DEVELOPMENT OF A NEW TYPE OF CORIOLIS FLOWMETER WITH INDEPENDENT VIBRATION FRAMES FOR DRIVE AND TORSION

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Abstract

A new design concept for improving the sensitivity of a Coriolis flowmeter is proposed. The differences between the developed flowmeter and current commercial products lie in adoption of acceleration sensors and reinforcement frames. These features impart an interesting characteristic: sensitivity improves with increasing drive frequency. A flow tube has been fabricated on the basis of the new design concept, and subjected to basic experiments in order to confirm the characteristics of the measurement system. Although some problems still remain, the characteristics have been partially confirmed.

Introduction

Coriolis flowmeters have been widely used in many types of industrial flow measurements, by virtue of their ability to measure mass flow rate directly and their high accuracy. Many types of Coriolis flowmeters are based on a time measurement technique. A time difference between phase-shifts of two signals induced by Coriolis force is measured, and is proportional to mass flow rate (hereafter such a method is called “the time difference method”). The time difference method strongly contributes to high accuracy, for many reasons. Amplitude of driving vibration does not have to be subjected to exact control or measurement. In the field of electronic instruments, time measurement techniques are well developed and yield excellent measurement accuracy. Owing to the development of digital signal processing technology, drifts of phase shifts caused by analogue filters are suppressed to the minimum.

However, improving sensitivity of a flowmeter employing the time difference method is difficult; improved sensitivity is attained at the expense of various other parameters (for example, pressure loss, resisting-pressure, response speed). If pipe diameter is reduced in order to improve sensitivity, pressure loss increases. In the case of high-density fluids such as water and other liquids, the resultant sensitivity is almost sufficient. However many measurement fields demand increased sensitivity. A high-sensitivity Coriolis flowmeter that can measure gas at normal pressure has long been demanded. Currently, Coriolis flowmeters that resist extremely high pressure while maintaining sensitivity are demanded, because new fuel cell cars, which are equipped with high-pressure hydrogen tanks, require high-pressure (over 70 Mpa) filling stations. Despite these demands for highly sensitive Coriolis flowmeters, improving the sensitivity of this type (the time-difference method) of flowmeter is difficult.

In the present study, we investigate the possibility of further improving sensitivity by adopting another measurement method. A prototype flow tube has been designed and tested. The question of whether the new method yields final accuracy and cost performance comparable to those yielded by the time difference method remains unanswered. Here we focus our efforts on determining the possibility of improving sensitivity.

Theoretical sensitivity of Coriolis flowmeter

A Coriolis flowmeter having a U-tube serves as an example. Figure 1 shows the coordinate system employed here. The Coriolis flowmeter based on the time difference method converts the measured phase time difference into mass-flow rate (1). A simple theoretical analysis yields the following conversion equation:

$$Qm = C \cdot \frac{K_q}{2d^2} \cdot \frac{1}{R_t(a)} \cdot t\,, \quad R_t(a) = \frac{1}{(1-a^2)}, \quad a = \frac{w_f}{w_q} \quad \text{..................(1)},$$

where Qm is mass flow rate, C is a calibration constant, $R_t(a)$ is a frequency response function, and t is phase time difference. Moreover, K_q is the spring constant of the U-tube in torsional oscillation, d is width of the U-tube, a is natural frequency ratio (w_f / w_q), w_f is drive frequency of the U-tube in bending oscillation, and w_q is natural frequency of the U-tube in torsional oscillation (Coriolis frequency). For the sake of simplificity, damping factor is neglected and the tangent function of t is approximated to be equal to t .

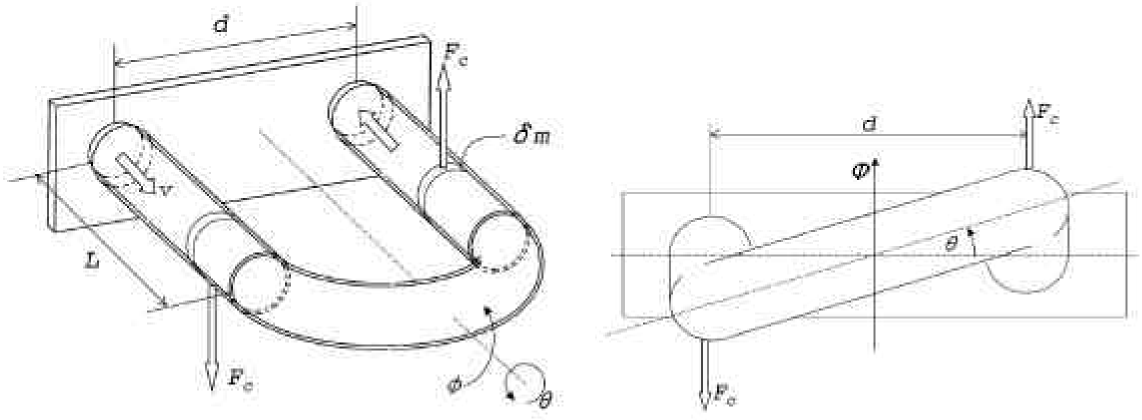

Fig. 1: Coordinate system

In order to improve sensitivity, the following design concepts are considered.

1. The value of a is adjusted in order to increase the frequency response function $R_t(a)$.
2. The U-tube is designed to be wide so as to make the width d large.
3. The spring constant in torsion K_q is made as small as possible.

However, improving the sensitivity is not easy. Trade-offs with other performance indices are thought to limit these design concepts.

As shown in Fig. 2, $R_t(a)$ has a point of divergence at a =1; the values of $R_t(a)$ at a <1 are greater than those at a >1. Assuming that the natural frequency ratio a is controlled so as to be approximately unity, sensitivity rapidly becomes high. However, the values of $R_t(a)$ change considerably in response to a small change in a near unity. In a flowmeter, an unstable proportion coefficient is undesirable. Therefore, the value of a is usually set below 0.5, where the value of $R_t(a)$ is stable.

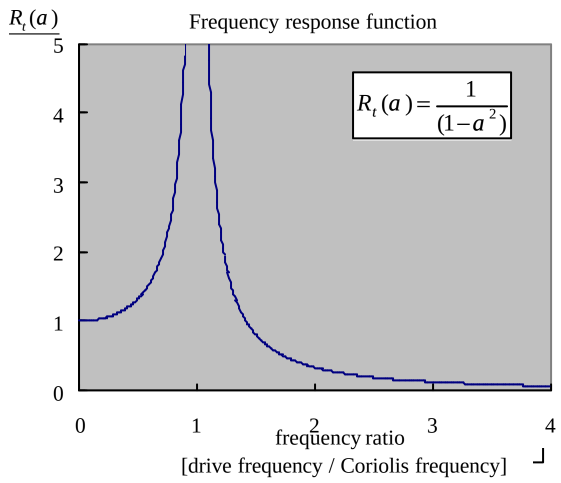

Fig. 2: Frequency response function in the time difference method.

Assuming that the U-tube is designed to be wider, the natural frequency in torsion ($w_q = \sqrt{K_q / I_q}$) becomes small, because the torsional moment of inertia I_q increases with the width d. Since the ratio a is limited to less than 0.5, the drive frequency w_f must also be small. The decrease in drive frequency w_f deteriorates the speed of response and signal-noise ratio.

So long as the drive frequency does not become exceedingly small, the torsional spring constant K_q is preferably small. Usually the tube diameter and the wall thickness are designed small. The tube diameter is reduced to the extent where pressure loss is maintained within the practicable range. Since the diameter is small, flow velocity becomes excessively fast in measurement of low density fluids (gas) before mass-flow rate becomes sufficient for sensitivity. This is one reason why the Coriolis flowmeter shows insufficient sensitivity for measurement of low density fluid. The tube wall is thinned within the limits of resisting pressure. If the wall thickness is increased in order to increase resisting pressure, measurement sensitivity is deteriorated.

For these reasons, difficulty is encountered in improving the sensitivity of this type (the time difference method) of flowmeter without deteriorating other performance indices.

Some types of Coriolis flowmeters employ another measurement method; instead of measuring the time shifts between the pickup signals, an amplitude ratio is measured. Specifically, the difference between the amplitudes of the pick-up signals (concerning torsion vibration) is divided by their mean value (concerning drive vibration). The present study adopts this amplitude ratio method.

The time difference is from the time a pick-up passes over a neutral line until the time the other pick-up passes the line. The time is torsion distance divided by bending speed. Therefore, the time difference t can be rewritten as $d\Theta_0 / L\Phi_0 w_f$. In the amplitude ratio method, the conversion equation changes as follows:

$$Qm = C \cdot \frac{K_q}{2d^2} \cdot \frac{1}{R_t(a)} \cdot \frac{d\,\Theta_0}{L\Phi_0 w_f} \quad \text{.............(2)},$$

where L is length of the U-tube, Θ_0 is amplitude of torsion angle of the U-tube in sinusoidal motion, and Φ_0 is amplitude of the bending angle caused by forced vibration in sinusoidal motion.

Usually, the pick-ups are electro-magnetic coil sensors. Measured values are voltage, which is proportional to velocity. In view that the measured value is, in effect, velocity, the equation is rewritten as:

$$Qm = C \cdot \frac{K_q}{2d^2} \cdot \frac{1}{R_t(a)} \cdot \frac{d\,\Theta_0 w_f}{L\Phi_0 w_f \cdot w_f} \quad \text{............(3).}$$

The difference between the amplitudes of the pick-up signals represents the velocity amplitude of torsional oscillation $V_{q0} = d\,\Theta_0 w_f$. The mean of the amplitudes of the pick-up signals represents the velocity of bending oscillation $V_{f0} = L\Phi_0 w_f$. However, the two signals should have the same amplitude.

The characteristics of sensitivity of the amplitude ratio method are discussed here.

In equation (3) the important term in proportion to the mass flow rate is $d\,\Theta_0 w_f$. The equation can be rewritten by reference to $w_f = a w_q$ and $w_q = \sqrt{K_q / I_q}$:

$$V_{q0} = d\,\Theta_0 w_f = Qm \cdot \frac{2d^2 L\Phi_0}{CI_q} \cdot R_V(a), \quad R_V(a) = \frac{a^2}{(1-a^2)} \quad \text{..............(4),}$$

This equation indicates that increasing only bending amplitude Φ_0 is effective for improving sensitivity. Assuming that the length L and the width d both become large, the effects are cancelled, because the torsional moment of inertia I_q is proportional to the length L and to the square of the width d. As shown in Fig. 3, the frequency response function in velocity measurement $R_V(a)$ has a point of divergence at a =1, and the values of $R_V(a)$ at a <1 are smaller than those at a >1. At a >>1, $R_V(a)$ becomes constant. Amplitude of driving vibration must be precisely controlled or measured, although sensitivity is not greatly improved. Although the amplitude ratio method has been known since the invention of the Coriolis flowmeter by J. E. Smith(2) in the 1970s, for various reasons many manufacturers have not adopted this method. However, unlike the time difference method, the amplitude ratio method leaves room for improving sensitivity. Further improvements in the amplitude ratio method are expected in the near future, because of developments in digital signal processing technology. Some manufacturers and researchers continue to develop the Coriolis flowmeter adopting this method(3). The differences between the flowmeter of this study and current commercial products lies in the adoption of acceleration sensors and reinforcement frames. Although a Coriolis flowmeter having rigid pipes and elastic suspension has already been researched by Cascetta *et. al.*(4), it employs displacement sensors (capacitive transducers).

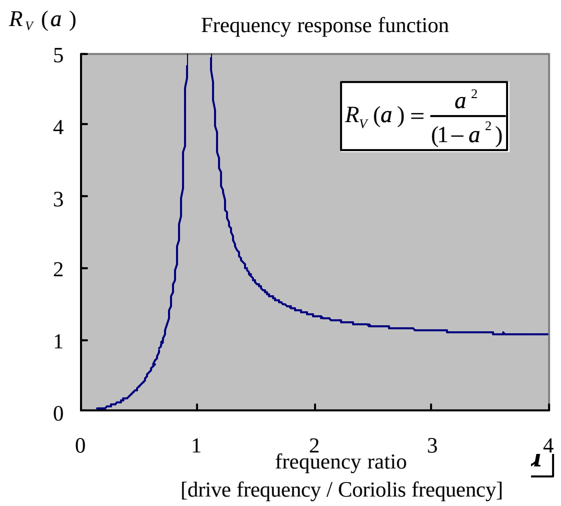

Fig. 3: Frequency response function in the amplitude ratio method (velocity).

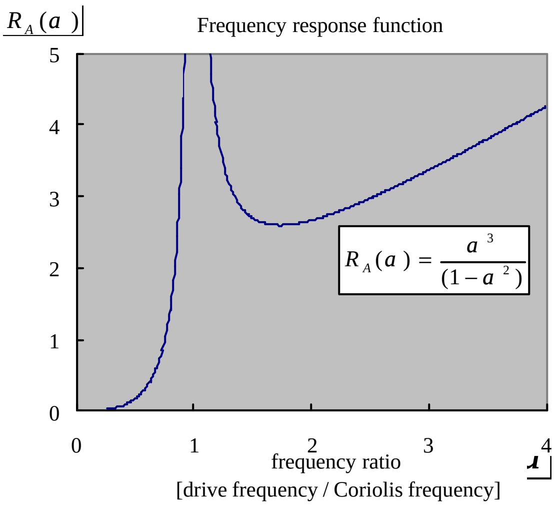

Fig. 4: Frequency response function in the amplitude ratio method (Acceleration).

Concept of the new type of Coriolis flowmeter

The measurement system characteristics of the prototype flowmeter are as follows:

1. **A ratio of the amplitudes** of two signals is calculated such that the difference between the amplitudes of the pick-up signals (concerning torsional vibration) is divided by their mean value (concerning drive vibration).
2. **Accelerometers** are adopted as the pick-up sensors.
3. The natural frequency ratio (drive frequency / Coriolis frequency) is **greater than unity**. (In the time difference method it is usually **less than unity**.)
4. The flow tubes have **reinforcement frames** for preventing the influence of higher-order vibration modes.

In this research, acceleration sensors are adopted as the pick-ups. In view that the measured value is acceleration, the equations can be rewritten further:

$$Qm = C \cdot \frac{K_q}{2d^2} \cdot \frac{1}{R_t(a)} \cdot \frac{d\,\Theta_0 w_f^2}{L\Phi_0 w_f^2 \cdot w_f}, \quad R_t = \frac{1}{(1-a^2)} \quad \text{...............(5)},$$

$$A_{q0} = d\Theta_0 w_q^2 = Qm \cdot \frac{2d^2 L\Phi_0 K_q^{1/2}}{C I_q^{3/2}} \cdot R_A(a), \quad R_A(a) = \frac{a^3}{(1-a^2)} \quad \text{...............(6)},$$

This equation (6) indicates that not only increases in Φ_0, but also increases in $w_q = \sqrt{K_q / I_q}$ and $R_A(a)$ are effective in improving sensitivity. This equation is interesting. Figure 4 shows the characteristics of frequency response function in acceleration measurement $R_A(a)$. The value of $R_A(a)$ increases with increasing a (at a >>1). The higher the driving frequency, the greater the sensitivity. High frequency drive should also improve signal-noise ratio. Sensitivity is improved despite the width and length, which determine the torsional moment of force, becoming small. Assuming that the natural frequency ratio a can be fixed (a >>1) as a design parameter, preferably the spring constant in torsion K_q is large and the torsional moment of inertia I_q is small. These may allow use of large-diameter pipes, thick-walled pipes, and compact piping design, thereby maintaining sensitivity. In the time difference method these usually worsen sensitivity. These relations suggest the possibility of developing a more sensitive Coriolis flowmeter for gas or a high-pressure-type Coriolis flowmeter, as well as the possibility of developing a compact Coriolis flowmeter. Normally, the sensor tube is regarded as a continuum. If this tube is forced to oscillate at a frequency higher than the natural frequency, influences of higher-order modes emerge. In order to prevent these influences of higher vibration modes, the tubes employed in this study have reinforcement frames for torsional vibration. To enable high-frequency drive, the measurement system also has a frame for forcing driving. To calculate mass-flow rate by using equation (5), denominator values ($L\Phi_0 w_f^2 \cdot w_f$) must be measured.

Experimental apparatus

A flow tube has been fabricated and subjected to basic experiments in order to confirm the characteristics of the measurement system. As a first step, a prototype model using a B-tube, in which the frequency ratio can be arbitrarily varied, has been fabricated. An experiment of various sensitivity characteristics has been conducted.

The prototype model has a frame for driving vibration supported by a bearing. The frame for driving is forced to vibrate around the f axis by a Voice Coil Motor. The Coriolis vibration frame is supported by other bearings on the driving vibration frame so that the Coriolis frame can rotate about the q axis. Flexible tubes are used for the piping connection between the driving vibration frame and the Coriolis frame. The natural frequency of driving vibration can be varied by applying springs of an arbitrary spring constant. The natural frequency of Coriolis vibration can also be varied by applying other arbitrary springs between the driving frame and the Coriolis frame.

Fig. 5 shows the prototype model system. A inner diameter of the B-tube is 8mm. The width d is 20mm and the length L is 345mm. Measurement have been conducted by use of a Frequency Response Analyzer (FRA5095:NF corporation), which has a oscillator and two channel inputs. The FRA sweeps the drive frequency, and then measures the amplitude ratio and the phase difference between the two vibration signals using phase-detection at that frequency. After being amplified by a power amplifier, the signal from the oscillator drives the voice coil motor so that the driving-frame vibrates. Movement of the Coriolis frame is measured by a servo accelerometer (JA-28GA: Japan Aviation Electronics Industry Ltd.). Vibration of the Coriolis frame is also measured by a velocity sensor, in the form of an electromagnetic coil at the same position. The acceleration amplitude of Coriolis vibration ($d\,\Theta_0 w_f^2$) is measured as the difference between signals from two accelerometers. In the case of velocity measurement, the velocity amplitude ($d\,\Theta_0 w_f$) is measured from the electromagnetic coil. Here, movement of the forced vibration frame ($L\,\Phi_0$) is measured by a laser vibrometer which produces a displacement output by use of a fringe counter (OFV-3001, OFV-512: Polytec Gmbh). In practical flowmeters, the amplitude of the forced vibration can be measured as the mean of two pick-ups signals, as an acceleration $(L\Phi_0 w_f^2)$. The oscillator controls the amplitude of output signal to maintain the drive vibration amplitude (Ch. 1) at a constant value (0.2mm peak to peak). Here, the "amplitude ratios" measured by use of the accelerometers and the velocity sensors are as follows:

$$Amplitude\,ratio(Acceleration\,measurement) = Ch.2 \div Ch.1 \times \sin(\Delta h_{ch2-ch1}),$$

$$Amplitude\,ratio(Velocity\,measurement) = Ch.2 \div Ch.1 \times \cos(\Delta h_{ch2-ch1}),$$

where $\Delta h_{ch2-ch1}$ is the phase difference between Ch. 1 and Ch. 2. To calcurate mass-flow rate, these amplitude ratios must be dvided by w_f^3 and w_f^2, respectively.

In the experimental system, an Electoromagnetic flowmeter is used as a reference meter. The Coriolis frequency is limited to a small value ($f_{Coriolis}$=17Hz) so that the Coriolis frame can be regarded as rigid over a wide frequency range.

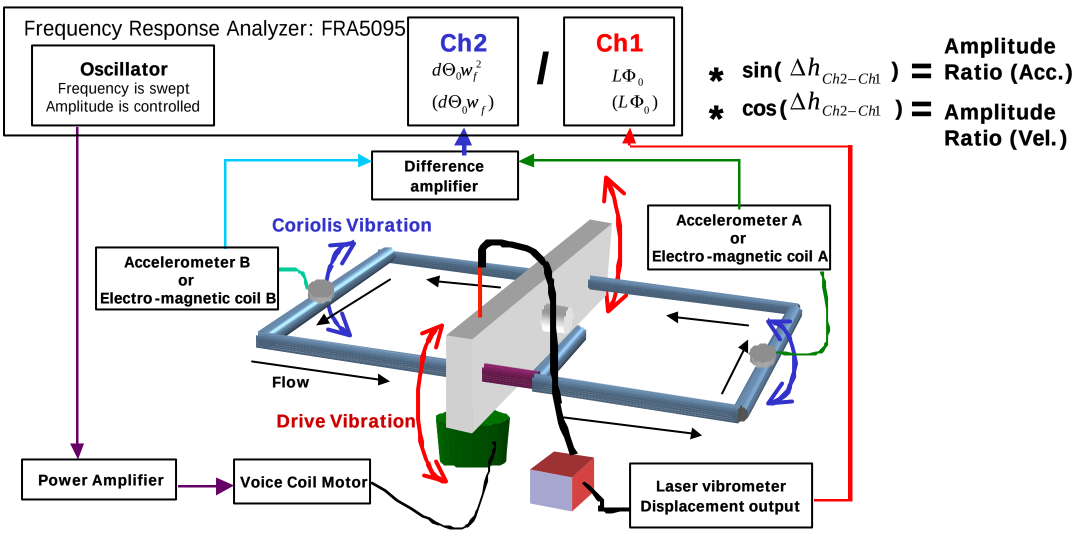

Fig. 5: Measurement system and flow tube of the prototype model.

Results and discussion

Experiments has been conducted with room temperature water at a constant flow rate of 0.2m[3]/h. Figure 6 shows the frequency response of the amplitude ratio ($d\,\Theta_0 w_f / L\Phi_0$) measured by velocity sensors. The solid line represents the frequency response function $R_V(a) = a^2/(1-a^2)$, with the magnitude adjusted to fit the experimental results. Thus, Fig. 6 is not intended to show agreement between theoretical and experimental values. However the distribution of experimental data shows close agreement with the shape of the solid line, except where $a \cong 3$. The disagreement at $a \cong 3$ was confirmed to be due to the influence of a noise oscillation of parts of the driving frame, in view that the disagreement appeared at the same drive frequency under other Coriolis frequency conditions.

Figure 7 shows the frequency response of the amplitude ratio ($d\,\Theta_0 w_f^2 / L\Phi_0$) measured by accelerometers. The solid line represents the frequency response function $R_A(a) = a^3/(1-a^2)$, with the magnitude adjusted to fit the experimental results. The value of amplitude ratio obtained by the experiment increases with increasing a (at a >2) at a slope similar to that of the theoretical line $R_A(a)$. Although increasing the frequency ratio considerably might require a special device or parts, the results indicate that the sensitivity improves with increasing frequency ratio.

To confirm that increasing the spring constant in torsion K_q improves sensitivity, the amplitude ratio is measured while changing the springs between the driving frame and the Coriolis frame. Figure 8 shows amplitude ratios at various Coriolis frequencies obtained by changing spring constant K_q.

The frequency ratio a was set a constant value (at a =2.0 or 2.7) by increasing the drive frequency. Under this condition, the Coriolis frequency is nearly proportional to $\sqrt{K_q}$ because replacement of the springs results in a small change in the torsional moment of inertia. Thus, as shown in Fig. 8, the amplitude ratios are proportional to the Coriolis frequency. Therefore, so long as the natural frequency ratio a is fixed, increasing the spring constant in torsion K_q is confirmed to improve sensitivity.

On the other hand, some problems with the present measuring method remain to be solved.

Since the moment of inertia appears in the equation as sensitivity, a change in the density of fluid influences sensitivity. In the time difference method, the positions of the additional devices (sensor coils) are adjusted so that the frequency ratio does not change. In this method as well, the tube design should be adjusted so as not to change the sensitivity.

This method requires accurate measurement of the amplitude and frequency of drive vibration. The reason for improvement in sensitivity at a >1, where sensitivity becomes low in the time difference method, is that in this area the denominator ($L\Phi_0 w_f^2 \cdot w_f$) increases faster than the numerator ($d\,\Theta_0 w_f^2$) in equation (5). This means that at a >>1 the denominator is much greater than the numerator. Thus, in case where the sensors measure amplitudes of both drive and Coriolis vibration, these sensors must exhibit a very wide dynamic range. Although the present study adopts servo-type accelerometers, which have very wide dynamic ranges, this type of accelerometer is expensive.

Some problems still remain in this method. If these problems can be solved by tube design and a new type of accelerometer, we might develop a new Coriolis flowmeter that exhibits high sensitivity and other novel characteristics.

This prototype model was designed to allow changing of parameters and was not optimized for improving sensitivity. Assuming that the spring is stiffened and the torsional moment of inertia is minimized, a remarkable improvement in sensitivity is expected. We are preparing new prototype models that are designed to be more compact and to have higher Coriolis frequency. In addition to use of the B-tube, adoption of a straight tube and a U-tube in the next prototype models is also planned.

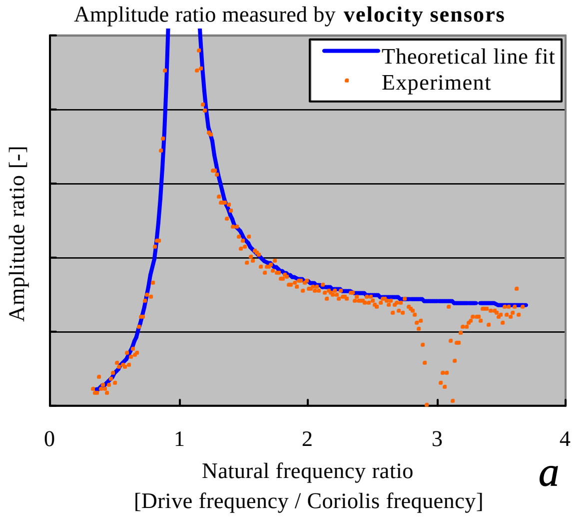

Fig. 6: Amplitude ratio measured by velocity sensors.

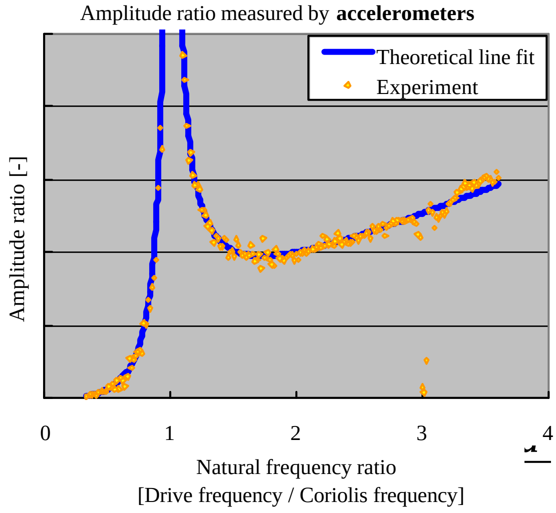

Fig. 7: Amplitude ratio measured by accelerometers.

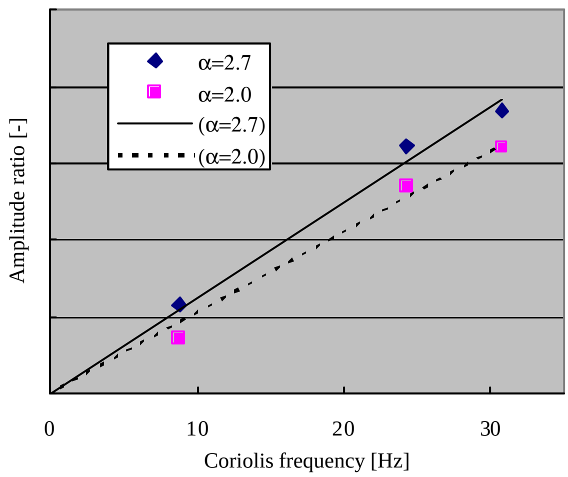

Fig. 8: Amplitude ratio at various Coriolis frequencies.

Conclusions

A new design concept for improving the sensitivity of Coriolis flowmeters is proposed. A flow tube has been fabricated and subjected to basic experiments in order to confirm the characteristics of the measurement system. Although some problems still remain to be solved, attainment of the desired characteristics has been partially confirmed.

References

(1) R. C. Baker, "Coriolis flowmeters: industrial practice and published information", Flow measurement Instrumentation, Vol.5 No.4 (1994), p229-246.

(2) J. E. Smith, U.S. Patent 3485098, Re31450

(3) M. P. Henry, D. W. Clarke, N. Archer, J. Bowles, M. J. Leahy, R. P. Liu, J. Vignos and F.B. Zhou, "A self-validating digital Coriolis mass-flow meter: an overview", Control Engineering Practice, 8 (2000), p487-506.

(4) F. Cascetta, S. Della Valle, A. R. Guido and P. Vigo, "A Coriolis mass flowmeter based on a new type of elastic suspension", Measurement, Vol. 7 No. 4 (1989), p182-191.