ULTRAGARSAS, 1996, Nr.1 (26)
UDK 534.193

Flow velocity measurement by coherently modulated ultrasound

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The measurement of flow parameters of oil products, natural and liquefied gas and other chemical materials is of prime importance in modern technology. Except the measurement of the flow rate it is very important for the leak-proofness of the pipelines transporting oil and other chemical products [1,2]. At such a way the measurement of flow velocity of gas and liquids with highest accuracy is very actual, especially when the flow rate is small. It requires specific choise of method and apparatus.

Recently many papers have appeared where frequency-modulated acoustic signals are proposed for more accurate measurement of flow velocity [3-5]. In frequency modulation of a measuring signal by low frequency signal, duration of its period is chosen as a multiple of time delay of acoustic signals in the flow under control. This is achieved when low frequency signal is generated by a generator in which the positive feed back is realised through the feedback loop with a delay in electroacoustic channel.

The use of frequency modulated signals instead of pulse timing in ultrasonic transit-time flow measurement gives independence of the speed of sound in the medium. To convert a pulse-time interval into a frequency by gating an oscillator does not overcome inaccuracies in sensing the edge of the received pulse. This problem is very actual when diameter of the pipeline and the flow rate are small, and we need to measure pulse edges to a few nanoseconds. There is difference between the resonant frequency of the phase-locked loop system and conventional pulse operation system. In one case a pulse is transmitted between the transducers. In the other there is a continuous wave on which a frequency is locked by a phase-locked loop so that the period is a measure of the transit time. The flow velocity is proportional to the difference between the downstream and upstream frequencies. In spite of wide fluctuations of flow velocity such a system provides wide range total flow measurement over a period.

There are few limitations of the continuos wave or so called coherent modulation system [3,5]. The only mechanical element is the piezo crystal which turns the electrical oscillations into waves in the media under control. A crystal has several resonancies and may generate spurious frequencies. This is particularly tiresome with a piezo ceramic element because its numerous modes of oscillation. If such transducer is used in a confined space then any spurious wave energy it generates may reflect and cause a standing wave of an unwanted frequency. This wave in certain circumstances can interfere with the frequency response of the system. For this reason the transducers should have the highest possible carrier frequency commensurate with path length of the measuring bases. So the attenuation and therefore the FM capture characteristics are enhanced and the beam angle is a minimum. This means that in practice the transducer for coherent modulation system use a frequency about ten times higher than for the pulse-echo one of the same path.

Two or more beams can be used simultaneously in both directions to enable the profile of a conduit to be ascertained continuously. But there are advantages in switching one beam instead of using two. It avoids any question of dissimilarities and the cost of duplicate circuits and transducers. However, the requirements of the switching system, be it an electronic circuit or a mechanical relay, gets more severe as the carrier frequency is raised, as it should be to maintain optimum operating conditions as the pipe size is reduced. The main problem is signal breakthrough due to capacitance effects on the contacts and the wiring of the switch. With the purpose to avoid standing wave effect we need a signal of the order of 10 microvolt to give a fully limiting FM signal, consequently the operating frequency is 10...100 times higher than would be practicable with pulse operation system. At such a way the techniques of the radio transmit/receive switching become stretched for ultrasonic signals because the receiving circuit requires only few microvolts to fully limit.

Measuring systems with the frequency modulation are proposed in the papers [3-5]. With the purpose to avoid standing wave effects the amplitude of received signal is limited and during the first halfperiod of frequency modulation the signal of certain frequency is radiated. During the second half period another frequency signal is radiated, different from the first one. In this case frequency of transmitting signal is adjusted to the coincidence of a phase of the transmitting and receiving signals.

In ideal case, the time which is needed for ultrasonic signals to travel from transmitter to receiver and in opposite direction may be expressed:

$$\tau_{01} = \frac{l}{c + v\cos\alpha} \quad \text{and} \quad \tau_{02} = \frac{l}{c - v\cos\alpha}, \qquad (1)$$

where l - the path length between transmitting and receiving surfaces of piezotransducers, c and v - sound and flow velocities respectively, α - the angle between tube axis and direction of probing.

In real case

$$\tau_1 = \tau_{01} + \tau_p = \frac{l}{c + v\cos\alpha} + \frac{l_b}{c_b} + \tau_{el}, \qquad (2)$$

$$\tau_2 = \tau_{02} + \tau_p = \frac{l}{c - v\cos\alpha} + \frac{l_b}{c_b} + \tau_{el}, \qquad (3)$$

where τ_p - the delay time of acoustic signal in an electroacoustical and electronic (τ_{el}) circuits, l_b - the length of acoustical waveguids or prisms and velocity c_b of sound in them respectively.

Then the flow velocity

$$v = \frac{l}{2\cos\alpha}\left(\frac{1}{\tau_1 - \tau_p} - \frac{1}{\tau_2 - \tau_p}\right) = \frac{l}{2\cos\alpha}\frac{F_1 - F_2}{(1 - F_1\tau_p)(1 - F_2\tau_p)} \qquad (4)$$

where $F_1 = 1/\tau_1$ and $F_2 = 1/\tau_2$ - the frequency of manipulation during down stream and upstream probing.

In accordance with (2) and (3)

$$v = \frac{1}{2\cos\alpha}\frac{F_1 - F_2}{\left[1 - F_1\left(\frac{l_b}{c_b} + \tau_{el}\right)\right]\left[1 - F_2\left(\frac{l_b}{c_b} + \tau_{el}\right)\right]}. \qquad (5)$$

How one can see from equations (2,3) manipulating frequency F_1 and F_2 depends not only from the velocity of flow. They depends from the delay time of signals in an electroacoustical and electronic circuits and from the velocity c of sound in the controllable flow

$$c = \frac{1}{2}\left[\frac{F_1}{1 - F_1\left(\frac{l_b}{c_b} + \tau_{el}\right)} + \frac{F_2}{1 - F_2\left(\frac{l_b}{c_b} + \tau_{el}\right)}\right], \qquad (6)$$

which is needed for the reference calibration of measuring system.

The main shortcoming of proposed systems [3-5] is that in the real flow of liquid a gas bubbles, other unhomogenuities and flow velocity fluctuations exists and a phase of acoustical signals is fluctuating. It leads to great difficulties when different half periods of manipulating signal are identified and accuracy of measurement of flow parameters is decreased. With the purpose to increase the accuracy of flow velocity measurement it is proposed to insert two channel phase adjustment. In the coarse screening channel phases of transmitted and received signals of manipulating frequency are compared. The exact channel serves for adjustment of phases of transmitted and received signals of carrier frequency. Thus accuracy of flow velocity measurement is increased. Block diagram of flow velocity meter with two channel phase adjustment is shown in fig. 1.

The principle of operation of the system is based on the radiation of frequency manipulated acoustic signal in a flow under control. The duration of a period of manipulation frequency corresponds to the delay time of an acoustic signal in a flow under control. The information about flow velocity is obtained from the manipulation frequency during upstream and downstream probing. Transmitted signal is obtained from the controllable LC generator dividing of its reference frequency f_o by n-1 or n+1 and passing the signal through the power amplifier and commutator. The carrier signals of frequencies $f_1=f_o/(n-1)$ and $f_2=f_o/(n+1)$ fill up the different halfperiods of a

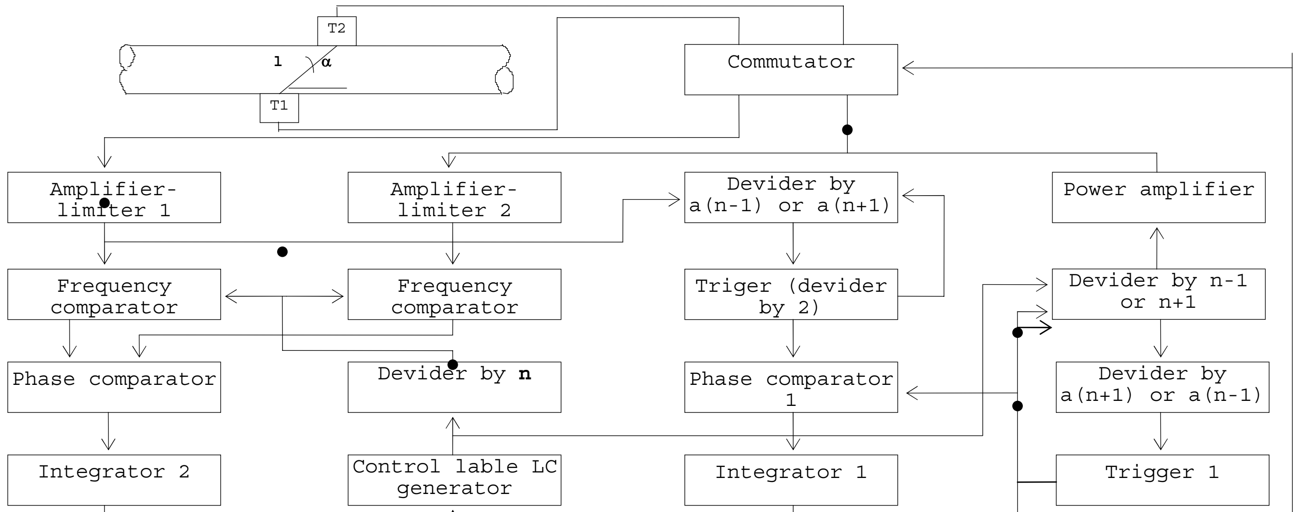

Fig. 1. Block diagram of flow velocity meter with two channel phase adjustment

manipulating signal. Manipulating signal is obtained by dividing the carrier frequencies f_1 and f_2 by a(n+1) and a(n-1) respectively and after division by 2 in a trigger 1. After that it is send to the 1 input of the first phase comparator and to the unit of second processing of information through the communication line. The unit of second processing of information is similar to that which was described in the paper [5]. The signals received by ultrasonic receiver and radiated to the flow under control are transmitted to corresponding amplifier-limiters and to the frequency comparators. Signals from the firs amplifier-limiter is divided by a(n-1) or a(n+1) and after triggering is sent to the second input of the first phase comparator. Phases of transmitted and received manipulating signals in the firs phase comparator are compared and their differential signal in the coarse screening channel serves for controlling the frequency f_o of a reference signal. In the frequency comparators of exact channel the comparison of duration of a period of reference signal f_o divided by n with the carrier frequency periods is made and different halfperiods of manipulating signal are identified. Phases of received and transmitted signals in phase comparator 2 are compared. Their differential signal serves for exact controlling the frequency f_o of a reference signal. Frequency f_o of a reference signal changes so that in the area gap between transmitter and receiver one period of manipulating frequency is always located. One half period of manipulating frequency is filled up by a(n+1) periods of f_1 frequency. Second halfperiod of manipulating frequency is filled up by a(n-1) periods of f_2 carrier frequency. In such a way the accuracy of flow velocity measurement becomes like as in phase measurement methods and this method has a great advantage over other ones.

In the proposed method there is no need to fix the moment of arriving of each period of manipulating frequency. This is the advantage of the develop system over those working according to the principle of sing-around system. Fluctuations of amplitude of acoustic signals makes no difference since the information is carried by the frequency of manipulation which is obtained by dividing of reference frequency. Reference frequency itself changes depending on the time delay of acoustic signals in the medium under control. Instantaneous value of manipulating frequency is determined by mean value of an acoustic signals pass time from transmitter to receiver. Thus each accidental disturbance coming asynchronously when manipulating signal passes through zero does not significantly effect upon the frequency of manipulation. It may be changed only when changing the controlling voltages in the outputs of an integrators. On the basis of this method there lies averaging of results both of duration of each separate period of carrier and manipulating frequencies.

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Srauto greièio matavimas panaudojant koherentiðkai moduliuotus akustinius signalus

Reziumë

Darbe nagrinëjamos skysèiø ir dujø srautø greièio matavimo galimybës, panaudojant koherentiðkai moduliuotus nepertraukiamus akustinius signalus. Parodoma, kad, priklausomai nuo matavimø bazës ilgio ir signalo slopinimo aplinkoje, matavimams tikslinga panaudoti galimai aukðtesnio daþnio akustinius signalus, kuriø amplitudë priimanèio keitiklio iðëjime neturi virðyti keleto mikrovoltø. Pateikiama ir apraðoma ultragarsinio árenginio su akustinio signalo neðanèiojo daþnio manipuliacija struktûrinë schema. Signalø koherentiðkumui pasiekti zonduojantys signalai, kuriø daþnis kiekvieno manipuliuojanèio signalo pusperiodþio metu yra skirtingas, kaip ir pats manipuliuojantis signalas, kurio periodas atitinka akustinio signalo sklidimo nuo siuntiklio iki imtuvo laikà, gaunami dalinant atraminá aukðto daþnio signalà. Matavimø tikslumo padidinimui siûloma nepertraukiamo atraminio signalo daþná paderinti ne tik pagal siunèiamo ir priimamo moduliuojanèio signalo faziø skirtumà, bet ir pagal siunèiamo ir priimamo moduliuojamo neðanèiojo daþnio faziø skirtumà. Tai ágalina padidinti maþø srauto greièiø matavimø tikslumà ir gautø rezultatø patikimumà.

DOI: 10.5755/j01.u.26.1.7830