A clamp-on Doppler ultrasonic flow profile meter in which the transmission frequency of the ultrasonic wave and the angle of incidence onto the pipe are adequately selected to allow a flow velocity or flow rate of fluid to be measured with high accuracy is provided. An ultrasonic flow profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid in the pipe to measure a flow velocity profile. The ultrasonic wave is reflected by a reflector in the fluid, and is changed depending on a flow velocity due to Doppler effect, and a sound wave propagative wedge placed between the ultrasonic wave transducer and the pipe.
ABSTRACT

A clamp-on Doppler ultrasonic flow profile meter in which the transmission frequency of the ultrasonic wave and the angle of incidence onto the pipe are adequately selected to allow a flow velocity or flow rate of fluid to be measured with high accuracy is provided. An ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid in the pipe to measure a flow velocity profile. The ultrasonic wave is reflected by a reflector in the fluid, and is changed depending on a flow velocity due to Doppler effect, and a sound wave propagative wedge placed between the ultrasonic wave transducer and the pipe.
CLAMP-ON DOPPLER ULTRASONIC FLOW VELOCITY PROFILE METER

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a clamp-on Doppler ultrasonic flow velocity profile meter for non-contact measurement of a flow velocity profile of a fluid by applying Doppler effect of an ultrasonic wave. The flow velocity profile meter transmits an ultrasonic wave incident on a fluid in a pipe from an ultrasonic wave transducer mounted on the outside of the pipe.

2. Background

As known in the art, the clamp-on Doppler ultrasonic flow velocity profile meter measures a flow velocity profile or a flow rate of a fluid by measurement of moving velocities of suspended particles or bubbles contained in the fluid on the principle that the suspended particles or bubbles move at the same velocity as that of the fluid.

Namely, as shown in FIG. 14, the operation principle of a Doppler ultrasonic flow velocity profile meter is illustrated. An ultrasonic wave transducer 11 is secured to an outer surface of a pipe 21 inclined to the pipe 21 with a sound wave propagative wedge 31 between them. From the ultrasonic wave transducer 11, an ultrasonic wave pulse with a fundamental frequency of \( f_0 \) is transmitted to the pipe 21 at an angle of incidence \( \theta_w \). The incident ultrasonic wave pulse is reflected by reflectors 23, such as suspended particles in a fluid 22, with an echo frequency shifted from the fundamental frequency depending on the velocity of the reflectors 23 (flow...
velocity of the fluid) by the Doppler effect. A Doppler shift frequency \( f_d \) of the echo, is expressed by the expression (1):

\[
f_d = \frac{2 \cdot V_f \cdot \sin \theta_r \cdot f_0}{C_f}
\]  

(1)

where, \( V_f \) is the flow velocity of the fluid 22, \( \theta_r \) is an angle of refraction of the ultrasonic wave at the boundary plane between the pipe 21 and the fluid 22, and \( C_f \) is the sound velocity in the fluid 22.

Therefore, the flow velocity \( V \) of the fluid 22 can be obtained by the following expression (2). The flow velocity \( V_f \) and the Doppler shift frequency \( f_d \), each being a function of a position \( x \) along the radial direction, are to be expressed as \( V_f(x) \) and \( f_d(x) \), respectively:

\[
V_f(x) = \frac{C_f \cdot f_d(x)}{2 \cdot \sin \theta_r \cdot f_0}.
\]  

(2)

FIGURE 15 is a diagram explaining the principal part of the flow velocity profile meter shown in FIG. 14 and a flow velocity profile dependent on the above-described position \( x \) in the pipe 21.

From the above expression (2), flow velocities \( V_f \) on a measuring line ML of the ultrasonic wave pulse are measured at specified intervals to obtain a flow velocity profile. The obtained profile is integrated about the cross sectional area \( A \) of the pipe 21 as expressed in the expression (3) to obtain the flow rate of the fluid 22:

\[
Q = \int V_f \cdot dA
\]  

(3)

Next, FIG. 16 is a block diagram showing the arrangement of the clamp-on Doppler ultrasonic flow velocity profile meter (a block diagram showing the ultrasonic wave transducer 11 and an inner arrangement of a converter 18 connected to the transducer 11. The arrangement is
substantially the same as that of, for example, the Doppler ultrasonic

In FIG. 16, reference numeral 12 denotes a transmission and
reception timing control unit for controlling the transmission of an ultrasonic
wave pulse and reception of the echo. The transmission and reception
timing control unit 12 starts operation of transmitted pulse generating unit 13
which produces an ultrasonic wave pulse transmitted from the ultrasonic wave
transducer 11. The ultrasonic wave transducer 11 also receives the resulting
echo. The received echo signal is amplified by a received signal amplifying
and controlling unit 14. The amplified received signal is subjected to analog
to digital conversion at A/D converting unit 15, according to the A/D sampling
clock from the transmission and reception timing control unit 12. The
digitized signal is subjected to an operation according to the above
expression (2) at a flow velocity profile operation unit 16 to obtain the flow
velocity profile. The flow velocity profile is further subjected to the operation
according to the above expression (3) at a flow rate operation unit 17, to
obtain a flow rate.

According to the above explained principle, it must be possible that
the flow velocity $V_f$ and the flow rate $Q$ of the fluid 22 are actually obtained by
operations of the expression (2) and the expression (3) without depending on
the transmission frequency $f_0$ of the ultrasonic wave pulse. However, the
difference in transmission frequency $f_0$ of an ultrasonic wave results in
changes in the obtained flow velocity $V_f$ and the flow rate $Q$ and, in particular,
such frequency dependence becomes remarkable when the pipe 21 is made
of thin metallic material, while the frequency dependence becomes small when the pipe 21 is made of plastic.

Moreover, in an ultrasonic flow velocity profile meter disclosed in Japanese Patent Application No. 2003-396755, an ultrasonic wave transducer is secured to a wedge while being inclined to a pipe, by taking an angle of incidence of an ultrasonic wave incident on the pipe, from the wedge, being no less than the critical angle for a longitudinal wave in the pipe, and no more than the critical angle for a shear wave in the pipe. This provides that only a shear wave is propagated in the pipe when the sound velocity of the shear wave of an ultrasonic wave propagated in a pipe is equal to, or more than, the sound velocity of the longitudinal wave in a wedge (when a metallic pipe is used).

According to the flow velocity profile meter, the echo from the reflectors in the fluid becomes a wave due to only a shear wave propagated in the pipe before being incident on the fluid. Thus, no echo due to a longitudinal wave is received by the transducer to reduce acoustic noises. However, the problem of frequency dependence of the above-described flow velocity $V_f$ and the flow rate $Q$ is unsolved.

Accordingly, there is a need for a clamp on Doppler ultrasonic flow velocity distribution profile meter which has a small frequency dependence and is capable of measuring a flow velocity and a flow rate with high accuracy by adequately setting a transmitted frequency of an ultrasonic wave and an angle of incidence of the ultrasonic wave to the pipe.
SUMMARY OF THE INVENTION

In accordance with a first aspect of the present invention, there is provided a clamp-on Doppler ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, made incident onto a fluid to be measured in the pipe to measure a flow velocity profile of the fluid to be measured by applying the principle that a frequency of an ultrasonic wave, reflected by a reflector existing in the fluid, is changed depending on a flow velocity due to Doppler effect, and a sound wave propagative wedge is placed between the ultrasonic wave transducer and the pipe, the frequency of the transmitted ultrasonic wave is set at a frequency other than the frequency at which an angle of refraction of a wave in each mode of Lamb wave in the pipe becomes 90°, the frequency being calculated from an angle of incidence of the ultrasonic wave made incident onto the pipe from the wedge, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

In accordance with a second aspect of the present invention there is provided, in a clamp-on Doppler ultrasonic flow velocity profile meter, the frequency of the transmitted ultrasonic wave is set around a central frequency between two frequencies at each of which an angle of refraction of a wave in each of two successive modes of Lamb wave in the pipe becomes 90°, the two frequencies being calculated from an angle of incidence of the ultrasonic wave made incident onto the pipe from the wedge, a sound velocity in the
wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

In accordance with a third aspect of the present invention, there is provided in a clamp-on Doppler ultrasonic flow velocity profile meter, the frequency of the transmitted ultrasonic wave is set at a frequency lower than the frequency at which an angle of refraction of a wave in a first order mode of antisymmetric Lamb wave in the pipe becomes 90°, the frequency being calculated from an angle of incidence of the ultrasonic wave made incident onto the pipe from the wedge, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

In accordance with a fourth aspect of the present invention, there is provided, in a clamp-on Doppler ultrasonic flow velocity profile meter, the ultrasonic wave is made incident from the wedge onto the pipe at an angle of incidence larger than the angle of incidence at which an angle of refraction of a wave in a first order mode of anti-symmetric Lamb wave in the pipe becomes 90°, the frequency being calculated from a frequency of the transmitted ultrasonic wave, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

In accordance with a fifth aspect of the present invention, there is provided, in a clamp-on Doppler ultrasonic flow velocity profile meter, the frequency of the transmitted ultrasonic wave is set at a frequency lower than a cutoff frequency of a wave in a first order mode of anti-symmetric Lamb wave,
the cutoff frequency being determined from a dispersion curve of the Lamb wave.

In accordance with a sixth aspect of the present invention, there is provided, an asymptotic solution of a characteristic equation of Lamb wave is used as a phase velocity of the Lamb wave for determining one of the frequency or the angle of incidence of the transmitted ultrasonic wave.

In accordance with a seventh aspect of the present invention, there is provided, an actual flow calibration constant for calibrating a flow rate derived from a measured flow profile is given by a ratio of a value of a flow rate derived from a flow velocity profile measured with the ultrasonic wave transducer mounted on a reference pipe including fluid flowing at a reference flow rate to a value of a flow rate as the reference flow rate of the fluid flowing in the reference pipe simultaneously measured by a reference flow rate measuring device provided besides the ultrasonic wave transducer.

In accordance with an eighth aspect of the present invention, there is provided an actual flow calibration constant is held as a calibration constant characteristic of each ultrasonic wave transducer.

In accordance with a ninth aspect of the invention, there is provided for, a measured value is corrected on the basis of a result of calculation of an error of measurement due to Lamb wave.

According to the invention, adequately setting of a transmitted frequency of an ultrasonic wave and an angle of incidence of the ultrasonic wave to a pipe enables realization of a clamp-on Doppler ultrasonic flow velocity profile meter which reduces frequency dependence of a measured
value due to Lamb wave to bring an error of measurement to around a minimum value.

Moreover, the actual flow calibration of the ultrasonic wave transducer allows an offset error to be cancelled and allows interchangeability between transducers, by which a high accuracy can be maintained even when the converter is changed.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagram showing propagation of an ultrasonic wave diagonally incident onto a pipe with an angle of incidence not more than the critical angle for a longitudinal wave in the pipe;

FIG. 2 is a diagram showing propagation of an ultrasonic wave diagonally incident onto a pipe with an angle of incidence not less than the critical angle for a longitudinal wave in the pipe and not more than the critical angle for a shear wave in the pipe;

FIG. 3 is a diagram showing examples of dispersion curves of Lamb waves;

FIG. 4 is a schematic view showing an arrangement of an ultrasonic flow velocity profile meter according to the embodiment;

FIG. 5 is a graph showing a relationship between a transmitted frequency and an angle of refraction for each mode of Lamb wave;

FIG. 6 is a diagram showing a relationship between a transmitted frequency and an error of flow rate measurement;
FIG. 7 is a diagram showing flow velocity profiles of water each measured about each of modes of Lamb wave;

FIG. 8 is a diagram showing a result of calculation about a relationship between a transmitted frequency and a flow rate error;

FIG. 9 is a diagram showing a relationship between a plate thickness of a pipe and an error of flow rate measurement;

FIG. 10 is a list showing examples of frequencies by pipe plate thickness, at each of which frequencies an angle of refraction for each mode of Lamb wave reaches 90°, the frequencies being calculated out as asymptotic solutions of characteristic equation of Lamb wave;

FIG. 11 is a diagram showing an arrangement of a calibration facility with an actual flow;

FIG. 12 is a diagram illustrating the operation of the calibration facility shown in FIG. 11;

FIG. 13 is a conceptual illustration of the calibration with an actual flow in the embodiment of the invention;

FIG. 14 is a diagram illustrating the operation principle of a Doppler ultrasonic flow velocity profile meter;

FIG. 15 is a diagram for explaining the principal part of the flow velocity profile meter shown in FIG. 14 and a flow velocity profile in a pipe;

and

FIG. 16 is a block diagram showing the whole arrangement of the clamp-on Doppler ultrasonic flow velocity profile meter.
DETAILED DESCRIPTION

An exemplary embodiment of the invention will be explained with reference to drawings.

Firstly, the above frequency dependence is caused by a dispersion phenomenon (a phenomenon of sound velocity variation depending on a frequency) occurring in a pipe. In considering the dispersion phenomenon, a plate having the same thickness as that of the pipe functions as a waveguide, caused by normal modes of waves propagating within the plate. Each of the normal modes of waves in a plate is a sound wave having a specified frequency and a specified wavelength satisfying a boundary condition and propagating along the infinitely extending flat plate having a finite thickness. The occurrence of the normal modes of waves in a plate depends on the material and the thickness of the plate.

The normal modes of waves in a plate are presented as an SH wave (a horizontally-polarized shear wave) and Lamb wave. Here, the Lamb wave is a wave in which a longitudinal wave and an SV wave (a vertically-polarized shear wave) are combined causing mode conversion on the upper face of a flat plate.

Of the normal modes of waves in a plate, the SH wave, causes no longitudinal wave at the boundary between the flat plate and a fluid, and is considered not to propagate in the fluid. Therefore, the Lamb wave causes
the dispersion phenomenon, and the behavior of the Lamb wave is considered to be the cause of the previously described frequency dependence.

FIGURE 1 and FIGURE 2 are diagrams each showing a dispersion model of Lamb wave when an ultrasonic wave is diagonally incident to a plate (a pipe) and propagates in the plate. FIGURE 1 shows the case in which an angle of incidence $\theta_w$ onto the pipe is given as $\theta_w \leq$ (the critical angle for a longitudinal wave in the pipe). FIGURE 2 shows the case in which the angle of incidence $\theta_w$ is given as (the critical angle for a longitudinal wave in the pipe) $\leq \theta_w \leq$ (the critical angle for a shear wave in the pipe).

It is considered that a plurality of Lamb waves are induced in the pipe with their frequencies kept at a constant frequency due to difference in phase velocities ($= \omega/k$, $\omega$: angular frequency, $k$: wave number) when an ultrasonic wave is incident onto a wedge to the pipe. With the angle of incidence $\theta_w$ given as $\theta_w \leq$ (the critical angle for a longitudinal wave in the pipe) as shown in FIG. 1, antisymmetric Lamb waves with modes $A_m$ and symmetric Lamb waves with modes $S_m$ ($m$ represents the successive orders of mode corresponding to difference in wavelength given as $m = 0, 1, 2, ...$), each having a wave length determined by the later explained characteristic equation, are induced in addition to an $L$ wave (a longitudinal wave) and an $SV$ wave. A part of the induced anti-symmetric and symmetric Lamb waves are incident onto the fluid. Moreover, as shown in FIG. 2, with the angle of incidence $\theta_w$ given as (the critical angle for a longitudinal wave in the pipe) $\leq \theta_w \leq$ (the critical angle for a shear wave in the pipe), in addition to the $SV$
wave, Lamb waves with the modes $A_m$ and the modes $S_m$ are induced in the same way, a part of which are to be incident onto the fluid.

According to Cho-onpa Benran Henshu lin-kai (Ultrasonics Handbook Editorial Committee), Ed., Cho-onpa Benran (Ultrasonics Handbook), pp 63 to 65, Maruzen Co., Ltd. (in Japanese)), herein identified as Reference 1, the characteristic equations of Lamb waves are expressed by the expression (4) to the expression (7):

$$\beta_1^2 = (-\beta_2)^2 = (\omega/V_l)^2 - k^2$$  \hspace{1cm} (4)

$$\beta_3^2 = (-\beta_4)^2 = (\omega/V_s)^2 - k^2$$  \hspace{1cm} (5)

$$\tan(\beta_1 d/2)/\tan(\beta_3 d/2) = -(k^2 - \beta_3^2)^2/(4k^2\beta_1\beta_3): \text{in the case of symmetric mode}$$  \hspace{1cm} (6)

$$\tan(\beta_3 d/2)/\tan(\beta_1 d/2) = -(k^2 - \beta_3^2)^2/(4k^2\beta_1\beta_3): \text{in the case of anti-symmetric mode.}$$  \hspace{1cm} (7)

In the expression (4) to the expression (7), $\beta_1$ to $\beta_4$ are sound propagation coefficients, $d$ is the plate thickness, $\omega$ is the angular frequency, $V_l$ is the sound velocity of the longitudinal wave, $V_s$ is the sound velocity of the shear wave, and $k$ is the wave number.

By the above characteristic equations, about each mode $m$ ($m$th order) of the symmetric Lamb waves and the anti-symmetric Lamb waves, relations between their frequencies and their wavelengths can be calculated. Moreover, a phase velocity $V_p$ and a group velocity $V_g$ as an actual propagation velocity of a wave packet (in general, $V_g \neq V_p$, and without presence of a dispersion phenomenon, $V_g = V_p$) can be obtained by the following expressions (8) and (9):
\[ V_p = \frac{\omega}{k} \]  \hspace{1cm} (8)
\[ V_g = \frac{\partial \omega}{\partial k} \]  \hspace{1cm} (9)

Furthermore, from the above phase velocity and Snell's law, an angle of refraction \( \theta_p \) of each mode of the Lamb wave at the pipe can be calculated.

FIGURE 3 is a diagram showing examples of dispersion curves (\( \omega - k \) dispersion curves) of Lamb waves obtained by solving the above characteristic equations. The diagram is contained on page 64 in the Reference 1. Each solid line represents a dispersion curve of each mode \( A_m \) of the anti-symmetric Lamb wave and each broken line represents a dispersion curve of each mode \( S_m \) of the symmetric Lamb wave.

The horizontal axis in FIG. 3 corresponds to the wave number of an ultrasonic wave and the vertical axis corresponds to the transmitted frequency of the ultrasonic wave. A mode of a Lamb wave induced at a transmitted frequency, a pipe thickness, and a sound velocity in a pipe is the mode of a dispersion curve intersecting a horizontal line orthogonal to the vertical axis at a point with a value corresponding to the transmitted frequency. However, actually induced modes are limited to those in the case in which a critical angle determined by the sound velocity in the wedge and the phase velocities of every mode is larger than the angle of incidence \( \theta_w \) onto the pipe.

The exact solutions for the frequency and the wavelength in each mode of Lamb wave are obtained by solving the previously explained characteristic equations. However, when a product \( kd \) of a wave number \( k \) and a plate thickness \( d \) is large, the calculation can be practically simplified by substituting asymptotic solutions for exact solutions. Namely, a phase
velocity $V_p$ asymptotically approaches the phase velocity $V_R$ of Rayleigh
wave for the zero order mode ($m = 0$) as is expressed in the expression (10).
While, for the higher order modes ($m = 1, 2, ...$), the velocity $V_p$ asymptotically
approaches each solution (a sound velocity $V_s$ of the shear wave) of the
characteristic equations of the shear waves of the corresponding modes as
are expressed in the equations (11):

$$V_p^{(AD)} = V_p^{(SO)} = V_R \quad (m = 0) \quad (10)$$

$$V_p^{(Am)} = \omega / \sqrt{((\omega / V_S)^2 - (2m\pi/d)^2)^{1/2}}$$

$$V_p^{(Sm)} = \omega / \sqrt{((\omega / V_S)^2 - ((2m+1)\pi/d)^2)^{1/2}} \quad (m = 1, 2, ...) \quad (11)$$

In the equations (11), superscripts Am and Sm represent an $m$th order
mode of the anti-symmetric Lamb wave and that of the symmetric Lamb wave,
respectively.

Moreover, because of presence of an approximate solution in the
equation about the phase velocity of the Rayleigh wave, in applying the above
expression (10), the approximate solution is practically substituted for the
exact solution to allow the calculation to be simplified.

In the Katsuo Negishi et al., Cho-onpa Gijutsu (Ultrasonics Technology), pp 173 to 174, Tokyo Daigaku Shuppan-kai (Publication
Association of University of Tokyo) (in Japanese)), herein identified as
Reference 2, there is described that the exact solution for the phase velocity
$V_R$ of Rayleigh wave can be obtained as the solution of the equation (12) by
setting $L$ and $S$ as

$$L = \{1 - (V_R/V_l)^2\}^{1/2}, \quad S = \{1 - (V_R/V_s)^2\}^{1/2}.$$
Furthermore, there is described that the approximate solution is expressed by the expression (13) by letting Poisson ratio be $\sigma$:

\[
4LS - (1 + S^2)^2 = 0 \tag{12}
\]

\[
V_R = V_S(0.87 + 1.12\sigma)/(1 + \sigma). \tag{13}
\]

Next, FIG. 4 is a schematic view showing an arrangement of an ultrasonic flow velocity profile meter according to the embodiment. In the arrangement as shown in FIG. 4 including an ultrasonic wave transducer 11, a wedge 12 and a pipe 21 of stainless steel, relationship between the transmitted frequency of the ultrasonic wave and an angle of refraction $\theta_p$ for each mode of Lamb wave is calculated. The calculation is carried out by the expressions (14) and (15) by using the asymptotic solutions for the phase velocities expressed as the expressions (10) and (11) and Snell’s law about the case in which an angle of incidence $\theta_w$ onto the pipe 21 is not less than the critical angle for the longitudinal wave in the pipe 21 and not more than the critical angle for the shear wave (equivalent to the case shown in FIG. 2):

\[
\theta_p^{(Am)} = \sin^{-1}(V_p^{(Am)}/C_w \cdot \sin \theta_w)
\]

\[
\theta_p^{(Sm)} = \sin^{-1}(V_p^{(Sm)}/C_w \cdot \sin \theta_w). \tag{14}
\]

In the expression (14), $C_w$ is the sound velocity in the wedge 31.

FIGURE 5 is a graph showing a relationship between the transmitted frequency and the angle of refraction for each mode of Lamb wave calculated by using above expression.

Moreover, by using a pipe 21 similar to the above, a relationship between the transmitted frequency and an error of flow rate measurement can be measured. The result is shown in FIG. 6.
FIGURE 5 and FIGURE 6 indicate that the error of measurement becomes maximum around the frequency \( f_{\text{critical}} \) at which angles of refraction \( \theta_p^{(Am)} \) and \( \theta_p^{(Sm)} \) of Lamb wave in a certain order of a mode (for example, \( A_2, S_1 \)) reach 90°. Here, the above frequency \( f_{\text{critical}} \) can be obtained by the following expressions (15). The expressions (15) are derived by taking \( \theta_p^{(Am)} \) and \( \theta_p^{(Sm)} \) in the expressions (14) as \( \theta_p^{(Am)} = \theta_p^{(Sm)} = 90° \), substituting \( V_p^{(Am)} \) and \( V_p^{(Sm)} \) in the expressions (11) for those in the expressions (14), and then solving the expressions (14) for \( \omega (= 2\pi f) \):

\[
f_{\text{critical}}^{(Am)} = \frac{m}{((1/V_s)^2 - (\sin \theta_w/C_w)^2)^{1/2}/d}
\]

\( (m = 1, 2, \ldots) \)

\[
f_{\text{critical}}^{(Sm)} = \frac{(2m + 1)}{((1/V_s)^2 - (\sin \theta_w/C_w)^2)^{1/2}/d/2}
\]

\( (m = 1, 2, \ldots) \) \hspace{1cm} (15)

Therefore, by setting the transmitted frequency of the ultrasonic wave at a frequency other than the above frequency \( f_{\text{critical}} \), the error of measurement of flow rate can be prevented from being brought to around a maximum.

In FIG. 5 and FIG. 6, the set frequency is shown at the intermediate point between two frequencies at which the angles of refraction \( \theta_p^{(A2)} \) and \( \theta_p^{(S1)} \) of modes \( A_2 \) and \( S_1 \) of Lamb wave reach 90°, respectively. At the intermediate point, the error of measurement is around a minimum. In this way, at the intermediate point between the frequencies at which the angles of refraction \( \theta_p^{(A2)} \) and \( \theta_p^{(S1)} \) of two successive modes of \( A_2 \) and \( S_1 \) of Lamb wave reach 90°, respectively, there exists a frequency at which the error of measurement is reduced to an amount around a minimum. Therefore, by
setting the frequency at the intermediate point as the transmitted frequency, it becomes possible to reduce the error of measurement to an amount around a minimum by avoiding the error becoming a maximum.

Each mode of Lamb wave has a different propagation time $\tau$ in the pipe due to difference in angle of refraction $\theta_p$ in the pipe caused by difference in phase velocity, and due to difference in group velocity $V_g$. Here, group velocities $V_g$ as asymptotic solutions for various modes of Lamb wave are shown in the expressions (16). Moreover, the propagation time $\tau$ in the pipe becomes different depending on a group velocity $V_g$ as expressed in expressions (17):

$$V_g^{(AO)} = V_g^{(SO)} = V_R$$
$$V_g^{(Am)} = V_s^2 N_p^{(Am)}$$
$$V_g^{(Sm)} = V_s^2 N_p^{(Sm)}$$

(16)

$$\tau^{(Am)} = d / \cos \theta_p^{(Am)} / V_g^{(Am)}$$
$$\tau^{(Sm)} = d / \cos \theta_p^{(Sm)} / V_g^{(Sm)}$$

(17)

Therefore, the echo is received in a form in which, on the echo of the ultrasonic wave following the primary principle expression (for example, the SV wave of the shear wave and the L wave of the longitudinal wave), echoes of other Lamb waves (interference waves) are superposed with their respective timings being shifted. Thus, the obtained flow velocity profile has current distribution derived from various modes of Lamb waves superposed on the original flow velocity profile. This causes the error of measurement of the flow velocity profile, and therefore, the error of measurement of the flow rate.
Expression (18) expresses a propagation time $T$ of Lamb wave in a fluid (in water), where $D$ is the inner diameter of a pipe. Due to the propagation time $T$ in a fluid and propagation times $\tau$ in a pipe, each mode of Lamb wave causes a positional difference in the radial direction as is expressed in each of the expressions (19):

$$T = D / \cos \theta_f / V_f$$ (18)

$$r^{(Am)}/R = 2(\tau^{(Am)} - \tau^{(Vs)}) / T$$

$$r^{(Sm)}/R = 2(\tau^{(Sm)} - \tau^{(Vs)}) / T$$ (19)

where $R$ is the radius (= $D/2$) of the pipe having the inner diameter $D$, and $r$ is the distance ($r \leq R$) along the radius $R$ from the center of the pipe.

FIGURE 7 shows flow velocity profiles of water each measured about each of modes $A_0$ to $A_2$, $S_0$ and $S_1$ of Lamb wave, and the SV wave ($V_s$) as the shear wave. The horizontal axis represents the position relative to the radius of the pipe from the center of the pipe in the direction of the radius and the vertical axis represents the measured value of the flow velocity. In the measurement, the averaged flow velocity of water is 2m/s.

In FIG. 7, the flow velocity profile is different depending on each of the modes $A_0$ to $A_2$, $S_0$ and $S_1$, and positional differences are caused in the radial direction for the same flow velocity, which cause errors of measurement.

Moreover, FIG. 8 is a diagram showing a flow rate error calculation result carried out by using a model the same as the pipe used for obtaining the flow velocity profiles shown in FIG. 7. In FIG. 8, the error is maximum around the frequencies of $f_{critical}$ (around 1.4MHz and 1.9MHz) at each of which an angle of refraction of Lamb wave becomes 90°.
Furthermore, the expression (20) is for calculating a flow velocity profile of a turbulent flow for obtaining the flow velocity profiles shown in FIG. 7. Expression (21) is for obtaining the flow rate error shown in FIG. 8. In FIG. 8, errors in all of modes of Lamb wave are simply averaged.

\[ V(r) = V_{\text{max}} \left\{ 1 - (r - r^{(\text{Am})})/R \right\}^{1/n}, \]

or

\[ V(r) = V_{\text{max}} \left\{ 1 - (r - r^{(\text{Sm})})/R \right\}^{1/n} \]

\[ n = 2.1 \log \text{Re} - 1.9 \]

\[ \text{Re} = V_{\text{av}} D / \nu \]  \tag{20}

where, \( \text{Re} \) is Reynolds number, \( V_{\text{max}} \) is the maximum flow velocity, \( V_{\text{av}} \) is an averaged flow velocity, and \( \nu \) is a kinematic viscous coefficient:

\[ \Delta Q^{(\text{Am})}/Q_0 = \{(2n + 1)/n\} \{2r^{(\text{Am})}/R - (r^{(\text{Am})}/R)^{1 + 1/n}\} \]

\[ + (1 - r^{(\text{Am})}/R)^2 + 1/n - (r^{(\text{Am})}/R)^2 + 1/n - 1 \]

\[ \Delta Q^{(\text{Sm})}/Q_0 = \{(2n + 1)/n\} \{2r^{(\text{Sm})}/R - (r^{(\text{Sm})}/R)^{1 + 1/n}\} \]

\[ + (1 - r^{(\text{Sm})}/R)^2 + 1/n - (r^{(\text{Sm})}/R)^2 + 1/n - 1 \]

\[ \Delta Q/Q_0 = \Sigma (\Delta Q^{(\text{Am})} + \Delta Q^{(\text{Sm})})/Q_0/N \]  \tag{21}

where \( N \) is the number of modes.

In addition, by using three kinds of pipes made of stainless steel each with a different thickness, a relationship between the plate thickness and the flow rate error can be measured. In the measurement, as a transmitted frequency is set at around the intermediate point between two frequencies. At each of the two frequencies, the angle of refraction \( \theta_p \) of Lamb wave in each of two successive modes, such as the previously described modes \( A_1 \) and \( S_1 \) of Lamb wave, reaches 90°. The results are shown in FIG. 9. In
FIG. 9, transmit frequencies of 1.9MHz, 1.6MHz and 1.8MHz are corresponding to plate thicknesses \( d_1, d_2 \) and \( d_3 \), respectively are set.

According to FIG. 9, it is possible to reduce each error of measurement regardless of the thickness of the pipe.

Furthermore, as another way of suppressing frequency dependence, a transmitted frequency is made lower than the frequency at which an angle of refraction \( \theta_p \) of an anti-symmetric Lamb wave in a first order mode \( A_1 \) reaches 90°. With a frequency lower than the frequency at which the angle of refraction \( \theta_p \) reaches 90°, no mode \( A_1 \) is generated. Along with this, only SV wave and zero order modes of \( A_0 \) and \( S_0 \) of Lamb wave are generated, by which the frequency dependence can be considerably suppressed.

FIGURE 10 is a list showing examples of calculation results of frequencies at each of which an angle of refraction \( \theta_p \) for each mode of Lamb wave reaches 90°. The frequencies are for various plate thicknesses of pipes as asymptotic solutions of the characteristic equation of Lamb wave.

As the order of a mode \( m \) of Lamb wave increases, the frequency at which an angle of refraction of Lamb wave reaches 90° becomes higher. It is therefore known that a transmitted frequency made lower than the frequency at which the angle of refraction \( \theta_p \), of the above-described mode \( A_1 \) reaches 90°, does not generate Lamb waves with modes of first order and above.

As further another way of suppressing frequency dependence, an angle of incidence of an ultrasonic wave onto the pipe can be made larger than the critical angle for an anti-symmetric Lamb wave of the first order mode \( A_1 \). As the order of the mode of Lamb wave becomes higher, the phase
velocity of Lamb wave becomes faster and the critical angle becomes smaller. Therefore, an ultrasonic wave, made incident at an angle of incidence larger than the critical angle for the anti-symmetric Lamb wave of the first order mode $A_1$, does not generate Lamb waves with modes of first order and above to allow frequency dependence to be considerably suppressed.

Furthermore, a way of making the transmitted frequency lower than the cut-off frequency of the anti-symmetric Lamb wave of the first order mode $A_1$ can be also considered. The cut-off frequency is a frequency at which the phase velocity becomes infinity and the group velocity becomes zero (the value at $kd = 0$ in the diagram in FIG. 3, i.e. an intercept on the vertical axis). At a frequency lower than the cut-off frequency, no Lamb wave of the mode $A_1$ is generated regardless of the angle of incidence $\theta_w$. The cut-off frequency increases as the order of the mode becomes higher. Therefore, at a frequency lower than the cut-off frequency of Lamb wave of the mode $A_1$, no mode higher than the mode $A_1$ is generated, which allows frequency dependence to be considerably suppressed regardless of the angle of incidence $\theta_w$.

Incidentally, as shown in previously presented FIG. 6 and FIG. 8, even in the case in which the set frequency is taken as a frequency approximately in the middle of the frequencies at which the respective angles of refraction $\theta_p$ of two successive modes of Lamb wave reach $90^\circ$, offset errors are caused as shown in FIG. 8. The offset error can be cancelled by carrying out calibration of an ultrasonic wave transducer with an actual flow at a reference pipe as described in Japanese Patent Application No. 2004-50998. The
calibration with the actual flow described in the Japanese Patent Application No. 2004-50998 is proposed for the purpose of suppressing variations in $\theta_\omega$ and $C_\omega$.

FIGURE 11 is a diagram showing an arrangement of a calibration facility with an actual flow presented in the above Japanese Patent Application No. 2004-50998. FIGURE 12 is a diagram illustrating the operation of the calibration facility. The calibration facility with an actual flow is provided with a reference pipe 21A, a reference flowmeter 41, a flow control valve 42 and a reference converter 51. The reference converter 51 has the arrangement with the blocks 12 to 17 in the previously presented FIG. 16.

The reference pipe 21A has an inner face processed so as to have an accurate cross sectional area $A$. Along with this, the inner face is smoothly finished over a sufficiently long straight pipe length so that a flow of fluid in the pipe sufficiently grows into an axisymmetric flow. Moreover, the outer face of the reference pipe 21A is also smoothly finished so as to be in parallel with the inner face.

Thus, the flow rate of the fluid flowing in the reference pipe 21A can be made accurately established or controlled by adjusting the opening of the flow control valve 42 while the flow rate being monitored by the reference flowmeter 41. For accurately controlling the flow rate of the fluid, a reference tank 43 can be used instead of the reference flowmeter 41 to accurately measure the fluid, flowing through the reference flowmeter 41 and stored in the reference tank 43, about an amount being stored in every unit time.
The ultrasonic wave transducer 11 is mounted on and secured to the reference pipe 21A. Along with this, the reference converter 51 is connected to the ultrasonic wave transducer 11 to carry out a flow velocity measurement and a flow rate measurement by the ultrasonic wave transducer 11 and the reference converter 51. The measurements are carried out while making the fluid flow with a known (true) flow rate \( Q_s \) accurately set by the reference flowmeter 41 and the flow control valve 42. On the basis of the flow rate \( Q_r \) measured at this time and the known flow rate \( Q_s \), an actual flow calibration constant \( \alpha \) of the ultrasonic wave transducer 11 is calculated out as \( \alpha = Q_s/Q_r \).

The calibration constant \( \alpha \) is stored in an ultrasonic flowmeter using the transducer 11 as the constant characteristic of the transducer 11 for carrying out calibration of the measured flow rate.

According to this Japanese Patent Application No. 2004-50998, the angle of refraction \( \theta_r \) at the boundary plane between the pipe and the fluid and the sound velocity \( C_r \) in the fluid in the previously presented expression (2) are substituted by the angle of incidence \( \theta_w \) onto the pipe and the sound velocity \( C_w \) in the wedge, according to Snell's law presented as the expression (22). Thus, the expression (2) becomes the expression (23):

\[
\frac{C_r}{\sin \theta_r} = \frac{C_p}{\sin \theta_p} = \frac{C_w}{\sin \theta_w} \tag{22}
\]

\[
V_f(x) = \frac{(C_w \cdot f_d(x))}{(2 \cdot \sin \theta_w \cdot f_0)}. \tag{23}
\]

In the description of Japanese Patent Application No. 2004-50998, for obtaining the flow velocity \( V_f(x) \) of the fluid given by the expression (23) with high accuracy, \( \theta_w \) and \( C_w \) are corrected by the calibration with an actual flow.

Compared with this, in the present invention, not only \( \theta_w \) and \( C_w \) but
also the offset error is to be corrected together by the calibration with an actual flow.

Also in the invention, the calibration with an actual flow is to be carried out by a comparison with the flow rate measured with high accuracy by using the reference flowmeter 41 or the reference tank 43. With the measured flow rate by using the reference flowmeter 41 taken as \( Q_s \), the ratio of \( Q_s \) to the flow rate \( Q_r \), based on the flow velocity profile measured by the ultrasonic wave transducer 11, is taken as an actual flow calibration constant \( \alpha \). At this time, \( Q_s \) is expressed by the expression (24):

\[
Q_s = \alpha \cdot Q_r = \int \{ \alpha (C_w \cdot f_d(x))/(2 \cdot \sin \theta_w \cdot f_0) \} \cdot dA. \tag{24}
\]

Namely, in FIG. 13, as a conceptual illustration of the calibration with an actual flow in the embodiment of the invention, the flow rate \( Q_r \), measured by using the ultrasonic wave transducer 11 and a converter 18, is multiplied by the actual flow calibration constant \( \alpha \). This allows a measured value of the flow rate to be obtained with the same high accuracy as that of the flow rate measured by the reference flowmeter 41. Therefore, without separately measuring and correcting \( \theta_w \), \( C_w \) and an offset error, they can be simultaneously corrected by using only one calibration constant \( \alpha \).

With the calibration constant \( \alpha \) taken as a constant characteristic of each ultrasonic wave transducer 11 and made shown on its nameplate, the measured flow rate is to be multiplied by the characteristic calibration constant \( \alpha \) shown on the transducer 11 being used. This allows a highly accurate flow
rate to be obtained even when the combination of the transducer 11 and the converter 18 is changed, by which interchangeability between transducers is to be ensured.

Moreover, as another way of correcting the offset error, calculated values of errors shown in FIG. 8 can be used with or without the calibration with actual flow. Furthermore, when a pipe with different material and plate thickness from those of the reference pipe 21A is used, the correction can be made by using results of calculation carried out about the difference in offset error from the offset error in the case of using the reference pipe 21A.

The invention can be also applied to the previously explained ultrasonic wave flow velocity profile meter disclosed in Japanese Patent Application No. 2003-396755. In the ultrasonic flow velocity profile meter, as already explained, the ultrasonic wave transducer is secured to the wedge while being inclined to the pipe by taking the angle of incidence of the ultrasonic wave incident on the pipe from the wedge as being no less than the critical angle for a longitudinal wave in the pipe and no more than the critical angle for the shear wave in the pipe. This is provided so that only the shear wave is propagated in the pipe when the sound velocity of the shear wave of an ultrasonic wave propagated in a pipe is equal to or more than the sound velocity of the longitudinal wave in a wedge. Also in this case, there can be reduced the frequency dependence in measured flow velocity and flow rate caused by Lamb wave.

While the present invention has been particularly shown and described with reference to the preferred embodiment thereof, it will be
understood by those skilled in the art that the foregoing and other changes in form and details can be made therein without departing from the spirit and scope of the present invention.
CLAIMS

1. In a clamp-on Doppler ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid to be measured in the pipe to measure a flow velocity profile of the fluid to be measured by applying the principle that a frequency of an ultrasonic wave, reflected by a reflector existing in the fluid, is changed depending on a flow velocity due to Doppler effect, the ultrasonic flow velocity profile meter having a sound wave propagative wedge put between the ultrasonic wave transducer and the pipe,

   the improvement wherein

   the frequency of the transmitted ultrasonic wave is set at a frequency other than the frequency at which an angle of refraction of a wave in each mode of Lamb wave in the pipe becomes 90°, the frequency being calculated from an angle of incidence of the ultrasonic wave made incident onto the pipe from the wedge, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

2. In a clamp-on Doppler ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid to be measured in the pipe to measure a flow velocity profile of the fluid to be measured by applying the principle that a frequency of an ultrasonic wave, reflected by a reflector existing in the fluid, is changed depending on a flow
velocity due to Doppler effect, the ultrasonic flow velocity profile meter having a sound wave propagative wedge placed between the ultrasonic wave transducer and the pipe,

the improvement wherein

the frequency of the transmitted ultrasonic wave is set around central frequency between two frequencies at each of which an angle of refraction of a wave in each of two successive modes of Lamb wave in the pipe becomes 90°, the two frequencies being calculated from an angle of incidence of the ultrasonic wave made incident onto the pipe from the wedge, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

3. In a clamp-on Doppler ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid to be measured in the pipe to measure a flow velocity profile of the fluid to be measured by applying the principle that a frequency of an ultrasonic wave, reflected by a reflector existing in the fluid, is changed depending on a flow velocity due to Doppler effect, the ultrasonic flow velocity profile meter having a sound wave propagative wedge put between the ultrasonic wave transducer and the pipe,

the improvement wherein

the frequency of the transmitted ultrasonic wave is set at a frequency lower than the frequency at which an angle of refraction of a wave in a first
order mode of antisymmetric Lamb wave in the pipe becomes 90°, the frequency being calculated from an angle of incidence of the ultrasonic wave made incident onto the pipe from the wedge, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.

4. In a clamp-on Doppler ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid to be measured in the pipe to measure a flow velocity profile of the fluid to be measured by applying the principle that a frequency of an ultrasonic wave, reflected by a reflector existing in the fluid, is changed depending on a flow velocity due to Doppler effect, the ultrasonic flow velocity profile meter having a sound wave propagative wedge put between the ultrasonic wave transducer and the pipe,

the improvement wherein

the ultrasonic wave is made incident from the wedge onto the pipe at an angle of incidence larger than the angle of incidence at which an angle of refraction of a wave in a first order mode of antisymmetric Lamb wave in the pipe becomes 90°, the frequency being calculated from a frequency of the transmitted ultrasonic wave, a sound velocity in the wedge, sound velocities of a shear wave and a longitudinal wave in the pipe, and a plate thickness of the pipe.
5. In a clamp-on Doppler ultrasonic flow velocity profile meter in which an ultrasonic wave, transmitted from an ultrasonic wave transducer mounted on the outside of a pipe, is made incident onto a fluid to be measured in the pipe to measure a flow velocity profile of the fluid to be measured by applying the principle that a frequency of an ultrasonic wave, reflected by a reflector existing in the fluid, is changed depending on a flow velocity due to Doppler effect, the ultrasonic flow velocity profile meter having a sound wave propagative wedge put between the ultrasonic wave transducer and the pipe,

the improvement wherein

the frequency of the transmitted ultrasonic wave is set at a frequency lower than a cutoff frequency of a wave in a first order mode of antisymmetric Lamb wave, the cutoff frequency being determined from a dispersion curve of the Lamb wave.

6. The Doppler ultrasonic flow velocity profile meter as claimed in any one of claims 1 to 5 wherein an asymptotic solution of a characteristic equation of Lamb wave is used as a phase velocity of the Lamb wave for determining one of the frequency or the angle of incidence of the transmitted ultrasonic wave.

7. The Doppler ultrasonic flow velocity profile meter as claimed in any one of claims 1 to 6 wherein an actual flow calibration constant for calibrating a flow rate derived from a measured flow profile is given by a ratio of a value of a flow rate derived from a flow velocity profile measured with the
ultrasonic wave transducer mounted on a reference pipe including fluid flowing at a reference flow rate to a value of a flow rate as the reference flow rate of the fluid flowing in the reference pipe simultaneously measured by a reference flow rate measuring device provided besides the ultrasonic wave transducer.

8. The Doppler ultrasonic flow velocity profile meter as claimed in claim 7 wherein the actual flow calibration constant is held as a calibration constant characteristic of each ultrasonic wave transducer.

9. The Doppler ultrasonic flow velocity profile meter as claimed in any one of claims 1 to 8 wherein a measured value is corrected on the basis of a result of calculation of an error of measurement due to Lamb wave.
FIG. 1

FIG. 2
FIG. 5

ANGLE OF REFRACTION $\theta_p$ (degree)

TRANSMITTED FREQUENCY (MHz)

FIG. 6

ERROR OF MEASUREMENT (%)
FIG. 7

Vav=2m/s, Water

FIG. 8

SET FREQUENCY

OFFSET ERROR
RELATIONSHIP BETWEEN PLATE THICKNESS AND ERROR (STAINLESS STEEL PIPE)

(WITH FREQUENCY SET BETWEEN FREQUENCIES AT EACH OF WHICH ANGLE OF REFRACTION OF LAMB WAVE REACHES 90°)

FIG. 9

<table>
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<tr>
<th>MODE</th>
<th>A1</th>
<th>2.70</th>
<th>1.35</th>
<th>0.90</th>
<th>0.68</th>
<th>0.54</th>
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<td>2.03</td>
<td>1.35</td>
<td>1.01</td>
<td>0.81</td>
</tr>
<tr>
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<td></td>
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<td>1.80</td>
<td>1.35</td>
<td>1.08</td>
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<tr>
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<td>3.38</td>
<td>2.25</td>
<td>1.69</td>
<td>1.35</td>
</tr>
</tbody>
</table>

(V_s = 3075(m/s), C_w = 2730(m/s), \theta_w = 46.9°)

FIG. 10
FIG. 11

 suffciently grown axisymmetric flow

smooth and parallel

FIG. 12

calibration constant \( \alpha = \frac{Q_s}{Q_f} \)
$V_f(x) : \text{FLOW VELOCITY AT POSITION } x \text{ IN PIPE}$

$$V_f(x) \cdot Cf \cdot fd(x) / (2 \cdot \sin \theta_f \cdot f_0)$$

FIG. 15