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Fuzzy Mathematical Analysis of Blood flow through Brachial Artery

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ABSTRACT

Hypertension is a common disease that can be caused by a number of factors. Antidepressants. A variety of methods, including Doppler Ultrasonography, can be used to detect hypertension, which is aided by High Blood Pressure. In this paper, Fuzzy value of speed is 12 cm/s, and corresponding Mamdani's value is 11.8 cm/s with 0.2 difference. Fuzzy value of flow rate is 14.5 mL/min, and corresponding Mamdani's value is 14.5 mL/min with 0.0 difference. Our Fuzzy Mathematical analysis provides values of Blood Speed with 1% margin of error as well as values of Blood Flow within 0% margin of error. The fuzzy logic approach is ideal for combining human expert knowledge with pre-existing numerical data. Fuzzy logic systems use human reasoning and decision-making to generate reliable output even when precise information is unavailable. In the case of biological systems, mathematical modelling is extremely complex, but fuzzy linguistic rules have been shown to aid in the resolution of complexity.

Keywords: Hypertension, Doppler Ultrasonography, Fuzzy logic systems

Introduction:

Hypertension, more frequently known as High Blood Pressure, affects around 1 billion people with an estimated annual death rate of 10,000,000 by the condition worldwide. Hypertension is defined as increased blood pressure in the body [1]. For a vivid understanding, blood pressure is the force exerted by blood, which comprises red blood cells, white blood cells, plasma, etc., on the walls of arteries, the major blood vessels that carry blood away from the heart and to the organs. Hypertension can be classified into two types: essential hypertension (primary hypertension) and inessential hypertension (secondary hypertension) [2].

Essential Hypertension is the more common form of hypertension, affecting 85% of all patients suffering from High Blood Pressure. Essential hypertension is the type of hypertension with no observable secondary cause [3]. Although essential hypertension has no observable cause, there are certain factors that increase its probability of occurring. Certain mechanisms are caused by Obesity such as the activation of the sympathetic nervous system, which has been found to cause hypertension. Excessive Alcohol Intake can also increase hypertension risk as it is known to increase blood pressure over time [4]. Aging also has a positive relation with hypertension risks because as we grow older, our arteries tend to stiffen out, which can result in decreased vascular compliance. Furthermore, renin elevation i.e. high renin levels have been found to cause increased sodium retention which can lead to increased blood pressure. Moreover, a poor exercise routine is known to have a positive correlation with increased blood pressure. Vitamin deficiency, specifically Vitamin D deficiency, is also observed to be related to cardiovascular diseases, increasing both systolic and diastolic pressure [5]. However, there is also a factor that is not in our control: Genetics. It is known that one is more probable to suffer hypertension if he/she has a family history of hypertension. Furthermore, African-Americans are also more likely to suffer from hypertension [6].

Secondary Hypertension, on the other hand, is much less common, affecting only 15% of all patients suffering from high blood pressure [7]. By definition, it has an identifiable cause. These causes may include kidney disease, which may increase renin levels, and as we know, renin elevation may cause increased blood pressure. Adrenal Disease may also cause Hypertension when adrenal glands produce an unbalanced number of hormones which can cause various other diseases, leading to increased blood pressure. Furthermore, Hyperparathyroidism may also play a role in Hypertension as Parathyroid glands overproduce hormones to regulate calcium levels, causing increased blood pressure. Furthermore, abnormal thyroid functions and certain medications are found to be positively correlated with increased blood pressure [8]. Such medications include Hormonal contraceptives, Antidepressants, Immune system suppressants, Decongestants, Acetaminophen, etc. [9].

Hypertension, like many other diseases, have stages as well. Normal blood pressure is less than 120mmHg/80mmHg (Systolic BP/Diastolic BP). Stage 1 Hypertension has a blood pressure of approximately 135mmHg/85mmHg whereas stage 2 Hypertension has a blood pressure of greater than 145mmHg/90mmHg. Typically, both systolic and diastolic blood pressure have a positive correlation. However, sometimes, only one of the two blood pressures rise. This is called Isolated Diastolic Hypertension, where only the diastolic blood pressure rises, and Isolated Systolic Hypertension, where only the systolic blood pressure rises [10].

But why is hypertension so detrimental to begin with? High Blood Pressure causes the wear and tear of endothelial cells that line the interior of blood vessels. This results in narrowed arteries which may lead to blockades by built-up fat or even the formation of an aneurysm [11]. In specific, large arteries have a 15-40% increase in intima-media thickness and as time passes, they lose their elasticity over time, becoming stiff, which can cause atherosclerosis. For small arteries, hypertension leads to a greater media thickness, a decrease in the lumen, and an increased media to lumen ratio. There is no significant change in the amount of total wall tissue. As a result, there is an increase in vascular resistance and impairs the regulation of blood flow. Hypertension also can cause many diseases to major organs including coronary heart disease, glomerulosclerosis, and a transient ischemic attack [12].

Therefore, a quick, accurate, and reliable method of identifying Hypertension is very important before any crucial damage takes place. For calculating the blood flow rate, we will be using Doppler Ultrasonography on the Brachial Artery [13]. Before going into how we will do this, we will first explain the physics behind this method of ultrasound. The fundamental physics of Doppler Ultrasonography is, as the name states, the Doppler Effect. By definition, Doppler Effect is a shift in any wave, e.g. sound or light, as the distance between the wave source and observer changes. To better visualize this effect, let's take a scenario of a duck in a pond. As the duck moves up and down slightly while staying in the same position relative to the surface of the pond, observers can see a ripple effect or circular waves going away from the duck [14]. As the duck moves, the waves in the direction of movement have a higher frequency and vice versa. For a police car, the siren becomes progressively louder as it is approaching you. Although this seems very intuitive and common sense, it is a major component of physics [15].

We have explained the fundamental principle behind Doppler Ultrasonography, and now we will explain how it is done. A transducer (a device that we are using to emit sound waves at frequency F_E) is lightly placed on the skin and a series of pulses is transmitted to detect movement of blood, which consists of red blood cells, white blood cells, plasma, etc. [16]. The transducer, using a microphone, amplifies the returning sound wave and stores its frequency F_R. The transducer, connecting to a computing device, automatically finds the change in Doppler shift F_D, or change in frequency, by the formula:

$$F_D = F_E - F_R.$$

The velocity of blood can be calculated using the formula:

$$F_D = \frac{2F_T cos(\theta)}{c},$$

where c is the speed of sound in tissue and θ is the angle of insonation, the angle between the transmitted beam of sound and the blood flow direction - which is optimal at 45 - 60 degrees [17].

There are two most common types of Dopplers: Color Doppler & Spectral Doppler. Color Dopplers create an image of the blood vessel and the information from the doppler ultrasonography. This information is fed into an algorithm to produce colors on each pixel of the image. Typically, the color red shows that blood is moving away from the transducer and the color blue shows blood moving towards the transducer. The shade of red or blue determines the intensity of blood flow which can be measured using a color scale [18].

Spectral Dopplers, on the contrary, produce a graph or spectral waveform from the information from the Doppler ultrasonography using Fourier analysis. The spectrum is the doppler shift displayed against time. Through proper analysis of the spectrum, we can obtain important characteristics of vascular flow which include the Peak Systolic Velocity (PSV) which is the greatest velocity blood travels in a vessel during systole [19], the End Diastolic Velocity (EDV) which is the velocity, and the end of the cardiac cycle, just before the PSV, the Systolic/Diastolic Ratio (S/D), the acceleration index which is the gradient of the systolic upstroke, the volume flow, the Pulsatility Index (PI), and the Resistivity Index (RI) which is used alongside PI to assess the resistance in a vascular system. The Resistivity and Pulsatility Index can be calculated from the following formulae respectively [20].

$$RI = \frac{PSV - EDV}{PSV}$$

$$PI = \frac{PSV - EDV}{Vmean}$$

Due to these values, along with added sensitivity to change in frequency, Spectral Doppler is the preferred method to calculate blood flow.

The arterial blood velocity ranged from 4.9 cm/sec to 19 cm/sec, whereas venous blood flow was meaningfully slower, ranging from 1.5 cm/sec to 7.1 cm/sec. Hence, blood flow rates of 3.0 ml/min to 26 ml/min in arteries are obtained when the corresponding vessel diameters range from 800 micro meter to 1.8 milli meter [21]. The frequency 20 MHz to 200 MHz, is required to measure blood flow rate in the artery [22]. In conditions that are nonlinear and time-dependent, however, fuzzy based methods work well with fast convergence and less complexity. Fuzzy logic is the opposite of Boolean logic. Boolean is binary, meaning two: either 1 or 0, or True or False. Fuzzy logic, however, gives the degree of truths, such as 0.8, 0.2 and 0.5. This is advantageous to algorithms since they can produce outputs with more precise and broader range of data, instead of a crisp value. As fuzzy logic clone's human decision making, it is effective in problems with no clear input. Furthermore, it is also much easier to program. For incorporation of human expert knowledge and already available numerical data, fuzzy logic approach is highly suitable. Fuzzy logic systems utilized human reasoning and decision-making; these systems are based on IF-THEN rules to develop reliable output even without the availability of precise information [23, 24]. In the case of biological systems, mathematical modeling is highly complicated, but linguistic rules of fuzzy prove to help solve complexity [25].

S. Tayyab et al. used a fuzzy logic control system to perform simulations for flow control in straight microchannels. The results show that fluid flow systems can be developed precisely under different channel widths and varied applied pressure [26]. M. Javaid et al. used FLC for estimation of flow rate and velocity of ascending and descending sinusoidal microchannel to be utilized as replacement n varicose vein for maintaining blood flow [27, 28]. M. W. Ashraf et al. performed fuzzy simulations to manipulate the pore diameter of Anodized aluminum oxide membrane for successful applications in biotechnology [29]. Different researchers use ANSYS and Fuzzy simulation for different researches and get very useful results [30-36].

In this paper, fuzzy logic controller in MATLAB is used for simulation and analysis of fluid flow speed and flow rate. Mamdani's mode is used for calculation of the results and simulated and calculated results are then compared to check the reliability of results.

Fuzzy simulation method

The block Simulink of fuzzy represents the two input variables (length and radius) against two outputs (speed and flow rate) for the fussy analysis as shown in figure 1. Three membership functions are assigned to each input and output variable as shown in figure 2, 3, 4 and 5. The range of each input is defined by using literature study and the range of output variables is defined by using the following calculations:

$$F_D = \frac{2F_T\, v\cos(\theta)}{c} \text{-----------------------------}(1)$$

The flow rate is given by:

$$Flow\ rate = \frac{1}{4}\,\pi d^2 v ------(2)$$

Where d = diameter and v = speed

Table 1. Calculations with minimum, average, and maximum values of variables.

Value	**Frequency (MHz)**	**Diameter (mm)**	**Speed cm/s**	**Flow rate mL/min**
Mf1	2	0.008	4.9	3
Mf2	101	0.904	11.95	15
Mf3	200	1.8	19	26

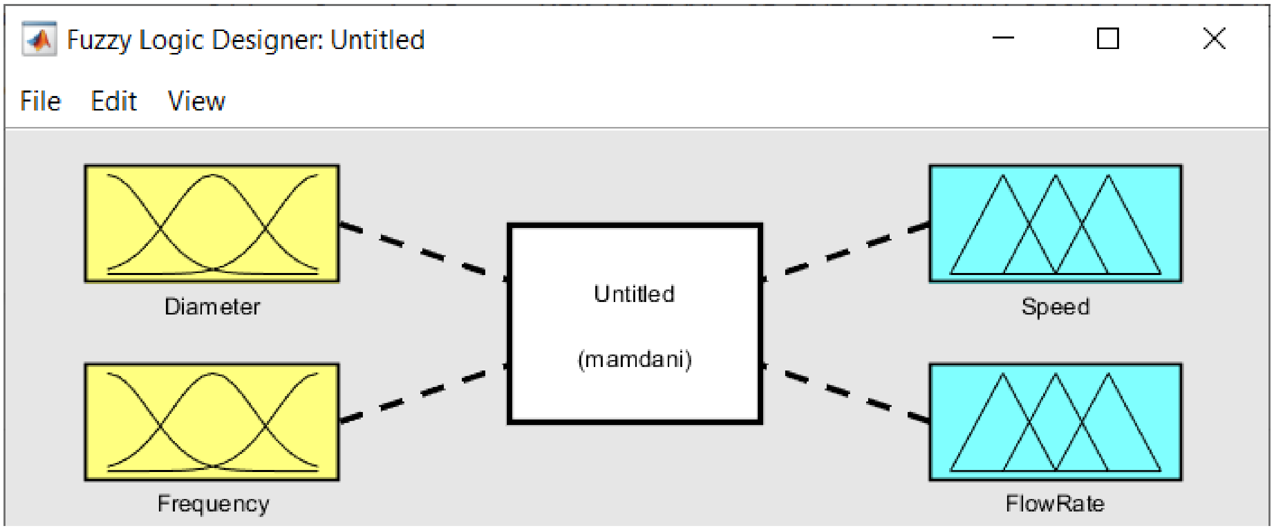

Fig. 1: Fuzzy interface of inputs and corresponding outputs

There are two inputs in the FLC: diameter and frequency. Using these, there are two outputs: Speed and Flow rate.

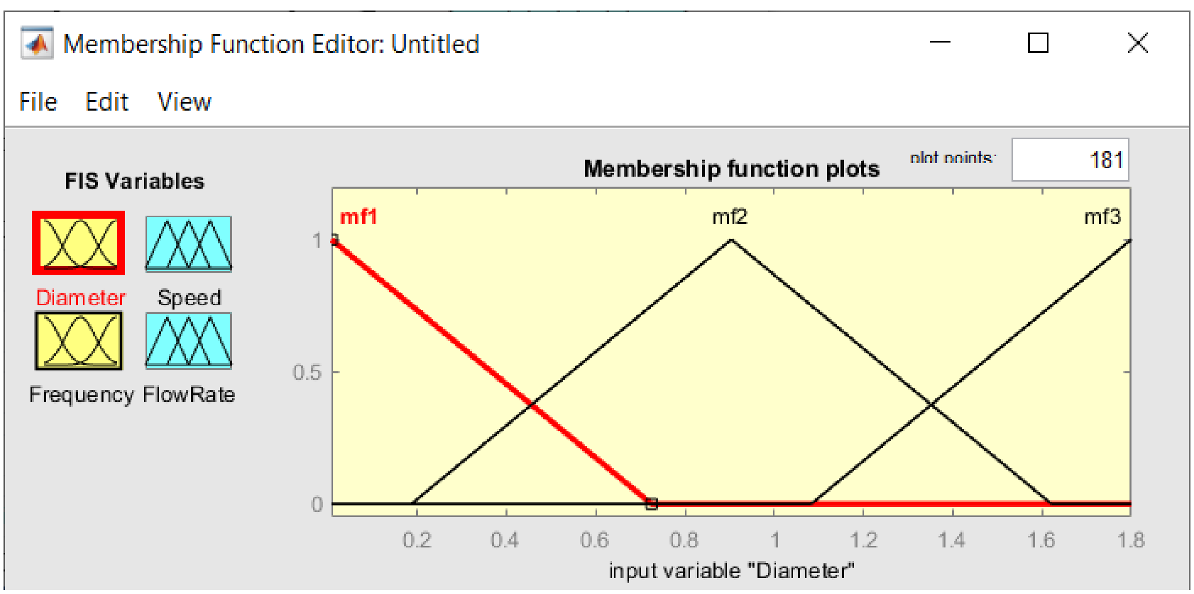

Fig. 2: Membership function for Input "Diameter"

There are three sections to the Membership function for “diameter”: mf1, mf2, and mf3. The range is 0.008 mm to 1.8 mm.

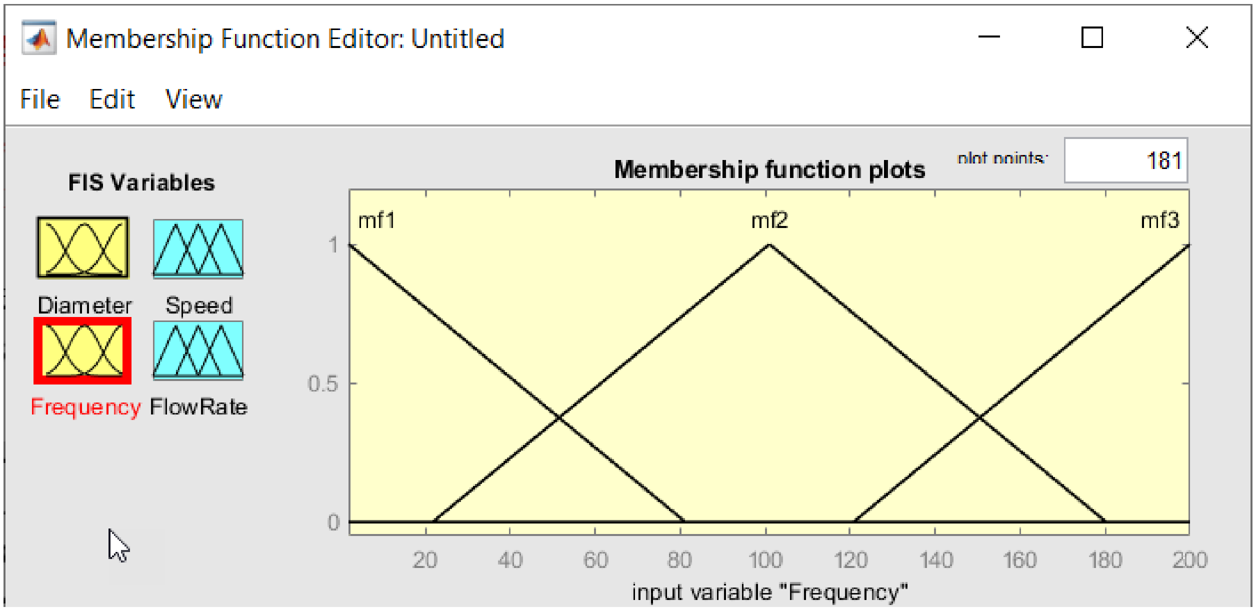

Fig. 3: Membership function for Input "Frequency"

There are three sections to the Membership function for “frequency”: mf1, mf2, and mf3. The range is 2 to 2008 MHz.

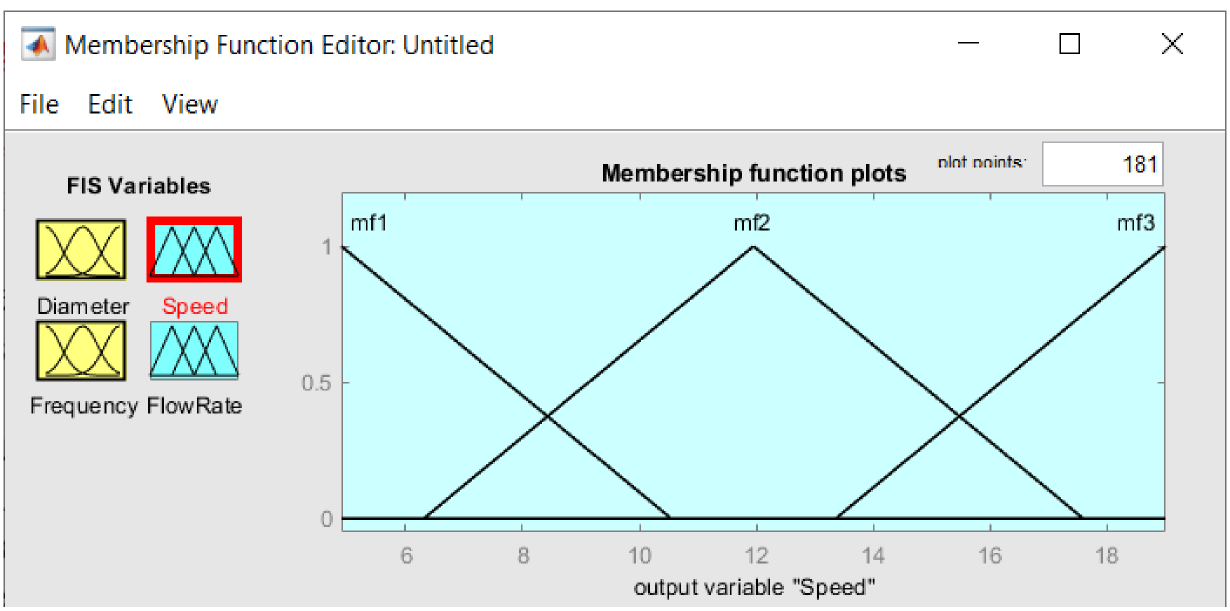

Fig. 4: Membership function for output "Speed"

There are three sections to the Membership function for “speed”: mf1, mf2, and mf3. The range is 4.9 cm/s to 19 cm/s.

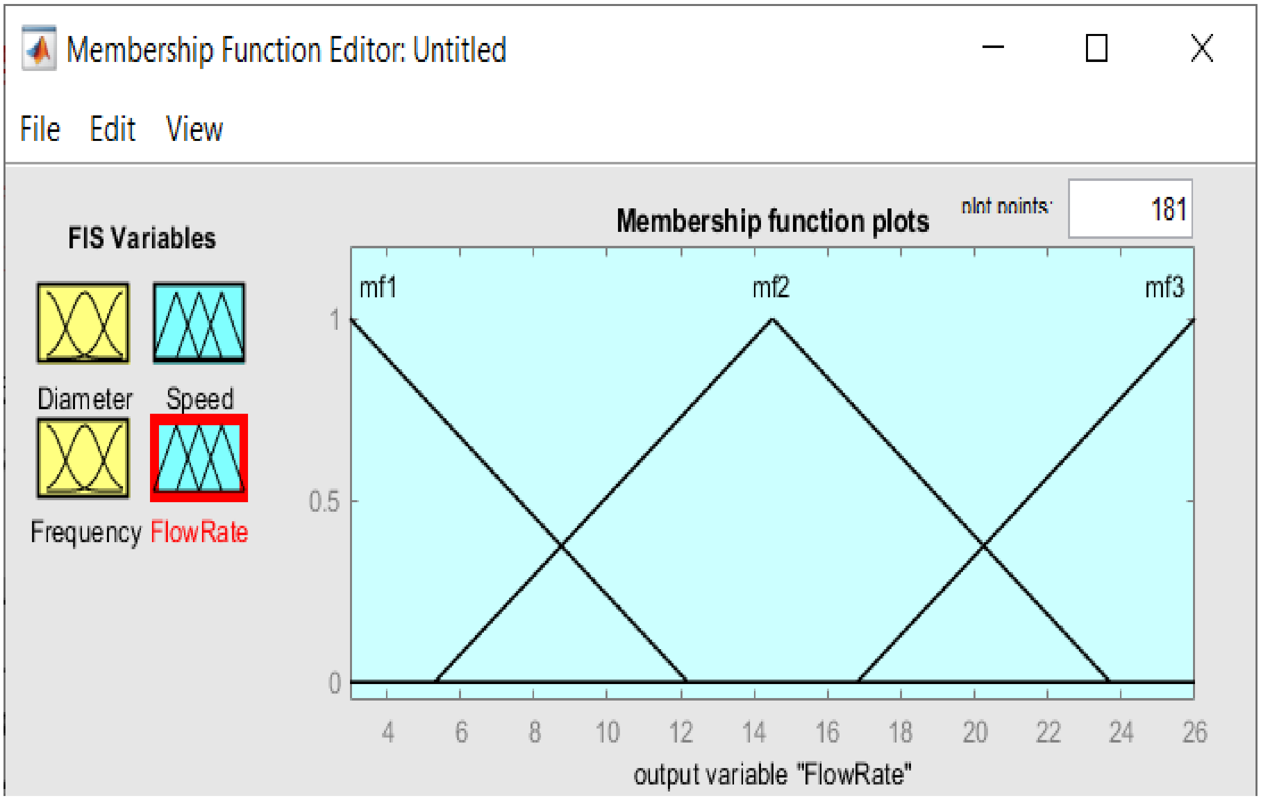

Fig. 5: Membership function for output "Flow rate"

There are three sections to the Membership function for “flow rate”: mf1, mf2, and mf3. The range is 3 mL/min to 26 mL/min. Using Mamdani’s model $3^2 = 9$ rules are defined for simulations as given in rule editor. The rule viewer graph from fuzzy analysis is given in Figure 12. From this graph the crisp values of each input are noted for calculation of output values using Mamdani’s model calculations:

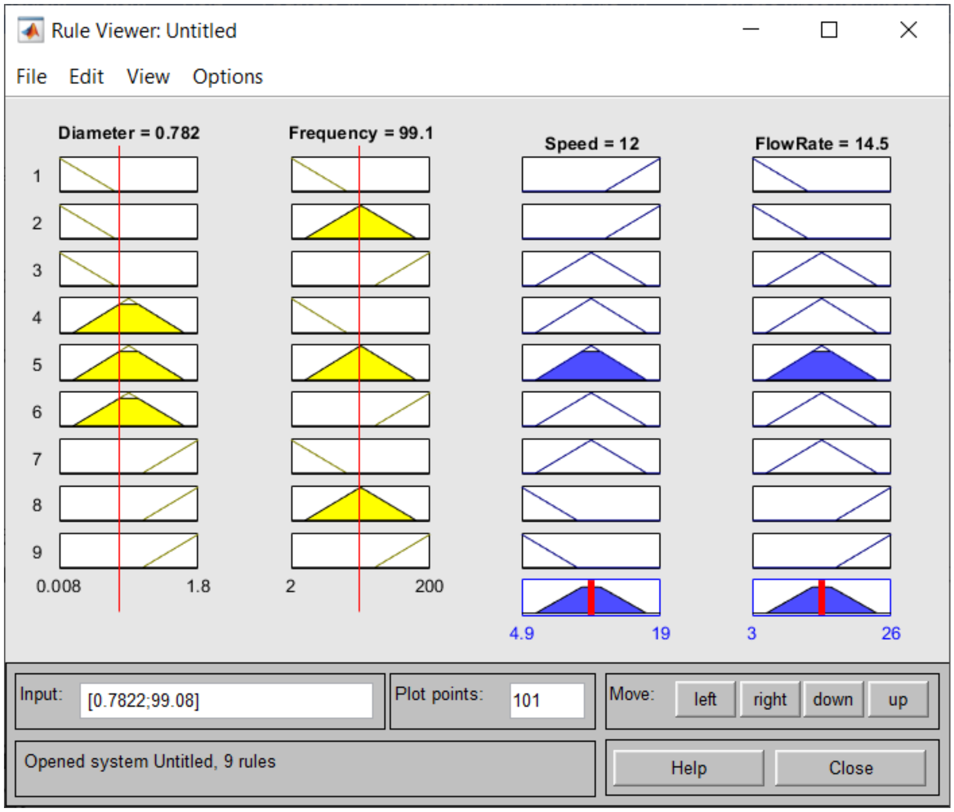

Fig. 7: Rule viewer for input and output crisp values calculation

In this Figure 7, with an input of diameter = 0.782 mm and frequency = 99.1 MHz, the output is Speed = 12 cm/s and Flow Rate = 14.5 mL/min.

Results and Discussion

The 2D and 3D graphs for inputs versus outputs to show the variations in output are obtained from fuzzy analysis. There is a decreasing relationship between diameter and speed. When the speed is 16, the diameter is 0.1. When the speed is 13, the diameter is 1.5. When the speed is 10, the diameter is 1.5. There is an inverse relationship between speed and diameter. There is an increasing relationship between flow rate and length. When the flow rate is 10, the diameter is 0.3. When the flow rate is 15, the diameter is 1. When the flow rate is 20, the diameter is 1.5. There is a direct relationship between flow rate and diameter.

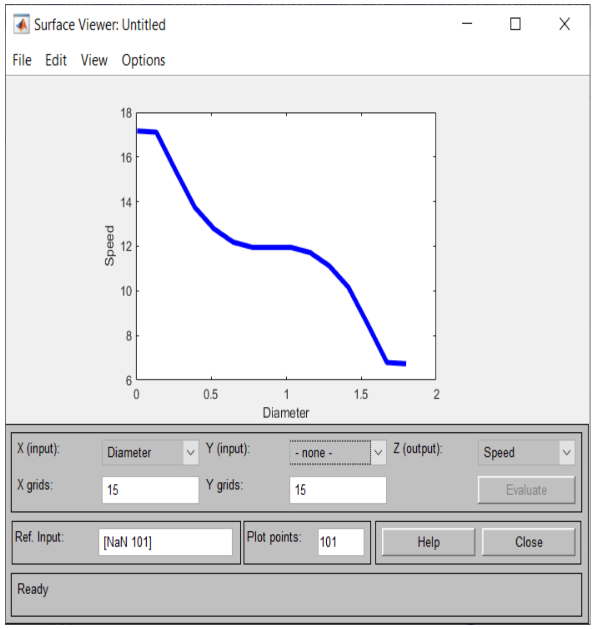

Fig. 8: 2D graph for speed and diameter

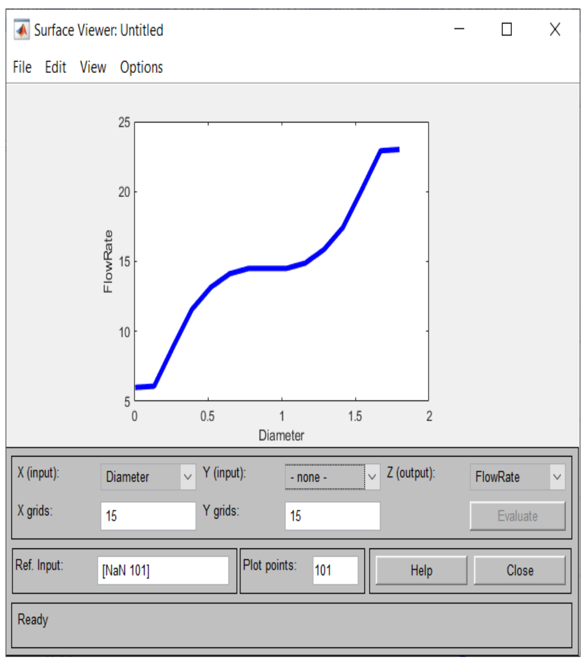

Fig. 9: 2D graph for Flow rate and diameter

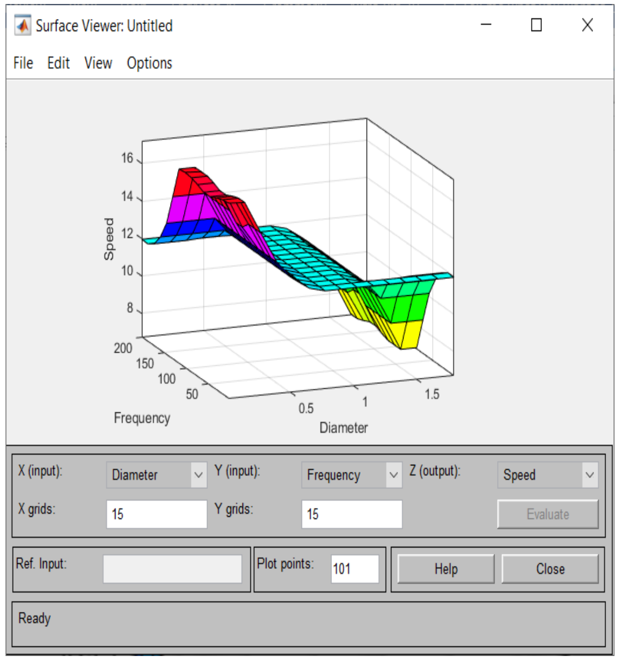

Fig.10: 3D graph between diameter, frequency and speed

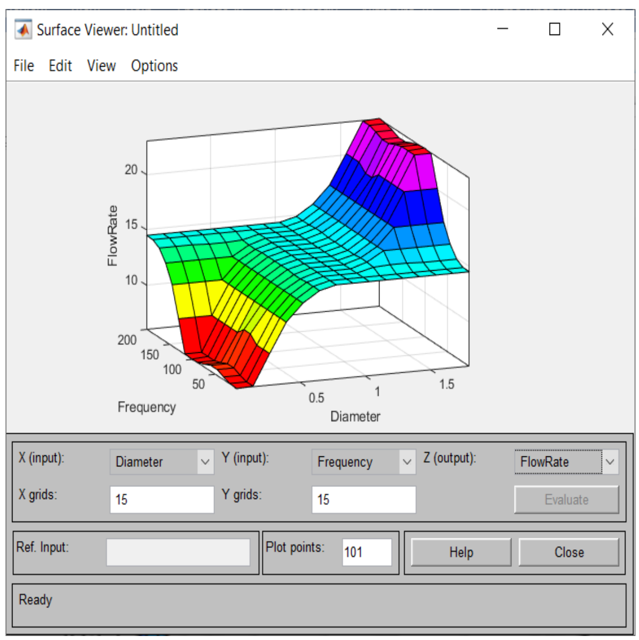

Fig. 11: 3D graph between diameter, frequency and flow rate

Mamdani Mathematical Calculations for speed and flow rate

Here, Mamdani's method is used for the verification and authentication of Fuzzy Simulation. Now for speed, Membership function calculations using crisp values

$$K1 = 1.8 - \frac{0.8}{1.8} = 0.55$$

$$K2 = 1 - K1 = 0.45$$

$$K3 = 200 - \frac{150}{200} = 0.25$$

$$K4 = 1 - K3 = 0.75$$

Table 2. Calculations of speed

Length	Radius	Speed	Minimum Membership function value	Min. Value (Mi)	Singleton value (Si1)	Speed Mi x Si1
Mf1	Mf1	Mf3	K1^K3	0.25	0.19	0.0475
Mf1	Mf2	Mf3	K1^K4	0.55	0.19	0.1045
Mf1	Mf3	Mf1	K2^K3	0.25	0.004	0.001
Mf2	Mf1	Mf1	K2^K4	0.25	0.004	0.001

$\Sigma Mi = 1.3$ and Σ (Mi x Si1) $= 0.154$

Expression of Mamdani's Model = $\frac{\Sigma\,(Mi \times Si1)}{\Sigma Mi} * 100$

$$= \frac{(0.154)}{1.3} * 100$$

$$= 11.8$$

Here, Mamdani's method is used for the verification and authentication of Fuzzy Simulation. Now for flow rate, Membership function calculations using crisp values

$$K1 = 1.8 - \frac{1.2}{1.8} = 0.33$$

$$K2 = 1 - K1 = 0.67$$

$$K3 = 200 - \frac{90}{200} = 0.55$$

$$K4 = 1 - K3 = 0.45$$

Table 3. Calculation of flow rate

Length	Radius	Flow rate	Minimum Membership function value	Min. Value (Mi)	Singleton value (Si2)	Flow rate Mi x Si2
Mf1	Mf1	Mf2	K1^K3	0.33	0.145	0.04785
Mf1	Mf2	Mf2	K1^K4	0.33	0.145	0.04785
Mf1	Mf3	Mf2	K2^K3	0.55	0.145	0.07975
Mf2	Mf1	Mf2	K2^K4	0.45	0.145	0.06525

$\Sigma \text{Mi} = 1.66$ and $\Sigma (\text{Mi x Si2}) = 0.24071$

Expression of Mamdani's Model $= \frac{\Sigma (\text{Mi} \times \text{Si2})}{\Sigma \text{Mi}} * 100$

$$= \frac{(0.24071)}{1.66} * 100$$

$$= 14.5$$

The difference between simulated and calculated results of both outputs is zero that proves that the results obtained are reliable for future applications.

Conclusion

In this paper, Fuzzy method has been used for simulation. Fuzzy value of speed is 12 cm/s, and corresponding Mamdani's value is 11.8 cm/s with 0.2 difference. Fuzzy value of flow rate is 14.5 mL/min, and corresponding Mamdani's value is 14.5 mL/min with 0.0 difference. Our Fuzzy Mathematical analysis provides values of Blood Speed with 1% margin of error as well as values of Blood Flow within 0% margin of error. As a result, our proposed method, alternate to Doppler Ultrasonography, will decrease expense financially and in terms of time while keeping our data extremely accurate. Results are shown in Table 4 and 5 below.

Table 4: Calculation for speed

Speed	Value (cm/s)
Fuzzy Value	12
Mamdani Value	11.8
Difference	0.2
Percentage Error	1%

Table 5: Calculation for flow rate

Blood Flow	Value (mL/min)
Fuzzy Value	14.5
Mamdani Value	14.5
Difference	0.0
Percentage Error	0.0%

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