Ultrasonic Doppler Effect: Flow Measurements

(Item No.: P5142100)

Curricular Relevance

Area of Expertise: Applied Sciences Engineering

Education Level: University

Topic: Applied Mechanics

Subtopic: Fluiddynamics and Aerodynamics

Experiment: Ultrasonic Doppler Effect: Flow Measurements

Difficulty	Preparation Time	Execution Time	Recommended Group Size
Difficult	20 Minutes	2 Hours	2 Students

Additional Requirements:

- PC

Experiment Variations:

Keywords:

Doppler effect, Doppler sonography, Frequency shift, Scattering

Overview

Principle

The aim of this experiment is to study the relationship between the ultrasonic Doppler effect and the flow velocity or the Doppler angle.

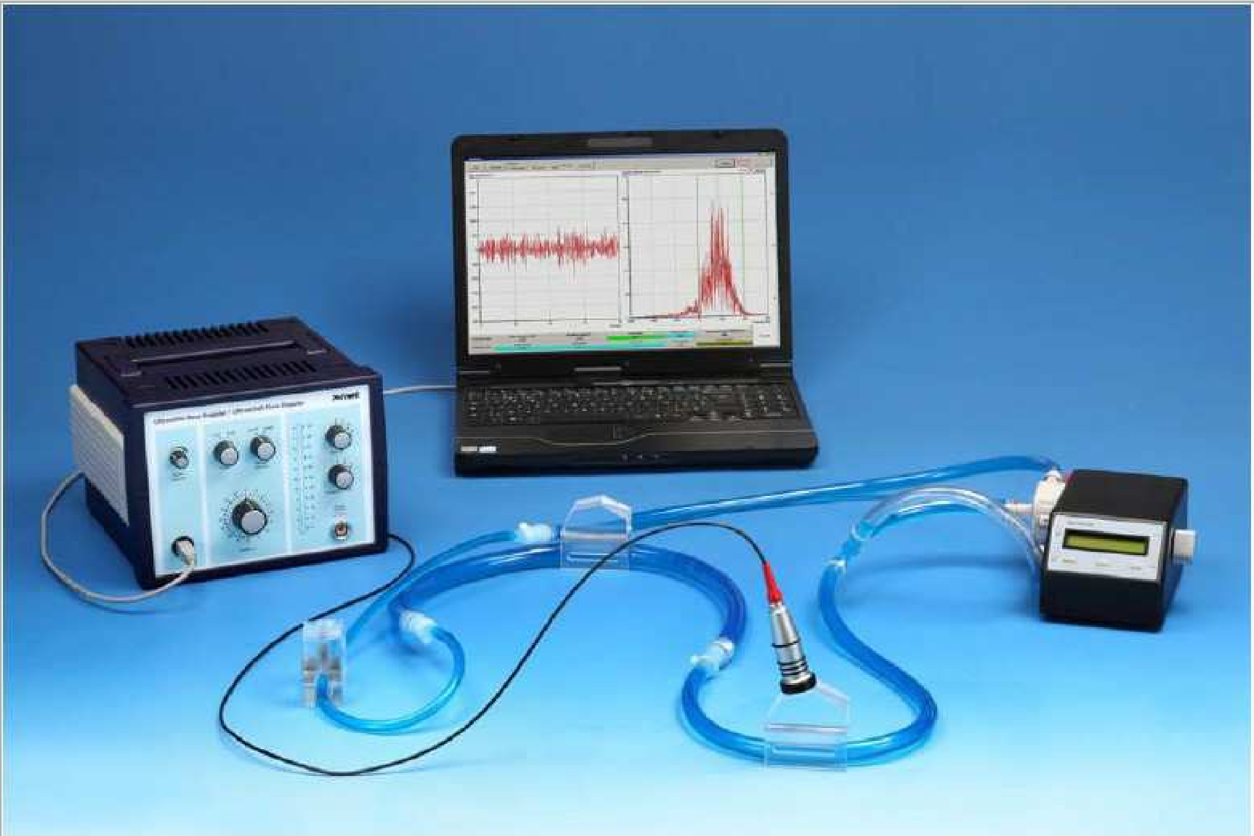

Fig. 1: Setup for P5142100 Ultrasonic Doppler Effect: Flow Measurements

Equipment

Position No.	Material	Order No.	Quantity
1	Basic set Ultrasonic Doppler technique, consisting of:	13923-99	1
	Doppler ultrasound unit		1
	centrifugal pump		1
	ultrasound gel		1
	sonography liquid, 1 l		1
	ultrasonic probe, 2 MHz		1
	Doppler prism, 3/8		1
	set of tubes		1
	software "measure ultraflow"		1
Additional material			
	PC with USB port, Windows XP or higher		1

Tasks

1. Measure the frequency shift as a function of the flow velocity and angle of incidence.
2. Use this value to calculate the flow velocity.
3. Represent the frequency shift in graphic form as a function of the pump speed.

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Set-up and procedure

Instructions for using the centrifugal pump

The centrifugal pump can generate continuous as well as pulsating flows. For the Doppler experiment, however, only continuous flows are used. For this purpose, the pump is used in the M0 or M1 mode. The flow can be started and stopped with the buttons "START" and "STOP". The rotary knob on the right-hand side determines the flow velocity. We recommend turning the rotary knob completely to the left (minimum) prior to starting a measurement. Then, when the "START" button has been pressed, increase the pump speed slowly (please also refer to the safety instructions).

In the M0 mode, the pump power is displayed in %. This corresponds to the pump speed, with 100% being the maximum speed. In the M1 mode, the flow rate is displayed in l/min. This value must be recalibrated for every circuit since the flow resistance changes. (The flow rate can be calibrated with the "START" button and the small rotary knob on the left-hand side of the pump. For a more detailed description, please refer to the operating instructions of the pump.)

Safety instructions

When connecting the tubes to the pump, we recommend disconnecting the pump from the power supply (unplug the mains power plug). This is particularly important when filling the tube system with the fluid. The pump should be put aside during this process in order to ensure that no fluid can penetrate the pump housing. Prior to switching the pump on, turn the "SPEED" controller to the front until it reaches the stop (counter-clockwise). After the pump has been switched on, slowly increase the speed in order to prevent the fluid from splashing out, when the tube system is still open, or to prevent the pump from sucking in air.

The housing of the pump module has vent holes at the back and at its bottom surface. Do not cover these vent holes.

ATTENTION: The pump is not suitable for continuous operation at maximum pump speed. The runtime at 100% speed should be limited to 30 minutes maximum.

We suggest that the experiment is set up by lab course staff since first-time set-up is very time-consuming and error-prone. This applies particularly in filling the tube system with the sonography liquid. When the experiment is not in use for a longer time, be aware that the glass beads in the sonography liquid sediment. In this case, bringing the beads into solution again will take some time, with repeated switching on and off of the pump.

Set up the experiment as shown in Fig. 1.

Set-up and filling of the circuit:

First, a circuit is set up with the aid of the set of tubes and the centrifugal pump. The tee of the tube set should be located at the entry point into the pump. If this is not the case, the Doppler fluid may splash out of the tee if the circuit is open and the speed is too high. Once the circuit is complete, it must be filled with Doppler fluid with the aid of a funnel on the tee. Prior to filling the fluid into the circuit, shake the bottle with the Doppler fluid vigorously in order to stir up the scattering particles. If there are not enough scattering particles in the circuit, the resulting scatter signal may be too low for the measurements. When filling the circuit, try also to produce as few air bubbles as possible. Since this cannot be completely avoided, the bubbles should be guided to the tee after filling in order to remove them from the circuit. This can be achieved by slightly lifting the tube element or by letting the pump run at low speed. As a result, the bubbles will move and they can be separated at the tee. When the circuit is filled completely, we recommend sealing the tee with a stopper.

Doppler prism and transducer:

Next, couple the Doppler prism to the tube. We use the 3/8" prism for the experiment. The place for attaching the prism should not be located directly behind one of the connectors or behind a strong curvature of the tube since these areas are often subject to eddies and turbulences in the flow, which might affect the measurement results. The ideal solution is to have a long, straight piece of tube before the measuring point.

Prior to attaching the prism, apply a film of ultrasound gel to its curved inner surface. This is necessary in order to achieve a good acoustic coupling between the prism and the tube. Secure the prism on the tube with the aid of the plate.

In the next step, the surface of the transducer or the corresponding surfaces of the prism must also be treated with gel. Ensure that there is always a sufficient amount of gel between the transducer and the prism during the measurement in order to ensure sufficient signal intensity.

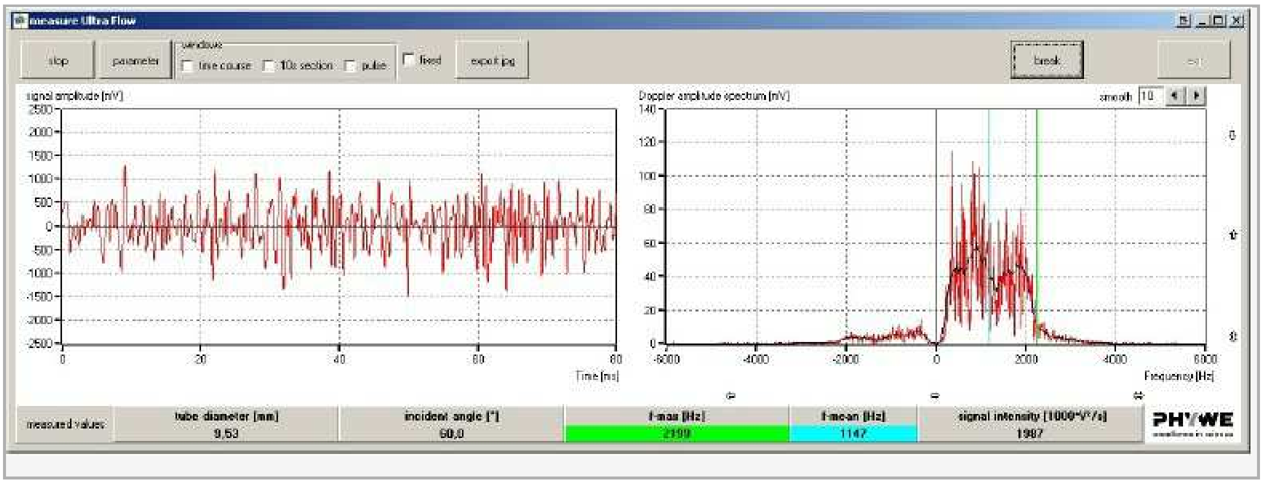
Plug the connector of the transducer into the probe socket of the Doppler sonograph.

Doppler sonograph:

First, set the transducer frequency that is used (2 MHz) at the Doppler sonograph.

The correct setting of the "Sample Volume" switch is also important. For the Doppler experiment, it must be set to "Large". (In the case of "Small", signals would be measured only of a small part of the tube. If the switch is set to "Large", the "Depth" controller has no effect. This is correct since it is not required for the Doppler experiment.) The "Power" controller can be used to vary the transmission power. "Gain" controls the reception gain. "Power" and "Gain" should always be set so that the signal intensity that is displayed by the software is sufficiently high without overshooting. Do not change the settings during the measurement if you can avoid it. The sound volume of the acoustic measurement signal can be controlled with the "Audio Volume" controller.

Software:



The software reads the measurement data from the Doppler sonograph and represents it in graphical form. The left window shows the current scattering intensities, while the window on the right-hand side shows the spectrum of these data. Based on the spectrum, two frequency values – f-mean and f-max – are determined and displayed. For the Doppler experiment, the f-mean value is used. It is the measure of the frequency shift due to the Doppler effect.

Procedure

At the centrifugal pump, three different flow velocities are set in %. For each of these velocities, the frequency shift is measured at the three different angles of incidence (α_P = 15°, 30°, and 60°). For this purpose, the transducer is coupled to the corresponding prism surface (do not forget the gel). Then, the frequency value f-mean can be read in the software. These values are documented together with their respective angles:

Pump [%]	30	30	30	50	50	50	70	70	70
Angle of incidence	15°	30°	60°	15°	30°	60°	15°	30°	60°
F-mean [Hz]	185	342	570	285	515	920	405	700	1320

Note: Maintenance

After the measurement, the tubes and Doppler prism must be cleaned in order to remove the ultrasound gel. Do not use any aggressive cleaning agents or alcohol since these substances may damage the acrylic glass of the prism. Simply use a moist cloth instead.

Theory and evaluation

Flow measurements can be performed with numerous different processes and methods.

A simple yet highly effective method is gauging the capacity in litres. During this process, measure how long it takes to fill a vessel of a known volume (e.g. a measuring jug). If you then divide this volume by the time needed, you will directly obtain the flow rate in l/min or ml/s.

A disadvantage of this method is that it is not very suitable for continuous measurements. However, it can be used in laboratories for calibrating other measuring methods or equipment.

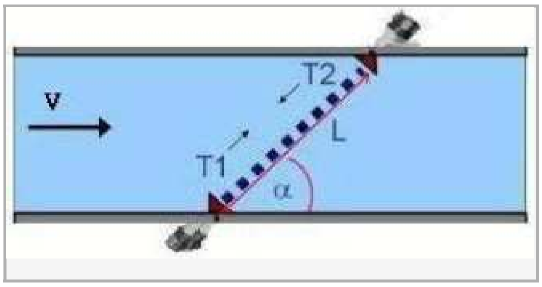
Floats are an example of mechanical flow meters. In a vertical, tapered tube with the widest part at the top, a float is lifted upwards against the gravitational force due to the friction with the liquid. The flow velocity of the liquid decreases towards the top since the cross-section of the tube increases. If the frictional force and the gravitational force balance each other out, the float then floats.

Rotary-vane flow meters are another example of mechanical flow meters. In these flow meters, a hydrometric vane is rotated by the inflowing liquid. The higher the flow velocity is, the more quickly the vane rotates. This rotation can be measured very well as a frequency with the aid of a pulse generator and, thereby, provides an electrical signal that can be evaluated very easily.

Both methods strongly depend on the viscosity, which is why they must be recalibrated for every new liquid. They are not only applied in combination with liquids but also with gases.

Today, ultrasonic flow meters are used in numerous industrial, medical, or research-related fields. Most widely used are ultrasonic flow meters in which the evaluation is based on the measurement of the time of flight. They make use of the fact that sound waves are entrained in flowing media and, thereby, of the directional, effective velocity of sound propagation. Similar to a float that moves against the flow, ultrasound moves slower against the direction of flow of the medium than it does with the flow.

First, a pulse is transmitted with the flow and its time of flight T_1 is measured. Then, the time of flight T_2 of a second pulse, which this time is transmitted against the flow, is measured. The determination of the difference in time of flight Δt enables the calculation of the flow velocity v. The volume flow results from a calculation based on the flow velocity and tube cross-section.



With c as the sound velocity of the medium, the following applies:

$$c_1 = c + \vec{v} \cos \alpha$$

$$c_2 = c - \vec{v} \cos \alpha$$

$$\Delta t = T_2 - T_1 = \frac{L\vec{v}\cos\alpha}{c^2 - \vec{v}^2 \cos^2\alpha} \approx \frac{L\vec{v}\cos\alpha}{c^2}$$

L, c, and $\cos\alpha$ must be known and it must be taken into consideration that c is temperature-dependent.

The advantages of this method are that measurements can be performed even with large cross-sections, cross-sectional constructions are not required, and measurements can also be performed in combination with non-conductive and dirty fluids. However, the generation and evaluation of the ultrasound signals require a certain effort.

In the field, numerous different arrangements can be found. Apart from a simple through-transmission of sound, measurements can also be performed crosswise or in the reflection mode.

Clamp-on sensors are particularly versatile. They are simply clamped on the tubes and measure in the reflection mode.

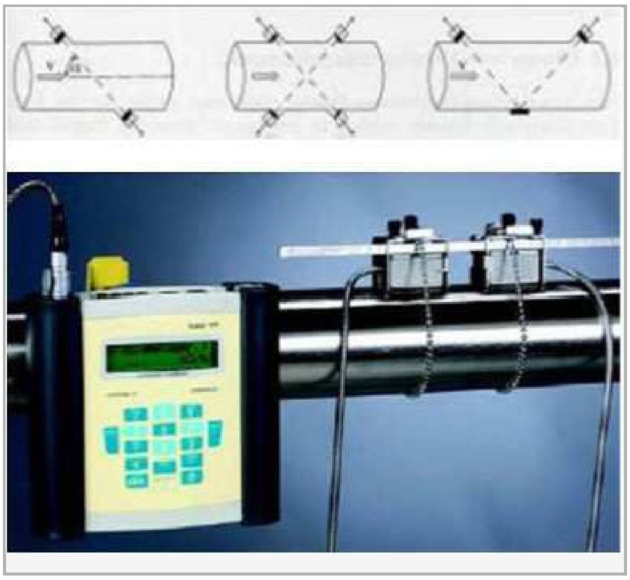
If the Doppler method is applied, the frequency shift that occurs when the sound wave is scattered at small particles or impurities is measured. If an ultrasound wave with the frequency f_0 hits a moving object, this causes a frequency shift due to the Doppler effect. For a small velocity of motion v of the object compared to the sound velocity c in the medium, the following applies:

$$\Delta f = f_0 \frac{v}{c} (\cos\alpha + \cos\beta) \quad (1)$$

α and β are the angles between v and the wave normal. For a pulse-echo-system with an ultrasound transmitter $\alpha = \beta$ and therefore:

$$\Delta f = 2 f_0 \frac{v}{c} \cos\alpha \quad (2)$$

The Doppler effect is used in medical diagnosis when motions and moving structures are examined. One distinguishes the CW (continuous wave) method and the pulsed-wave Doppler method. While simple Doppler detectors can only detect motions, directional systems or pulsed-wave Doppler systems provide results with a higher level of differentiation. Doppler sonography as a diagnostic method is mostly applied for the detection of the flow of blood in arteries and veins. With this method, the flow of blood can be detected and assessed qualitatively and quantitatively in a non-invasive manner. With pulsed-wave Doppler units, not only the velocity of motion of a particle but also its distance with regard to the sound transducer can be determined. The combination of pulsed-wave Doppler and real-time B-scan systems enables the anatomical assignment of the sample volume in the sectional image. These types of systems are predominantly used in cardiology and foetal diagnosis.



Results

In order to be able to use the Doppler formula (2), we must first determine the Doppler angle α . The angle of incidence α_{P} of the prism is known. When the sound propagates from the prism into the liquid, the angle changes in accordance with the law of refraction and as a function of the different sound velocities. (In order to simplify things, we assume that the tube wall is a plane-parallel layer, which allows us to omit it from the calculations).

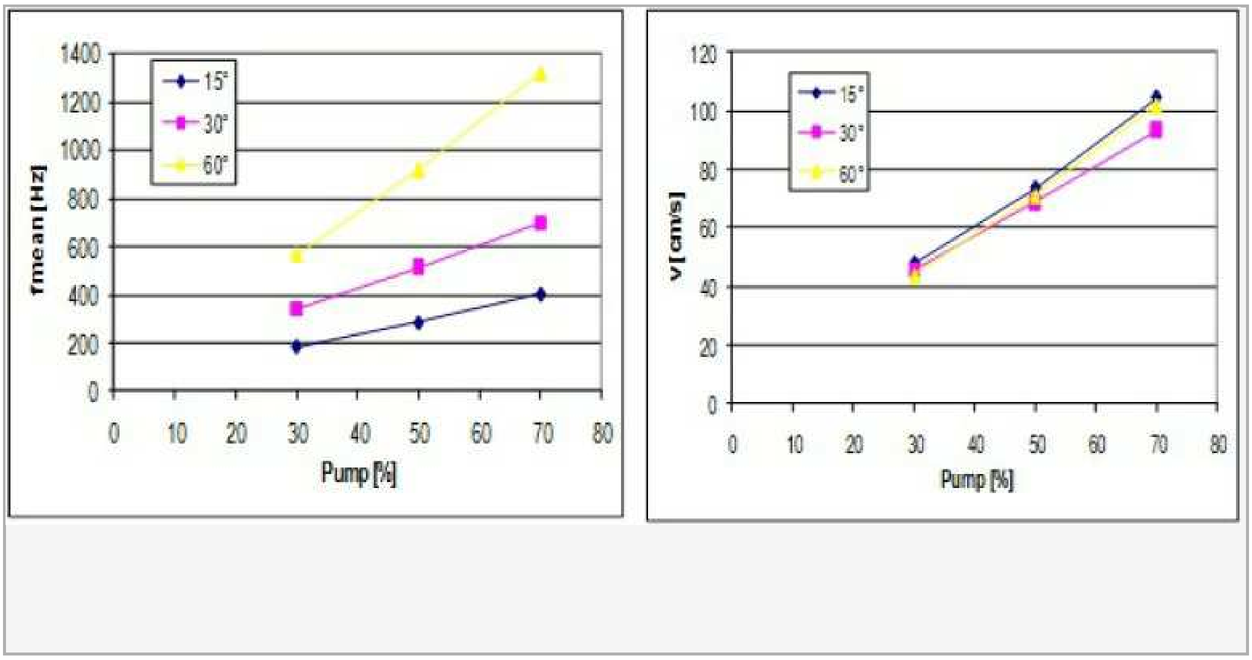
Based on the law of refraction, the Doppler angle results as:

$$\alpha = 90^{\circ} - \arcsin\left(\sin\alpha_{\mathrm{P}}\frac{c_{\mathrm{L}}}{c_{\mathrm{P}}}\right) \quad (3)$$

Here, α_{P} is the angle of incidence, c_{P} is the sound velocity in the prism, and c_{L} is the sound velocity in the liquid.

This equation and the Doppler equation (2) can now be used to calculate the flow velocity.

f_0 = 2 MHz			C_P [m/s] = C_L [m/s] = C_L [m/s] =	2670 1800 1480	Acrylic glass Doppler fluid water	
Pump [%]	Angle [°]	F-mean [Hz]	Doppler angle α	Doppler angle α [°]	$\cos(\alpha)$	v [cm/s]
30.0	15°	185	1.40	80.0	0.17	47.71
50.0	15°	285	1.40	80.0	0.17	73.50
70.0	15°	405	1.40	80.0	0.17	104.45
30.0	30°	342	1.23	70.3	0.34	45.66
50.0	30°	515	1.23	70.3	0.34	68.75
70.0	30°	700	1.23	70.3	0.34	93.45
30.0	60°	570	0.95	54.3	0.58	43.93
50.0	60°	920	0.95	54.3	0.58	70.91
70.0	60°	1320	0.95	54.3	0.58	101.74



The diagram on the right-hand side shows the calculated velocity. It shows that for any given speed, the quotient of Δf/cos(α) is nearly constant, i.e. there is no angle-dependent measurement error.The diagram on the left-hand side shows that the Doppler frequency shift increases when the pump speed increases and also when the Doppler angle decreases.