

Analyzing the Fluid Flow of Transit-Time Ultrasonic Flowmeter with Image Processing Technique and Developing a Quality Metric Depending on Pipe Profile

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Abstract— The ultrasonic transit-time method measures the velocity and quantity of fluids in circular type pipes by using the difference of transit time between the ultrasonic pulses propagating with and against the flow direction. This method gives the average velocity of the fluid along a particular acoustic path. At least two ultrasonic transducers are used for an acoustic path. The multipath ultrasonic flowmeters have more acoustic paths. In this paper, the acoustic path between two transducers is described as pixels for the turbulent flow and formed a flow map for ideal flow conditions such as no elbow or bend depending on pipe profile. This map is used to analyze the fluid flow for different Reynolds numbers. Additionally, for any acoustic path between two transducers, the average fluid velocity is calculated using the obtained pixel values. Thus, a quality metric is developed in this paper. This metric calculates the ideal average fluid velocity ratio between the acoustic paths. The developed metric can be used to evaluate the quality of the ultrasonic flowmeter in the domain of turbulent flow.

Index Terms— Fluid Flow, Image Processing, Quality Index, Ultrasonic Flowmeter

I. INTRODUCTION

ACCORDING TO the measurement principle, the ultrasonic flowmeters are divided into two groups: Transit-Time Difference (TTD) and Doppler methods. The Doppler method is used for fluids containing particles such as bubbles and sand. This method relies on particles flowing through the fluid. Generally, this method is considered as having low performance due to the fact that the particle velocity is different from the fluid velocity. TTD ultrasonic flowmeter is used for homogeneous fluids that do not contain particles and has many advantages such as high accuracy, low maintenance and economical.


Many techniques have been developed to enhance the

precision of TTD ultrasonic flowmeters, some of which find the optimal transducer angle [1], design the pipe [2], filter the signals [3, 4] and use FPGA [5, 6]. Zero-crossing and correlation methods are the most commonly used methods to find TTD [7]. Some of the scientists have studied to increase the “sensitivity for the zero-crossing method [8, 9]. Least-square-sine-fitting technique is considered as an alternative method to obtain TTD [10].

To increase the accuracy in measuring, the multipath design has different acoustic paths. The calculation method for multipath ultrasonic flowmeter is described as follows: The fluid velocity is calculated for each path as in the one-path ultrasonic flowmeter. The average velocity is calculated by multiplying the calculated velocity value with the weight value for each path. The simplest way to calculate the weight value is the averaged method involving an equally weighted average of the path velocities [11]. In another method, the weight values are determined according to the geometric position of the transducers [12]. In this method, weight values are calculated by reference to the distance of the transducers from the pipe center. The transducer, which is close to the center, has a higher weight value. It has less weight value as it moves away from the center. Several path arrangement designs exist with weights to prescribe the position of acoustic paths, and an integration method is used such as Gauss-Jacobi and Optimal Weighted Integration for Circular Sections (OWICS) [13-15]. The major disadvantage of these methods is that weights are calculated based on fixed transducer positions. Researchers have focused on eliminating such disadvantages and increasing the accuracy by using a different algorithm such as Generalized Inverse Matrix, Levenberg-Marquardt, and variances of path velocities [16-18].

Although there are many studies on TTD ultrasonic flowmeters, research continues. This paper presents a flow map for ideal flow condition (FMIFC). FMIFC is formed in the domain of turbulent flow (i.e., Reynolds number (Re) > 4000) of transit-time ultrasonic flowmeter depending on pipe profile. Thus, researchers can analyze the fluid flow depending on Re . Furthermore, using FMIFC, a quality metric is developed. The developed metric calculates the ideal average fluid velocity ratio between the acoustic paths to obtain a reference value for ideal flow conditions. For the multiple

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acoustic paths, researchers can compare the application values with the reference values to evaluate their designs. In this paper, the following section presents the measurement principle of the transit-time ultrasonic flowmeter. FMIFC and the proposed quality metric are considered in Section III. Results and discussion are presented in Section IV. Finally, Section V concludes this paper.

II. OPERATING PRINCIPLE OF TRANSIT-TIME ULTRASONIC FLOWMETER

Due to the simplicity of the measurement principle, TTD method is often used in industrial applications [19]. At least two ultrasonic transducers are placed on the surface of the pipe. The transducers send ultrasonic pulses to each other. The fluid flow velocity is calculated by using the propagation time of the received pulses. The operating principle of the TTD method is shown in Fig. 1.

In Fig. 1, r_0 is the pipe radius, t_{AB} and t_{BA} are the transit times, θ is the angle between the pipe and the direction of the ultrasonic wave and v_m is the velocity on the center. In TTD method, the ultrasonic flowmeter measures the average velocity along the path between the ultrasonic transducers. Two ultrasonic transducers (shown as transducer A and transducer B in Fig. 1) send pulses propagating into and against the direction of the fluid flow. The transit time from transducer B to transducer A (t_{BA}) is greater than the transit time from transducer A to transducer B (t_{AB}) and they are calculated as follows:

$$t_{AB} = \frac{L}{c + v \cos \theta} \tag{1}$$

$$t_{BA} = \frac{L}{c - v \cos \theta} \tag{2}$$

where L is the distance between the transducer A and transducer B, v is the fluid flow velocity and c is the ultrasound speed in the fluid. The TTD is calculated as follows:

$$\Delta t = t_{BA} - t_{AB} = \frac{L}{c - v \cos \theta} - \frac{L}{c + v \cos \theta} \tag{3}$$

From the Eq. (3), we can obtain the v :

$$v = \frac{L}{2 \cos \theta} \left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) = \frac{r_0}{\sin \theta \cos \theta} \left(\frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right) = \frac{r_0 \Delta t}{\sin \theta \cos \theta t_{AB} t_{BA}} \tag{4}$$

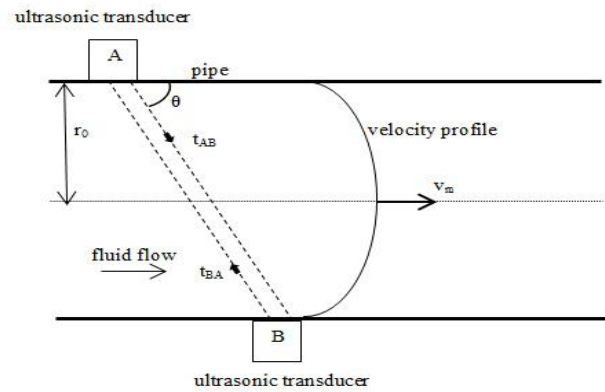


Fig.1. The principle of transit-time method

At low fluid flow velocities, the flow tends to be dominated by laminar flow, while at high fluid flow velocities flow is referred to as the turbulent flow. This paper is about the turbulent flow, i.e., $Re > 4000$. In the domain of turbulent flow, the velocity profile is called the “pipe profile” given by [20, 21]:

$$v(r) = v_m \left(1 - \frac{r}{r_0} \right)^p \tag{5}$$

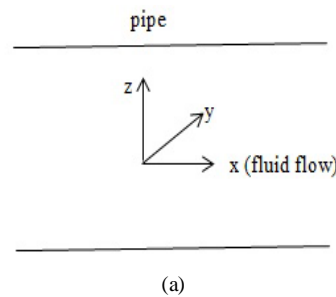
where r is the distance from the center and p is a parameter as chosen [21, 22]:

$$p = 0.25 - 0.023 \log_{10} Re \tag{6}$$

Remark that this parameter decreases with increasing Re and hereby $v(r)$ approaches to v_m . Therefore, the ratio of $v(r)$ to v_m can be calculated depending on the Re .

III. FMIFC AND THE PROPOSED QUALITY METRIC

At first, in this paper, the fluid flow in circular type pipe for ultrasonic flowmeter application is described as pixels. The schematic of an ultrasonic flowmeter is shown in Fig. 2. The fluid flow direction in Fig. 1 corresponds to the x -direction (axial direction) in Fig. 2. The y and z directions correspond to horizontal and vertical directions, respectively. When the fluid flow in Fig. 2 is described by pixels, the pixel values along the axial direction have the same values. Thus, the pixel values are obtained along the horizontal and vertical directions to describe the fluid flow in this paper.



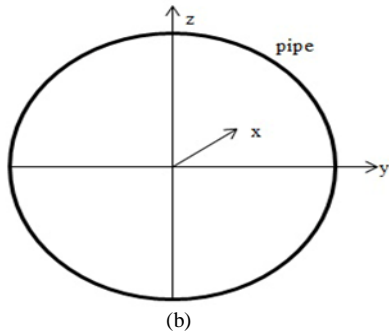


Fig.2. Schematic of an ultrasonic flowmeter (a) Longitudinal cross-section (b) Transverse cross-section

The pipe profile in Eq. (5) gives the velocity profile on the horizontal direction as shown in Fig. 1 and Fig. 2. If the ultrasonic transducers are placed on both ends of the y-axis shown in Fig. 2b, the acoustic path between these transducers can be described as pixels in Fig. 3.

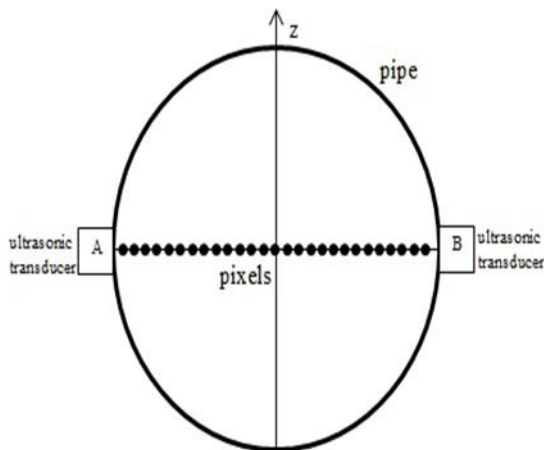


Fig.3. The acoustic path in the middle of the pipe

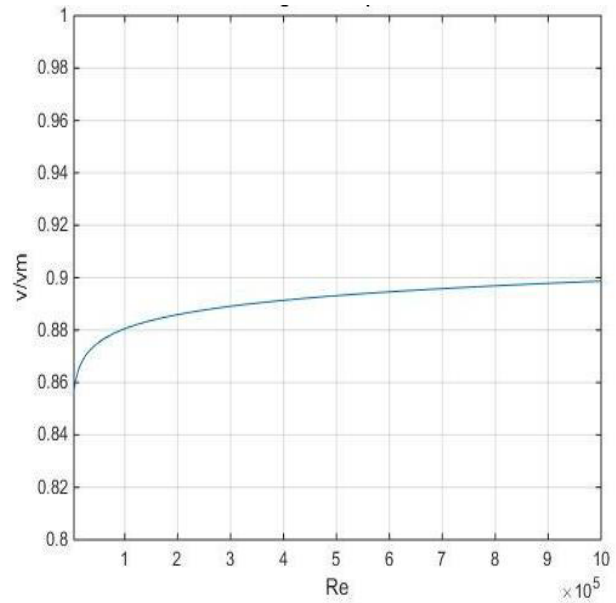
Any pixel value shown in Fig. 3 is between 0-255 and depends on fluid velocity. The greater fluid velocity means the bigger pixel value. Each pixel value can be calculated using Eq. (5). $r=r_0$ corresponds to the pipe surface where the velocity equals zero ($v(r) = 0$) and pixel value is zero. The pixels, which is close to the center, has a bigger value. $r=0$ corresponds to the center of the pipe where velocity is the maximum ($v(r) = v_m$) and pixel value is 255. As mentioned above, for the larger Re , $v(r)$ approaches to v_m , resulting in bigger pixel value. After calculating each pixel value on the acoustic path, the average fluid velocity on the acoustic path can be obtained by averaging the calculated pixel values.

The velocity v given by Eq. (4), corresponding to the average fluid velocity on the acoustic path between the ultrasonic transducers shown in Fig. 3, can be obtained by using v_m as follows [21]:

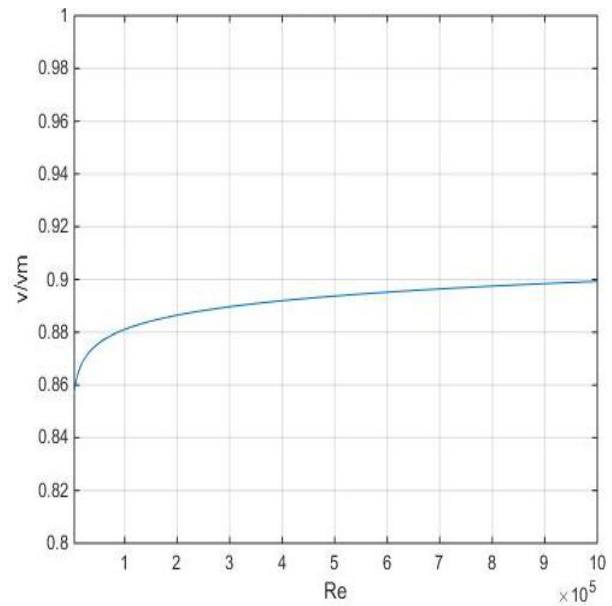
$$v = \frac{v_m}{1 + p} \tag{7}$$

v values are calculated by using both pixels shown in Fig. 3

and Eq. (7) between $Re=4000$ and $Re=1000000$. The obtained values are normalized with v_m and shown in Fig. 4. Instead of handling the entire distance between the two transducers, shown in Fig. 3, only the pixels between the ultrasonic transducer A and center are handled to avoid extra processing.



(a)



(b)

Fig.4. Obtained normalized average flow velocity vs. different Re values on the acoustic path in the middle of the pipe by using (a) Pixels (b) Eq. (7)

As shown in Fig. 4b, the normalized v value for the $Re=4000$ is 0.856. It is approaching v_m as the Re increases, and this value is 0.899 for the $Re=1000000$. Comparing Fig. 4a and Fig. 4b, the normalized values obtained by pixels and Eq. (7) are equal to each other. If we consider the acoustic path in Fig. 3 as in Fig. 5, the pixel values of the acoustic path between each ultrasonic transducer pair and average flow velocity for

the corresponding acoustic path can be calculated by the method mentioned above.

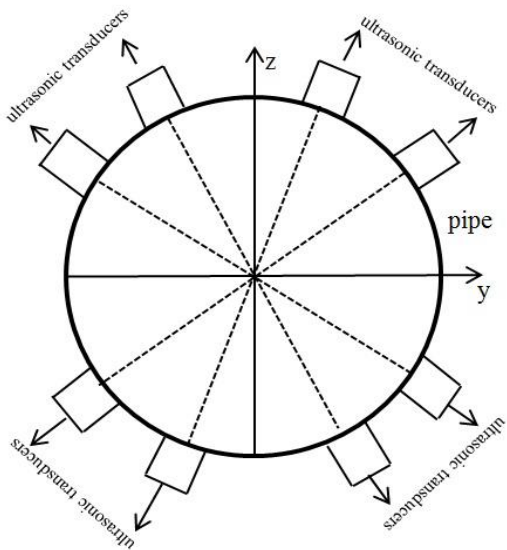


Fig.5. The transducers placed around the pipe

Usually, for ultrasonic flowmeter applications in the industry, ultrasonic transducers have a design as shown in Fig. 6.

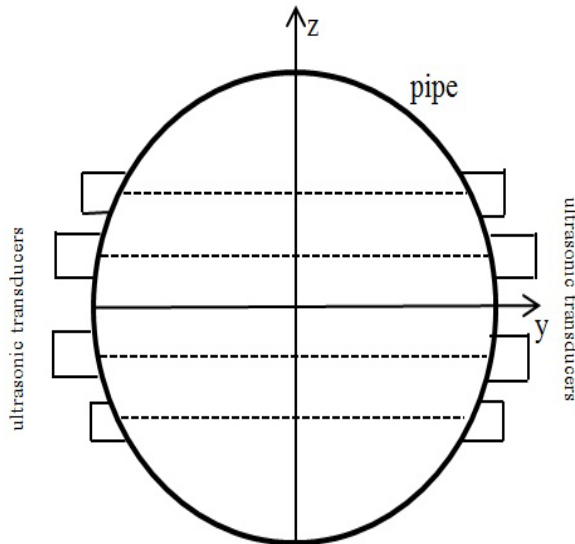


Fig.6. Ultrasonic transducers located in the z-direction

The ultrasonic transducers may be located in the middle of the pipe (as shown in Fig. 3) or at any point in the z-direction (as shown in Fig. 6). Thus, each transducer pair has a different velocity and acoustic path length information. In this paper, the normalized average flow velocity value of each acoustic path shown in Fig. 6 is calculated using pixels. For this purpose, the acoustic paths between the ultrasonic transducers are first illustrated by pixels as shown in Fig. 7. Instead of handling the entire distance between two transducers, only the pixels between the ultrasonic transducer A and center (as shown in Fig. 3) are handled to avoid extra processing.

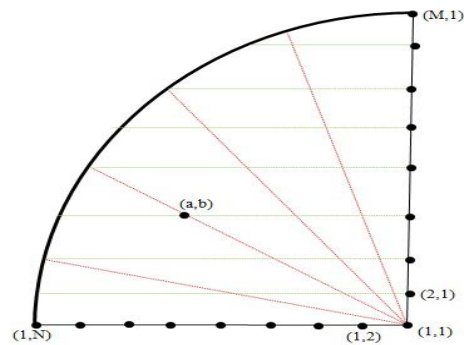


Fig.7. Finding pixel value on the acoustic path at any point in the z-direction

The pixel values of the red acoustic paths can be calculated as previously stated in this paper. The green acoustic paths indicate the acoustic paths between the ultrasonic transducers located in the z-direction as shown in Fig. 6. While N represents the number of pixels in each acoustic path, M indicates the acoustic path number. Increasing the number of M and N means more precise result but more processing. So, in this study, M and N values are chosen as 1000 (that means the image shown in Fig. 7 has 1000*1000 pixels). a and b are the vertical and horizontal positions of the pixel to be calculated, respectively. To find the pixel (a, b) value, the following algorithm is applied:

- Calculating the transducer distance = $\sqrt{r_0^2 - (a - 1)^2}$ (8)

- Calculating the point distance = $\text{transducer distance} * \frac{b - 1}{r_0}$ (9)

- Calculating the r distance = $\sqrt{(\text{point distance})^2 + (a - 1)^2}$ (10)

- $v(a, b) = v_m \left(1 - \frac{r \text{ distance}}{r_0} \right)^p$ (11)

where v (a, b) is the pixel value at (a, b). Transducer distance, point distance, and r distance shown in Eqs. (8-11) are indicated in Fig. 8:

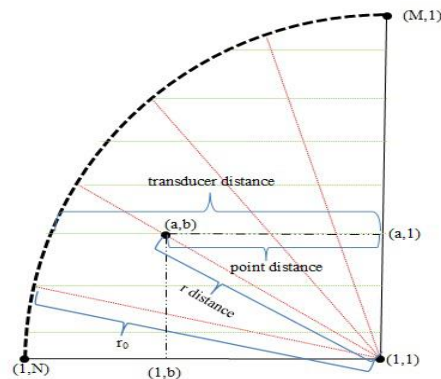


Fig.8. Transducer distance, point distance, and r distance

The lengths of the vertical position and horizontal position of the pixel (a, b) are (a-1) and (b-1), respectively. The value

of the r_0 is $M-1$ or $N-1$. All pixel values on the green acoustic paths shown in Fig. 7 can be calculated by using Eqs. (8-11) to obtain FMIFC. The r distance is calculated using Eqs. (8-10) to obtain any $v(a, b)$ value in the image. For example, let the image has 10×10 pixels and calculate the r distance for $v(3, 8)$. In this case, the transducer distance is the distance from $(3, 10)$ to $(3, 1)$, while the point distance is the distance from $(3, 8)$ to $(3, 1)$. Thus the r distance is the distance from $(3, 8)$ to $(1, 1)$. After calculating the r distance, $v(a, b)$ value is obtained using Eq. (11). v_m which is pixel value at $(1, 1)$ is 255. As stated in Eq. (6), parameter p shown in Eq. (11) depends on the Re . Thus, FMIFC can be obtained for each Re . Fig. 9 shows FMIFC having 1000×1000 pixels for $Re=100000$.

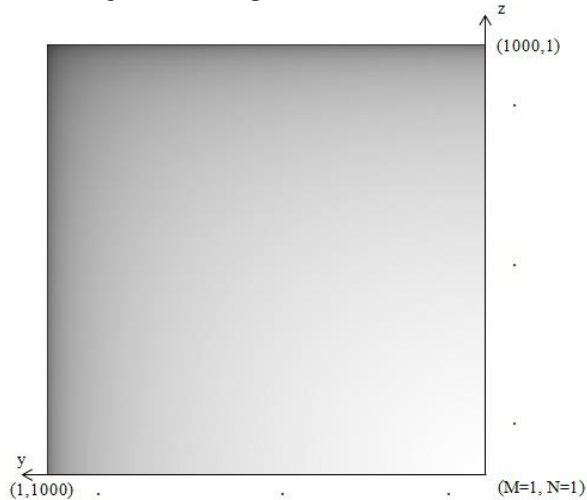


Fig.9. FMIFC for $Re=100000$

Fig. 9 is the diagram showing the rectangular form of Fig. 7 after calculating the pixels on the acoustic paths shown in Fig. 7. There are 1000 acoustic paths and each acoustic path has 1000 pixels in Fig. 9. The pixel at $(M=1, N=1)$ corresponds to the v_m . The pixels at $M=1000$ or $N=1000$ correspond to the pipe surface. FMIFC can be used to analyze fluid flow for different Re values. Besides, FMIFC can be used to obtain the ideal average fluid velocity ratio between the acoustic paths in the z -direction. The average fluid velocity, for any acoustic path in the z -direction, is calculated by averaging the obtained pixels on this acoustic path. Thus, a quality metric is obtained in this paper, which indicates the ratio of the average fluid velocities of different acoustic paths. The quality metric based on pixel (Q_{bp}) is calculated as follows:

$$Q_{bp} = \frac{Q_{bpr}}{Q_a} \quad (12)$$

where Q_{bpr} and Q_a are the quality metrics for reference and application, respectively and defined as

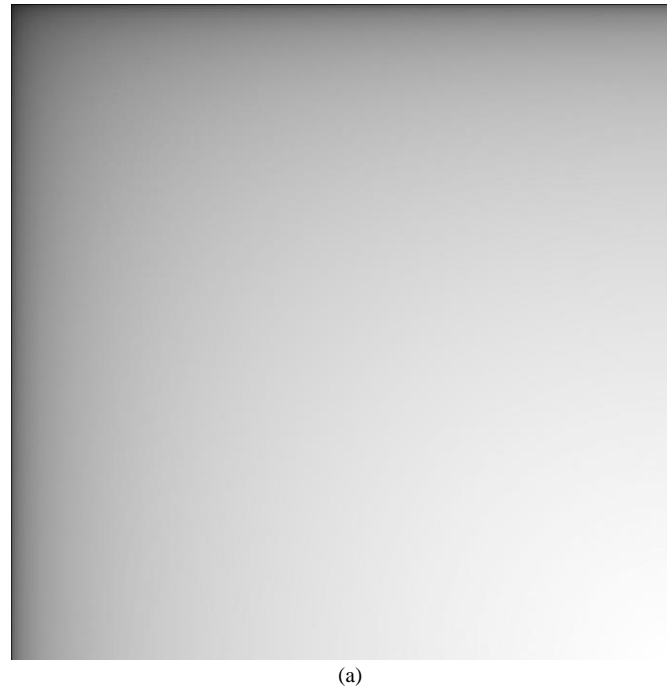
$$Q_{bpr} = \frac{v_{bp1}}{v_{bp2}} \quad (13)$$

$$Q_a = \frac{v_1}{v_2} \quad (14)$$

where v_{bp1} and v_{bp2} are the normalized average fluid velocities based on pixel for reference, v_1 and v_2 are the average fluid velocities for the application. A researcher places the ultrasonic transducers in any positions along the z -direction on the pipe. To obtain two different flow velocities, v_1 and v_2 , from two different transducer pairs, the average fluid flow velocity on the acoustic path between each ultrasonic transducer pair is measured for turbulent flow and ideal flow conditions. v_{bp1} and v_{bp2} are obtained by the method mentioned above for reference. If there is problem such as the placement of transducers in the design, the ratio between Q_{bpr} and Q_a is different from 1. That the ideal value of Q_{bp} is 1 indicates excellent compatibility between the transducer pairs. Thus, this metric can be used to assess the quality of the ultrasonic flowmeter for turbulent flow.

IV. RESULTS AND DISCUSSION

In this paper, FMIFC is obtained in MATLAB environment to analyze fluid flow for different Re values. Fig. 10 shows FMIFC for $Re=10000$, 100000 and 1000000 .



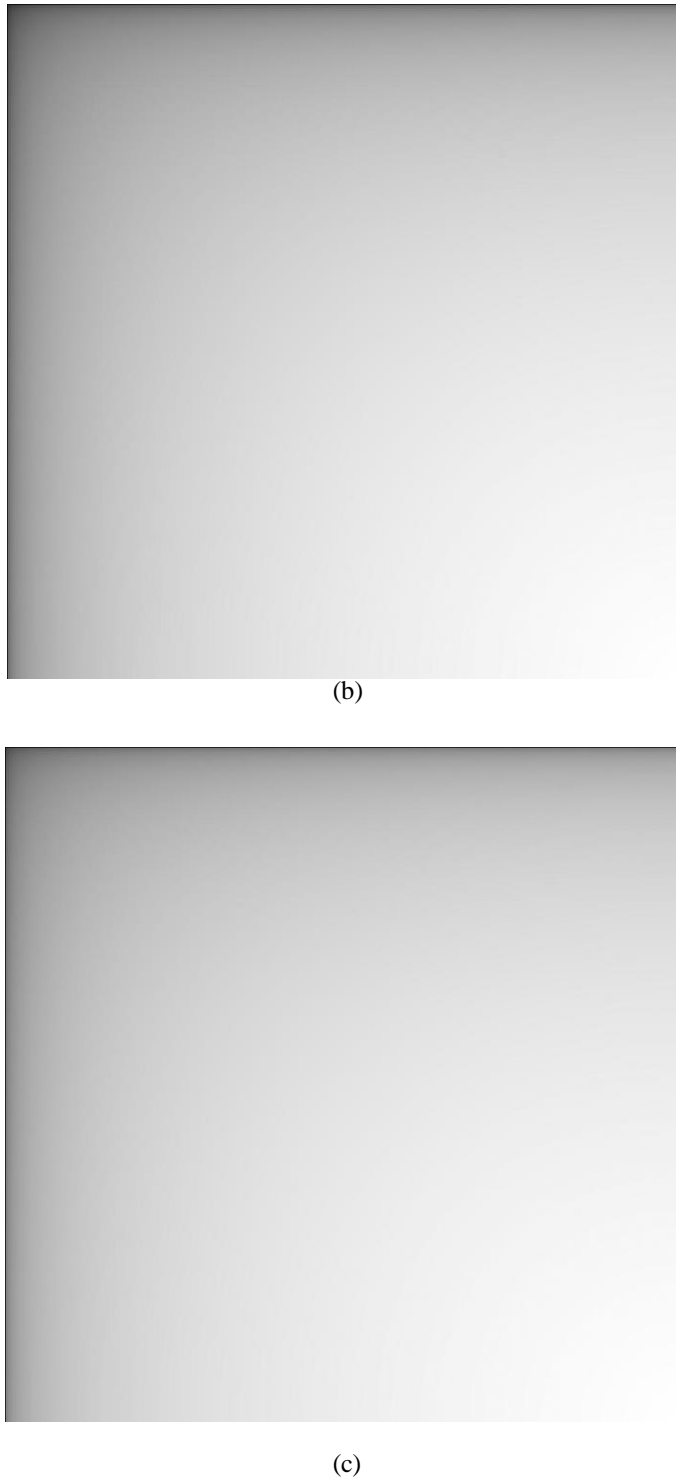


Fig.10. FMIFC for Re is (a) 10000 (b) 100000 (c) 1000000

As mentioned above, subfigures in Fig. 10 have 1000*1000 pixels (i.e., they have 1000 acoustic paths and each acoustic path has 1000 pixels). The value of the pixel at (M=1, N=1) is 255 for each figure. Comparing the subfigures in Fig. 10, FMIFC has whiter pixels for the larger Re. That means any acoustic path in the z-direction has greater velocity (larger pixel value) for larger Re. By using FMIFC, the normalized fluid velocities are obtained for M=1, 500, 1000 and Re=10000, 100000 and 1000000 (shown in Fig. 11).

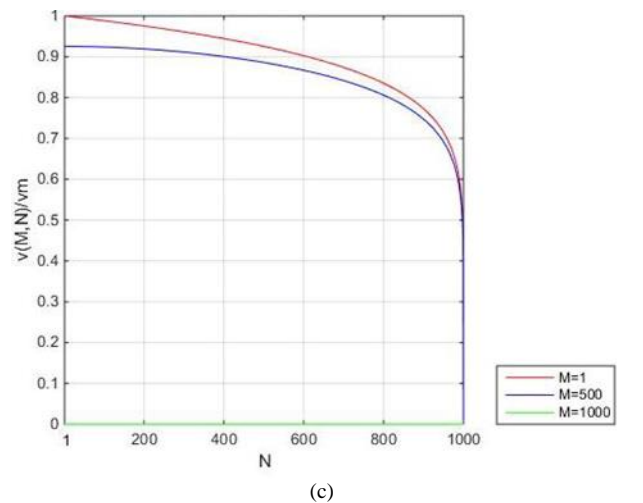
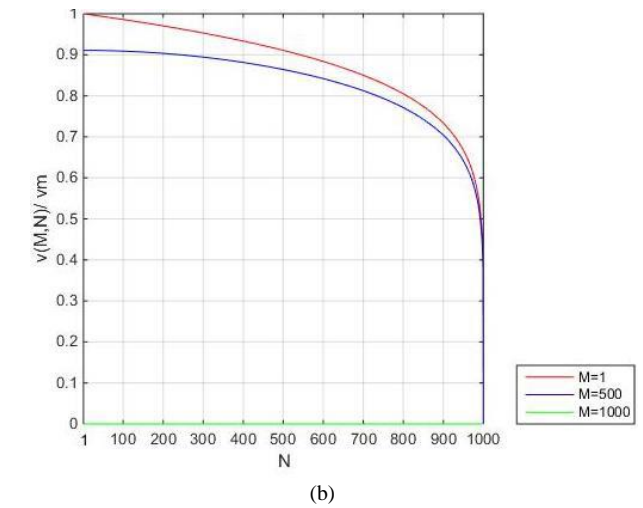
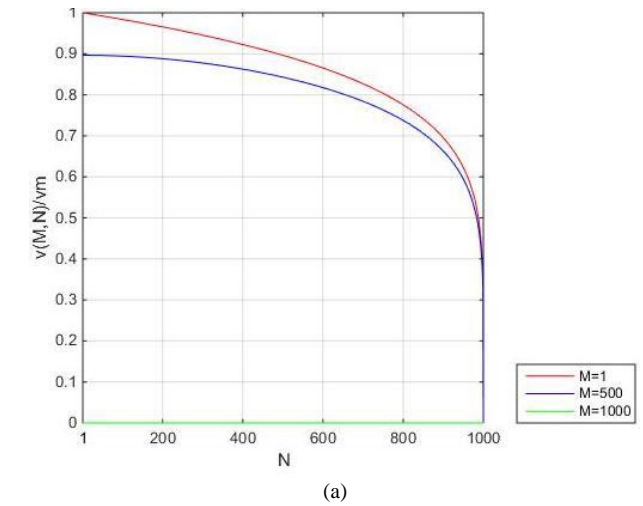


Fig.11. Normalized fluid velocity for M=1, 500 and 1000. (a) Re=10000 (b) Re=100000 (c) Re=1000000

$v(M, N)$ shown in Fig. 11 indicates the pixel value of the fluid velocity at the position (M, N). The $v(1, 1)$ value (i.e. M=1 and N=1) is equal to v_m in three figures. While normalized $v(500, 1)$ is 0.896 for Re=10000, it is 0.911 and

0.925 for $Re=100000$ and 1000000 , respectively. The pixels at $M=1$ or $N=1$ are also calculated with Eq. (5) but other pixels are calculated with pixel-based calculation method. To find normalized v (1,600) (whose values are 0.865, 0.884 and 0.903 for $Re=10000$, 100000 and 1000000 , respectively), both Eq. (5) and pixel-based method are used. To find normalized v (500,600) (whose values are 0.818, 0.842 and 0.867 for $Re=10000$, 100000 and 1000000 , respectively), only the pixel-based method is used in this paper. $M=1000$ or $N=1000$ indicates the pipe surface and the values of v are zero for these positions. Fig. 11 is also used to calculate Q_{bpr} which is indicated in Eq. (13). For any acoustic path in the z -direction, v_{bp} is obtained by averaging the pixels. Fig. 12 shows the obtained v_{bp} values for different acoustic paths.

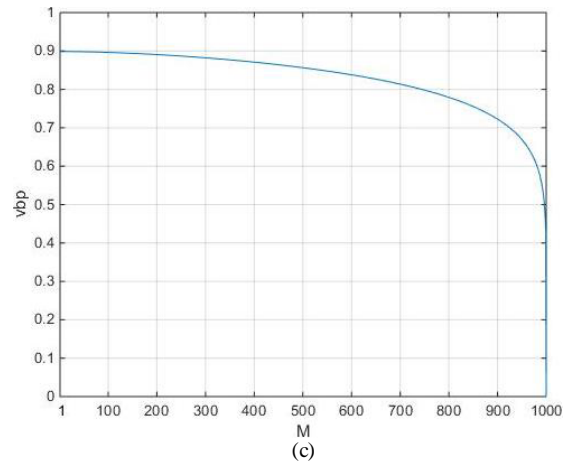
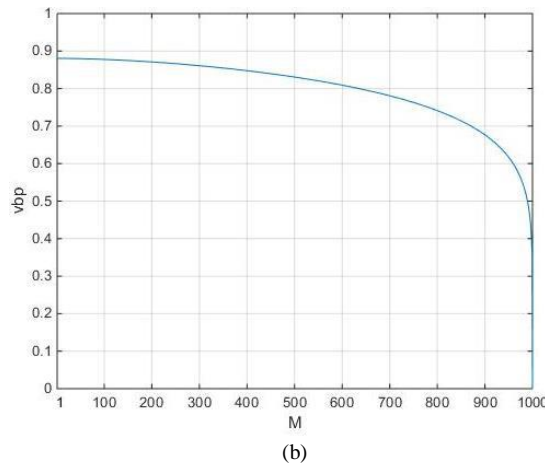
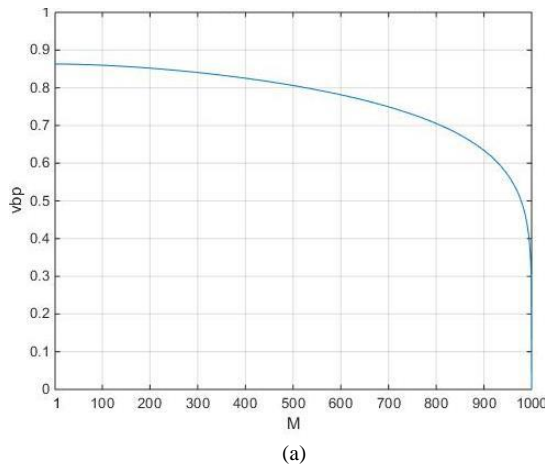


Fig.12. Obtained v_{bp} values for different acoustic paths (a) $Re=10000$ (b) $Re=100000$ (c) $Re=1000000$



In Fig. 12, $M=1$ indicates the acoustic path in the middle of the pipe. In this position, v_{bp} is 0.863, 0.881 and 0.899 for $Re=10000$, 100000 and 1000000 , respectively. These values are also shown in Fig. 4 and can also be obtained with Eq. (7). But for other acoustic paths, the values of v_{bp} are obtained with the pixel-based calculation method. These values are used to evaluate the quality of the ultrasonic flow meter systems. If the ultrasonic transducers are placed in positions $M=309$ and $M=809$, we obtain that v_{bp1} is 0.839 for the position $M=309$ and v_{bp2} is 0.7 for the position $M=809$ as shown in Fig. 12a for $Re=10000$. According to Eq. (13), Q_{bpr} is 1.199. To evaluate the design, Q_{bpr} is used for reference value. The researcher calculates Q_{bp} by using the results of the application (v_1 and v_2 shown in Eq. (14)). The value of Q_{bp} shows the compatibility between the ultrasonic transducers. The ideal value of Q_{bp} is 1. For example, the researcher designs the ultrasonic flowmeter and calculates Q_{bp} with the method given in this paper, and then changes the design and recalculates Q_{bp} . If the value of the recalculated Q_{bp} is closer to 1 after the operation, this means the change has improved the design. Otherwise, the change has damaged the performance of the design. Thus, Q_{bp} can be used to analyze the design for any Re and acoustic path.

V. CONCLUSION

TTD method measures the average velocity of the fluid along the acoustic path between the two ultrasonic transducers. Currently, there are many studies on TTD ultrasonic flowmeters. For researchers, it is very important to analyze their designs. This paper presents FMIFC to analyze the fluid flow depending on Re for the ideal flow conditions and the turbulent flow. FMIFC is obtained with the pixels describing the acoustic paths. FMIFC in this paper has 1000×1000 pixels which represent the number of acoustic paths and the number of pixels in each acoustic path. Any pixel in FMIFC has a greater grey level value for greater velocity. Furthermore, a quality metric is developed by using the obtained FMIFC. This metric indicates the reference ratio of the average fluid velocity of different acoustic paths. The results show that the proposed metric is easy to use for any acoustic path or Re .

Thus, it is recommended as a useful alternative metric to evaluate the performance of the ultrasonic flowmeter.

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BIOGRAPHY



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