Flow disturbance suppression for pneumatic anti-vibration apparatus by central pattern generator using reciprocal inhibition oscillator model

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Abstract

Pneumatic anti-vibration apparatus (AVA) has been used in order to suppress vibration from a floor. In this paper, central pattern generator (CPG) composed of reciprocal inhibition oscillator (RIO) model is applied for suppression of flow disturbance caused by pressure fluctuation of compressed air supplied to the pneumatic AVA. Concretely, the disturbance suppression is confirmed by implementing it to the control system of the AVA. In addition, this paper shows that the control system using internal information in CPG can realize the stable levitation and the disturbance suppression simultaneously. In the industry situation, the flow disturbance is not periodic because the consumption flow rate of the compressed air changes. Therefore, the band-pass filter in CPG using RIO model is redesigned to be broadband, and the disturbance can be suppressed without declining performance even when the disturbance period changes. Moreover, this paper illustrates the roles of the sigmoid function and the connection between two neurons in CPG using RIO model. When the sigmoid function is replaced with the proportion function and the saturation function, the influence is verified by experiments.

Keywords: Pneumatic equipment, Vibration control, Flow disturbance, Neural network, Central pattern generator, Reciprocal inhibition oscillator

1. Introduction

In the precision positioning field, pneumatic anti-vibration apparatus (AVA) has been widely used for reducing vibration transmitted from a floor (Butler, 2011) (Rivin, 1995). The authors have already shown the application of central pattern generator (CPG) in order to suppress flow disturbance (Shirani and Wakui, 2010) caused by pressure fluctuation of compressed air supplied to the pneumatic AVA (Kashiwazaki and Wakui, 2017a). CPG exists in the spinal cord of an organism and controls the rhythmic movement observed in animal locomotion. Various models have been proposed for CPG. In the previous study, CPG was composed of neural oscillator model proposed by Matsuoka (Matsuoka, 1985, 1987). The CPG implemented in the closed loop suppressed the vibration of the isolated table due to the flow disturbance (Kashiwazaki and Wakui, 2017a). In addition, internal information in CPG was introduced as outputs corresponding to differential and integral signals (Kashiwazaki and Wakui, 2017b). By using internal information, the stable levitation of the isolated table and the suppression of the disturbance were simultaneously realized without PI compensator which has the role of the stable levitation (Kashiwazaki and Wakui, 2019).

CPG composed of neural oscillator model in the previous study was complicated in structure and took some tasks to set parameters for implementation. Therefore, this paper applied reciprocal inhibition oscillator (RIO) model (Friesen, 1994) (Futakata and Iwasaki, 2008), which is a simpler structure. RIO model imitates the connection of two neurons, and has a characteristic of generating an output synchronized with the input. CPG composed of the model has been mainly used for the generation of desired values and patterns in a fish robot (Bliss et al., 2013) and a crankshaft (Iwasaki and Liu, 2004). Thus, RIO model is introduced to the vibration control of the AVA as a second application.
Moreover, instead of comparing the absolute suppression performance of RIO model and neural oscillator model, this paper compares and examines the possibility and the practicality of both models in order to consider industrial applications.

Firstly, CPG using RIO model is transformed into a suitable form for implementation, and is implemented in the control system of the AVA. Experimental results show the effectiveness of the disturbance suppression. Furthermore, an integral output is extracted as the internal information in CPG using RIO model. The control system using the internal information can realize the stable levitation and the disturbance suppression simultaneously. Secondly, the flow disturbance is not periodic because the consumption flow rate of the compressed air changes in the industry situation. Therefore, the proposed method prevents a decline in the suppression performance when the period of the disturbance varies. Specifically, the band-pass filter in CPG using RIO model is redesigned to be broadband. The vibration of the isolated table is suppressed without declining performance in any disturbance period. Finally, RIO model has a sigmoid function, which is a nonlinear element that imitates the operation of neurons, and a path that mutually connects two neurons. The simulated waveforms disclose differences in roles of both the nonlinear function and the connection in CPG. In addition, the influence for the AVA is investigated by experiments results when the sigmoid function is replaced with the proportion function and the saturation function.

This paper is organized as follows. Section 2 describes pneumatic AVA, flow disturbance, and CPG using neural oscillator model. Section 3 explains the structure and the implementation method of CPG using RIO model, and verifies the effectiveness of the proposed method. Moreover, the control system using internal information in CPG can realize the stable levitation and the disturbance suppression simultaneously. Section 4 improves the band-pass filter in CPG using RIO model as a method of improving the performance at the variation of the disturbance period. The suppressing performance by the proposed method is verified when the disturbance period changes. Section 5 illustrates the role of the sigmoid function and the neuron coupling in CPG using RIO model. When the function is changed to the proportion function and next the saturation function, the influence by the experiment is confirmed. Finally, conclusions are drawn in Section 6.

2. Backgrounds

2.1 Pneumatic anti-vibration apparatus

Figure 1 shows the photograph of the pneumatic AVA. The AVA has an air spring, which supports an isolated table. The vibration from a floor is suppressed by adjusting the flow rate of the compressed air supplied to the air spring. A position sensor is attached to the AVA in order to measure the relative position between the isolated table and the floor. Moreover, an air slider restricts the motion of the table to the vertical direction.

Figure 2 shows the block diagram of the pneumatic AVA and its control system. The region enclosed by the red dotted line represents PI compensator as position control for stabilizing the isolated table to equilibrium position. The proportional gain of the compensator is set to $K_p=0.05$, the integral gain is set to $K_i=0.0943$, and other parameters and variables are summarized in Table 1. The region enclosed by the blue dashed line in Fig. 2 represents CPG using RIO model. The details of the structure and the implementation method will be described in Sections 3.1. In addition, saw-tooth waveform $d$ shows flow disturbance. The cause and the effect will be described in Section 2.2.
2.2 Flow disturbance

Figure 3 illustrates the experimental setup. Air compressor generates the compressed air supplied to the air spring of the pneumatic AVA. While repeating start and stop, the compressor generates the air by rotating the internal piston at high speed. Therefore, the pressure fluctuation of the compressed air is confirmed by a pressure sensor as shown in the lower left balloon of Fig. 3. In addition, the period $T$ of the fluctuation is assumed to be 66 s.

The compressed air is supplied 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 fluctuation of the air. However, the fluctuation is not completely suppressed. As a result, it causes the flow rate of the air supplied for the air spring to vary. The variation is called flow disturbance (Shirani and Wakui, 2010) and causes the vibration of the isolated table as shown in the lower right balloon of Fig. 3. In order to suppress the disturbance to the pneumatic AVA, pressure control has been proposed with a high precision, quick response regulator that detects slight changes in the pressure. (Kato et al., 2010). This paper examines the suppression effect by observing the pressure of the compressed air, which is easier to measure than the flow rate.

Table 1 Parameters and variables of pneumatic AVA and its control system.

| 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 | $7.8 \times 10^{-3}$ | m²    |
| $f_0$  | Compressibility | $2.74 \times 10^4$ | 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 | -     | V    |
| $d$    | Flow disturbance | -     | m³/s |
| $x$    | Isolated table’s position | -     | m    |

2.3 CPG using neural oscillator model

In the previous study (Kashiwazaki and Wakui, 2017), CPG using neural oscillator model has already been applied to the control system of the AVA, and suppressed the vibration of the isolated table caused by the flow disturbance. This section briefly describes the structure and the parameter setting.

Figure 4 shows the block diagram of CPG using neural oscillator model proposed by Matsuoka (Matsuoka, 1985, 1987). The meanings of the symbols and the value of the parameters are shown in Table 2. Max function is a nonlinear function that sets the negative values as 0. Time constants $r_1$ and $r_2$ determine the intrinsic frequency of CPG. They are adjusted to 0.0152 Hz (period 66 s), which is the fundamental frequency of the disturbance. $\gamma$ and $\beta$ indicate the degrees of mutual and self-suppression of the neural elements in the upper and lower loops of Fig. 4, and determine the shape of the output waveform of CPG. Therefore, they are set so that the output waveform reproduces supplied air pressure waveform as shown in the lower center balloon of Fig. 3. Moreover, $u_0$ is switch input that turns off at 0 V and turns on at 1 V.

3. Introduction of CPG using RIO model
3.1 Flow disturbance suppression by CPG using RIO model

From the biological points of view, RIO model and CPG composed of it have been expressed in the related literature (Futakata and Iwasaki, 2008) as shown in Fig. 5 (a) and (b). RIO model in Fig. 5 (a) indicates two neurons $N$...
Table 2 Parameters and variables of CPG using neural oscillator model.

| Symbol | Description           | Value | Unit |
|--------|-----------------------|-------|------|
| $r_1$  | Time constant         | 5.2   | s    |
| $r_2$  |                       | 10.4  | s    |
| $\gamma$ | Strength of inhibitory connections | 1 | - |
| $\beta$ | Adaptation constant | 1 | - |
| $u_0$  | Switch input          | 1     | V    |
| $u_f$  | CPG input             | -     | V    |
| $x_i$  | ($i=1, 2$) Membrane potential | - | V |
| $v_i$  | ($i=1, 2$) Self-inhibitory input | - | V |
| $m_i$  | ($i=1, 2$) Neuron output | - | V |
| $y_f$  | CPG output            | -     | V    |

with inhibitory connections of synaptic strength $\mu$. In order to unify the expression in the paper, the symbols used in Fig. 5 are different from those used in the literature (Futakata and Iwasaki, 2008). However, the meanings are the same. From the viewpoints of the control field, when the connection and the input-output relationship of RIO model are summarized, the blocks of Fig. 5 are integrated as shown in Fig. 6. The region enclosed by the dashed line in the figure shows RIO model. Furthermore, the internal structure of the neurons is clearly described for the implementation in the control system of the AVA. Therefore, CPG using RIO model in this paper is a block diagram of Fig. 7. This figure is represented by the following equations:

$$w_i = -u - \mu y_2 = r_1 - \mu y_2$$  \hspace{1cm} (1)

$$w_2 = -u - \mu y_1 = r_2 - \mu y_1$$  \hspace{1cm} (2)

$$y_1 = \tanh \left[ \frac{2\omega_1 s}{(s + \omega_1)} w_1 \right] = \tanh \left[ q_1 \right]$$  \hspace{1cm} (3)

$$y_2 = \tanh \left[ \frac{2\omega_1 s}{(s + \omega_1)} w_2 \right] = \tanh \left[ q_2 \right]$$  \hspace{1cm} (4)

$$y = y_1 - y_2$$  \hspace{1cm} (5)

The meanings of the symbols in Fig. 7 are shown in Table 3. Two synaptic strengths $\mu$ in Equations (1) and (2) are values of 0 or more and indicate the degree of suppression between upper and lower neurons. The shape of the output waveform is determined. In order to reproduce the supplied air pressure waveform in the lower left balloon of Fig. 3, two $\mu$ are set to 0.5 for trial and error. Moreover, two $\omega_1$ are expressed as the intrinsic frequency or the center frequency of the band-pass filter in Equations (3) and (4). Thus, the intrinsic frequency is set to $\omega_1=0.0952$ rad/s because the frequency of the flow disturbance is 0.0152 Hz (period 66 s). In Equations (3) and (4), sigmoid function “tanh” known as activation function is used.

RIO model in Fig. 7 and neural oscillator model in Fig. 4 have a common characteristic that two upper and lower paths suppress each other. On the other hand, compared to neural oscillator model, RIO model has few parameters to be set and can be implemented more easily.

Next, the effectiveness of the proposed method is verified by actual experiment. In the same way shown in the previous study (Kashiwazaki and Wakui, 2018), CPG using RIO model is implemented in the control system of the AVA as enclosed by the blue dashed line in Fig. 2. In order to increase the loop gain of the control system, CPG is connected in parallel with the PI compensator at the summing point in the front stage of flow gain $G_q$ based on the...
phase relationship of CPG input and output. The values of the parameters in CPG are shown in Table 3. The adjustable parameters $k_1$ and $k_2$ in Fig. 2 are set to $k_1=k_2=0$ when only the PI compensator is used. These parameters are set to $k_1=1$ and $k_2=1$ when CPG is used in addition to PI compensator. The supplied air pressure waveform and the position waveform $k_{posx}$ of the isolated table are shown in Fig. 8. Compared to the control system using only PI compensator on the left side, the control system using CPG on the right side suppresses the vibration of the isolated table. Therefore, CPG using RIO model is additionally applied to the control system and suppresses the effect of the flow disturbance.

| Symbol | Description         | Value   | Unit |
|--------|---------------------|---------|------|
| $\omega_1$ | Intrinsic frequency  | 0.0952  | rad/s |
| $\mu$ | Synaptic strength    | 0.5     | -    |
| $u$   | CPG input            | -       | V    |
| $r_i$ ($i=1, 2$) | Feedback signal     | -       | V    |
| $w_i$ ($i=1, 2$) | Synaptic input      | -       | V    |
| $q_i$ ($i=1, 2$) | Internal variable    | -       | V    |
| $y_i$ ($i=1, 2$) | Membrane potential  | -       | V    |
| $y$   | CPG output           | -       | V    |

Fig. 8  Experimental results of the isolated table’s position without and with CPG. Compared to the control system using only PI compensator, the vibration of the isolated table is more suppressed when CPG is used.

### 3.2 Stable levitation and disturbance suppression using internal information

Previous study (Kashiwazaki and Wakui, 2019) proposed the control system using only CPG by introducing differential and integral signals as internal information in CPG using neural oscillator model. The proposed method can
stabilize the isolated table and simultaneously suppress the flow disturbance without PI compensator. Therefore, internal information is newly introduced in CPG using RIO model. The block of the band-pass filter in Fig. 7 is represented by Fig. 9 through equivalent transformation. From the figure, integral output $y_s$ is expressed by Eq. (6) when CPG input $u$ is used:

$$y_s = \frac{1}{s} u \quad (6)$$

Next, the frequency response $y/u$ of CPG using RIO model in Fig. 9 is measured. The measurement is performed by a frequency response analyzer (another name “servo analyzer”) that inputs sinusoidal wave and analyzes only the fundamental wave synchronized with $u$. Since it takes long time to measure the responses in the low frequency band, the intrinsic frequency $\omega_1$ is shifted to 15.2 Hz by changing $\omega_1$ in Fig. 9. There is no change in the outline of the frequency response because other parameters in CPG are fixed. When CPG input $u$ is changed to 0.1, 0.5, and 1.0 V in consideration of sigmoid function “tanh” which is a nonlinear element, the response is shown in the left side of Fig. 10. This figure shows that the gain of the resonance peak decreases as $u$ increases. Thus, CPG using RIO model has saturation characteristics. Moreover, the DC gain does not exist because the gain in the low frequency band decreases. Therefore, when CPG is implemented in the control system of the AVA, it is possible to maintain the stable performance of the device without changing the loop gain.

![Block diagram of CPG using RIO model transformed from Fig. 7.](image)

The frequency response $y_p/u_f$ of CPG using neural oscillator model in Fig. 4 is also measured in the same way. The response is shown in the right side of Fig. 10. From the figure, the gain of the resonance peak decreases as $u_f$ increases. Thus, CPG using neural oscillator model has also saturation characteristics. On the other hand, the DC gain exists because the gain in the low frequency band does not decrease.

Next, the control system, which uses internal information in CPG using RIO model, is implemented in the AVA. From the left side of Fig. 10, CPG does not have the DC gain. Therefore, in order to stabilize the isolated table, P compensator is implemented as shown in Fig. 11. The proportional gain of the compensator is $K_p=0.05$. Moreover, CPG using RIO model is connected in parallel to P compensator as shown in the figure. Adjustable parameters $k_1$, $k_2$, and $k_3$ are set as shown in Fig. 11. The parameters in CPG are shown in Table 3. Integral output $y_s$ in Fig. 9 is derived from the next stage of $r_2$. However, even if it is drawn from the next stage of $r_1$, the sign at the addition point after $k_3$ is adjusted. It is obvious that internal information can be introduced in this way.

From the actual experiment, the effectiveness of the proposed control system is verified. First, when PI compensator is used, the supplied air pressure waveform and the position waveform $k_{pos}x$ of the isolated table are shown on the left side of Fig. 12. Secondly, when using only $y_s$, the adjustable parameters in Fig. 11 are set to $k_1=1$, $k_2=0$, and $k_3=0.0943$. The results are shown in the center of Fig. 12. Finally, when using CPG output $y$ and $y_s$ simultaneously, the adjustable parameters in Fig. 11 are set to $k_1=1$, $k_2=1$, and $k_3=0.0943$. The results are shown in the right side of Fig. 12. From the center, the isolated table floats 1,500 $\mu$m from the seating status and is stabilized at the equilibrium position by using $y_s$. Moreover, the waveforms $k_{pos}x$ on the left side and the center are the same. From the right side of Fig. 12, the stable levitation of the isolated table and the suppression of the flow disturbance are confirmed by the proposed method.
The control system, which uses internal information in CPG using RIO model of Fig. 11, is transformed in Fig. 13. This control system can be interpreted as parallel connection of PI compensator and CPG. In other words, PI compensator plays the role of the stable levitation of the AVA, and CPG has the role of the disturbance suppression.

Fig. 10 Frequency responses of CPG using RIO and neural oscillator model.

Fig. 12 Experimental results of the control of the isolated table’s vibration. The levitation of the isolated table and the suppression of the flow disturbance are simultaneously realized when CPG output $y$ and integral output $y_s$ are used.

### 4. A method of improving suppression performance against periodic variation

#### 4.1 Design of broadband band-pass filter

In the situation of industrial applications, the consumption flow rate of the compressed air varies depending on the number of the pneumatic equipment connected to the air compressor as shown in Fig. 3. Thus, the period $T$ of the flow disturbance varies. The purpose of this section is to improve the suppression performance when $T$ varies. Specifically, band-pass filter (BPF) in CPG using RIO model of Fig. 7 is redesigned to be broadband. BPF in the left side of Eq. (7) shows the adaptation effect and the time delay between cell membrane and synapse. The block is transformed like the right side of the equation:

$$\frac{2\omega_1 s}{(s + \omega_1)^2} = \frac{2}{\left(1 + \frac{s}{\omega_1}\right)\left(1 + \frac{s}{\omega_1}\right)}$$

When $s=\omega_1$ is substituted for the right side of Eq. (7), the gain of BPF is 1(0 dB). Thus, the coefficient 2 in the numerator is a value that corrects the peak gain to 0 dB at the intrinsic frequency $\omega_1$. Bode diagram of Eq. (7) is the blue line indicated by $n=1$ in Fig. 14. $n$ represents the passband width of BPF. This figure shows that the gain is 0 dB at the frequency 0.0152 Hz (period 66 s). In addition, the peak of BPF is narrow at $\omega_1$.

Therefore, the narrowband BPF indicated by the blue line in Fig. 14 is transformed into a trapezoidal broadband BPF, while correcting the peak gain to 0 dB. As a result, when $T$ varies, the reduction of the gain is prevented. Thus,
declining the suppression performance is avoided. First, in order to broaden the passband of BPF, the left side of Eq. (7) is generalized and replaced with the subscript $n$ as shown in the left side of Eq. (8).

$$\frac{K_n s \omega_{in}}{(s + \omega_{in})(s + \omega_{in})} = K_n \frac{s}{s + \omega_{in}} \frac{\omega_{in}}{s + \omega_{in}}$$  \hspace{1cm} (8)

From the right side of Eq. (8), the proposed BPF is composed of a gain correction term $K_n$, a high-pass filter, and a low-pass filter. When the center frequency is $\omega_1 = 0.0152$ Hz (period 66 s), the cutoff frequencies $\omega_{in}$ and $\omega_{in}$ on the low and high frequency side are expressed as follows.

$$(\omega_{in}, \omega_{in}) = \left( \frac{\omega_1}{n}, \frac{\omega_1}{n} \right) = \left( \frac{2\pi}{66n}, \frac{2\pi}{66} \right)$$  \hspace{1cm} (9)

Moreover, since a gain of BPF is 0 dB at $\omega_1$, an equation for $K_n$ is derived as follows:

$$20 \log_{10} \left| \frac{K_n s \omega_{in}}{(s + \omega_{in})(s + \omega_{in})} \right| = 0$$  \hspace{1cm} (10)

When Eq. (9) and $s=j\omega_1$ are substituted for Eq. (10), $K_n$ is expressed by $n$ as follows:

$$K_n = \frac{n^2 + 1}{n^2}$$  \hspace{1cm} (11)

Substitute $n=1$ into Eq. (11), $K_n$ is 2. It coincides with the value of the gain correction in Eq. (7). When $n$ is infinite, $K_n$ is 1. If the passband is broadened greatly, it is not necessary to correct the gain at $\omega_1$.

As a result, Bode diagram of the proposed BPF is indicated by the green line ($n=3$) and the red line ($n=6$) in Fig. 14. This figure shows that the trapezoidal broadband BPF is realized while keeping the peak gain constant at 0 dB. When the period $T$ of the flow disturbance decreases from 66 s to 33 s or 22 s, the transformed BPF of $n=3, 6$ is less reduction of the gain compared to BPF of $n=1$.

4.2 Experimental verification

From the actual experiment, the effectiveness of the proposed method is verified. First, the block of BPF shown in the left side of Eq. (7) is changed to the block shown on the left side of Eq. (8). The block of BPF in Fig. 9 is modified as shown in Fig. 15. The figure shows only the upper part of Fig. 9.

Next, the control system, which uses internal information in CPG using RIO model, is implemented in Fig. 16. In this experiment, the influence of the fundamental wave of the disturbance must be clearly confirmed. Moreover, it is impossible to easily change the period $T$ of the flow disturbance. Therefore, this experiment uses the sinusoidal wave disturbance shown in Fig. 16 instead of the saw-tooth flow disturbance. The sinusoidal wave disturbance is applied by installing an addition terminal in the front stage of flow gain $G_p$. The parameters in CPG are shown in Table 3. The
adjustable parameters in Fig. 16 are set to \( k_1=1, k_2=1, k_3=0.0943 \). In addition, the proportional gain of P compensator is \( K_P=0.05 \).

The position waveform \( k_{pos,x} \) of the isolated table is shown in the upper part of Fig. 17, when BPF is conventional \((n=1)\). \( k_{pos,x} \) is shown in the lower part, when BPF is transformed into broadband \((n=6)\). The left side of Fig. 17 is the result when \( T = 66 \text{ s} \). In addition, \( T = 33 \text{ s} \) at the center and \( 22 \text{ s} \) at the right. In the conventional method, the vibration of the isolated table increases when \( T \) decreases. In the proposed method, the vibration does not change even if \( T \) decreases. Therefore, it is possible to prevent declining the suppression performance when \( T \) varies.

Fig. 15  Transformed block diagram of CPG using RIO model.  
Fig. 16  Block diagram of proposed control system by CPG using RIO model.

![Block Diagram](image)

![Waveform](image)

**Fig. 17** Experimental results of the control of the isolated table’s vibration caused by sinusoidal wave disturbance. The disturbance is suppressed by the proposed method in any disturbance period.

### 5. Saturation characteristics of CPG and its application
#### 5.1 Saturation characteristics of CPG

In RIO model, there is a sigmoid function “\( \text{tanh} \)”, which is a nonlinear element imitating the action of neurons, and a path which connects two neurons mutually. This section illustrates how those components work in the output generation process from the simulation results. In addition, this section analyzes neural oscillator model in the same way and verifies the difference in the roles of the components of both models.

First, the input and output characteristics of CPG are verified from the time response. The simulated waveforms of RIO model are shown in the upper part of Fig. 18 when CPG input \( u \) in Fig. 7 is a sinusoidal wave with a period 66 s. When \( u \) is changed to 0.1, 1, and 10 V, the results are shown in the left side, the center, and the right side of Fig. 18. Similarly, the waveforms of neural oscillator model in Fig. 4 are shown in the lower part of Fig. 18. This figure shows that CPG output \( y_p \) inverted waveform against \( u_r \). Furthermore, the gain decreases as \( u_r \) increases. As a result, both RIO model and neural oscillator model CPG have saturation characteristics. From the results of the frequency response in Fig. 10, the gain of the resonance peak decreases as \( u \) or \( u_r \) increases. Thus, CPG using both models shows saturation characteristics.

Next, the roles of sigmoid function “\( \text{tanh} \)” and the path connecting the two neurons in CPG using RIO model are examined. Figure 19 shows the block diagram of CPG and the waveform of each state variable. CPG input \( u \) is a sinusoidal wave with a period 100 s and amplitude 1 V. From the waveforms \( q_1 \) and \( y_1 \) before and after “\( \text{tanh} \)”, the amplitude peak decreases. Thus, the saturation characteristic of CPG using RIO model is caused by “\( \text{tanh} \)”. From the
waveforms $r_1$ and $-\mu y_2$ at the summing point connecting neurons in Fig. 19, they are added mutually with the same polarity. Section 3.1 states that RIO model has inhibitory connection because the plus and minus signs at the summing point are different. However, the connection of strength $\mu$ is excitatory from the waveforms. In the related literature, “mutually inhibitory synaptic connections” (Futakata and Iwasaki, 2008) and “inhibitory connections” (Bliss et al., 2012) are stated. There is no expression called excitatory connection in any document.

Finally, CPG using neural oscillator model are examined in the same way. Figure 20 shows the block diagram of CPG and the waveform of each state variable. When the summing point on the input side of Fig. 4 is drawn, the block diagram at the lower left of Fig. 20 is obtained. In the figure, $z_1$ and $z_2$ are defined as new state variables. From the waveforms $x_1$ and $m_1$ before and after max function on the output side, the function sets the negative values as 0 V and cuts the waveform. From the waveforms $z_1$, $-\gamma m_2$, and $\beta v_1$ at the summing point on the input side in Fig. 20, the two connections of the upper and lower neural elements work as mutual inhibition $\gamma$ and self-inhibition $\beta$. By this inhibitory connection, CPG using neural oscillator model shows saturation characteristics.

In other words, CPG using RIO model shows saturation characteristics by sigmoid function “tanh”, and the path connecting the two neurons is excitatory. On the other hand, max function in CPG using neural oscillator model affects the generation of the output waveform. The saturation characteristic is caused by the inhibitory connection. As a result, the roles of nonlinear element and connection of both models are different.
Fig. 20  Transformed block diagram of CPG using neural oscillator model and the simulated waveforms of each state variable when CPG input $u_f$ is sinusoidal wave. The saturation characteristic of CPG using neural oscillator model is caused by the connection of mutual inhibition (strength $\gamma$) and self-inhibition ($\beta$) of neural elements.

5.2 Application of sigmoid function

Section 5.1 shows that the saturation characteristic is caused by sigmoid function “tanh” in CPG using RIO model. As a similar situation in industrial scenes, safety is ensured by utilizing a saturation function so as not to add over the rated voltage of the motor. Therefore, the role of “tanh” in RIO model is interpreted in order to apply CPG to the control system of the AVA.

Figure 21 shows only the upper part of the path imitating the neuron in Fig. 9. Sigmoid function “tanh” enclosed by dashed line in Fig. 21 is expressed as $y_i = \tanh(q_i)$ when using internal variable $q_i$ and membrane potential $y_i$. The graph “tanh” is indicated by the blue line in Fig. 22. When $q_i$ is $\pm 2$ or more, $y_i$ is saturated at $\pm 1$. In addition, when $q_i$ is near 0, the slope is 1. When the isolated table is floating, CPG input $u$ is large amplitude. Thus, the sigmoid function can be regarded as a saturation function with upper and lower limits $\pm 1$. Moreover, when the isolated table is stabilized at the equilibrium position, $u$ is near 0. Thus, the sigmoid function can be regarded as a proportion function.

Therefore, when the sigmoid function in CPG using RIO model is replaced with the proportion function and the saturated function as shown in Fig. 21, the influence is verified by actual experiment. The proportion function is expressed as $y_i = q_i$. In addition, the saturation function is an approximation of the sigmoid function shown in the blue line in Fig. 22. As a result, the saturation function becomes a green dashed line in the figure and is expressed by the following equation:

$$y_i = \begin{cases} -1 & (q_i < -1) \\ q_i & (-1 \leq q_i \leq 1) \\ 1 & (1 < q_i) \end{cases}$$  \hspace{2cm} (12)

In both transient and steady state responses, the effect of the replacement is verified. The control system using internal information in Fig. 11 is adopted in the experiment. Moreover, the adjustable parameters are constant at $k_1=1$, $k_2=1$, $k_3=0.0943$.

First, Figure 23 shows the transient-state responses of the table position $k_{posx}$ and CPG output $y$, when CPG is started after 40 s. The left side of the figure shows the waveform when the sigmoid function is used. Moreover, the center and the right side show the waveforms when the proportion and the saturation function are used respectively. From the upper part of Fig. 23, the isolated table is floating at the equilibrium position while hitting at the upper and lower mechanical limits of the AVA. $k_{posx}$ of the sigmoid function almost coincides with that of the saturation function. When the proportion function is used, it takes long time to float at the equilibrium position. On the other hand, when the sigmoid and the saturation function are used, CPG output $y$ in the lower part of Fig. 23 is saturated at $\pm 2$ V. This is because CPG using RIO model has “tanh” in the upper and lower paths as shown in Fig. 7. As a result, when the
isolated table is floating, CPG input $u$ becomes a large amplitude signal. By replacing the sigmoid function with the saturation function, its characteristic prevents high gain due to large amplitude operation. Furthermore, it is possible to guarantee the stability of the control loop.

Next, Figure 24 shows the steady-state responses of the supplied air pressure waveform and the table position $k_{pos}x$. From the lower part, there is no difference in the suppression effect even when any function is used. As a result, $u$ becomes a small amplitude signal after the isolated table is stabilized at the equilibrium position. Therefore, the stability of the control loop is not affected by the function to be used.

Finally, when CPG using RIO model is applied to the control system of the AVA, the sigmoid function has the role of saturation to ensure the safety of the device. It plays the same role as hard limiter in industrial field. In addition, when the sigmoid function is replaced with the saturation one, experimental verification shows that both have equivalent characteristic.
6. Conclusions

CPG consisting of RIO model is introduced in order to suppress the vibration caused by the flow disturbance. Considering industrial application, this paper pursues and examines the possibility and the practicality of the disturbance suppression. The conclusions are as follows:

(1) CPG using RIO model was implemented in the control system of the pneumatic AVA. The effectiveness of the proposed method was confirmed by actual experiment. Furthermore, the stable levitation and the disturbance suppression were simultaneously realized by introducing integral output as internal information.

(2) In consideration of industrial application, the suppression performance was improved when the period of the disturbance varies. Specifically, the band-pass filter in CPG using RIO model was redesigned to be broadband. As a result, the vibration caused by the sinusoidal wave disturbance can be suppressed without declining the performance.

(3) The simulated waveforms show that mutual connection in CPG using RIO model is excitatory and the saturation characteristics is caused by the influence of the sigmoid function “tanh”. In addition, when the sigmoid function is replaced with the saturation function, they exhibit the same characteristic at both transient and steady state responses.

References

Bliss, T., Werly, J. and Iwasaki, T., Experimental validation of robust resonance entrainment for CPG-controlled tensegrity structures, IEEE Transactions on Control Systems Technology, Vol.21, No.3 (2013), pp.666-678, DOI:10.1109/TCST.2012.2189400.

Bliss, T., Iwasaki, T. and Bart-Smith, H., Central pattern generator control of a tensegrity swimmer, IEEE/ASME Transactions on Mechatronics, Vol.18, No.2 (2013), pp.586-597, DOI:10.1109/TMECH.2012.2210905.

Butler, H., Position control in lithographic equipment, IEEE Control Systems Magazine, Vol.31, No.5 (2011), pp.28-47.

Friesen, W., Reciprocal inhibition: A mechanism underlying oscillatory animal movements, Neuroscience and Biobehavioral Reviews, Vol.18, No.4 (1994), pp.547-553.

Futakata, Y. and Iwasaki, T., Entrainment of central pattern generators to natural oscillations of collocated mechanical systems, Proceedings of the 47th IEEE Conference on Decision and Control (2008), pp.5220-5225.

Iwasaki, T. and Liu, B., Feedback control with central pattern generator for decentralized coordination of prototype mechanical rectifier, Proceeding of the 2004 American Control Conference (2004), pp.3059-3064.

Iwasaki, T. and Zheng, M., Sensory feedback mechanism underlying entrainment of central pattern generator to mechanical resonance, Biological Cybernetics, Vol.94, No.4 (2006), pp.245-261, DOI:10.1007/s00422-005-0047-3.

Kashiwazaki, S. and Wakui, S., Control for flow disturbance suppression of pneumatic anti-vibration apparatus using asymmetric central pattern generator, Transactions of the JSME (in Japanese), Vol.83, No.854 (2017a), DOI:10.1299/TRANSJSME.17-00189.

Kashiwazaki, S. and Wakui, S., A trial of flow disturbance suppression for pneumatic anti-vibration apparatus using internal information in central pattern generator, Mechanical Engineering Letters, Vol.3 (2017b), DOI:10.1299/mel.17-00346.

Kashiwazaki, S. and Wakui, S., Stable levitation and flow disturbance suppression for pneumatic anti-vibration apparatus using only central pattern generator, IEEJ Transactions on Electronics, Information and Systems, Vol.139, No.4 (2019) (in Japanese).

Kato, T., Kawashima K., Funaki, T., Tadano, K. and Kagawa, T., A new, high precision, quick response pressure regulator for active control of pneumatic vibration isolation tables, Precision Engineering, Vol.34, No.1 (2010), pp.43-48.

Matsuoka, K., Sustained oscillations generated by mutually inhibiting neurons with adaptation, Biological Cybernetics, Vol.52, No.6 (1985), pp.367-376.

Matsuoka, K., Mechanisms of frequency and pattern control in the neural rhythm generators, Biological Cybernetics, Vol.56, No.5-6 (1987), pp.345-353.
Rivin, E. I., Vibration isolation of precision equipment, Precision Engineering, Vol.17, No.1 (1995), pp.41-56.
Shirani, H. and Wakui, S., Control of an isolated table’s fluctuation caused by supplied air pressure using a voice coil motor, Journal of System Design and Dynamics, Vol.4, No.3 (2010), pp.406-415.