Flow and Acoustic Simulation for a Multi-layer Ultrasonic Flow Meter

Hidetomo Nagahara [1,*], Masato Sato [1], Motoyuki Nawa [2]
Huilai Zhang [3], Takeshi Okabe [3], Makoto Tsubokura [4]

[1]Smart Energy System Business Division, Panasonic Corporation, Yamatokoriyama, Japan
[2] PERSOL Panasonic HR PARTNERS Co., LTD, Osaka, Japan
[3] Numerical Flow Designing Co., LTD, Tokyo, Japan
[4] Computational Fluid Dynamics Laboratory, Kobe University, Kobe, Japan
*corresponding author: nagahara.hidetomo@jp.panasonic.com

Abstract This paper deals with a multi-layer ultrasonic flow meter which measures flow rate in a stable laminar condition by making use of a multi-layer section. Our purpose exists in attaining comprehension of fluid phenomena, and estimation of characteristic of the multi-layer ultrasonic flow meter by an ultrasonic and a flow simulation. Firstly, we developed an analytical algorithm for the ultrasonic propagation simulation by use of the decoupling method of wave and Navier-Stokes equations, and applied this algorithm to a multi-layer duct model. As a result, propagation behavior of an ultrasonic wave in the multi-layer duct was observed. The flow velocity could be obtained by using a transit time of an ultrasonic wave calculated by simulation. The calculation error for the sound velocity, and the fixed velocity was under ±1 %. By these results, the validity of this algorithm was verified. The calculation error was less than 1 % for the multi-layer duct flow. Next, we conducted a flow simulation for an actual model assembled above mentioned multi-layer flow path. In this flow meter, there exists a transition region from turbulent to laminar condition, a flow analysis was conducted by DNS using the Japanese super computer 'K'. As a result, the transition process of relaminarization from the turbulent flow could be observed. Furthermore, the developing process of the boundary layer in the multi-layer flow path could be indirectly understood.
Keywords: ultrasonic flow meter, flow simulation, DNS, transition, ultrasonic simulation

1 Introduction

This paper deals with a multi-layer ultrasonic flow meter [1] which measures flow rate in a stable laminar condition by making use of a multi-layer section.

In the field of ultrasonic simulation, there is a study in which a flow velocity was obtained from an ultrasonic transit time [2]. However it was conducted for a single flow path. An ultrasonic analysis for a multi-layer flow path was not found before.

Firstly, we developed a simulation program for an ultrasonic propagation in a flow. By using this program, we analyzed the multi-layer flow path in which ultrasonic waves reflect in a complicated manner, and obtained a flow velocity within a small error.

In this ultrasonic flow meter, there exists transition region between turbulent and laminar condition, at upstream and downstream of the multi-layer section. In order to analyze such flow, we need to apply DNS method for a simulation analysis.

Nowadays many paper exist using DNS method for turbulent or transition analysis. For example, flow analysis in a channel flow [3] [4] were reported, and an analysis for the developed turbulent flow on a flat plate [5] was also reported. However, a flow analysis for a multi-layer flow by DNS could not be found.

We tried to analyze the multi-layer flow including transition region with DNS method by making use of super computer "K" in Japan, and obtained behavior of relaminarization.

Above mentioned results, we could attain a possibility of comprehension of the fluid phenomena, and estimation of the characteristic of the multi-layer ultrasonic flow meter.

2 Principle of Measurement

Figure 1(a) shows the front cross sectional view and Fig. 1(b) shows the side view of the measurement section for five-layer type. The flow comes from the left side as an arrow F. As shown in Fig. 1 (b), the flow measurement section is divided into multi-layers by plural splitting plates. In this example, the

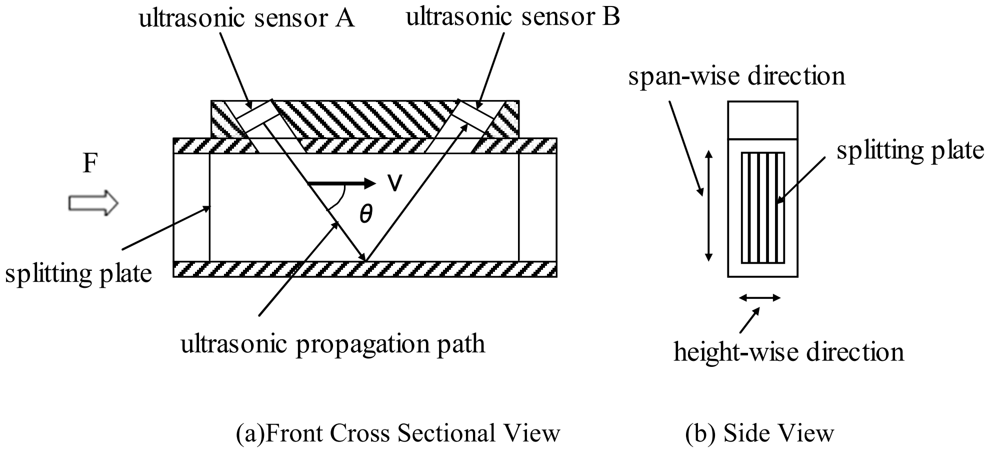

Fig. 1 Measurement principle

channel is divided into five layers, each of which has uniform height.

Ultrasonic sensors A and B are arranged on the same side of a channel so that an ultrasonic propagation path of these two sensors makes a V-shape parallel to the multi-layers mentioned above.

In this construction, an ultrasonic wave is issued from A to B, and B to A. When the downstream propagation time from A to B is Ta, and the upstream propagation time from B to A is Tb, flow velocity V is obtained by time of flight method as:

$$V = \{L / 2\cos\theta\}\{(1/Ta) - (1/Tb)\} \tag{1}$$

Here, L denotes the ultrasonic propagation length between ultrasonic sensor A & B, and θ denotes the angle between the flow direction and the ultrasonic propagation path as shown in Fig.1(a).

However, there exists various errors in an actual measurement, this velocity obtained from Eq. (1) is not always the mean velocity of the channel. Therefore, a correction factor “k” has to be introduced to have the mean velocity. The flow rate can be obtained using Eq. (2) as below, where S denotes the cross-sectional area of the channel.

$$Q = kVS \tag{2}$$

In order to attain accurate measurement, it is desirable for the flow rate correction factor “k” to be constant regardless of the flow rate. From the standpoint of velocity profile, uniform profile in height-wise and span-wise direction is requested. However, in general, it is difficult to obtain such condition, because the velocity profile changes from laminar to turbulent, and the velocity vector has basically three-dimensional components.

In this method, the rectangular cross-sectional channel is divided into multi-layers by splitting plates so as to make the velocity profile uniform between layers in the height-wise direction, and at the same time to attain two-dimensional flow in the span-wise direction. A uniform velocity profile between layers is realized by making use of flow resistance induced by the boundary layer that develops in the multi-layer channel. Two-dimensional flow is realized by making use of the high aspect ratio of the section in each layer. Both features are attained by determining the layer height so that the flow in the layer is laminar.

3 Ultrasonic propagation simulation

3.1 Analysis model

Fig. 2 shows a simulation model used for ultrasonic propagation analysis. Every dimensions shown are inside dimensions in all Figures after this. The unit of the numerical value of all drawings is mm.

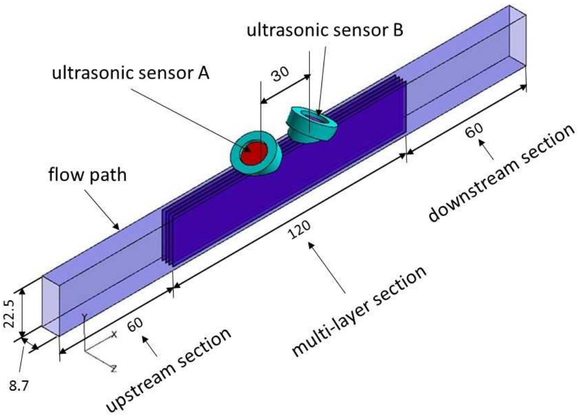

Fig. 2 Analysis Model for Ultrasonic Simulation

This model is a duct which cross section is rectangular, and a part of this duct is formed multi-layer. A pair of ultrasonic sensors are arranged on the upper side of the multi-layer section. The angle θ, and length L mentioned in chapter 2 are 60°, and 59.9 mm each. Detailed dimensions of the multi-layer section is as same as the dimensions shown in Fig.9 which is explained in clause 4.1. There are an upstream and a downstream section, each of which are located at the upstream and downstream of the multi-layer section.

Firstly, flow simulation was carried out for a flow on the condition of constant velocity at the inlet of the duct. This velocity is calculated from the constant flow rate of 6000 litter/h. In this study, the objective fluid is air.

Next, ultrasonic simulation was conducted. The boundary condition of the ultrasonic transmission was given by the flow velocity change which corresponds to the ultrasonic vibration of the sensor. The ultrasonic frequency is 500 kHz. The transmitting wave consists of 10 consecutive waves which wave form is similar to an actual one. This vibration was given uniformly on the surface of the sensor.

Minimum resolution of mesh is 0.1 mm for the x direction (the flow direction), and 0.11 mm for each y and z direction. This value is so chosen that the y+ becomes the order of 1 on the stand point of flow analysis, and that the mesh divides one ultrasonic wave length into more than 6, on the stand point of ultrasonic analysis. Courant number is less than 0.83, and Acoustic Courant number is less than 0.285 in this mesh resolution.

The number of mesh of this model is 145 million in total. This mesh was split into 1920 threads. Calculation was carried out by MPI parallel method. Time resolution is 100 ns.

3.2 Basic Equations

The development of the basic equation was based on Vladimir et al. [6].

By considering the minute fluctuating component like the sound wave in the flow field, the governing equation is given as follows:

$$\frac{\partial p}{\partial t} + \overline{V} \cdot \nabla p + \rho C^2 \nabla \cdot \overline{w} = 0 \tag{3}$$

$$\frac{\partial \overline{w}}{\partial t} + \overline{V} \cdot \nabla \overline{w} + \overline{w} \cdot \nabla \overline{V} + \frac{\nabla p}{\rho} = 0 \tag{4}$$

Here, $\overline{V}$ is the velocity of the flow field, and, $\overline{w}$ and p are the velocity and pressure of the minute fluctuation component. The predicted field of velocity is calculated implicitly and Poisson's equation of pressure correction of minute component is solved and correction terms of pressure and velocity is obtained.

3.3 Simulation Results

Fig. 3 shows the vertical cross sectional view of the analysis model. At first, transit time Ta from sensor A to B was obtained by analysis. Next, adverse transit time Tb from sensor B to A was obtained similarly. And then, flow velocity V was calculated by substituting these time Ta and Tb into equation (1). There are cavity regions between each sensor A, B, and the flow path.

Fig. 4 shows a propagation behavior of an ultrasonic wave from sensor A to B on the condition of no flow in the duct. This analysis result is shown in the same cross sectional view as in Fig.3. These sequential figures were taken every 200 steps which means 20 μsec. As shown in Fig.4, the behavior of the top wave front which comes from the sensor A reflects on the opposite side of the duct, and reaches to the sensor B is clearly observed.

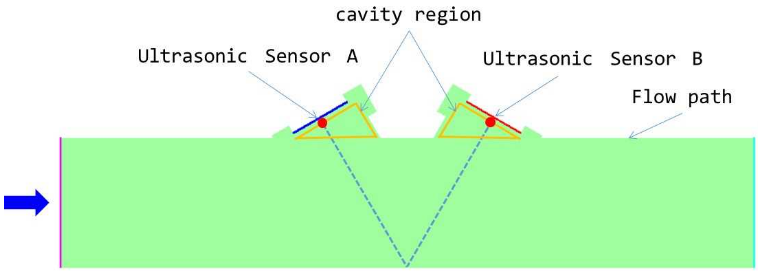

Fig. 3 Vertical Cross Sectional View of Analysis Model

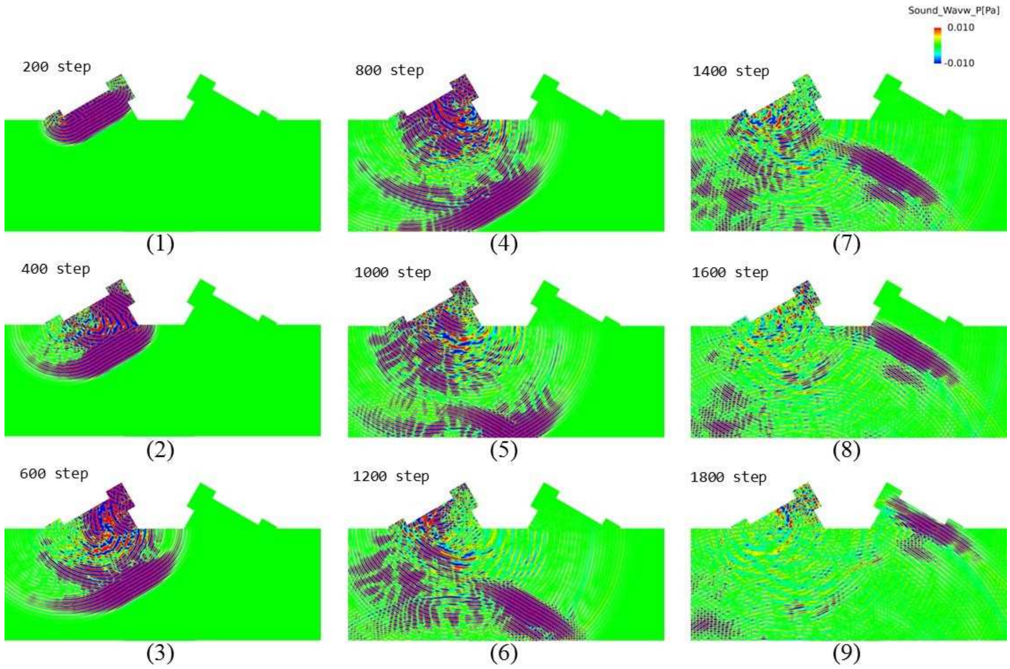

Fig. 4 Propagation Behavior of Ultrasonic Wave

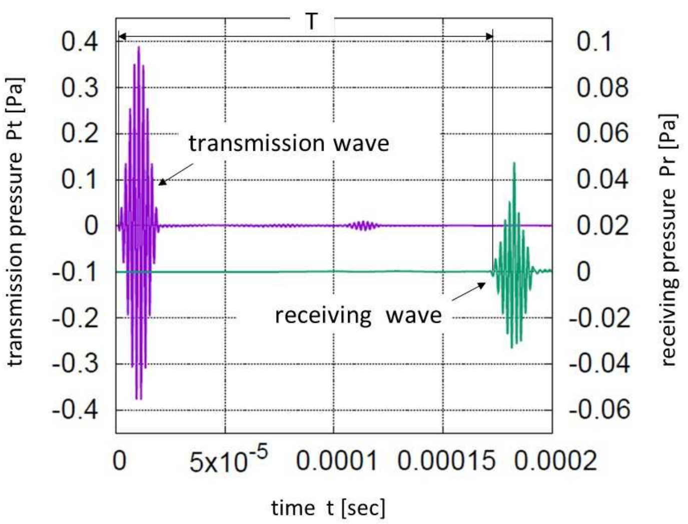

Fig. 5 Waveform of Transmission & Receiving Wave

Fig.5. shows a transmitting and receiving waveform on the same graph at the flow rate of 6000 litter/h. The left vertical axis represents the transmitting pressure Pt, and the right vertical axis represents the receiving pressure Pr. The horizontal axis represents the elapsed time t. In Fig.5, T means the transit time from sensor A to B. Here T is defined as the time difference between two zero crossing points, one of which is derived from the transmitting waveform, and the other is from the receiving waveform. Each zero crossing point is defined where a half wave length in the first wave crosses the zero level axis.

When there is no flow in Fig.3, an ultrasonic wave from sensor A to B propagates at the sound velocity. Therefore, the sound velocity is calculated using the operation L/Ta. On the other hand the sound velocity is well-known and written in physical data book. Table 1 shows the comparison of these velocities. As shown in Table1, the calculation error for the sound velocity is 0.39%.

Next, flow velocity U was calculated on the condition of fixing the flow velocity $\overline{V}$ as 10 m/s (Uo) in equation (3), and (4). Table 2 shows the comparison of these velocities. As shown in Table 2, the calculation error for the fixed velocity is -0.94%.

As mentioned above, the calculation error is within ±1% for the sound velocity, and the fixed velocity. By these results, the validity of this algorithm was verified.

On the basis of these results, the flow velocity U_T was calculated from the transit time for the flow rate of 6000 litter/h. In order to obtain the error percentage, the estimated true velocity U_F is required. This estimation was carried out by averaging the velocity along the propagation plane as shown in Fig.6. The comparison of the calculated velocity U_T, and the mean velocity U_F are shown in Table 3. As shown in Table 3, we obtain the simulation result with the calculation error of about 0.94 %. It means that the simulation program works well for the multi-layer duct flow.

Although there are cavity regions in this ultrasonic propagation path as shown in Fig.3, and Fig.6, both of these velocities U_T and U_F include this influence to the same extent. This cavity influence has to be considered when we obtain correction coefficient ‘k’ as mentioned in the chapter 2. About this problem, detailed discussion will be given in the near future.

Table 1 Calculation Error for Sound Velocity

transit time	sound velocity	sound velocity	error
calculated	calculated	known	
T [s]	C [m/s]	C_0 [m/s]	$(C-C_0)/C_0$
1.739×10^{-4}	344.45	343.10	0.39%

Table 2 Calculation Error for Fixed Flow Velocity

transit time	flow velocity	flow velocity	error
calculated	calculated	given	
Ta [s] Tb [s]	U [m/s]	U_0 [m/s]	$(U-U_0)/U_0$
1.714×10^{-4} 1.764×10^{-4}	9.91	10.0	- 0.94%

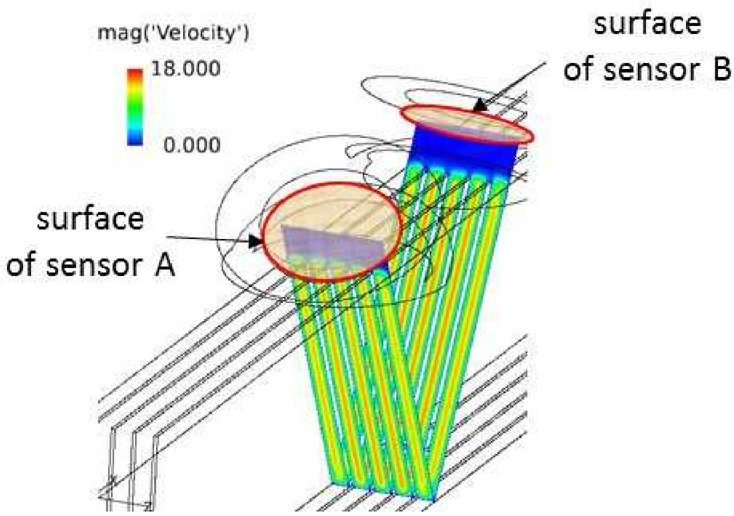

Fig. 6 Estimation of Average Flow Velocity

Table 3 Calculation Error in Multi-layer Duct Flow

flow velocity	flow velocity	error
Calculated (ultra sonic simulation)	Calculated (flow simulation)	
U_T [m/s]	U_F [m/s]	$(U_T-U_F)/U_F$
8.55	8.47	0.94%

4 Flow simulation

4.1 Analysis model

Fig.7 shows a perspective view of an analysis model of an actual flow meter. In Fig.7, a front panel is removed so as to be easy to see inside of a body. Flow enters to the body from an inlet and further enters into a flow path arranged inside of the body. After that, flow goes out from an outlet. The flow path is arranged at the center of the body in its depth direction.

Fig.8 shows a construction of the flow path. The flow path is composed of a bell mouth, an entrance region, a multi-layer section, and an exit region from left to right. The entrance region is 8.7 mm, the multi-layer section is 120 mm, and the exit region is 15.5 mm each in length. The entrance and the exit regions are formed as a single duct with rectangular cross section, and are not divided into multi-layer.

Fig. 9 shows a perspective view of the multi-layer section. In the multi-layer section, the rectangular cross section is divided into 5 layers by 4 splitting plates. Each layer has the same height of 1.5 mm. In Fig. 9, a coordinate system is also shown.

In Fig.1 (a), a pair of ultrasonic sensors are equipped on the multi-layer section. However in this actual model, sensors are not arranged. This is because that in this flow analysis, model is formed to comprehend flow phenomena without an influence of cavity.

Flow rate given is 6600 litter/h. Reynolds number defined by using flow path height as its representative length is 5080 for the entrance region, and 1016 for the multi-layer section.
Simulation is conducted using FrontFlow/red. Mesh resolution for the multi-layer section is the same as mentioned in clause 3.1. The number of mesh of this model is 370 million in total. This mesh was split into 9216 threads. Calculation was carried out by MPI parallel method.

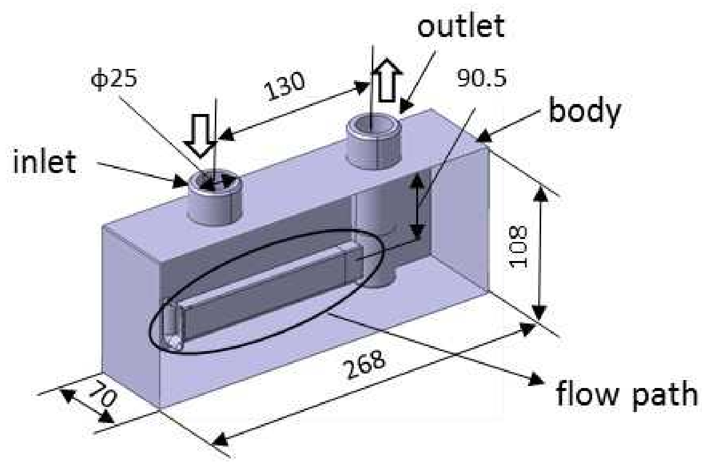

Fig. 7 Actual Model

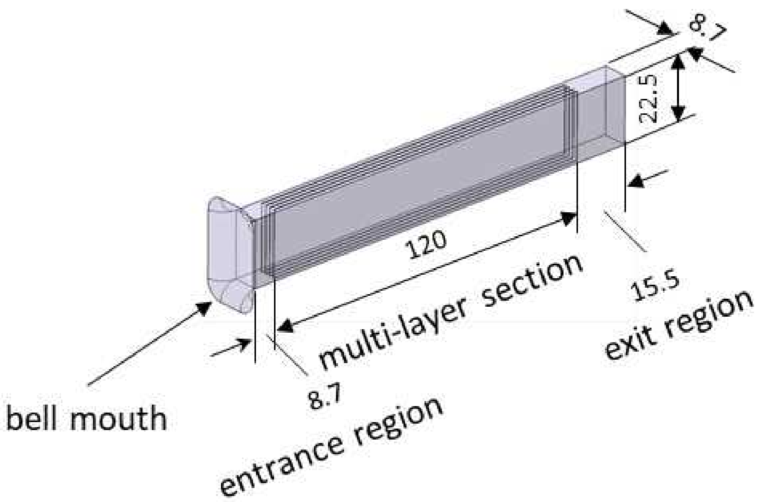

Fig. 8 Flow Path

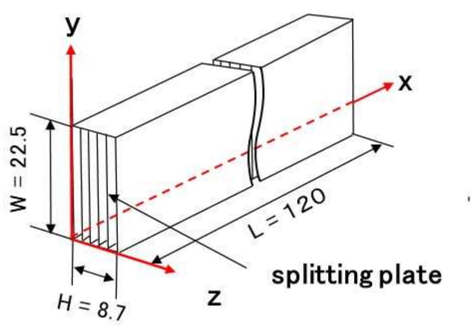

Fig. 9 Multi-layer Section

4.2 Basic Equations

The basic equations of flow consist of mass conservation equation and momentum conservation equation (Navier-Stokes equation) for incompressible flow.

・mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho\, u_j) = 0 \tag{5}$$

・momentum conservation equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{6}$$

Here, ρ is the density of the fluid, u is the velocity of the fluid. And p is the pressure, and μ is the coefficient of viscosity. Subscript i, and j represent 3 component of a coordinate system.

The governing equations are discretized by using the vertex-centered unstructured finite volume method. The second-order central differencing scheme is applied to the discretization of the convection term. The Euler implicit method is used for the time integration method, and SMAC method is used for the velocity and pressure coupling.

4.3 Simulation Results

Fig.10 shows a vertical cross sectional view of the body shown in Fig.7 cut at the center in its depth direction. This drawing shows only analysis region except the thickness part of the flow path. The red line means the position of the multi-layer section.

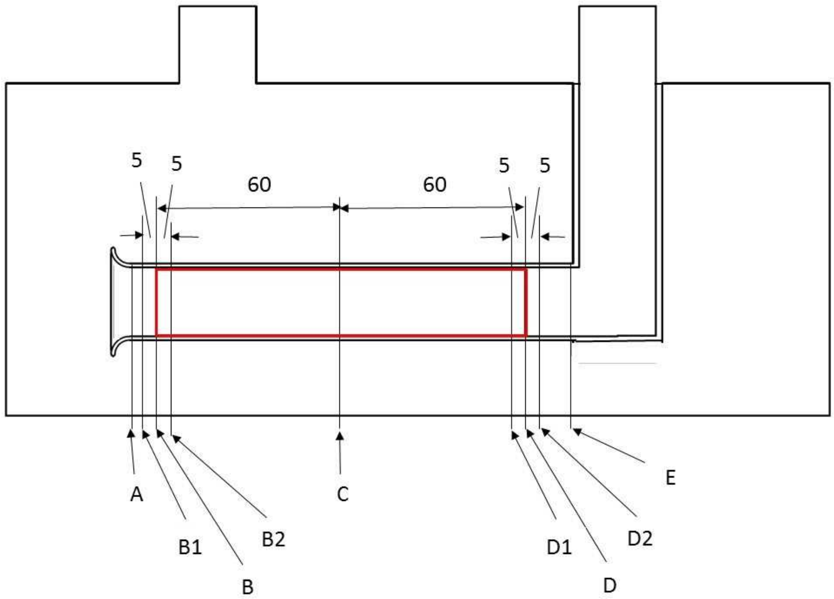

Fig.10 Appreciation Position for Flow Velocity Distribution

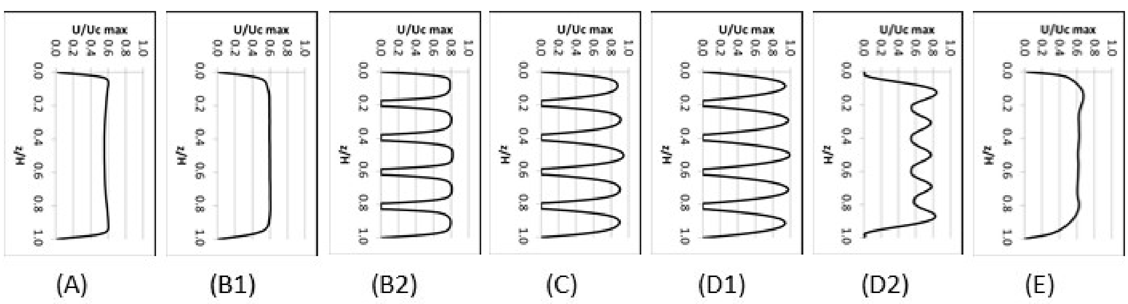

Fig.11 Normalized Flow Velocity Distribution at Each Positon shown in Fig.10

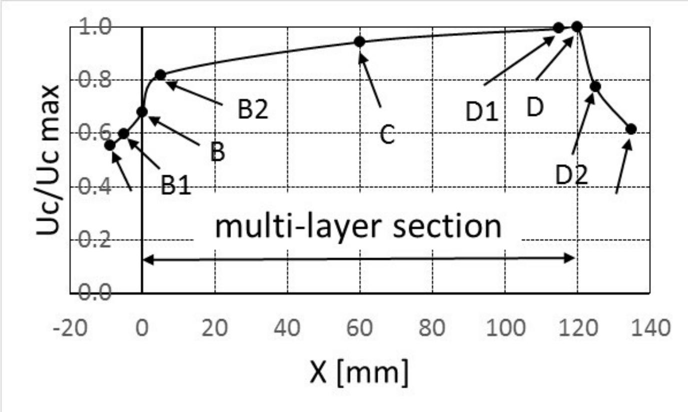

Fig.12 Normalized Center Flow Velocity Trend along Center Line of Mid-layer

Capital letters shown in Fig.10 indicate the positions at which the velocity distribution was appreciated.

Fig.11 shows the velocity distribution at the corresponding position in Fig.10.

In Fig.11, these graphs show the velocity distribution of velocity U in the x direction on the xz-plane at the central position of width (y = 11.25 mm) in Fig.9. In each graph, the horizontal axis is the normalized position z/H, where z means the height position in the z direction, and H means the maximum height of 8.7 mm. The vertical axis is the normalized velocity U/Uc max, where Uc max is the maximum velocity of U at the center of height H.

As shown in Fig.11, the velocity profile shows the turbulent flow pattern at B1. After that, the flow is divided into 5 layers in the multi-layer section. And then, the divided flows are combined to one to become the turbulent flow pattern again at E. Through this process, in the multi-layer section, from B2 to D1, the velocity profile becomes from the flat turbulent flow pattern to the parabolic laminar flow pattern in each layer. This process shows the relaminarization of the flow.

Fig.12 shows the trend of the center flow velocity Uc along the centerline of the mid-layer in the x direction. This curve is an approximated one which connects black circle marks. These marks correspond to the appreciating positions indicated in Fig.10. The horizontal axis is the distance x when the most upstream position of the multi-layer section is defined as the origin of the x axis. While the vertical axis is the normalized velocity Uc/Ucmax.

Here, we focus on the center velocity behavior in the multi-layer section. As shown in Fig.12, there is a steep increase of the center velocity from B to B2. This is due to a sudden decrease of cross sectional area and an influence of Vena Contracta at the entrance of the multi-layer section. After that, although the center velocity increases, the increase tendency becomes gradually small toward the downstream direction. This seems to be due to the increase of the boundary layer thickness in accordance with the development of the boundary layer. The curve shown in Fig.12 almost saturates at D which is the end of the multi-layer section. By observing such curve, developing process of the boundary layer in the multi-layer section could be understood although indirectly.

5 Conclusion

(1) Ultrasonic propagation simulation in multi-layer path

We proposed a numerical algorithm by use of the decoupling method of wave and Navier-Stokes equations.
By applying this algorithm to the multi-layer duct model, following results were obtained.
The calculation error for the sound velocity, and the fixed velocity was within ±1%.
By these results, the validity of this algorithm was verified.
The calculation error was less than 1 % for the multi-layer duct flow.

(2) Flow simulation in multi-layer path

By applying DNS simulation for the actual model of the multi-layer ultrasonic flow meter, following results were obtained.

The transition process of relaminarlization from the turbulent flow could be observed.
The developing process of the boundary layer in the multi-layer section could be indirectly understood.
Above mentioned results, we could attain a possibility of comprehension of fluid phenomena, and estimation of characteristic of the multi-layer ultrasonic flow meter by making use of the ultrasonic and the flow simulation.

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