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Article

Optimizing ultrasound Doppler measurement precision: a comprehensive experimental approach

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Abstract. Experimental studies were conducted utilizing advanced equipment comprising a generator, tubing system, pump module, sonographer, and PC. The generator serves as the central component connected by tubes to the pump, forming a closed circuit. A tee in the tubing set prevents Doppler fluid leakage, with the fluid poured through a special funnel into the circuit post-connection. The Doppler fluid is evenly mixed by shaking its bottle to enhance signal strength. The entire system is sealed. The centrifugal pump generates continuous flows; different power modes were tested for 30 minutes each, with frequency shifts measured at angles α=15°, 30°, and 60°. Pump disconnection from the power supply prevents liquid entry during tubing connection. The pump module housing includes ventilation holes. A 3 by 8 cm Doppler prism, treated with ultrasonic gel, was connected to the tubing to capture data. A sonographer emitting signals at 2 MHz, with a gain range of 10 to 40 dB, was utilized for sound spectra analysis. High-mode operation, 4 microseconds pulse duration, and a 32 microseconds receiver gate were set. The ultrasound apparatus dimensions were 230 x 236 x 168 mm, with a power consumption of 27 VA. Data visualization was facilitated by an LED panel, with adjustable acoustic signal volume. A USB interface enabled connection to a PC for ease of use and data analysis. Special software facilitated graph generation depicting frequency vs. time dependence measurements. Frequency analysis yielded average (f-mean) and maximum (f-max) frequency values, with f-mean utilized to measure Doppler effect frequency shift. The presented data showcases various pump speeds and incidence angles, each yielding distinctive frequency characteristics.
Keywords: ultrasonic, Doppler Effect, frequency shift, incidence angles, pump speed.

1. Introduction

In classical hydromechanics it is common to consider a fluid as a homogeneous medium. However, real environments surrounding us are most often heterogeneous, consisting of different components - liquid, solid and gaseous [1]. Examples of multiphase media are gas suspensions, aerosols, suspensions, emulsions, liquids with gas bubbles, composite materials, liquid-saturated soils, nanofluids and others. Interactions between phases can have a significant effect on flow dynamics, drag, and heat transfer [2]. For example, when flying at supersonic speeds in a dusty atmosphere, it is necessary to consider the effect of dust particles on the surface of the aircraft. When transporting hydrocarbons through pipelines, the presence of the gas phase can lead to the formation of plugs [3]. When it comes to the movement of blood through vessels, it is important to remember that blood is a multiphase medium in which plasma is the liquid phase and leukocytes, platelets, and red blood cells are suspended solids.

The description of motion in inhomogeneous media is a complex problem. To build a mathematical model, it is necessary to develop a technique for averaging flow parameters in such a way as to take into account several characteristic scales: molecular, macroscopic, and the scale corresponding to the size of inclusions [4]. Closure of the system of equations requires the development of models describing friction phenomena, energy transfer in different phases, and interphase interaction [5]. One of the most successful methods of analyzing the motion of moving structures is the ultrasound Doppler Effect, which is widely used in medicine. There are two main approaches to its application: the continuous wave method and the pulsed-wave method [6]. While conventional Doppler detectors can only detect the presence of motion, directional or pulsed-wave Doppler systems provide results with a higher level of detail.

The application of ultrasound of all things has aroused some interest. For example, a group of scientists [7-9] used a method to determine the refractive index of isolated solids by immersing them in liquids with a predetermined refractive index. However, such an effective method is not always practical. Other scientists [10] have examined the relationship between acoustic attenuation and the reflection coefficient of longitudinal ultrasonic waves, where the main idea was to determine surface parameters using either of the ultrasonic or reflection coefficients with negligible error.

Recently, research has been actively conducted to improve the accuracy of distance and velocity measurements using Doppler ultrasound by improving data processing techniques. Of particular interest is the high-precision velocity and distance measurement technique, which includes a special signal processing algorithm that uses oversampling using two modulated waves [11].

Therefore, This study investigates strategies to improve the accuracy of distance measurement with an ultrasonic transducer using improved Doppler technology.

2. Methods

Experimental studies were carried out with advanced equipment consisting of several parts: generator, tubing system, pump module, sonographer and PC. All setups manufactured from the P. Harris Company. The central part is the generator connected by tubes to the pump, which form a complete circuit. The tee of the tubing set was installed at the pump inlet point to prevent Doppler fluid from leaking out of the tee. Using a special funnel on the tee, the Doppler fluid is poured into the circuit once it is fully connected. The bottle of Doppler fluid is shaken to evenly mix the scattering particles. This procedure is necessary to obtain a stronger resultant signal during measurements. The entire system is completely sealed.

The centrifugal pump is capable of generating both continuous and pulsating flows. However, only continuous flows were used in this study. To generate continuous flows, the pump was operated in several modes for 30 minutes, depending on the % power fixed, which corresponds to the pump speed. For each speed, the frequency shift was measured at three different incidence angles (α=15°, 30° and 60°). When the tubing is connected, the pump is disconnected from the power supply to prevent liquid from entering the pump housing, which is especially important when filling the tubing system with liquid. The pump module housing is equipped with ventilation holes on the rear and bottom surfaces.

For this purpose, the sensor was connected to the corresponding prism surface. The 3 by 8 cm Doppler prism was mounted to the tubing using plates just behind one of its connectors, as these locations often experience vortices and flow turbulence. The transducer surfaces as well as the curved inner surface of the prism were treated with a special ultrasonic gel before installation to ensure good acoustic coupling and sufficient signal intensity between the prism and the tube.

A sonographer with a frequency range of 2 MHz emitted signals; a gain range varying from 10 to 40 dB was used to analyze the sound spectra. The power was determined by high mode of operation, with a pulse duration of 4 microseconds. The signal sampling volume was set to a high mode sampling volume with a full receiver gate of about 32 microseconds. The overall dimensions of the ultrasound apparatus were 230 x 236 x 168 mm, making it compact and mobile in use. The basic supply voltage of the device was standard 220 volts at a frequency of 50/60 Hz, and its power consumption is 27 volt-amperes (VA). To visualize the obtained data, the apparatus is equipped with an LED panel and also provides the possibility of adjusting the volume of the acoustic signal. To ensure ease of use and data analysis, the ultrasound pulsed Doppler device is equipped with an interface for connection to a personal computer via USB.

With the help of special software designed for visualization of data from the sonographer, graphs of frequency vs. time dependence measurement were obtained. Data processing, including curve fitting and statistical evaluation, was performed using MATLAB R2020a. Nonlinear least squares regression tools were employed to model the relationship between Doppler frequency shifts, pump power, and incidence angles. The accuracy and consistency of the models were verified through residual diagnostics and coefficient of determination (R^2), ensuring the statistical reliability of the results.

3. Results and Discussion

It is known that for sound waves, the observed frequency varies depending on whether the sound source is moving toward a resting observer or the observer is approaching a resting source. Figure 1 shows the current scattering intensity obtained from the sonographer. For deeper analysis of the received data it is necessary to perform decomposition of the signal into spectra (Figure 2). Based on the spectral analysis, two frequency characteristics are determined - the average value f-mean and the maximum value f-max. These values are determined and displayed. In the context of a Doppler experiment, the average frequency value (f-mean) is used as a measure of the frequency shift due to the Doppler Effect.

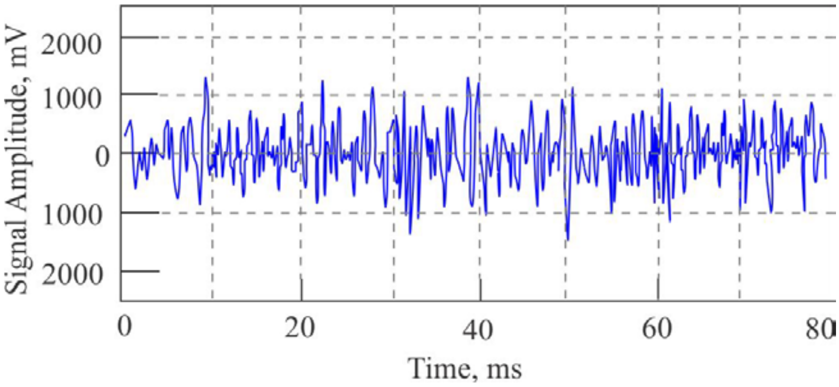

Figure 1 – Current scattering intensity of flow

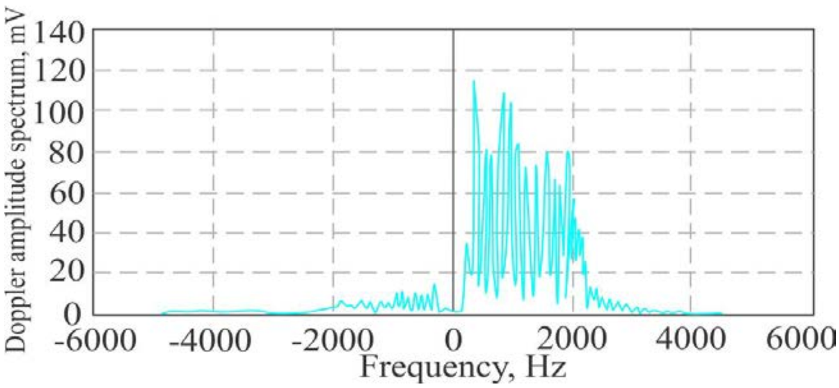

Figure 2 – Decomposition of the signal into spectra

Let us consider the process of the Doppler Effect in our pipe system, which is schematically represented in Figure 3. First of all, a pulse is generated along the fluid flow for a certain time T_1 of its flow. At the same time, the second impulse is transmitted against the flow for the time fixed as T_2.

Using the resulting difference in pulse transit time Δt, the flow velocity v was calculated. As a result of the calculation, the volumetric flow rate was calculated based on the flow velocity and the cross section of the tube. Thus, using that c is the speed of sound in the medium, the following can be done:

$$c_1 = c + \vec{v}cos\alpha \tag{1}$$
$$c_2 = c + \vec{v}cos\alpha \tag{2}$$
$$\Delta t = T_2 - T_1 = \frac{L\vec{v}cos\alpha}{c^2 - v^{-2}\, cos^2\alpha} \approx \frac{L\vec{v}cos\alpha}{c^2} \tag{3}$$

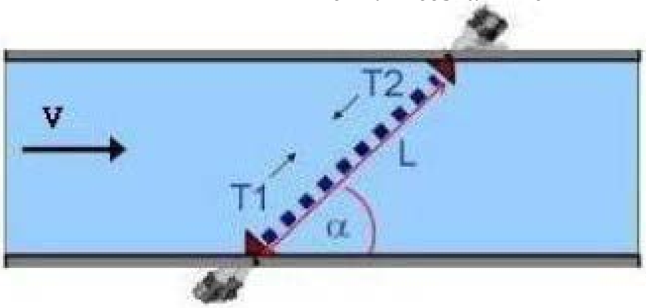

Figure 3 – The process of the Doppler effect in pipe system

In this case, it is important to take into account that the parameters of signal intensity I, c и $cos\alpha$ must be known, and that the sound speed c is a function of the temperature of the medium, and this dependence must be taken into account in calculations or measurements.

This method has several advantages. Firstly, it allows measurements even with large cross-sections. Secondly, it does not require the construction of a special cross section. In addition, it allows measurements in non-conductive and contaminated liquids, which further extends the scope of its application and provides ease of use. However, it should be considered that the use of clamp-on sensors allows measurements to be made in reflection mode Figure 4. That is, the Doppler method measures the frequency shift that occurs when a sound wave scatters on small particles or impurities. Thus, the incident ultrasonic wave with a certain frequency on a moving object leads to a frequency shift f_0.

When the velocity of an object v is negligible compared to the speed of sound c in the medium, the following occurs:

$$\Delta f = f_0 \frac{v}{c}(cos\alpha - cos\beta) \tag{4}$$

Where: α and β are angles between v and the wave normal. For a pulsed echo system with an ultrasonic transmitter, where the transmission and reflection coefficients are equal $\alpha = \beta$, hence:

$$\Delta f = 2\, f_0 \frac{v}{c} cos\alpha \tag{5}$$

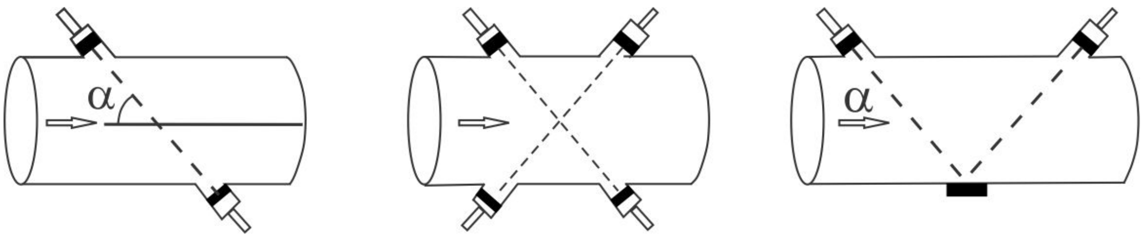

Figure 4 – Scheme of flow in the pipe cross-section

When calculating by formula (2), it is necessary first of all to determine the Doppler angle α, which is determined by the angle of incidence α_{P} on the prism.

When sound propagates from the prism into the liquid, the angle changes according to the law of refraction and depends on different sound velocities. The tube wall is assumed to be a plane-parallel layer, which allows it to be omitted in the calculations. According to the law of refraction, the Doppler angle can be calculated as follows:

$$\alpha = \ 90^o - \arcsin\left(sin\alpha_P \frac{C_L}{C_P}\right) \tag{3}$$

Where: α_{P} – denotes the angle of incidence, C_P – denotes the speed of sound in the prism, and C_L – denotes the speed of sound in the fluid. Using formulas 2 and 3, the flow characteristics presented in Table 1 were calculated.

Table 1 – Calculated flow characteristics

Pump, %	Angle, °	F – mean, Hz	Doppler angle α,	$\cos\alpha$, °	$v, \frac{sm}{s}$
30	15	185	80.0	0.17	47.71
50	15	285	80.0	0.17	73.50
70	15	405	80.0	0.17	104.45
30	30	342	70.3	0.34	45.66
50	30	515	70.3	0.34	68.75
70	30	700	70.3	0.34	93.45
30	60	570	54.3	0.58	43.93
50	60	920	54.3	0.58	70.91
70	60	1320	54.3	0.58	101.74

Figures 5 and 6 show the dependence of Doppler shift on frequency and velocity, respectively, for set angles of 15 30 and 60 degrees.

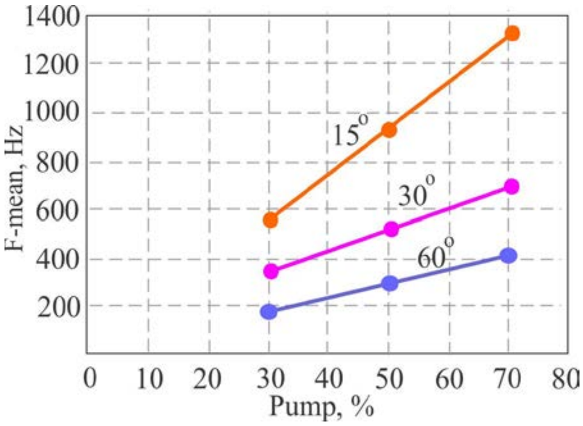

Figure 5 – Dependence of Doppler shift on frequency

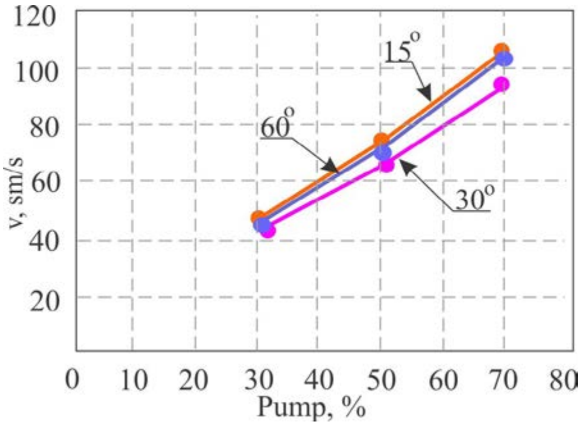

Figure 6 – Dependence of Doppler shift on velosity

Figure 3 demonstrates that the Doppler frequency shift increases with increasing pump speed as well as decreasing Doppler angle. A similar increase in shift is observed for all angle values between 15 and 60 degrees. Figure 4 shows the calculated velocity, which demonstrates that for any given velocity, the coefficient $\Delta f/\cos(\alpha)$ remains nearly constant, indicating that there is no measurement error as a function of angle.

4. Conclusions

In conclusion, the experimental investigation conducted with advanced equipment, including a generator, tubing system, pump module, sonographer, and PC, and provided valuable insights into the Doppler Effect phenomenon. The meticulous design and operation of the experimental setup ensured accurate measurements and robust data acquisition. Through careful control of pump speed and Doppler angles, the study systematically explored the relationship between Doppler frequency shift and varying experimental parameters. The results revealed significant trends, including an increase in the Doppler frequency shift with higher pump speeds and decreasing Doppler angles 15°, 30°, 60°. Furthermore, the analysis demonstrated the consistency of the coefficient $\Delta f/\cos(\alpha)$ across different velocities, indicating the absence of measurement errors as a function of angle. Overall, these findings contribute to a deeper understanding of the Doppler Effect and its implications in fluid dynamics research and medical diagnostics. The comprehensive methodology and rigorous data analysis underscore the reliability and significance of the experimental findings presented in this study.

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Author Contribution:
Alima Aidarbek – concept, methodology, resources, data collection, testing, modeling, analysis, visualization, interpretation, drafting, editing, funding acquisition.

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Post-Publication Notice

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In the originally published version of this article, the Methods section did not provide sufficient information regarding the equipment manufacturers, data processing tools, and statistical evaluation of results. The following corrections have been introduced:

1. Section 2 (Methods):

- The updated text now specifies that all setups were manufactured by P. Harris Company and data analysis was performed using MATLAB R2020a.
- Details on nonlinear least squares regression modeling, residual diagnostics, and coefficient of determination (R^2) evaluation have been added.
- These clarifications enhance reproducibility and confirm the statistical reliability of Doppler measurement results.

2. Editorial improvements were made to refine technical descriptions and improve methodological transparency.

Additionally, Figure 4 has been improved to enhance visual clarity and data representation.

Also, the reference "Ultrasonic evaluation of geometrical and surface parameters of rough defects in solids / M.D. Billy, F. CohenTénoudji, G. Quentin, K. Lewis, L. Adler // Journal of Nondestructive Evaluation. — 1980. — Vol. 1, No. 4. — P. 249–261." has been replaced with "Optimization extraction and characterization of: Artemisia ordosica polysaccharide and its beneficial effects on antioxidant function and gut microbiota in rats / Y.Y. Xing, Y.Q Xu, X. Jin, L. L. Shi, S. W. Guo, S. M. Yan, B. L. Shi // RSC Advances. — 2020. — Vol. 10, No. 44. — P. 26151–26164. https://doi.org/10.1039/d0ra05063f".

These corrections do not alter the findings, discussion, or conclusions of the study but strengthen the rigor and clarity of reported experimental procedures.

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