A trial of flow disturbance suppression for pneumatic anti-vibration apparatus using internal information in central pattern generator

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Abstract
Pneumatic anti-vibration apparatus (AVA) has been used for suppression of vibration from floor in the field like semiconductor manufacturing. The compressed air supplied to the pneumatic AVA is generated by the air compressor. During the compression process of the air, the pressure of the compressed air varies. Consequently, the pressure variation changes the flow rate of the air supplied to the pneumatic AVA, which is called flow disturbance. Based on the internal model principle, the suppression of vibration of AVA due to flow disturbance has been confirmed by using Central Pattern Generator (CPG). Previous studies in the field of biology have confirmed the existence of a neuronal network that generates a walking rhythm in the spinal cord of an organism, and this is called CPG. Some researchers have applied CPG to such as walking of biped-robots. However, there are no applications using information inside CPG. This letter proposes using internal information in CPG as new method for further vibration suppression, compared with the conventional method. Specifically, this method makes use of outputs corresponding to differential and integral signals inside the CPG. It is shown the effectiveness of the proposed method by experimental results.

Keywords: Pneumatic equipment, Vibration control, Spectrum analysis, Flow disturbance, Neural network, Central pattern generator

1. Introduction

Pneumatic anti-vibration apparatus (AVA) is widely used in the field of semiconductor manufacturing in order to reduce effects of the vibration transmitted from floor (Shin and Kim, 2009). The isolated table of the AVA is supported by the air spring. The air compressor supplies compressed air to the air spring. At that time, the vibration from floor is suppressed by adjusting the flow rate of the compressed air. However, the generated compressed air has the pressure variation called pressure disturbance. This disturbance varies the flow rate of the compressed air sent to the AVA. This variation of flow rate is called flow disturbance and causes vibration of the AVA (Shirani and Wakui, 2010).

Previously, some authors tried to suppress the flow disturbance by using a kind of oscillator called Central Pattern Generator (CPG). CPG exists in the spinal cord of an organism and consists of single or multiple neural oscillators (Matsuoka, 1985, 1987). This oscillator has a characteristic of generating an output entrained with a certain external input. Therefore, by installing CPG in the closed loop of the control system, the suppression of the flow disturbance was confirmed based on the internal model principle (Nakamura et al., 2015) (Kashiwazaki and Wakui, 2017).

Until then, CPG has been applied to analysis of walking motion of living organisms (Taga et al., 1991) and control of robot arm (Williamson, 1998). However, there is no application in which signal inside the CPG is outputted and used within the range of author’s literature survey. This is because the neural oscillator simulates neural circuit of living organism, and CPG’s detectable output is limited when following its position. However, when CPG is illustrated by block diagram, it is easy to extract signal representing information in cell nucleus in the organism. Therefore, this letter proposes using signal inside the CPG together with conventional output of the CPG as an attempt. Specifically, the
suppression of further disturbance is performed by a control method similar to PID compensation using outputs corresponding to differential and integral signals in CPG.

This letter is organized as follows. Section 2 shows the experiment setup and the control system of the pneumatic AVA. Then, it shows the effectiveness of CPG synchronized with the fundamental wave of the disturbance. In Section 3, a control system using differential and integral signals in CPG is introduced, and its effectiveness from experiments is confirmed. Section 4 examines the experiment results. Finally, conclusions are drawn in Section 5.

2. Flow disturbance suppression using CPG
2.1 Pneumatic anti-vibration apparatus

Figure 1 shows the photograph of the pneumatic AVA that is considered in this letter. The AVA has the air spring as an actuator and supports the isolated table by its driving force. A position sensor is attached to the AVA in order to measure the relative position between the isolated table and the floor. Moreover, the vibration direction is limited only in the vertical direction by air slider.

Figure 2 shows the block diagram of the pneumatic AVA and its control system. In this system, position control is provided in order to control the isolated table to equilibrium position. PI compensator $C_{pos}(s)$ is expressed as follows:

$$C_{pos}(s) = k_p \frac{1 + T_p s}{T_p s}$$

The gain of the compensator is set to $k_p = 0.05$, the time constant is set to $T_p = 0.53$ s, and other parameters are summarized in Table 1. The region encircled by the dashed line in Fig. 2 represents CPG. Then, the details of this structure and installing method will be described in Sections 2.3 and 2.4.

2.2 Flow disturbance

Figure 3 illustrates the experimental setup. Air compressor is employed to provide compressed air to the air spring of the pneumatic AVA. During the compression process of the air, the pressure of the compressed air varies as shown in the lower left balloon of Fig. 3. Also, this pressure variation is called pressure disturbance.

The generated air is sent to the air spring via regulator and servo valve. As shown in the lower center balloon of Fig. 3, the regulator can smooth the pressure variation of the compressed air; however, it cannot suppress the variation completely. As a result, the flow rate of the air sent to the isolated table varies as shown in the lower right balloon of Fig. 3. This flow rate variation is called flow disturbance (Shirani and Wakui, 2010), which causes the isolated table to vibrate. This letter examines the suppression effect by detecting the pressure of the compressed air which is easier to measure than the flow rate.
2.3 CPG

CPG is constructed by the neural oscillator model proposed by Matsuoka (Matsuoka, 1985, 1987). The behavior of CPG is represented by the following equations:

\[ \tau_1 \dot{x}_1 = -x_1 - \beta v_1 - \gamma [x_2]^+ - [u_f]^+ + u_0 \]  
\[ \tau_2 \dot{x}_2 = -x_2 - \beta v_2 - \gamma [x_1]^+ - [u_f]^+ + u_0 \]  
\[ \tau_3 \dot{v}_1 = -v_1 + [x_1]^+ \]  
\[ \tau_3 \dot{v}_2 = -v_2 + [x_2]^+ \]  
\[ [u_f]^+ = \max(\pm u_f, 0) \]  
\[ y_p = [x_1]^+ - [x_2]^+ \]  

These equations are represented by a block diagram as shown in Figure 4. The meanings of the symbols in the figure are shown in Table 2. Max function in Equation (6) is a nonlinear function that sets the value less than the threshold value as 0. Time constants \( \tau_1 \) and \( \tau_2 \) determine the resonance frequency of CPG. \( \gamma \) and \( \beta \) in Equations (2) and (3) indicate the suppression degree of the oscillator, and determine the shape of the waveform output of CPG. Therefore, they are set so that the output waveform of CPG can reproduce supplied air pressure waveform shown in the lower center balloon of Figure 3. Moreover, \( u_0 \) is switch input that turns off at 0 V and turns on 1 V. Also, Equations (4) and (5) represent upper and lower first order lag system in Fig. 4, and two integrators are drawn out before summing point. \( y_d \) and \( y_i \) indicated by bold lines in the figure are described in Section 3.1.

### Table 1 Parameters of control system for pneumatic AVA.

| Symbol | Description                      | Value  | Unit   |
|-------|----------------------------------|--------|--------|
| \( M \) | Mass of isolated table          | 120    | kg     |
| \( D \) | Viscous damping coefficient      | 479    | N·s/m  |
| \( K \) | Spring constant                  | 5120   | N/m    |
| \( A_0 \) | Effective area                   | 7.8 \times 10^{-4} | m²     |
| \( \beta_0 \) | Compressibility                  | 2.74 \times 10^{-6} | 1/Pa   |
| \( V_0 \) | Volume of air spring             | 1.50 \times 10^{-3} | m³     |
| \( c \) | Flow conductance                 | 4.60 \times 10^{-10} | m³/s/Pa|
| \( G_q \) | Flow gain                        | 1.65 \times 10^{-5} | m³/s/V |
| \( k_{pos} \) | Position sensor sensitivity      | 6670   | V/m    |
| \( r \) | Reference                        | 0      | V      |
| \( d \) | Flow disturbance                 | 0      | m³/s   |
| \( x \) | Isolated table’s position        | 0      | m      |

2.4 CPG synchronized with fundamental wave

CPG is installed in the control system of the pneumatic AVA as shown in the region encircled by the red dashed line in Figure 2. As previous study (Nakamura et al., 2015) (Kashiwazaki and Wakui, 2017), the CPG was connected in parallel to the PI compensator. In order to reproduce supplied air pressure waveform, \( \gamma \) and \( \beta \) were set to trial and error with \( \gamma=1.0 \) and \( \beta=1.0 \). Also, \( y \) in the region encircled by the dashed line in Fig. 2 represents CPG output.

Next, the resonance frequency of CPG is adjusted to the frequency of the fundamental wave of the disturbance by...
plotting Bode diagram from transfer function. The transfer function of CPG was derived from linearly approximating nonlinear elements by describing function method (Katayama and Kitamura, 1998). Since the period of the disturbance is constant at 66 s (frequency 0.0152 Hz), the time constant of the CPG was set to $\tau_1=5.2$, $\tau_2=10.4$. Therefore, the disturbance is suppressed using synchronization of CPG.

Experimental results are shown in Figure 5 when the adjustable parameters in Fig. 2 are set with $k_1=30$, $k_2=0.05$, $k_3=0$, $k_4=0$. From the results shown in Fig. 5, vibration of the isolated table is suppressed when CPG is used, as compared to the control system only with PI compensator.

![Block diagram of CPG](image)

**Fig. 4** Block diagram of CPG. The bold lines represent the differential signal $y_d$ and the integral signal $y_i$.

![Isolated table's position without and with CPG](image)

**Fig. 5** Isolated table's position without and with CPG (experiment). Compared to the control system using only the PI compensator, the vibration of the isolated table is more suppressed when CPG is used.

### 3. Flow disturbance suppression using internal information in CPG

#### 3.1 Differential and integral signals in CPG

In Section 2.4, the suppression of the vibration due to the flow disturbance was confirmed by installing CPG synchronized with the fundamental wave. However, the waveform of the position with CPG in Figure 5 still has vibration seen as transient response and low frequency vibration. Therefore, this letter proposes using internal information in CPG as an attempt to suppress further vibration. Specifically, the suppression is performed by a control method similar to PID compensation using outputs corresponding to differential and integral signals in the CPG.

First, the outputs corresponding to the differential signal $y_d$ and the integral signal $y_i$ are verified. From the bold lines in Figure 4, $y_d$ is the sum of the value before the integrator of $x_1$ and $x_2$, $y_i$ is the sum of the value after the max function and the integrator of $x_1$ and $x_2$. They are expressed by the following equations:

$$y_d = \dot{x}_1 - \dot{x}_2$$  \hspace{1cm} (8)

$$y_i = \int [x_1] dt - \int [x_2] dt$$  \hspace{1cm} (9)

Next, simulation waveforms of the proportional output $y_p$, the differential signal $y_d$ and the integral signal $y_i$ are shown in Figure 6 when a sine wave with period of 100 s is directly inputted to CPG in Fig. 4. From Fig. 6, $y_d$ and $y_i$ are respectively integral and differential signals against $y_p$. Also, $y_i$ has a large offset.

### Table 2 Parameters of CPG.

| Symbol | Description          | Unit |
|--------|----------------------|------|
| $\tau_i$ ($i=1, 2$) | Time constant | s    |
| $\gamma$ | Strength of inhibitory connections | -    |
| $\beta$ | Adaptation constant | -    |
| $u_f$ | CPG input | V    |
| $u_0$ | Switch input | V    |
| $x_i$ ($i=1, 2$) | Membrane potential | V    |
| $y_i$ ($i=1, 2$) | Self-inhibitory input | V    |
| $y_p$ | CPG proportional output | V    |
| $y_d$ | CPG differential signal | V    |
| $y_i$ | CPG integral signal | V    |
3.2 Flow disturbance suppression using differential signal

In addition to CPG synchronized with the fundamental wave of the disturbance in Section 2.4, the differential signal \( y_d \) is used at the same time. Vibration suppression is attempted by a control method similar to PD compensation using \( y_p \) and \( y_d \). Experimental results are shown in Figure 7 when the adjustable parameters in Figure 2 are set with \( k_1=30, k_2=0.05, k_3=0.03, k_4=0 \). From Fig. 7, the control system using both \( y_p \) and \( y_d \) suppresses the vibration of the isolated table compared to that using only \( y_p \).

3.3 Flow disturbance suppression using differential and integral signals

In addition to CPG synchronized with the fundamental wave of the disturbance in Section 2.4, the differential signal \( y_d \) and the integral signal \( y_i \) are used at the same time. Vibration suppression is attempted by a control method similar to PID compensation using \( y_p \), \( y_d \) and \( y_i \). Experimental results are shown in Figure 8 when the adjustable parameters in Figure 2 are set with \( k_1=30, k_2=0.05, k_3=0.03, k_4=0.01 \). From Fig. 8, the control system using \( y_p \), \( y_d \) and \( y_i \) suppresses the vibration of the isolated table compared to that using only \( y_p \). Moreover, in the control system using \( y_p \), \( y_d \) and \( y_i \) at the same time, the output waveform of CPG is not rounded but linear, and it coincides with supplied air.
pressure waveform. Then, the vibration of low frequency when pressure gradually decreases is suppressed. Also, when \( y_p, y_d \) and \( y_i \) are used at that same time, a large offset is generated in the waveform of CPG output in Fig. 8. This is due to the use of the integral signal \( y_i \) having a large offset as shown in Figure 6.

The waveform with CPG in Figure 5 and with only \( y_p \) in Figures 7 and 8 are different due to the change in the condition of the load connected to the air compressor, but all parameters of the control system are the same.

4. Interpretation of the experimental results
4.1 Spectrum analysis

By analyzing the waveform of the position in Figures 7 and 8, it is confirmed which frequency component is changing by using \( y_d \) and \( y_i \). From the analysis results of (a) and (b) in Figure 9, the control system using both \( y_p \) and \( y_d \) suppressed the remaining high frequency components when only \( y_p \) is used. Therefore, high frequency vibration is suppressed by the control method similar to PD compensation by CPG. From the results of (b) and (c) in Fig. 9, the control system using \( y_p, y_d \) and \( y_i \) suppressed the remaining low frequency components when both \( y_p \) and \( y_d \) are used. Therefore, low frequency vibration is suppressed by the control method similar to PID compensation by CPG.

When changing from the control system using only \( y_p \) to that using both \( y_p \) and \( y_d \), the high frequency spectrum is excited. This is a spectrum oscillated at approximately 2 Hz which is the natural frequency of the isolated table.

![Fig. 9 Frequency spectrums of waveform of isolated table's position with P, PD and PID compensation (experiment). Compared to P and PD compensation, the remaining vibration is eliminated by PID compensation.](image)

4.2 Fourier series expansion of supplied air pressure waveform

From the waveform of CPG output in Figure 8, there is a difference in the spectrum of CPG output between the control system using only \( y_p \) and that using \( y_p, y_d \) and \( y_i \). In this section, in order to verify the reproducibility of supplied air pressure waveform by the CPG, the waveform is analyzed.

The supplied air pressure waveform in the upper stage of Fig. 8 is represented by the mathematical expression in Figure 10. From the figure, Fourier series expansion is represented by the following equations:

\[
d(t) = \frac{2A}{T_1 + T_2} \sum_{n=1}^{\infty} \left[ a_n \sin(n\omega_0 t) + b_n \cos(n\omega_0 t) \right] = \frac{2A}{T_1 + T_2} \sum_{n=1}^{\infty} \left[ a_n^2 + b_n^2 + \sin n \left( \omega_0 t + \frac{n\pi T_1}{T_1 + T_2} \right) \right]
\]

\[
a_n = \frac{\sin(n\omega_0 T_1)}{n^2 \omega_0^2 T_1} - \frac{\sin(n\omega_0 T_2)}{n^2 \omega_0^2 T_2} - \frac{\cos(n\omega_0 T_1)}{n\omega_0} + \frac{\cos(n\omega_0 T_2)}{n\omega_0}
\]

\[
b_n = \frac{\sin(n\omega_0 T_1)}{n\omega_0} + \frac{\sin(n\omega_0 T_2)}{n\omega_0} - \frac{\cos(n\omega_0 T_1)}{n^2 \omega_0^2 T_1} + \frac{\cos(n\omega_0 T_2)}{n^2 \omega_0^2 T_2}
\]

Table 3 shows amplitude and phase of each harmonic when \( T_1=8.91 \) s, \( T_2=57.09 \) s, \( \omega_0=0.095 \) rad/s, \( A=1.055 \) are substituted into Equations (10)~(12). From the table, the supplied air pressure waveform has the spectrum of each harmonic and is composed on waves whose phases are different by 24.3 degrees. Incidentally, since the pressure disturbance is defined as the change amount of the pressure, the model of Fig. 10 sets DC component to 0.

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Table 3  Amplitude and phase of each harmonic of supplied air pressure waveform.

| Harmonic | Amplitude [ ] | Phase [deg] |
|----------|---------------|-------------|
| Fundamental wave | 0.377 | 24.3 |
| Second wave | 0.172 | 48.6 |
| Third wave | 0.097 | 72.9 |
| Fourth wave | 0.057 | 97.2 |
| Fifth wave | 0.031 | 121.5 |

4.3 Comparison of phase difference

This section compares CPG output between the control system using only $y_p$ and that using $y_p$, $y_d$ and $y_i$ at the same time. Each waveform is analyzed by using power spectrum and cross spectrum. When $D(f)$ and $Y(f)$ are the Fourier transformation of supplied air pressure waveform $d(t)$ and CPG output $y(t)$, the power spectrum $P_{dd}(f)$ and $P_{yy}(f)$ of $d(t)$ and $y(t)$ are expressed by Equations (13) and (14). Since the cross spectrum $C_{dy}(f)$ between the two channels is generally a complex function, it is expressed by Equation (15).

\[
P_{dd}(f) = D(f)^* \cdot D(f)
\]

\[
P_{yy}(f) = Y(f)^* \cdot Y(f)
\]

\[
C_{dy}(f) = D(f)^* \cdot Y(f) = |C_{dy}(f)| e^{i\theta(f)}
\]

$|C_{dy}(f)|$ in Eq. (15) represents the amplitude component of the common frequency component included in the two signals, and $\theta(f)$ represents the phase difference between the two channels. Therefore, the difference is verified from $\theta(f)$ of the two signals of supplied air pressure waveform and CPG output.

The phase difference of CPG output $y(t)$ to supplied air pressure waveform $d(t)$ is verified from experiment. First, $d(t)$ and $y(t)$ at each measurement are shown in Figure 11, and the power spectrum $P_{dd}(f)$ and $P_{yy}(f)$ of each waveform are shown in Figure 12. The adjustable parameter $k_1$ in Figure 2 was constant at 30, and $k_2$ was set so that the amplitude of $y(t)$ was the same magnitude. From Fig. 12, since $d(t)$ varies at the time of measurement of each control system, the magnitudes of the spectrum do not coincide. Next, Figure 13 shows the results of the amplitude $|C_{dy}(f)|$ and the phase $\theta(f)$ of the cross spectrum $C_{dy}(f)$ of $y(t)$ to $d(t)$. From $\theta(f)$ in the lower part of the figure, CPG output when $y_p, y_d$ and $y_i$ are used has less phase difference than that when only $y_p$ is used, and is reproduced more faithfully.
Fig. 13  Cross spectrums and phase differences of CPG outputs at P and PID compensation for supplied air pressure waveform (experiment). Compared to the output at P compensation, that at PID compensation has less phase difference against supplied air pressure waveform.

5. Conclusions

In this letter, a suppression method using internal information of CPG is newly investigated for the vibration of the pneumatic AVA caused by the flow disturbance. Conclusions are summarized as follows:

(1) Based on the internal model principle, vibration suppression was confirmed by installing CPG synchronized with fundamental wave of disturbance. Next, in order to suppress further disturbance, a control method using output corresponding to differential and integrated signals in CPG was introduced.

(2) First, suppression of high frequency vibration was conducted by a control system similar to PD compensation using $y_p$ and $y_d$ of CPG at the same time. Next, suppression of low frequency vibration was conducted by a control system similar to PID compensation using $y_p$, $y_d$ and $y_i$ of CPG at the same time.

(3) It is found that CPG output when using $y_p$, $y_d$ and $y_i$ has less phase difference with respect to supplied air pressure waveform than that when using only $y_p$ and reproduces the waveform more faithfully.

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