HIGH-RELIABILITY VORTEX FLOW METER WITH DUAL-COUPLED ULTRASONIC SENSORS

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Abstract: Confirmation of measuring technology for flow rate of high pressurized gas is required. So, in order to build up measuring technology keeping 'High Sensitiveness', 'Wide Rangeability', 'High Accuracy', up to now, we have developed a vortex flow meter for gas with 'one' coupled ultrasonic sensors. And we confirmed this effectiveness by testing on an existing gas pipe line with high pressure. This type of vortex flow meter has a hole inside the bluff body situated in the flow, and the change of flow which are generated by vortexes lead to this hole. Ultrasonic sensors situated both side of this hole detect the change of flow in the hole.
This type of vortex flow meter has features as follows.
High sensitiveness (Min. Sensitiveness velocity 0.4m/sec)
Anti-pipe-vibration characteristics (Max. 3G)
High pressure capacity (Max. 7MPa)
High accuracy (error +/-1%RD)
Explosion proof structure (Exd II BT4 equivalent)

This time we developed a new type vortex flow meter with 'dual' coupled ultrasonic sensors and two holes inside the bluff body for the purpose of improvement on robustness against pulsation change of pressure and temperature of gas and other purpose is to improve on reliability against electrical circuit troubles, and so on.
The most remarkable structural feature of this meter is to have the bluff body with two holes and two pairs of ultrasonic sensors. This structure can get the advantages as follows.
1. The new vortex flow meter can eliminate noises such as pulsation change of pressure and temperature of gas.
The gas in the holes moves to opposite phase according to vortexes. The gas in the holes moves to the same phase according to various kinds of noise. Comparing each signals, same phase is canceled and opposite phase can be detected effectively. So it can eliminate noise and sensitiveness of vortexes is doubled in comparison with 'one' coupled ultrasonic sensors. It does not require some compensation circuit for pressure or temperature changes. It can keep stable measurement even in low flow rate.

2. The new vortex flow meter can measure if one of the ultrasonic sensors or

circuits has broken down or of a mal-function.

Ultrasonic sensors and some circuits are partially duplicated, if one of them has broken down or of a mal-function, another one can backup. So flow measurement signal does not suddenly stop. Self-diagnosis function provides us to indicate those trouble under operation.

We also designed fitting of ultrasonic sensors to the body with sonic insulation for the purpose to improve S/N ratio as is spread sensing range. Those opposite phase gas flow occurred by vortex in each hole in the bluff body should be sensed changing phase correctly. Transmitted signal is not only radiated in to the hole but also be conveyed in to the body of flow meter itself, this caused the error of phase. To eliminate those conveyed signal through the body is effective to spread the measuring range by improving minimum sensing flow rate.

The new type vortex flow meter can easily be used for not only gas pipe line but also pipe lines close to a compressor or a turbine in factories that caused strong pulsation change of pressure and temperature of gas, so conventional vortex flow meter could not measured steadily.

Keywords: ultrasonic ,vortex ,flow meter,sensor,buckup   cancel

1.   INTRODUCTION

Osaka Gas is now planning to pressurize up to 7MPa on the natural gas transmission pipelines in order to satisfy increasing demands and stable supply. For this purpose, we developed the vortex flow meter with one pair of ultrasonic sensors which is high pressure capacity, high accuracy, high sensitiveness and wide rangeability. This meter was tested under high-pressure conditions (7 MPa) and showed satisfactory flow measurement characteristics ('98, at SWRI). Later, We developed the vortex flow meter with two pair of ultrasonic sensors which can cancel the sonic change caused by changes in gas pressure and temperature, thus ensuring stable measurement in the field and achieving high measuring sensitivity. As such, we have been improving flow meter models. Because high reliability is essential to the meters used in transmission pipelines and pipes installed in factories, we have added a self-diagnosis function to the amp circuit and a backup function for the purpose of improving reliability. The backup function monitors the two pairs of ultrasonic sensors. If one sensor malfunctions, the backup function uses the normal sensor pair to continue the measuring operation for uninterrupted flow measurement.

This report describes the measuring principle and features of the vortex flow meter with dual-coupled ultrasonic sensors, with a special focus on the resistance to the effects of sonic change caused by changes in gas pressure and temperature, and also explains the sensor backup function designed to improve reliability.

2.   STRUCTURE AND MEASURING PRINCIPLE OF THE ULTRASONIC VORTEX FLOW METER

2.1   Basic principle of the vortex flow meter

Karman vortices are constantly generated behind the bluff body situated in the gas pipe. The vortex flow meter measures the flow rate based on the well-known characteristic that the frequency generated by Karman vortexes is directly proportional to the flow velocity.

$$f = St \bullet V/d = K \bullet Q \tag{1}$$

Where f indicates the frequency generated by vortexes, d indicates the width of the bluff body, v indicates the average flow velocity in the pipe, Q indicates the flow rate, and K, which represents the K factor, indicates the pulse count per unit flow rate.

Based on the above equation, the frequency generated by a Karman vortex can be used to obtain the flow velocity, or flow rate.

In this equation, St, a constant called the Strouhal number, is dependent on the Reynolds number (Re) and the shape of the bluff body. When the shape of the bluff body is so designed that the St value remains constant in a wide range of Re number, the vortex flow meter offers high linearity. (Fig. 1)
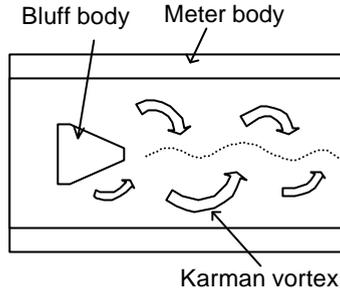
Bluff body   Meter body

Karman vortex

Fig.1 Principle of vortex flow meter

2.2 Principle of vortex detection by ultrasonic sensors

The principle used to detect a vortex with ultrasonic sensors is based on the phenomenon that a Karman vortex causes the modulation change of an ultrasonic wave propagating through the holes in the bluff body. The newly developed ultrasonic vortex flow meter uses two pairs of ultrasonic sensors to detect the modulation change of ultrasonic wave through the two holes in the bluff body generated by the Karman vortex for improving detection sensitivity and elimination of the effects caused by irregular change in gas pressure and temperature. This structure is called a cross-sensing system. (Fig. 2)

In the cross-sensing system, ultrasonic waves are transmitted through the two holes and ultrasonic sensors detect the modulation changes. The gas in the holes moves to opposite phase according to vortexes. The gas in the holes moves to the same phase according to noises such as irregular change in gas pressure and temperature. Comparing each signals, same phase is canceled and apposite phase can be detected effectively. So it can eliminate noise and sensitiveness of vortexes is doubled in comparison with one pair of ultrasonic sensors.
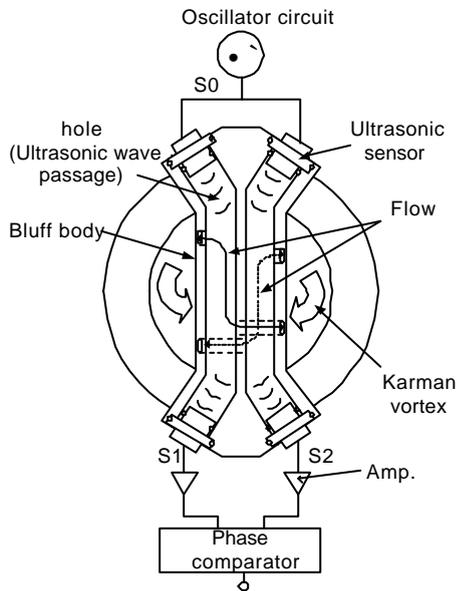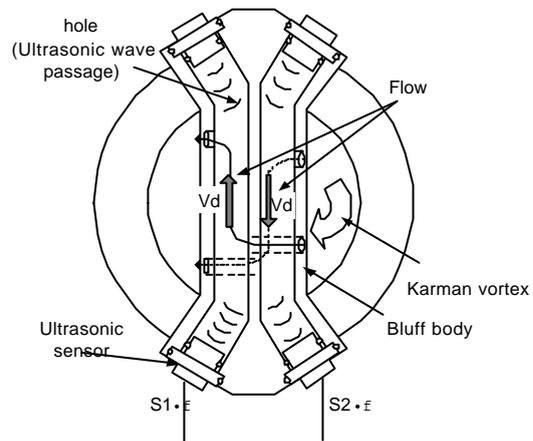
Fig.2 Structure of cross-sensing system   Fig.3   The gas in the holes moves to opposite phase according to vortexes

In an ultrasonic vortex flow meter, the ultrasonic wave transmitted through a gas can be expressed by the following equation.

The oscillator signal, S0, transmitted through a gas results in signals S1 and S2 as given below.

$$S0 = A \sin \grave{u} t \qquad (2)$$

$$S1 = S2 = A' \sin(\grave{u} t + \ddot{O}) \qquad (3)$$

(assuming that $\grave{u} = \partial f$)   Where A and A' indicate the amplitudes of the ultrasonic signals, f indicates the ultrasonic frequency, and $\ddot{O}$ is the phase delay resulting from the propagation through the gas.

When a gas current is produced in a hole due to the Karman vortex generated by the bluff body, the propagation speed of the ultrasonic wave changes. This change corresponds to flow velocity Vd, and it generates a signal whose phase differs from that expressed by equation (3). As shown in Fig. 3, when there is a Karman vortex on the right side of the bluff body, a current with flow velocity Vd results in each of the holes in the bluff body, and the currents in the two holes flow in the opposite direction to each other. Since the ultrasonic waves are transmitted in the same direction (from top to bottom in Fig.3), the modulations in the two holes that the ultrasonic waves receive from flow velocity Vd during the propagation are opposite in direction. The following equations yield ultrasonic wave S1' and phase modulation θ1, which result when the flow caused by the vortex is opposite in direction to the ultrasonic wave, and ultrasonic wave S2' and phase modulation θ2, which result when the flow caused by the vortex is in the same direction as the ultrasonic wave. (Fig. 4)

$$S1' = A'\sin(\grave{u}t+\ddot{O}+\grave{e}\ 1) \tag{4}$$

$$S2' = A'\sin(\grave{u}+\ddot{O}+\grave{e}\ 2) \tag{5}$$

$$\grave{e}1 = \frac{D}{C} - \frac{D}{(C-Vd)} \quad \grave{u}= \frac{VdD\grave{u}}{C(C-Vd)} \tag{6}$$

$$\grave{e}2 = \frac{D}{C} - \frac{D}{(C+Vd)} \quad \grave{u}= \frac{VdD\grave{u}}{C(C+Vd)} \tag{7}$$

D refers to the distance between the sending and receiving sensors, and C indicates the sonic speed in the gas.
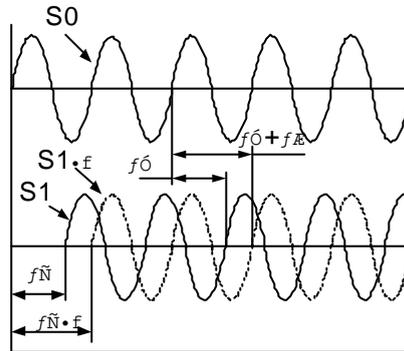

Fig. 4 Ttransmission of Ultrasonic wave

However, when the relationship between the sonic speed in the gas and flow velocity Vd is C >> Vd, equations (6) and (7) are replaced by the following equation.

$$|\grave{e}1| \cong |\grave{e}2| = \frac{VdD\grave{u}}{C^{\cdot Q}} \tag{8}$$

Furthermore, since the change in the velocity of a Karman vortex takes a sine wave form, the changes in θ1 and θ2 also take a sine wave form but they are opposite in phase. With $\tilde{n}$ expressing the vortex frequency, the phase difference, θ, synthesized (S1' - S2') by the phase comparator, is given as follows.

$$\grave{e} = \grave{e}1 - \grave{e}2 = 2\frac{VdD\grave{u}}{C^{\cdot Q}}\sin 2\partial\tilde{n}t \tag{9}$$

A phase comparison system that uses two pairs of ultrasonic sensors obtains twice as much information on the vortex as a system using one pair of sensors.

Sonic change (change in $\ddot{O}$), a factor that causes an accuracy problem in ultrasonic wave phase

comparison systems, can be canceled by comparing of S1' and S2'. This eliminates the need for a sonic speed correction circuit to compensate for the temperature and pressure changes, thus allowing for a simple circuit structure for the detection of a vortex in broad temperature and pressure ranges.

3.   SPECIFICATIONS OF THE ULTRASONIC VORTEX FLOW METER

Table 1 shows the specifications of the newly developed ultrasonic vortex flow meter.

Table 1   Specification of the ultrasonic flow meter

Applicable flowing substance	General gases,air
Accuracy(%Reading)	±1
Rangeability	1:40
Bore diameter	400A max
Pressure(MPa)	7 max
Temperature(C)	-10 to 80
Vibration resistance(G)	3 or higher
Self-diagnosis and backup functions	Circuits,sensor
Explosion-proof structure	ExdllBT4 explosion-proof

It is needed that the flow meters used in transmission pipelines and pipes installed in factories should not contain moving parts, and they must offer maintenance-free, high reliability. Vortex flow meters are used in a wide range of applications since they offer a wide measuring range and contain no moving parts. They are also easy to maintain and low in cost. By adding a self-diagnosis function to the amp circuit and a sensor backup function to ensure uninterrupted operation even in case of a sensor malfunction, we have developed a new flow meter that meets gas measurement demands in process management.

4.   STRUCTURE OF THE ULTRASONIC VORTEX FLOW METER

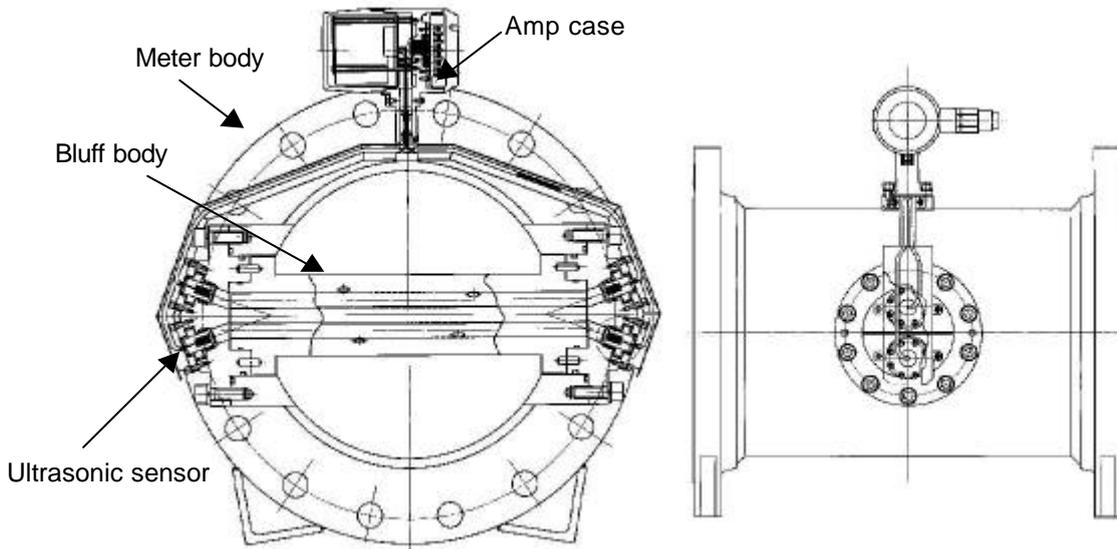Fig. 5 illustrates the structure of the ultrasonic vortex flow meter.

Fig. 5 Structure of the ultrasonic vortex flow meter

The bluff body has two lengthwise holes for the generation of currents corresponding to the Karman vortex, and each hole has a pair of ultrasonic sensors for detecting the generated current.

To achieve an explosion-proof structure, the amp case and ultrasonic sensors are connected with a stainless steel tube. The unit obtains the JIS ExdIIBT4 explosion-proofing.

4.1   Sonic change canceling mechanism

The ultrasonic vortex flow meter detects the Doppler effect that the Karman vortex causes to the ultrasonic waves propagating through the holes inside the bluff body by comparing the phases, and it obtain the flow measurement by measuring frequency of the Karman voltex.

Since Karman vortices are generated alternately, the phase comparator output takes a sine wave form. However, ultrasonic resonance is present in the holes. If the effect of this ultrasonic resonance is large, change in the resonance condition caused by a quick change of sonic velocity in the gas due to temperature and pressure fluctuations can result in a detectable phase shift. Therefore, if the flow meter is installed near compressors and turbines, there is a large pulsation of the gas flowing in the pipe, the flow meter may detect a phase difference output that corresponds to the pressure and temperature change.

Basically it is possible to detect a Karman vortex by comparing the phase of an ultrasonic oscillator signal and a sensor signal modulated by the Karman vortex. However, with this basic system, when sonic change occurs in the gas, only the ultrasonic wave propagating through the gas is affected by the change. As a result, the sonic change is output as a phase difference based on the comparison of the phases of the modulated sensor signal and oscillator signal. Fig. 6 shows a phase difference signal which was generated when constant pressure pulsation was given and the frequency of ultrasonic oscillator frequency was swept near the resonance frequency. It shows the output of a phase difference caused by pressure pulsation (sonic change), but the amplitude of the phase difference output varied in accordance with the change in the ultrasonic oscillation frequency. It is suspected that, in addition to the Doppler effect (phase modulation), the resonance present in the hole effected as an additional factor to cause a change in the phase.
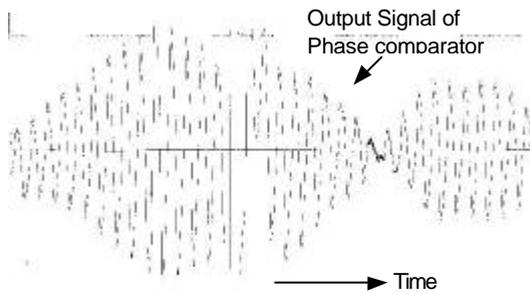
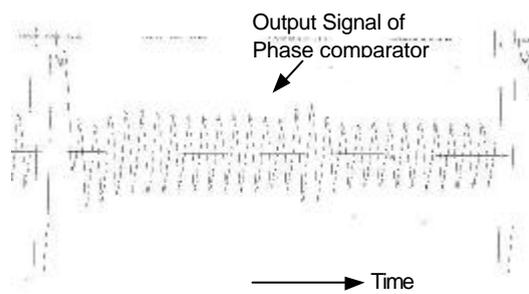Fig. 6   Phase difference signal   Fig. 7 Phase difference signal

Fig. 7 indicates the phase difference output signal that was generated when the resonance was reduced by the sound insulating material attached to the inside walls of the hole in the bluff body. The fact that the amplitude remained the same regardless of the ultrasonic frequency indicates that the sound insulating material reduced the effect of the resonance and that only the sonic change caused by pressure pulsation was output. The phase difference output shown in Fig. 8 was produced by a meter that used two pairs of ultrasonic sensors designed to cancel the effects of the sonic change caused by pressure pulsation. It shows more effective cancellation of the sonic change as compared to the phase difference output of a system with one pair of ultrasonic sensors.

The above results confirmed that using two pairs of ultrasonic sensors and comparing the phases of the received signals could effectively cancel the effects of the sonic change.
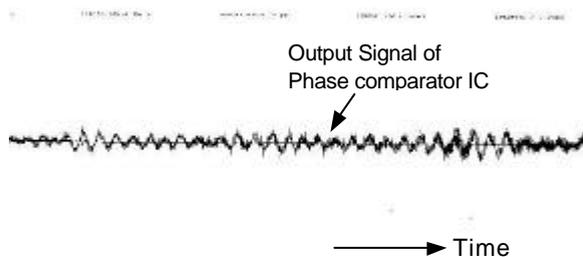
Fig. 8   Phase difference signal

4.2   Structure of the ultrasonic sensor

In an ultrasonic sensor, a piezoelectric element that generates an ultrasonic wave is acoustically bonded to a protective case (holder), and the bonding surface serves as an acoustic diaphragm to transmit an ultrasonic wave through the gas.

Ultrasonic sensors are installed in such a way that they do not contact the meter body directly. The ultrasonic wave generated by an ultrasonic sensor propagates through a gas, then is received by the ultrasonic sensor on the receiving side to detect the flow corresponding to the vortex.   However, portions of the ultrasonic wave sent from the sensor are received through the meter body and bluff body. If the S/N ratio (Signal: ultrasonic wave transmitted through the gas, Noise: ultrasonic wave transmitted through the meter body and bluff body) is low, the meter cannot achieve stable flow measurement (Karman vortex detection).   To prevent this, packing and O-rings are inserted between the ultrasonic sensors and meter body to minimize the ultrasonic wave amounts transmitted through the meter body and bluff body.   Fig. 9 shows the structure, and Fig. 10 indicates the ultrasonic propagation characteristic of ultrasonic sensor which has the resonance frequency at approximately 59 kHz.   The graph shows an S/N ratio of 1:5 or better near the sensor resonance frequency, indicating stable ultrasonic wave transmission and reception.
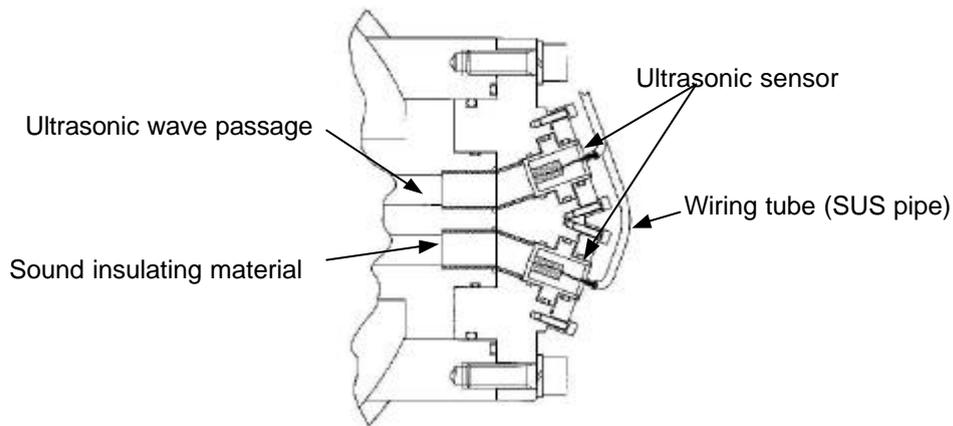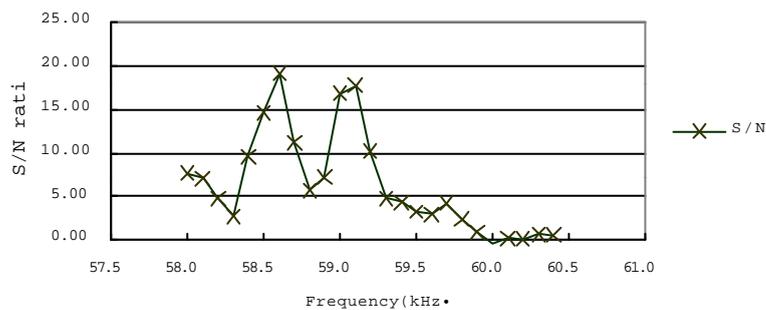

Fig. 9 Structure of the ultrasonic sensor

Fig. 10 Performance of Ultrasonic sensor

4.3   Sensor backup function

To improve the maintenance and reliability of the flow meter, the backup function monitors the ultrasonic sensors and main circuits and ensures continuous flow measurement even if one sensor malfunctions.

In case one of the sensors in the two-pair cross-sensing system malfunctions, the faulty ultrasonic sensor signal input to the phase comparator circuit is changed to a sensor oscillation signal. The flow meter outputs an alarm while continuous flow measurement with one pair ultrasonic sensors. This is effective for pipelines which cannot be easily stopped. Fig. 11 shows a block diagram of the amp circuit equipped with the sensor backup function.

The amp circuit has a built-in microcomputer to provide a number of functions, such as the flow rate computation, flow rate signal and alarm output function, and self-diagnosis function.

The amp circuit does not require sensitivity adjustment or zero-point adjustment, which is necessary in most other kind of flow meters. The measuring accuracy remains the same even when the sensor backup function is operating (when measurement is conducted by one pair of ultrasonic sensors). Unlike an ultrasonic flow meter using multi-measurement-lines, the newly developed flow meter maintains the same measuring accuracy even when a sensor malfunction occurs.
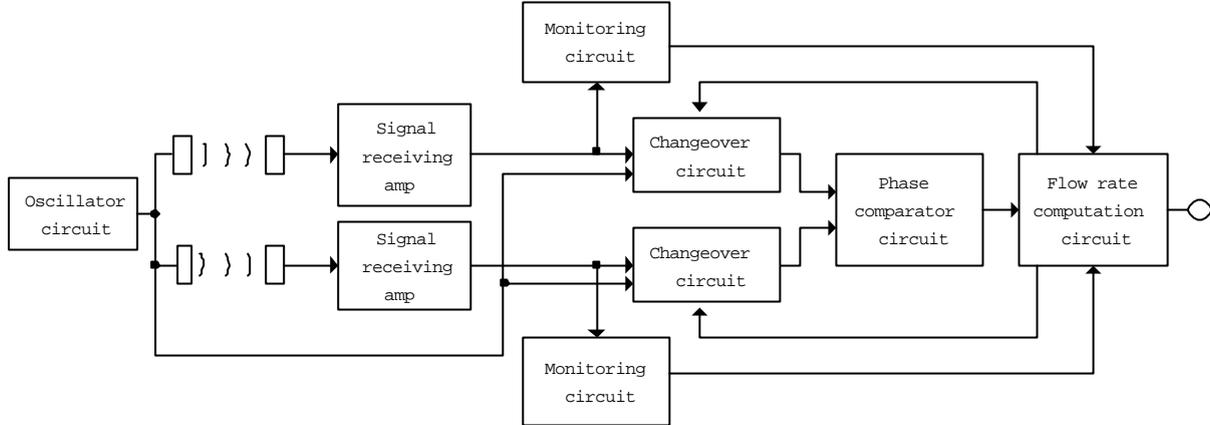
Fig. 11 Block diagram of the amp circuit equipped with the sensor backup function

5.   ADVANTAGES OF THE ULTRASONIC VORTEX FLOW METER

In addition to the high accuracy, high sensitivity, maintenance-free operation and low cost, the newly developed ultrasonic vortex flow meter provides the following advantages.

(1)   The ultrasonic cross-sensing system ensures stable flow measurement even when the installation site is subjected to temperature and pressure fluctuations.

(2)   Since the ultrasonic vortex flow meter offers higher vibration resistance than conventional vortex flow meters (piezoelectric type and electric capacitance type), the vibration-resistance work can be reduced.

(3)   The self-diagnosis and sensor backup functions prevent sudden interruptions in flow measurement, and allow efficient maintenance work.

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