing pulse would not last shorter than 0.1s under any circumstances.

In some case, the duration of zone B may become extremely long in comparison to the duration of the fronts A and C. Then there is no need to measure the flow rate during these fronts, it is enough just to detect the beginning and the end of the dosing pulse. Let's consider the simplified dosing pulse as trapezium: the flow rate during the zone B is constant $Q_{VB} = Q_{Vnom} = const.$, the flow rate during the fronts increases and decreases linearly. Then the total volume dosed

$V = 0.5Q_{Vnom}(t_2 - t_1) + Q_{Vnom}(t_3 - t_2) + 0.5Q_{Vnom}(t_4 - t_3)$.

Let's denote the time intervals: $\tau_{f1} = t_2 - t_1$, $\tau_B = t_3 - t_2$ $\tau_{f2} = t_4 - t_3$ and $\bar{\tau}_f = (\tau_{f1} + \tau_{f2})/2$. Then $V = Q_{Vnom}\tau_B + Q_{Vnom}\bar{\tau}_f$. The assumption that the volume dosed during fronts B and C may be neglected should be based on the absolute uncertainty of measurement of the total volume. As duration of the fronts is short $\bar{\tau}_f << \tau_B$, $\Delta V \cong \Delta V_B = \Delta Q_{Vnom}\tau_B = \delta_B Q_{Vnom}\tau_B / 100$, while volume dosed during the fronts is $V_f = Q_{Vnom}\bar{\tau}_f$. Here δ_B is the related flow rate measurement uncertainty in the zone B. It should be correct to state that if the volume dosed during the dosing pulse fronts is less than 10% from the total measurement uncertainty, that approximately is the same as from the measurement uncertainty of the zone B, the influence of fronts may be neglected. It means that influence of fronts may be neglected if $V_f \le 0.1\Delta V_B$, in other words if $\bar{\tau}_f / \tau_B \le 0.001\delta_B$. As the minimal possible

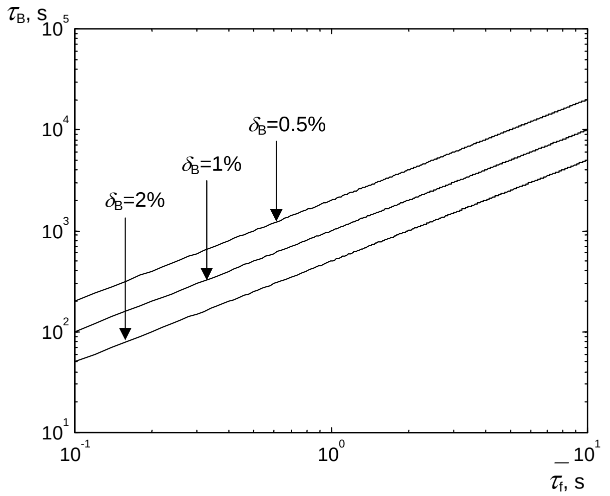


Fig. 4. **The minimal required duration of the dosing pulse when the influence of fronts may be neglected**

duration of any front is 0.1s, and it would hardly exceed 10s, the required combination of values of τ_B and $\bar{\tau}_f$ under some defined δ_B may be calculated. These calculation results are presented in Fig. 4.

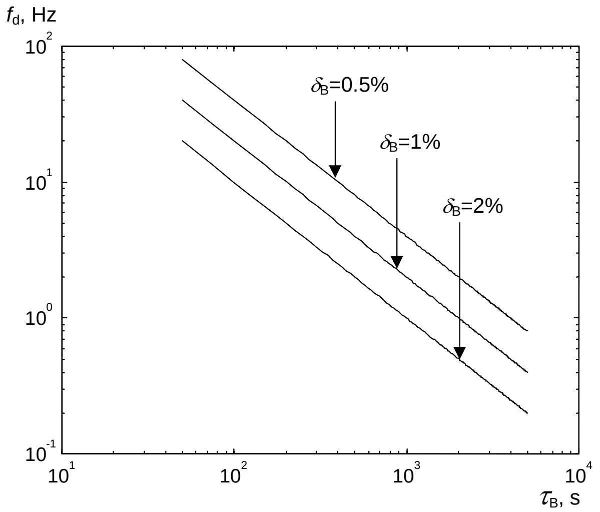


Fig. 5. **The minimal required sampling frequency of the dosing pulse when the influence of fronts is neglected**

If fronts of the dosing pulse are neglected, the minimal sampling frequency (of discretisation) may be calculated. The maximal value of the volume dosed that may not be estimated because of discretisation of the pulse in time is $\Delta V_d = 2T_d Q_{V\_nom}$. Here T_d is the sampling time interval.

It should be correct to state that the time interval of discretisation is short enough if $\Delta V_d \le 0.1\Delta V_B$. Then the value of the time interval of discretisation is

$T_d \le \delta_B \tau_B 0.5 \cdot 10^{-3}$. The dependence of more informative parameter – the minimal sampling frequency upon the duration of the dosing pulse under defined δ_B is shown in Fig. 5.

The structure of the ultrasonic signals

There had been investigated ultrasound speed dependencies upon temperature of three viscous foodstuff liquids: the sunflower oil, the emulsifier lecithin, and the palm oil in [3]. The data show that the change of temperature from +5^{O}C up to +95^{O}C changes the speed of the ultrasound from 1550m/s down to 1220m/s correspondingly. Let's consider some larger range of variation of the ultrasound speed: c=1000…1800m/s – that would cover a wider temperature range or liquids with different physical properties. It had also been established in [3] that the only one suitable design of the ultrasonic flowmeter for dynamic flow of viscous liquids is the transit time flowmeter with an angular installation of the ultrasound path, as shown in Fig. 6.

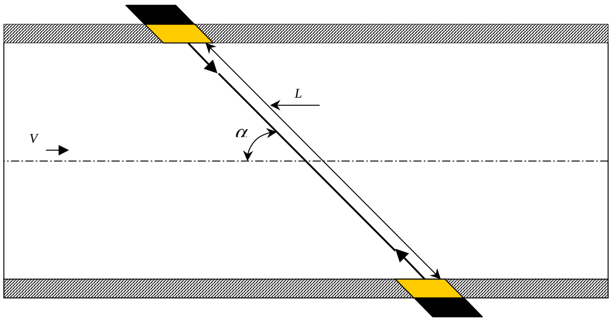


Fig. 6. **Transit time ultrasonic flowmeter with angular installation of the bi-directional ultrasound path**

Figure shows an installation with one bi-directional path of the ultrasound. However, there may be used two separate paths upstream and downstream as shown in Fig. 7.

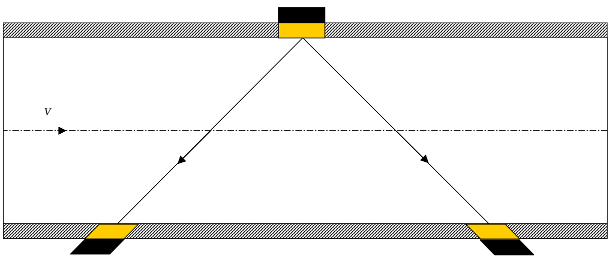


Fig. 7. **Transit time ultrasonic flowmeter with single transmitter and two separate measurement channels downstream and upstream**

It enables to send exactly the same ultrasonic signal upstream and downstream with no time delay between them. Additionally it allows obtaining the information about the flow from upstream and downstream signals at the same instance.

The time required for the ultrasound to propagate from the transmitter to the receiver downstream τ_1 is expressed in (1) and upstream τ_2 - in (2).

$$\tau_1 = \frac{L}{c + v\cos\alpha}, \qquad (1)$$

$$\tau_2 = \frac{L}{c - v\cos\alpha}. \qquad (2)$$

Here L is the length of the propagation path, α is the angle between the path and centerline of the pipe, c is the ultrasound speed in the fluid, and υ is the velocity of the flow.

It is important to determine the time τ_c , required for the ultrasound to propagate the distance L , while there is no flow in the pipe, dependence upon the ultrasound speed in the liquid. The distance L is calculated from conditions, that the pipe used is DIN50 and the angle $\alpha = 45^\circ$. The analyzed range of the ultrasound speed in the liquid is $c = 1000...8000 m/s$ that approximately corresponds to the range of temperature of a liquid $T = 0...100^\circ C$. The calculation results are presented in Fig. 8.

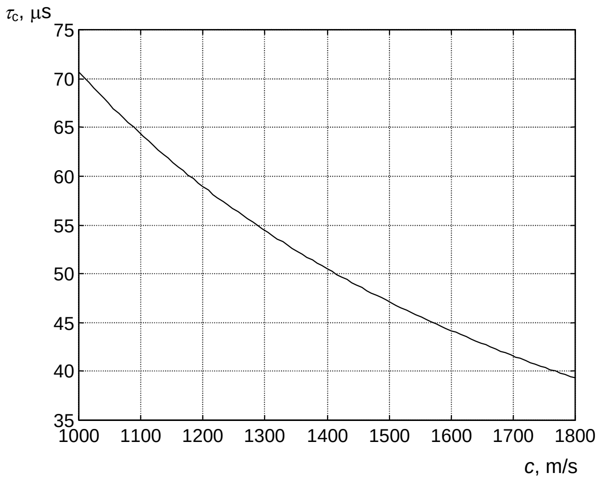


Fig. 8. **The dependence of propagation time of ultrasound the distance *L* (DIN50 pipe, 45^{O} angle) upon the ultrasound speed in the liquid**

It is seen that the change of temperature in 100K changes the ultrasound speed in liquid almost twice.

When the ultrasonic pulse is sent from the transmitter, it propagates not only directly to the receiver but under other angles as well. The reflected signals from the walls of a pipe also arrive to the receiver but later than the direct signal. While these reflected signals are not attenuated by the fluid enough, it is not recommended to send another ultrasonic pulse. In order to avoid receiving false reflections, it is used to wait not less than five times duration of the ultrasound propagation time after the first – direct signal had been received. The information about the velocity of the flow is obtained from difference of the propagation times:

$$\Delta\tau = \tau_2 - \tau_1 = \frac{2Lv\cos\alpha}{c^2 - v^2\cos^2\alpha} \approx \frac{2Lv\cos\alpha}{c^2}. \qquad (3)$$

When bi-directional measurement channel is used, the ultrasonic signal is sent along the flow, its propagation time lasts τ_1, and afterwards reflection-attenuation time, not shorter than $5\tau_1$, has to be waited. Then signal against the flow has to be sent that lasts τ_2, and reflection-attenuation time, not shorter than $5\tau_2$, has to be waited again. Only then, another ultrasonic pulse along the flow may be sent and so on. The process consisting of sending the ultrasonic pulse one direction, waiting reflection-attenuation time, sending another direction, waiting reflection-attenuation time till sending the pulse the previous direction may be called one value measurement cycle. Therefore, one value measurement cycle for bi-directional channel would last not shorter than $6\tau_1 + 6\tau_2$. When there is no flow in the pipe $\tau_1 = \tau_2 = \tau_c$ and one measurement cycle lasts $12\tau_c$. Time distribution of τ_1, τ_2 and informative signals is shown in Fig. 9.

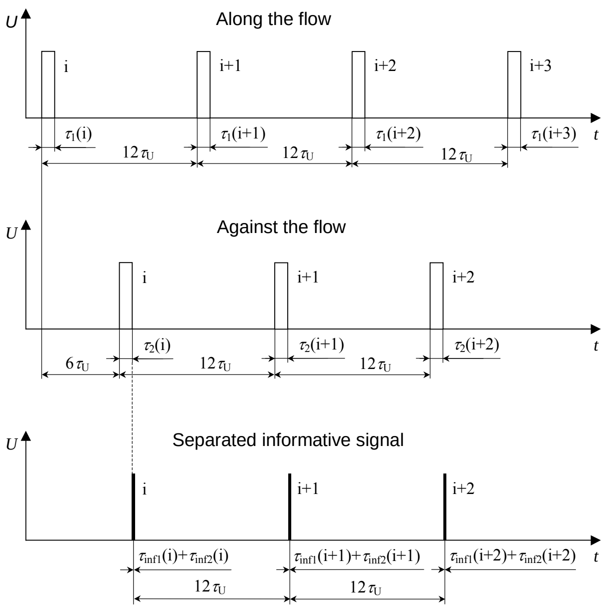


Fig. 9. **Time distribution of ultrasonic signals**

With the change of temperature and flow velocity, τ_1 and τ_2 would change as well, and that would change the measurement cycle duration and what is even worse – the repetition frequency of measurement cycles. In practice, it is desirable to have constant frequency of repetition of ultrasonic pulses $f_m = 1/T_m$, therefore the measurement cycle duration T_m should be chosen constant as at the lowest speed of the ultrasound in the fluid under investigation $T_m = 12\tau_U = const$ and $\tau_U > \tau_1(c = c_{\min}; Q_V = Q_{V\max})$, $\tau_U > \tau_2(c = c_{\min})$. In such a way, the repetition frequency f_m of measurement cycles shall neither depend on the ultrasound speed in the fluid – the same way on temperature, nor on the velocity of the flow. If temperature doesn't change much and the flow velocity is low, $\tau_U \approx \tau_1 \approx \tau_2$.

If flow changes fast and $T_m = 12\tau_U = const$, long duration of measurement cycle may lead to errors due to loss of the information between two neighboring measurements, therefore faster measurement repetition may be required. In such a case, duration of the measurement cycle should be made variable, thus sometimes shorter and mainly dependent on the ultrasound speed in the liquid $T_m = 12\tau_U = 12\tau_2 \approx 12\tau_c \neq const$. Fig. 10 shows how many such measurement cycles it is possible to perform during 0.1s, e.g., duration of the shortest possible rising or falling front of the dosing pulse.

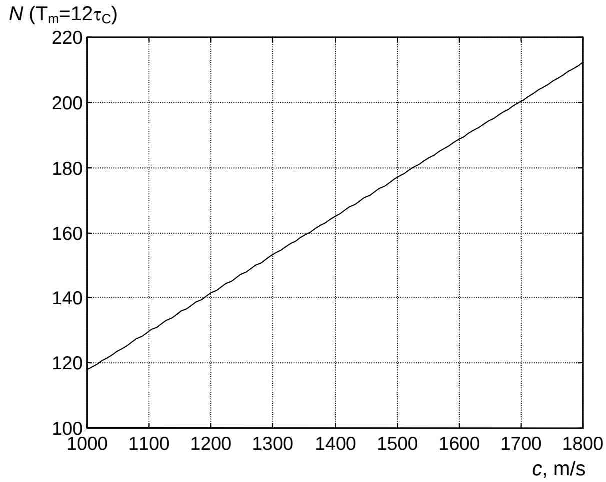
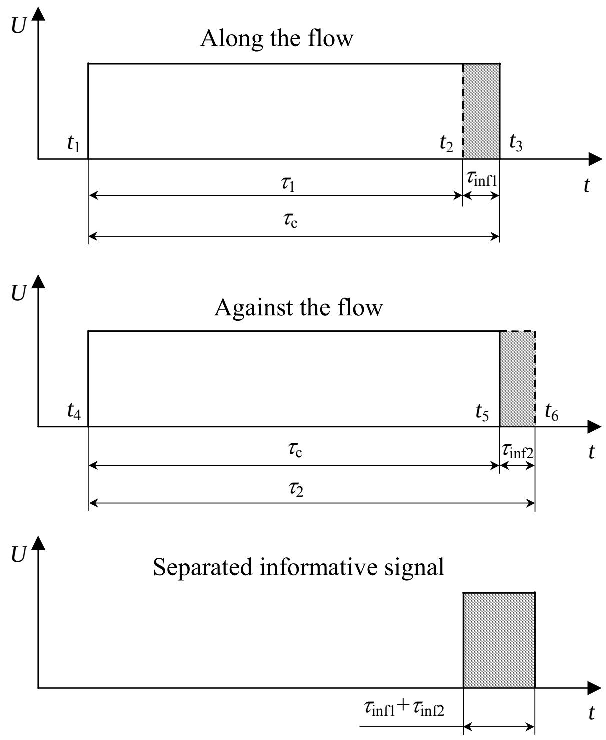


Fig. 10. **Number of cycles of measurement that possible to perform 0.1 s – the duration of the dosing pulse front in a case of bi-directional ultrasound path**



.Fig. 11. **The transit time of the ultrasound along the flow, against it and separated informative signal**

It is seen that one measurement cycle lasts approximately 0.5…1% of duration of the shortest possible front.

However, if temperature of the liquid doesn't change much, τ_c wouldn't change much as well and such a method won't be effective noticeably. The use of two separate measurement channels downstream and upstream would increase the number N twice.

Fig. 11 shows duration of transit time of the ultrasound along the flow and against it and separated informative signal. The short ultrasonic pulse is transmitted at t_1 (downstream) and at t_4 (upstream). If there is no flow, duration of transit time upstream and downstream is the same $t_3 - t_1 = t_5 - t_4 = \tau_c$. If there is flow, the downstream ultrasound pulse is hastened by the flow and it arrives earlier at t_2 - the transit time is $\tau_1 = t_2 - t_1$ while in an upstream case, the ultrasound is slowed and pulse arrives later at t_6 - transit time is $\tau_2 = t_6 - t_4$. τ_c doesn't contain information of the flow velocity thus may be called as non-informative, while $\tau_{\inf 1}$ and $\tau_{\inf 2}$ contain such information therefore they may be called informative signals. If velocity of the flow in time interval $t_6 - t_1 = 7\tau_U \approx 7\tau_C$ changes, the resulting $\tau_{\inf} = \Delta\tau = \tau_{\inf 1} + \tau_{\inf 2}$ would contain a sum of flow velocities in time intervals $t_2 - t_1$ and $t_6 - t_4$ $\tau_{\inf} \sim v(t_2 - t_1) + v(t_6 - t_4)$. Unfortunately, information of the flow velocity in time interval $t_4 - t_3$ would be dismissed.

Measurement methods

The time interval $\tau_{\inf}$ depends on the ultrasound speed in a liquid and on the velocity of the flow that in practice is expressed via flow rate. As ultrasound speed dependencies upon temperature had been investigated in [3], possible limits of flow rate in a pipe of a fixed diameter should be analyzed in order to define the practical limits of variation of informative signal $\tau_{\inf}$.

If the diameter of a pipe is fixed (let's take it DIN50), the capacity of the pumps, thus the flow rate and velocity of the flow is limited by hydraulic losses, that depend on a viscosity of the liquid. When a fluid is low viscous, the flow rate may reach as high values as Q_{m_max}=2000kg/h. When the fluid is very viscous, the nominal flow rate may fall as low as Q_{m_min}=300kg/h. Therefore, the practical range of the nominal mass flow rate in DIN50 pipeline at the top of the dosing pulse would be Q_{m_nom}=300…2000kg/h. If the density of a fluid were considered equal $\rho = 1000$ kg/l, the volume flow rate were Q_{V_nom}=300…2000l/h, and the average flow velocity at the top of the dosing pulse were $\bar{v}_{nom}$ =0.042…0.28m/s. The average velocity of the flow during the dosing pulse fronts would change from zero to its nominal value and backwards, thus it is necessary to measure even smaller velocities than defined nominal above. For instance at 10% of the front of the dosing pulse the velocity of the flow would be $\bar{v}_{10\%}$=4.2…28m/s.

The way of extraction of $\tau_{\inf}$ from τ_1 and τ_2 depends on a measurement method. Mainly are used these measurement methods:

- Sing-around
- Pulse
- Phase shift

Sing-around method.

The ultrasonic pulse is send along the flow and when it arrives to receiver, it is immediately send the same direction again. The frequency of repetition of pulses would be F_1. When pulses are send against the flow, their repetition frequency would be F_2 correspondingly. If there is no flow, $F_1 = F_2$; with increase of the flow F_1 becomes greater than F_2. Their difference is proportional to the velocity of the flow:

$$\Delta F = F_1 - F_2 = \frac{2v\cos\alpha}{L}. \qquad (4)$$

As it is seen from (4), velocity of the flow directly depends on ΔF and doesn't depend on the ultrasound speed in the liquid:

$$v = \frac{\Delta F L}{2\cos\alpha}. \qquad (5)$$

In a case of bi-directional ultrasound path informational frequencies F_1 and F_2 are separated in time because they are obtained alternately. In a case of two measurement channels, they may be obtained simultaneously but two separate pairs of transducers mounted away from each other should be used. It had been calculated what values of ΔF would be when flow rate changes from zero to its practical nominal values Q_V=300l/h and Q_V=2000l/h. Results are presented in Fig. 12.

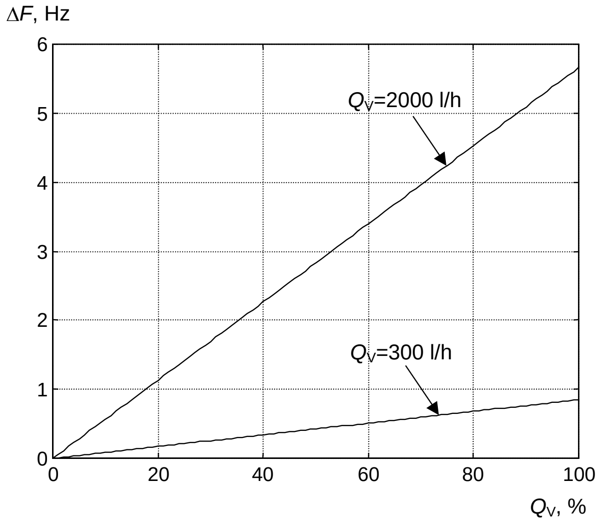


Fig. 12. **The differential informative frequency dependence on the flow rate in DIN50 pipe.**

Fig. 12. shows that informative frequency at the top of the dosing pulse (100% of its amplitude) would be ΔF=5.6Hz for nominal flow rate Q_V=2000l/h and ΔF=0.85Hz for nominal flow rate Q_V=300l/h. If the flow is stabilized and there is enough time, it is possible to measure such frequencies accurately. However, duration of the front of the dosing pulse is 0.1s and if it is desirable to have at least 10 data points during it, it is required to make measurements each 10ms. The change of ΔF between two neighboring points would be 0.56Hz in the case of

nominal flow rate Q_V=2000l/h and 0.085Hz in the case of nominal flow rate Q_V=300l/h correspondingly. It is impossible to measure accurately even the highest possible frequency of 5.6Hz (one period duration would be 180ms) in 10ms. In the case of lower flow rates, the measurement is even more unrealistic. However, if the dosing pulse is long and its fronts are short enough, the influence of the fronts may be neglected. Then the differential frequency ΔF may be considered as a sampling frequency. As seen from Fig. 12., this frequency is in limits of $\Delta F = 0.8...5.8$ Hz in the zone B of a dosing pulse. If flow rate measurement uncertainty in zone B is $\delta_B = 1\%$, the total volume dosed may be measured accurately if duration of the part B is $\tau_B = 1500$ s for $\Delta F = 0.8$ Hz and $\tau_B = 300$ s for $\Delta F = 5.8$ Hz correspondingly (as seen from Fig. 5.). According to Fig. 4., fronts of the dosing pulse may be neglected if the average duration of a front is not longer than $\bar{\tau}_f = 1.5$ s for $\tau_B = 1500$ s and $\bar{\tau}_f = 0.3$ s for $\tau_B = 300$ s correspondingly. However in practice, duration of fronts is often longer and duration of the part B is shorter, than required in statements above. Therefore, sing-around measurement method may be used for ultra slow flows in a dosing regime only with the strict limitations to duration of $\bar{\tau}_f$ and τ_B, and they do not cover all the possible ranges of their variation.

Pulse method.

Measurements along the flow and against it are separated in time if one bi-directional measurement channel is used. In the case of two separate channels, measurements in them may be performed simultaneously. In any case, duration between two one-direction pulses has to be $6\tau_U$. If bi-directional channel is used, as shown in Fig. 7, duration of one value measurement cycle lasts $T_m = 12\tau_U$.

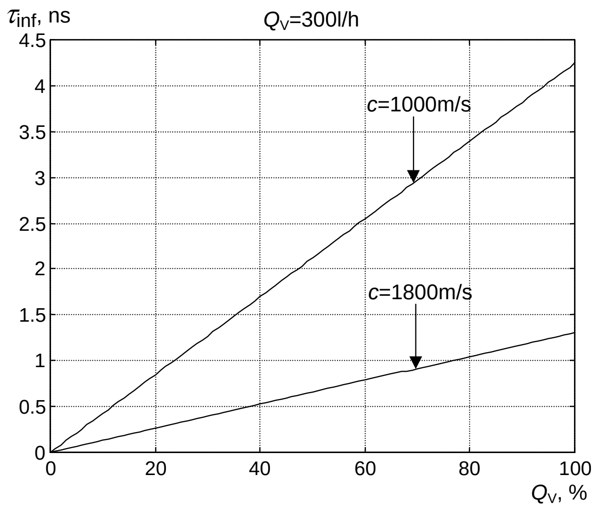


Fig. 13. **The informative τ_{inf} dependence on the flow rate in DIN50 pipe when the nominal flow rate is Q_V=300l/h.**

If two separate measurement channels are used, one along the flow and another against it one value measurement cycle may be shortened down to $T_m = 6\tau_U$.

Measurement of τ_{inf} may be performed in two ways:

- values of τ_1 and τ_2 are measured immediately as they appear and τ_{inf} is obtained as their difference;
- the beginning of τ_1 is delayed till the beginning of τ_2 and τ_{inf} is obtained as a difference of their duration.

There had been made calculations what values τ_{inf} would reach at different ultrasound speeds in a liquid at different flow rates. Results are presented in Fig. 13 to 15.

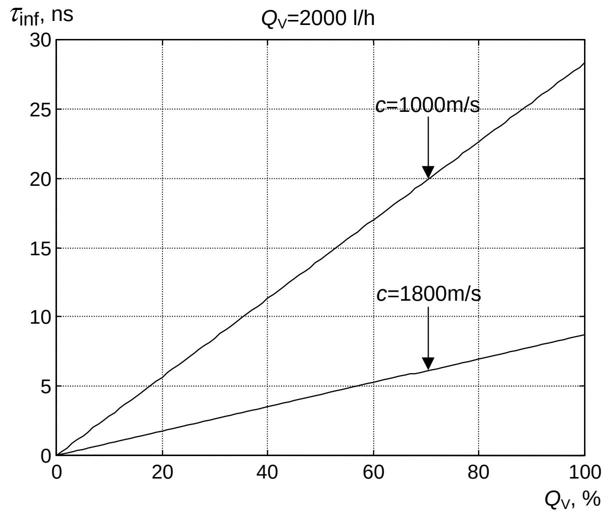


Fig. 14. **The informative τ_{inf} dependence on the flow rate in DIN50 pipe when the nominal flow rate is Q_V=2000l/h**

It is seen from these figures that duration of the informative signal is highly influenced by ultrasound speed in the liquid. The increase of the ultrasound speed from 1000m/s up to 1800m/s that corresponds to temperature change from 100°C down to 0°C approximately, may change the duration of the informative signal up to four times.

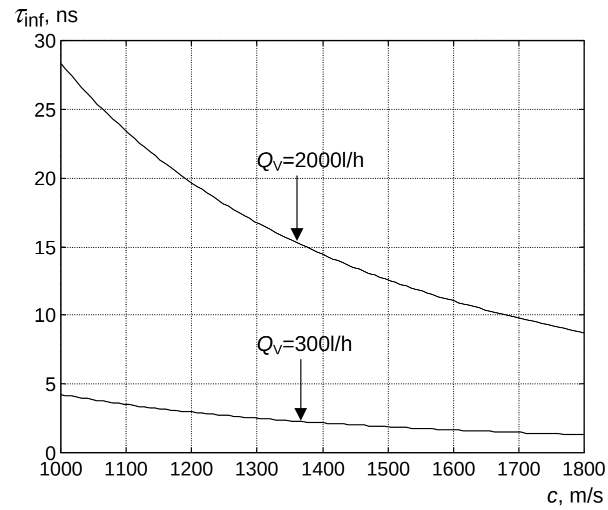


Fig. 15. **The informative τ_{inf} dependence on the ultrasound speed in the liquid in DIN50 pipe.**

At the top of the dosing pulse (part B in Fig. 1) τ_{inf} may be measured accurately with no any special means only when Q_V=2000l/h - $\tau_{inf} = 8...28$ ns. When the flow rate is low Q_V=300l/h - $\tau_{\inf} = 1.3...4.3$ ns. Fronts of the dosing pulse rise even greater problems because the duration of $\tau_{\inf}$ here is shorter. Direct and accurate measurements of pulses with duration less than 1ns presently don't seem realistic. There exist techniques for measurement such short time intervals, however they are very expensive. As one of the goals for such a flowmeter is a conditionally low price, pico-second techniques at the moment may not be used here.

The problem of short duration of $\tau_{\inf}$ may be partly solved applying either extension or accumulation of ultrasonic signals, or both these analogue techniques. An analogue extension in time and accumulation may be applied either to direct signals τ_1 and τ_2 or to the separated informative signal $\tau_{\inf}$. The single signal is extended to the value that may be easily measured $\tau_{\inf}^{ext} = \tau_{\inf} \cdot M$ and afterwards its value in is divided by the extension rate M. Accumulation enables to accumulate several analogue values in turn to the value sufficient for measurements: $\sum \tau_{\inf} = \tau_{\inf 1} + \tau_{\inf 2} + .. + \tau_{\inf K}$, afterwards it is measured and divided by the accumulation rate K. The value sufficient for measurement may be converted into a digital form before its division by extension or accumulation rate. The accumulation is a form of averaging with the purpose of extension of short time intervals. However, the averaging, that follows after it, not only minimizes the random errors of measurement but also may lead to the loss of information, as the measurand changes itself. While accumulation and afterwards averaging of $\tau_{\inf}$ values is suitable at the top of the dosing pulse when the flow is conditionally steady, it would lead to dynamic errors during the dosing fronts. Therefore, accumulation is not effective there as much as on the top of dosing pulse. Neither extension nor accumulation solve the problem of detection of fronts of a pulse.

If two separate measurement channels along and against the flow were used, the measurement speed may be increased up to two times. According to Fig. 10. it is possible to perform from 240 up to 440 separate measurements during the dosing pulse front. If accumulation of informative signals were used, duration of $\sum \tau_{\inf}$ may be increased. However, in the case of low flow rate and high ultrasound speed in the liquid the accumulated informative signal would remain extremely short. For instance if accumulation rate is 10, $Q_{V\_nom} = 300$ l/h and $c = 1800$ m/s, the duration of accumulated informative signal in the middle of the dosing pulse is $\sum \tau_{\inf} = 10 \cdot 0.7 = 7$ ns. The value is still too small for the direct accurate measurement.

The pulse method with accumulation techniques of short time intervals may be effectively applied for the measurement of semi steady flow. Such is the top of the dosing pulse. When duration of dosing pulse fronts is short in comparison to its total duration and their influence may be neglected, pulse method may be applied for the whole dosing pulse. If duration of the dosing pulse fronts may not be neglected, pulse method may not be applied for the whole dosing pulse.

Phase shift method.

When harmonic signal of frequency ω is sent along or against the flow, the received signal would be of the same frequency ω, however its phase would depend on the flow velocity. The phase difference of received signals upstream and downstream $\Delta\varphi = \varphi_2 - \varphi_1$ is proportional to velocity of the flow (6):

$$\Delta\varphi = \varphi_2 - \varphi_1 = \omega(\tau_2 - \tau_1) \approx \frac{2L\omega\cos\alpha}{c^2} v . \tag{6}$$

Here φ_1 is the phase of the received signal downstream and φ_2 is the phase of the received signal upstream. The flow velocity is given by:

$$v = \frac{c^2}{2L\omega\cos\alpha} \Delta\varphi . \tag{7}$$

The practical range of excitation frequency used in ultrasonic transducers is $f = 1...10$ MHz. For further analysis there had been taken the mean value $f = 5$ MHz. There had been calculated:

- how the phase shift depends on the volume flow rate during the front of the dosing pulse;
- how the phase shift depends on the ultrasound speed in the liquid.

Results are presented in Fig. 16 to 18.

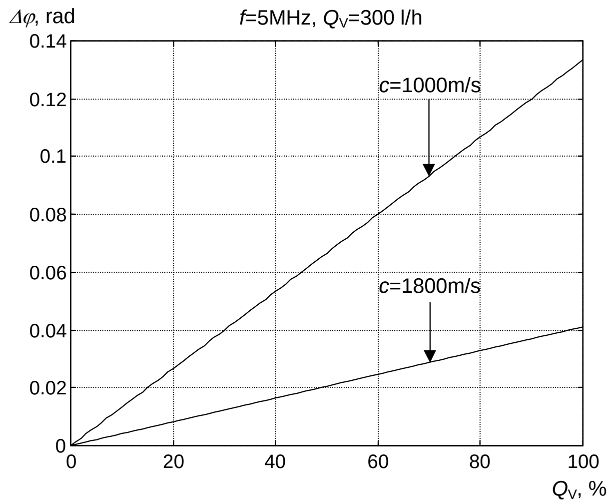


Fig. 16. **The informative phase shift dependence on the flow rate in DIN50 pipe when the nominal flow rate is Q_V=300l/h**

The phase shift depends on the frequency ω, therefore this frequency has to be of a high stability – what is a disadvantage of the method. On the other had, this dependence enables to adjust $\Delta\varphi$ to the required value via adjustment of ω. Using this method, the measurement range is limited from the upper values, as maximal phase shift should not exceed the value of π.

Here also may be used either two separate measurement channels along the flow and against it or one bi-directional channel. Bi-directional channel requires measurement of phase shift between received and transmitted signal. With a use of two separate channels, the phase shift between upstream and downstream signals may be measured directly and immediately. In addition, two separate measurement channels allow performing phase shift measurements faster twice than in the case of bi-directional channel and only one additional ultrasonic receiver may to be used.

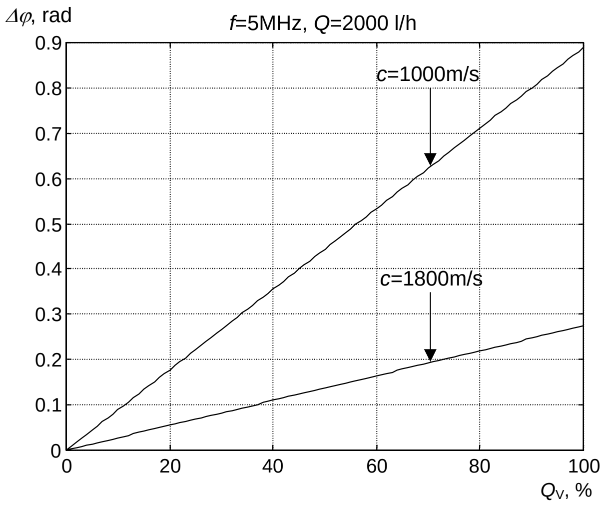


Fig. 17. **The informative phase shift dependence on the flow rate in DIN50 pipe when the nominal flow rate is Q_V=2000l/h**

The measurement of a phase shift may be performed in two ways:

- the phase shift is measured as the time interval during that the phase changes the desired number of radians or degrees;
- the phase shift is measured as a differential voltage or current of received signals.

The conversion of phase to time interval is more often used, however the time interval would be short (the same as shown in pulse method analysis) and measurement of its duration would have the same problems as described there. However this way enables to obtain more measurement data as the time interval between two neighboring measurement values is $T = 1/\omega$, not $6\tau_U$ or $12\tau_U$ as in pulse method (bigger about 1000 times). Thus, it is possible to apply accumulation of $\Delta\tau$ of much higher rate than in pulse method.

If the phase shift is measured as a differential voltage or current, the amplitudes of harmonic signals have to be the same. However, the amplitude of a received signal would not be constant and of course not the same as of the other signal (either received by another receiver, or taken from the transmitter). Its amplification either would not ensure stability of amplitude in short time intervals, or the phase shift on the output of amplifier would depend on the amplitude of the input signal. The solution is an over-amplification that converts harmonic signal into meander pulses of known and stable amplitude. As there won't be a need to track the amplitude of input signal, in order to adjust the amplification rate, the phase shift between the input and output pulses would be constant.

A harmonic signal upstream and downstream may be sent either continuously, or by some packets as a pulse modulation of a harmonic signal. When signal is sent continuously, the part of it is reflected by the receiver and it propagates backward to the transmitter, part of it is reflected by the transmitter and propagates to the receiver, and so on. It gives rise of a standing ultrasonic wave in the ultrasound path. That affects the phase of the received signal in unpredictable manner. If two separate measurement channels are used, standing ultrasonic waves in their ultrasonic paths would affect the phases of received signals differently and that course measurement errors as well. Advantage of a continuous ultrasonic signal is that measurements may be performed almost continuously, with the measurement rate up to $\omega/(2\pi)$ measurement values per second. The effect of the standing wave may be avoided if harmonic signal is sent by pulses. The duration of pulse should not be longer than $2\tau_c$ and another pulse may not be sent earlier than $5\tau_c$ after the end of previous pulse. That would decrease the measurement rate not less than 5 times, however it still is high enough.

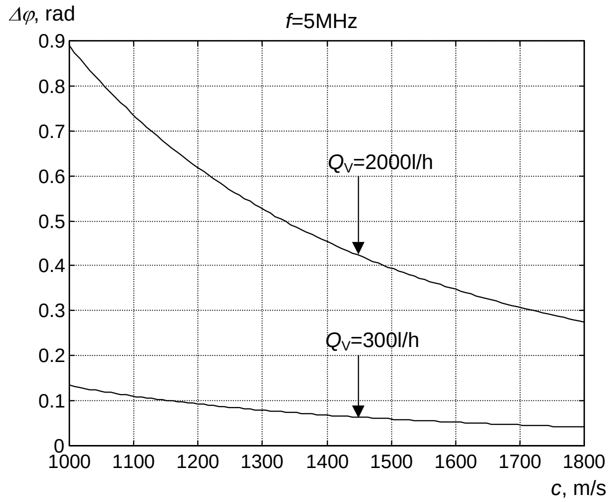


Fig. 18. **The informative phase shift dependence on the ultrasound speed in the liquid in DIN50 pipe**

Advantages of the phase method are following:

- it ensures the highest possible measurement rate in comparison to the other methods analyzed here;
- there is no need to separate informative signal as in the pulse method if two separate measurement channels are used;
- it is comparably easy to measure low flow velocities, as high frequency of excitation of transducer ensures measurable values of the phase shift;
- the measurement of phase shift converted into voltage or current is more precise than measurement of extremely short time intervals.

Disadvantages:

- the excitation frequency of transmitter has to be of a high stability, as the phase shift is highly sensitive to it;
- the shape of the signal transmitted has to be strictly harmonic;
- the standing ultrasonic wave between transducers would increase a measurement uncertainty;
- the phases of received signals would have some initial (zero) phase shift. They may be abolished by the means

of the delay line, however jitter time of the delay line increase a measurement uncertainty;

- the ultrasonic signal travels through the metal pipe faster than through the liquid and the signal at the receiver would contain not only informative signal that had propagated through the liquid but the parasite ones from the pipe as well; there may be an infinity number of paths for ultrasound around the pipe, therefore lots of signals with different phase shifts would reach the receiver. An efficient acoustical isolation of transducers from the pipe should be considered.

Conclusions

The duration of the dosing pulse fronts lasts not shorter than 0.1s, while the semi-steady zone B lasts from several seconds up to tenths of minutes (Fig. 1.). If the zone B of the dosing pulse is long and its fronts are short enough, the influence of the fronts may be neglected. Then there is no need of measurement of the flow rate during the fronts where the flow rate is much lower than in the zone B.

Analysis of the measurement methods revealed that:

The sing-around method may be applied for measurement of ultra slow flows in a dosing regime only when influence of the fronts of the dosing pulse may be neglected. However, it may not be used for any shape of the dosing pulse, as this method sets limits to the duration of $\bar{\tau}_f$ and τ_B. When duration of the zone B is short thus, the influence of the fronts cannot be neglected, this method may not be applied, as the informative frequency during the fronts even under the best conditions would be too low for the accurate measurements. The reduction of the flow rate because of a high viscosity caused by a low temperature decreases the informative frequency down to immeasurable values.

If ultrasonic pulse is send, in order to avoid influence of the false reflections, not less than five τ_c has to be waited till another pulse may be sent. That decreases the measurement rate. If single measurement channel is used, the measurement rate will decrease twice more. The ratio between informative part of one-direction signal $\tau_{\inf 1}$ or $\tau_{\inf 2}$ and τ_c is (20…200)10^{-6} on the top of the dosing pulse. Therefore, τ_1 and τ_2 mainly consist of non-informative τ_c. The duration of informative signal when the flow velocity is very low would be extremely short. Standard short time interval measurement methods don't allow measurement of time intervals shorter than 1ns accurately. The usage of two separate measurement channels would increase duration of informative signal twice. The measurement rate is low; thus, even the highest possible accumulation of measured values during the dosing pulse fronts is not sufficient for the accurate measurements. However, if the top of the dosing pulse is long, the accumulation technique there may be applied effectively. The pulse method may be used only in a case when duration of the dosing pulse fronts is utterly short in comparison to the zone B. The beginning and the end of the zone B, thus of the dosing pulse in such a case would be detected with a sufficient precision.

The phase shift method may be applied in two ways. The phase shift may be measured as the time interval – the same problems and advantages as in the pulse duration method. The phase shift may be converted into the difference of magnitudes of two harmonic signals at some time instance. As time passes by, this differential signal changes as well however its effective value is proportional to the phase shift between initial signals. In order to make the phase shift undependable on the amplitudes of compared harmonic signals over-amplification has to be used that converts sinus signals into pulses. Measurement rate for this method is extremely high – up to $\omega/(2\pi)$ measurement values per second, thus accumulation and averaging of single measured values may be applied easily and effectively. If two separate measurement channels upstream and downstream were used, the measurement rate may be increased twice. In order to avoid standing ultrasonic wave between the transducers, the harmonic signals have to be sent in pulses. Duration of the single pulse should not exceed $2\tau_c$ and another pulse may be sent when $5\tau_c$ passes after the end of the previous one. That decreases the total measurement rate more than five times, however the rate is still high enough. In order to avoid the phase jitter because of the false signal travelling through the material of the pipe, the sufficient acoustical isolation of transducers from the pipe should be used. This method enables the measurement of extremely slow flow even if its velocity changes fast.

References

1. **Poviliūnas G., Kažys R.** Analysis of flow profiles of liquid food products in a wide temperature range. – Ultragarsas, Nr.2(30), KTU, Kaunas. 1998.
2. **Poviliūnas G., Kažys R**. Peculiarities of flow rate measurement of viscous liquids. – Ultragarsas, Nr.2(32), KTU, Kaunas. 1999.
3. **Poviliūnas G., Kažys R.** Application of ultrasonic techniques for measurement of a flow rate of viscous liquids in a wide temperature range. – Ultragarsas, Nr.3(33), KTU, Kaunas. 1999.
4. **Spitzer D. W.** Flow Measurement: Practical Guides for Measurement and Control. - Instrument Society of America, USA, p.611. 1993.
5. **Schramm G.** A Practical Approach to Rheology and Rheometry. - Gebrueder HAAKE GmbH, Karlsruhe, FRG, p.290. 1994.
6. **Kažys R.** Neelektrinių dydžių matavimo metodai. - Technologija, Kaunas, p.239. 1997.
7. **Vaidakavičius A., Macevičius J.** Hidraulika ir hidraulinės mašinos. - Mokslas, Vilnius, p.321. 1984.
8. **Walus S.** Przeplywomierze ultradzwiekowe. Metodika stosowania. - Wydanstwo Politechniki Slaskiej, Gliwice, Polska, p.152. 1997.
9. **Novickyj P. V., Zograf I. A.** Ocenka pogreshnostei rezultatov izmerenyj. - Energoatomizdat, Leningrad, c.247. 1997.
10. **Chamidullin V. K.** Ultrazvukovyje kontrolno-izmeritelnyje ustroistva i sistemy. - Izdatelstvo Leningradskovo universiteta, Leningrad, c.243. 1989.
11. **Vlasov A. D., Murin B. P.** Edinicy fiziczeskich veliczin v nauke i technike. Spravocznik. - Energoatomizdat, Moskva, c.176. 1990.
12. **Idelczik I. E.** Spravozcnik po gidravlizceskim soprotivlenijam. – Mashinostroenije, Moskva, c.558. 1975.

G. Poviliūnas, R. Kažys

Ypač lėtų dinaminių srautų matavimas

Reziumė

Klampiems skysčiams tekant vamzdžiu, srautas bus laminarus, o kad būtų išvengta hidraulinių nuostolių, srauto greitis turi būti mažas. Realus nominalus debitas dozavimo impulso viršūnėje Q_V=300…2000*l*/*h*, kas atitinka vidutinį srauto greitį DIN50 vamzdyje v=4.2…28 cm/s. Dozavimo impulso tiek priekinio, tiek galinio frontų trukmės bus didesnės negu 0.1 s, tuo tarpu impulso viršūnės trukmė gali būti nuo kelių sekundžių iki keliasdešimt minučių. Jei vamzdžiu siunčiami pavieniai ultragarso impulsai, siekiant išvengti parazitinių atspindžių įtakos matavimo rezultatams, po impulso priėmimo ne mažiau kaip penkių sklidimo trukmių laikotarpį reikia palaukti, kad atspindžiai spėtų nuslopti. Todėl esant vienam ultragarsiniam matavimo kanalui vienos reikšmės matavimas trunka dvylika UG sklidimo trukmių, o esant dviem atskiriems kanalams tam užtenka šešių sklidimo trukmių. Kadangi srautas labai lėtas, vienakrypčio ultragarso signalo informacinė dalis labai trumpa – dozavimo impulso viršūnėje ji bus 0.7…14 ns, priklausomai nuo ultragarso greičio skystyje ir nominalios Q_V reikšmės, tuo tarpu pats impulsas trunka 39…71 μs. Tad informacinio signalo ir pagrindinės pastovios dalies santykis yra labai mažas (20…200)*10^{-6}.

Matavimo metodų analizė parodė, kad dažninis metodas ypač lėtiems dinaminiams srautams netinka, nes informacinis dažnis esti labai mažas, palyginti su laiko tarpu, per kurį jį reikia išmatuoti. Informacinis dažninis signalas yra ne harmoninis, o impulsinis, todėl jam matuoti keitimai – dažnio pokytis – fazės pokytis – amplitudės pokytis netinka. Fazinis metodas gali būti taikomas, tačiau jei fazių skirtumas bus matuojamas laikiniais metodais, matavimo specifika daug nesiskirs nuo impulsinio (sklidimo trukmės) metodo. Naudojant du atskirus matavimo kanalus, fazinis metodas leidžia pasiekti didelį matavimo greitį – iki 10^7 matavimų per sekundę, todėl atskirų matavimų rezultatus galima sėkmingai kaupti ir vidurkinti. Čia, priešingai negu taikant dažninį metodą, fazės skirtumą galima keisti į amplitudę, tuo atsisakant ypač trumpų laikų matavimo. Impulsinio metodo atveju matavimo greitis yra mažas – iki 2000 matavimų per sekundę, o informacinio signalo trukmė labai maža. Net kaupiant po 10 reikšmių ir naudojant du atskirus matavimo kanalus, dozavimo impulso fronto viduryje informacinio signalo trukmė tesieks 7 ns. Standartinėmis priemonėmis tokių laiko intervalų tiksliai išmatuoti nepavyks, jau vien dėl impulsų frontų iškraipymo, t.y. laiko atskaitos neapibrėžtumo.

Pateikta spaudai 2000 04 25