Information-Measuring System to Measure Fluid and Granular Media Flow Velocities in Pipelines

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1. Introduction

The modern information systems used in most industries are inconceivable without rather complex processing of data obtained by not only manual input but also automatic measurement. There is a growing need for developing information-measuring systems (IMS) to receive and process the data provided, estimate their reliability, and make real-time decisions [1].

As practice shows, modern information-measuring systems for geographically remote objects are increasingly using GSM-based communication channels [2]. Using cellular communication in information-measuring systems is determined by the wide coverage of the areas where production facilities requiring continuous monitoring and control are located.

Herewith, many industries and the transport sector have a lot of facilities, machines, and equipment, geographically distributed and considerably remote from each other but requiring continuous monitoring and control of process parameters. Thus, currently, cryogenic, construction, flour-grinding, and other industries do not have means to measure the main process parameters of the pipeline flows.

The IMS functions should ensure high operating reliability, timely maintenance of process and emergency requests, and the generation of control responses to these requests [3].

The study proposes the principle of building an IMS to measure the velocity of two-component media in pipelines, based on the interaction of electromagnetic waves with the liquid and granular media flows in pipelines with further processing of data signals. Thereat, the proposed IMS operating principle provides for obtaining primary measurement data and statistical processing of the data signal.
2. Choosing a primary converter

Today, a Doppler converter is a promising way of contactless measuring the velocity of the liquid and granular two-component flows in pipelines [4]. Figure 1 shows a block diagram of a Doppler primary velocity converter. The converter operating principle is based on measuring the Doppler shift of the sounding and scattered EM frequencies on the moving flow inhomogeneities.

![Diagram of a Doppler primary velocity converter](image)

**Figure 1.** A block diagram of a Doppler primary velocity converter.

The Doppler converter circuit contains: 1 – microwave generator; 2, 3 – sections of, respectively, the transmitting and receiving waveguides located on the outer pipeline surface; 4 – mixer, and 5 – recorder.

Under real conditions, due to the random distribution of medium inhomogeneities moving in the flow and their arbitrary shapes and orientation, the signal corresponding to the Doppler frequency shift is modulated randomly in amplitude, phase, and frequency. This necessitates further statistical processing of this signal. Available radio wave Doppler primary velocity converters use spectral and correlation methods to process data signals [5, 6]. These devices are difficult to implement; moreover, their velocity measuring accuracy is not high.

3. The doppler signal assertions

The complex output signal of the Doppler primary velocity converter \( i_c \) is a set of partial signals \( i_c \) generated by the interaction of the emitted and the flow inhomogeneity-scattered fields in a nonlinear component – mixing microwave diode [7].

At a constant velocity of multiple scatterers \( N \), such a partial signal \( i_c \) can be characterized as follows:

\[
i_c = A_1F_1(t) + A_2F_2(t) \cos [2\pi f_d t + \phi] + t_n(t).
\]

Where \( F_1(t) \) is the normalized low-frequency signal component characterizing the time variation of the signal power of a specific scatterer,

\( F_2(t) \) is the normalized Doppler signal envelope proportional to the change in the scattered field density near the mixer,

\( A_1, A_2 \) are coefficients characterizing the absolute values of the above-mentioned signal components,

\( t_n(t) \) is the signal caused by the generator and mixer noise,

\( f_d \) is the Doppler frequency value determined from the condition

\[
f_d = 1/2\pi N \ K = NK_0 \cos \alpha = ND(\alpha),
\]

where \( \vec{N} \) is the velocity vector; \( \vec{K} \) is the wave vector; \( K_0 \) is the wavenumber; \( \alpha \) is the angle between \( \vec{N} \) and \( \vec{K} \); \( D = K_0 \cos \alpha \); \( \phi \) is the initial oscillation phase.

The \( i_c \) signal is not commonly a linear superposition of partial signals due to the nonlinearity of the mixer’s conversion function [8]. In this case, the pulses caused by the scattering signals of various
inhomogeneities lead to the generation of the so-called coherent signal components [9]. However, the presence of these components slightly affects the averaged signal characteristic determining the measurement accuracy such as its fluctuation spectrum width [10]. The impact of coherent components is also reduced due to the spatial signal averaging over the irradiated volume. Therefore, let us further assume zero impact of coherent components. Then the complex signal can be represented as the sum

$$\xi_c = \sum_{k=1}^{N} \left( A_1 F_1(t - t_k) + A_2 F_2(t - t_k)[\cos(2\pi f_{dk}(t - t_k)) + \phi_k] \right),$$

where $t_k$ is the k-th scatterer transit time through the central part of the measurement area; $f_{dk}$ is the Doppler frequency corresponding to the k-th scatterer; $N$ is the average number of scatterers with the most significant energy contribution to the complex signal; $\phi_k$ is the initial phase change caused by the k-th scatterer.

The N value is determined by the concentration of scatterers C, the measurement area length l, and the pipeline section radius r by the formula $N \approx Cl^4\pi r^2$. Let us further assume that N is large enough ($N > 10$) to talk about the average signal characteristics. In practice, this is always the case. Let us also assume that the absolute signal power significantly exceeds the additive noise level $t_n(t)$ [11]. Therefore, the latter can be neglected.

For a large N value, according to (1) and due to the limiting statistical properties [12, 13], the Doppler signal can be considered a narrow-band normal process with random amplitudes $A(t)$ and $\phi(t)$. This also requires the fulfillment of the condition

$$\sigma_{\alpha}^2 / u_0 < 10^{-1},$$

where $\sigma_{\alpha}^2$ is the scatterer velocity dispersion over the pipeline cross-section, $u_0$ is the average velocity. Then the Doppler signal component can be represented as an analytical signal

$$i_{c, d}(t) = \text{Re} \left( A(t) \exp[2\pi f_{do} t + \phi(t)] \right), \quad (2)$$

The components of this signal will be

$$a(t) = \sum_{k=1}^{N} A_1 F_1(t - t_k) \cos(2\pi f_{do} t),$$
$$b(t) = \sum_{k=1}^{N} A_2 F_2(t - t_k) \sin(2\pi f_{do} t),$$

and the signal frequency

$$f_{do} = \frac{d}{2\pi dt}[\arctan(b(t)/a(t))].$$

The Doppler frequency averaged over realizations $<f_{do}>$ can be determined knowing the joint distribution of the signal amplitude and the transverse scatterer coordinates YZW (AYZ), the joint distribution of the angle $\alpha$ and coordinates W(AYZ), and the velocity distribution over the section W(UYZ). As a result, for the averaged Doppler frequency

$$<f_{do}> = \frac{1}{2\pi} \int_0^0 \int_0^0 \frac{d}{dt}[arctan(b(A\alpha YZ/a(A\alpha YZ)) W(AYZ)W(\alpha YZ))W(uYZ)dydz]. \quad (3)$$

Analysis of equation (3) shows that the average Doppler frequency will uniquely (to an accuracy of a coefficient) correspond to the average (over the section) velocity of the scatterers $<U_0>$

$$= \int_0^0 \int_0^0 UW(uYZ)dydz$$

only with sufficiently narrow sections of the distributions $W(AYZ)$ and $W(\alpha YZ)$ over the parameters A and $\alpha$ and the symmetry of the sections of these distributions over the Y and Z coordinates relative to the distribution median W(AYZ). Measuring the average signal frequency (3) will allow inferring the average scatterer velocity (i.e., the flow velocity) and its time variation parameters with great reliability. Below we consider just such a case.

3.1. The Frequency-Tracking System Parameters

Using the specifics of determining the average signal frequency (2) from (14, 15), let us estimate the potential average Doppler frequency measuring accuracy and determine the meter parameters. Let us
thereat assume that frequency is measured using a frequency-tracking ring, the block diagram of which is shown in Fig. 2. Here MX is the mixer, FD is the frequency detector, LPF is the smoothing low-pass filter, and CG is the frequency control generator. The measured value \( \langle f_{d0} \rangle \) is determined by the low-pass filter output signal.

![Figure 2. A block diagram of a frequency-tracking ring.](image)

The signal spectral density function \( S(f) \) is the source function to estimate the velocity measurement accuracy; finding the exact form of this function commonly requires a detailed description of the \( F_2(t) \) function and the amplitude distribution \( W(A) \). However, approximately estimating the meter accuracy only requires an integral quantity such as the signal \( \Delta f_{c0} \) fluctuation (at a certain level) spectrum width [16].

For the large \( N > 100 \) and the same scatterer velocities, the spectral density function width \( \Delta f_{c0} \) at a level of 0.5 can be approximately estimated by the dependence

\[
\Delta f_{c0} = \frac{1}{\tau_{tr}} \frac{U_0}{l}.
\]

Where \( \tau_{tr} \) is the time of the measuring area transit by the scatterer; \( l \) is the measuring area size (length) determined by scattering between the radiating outlet and the mixer inlet, as well as the pipeline radius.

The spread of velocities, characterized by the distribution \( W(UYZ) \), leads to broadening the signal spectrum by \( 0.7\sigma_u D \), where \( \sigma_u = \int_{-\infty}^{\infty} U^2 W(U) Du \). Thus, the spectrum width \( \Delta f_d = \Delta f_{c0} + 0.7D \). The equation obtained allows estimating the measurement accuracy and the tracking system parameters in a linear mode. Fig. 3 shows the linearized diagram of this system. The input action on the system is the target value \( \langle f_{d0} \rangle \), and the output parameter is its estimated value \( \hat{f}_{d0} \). Here \( K_1 \) and \( P \) are the transmission and transformation input signal coefficients, respectively.

![Figure 3. A linearized diagram of a frequency tracking system.](image)

In this case, the fluctuation \( n_o(t) \) is white noise with a spectral density \( S_o = \Delta f_e + S_N \), where \( \Delta f_e \) is the Doppler frequency fluctuation range, \( S_N \) is the spectral fluctuation density determined by the finiteness of \( N \). \( S_N \) can be estimated by the number of samples \( N \) for the time \( \tau_r \). Then we get

\[
S_N = \sigma_d^2 D^2 \frac{\tau_r}{N}.
\]
Assuming that the chosen K1 value (see Fig. 3) is optimal [17], we obtain the dependence of the $\sigma_{f_0}^2$ variance on the initial (a priori) $\sigma_{f_A}^2$ variance and the averaging time T:

$$\sigma_{f_0}^2 = \sigma_{f_d}^2 / 1 + \sigma_{f_d}^2 T / 2Se$$

In this case, the optimal K1 value will be determined from the condition

$$K1(t) = \sigma_{f_d}^2 / 1 + \sigma_{f_d}^2 t / 2Se$$  \hspace{1cm} (4)

Fig. 4 shows some dependences of the change in the relative velocity measuring accuracy $\sigma_{u0}/U_0$ on the observation (averaging) time T, as well as the first approximation relative error $\sigma_{un}/U_0$ and the velocity spread over the pipeline cross-section $\sigma_{u}/U_0$. The dependencies show that the observation time of 2+3 s can ensure measuring the flow velocity of 1 m/s with an accuracy of 1 % max. This was confirmed by experiments on a model of the above measuring system structure. These studies have also shown that due to the low measuring noise, frequency tracking disruptions may be considered unlikely.

**Figure 4.** Dependences of the change in the relative velocity measuring accuracy on the observation time, where.

\[ N = 10, t = 0.4 \text{ m.} \]
\[ U_0 = 1 \text{ m/s.} \]
1. $\sigma_{um}/U_0 = 10 \%$, $\tau_u/U_0 = 5 \%$
2. $\sigma_{um}/U_0 = 10 \%$, $\tau_u/U_0 = 2 \%$
3. $\sigma_{um}/U_0 = 5 \%$, $\tau_u/U_0 = 5 \%$
4. $\sigma_{um}/U_0 = 5 \%$, $\tau_u/U_0 = 2 \%$

According to (4), the tracking system component parameters (Fig. 2) should meet the condition $\rho_d \rho_h K_1 = K_t$, $\rho_d$ is the discriminator transconductance [V/Hz]; $\rho_h$ is the controlling heterodyne transconductance [Hz/V]; $K_t$ is the integrator transmission factor.
3.2. Choosing the Frequency Discriminator Circuit
To achieve accuracy close to potential, real discriminator circuits that under specific conditions ensure indicators slightly differing from those of optimal circuits should be used as a frequency discriminator [18] in the tracking system (see Fig. 2). According to [19], a discriminator with a resonant circuit and a phase shifter meets such conditions. Fig. 5 shows the block diagram of such a discriminator. The input signal of this discriminator is divided into two branches: in one branch, it passes the resonant circuit (RC) and the limiter L, and in the other, the π/2 phase shifter and the second limiter. The signals of both branches are multiplied in a phase detector (PD) generating an output signal of the mismatch between the input signal frequency and the circuit frequency setting. In this case, the working branch of the discrimination characteristic [20] corresponds to the circuit phase characteristic type. The change in the transconductance is achieved by changing the circuit bandwidth, which, in turn, should be greater than the fluctuation spectrum width.

![Figure 5. A block diagram of a discriminator with a resonant circuit and a phase shifter.](image)

Explicitly implementing an oscillatory circuit with stable characteristics and a bandwidth of $10\times10^2$ Hz based on the L and C components is impossible. However, such parameters are easily ensured using a quadrature filter [21, 22], the diagram of which is shown in Fig. 6. In this diagram: BM1 and BM2 are the balanced modulators; LPF is the low-pass filters. The resonant circuit frequency setting and bandwidth are determined by the external generator G frequency and the low-pass RC-filter bandwidth, respectively. The balanced modulator role can be successfully played by analog electronic switches ensuring stable characteristics.

![Figure 6. A diagram of a quadrature filter.](image)
4. Discussion
The above points have been considered when choosing a circuit for a microwave data signal processing instrument – a tracking system-based velocimeter. The developed instrument operates as follows. After amplifying in the amplifier, the Doppler mixer output signal (see Fig. 1) is transferred to a higher reference frequency $f_0$ using a switch-type modulator and a quartz-crystal oscillator. After the broadband filter, the signal is fed to series-connected quadrature filters powered by a frequency-controlled heterodyne with a paraphase output. In these filters, the role of balanced modulators is played by analog switches, low-pass filters executed as active RC filters.

The quadrature filter output signals are normalized using zero level limiters, and the signal presence is ensured using a non-zero level limiter. Normalized signals are processed in a logical device functioning as a phase detector and a logical switch. The frequency tracking circuit is closed through an analog switch, an integrator, and a controlling heterodyne input. In the absence of a signal, a special switch allows closing the circuit for generating the search sawtooth voltage at the integrator’s output, which ensures switching the system into the memory mode. This circuit comprises a Schmitt trigger with a significant hysteresis band in switching mode.

In the instrument developed, the tracking ring features a circuit to automatically exclude the pickup and tracking of the image channel signal, which allows operating the scheme at very low Doppler frequencies. This circuit comprises logic elements and a logic selector, the output signal of which blocks the quadrature filter outputs at the corresponding frequency difference sign.

Based on the developed signal processing instrument circuit, a tracking system prototype was built, ensuring automatic tracking of the microwave meter’s Doppler shift at an input signal frequency of up to 104 Hz, which allows measuring the flow velocity within 0-50 m/s. The estimated signal frequency value was read using a standard frequency meter connected to the digital system output.

5. Recommendations
The theoretical study results concerning the superhigh-frequency Doppler primary converter can be used, e.g., in the express analysis of critical process parameters of granular and gas-liquid flows in dielectric pipelines such as continuity of the gas-liquid flow, the transported medium humidity, mass flow rate, and the substance density depending on the pipeline dimensions (the pipeline cross-sectional area, measuring section length), etc. In this case, the information parameters can be the resonance frequency, amplitude, and phase of EM oscillations interacting with flows. As per the frequency-tracking system theory, the provisions forming the basis for building it will, undoubtedly, allow performing the statistical analysis of randomly changing processes more efficiently and reliably and using it in regression and correlation analysis between one dependent and several independent values when processing these quantities while simplifying the process control algorithm.

6. Conclusion
The study results allow concluding that due to the synthesis of the superhigh-frequency Doppler primary velocity converter with a frequency-tracking system ensuring automatic tracking of the frequency shift with the change in velocity, the real possibility of building an innovative self-contained system measuring the velocity and volumetric flow rate of two-component flows in pipelines has been approved and justified. The results obtained have formed the basis for building a prototype meter tested to determine the volumetric flow rate of a cement-air mixture under real conditions. The theoretical prerequisites of a frequency-tracking system can be easily implemented in the form of digital input signals for a computer system with a further impact on the control of various technical and social processes.

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