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Control of directivity patterns of electroacoustical transducers when measuring gas flow parameters

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Introduction

Often when developing modern technologies one has to measure gas flow velocities in the range from 0.05 m/s to 30…60 m/s [1]. Therefore, the ratio of the highest and the smallest velocities of the gas flow, which must be measured by the same ultrasonic meter, reaches 600…1000. When seeking to increase the accuracy of such meters, the ratio of signal to noise must be ensured sufficiently high. It is to be noted that the accuracy of measurements is increased when the ratio of signal to noise is the same, but the frequency of signal is increased [2,3]. It is related to the fixing of the instant of signal arrival, which is fixed mostly when the signal is crossing the zero level, where steepness of the signal is the biggest. Steepness of the signal, when crossing the zero level, is growing when the frequency of signal is increased [2,3]. The absorption of acoustical signal in the gas media is increased with the frequency too [1-3]. Besides, the width of the directivity patterns of electroacoustical transducers is decreasing when the transverse dimensions of transducers are the same, but the frequency of signal is increased. On the other hand, when the width of directivity pattern of the transducer is decreasing, the signal to noise ratio is increasing, when the radiated power is constant. But when expanding the dynamical range of the measured gas flow velocity to the values 30…60 m/s, because of the drift of the signal in the gas flow, the electroacoustical transducers with more wider directional patterns are indispensable [1,3]. When using electroacoustical transducers with considerably narrow directivity patterns it is proposed to arrange the axes of transducers inclined at an angle φ to the intertransducer centerline [1]. The angle φ between the axis of the transducer and the intertransducer centerline is called the ray rescue angle [1]. This additional angle of deflection of transducers usually has only a few or some degrees. When using this method, the rescue angles are calculated in advance in accordance with the highest flow velocity to be measured [1,4]. So the optimal signal to noise ratio is achieved for only one value of flow velocity, but it becomes worse for higher or lower velocities. With the purpose to optimize the operation of an ultrasonic system for measurement of dynamical parameters of gas flows we suggest to use the adaptive system with the controllable directivity patterns of electroacoustical transducers.

Electroacoustical transducers with the controllable directivity patterns are widely used when developing medical echoscopical equipment [5-9] and systems of nondestructive testing (NDT) [10,11]. But the transducers of such a type, as far as we know, never before were used for measurement of gas flow parameters. This is related with the complicated systems of control of directivity patterns of transducers and high costs of such an equipment. However, the costs of electronic control systems of directivity patterns of transducers are quickly decreasing with a rapid improvement of technology. These systems will be widely used when developing ultrasonic systems for measurement of gas flow parameters. Therefore, the purpose of this investigation was to study the possibilities of using the electroacoustical transducers with the controllable directivity patterns for measurement of gas flow velocity and other dynamical parameters.

Model of measuring channel

The principles of control of directivity patterns of electroacoustical transducers are widely analyzed in the scientific literature [5-11], therefore they will not be discussed in this investigation. We shall touch only the aspects of control of directivity patterns of transducers, which must be taken into account when ultrasonic methods are used for measurement of gas flow velocity and other dynamical parameters. First at all, it is necessary to take into account that earlier, when developing NDT and medical echoscopical equipment, the mechanical or electrical control of directivity patterns was used [12]. For ultrasonic measurement of gas flow velocity and other dynamical parameters, because of very rapid variation of direction of an ultrasonic beam, only electrical control of directivity patterns is possible. Besides that, when using an electrical forming and control of directivity patterns, the electronically scanned arrays, acoustical gratings and phased acoustical arrays can be used. The use of commutational equipment for control of the ultrasound beam is complicated and actually hardly possible in practice. Therefore the most useful for that purpose is to use the phased piezoelectric arrays.

In a general case, the directivity pattern of an electoacoustical transducer is the function of time and of three coordinates. The main are the directivity patterns of transducers in the two orthogonal planes and the time. Usually the directivity pattern can be changed in one plane only. It is the plane of the flow velocity vector and the flow sounding vector. When measuring the gas flow velocity it is sufficient to change the directivity pattern of the transducer in one plane. So for flow measurements it is expedient to use the linear phased arrays. The number of linear strip piezoelements, their dimensions in the scanning plane and the distance between them defines the width of the directivity pattern of transducers. The longitudinal dimensions of the linear piezoelements usually are substantially bigger. They predetermine the directivity pattern of the transducer in the plane perpendicular to the scanning plane.

Besides the peculiarities mentioned above, when developing ultrasonic systems for measurement of flow velocity, it is necessary to note that the additional angle of deflection of transducers depends not only on the velocity of flow, but on the sound velocity in the gas flow under control. Latter mostly depends on the composition, temperature, humidity and other parameters of gas medium [13]. The sound velocity in the gas media determines the time of flight of an acoustical signal in the measuring area between the transducers and so the time interval within which the flow was influencing the signal and therefore the angle of carry away of the signal.

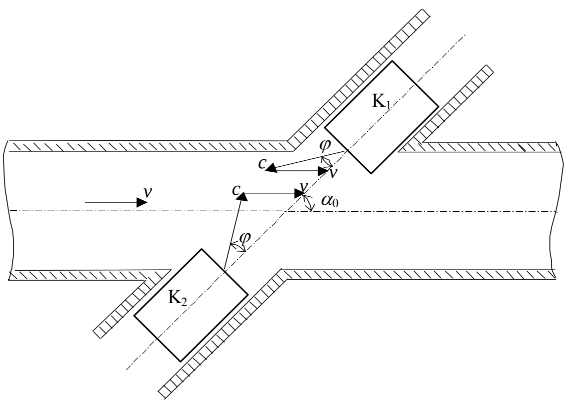

Fig. 1. **The model of measuring channel with the defkected directional patterns of electroacoustical transducers**

With the purpose to elucidate the influence of the carry away effect of acoustical signals to the additional deflection angles of the directivity patterns of electroacoustical transducers, the modeling was performed. For that reason, the model of acoustical signal propagation in the gas media was investigated (Fig.1).

Mathematical modeling

When modeling the drift of acoustical signals in the gas flow at first it was accepted that air flow velocity is measured in the circular channel, the flow profile is plane, the sound velocity in air flow c=340 m/s and the flow sounding angle α_0=30°, 45° and 60°. Then the additional angle φ, at which the directivity patterns of the transducers must be deflected against the flow, when the transducers radiate acoustical signals to the gas flow, are given by

$$\varphi = \arcsin \frac{v \sin \alpha_0}{c} \quad (1)$$

The results of calculation are shown in Fig.2.

As may be seen from Fig.2, the additional deflection angles φ of the electroacoustical transducers are rapidly increasing when the gas flow velocity and its sounding angle α are increasing.

How it was noted earlier, Eq.1 is valid only when the gas flow profile is flat. But the entirely flat gas flow profile does not exist in the turbulent gas flow. Therefore the distribution of the gas flow velocity in the cross-section of the measuring spoolpiece must be evaluated when calculating the additional deflection angles of the directivity patterns of electroacoustical transducers [14-17]. The distribution of the flow velocity in the cross-section of spoolpiece for the turbulent flow and for the Reynolds number Re>4000 may be expressed [14]

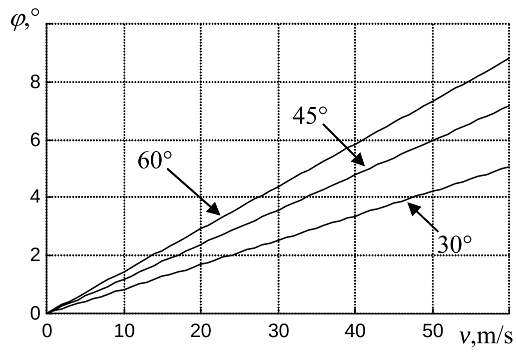

Fig.2. **The dependence of the additional angle φ of deflection of transducers with respect the gas flow velocity when the flow sounding angle α is changed**

$$v_r = v_m (1 - \frac{r}{r_0})^p , \quad (2)$$

$$v_m = v_{av}(1+p) * \left(1 + \frac{p}{2}\right), \quad (3)$$

where v_m is the maximal flow velocity in the center of pipe; v_{av} is the mean flow velocity in the cross-section; r is the distance from the flow axis; r_0 is the inside radius of pipe; p is the parameter, depending on the Reynolds number:

$$p = 0.25 - 0.23 \log_{10} \mathrm{Re} \quad (4)$$

By using expressions presented earlier, the profiles of the air flow velocity distribution in the pipe of 0.4m in diameter were calculated when the mean flow velocity is v_{av} = 5m/s and 60m/s (Fig.3)

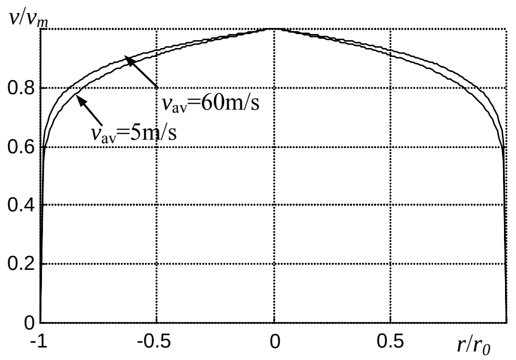

Fig.3. **The distribution of normalized air flow velocity in the pipeline of 0.4m in diameter when the averaged flow velocity v_{av} =5m/s and 60m/s**

When knowing the flow velocity distribution in the cross-section of a pipeline, the gas flow in the measuring spoolpiece was divided into n radial layers, the thickness of which in the radial direction are r_1, r_2,…r_k,…r_n. The velocities of an air flow in layers are v_1, v_2, .. v_n. Besides that, it was supposed that the gas flow is symmetrical in the axial direction and temperature, composition and sound velocity c in the airflow are constant. Then the deflection angles of directivity patterns of transducers in a turbulent flow may be calculated [18]

$$\alpha_{\pm} = \arccos\left(\frac{\pm k + \sqrt{2-k^2}}{2}\right), \qquad (5)$$

where α_+ is the angle between the direction of signal radiated to the gas flow and the normal to the flow axis when the sounding is downstream; α_- is the angle when the sounding is upstream; k is the coefficient depending on the gas flow profile in the pipeline [18]

$$k = (r_1 * v_1 + r_2 * v_2 + ... + r_n * v_n +)/(c * r_{sum}), \qquad (6)$$

where r_{sum} is the sum of thickness of radial layers which is equal to the inner radius r_0. But Eq.5 is valid only when the angle of flow sounding α_0 = 45° [18]. If the angle of the flow sounding is α_0=30°, 60° or another freely chosen angle, then the additional angle φ_+ at which against the flow movement direction must be turned the directivity pattern of the electroacoustical transducer radiating acoustical signal downstream is:

$$\varphi_+ = \arctan\frac{d_0}{\frac{d_0}{\tan\alpha_0} - 2s_+} - \alpha_0, \qquad (7)$$

where $s_+ = \sum_{k=1}^{n} \frac{r_k * v_k}{(c + v_k \cos\alpha_0)\sin\alpha_0}$; d_0 is the inside diameter of spoolpiece; α_0 is the angle of flow sounding. Another notations correspond the notations mentioned above. In analogy, the additional angle φ_- at which against the flow movement direction must be deflected the directivity pattern of the transducer radiating acoustical signal upstream, may be calculated

$$\varphi_- = \alpha_0 - \arctan\frac{d_0}{\frac{d_0}{\tan\alpha_0} + 2s_-}, \qquad (8)$$

where $s_- = \sum_{k=1}^{n} \frac{r_k * v_k}{(c - v_k \cos\alpha_0)\sin\alpha_0}$.

The additional angles φ, at which against the flow direction must be turned the directional patterns of transducers, are shown in Fig. 4.

How one can see from Fig. 4,when the turbulent flow profile is not entirely flat, the additional deflection angles of electroacoustical transducers are obtained bigger than the analogous angles for the flat turbulent flow and reaches φ=9.13° and φ=7.50° when the air flow velocity v=60m/s.

It is necessary to note, that the width of directivity pattern of electroacoustical transducer vibrating by thickness oscillations may be obtained [19]

$$\Theta = 2\arcsin\left(0{,}52\frac{\lambda}{D}\right), \qquad (9)$$

where λ is the length of acoustic wave; D is the diameter of the electroacoustical transducer; D=20mm; f=300kHz is the frequency of acoustical signal. The length of acoustical wave in the air is about λ=1.13mm. Then the width of directivity pattern of transducer Θ=3.75°. Since the directivity pattern of the transducer is symmetrical with respect to the longitudinal axis, the signal carry-along effect may reach only a half of that value, it is 0.5Θ=1.87°. Such a comparatively small width of the directivity pattern of the transducer shows that even at the 12…15m/s flow velocity the level of acoustical signal due to the signal drift may decrease up to 0.707 times from the nominal level. Besides that, the level of acoustical signal may decrease due to the turbulence of a flow, which grows when the gas flow velocity is increasing [1,3]. Therefore, the signal to noise ratio and the measurement accuracy are decreasing too. It shows that when measuring a gas flow velocity in a wide range it is necessary to use the acoustical transducers with deflection upstream directivity patterns of transducers. This problem may be solved by use of electoacoustical transducers with wider directional patterns. However, widening of directivity patterns, when the radiated power is constant, leads to decrease of the received signal and measurement accuracy. Besides that, it is useful to note that the additional deflection angles of directivity patterns of transducers are different when radiating and receiving acoustic signals. That is related with the demand to radiate an acoustical signal in such a way that the signal would by carried away by the flow to the geometrical center of the receiving transducer. The receiving transducer must be turned in such way that the front of the acoustical wave incidents on perpendiculary to the active surface of the receiving transducer. In that case a maximal energy of the signal will be received and the accuracy of measurement will be better. However the problems of orientation of the receiving transducers were not the main purpose of this investigation, so they will not be analyzed in this investigation.

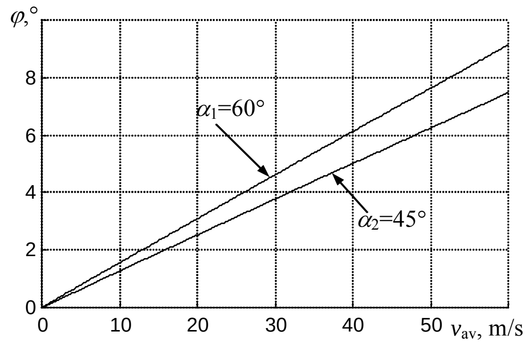

Fig 4. **The dependence of the additional angles of turn of the directivity patterns of transducers on the flow velocity when the angles of flow sounding α_1=60^0 and α_2=45^0**

During dynamical measurements after every sounding upstream the signal immediately must be radiated downstream, the directivity patterns of transducers must be changed at the moment when the direction of probing is reversed. Then the problems of rapid commutation of signal transmission direction and control angles of inclination of directional patterns of transducers arise. Especially it burdens because the levels of radiated and received signals differ about 120 dB.

The resembling problems arise also when controlling the directivity patterns of electroacoustical transducers in medical echoscopy. In this case the task of control of directivity patterns is slightly simpler because the directivity patterns in radiating and receiving mode coincide completely. When developing the ultrasonic systems for gas flow velocity measurement, the directivity patterns of transducers must be changed every time when the probing direction is changed. It is related with the use of the same pair electroacoustical transducers for radiation and reception of signals. The directivity patterns of radiating and receiving transducers may be controlled by the equipment, block diagram of which is shown in Fig. 5.

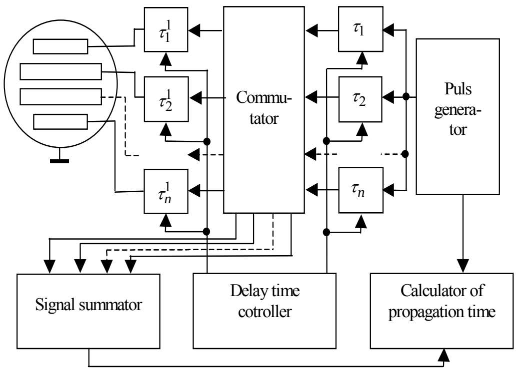

Fig. 5. **Block diagram of equipment for control of directivity patterns**

Since the directivity patterns of electroacoustical transducers in the radiating and receiving regimes are different, their control must be different too and becomes complicated enough. With the purpose to achieve good control of directivity patterns, the signals of the generator to the different segments of a radiating transducer, are transmitted by separate delay lines. After that these signals through the commutator are sent to the additional delay lines and after all to the corresponding segments of the radiating transducer. In the receiving mode, the signals from the corresponding segments through the additional delay lines and the commutator are transmitted to the signal summator. After that, the measuring signals serve for measurement of the time of propagation, flow velocity and sound velocity in the gas flow. Besides that, the received signals from the summator are sent to the equipment for calculation of sum and difference of the times of propagation. This information serves for measurement of delay times of measuring signals as well as for control of directivity patterns of the transducers. The commutator in this case separates the received signals from the influence of electric circuits of the generator.

Such an equipment for control of directivity patterns of the transducers enables one to optimize the measuring process of the gas flow velocity and other dynamical parameters. It enables to achieve the maximal ratio of signal to noise in the input of the acoustical receiver and to reach the maximum measuring accuracy.

Conclusions

When measuring the gas flow velocity and other dynamic parameters in the wide velocity range (v=0.05…60m/s) and trying to achieve sufficiently high measuring accuracy it is purposive to use electroacoustical transducers with the controllable directivity patterns.

By modeling the drift of acoustical signals in the gas flow it is shown that the angles of the signal drift depend on the gas composition, flow velocity and the angles of sounding and may reach a few degrees. The drift angles of the acoustical signal increase not only with the flow velocity, but and with the flow probing angles also.

The algorithms for calculation of the additional deflection angles of electroacoustical transducers are presented. The algorithms enable to calculate the additional deflection angles of the transducers when the angles of gas flow sounding, gas flow velocity and flow profile are changed.

It is determined that the influence of the gas flow profile to the additional deflection angles of electroacoustical transducers is comparatively insignificant when the gas flow profile is turbulent. In such a case the additional deflection angles of transducers may be calculated by using algorithms for the flat gas flow profile.

The block diagram of the system for control of directivity patterns of electroacoustical transducers is presented. It enables control of directivity patterns of transducers when radiating and receiving acoustical signals by the same pair of electroacoustical transducers.

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Elektroakustinių keitiklių kryptinių diagramų valdymas matuojant dujų srautų parametrus

Reziumė

Matuojant dujų srautų greitį ir kitus parametrus greičių ruože iki 50-60 m/s ir siekiant užtikrinti reikiamą matavimų tikslumą, tikslinga naudoti elektroakustinius keitiklius su elektriškai valdomomis kryptinėmis diagramomis. Pasiūlyti algoritmai akustinių keitiklių kryptinių diagramų papildomiems pasukimo kampams apskaičiuoti, kai kinta srauto greitis, profilis ir pradinis srauto zondavimo kampas. Modeliuojant akustinių signalų nunešimą dujų sraute, esant įvairiems srauto zondavimo kampams, parodoma, kad nunešimo kampai gali būti iki 9^0-10^0 ir didėti ne tik didinant srauto greitį, bet ir srauto zondavimo kampą. Atskleista, kad, esant turbulentiniam dujų tekėjimui, srauto profilio kitimo įtaka elektroakustinių keitiklių papildomiems pasukimo kampams yra palyginti nedidelė, ir pasukimo kampai gali būti apskaičiuojami taip kaip ir plokščiojo dujų srauto profilio atveju. Pasiūlyta ultragarsinių keitiklių kryptinių diagramų valdymo įrenginio struktūrinė schema, leidžianti keitiklių kryptines diagramas valdyti skirtingai esant signalų siuntimo ir priėmimo režimams.

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