Design and Simulation of Ultrasonic Blood Flow Measurement Using Discontinues Galerkin and Finite Element Method

Pratyusha Kolluri and Sitaramanjaneya Reddy Guntur

January 27, 2022

Design and Simulation of Ultrasonic Blood Flow Measurement Using Discontinues Galerkin and Finite Element Method

Pratyusha Kolluri
Department of Electronics and Communication Engineering,
Vignans Foundation for Science, Technology, and Research, Vadlamudi, Guntur 522213, India.
Email: sajjapratyusha09@gmail.com

Sitaramanjaneya Reddy Guntur
Department of Electronics and Communication Engineering and Biomedical Engineering,
Vignans Foundation for Science, Technology, and Research, Vadlamudi, Guntur 522213, India.
Email:drgsr_ece@vignan.ac.in

Abstract— **The Ultrasonic Flow Meter accesses the average velocity of flow transmission and receiving from the flow sensors. This attribute has been used for decades to ensure accurate measurement of fluid flow parameters. In many fields, the transit-time difference flow meter (TTDF) is used to measure the flow rate of oil, liquids, and gases. Ultrasound technology detects disease by measuring blood flow velocity, among which TTDF provides accurate results based on average blood velocity. In this paper, a simulation model of TTDF for water and blood is developed and tested using COMSOL Multiphysics coupled with Finite Element Method (FEM). This study models the propagation of acoustic waves according to time of flight (ToF) using discontinuous Galerkin (dG), and FEM analysis. The model determines the acoustic pressure and velocity for the ToF of different time intervals.**

Keywords—ultrasonic flow meter, transit-time, COMSOL, FEM.

I. Introduction

The ultrasound technology is the most preferred and significant technique across the globe because of its non-invasiveness. Ultrasound systems are more advantageous due to its non-intrusiveness, easy installation, and operation. Moreover, outputs obtained from those systems are accurate and can be easily analyzed. Due to these ultrasonic systems are gaining more popularity currently owing to its tremendous significance. The non-invasive method is used to determine the flaws of the flow of fluid that can be used for a wide array of applications such as oil, liquids, gasses, and in many other areas. Prior to this, the method which was used to measure the flow of fluid is an intrusive method has some limitations. The limitations are mainly due to interference in the flow, which causes pressure loss while measuring flow values that leads to an inaccuracy in measurement and the flow pipe must be drilled to insert the apparatus, which might get damaged due to the flow of fluid. This invasive method needs precise installation procedures and measurements. However, non-invasive measurement plays a pivotal role in measuring with less pressure drop and low maintenance [1-3].

The ultrasonic flow is frequently utilized for non-invasive measurement of the blood flow in arteries and veins. The measurement of human blood rheology and hemostasis plays a crucial and important role in the survival of life. Various conventional and advanced techniques are available for the measurement of blood flow in order to detect abnormalities. The measurement of blood velocity and flow rate of blood flow is predominant during clinical diagnosis and pathological state [4,5]. Basically, the blood flow measurement in arteries and veins is most significant to assess the functioning of blood vessels in cardiovascular diseases, heart valves thrombosis, atherosclerosis, and varicose veins. It can also be used to recognize flow velocity in the brain, retina, vascular damage, extremities, and vascular surgeries [6]. There are a few conventional blood flow estimation methods, such as the electromagnetic flow method, the Plethysmography method, etc. [7,8].

Moreover, certain types of mechanical blood flow meters and blood flow transducers are generally utilized in clinical investigations and other applications [9]. Nevertheless, the less spatial resolution of conventional techniques cannot measure the parameters and address the individual problems. Meanwhile, very few methods show better accuracy in measurements, and because of these better techniques are required. Numerous techniques are coming up to measure the blood flow average velocity to improve the resolution, non-invasiveness, and rapid test of which includes accumulation and diffusion techniques. So, the feasibility of flowmeters are as discussed above, the transit-time method determine the flow speed when an ultrasonic signal is transmitted through the main pipe flow to non-invasively determine its speed.

II. Ultrasonic flow sensor technique

A Transmit – Time difference Ultrasonic flow meter is used for the measurement of flow velocity. Apart from these, the transit-time flow meter is significant in measuring nanosecond time intervals and the nonexistence of moving parts [7,9]. TTDF elucidates the difference between the time of ultrasonic pulses propagating with and against the direction of flow as shown in Fig. 1. The time difference is measures for the average velocity of the fluid along the path of the ultrasound beam. The transit time method consists of two transducers as transmitter and receiver. During the upstream cycle, the ultrasound beam travels through the flow of the fluid and total transit time is increased by a flow-dependent amount. During the downstream cycle, the sound beam travels along with the flow, and the total time is decreased by the same flow-dependent amount. The time difference between downstream and upstream is the measurement of true volume flow [10]. The distance of ultrasonic waves between the transducer is Tu and Td.

$$d = \frac{2D}{Sin\ \alpha} \tag{1}$$

Therefore, the measured transmission time of signal from the source to the receiver is

$$T_d = \frac{2D}{Sin\ \alpha} \cdot \frac{1}{c + v\cos\alpha} \tag{2}$$

Therefore, the measured transmission time of signal from the receiver to the source is

$$T_u = \frac{2D}{Sin\,\alpha} \cdot \frac{1}{c - v\,cos\,\alpha} \tag{3}$$

where, v is the velocity of flow, T_u & T_d are two transducers, D is the distance of sound waves, α is the angle of the symmetric plane along to the flow of the pipe. The averaged flow rate measured by the velocity is

$$F = Av \tag{4}$$

Where F stands for flow rate, m^3/s, A is the area of the tube, $A = \pi r^2$, m^2, v is the velocity of the fluid, m/s.

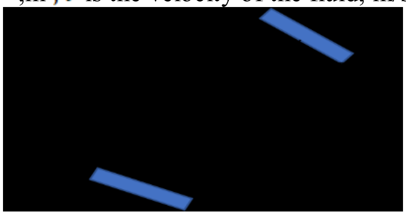


Fig. 1. A schematic represents the Transit-Time Difference Flowmeter

As of late, the transit-time stream technique has been utilized with expanding recurrence in the cardiovascular medical procedure. The use of travel time stream estimation is quick and straight forward even under surgical conditions, and artifacts influence results less severely than in other methods [9,12]. TTDF meter achieves the accuracy with 0.5-1% of full scale and concentration of liquids with particles are minimum (<30%).

III. SIMULATION MODELS

The most essential measurement of flow parameters is calculated when the sensors are fixed opposite to each other at an angle of incidence and the time-of-flight of the wave propagation is determined by taking the Z-type configuration of transit time flow meter technique. The present work specifies the design procedure of the simulation model together with the results of the magnitude and amplitude of the velocity of traversed time by the wave propagation from source to receiver.

A. The geometry of the model

The Z-type transit time flow meter is designed in working geometry and generates a mesh with ~~a~~ study that gives results to the designed model. The design considerations require a fluid flow pipe and transducers connected at opposite ends of the pipe. The geometric dimensions of fluid flow pipe are created with a cylinder type model having a length of 200mm and a diameter of 50mm to transmit the wave propagation and another cylinder is taken at the length of 113mm and diameter of 20mm. The rotation angle of 45° is connected to the transducer chambers and the cylinder geometry is set as to take into consideration to travel the propagation of the wave in the right direction between the transducers as shown in Fig. 2

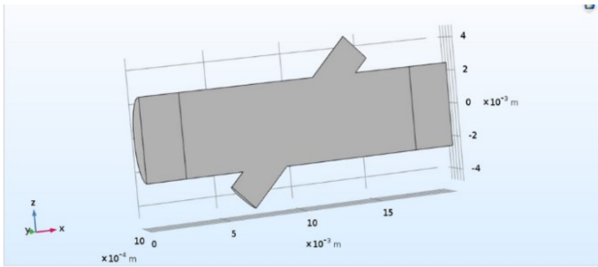


Fig. 2. Geometric configuration of a 2-D numerical simulation model of ultrasonic field exposed to fluid flow

B. Physiscs applied to the model

The model is simulated by using COMSOL Multiphysics, which can build the models based on different physics on one single platform. This software provides a complete design model and simulates in different modules and physics. It helps to check the performance of the system and develop new ideas [11]. The COMSOL Multiphysics (Version 5.3a, COMSOL Inc., Los Angeles, CA 90024, USA) is employed to design and simulate the model of Z-type configuration of transit time techniques by initializing two different modules as computational fluid dynamics (CFD) with turbulent flow and acoustics with the convicted wave equation, time explicit. The CFD defines and solves the model systems containing fluid flow and relates it with physics. The CFD module supports both the laminar and turbulent flow model simulations. The turbulent flow is calculated using the Reynolds-Averaged Navier-Stokes equations (RANS), which average the velocity and pressure in the time stated as

$$\rho(U.\Delta U) + \nabla.\left(\mu_T(\Delta U + (\nabla U)^T) - \frac{2}{3}\mu_T(\nabla.U)I\right) = -\nabla P + \nabla.\left(\mu(\nabla U + ((\nabla U)^T)) - \frac{2}{3}\mu(\nabla.U)I\right) + F \tag{5}$$

where, μ_T is the averaged turbulent velocity, ρ is the density, U and P are velocity and pressure, respectively. Another module used to simulate the acoustics, which supports the convected time explicit wave equation. This module not only suits for modeling linear sound wave applications but also consists of a stationary background flow. The innovation behind this interface originates from the discontinuous Galerkin (dG) strategy, called dG-FEM. The absorbing layers are included in the interface to set up effective nonreflecting boundary condition, this interface exists in 3D, 2D axisymmetric, and 2D. The governing equations solved by the convicted wave equation, Time explicit, and interferences are calculated by the Linearized Euler equations that can be represented by the equations.

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho u_0 + \rho_0 u_o) = 0 \tag{6}$$

$$\frac{\partial \rho}{\partial t} + (u_0.\nabla)u + (u.\nabla)u_0 + \frac{1}{\rho_0}\nabla p - \frac{\rho}{\rho_0^2}\nabla p_0 = 0 \tag{7}$$

$$p = c_0^2 \rho \tag{8}$$

where, ρ_0, u_0, and p_0 are the steady-state mean background flow variables of density, velocity, and pressure, respectively.

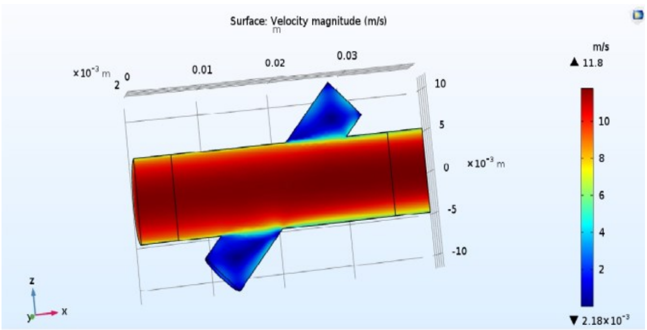
C. *Materials of the model*

To consider a reasonable delineation of the ultrasonic wave proliferation, the material affixed to the geometry for the conventional TTDF was considered as water with the speed of sound C_0 is 1481m/s and the medical applications are taken as blood with the speed of sound 1578.2m/s, where its properties are added to a blank material in the model.

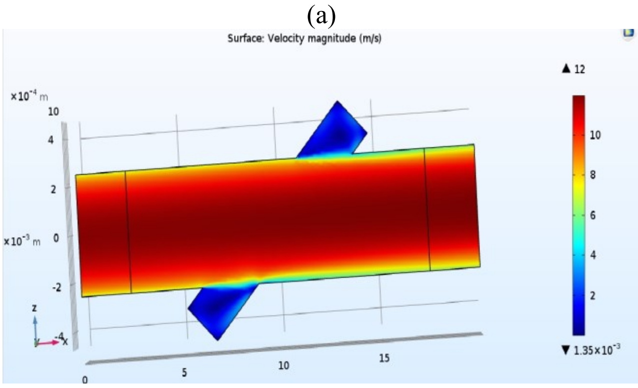
IV. SIMULATION RESULTS

A. *Turbulent Flow*

The simulation results of the predicted background mean flow average velocities along the pipe in water (Fig. 3. a) and blood (Fig.3. b) is shown in Fig. 3. The average flow velocity from one end to the other end through the pipe is estimated by using turbulent k-ε (SPF). The approximate estimation of time at which the two signals reach the receivers can be calculated by using the mean speed of the background flow. For this, the turbulent flow with Reynolds's number is considered as $5x10^4$.The 3D display of average flow velocity in water and blood is noted as 11.8m/s (Fig.3a) and 12m/s(Fig.3b), respectively.



(a)



(b)

Fig. 3. Turbulent flow of the transit-time flow meter: (a) Velocity find in water, (b) Velocity find in blood

B. *Acoustic Wave Propagation*

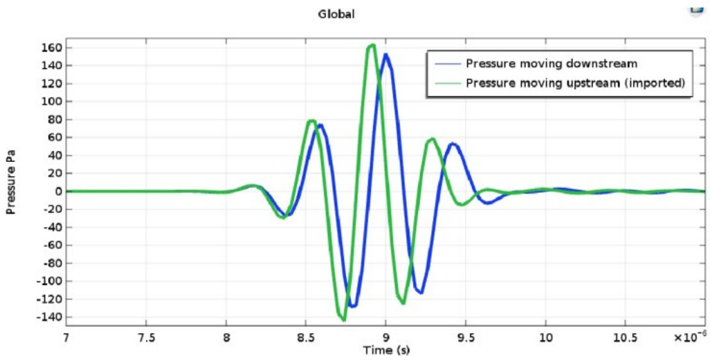
The acoustic wave propagation of the geometry model is generated by using the convected wave equation, time explicit. The propagated signal shows a slight difference in time between the pressure signals from source to receiver and vice-versa. The estimated pressure along the symmetry of the plane is 160Pa, and the forward flow signal propagates at 8.8x10-6s as shown in Fig. 4(a).

In consideration, the propagated signal in blood shows the wide difference between the two signals. The time difference of the propagated pressure wave along the symmetric plane is 174Pa and downstream signal propagates at 8.4x10^{-6}s as shown in Fig. 4(b). It indicates that the pressure wave transmitted from the source to the receiver stream plane has much difference in comparison with water. Since the medium of blood consists of some solid particles moving along the fluid and is more viscous than water, the time difference exists between the two streams are forward flow and reverse flow of wave propagation.

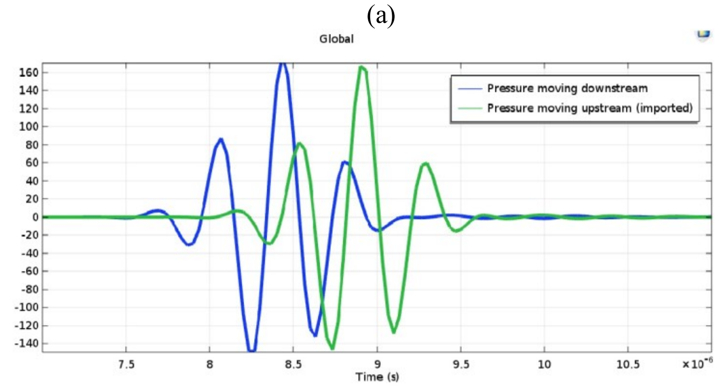
The predicted mean flow velocity, acoustic pressure, and pressure signal along the transducer of water and blood are listed in Table.1. Finally, the average pressure signals are plotted for the pulse propagation in forward and reverse flow transducers. The average pressure signal is recorded from the source to the receiver and vice versa.

TABLE I. PARAMETERS PREDICTED BY THE NUMERICAL SIMULATION IN WATER AND BLOOD EXPOSED TO THE ULTRASOUND FIELD

Parameter	Water	Blood
Mean flow velocity	11.8m/s	12m/s
Acoustic Pressure	239 Pa(4μs) 141Pa(6μs) 124Pa(9μs)	265 Pa(4μs) 140Pa(6μs) 140Pa(8μs)
Pressure signal along with the transducer	160Pa (8.8x10^{-6}s)	174Pa (8.4x10^{-6}s)

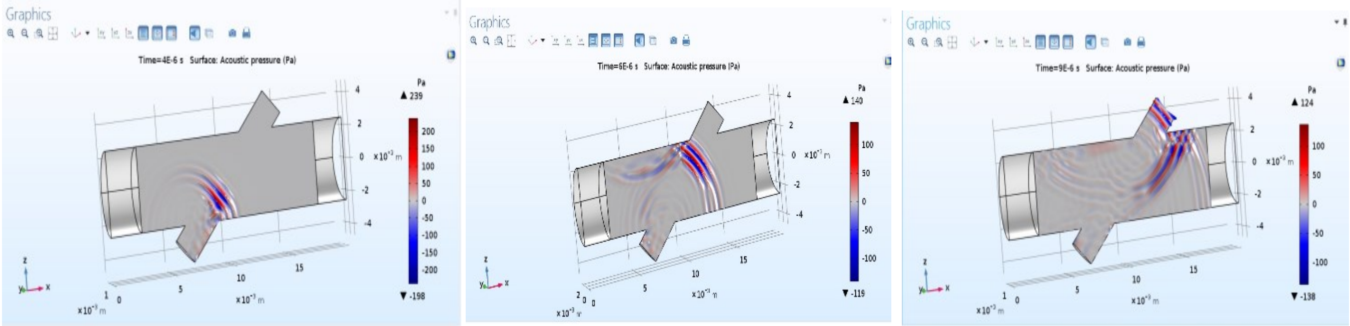


(a)



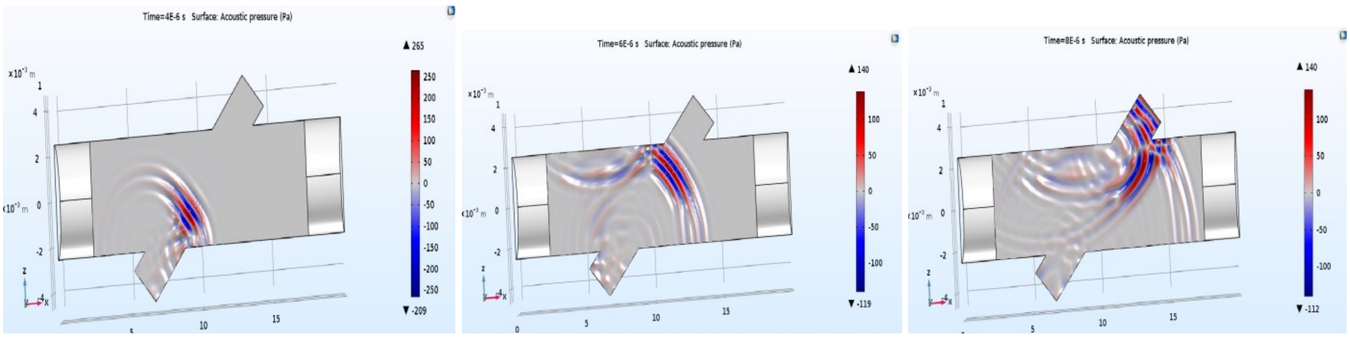
(b)

Fig. 4 The representation of pressure signal along with the transducer for forwarding flow and reverse flow in (a) water, and (b) blood.



(a) (b) (c)

Fig. 5 Acoustic pressure signal in the symmetry plane at (a) 4μs, (b) 6μs and (c) 9μs in water



(a) (b) (c)

Fig. 6 Acoustic pressure signal in the symmetry plane at (a) 4μs, (b) 6μs and (c) 8μs in blood

The propagation wave of acoustic pulse downstream in the tube with its interaction of diffraction effects and background flow is indicated by this concept. The recorded times of flight for the acoustic wave propagation in water for different intervals are shown in Fig.5. The acoustic pressure in the symmetry plane at 4μs, 6μs, and 9μs are 239Pa, 141Pa, and 124Pa, respectively (Fig. 5 a, b, c) in water. The acoustic pressure in the symmetry plane at 4μs, 6μs, and 8μs are 265 Pa, 140Pa, and 140 Pa, respectively for blood (Fig. 6. a, b, c). The time difference can be calculated between the two signals as ΔT, which derives the mean flow speed by using a correction factor which determines the accuracy of the model.

The flow profile correction factor results more accurate in instruments like varying flow speeds. FPFC is calculated by the difference of measured average flow speed along tube with actual average flow speed. By checking the values of each flow speed according to the correction factor the reliability of using the model is determined. The model is investigated and simulated by considering various factors affecting the performance such as steer clear off diffractions and refraction, acoustic signal emission from flow speed etc.

V. Conclusion

The ultrasonic flow meters measure the velocity and pressure accurately for the flow of fluid. The Z-type configuration transit-time flow sensor was designed and simulated using COMSOL Multiphysics coupled with the finite element method (FEM). The proposed geometry was modeled and simulated by using CFD with turbulent flow and acoustics with the convected wave equation, time explicit modules. The acoustic wave propagation of time of flight (ToF) is modeled by using discontinuous Galerkin (dG) and FEM method to measure the mean average velocity, flow profile, acoustic pressure. The time-of-flight during the forward flow and reverse flow was calculated. Referring to two cases wherein water is considered as clear fluid and blood is considered as the material containing some solid particles flowing in the fluid.

The acoustic pressure wave propagation of time-of-flight shows the variation along the symmetric plane. The propagation of pressure signal along the transmitter to the receiver in water and blood was 160Pa for 8.8x10-6s and 174Pa for 8.4x10-6s, respectively. The main limitation of the design is considered for blood flow measurement. In future deep study of acoustic parameters with respect to the variations in the temperature for different flow speeds are analyzed with including the experimental results.

Acknowledgment

Authors would like to thank the management, Vignan's Foundation for Science, Technology & Research, India, for providing administrative and research support with the licensed COMSOL Multiphysics software in the Biomedical computational laboratory.

References

[1] Deok-Woo Park, Shang-Yoon Hwang, Chungyong Kim, and Gyu-Sik Kim, "AStudy on an Ultrasonic Flow Meter," International Journal of Innovative Science, Engg. & Tech., vol. 4 Issue 8, 2017.

[2] L.C. Lynnworth and Yi Liu, “Ultrasonic flowmeters: Half-century progress report, 1955–2005,” Ultrasonics 44, 2006, pp.1371–1378.
[3] G. Rajita and Dr. Nirupama Mandal, “Review on Transit time Ultrasonic Flowmeter,” 2nd International Conf. on Control, Instrum., Energy &Commun. (CIEC), 2016.
[4] M. J. Simmonds, H. J. Meiselman, and O. K. Baskurt, “Blood rheology and aging,” Journal of Geriatric Cardiology, vol. 10, no. 3, 2013, pp. 291–301.
[5] I. A. Tikhomirova, O. O. Anna, and G. M. Svetlana, “Microcirculation and blood rheology in patients with cerebrovascular disorders,” Clinical Hemorheology and Microcirculation, vol. 49, no. 1–4, 2011, pp. 295–305.
[6] Tabrizchi R and Pugsley MK.," Methods of blood flow measurement in the arterial circulatory system," J Pharmacol Toxicol Methods, vol. 44, 2000.
[7] N. A. Lassen, O. Henriksen, and P. Sejrsen, “Indicator methods for measurement of organ and tissue blood flow,” Comprehensive Physiology, American Physiological Society, Rockville, MD, USA, 2011, pp.21–63.
[8] L. M.Blendis,V. C.Roberts, M. Spiro, and R. Williams, “The comparative measurement of splenic blood flow using 133 xenon and an electromagnetic flow meter,” Cardiovascular Research, vol. 4, no. 1, 1970, pp. 44–49.
[9] J. P. Woodcock, Theory and Practice of Blood Flow Measurement, Butterworth-Heinemann, Oxford, UK, 2013.
[10] J.Reyes and A.Acevedo, “Modeling and simulation of ultrasonic flowmeters: state of art,” IEEE ANDESCON, 2010.
[11] William B.J. Zimmerman, “CnTech. COMSOL Multiphysics finite element analysis of multiphysics modeling and analysis [M],” Beijing, China Communications Press, 2007.
[12] David Gareth Davies, Robert Cameron Bolam, YuriyVagapov, and Peter Excell **“**Ultrasonic Sensor for UAV Flight Navigation”, 25th International Workshop on Electric Drives: Optimization in Control of Electric Drives (IWED), 2018.