INDUCTIVE SENSING SYSTEM FOR ACTIVE MAGNETIC SUSPENSION CONTROL

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ABSTRACT

Inductive sensors discussed in this paper are divided from a magnetically suspended body by a thin wall made from non-magnetic stainless steel. Therefore the carrier applied to the sensors is set to a relatively low frequency, but an influence of eddy currents on the metal wall can not be neglected. The low-frequency carrier produces a deterioration of the frequency characteristics in the inductive sensing. In addition, the eddy currents cause a decline of the sensor's sensitivity. Such undesirable circumstances are somewhat mitigated by a synchronous detection system proposed here. This system can perform the good sample-hold operation with twice of the carrier frequency in principle. The performances as well as the frequency characteristics are examined using a tested device. The analysis may bring us an idea of digital self-synchronous detection newly.

INTRODUCTION

Recently the applications of magnetic suspension technology to actuators used in an ultra-high vacuum environment have been increasing in order to avoid the vacuum contamination (Watanabe, 1995a, 1995b ; Moriyama, 1996). In such applications, the actuators are often enclosed in an adequate case made from non-magnetic stainless steel because they generate dust particles and release impure gases. This means that there is a thin metal wall between electromagnets for the magnetic suspension and a suspended body, and the metal wall may impose severe restrictions on position sensors for the active control. Namely we are unable to use not only the optical sensors but also the most popular eddy current sensors. Probably the usable sensors will be only the inductive type with a low-frequency carrier. From a viewpoint of the frequency characteristics in the inductive sensing, however, it is better for the carrier frequency to be as high as possible. Therefore, the influence of eddy currents on the metal wall, that is a decline of the sensor's sensitivity, will be inevitable in the inductive sensing.

In this paper, a synchronous detection system is proposed for inductive sensors used under such undesirable circumstances. In order to mitigate a deterioration of the inductive sensing due

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to the low-frequency carrier and the eddy currents, the sensor's signal is converted to a full-wave rectified signal and the amplitude of the rectified signal is detected using a sample-hold circuit. The sample-hold operation is performed under a synchronization with the sensor's signal in consideration of the influence of an equivalent resistance due to the eddy currents. As a result, the synchronous detection will be completed with twice of the carrier frequency. This is confirmed through experiments with a tested device. In addition, since a decrease of the carrier frequency may become a remarkable problem in a synthesis of magnetic suspension control, the frequency response is studied theoretically and experimentally. There is a possibility that this problem reversely leads us to an unique synchronous detection method for digital control.

SYNCHRONOUS DETECTION SYSTEM

Figure 1 shows the basic structure of inductive sensors divided from the suspended body by a thin metal wall. The two sensor coils with series connection are alternately magnetized by the oscillator, and each sensor forms the magnetic paths through the sensor core, the two air gaps and the suspended body. The oscillator's frequency f_0 must be so low that the formation of the magnetic paths is not extremely obstructed by eddy currents on the metal wall, and the sensor's resistance should be sufficiently low in comparison with its reactance. An equivalent resistance, however, may not be neglected if an effect of the eddy currents remains somewhat. (It is noted that there is an equivalent resistance due to eddy currents on the suspended body as well.) Since such an equivalent resistance should be essentially estimated by the reduction of a concentrated resistance of the metal wall in consideration of mutual couplings between the sensor coil and the eddy current paths, it is naturally dependent on the gap length. Consequently, the voltage v_1 between the middle points of the sensor coils and the external resistors should be expressed as

$$v_1 = \left(\frac{R_2}{R_1 + R_2} - \frac{r_2 + j\omega_0 L_2}{r_1 + j\omega_0 L_1 + r_2 + j\omega_0 L_2} \right) v_0 \quad , \tag{1}$$

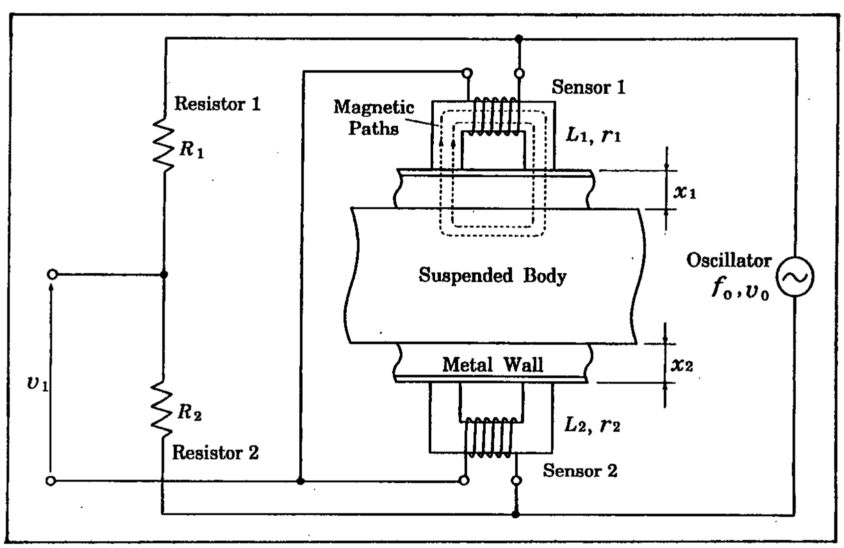

Figure 1. Basic Structure of inductive sensors.

where $\omega_0 = 2\pi f_0$, R_1 and R_2 are resistances of the external resistors, L_1 and L_2 are equivalent inductances of the two sensor coils and r_1 and r_2 are equivalent resistances of them. Defining the gap lengths as $x_1 = x_0 - x$ and $x_2 = x_0 + x$ and the external resistances as $R_1 = R_0 - R$ and $R_2 = R_0 + R$ and expressing the equivalent inductances as

$$L_1 = \frac{x_0}{x_0 - \alpha x} L_0 , \quad L_2 = \frac{x_0}{x_0 + \alpha x} L_0 , \tag{2}$$

and the equivalent resistances as

$$r_1 = \frac{x_0}{x_0 - \beta x} r_0 , \quad r_2 = \frac{x_0}{x_0 + \beta x} r_0 , \tag{3}$$

v_1 is approximately given by

$$v_1 \sim \left(\frac{R}{R_0} + \frac{\alpha + \beta \gamma^2}{1 + \gamma^2} \frac{x}{x_0} \right) \frac{v_0}{2} + j \frac{(\alpha - \beta)\gamma}{1 + \gamma^2} \frac{x}{x_0} \frac{v_0}{2} \tag{4}$$

under the conditions that $\alpha^2 x^2 << x_0^2$ and $\beta^2 x^2 << x_0^2$, where $\gamma = r_0 / \omega_0 L_0$. In the above equation, since the absolute value of the first term becomes larger than that of the second term in general, the amplitude of v_1 is decided by the first term alone. But, even if so, a phase difference between v_1 and v_0 due to the second term can not be neglected. It is important that the phase difference be dependent on the displacement x. (If the external resistors with the same resistance are used, such a phase difference will be kept nearly constant unless there is an unbalance between two sensors without displacement.)

Figure 2 shows the block diagram of a synchronous detection system proposed for inductive sensors as shown in Fig. 1. It is well-known that such a synchronous detection has the

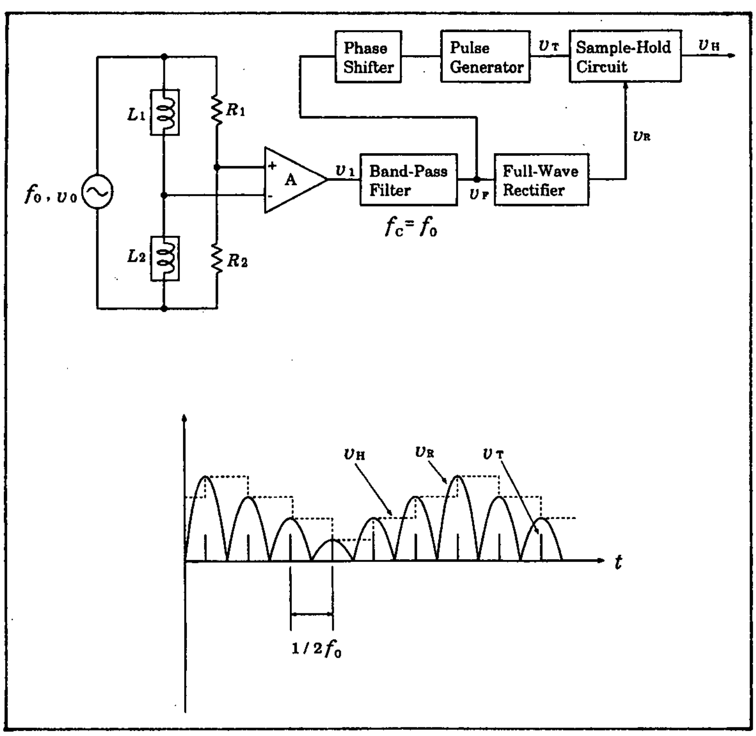

Figure 2. The proposed synchronous detection system.

advantage of good performances over the others, e.g., a square-law detection, a simple full-wave rectification and so on. For the above-mentioned reason, the carrier, that is the oscillator's signal v_0, will be probably set to a frequency less than 10 kHz, and there will be somewhat an equivalent resistance unless the frequency is very low. Of course, even if so, the amplitude of the band-pass filter's signal v_F becomes nearly proportional to the displacement x according to the first term of Eq. (4). Here the band-pass filter whose center frequency f_c is equal to the carrier frequency f_0 is a necessary device because the inductive sensors may pick up harmful signals due to magnetic couplings with electromagnets or some electromagnetic elements. The signal v_F is converted to the signal v_R using the full-wave rectifier, and the amplitude of v_R is detected using the sample-hold circuit. Here, by selecting adequate external resistors that $R_1 \neq R_2$, the amplitude of v_F never becomes zero. Therefore the sample pulse v_T can be made out of the signal v_F using the phase shifter and the pulse generator. As a result, the pulse v_T is always generated at the peak of v_R, as shown by waveforms in Fig. 2, even if there is a phase difference between v_F and v_0 as supposed from Eq. (4). The merit of this system is that the synchronous detection with a sample frequency of $2f_0$ is completed with a good linearity to the displacement x .

EXAMINATIONS OF SYNCHRONOUS DETECTION

In order to examine the performance of the proposed synchronous detection system, the inductive sensors shown in Fig. 1 were used in practice. The sensors, together with electromagnets and a linear pulse motor, are hermetically enclosed in a box-like case made from stainless steel (Moriyama, 1996). The thickness of the case is 0.5 mm at the sensor head. The sensor core and the suspended body are made from laminated silicon steel and magnetic stainless steel respectively, and the gap length x_0 between them is 1 mm. The suspended body is movable in the range that -0.35 mm $< x < 0.35$ mm. Figure 3 shows the frequency characteristics of the sensors. Eddy currents on the metal wall (and probably ones on the suspended body) seem to cause a saturation of the equivalent reactance $\omega_0 L_0$, an increase of the equivalent resistance r_0, a decrease of the reactance sensitivity α used in Eq. (2) and an appearance of the resistance sensitivity β used in Eq. (3).

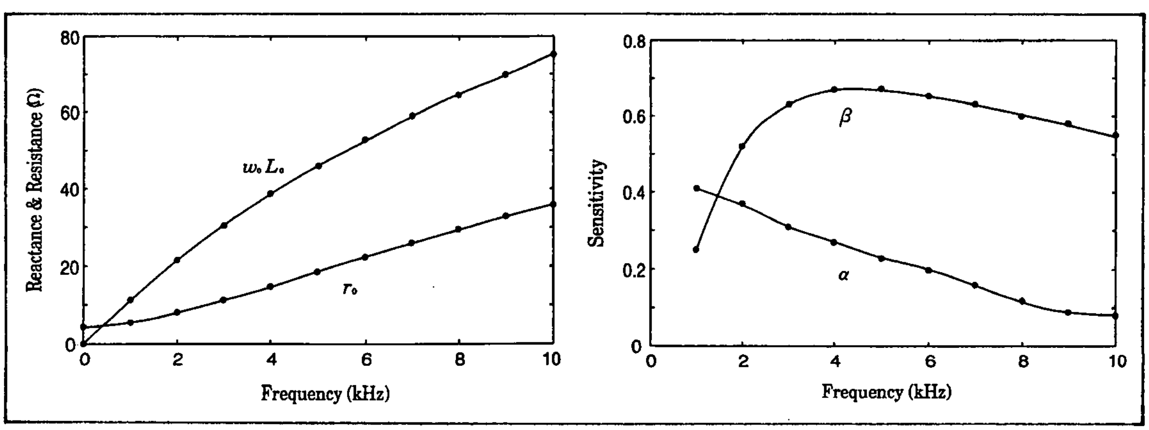

Figure 3. Frequency characteristics of inductive sensor.

The circuit under test is shown in Fig. 4. The carrier is set to a frequency of 4 kHz and an amplitude of 5V. The sample pulse at Terminal E is made of the band-pass filter's signal at Terminal F using the all-pass filter, the zero-cross comparator (LM311), the monostable multiviblator (TC4538) and the AND-gate circuit. Therefore it is always generated at the peak of the full-wave rectifier's signal at Terminal D even if the displacement x changes, as shown in Fig. 5. Figure 5 also shows that the phase difference between the carrier and the sensor's signal

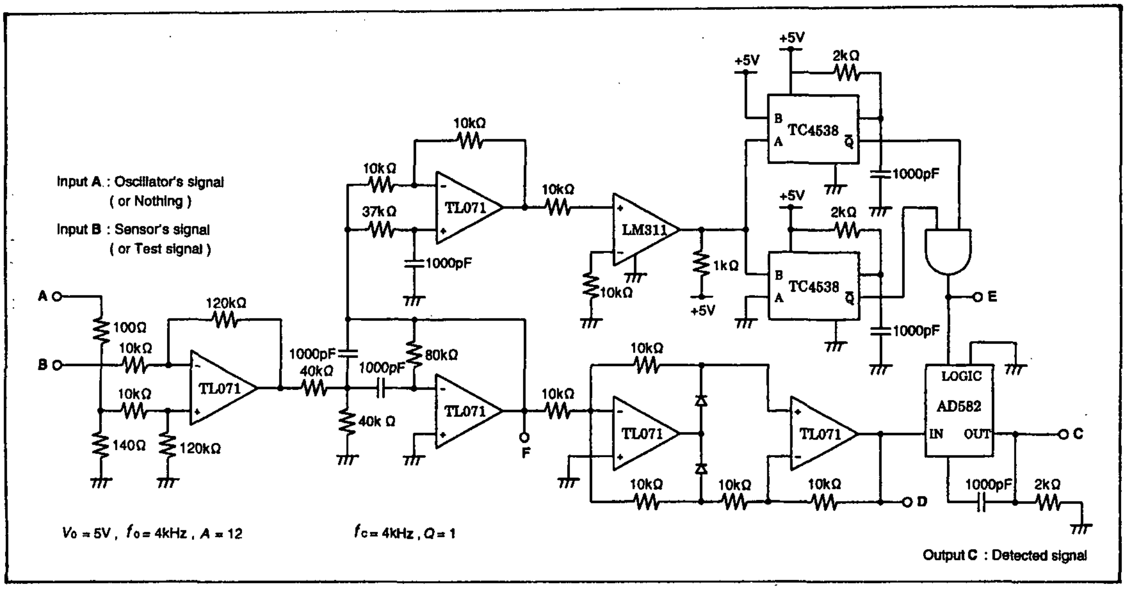

Figure 4. A tested circuit of the synchronous detection system.

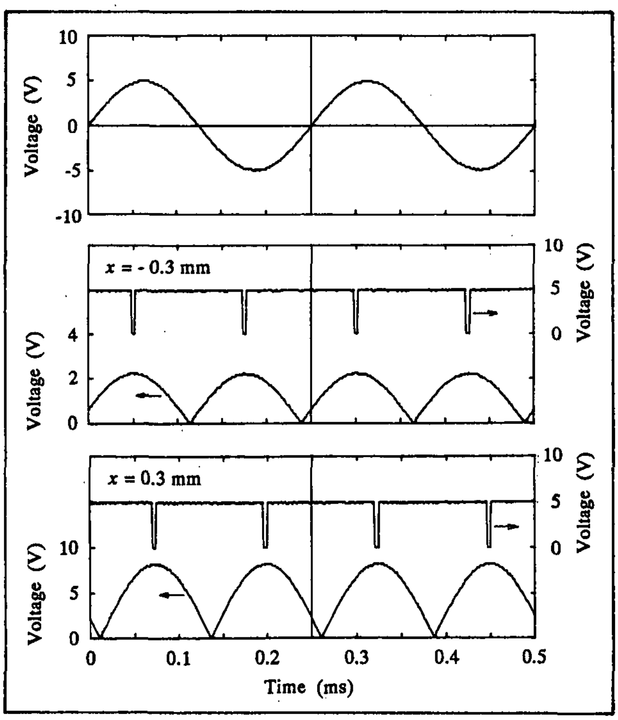

Figure 5. Waveforms of the carrier, the sample pulse and the rectifier's signal.

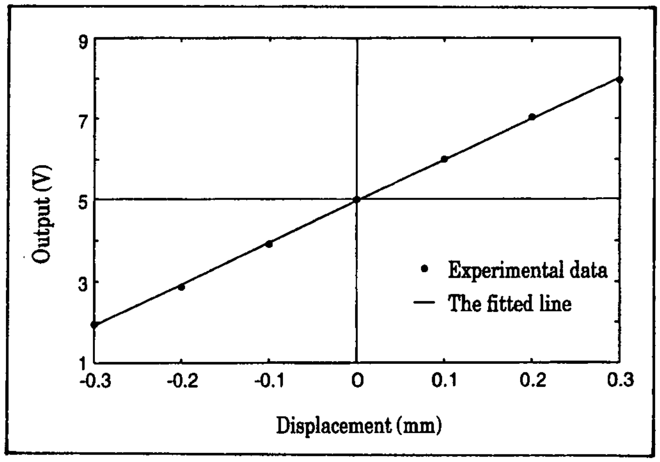

Figure 6. A characteristic of the detected signal versus the displacement.

appears according to the expectation from Eq. (4). On the other hand, the synchronous detection is performed with a sample frequency of 8 kHz using the sample-hold circuit (AD582). Figure 6 shows a characteristic of the detected signal versus the displacement. The linearity is excellent, and the detection sensitivity (10 V/mm) estimated from the fitted line is in agreement with the expectation (9.6 V/mm) from the first term in Eq. (4). Therefore it can be said that the proposed system has sufficient performance as expected in the previous section.

In the tested circuit shown in Fig. 4, it seems that the element determining the frequency characteristics is only the sample-hold circuit. The band-pass filter also, however, may have an influence on the frequency characteristics because the center frequency is half of the sample frequency. Its frequency response is expressed by

$$G(j\omega) = \frac{j\omega/\omega_0}{Q\left(1-\omega^2/\omega_0^2\right)+j\omega/\omega_0} = \frac{1}{R(\omega)+jX(\omega)}\ , \tag{5}$$

where the quality factor Q is set to a fixed value of 1 in the tested circuit. Since the band-pass filter's output is a sort of amplitude modulated wave, it can be written as

$$v_F = (V_0 + V_F\cos\omega_1 t)\cos(\omega_0 t + \theta) \tag{6}$$

and the input must be defined as

$$\begin{aligned} v_1 = V_0 &\{R(\omega_0)\cos(\omega_0 t+\theta) - X(\omega_0)\sin(\omega_0 t+\theta)\} \\ &+ \frac{V_F}{2}\{R(\omega_H)\cos(\omega_H t+\theta) - X(\omega_H)\sin(\omega_H t+\theta)\} \\ &+ \frac{V_F}{2}\{R(\omega_L)\cos(\omega_L t+\theta) - X(\omega_L)\sin(\omega_L t+\theta)\}\ , \end{aligned} \tag{7}$$

where $\omega_H = \omega_0 + \omega_1$ and $\omega_L = \omega_0 - \omega_1$. Considering the condition that $Q\,\omega_1^2 << \omega_0^2$, v_1 is approximately expressed as

$$\begin{aligned} v_1 &\sim \left\{V_0 + V_F\left(\cos\omega_1 t - 2Q\frac{\omega_1}{\omega_0}\sin\omega_1 t\right)\right\}\cos(\omega_0 t+\theta) \\ &= \{V_0 + V_1\cos(\omega_1 t+\phi)\}\cos(\omega_0 t+\theta)\ . \end{aligned} \tag{8}$$

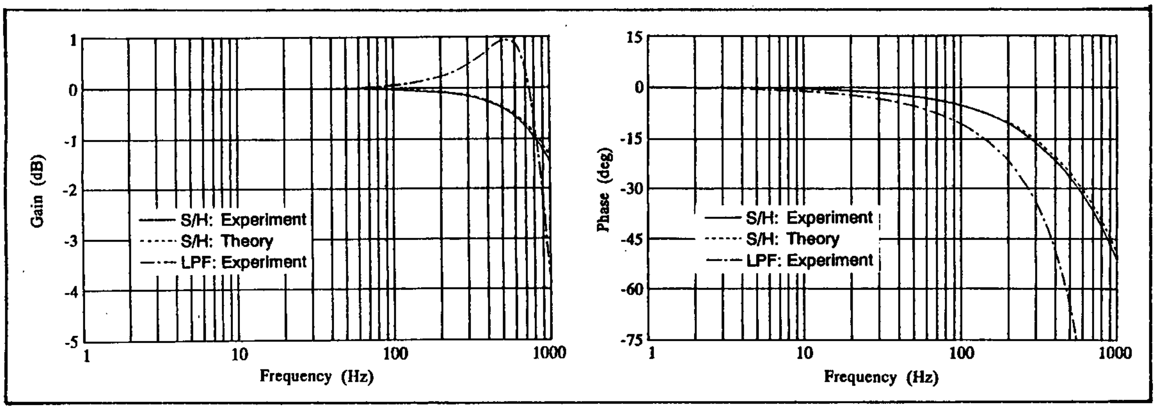

Figure 7. Frequency response from the base-band signal to the detected signal.

Comparing Eq. (6) and Eq. (8), it is found that the band-pass filter acts on the base-band signal $V_1 \cos(\omega_1 t + \phi)$ as the first-order lag element

$$G_1(j\omega_1) = \frac{1}{1 + j\omega_1 \tau} \quad , \tag{9}$$

where $\tau = 2Q / \omega_0$.

From the above consideration, it is supposed that the frequency characteristics of the synchronous detection system are prescribed by a transfer function

$$H(s) = \frac{1}{1 + \tau s} \frac{1 - e^{-Ts}}{Ts} \quad , \tag{10}$$

where $T = \pi / \omega_0$. In order to confirm this analysis, the frequency response of the tested circuit was measured by applying an amplitude modulated signal to Input B in Fig. 4. Figure 7 shows the frequency response from the base-band signal to the detected signal. Since the measured response is in good agreement with the theoretical one, it can be said that the expression of Eq. (10) is valid. Figure 7 also indicates that the synchronous detection is superior to a simple full-wave rectification whose response is measured using a second-order low-pass filter instead of the sample-hold circuit in Fig. 4. The low-pass filter is set to a cutoff frequency of 800 Hz and a quality factor of 1 in order to provide a sufficient attenuation for a fundamental component (a 8 kHz-component) of the rectifier's signal and a smaller phase lag for the base-band signal. Nevertheless the phase lag is larger than that of the synchronous detection.

APPLICATIONS TO MAGNETIC SUSPENSION CONTROL

We applied this synchronous detection method to the magnetic suspension control of a linear pulse motor (Moriyama, 1996). The motor includes four pairs of lower and upper linear magnetic bearings and the floating mover corresponds to a ladder-like arm for transferring a semiconductor wafer in a vacuum chamber. The magnetic bearings are used to the guide control as well as the lift one, and consequently the arm's attitude is actively controlled with respect to five degrees of freedom, that is, lifting, guiding, rolling, pitching and yawing motions. Figure 8 shows open-loop frequency characteristics with respect to rolling motion when the arm

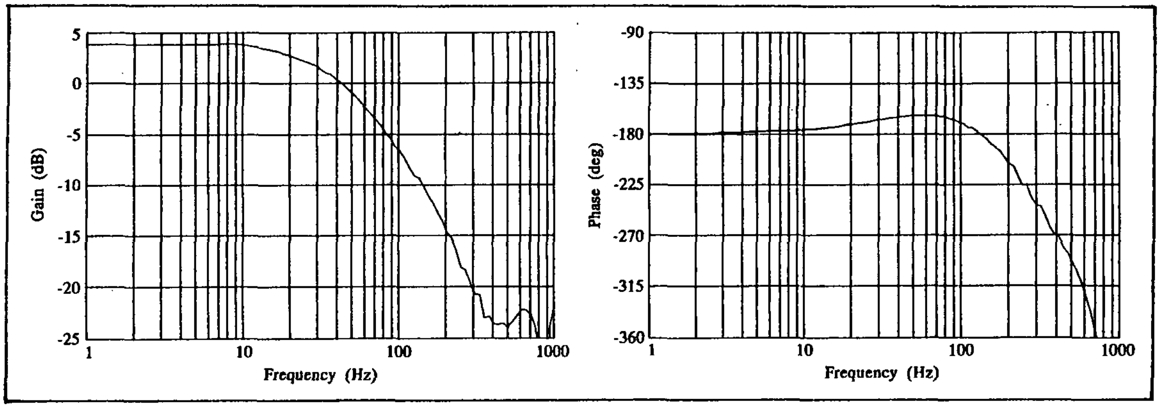

Figure 8. Open-loop frequency response with respect to rolling motion.

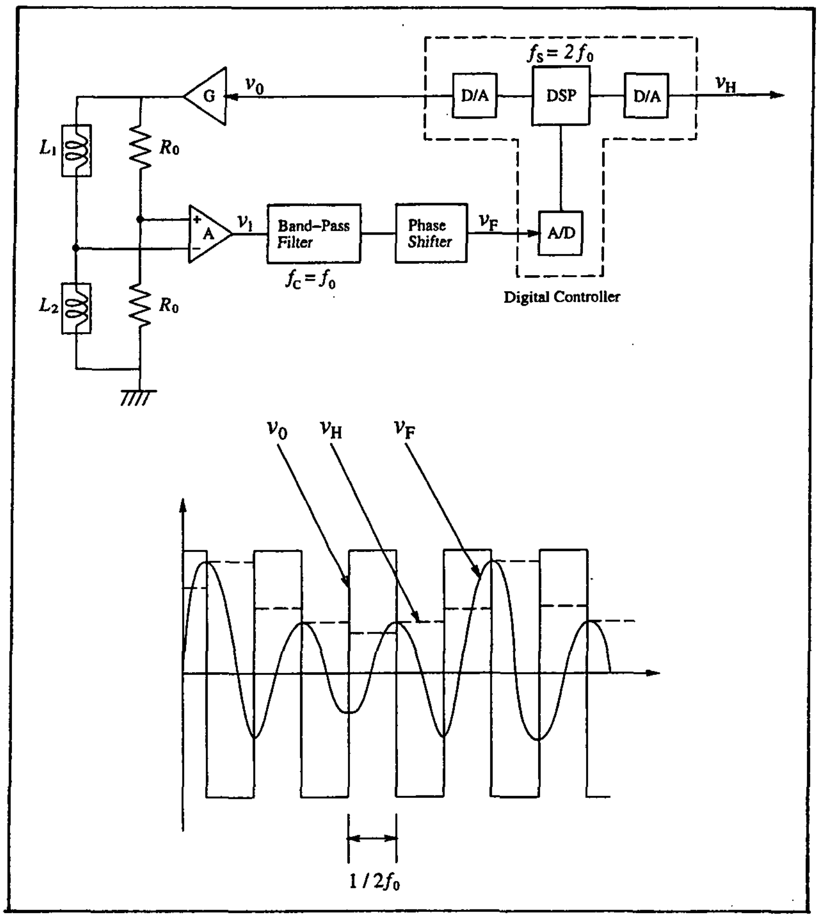

Figure 9. A self-synchronous detection system with digital signal processor.

is magnetically suspended. By changing the inductive sensing system from a simple full-wave rectification to such a synchronous detection, the gain margin increased by about two times under the same analogue PD controller.

As mentioned in the previous section, the synchronous detection system includes a zero-order hold element which is well-known in sampled-data control. This implies a possibility that the synchronous detection system is efficiently integrated into a digital control system. For example, we can work out a self-synchronous detection scheme as shown in Fig. 9. The left D/A converter in the digital controller outputs a rectangular-wave signal with half of the sampling frequency f_s, that is, a frequency of f_0. The signal is used as the carrier for inductive sensors and the resultant sensors' signal v_F is directly fed to the A/D converter. Finally, by reversing the sign of an amplitude of v_F by each sampling cycle, the synchronous detection is completed automatically in the digital signal processor (DSP). (The right D/A converter's output v_H is illustrated on the premise that the DSP executes only the reversing operation.) Since the external resistors have the same resistance, a phase difference between v_1 and v_0 will be kept nearly constant as mentioned in the second section. Therefore the self-synchronous detection will be successfully performed at the peak of v_F if a phase regulation due to the phase shifter is adequately done beforehand. Regarding the frequency characteristics, if a computing time of the DSP is not considered, this system also will be mathematically expressed by Eq. (10). But the time constant τ should be rewritten as $\tau = (2Q + \sin\phi)/\omega_0$ because the phase shifter, that is the all-pass filter having a frequency response

$$G(j\omega) = \frac{1 - j\omega/\omega_c}{1 + j\omega/\omega_c}, \tag{11}$$

also acts on the base-band signal as a lag element, where ϕ is the phase lag given at $\omega = \omega_0$.

CONCLUSION

A synchronous detection system for inductive sensors which are divided from the suspended body by a thin metal wall has been proposed from viewpoints of the application of a low-frequency carrier and the influence of eddy currents. The performance tests showed that the proposed system could perform the sample-hold operation with twice of the carrier frequency and the output had an excellent linearity with respect to the displacement of the suspended body. Therefore it seems that the undesirable effects of the inductive sensing are somewhat mitigated by this system. The frequency response of this system is determined by the band-pass filter as well as the sample-hold circuit, and the transfer function can be simply expressed with a first-lag element and a zero-order hold element. Though this system has been successfully integrated into the analogue control system of a magnetically suspended linear pulse motor, its fundamental idea may be expanded into a self-synchronous detection method for digital control.

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