1C14

Application of Fitz Hugh oscillator for semi-active control (Filtering of structure response and regulating of variable damper)

Kentaro SHINODA*, Daisuke IBA** and Junichi HONGU*,
Morimasa NAKAMURA** , Ichiro MORIWAKI**

** Kyoto Institute of Technology, Dept. of Mechanical and System Engineering
Gosyokaidou-cho, Matsugasaki Sakyo-ku, Kyoto, 606-8585, Japan
E-mail: iba@kit.ac.jp

Abstract

This study proposes a new semi-active base-isolation system using harmonically varying damping (parametric excitation of damping) and having a filter consisting of the neural oscillators. The harmonically varying damping is the oscillation of the damping coefficient by using a variable damper and can shift the frequency of the damping force by the frequency modulation. The new semi-active vibration control method using this parametric excitation of damping induces interference among structural vibration components by the controlled parametric excitation of damping, and the effect of the interference can reduce the vibration amplitude of structure excited by multiple frequency input. The key technology is extracting the designated frequency components from external input or structural vibration to modulate the frequency of the damping force to an appropriate frequency for the parametric excitation of damping. In this study, we use neural oscillators, called FitzHugh oscillators, as the filter to extract the frequency component, because such nonlinear oscillators have synchronization property with periodic external input in a frequency region close to the natural frequency of the oscillator. We show the special configuration of the neural oscillators for frequency modulation in this paper. The viability of the proposed system is tested in numerical simulation.

Keywords : Semi-active control, Harmonically varying damping, FitzHugh oscillator, Filter, Frequency modulation system

1. Introduction

Reducing seismic damage of civil and architectural structure is a matter of no small importance in Japan, because of the location in the Pacific Ring of Fire. The major countermeasure for structures has been the reinforcement against earthquakes to enhance earthquake safety, however, after the Great Hanshin-Awaji Earthquake, Japan has been having many base-isolation structures over the last two decades, because the isolated structures had no damage. In more recent years, active and semi-active base-isolation structures have been studied, and there are a number of research papers and some constructions have reported in Japan. Especially, the semi-active systems don't have the instability problem, and the number of such structures would be increased by the absence of uncertainty about the safety, if the performance of vibration reduction was improved more.

A semi-active control method for variable dampers, which oscillates the damping coefficient and shifts the frequency of the damping force by the frequency modulation, has been reported (Iba, et al., 2008). This method can induce resonance, even if the external input to structures doesn't have a sinusoidal wave at the natural frequency of structures. Iba and Spencer proposed a new semi-active vibration control method using this parametric excitation of damping (Iba and Spencer, 2008). The new control method induces interference among structural vibration components by the controlled parametric excitation of damping, and the effect of the interference reduces the vibration amplitude of

structure with multiple frequency input, such as feed-forward control. They tried to reduce the response of variable-damper-jointed structures, whose natural frequencies were different, by using the damping parametric excitation. This research derived a theoretical control law for sinusoidal input, and studied the effectiveness of the control method in numerical calculations. Moreover, they have considered expanding in application for seismic wave. They proposed a new filter using the Stuart-Landau equation of nonlinear oscillator, whose limit cycle is a circular motion, to extract frequency components aimed at reducing the amplitude and using for the parametric excitation from the structural response excited by earthquakes (Hirohata and Iba, 2013). However, the vibration reduction performance of the proposed system was not sufficient infrequently due to following error of the filter, when the large variations were observed in the phase of structural response by seismic waves.

On the other hand, nonlinear oscillators, which were models for rhythm generators consisting of neurons, have been studied in biological study (FitzHugh, 1961)(Shik and Orlovsky, 1976). These oscillators are called “neural oscillators”. The neural oscillators have a specific property to synchronize with periodic external input in a certain frequency range (Pikovsky, et. al., 2003). Mathematical models of the neural oscillators were also researched and proposed (Matsuoka, 1985), and some applications of walking robot were reported (Kimura, et. al., 2007). We have been studying a new control system for active mass dampers using the mathematical model of the neural oscillators (Iba and Hongu, 2011), which can follow the vibration behavior of high-rise buildings due to the synchronization characteristic. From these studies, we obtained the knowledge that the neural oscillator had better tracking performance for external input than the Stuart-Landau equation. Furthermore, it would be possible to build a network of neural oscillators by connecting some neural oscillators to create a high performance filter, which has less phase delay in a frequency range, or this system has scalability. However, no study to make use of a single and simple neural oscillator as a filter had been done, and the property of the neural oscillator as a filter is not clear for now.

Therefore, in this study, we develop a new semi-active base-isolation system having the parametric excitation of damping and a filter of the neural oscillator, and carry out a basic study of the utility the new proposed filter consisting of a neural oscillator to extract a required frequency component from the grand input. For this purpose, this paper deals with the effect of simple sinusoidal waves and a single neural oscillator as the filter, but in order to modulate the frequency of the filter output for the parametric excitation of damping, some neural oscillators are configured in parallel and one output of the oscillator is multiplied by the other output.

The semi-active control strategy is described briefly as follows. Firstly, the neural oscillator filter extracts a high frequency component, which is far away from the eigen-frequency of a structure and does not give too much damage to the structure, from the seismic wave. Secondly, the damping coefficient is oscillated at a frequency, whose frequency is the extracting frequency plus the eigen-frequency of the structure, with an appropriate phase. Then, as a result of oscillation of the damping coefficient at the appropriate frequency, the damping force has a newly component at the eigen-frequency and can interfere and suppress the earthquake-excited eigen-frequency component of the structure.

In this paper, we focus on the configuration method of the neural oscillators in the semi-active control system using the parametric excitation of damping as a fundamental study. The proposed semi-active control system has three neural oscillators. One of these oscillators is set to synchronize with a response in a frequency-band, which is close to the natural frequency ω_n ($=\omega_1$) of a structure, and the other oscillator is set to synchronize with a ground motion at a frequency ω_2 , which is far away from the natural frequency of the structure. Then, the one output is multiplied by the other output to multiply the frequency ω_1 by the frequency ω_2 . As a result of the multiplication, the frequency modulation is obtained, and one of the modulated frequencies is $\omega_2 - \omega_1$. The third oscillator is set to synchronize with the modulated frequency $\omega_2 - \omega_1$, and the output of the oscillator is used as the change of damping coefficient for a variable damper. In this paper, we test the viability of the proposed system in numerical simulation. Especially, the synchronization property of the oscillators is very important for the system, therefore, the responses of the oscillators with sinusoidal input are verify in the simulation. In this study, the installed oscillators are a FitzHugh oscillator, which is the most basic model of neural oscillator.

2. FitzHugh oscillator

Nonlinear oscillators can synchronize with periodic external force in a frequency region designated by the natural frequency of the oscillators (Pikovsky, et. al., 2003)(Kuramoto, 2003). In this study, we use the nonlinear oscillator as a filter and modulation mechanism to generate new frequency components by multiplying one output of the oscillator by the other. In this study, a FitzHugh oscillator, which is one of the neural oscillator models, is used as the nonlinear oscillator. The FitzHugh oscillator models firing activity of the nerve cell membrane of squid (FitzHugh, 1961). The dynamic property of the cell membrane excitatory is given by the dimensionless simultaneous ordinary differential equation of two variables as follow.

$$\begin{cases} \dot{u} = c(-bu + v + a) + z \\ \dot{v} = I - v^3 / 3 + v - u \end{cases} \quad (1)$$

Where, u is called as a recovery variable and represents the effect of ion channels of the cell membrane, and v represents the membrane potential of the cell. Constant parameters a, b, c change the oscillation state of the oscillators I is constant input to the cell (FitzHugh, 1961). In this study, the external input z to the FitzHugh oscillator acts on the second equation of equation 1. Figure 1 shows the autonomous vibration state of the FitzHugh oscillator. Table 1 shows the parameters of the oscillator in the simulation.

Fig. 1 The autonomous oscillation of the FitzHugh oscillator. The variables u, v are plotted with the solid (blue) and solid (green) curves, respectively. The horizontal axis is the time, and the vertical line is the dimensionless amplitude.

Table 1 Oscillator's parameters.

Parameters	Value
a	0.7
b	0.8
c	0.08
I	0.4

The FitzHugh oscillator can synchronize with periodic external output whose frequency is close to the natural frequency of the oscillator. Here, the adjustment method of the natural frequency of the oscillator is obtained by reference to our previous study (Shinoda, et. al., 2013).

The state-space representation of the FitzHugh oscillator is obtained as follow.

$$\begin{cases} \dot{x}_{f,n} = A_n x_{f,n} + B_n x_{f,n}^3 + C_n + D_n p_n(t) \\ y_{f,n} = E_n x_{f,n} \end{cases} \quad (2)$$

Where,

$$x_{f,n} = \begin{bmatrix} u_n \\ v_n \end{bmatrix}, A_n = \begin{bmatrix} -b_n c_n & c_n \\ -1 & 1 \end{bmatrix}, B_n = \begin{bmatrix} 0 & 0 \\ 0 & -1/3 \end{bmatrix}, C_n = \begin{bmatrix} a_n c_n \\ I_n \end{bmatrix}, D_n = \begin{bmatrix} 0 \\ \varepsilon_n \end{bmatrix}, E_n = \begin{bmatrix} 0 & 1 \end{bmatrix}$$

In addition, subscript n means the number of the neural oscillators in the proposed system, and $n = 1, 2, 3$ in this paper. ε_n is the input gain to the oscillators. p_n is the external input to the FitzHugh oscillator.

3. Harmonically varying damping (parametric excitation of damping)

In this section, the effect of harmonically varying damping on structural response is explained along with some key simulation results to illustrate the phenomenon.

3.1 base-excited model

In this study, a base-excited single-degree-of-freedom system is considered as shown in Fig. 2. A mass m is supported by a spring k and a variable damper $c(t)$ that are connected in parallel. The terms x and z are the absolute displacements of the mass and base, respectively.

Fig. 2 The single-degree-of-freedom vibration system with a variable damper. This system is the typical vibration isolation model for the semi-active control system via the variable damper, and has the base-input as earthquakes.

The dimensionless equation of motion is as follows.

$$\ddot{x}(t) + 2\zeta(t)\dot{x}(t) + x(t) = 2\zeta(t)\dot{z}(t) + z(t) \quad (3)$$

Here ζ is the damping ratio and is represented as $\zeta(t) = \frac{c(t)}{2\sqrt{mk}}$. The input-related terms are moved to the right-hand side of the equation. The damping ratio $\zeta(t)$ can be controlled by the use of controllable devices such as an MR damper (Spencer *et al.*, 1997; Dyke *et al.*, 1998).

Furthermore, the base displacement z contains two sinusoidal components: z_1 is the disturbance and z_2 is the secondary base excitation. In this case, z is expressed as follow.

$$z(t) = z_1(t) + z_2(t) = Z_1 \sin(\omega_1 t + \gamma_1) + Z_2 \sin(\omega_2 t + \gamma_2) \quad (4)$$

Where, Z_1 and Z_2 are the amplitudes of the input, ω_1 and ω_2 are the frequencies of the input, and γ_1 and γ_2 are the phases of the input.

3.2 Variable damping force

The effect of harmonically varying damping on the response of the single-degree-of-freedom structure represented by equation (3) is explained in this subsection. The parameters of the base-excitation of equation (4) are considered as $Z_1 = 1, \omega_1 = \omega, \gamma_1 = \pi/2$ and $Z_2 = 0$ resulting in the following excitation.

$$z(t) = \cos(\omega t) \quad (5)$$

Then, the controllable damping ratio $\zeta(t)$ is considered to vary harmonically with a frequency ω_ζ , to yield:

$$\zeta(t) = \alpha \cos(\omega_\zeta t + \beta) + \zeta_{DC} \quad (6)$$

where α is the amplitude, β the phase, and ζ_{DC} the DC offset of the damping ratio. The parameters are chosen to meet the constraint $\zeta(t) > 0$.

The damping force on the right-hand side of equation (3) is given as the product of the damping ratio and the input velocity, with the associated damping force becoming:

$$\begin{aligned} f_{damp} &= 2\zeta(t)\dot{z}(t) = -2\{\alpha \cos(\omega_\zeta t + \beta) + \zeta_{DC}\}\omega \sin(\omega t) \\ &= -2\omega\zeta_{DC} \sin(\omega t) - \alpha\omega \sin\{(\omega + \omega_\zeta)t + \beta\} - \alpha\omega \sin\{(\omega - \omega_\zeta)t - \beta\} \end{aligned} \quad (7)$$

where ω_ζ is the frequency of the damping ratio $\zeta(t)$ and ω is the frequency of the velocity $\dot{z}$. From equation (7), the damping force f_{damp} is the sum of three sinusoidal waves with three different frequencies: the input frequency ω and two modulated frequencies $\omega_\zeta - \omega$, $\omega_\zeta + \omega$. Therefore, by adjusting the frequency of the harmonically-varying damping, resonance can be induced even if the frequency of the input z_I is not at the natural frequency of the structure (Iba *et al.*, 2008).

4. Semi-active disturbance cancellation concept

This section explains a proposed method for vibration control using the resonance phenomenon for harmonically varying damping (Iba and Spencer, 2011) that was described in the previous section. First, the expression for the harmonically varying damping controller is developed for the ideal variable damping device.

4.1 Disturbance from the base

From equation (4), the disturbance component on the right-hand side of equation (7) is given by

$$z_1(t) + 2\zeta_{DC}\dot{z}_1(t) = Z_1\sqrt{1 + (2\zeta_{DC}\omega_1)^2} \cos(\omega_1 t + \gamma_1 - \phi) \quad (8)$$

where,

$$\phi = \tan^{-1}\left(\frac{1}{2\zeta_{DC}\omega_1}\right) \quad (9)$$

4.2 Controllable damping force through variable damping and secondary base-input

In this section, the controllable damping force generated by harmonically varying damping combined with a secondary base excitation z_2 is considered. The velocity corresponding to z_2 is

$$\dot{z}_2(t) = Z_2\omega_2 \cos(\omega_2 t + \gamma_2) \quad (10)$$

Similar to equation (7), the harmonically varying damping force is obtained as

$$\begin{aligned}
 2\zeta(t)\dot{z}_2(t) &= 2\left\{\alpha \cos(\omega_\zeta t + \beta) + \zeta_{DC}\right\} Z_2 \omega_2 \cos(\omega_2 t + \gamma_2) \\
 &= -2Z_2 \omega_2 \zeta_{DC} \cos(\omega_2 t + \gamma_2) + Z_2 \alpha \omega_2 \cos\{(\omega_2 - \omega_\zeta)t + \gamma_2 - \beta\} + Z_2 \alpha \omega_2 \cos\{(\omega_2 + \omega_\zeta)t + \gamma_2 + \beta\}
 \end{aligned}
 \quad (11)$$

Where, the second term is extracted from the equation as follows.

$$u(t) = Z_2 \alpha \omega_2 \cos\{(\omega_2 - \omega_\zeta)t + \gamma_2 - \beta\} \quad (12)$$

In this study, the extracted damping force (12) is considered as the available control force. The third term of the equation (11) is also a candidate for the control force; however, both modulated damping forces cannot be specified simultaneously as the control force.

4.3 Condition for cancellation of input effect

To cancel the response due to the base-input component of the excitation given by (8) (i.e., the disturbance $z_f(t)$) using the control force given in equation (12), the following two condition are required: (i) matching both amplitudes and (ii) ensuring that the phases are 180° apart. The following equations are required for achieving the amplitude and phase conditions, respectively.

$$Z_2 \alpha \omega_2 = Z_1 \sqrt{1 + (2\zeta_{DC} \omega_1)^2} \quad (13)$$

$$(\omega_2 - \omega_\zeta)t + \gamma_2 - \beta \pm \pi = \omega_1 t + \gamma_1 - \phi \quad (14)$$

For these conditions to be satisfied, the amplitude and phase of the harmonically varying damping can be determined as follows

$$\alpha = \frac{Z_1 \sqrt{1 + (2\zeta_{DC} \omega_1)^2}}{Z_2 \omega_2} \quad (15)$$

$$\omega_\zeta t + \beta = (\omega_2 t + \gamma_2) - (\omega_1 t + \gamma_1) + \phi \mp \pi \quad (16)$$

From equation (16), $\omega_\zeta = \omega_2 - \omega_1$, $\beta = \gamma_2 - \gamma_1 + \phi \mp \pi$.

In addition, because the damping ratio is positive, the following restriction must be satisfied

$$0 \leq \alpha \leq \zeta_{DC} \quad (17)$$

where, $\zeta_{DC} = \frac{\zeta_{\max}}{2}$, and $\zeta_{\max}$ is the maximum realizable damping ratio of the system.

5. Semi-active control using damping parametric excitation and neural oscillators.

This section shows the proposed new semi-active base-isolation system having the parametric excitation of damping and a filter of the neural oscillator. The semi-active control strategy is that, firstly, the neural oscillator filter extracts a high frequency component, which is far away from the eigen-frequency of a structure, from the base input. Secondly, the damping coefficient is oscillated at a frequency, whose frequency is the extracting frequency plus the eigen-frequency of the structure. Then, as a result of oscillation of the damping coefficient, the damping forces have a newly component at the eigen-frequency and can interfere and suppress the earthquake-excited eigen-frequency component of the structure.

5.1 System configuration

The configuration method of the neural oscillators in the semi-active control system using the parametric excitation of damping is explained. As mentioned above, the damping coefficient is oscillated at a high frequency to modulate the external input including high frequency components, which is far away from the eigen-frequency of structure. Extracting the high frequency component in the external input and oscillating the damping coefficient at the extracted frequency plus the eigen-frequency of the structure, the neural oscillators are introduced to the system. We use three neural oscillators in the proposed semi-active system. One of these oscillators is set to synchronize with a response in a frequency-band, which is close to the natural frequency ω ($=\omega_1$) of a structure, and the other oscillator is set to synchronize with a ground motion at a frequency ω_2 , which is far away from the natural frequency of the structure. Then, the one output is multiplied by the other output to multiply the frequency ω_1 by the frequency ω_2 . As a result of the multiplication, the frequency modulation is obtained, and one of the modulated frequencies is $\omega_2 - \omega_1$. The third oscillator is set to synchronize with the modulated frequency $\omega_2 - \omega_1$, and the output of the oscillator is used as the change of damping coefficient for the variable damper. The schematic block diagram of the neural oscillator configuration is shown in Fig. 3.

Fig. 3 The schematic block diagram of the neural oscillator configuration. To oscillate the variable damping coefficient at an appropriate frequency for frequency modulation, two neural oscillators extract respective frequency components, in this case, the eigen-frequency and a high frequency, from the input. To modulate the extract frequency, the one output from the neural oscillator is multiplied by the other output. The output has many frequencies due to the modulation, therefore, the third oscillator is set to synchronize with the one modulated frequency $\omega_2 - \omega_1$.

Again, the state-space representation of the FitzHugh oscillator is shown, here.

$$\begin{cases} \dot{x}_{f,n} = A_n x_{f,n} + B_n x_{f,n}^3 + C_n + D_n p_n(t) \\ y_{f,n} = E_n x_{f,n} \end{cases} \quad (18)$$

According to the oscillator configuration in Fig. 3, three FitzHugh oscillators are designed to synchronize with the frequency ω_1 , ω_2 , $\omega_2 - \omega_1$, respectively. Neuron 1 and 2 has the base-displacement input; $p_1(t) = p_2(t) = z(t)$. Neuron 3 has the modulated components as input and synchronize with the one modulated component $\omega_2 - \omega_1$, or $p_3(t) = y_{f,1} \cdot y_{f,2}$ in equation (18). In this paper, the output of the Neuron 3 $y_{f,3}(t)$ is used as the parametric excitation of damping as follow.

$$\zeta(t) = \alpha_f y_{f,3}(t - L) + \zeta_{DC} \quad (19)$$

where, α_f is the gain for the damping, L is the delay time expressed by $L = -\beta/\omega_\zeta$.

5.2 Simulation results of synchronization and modulation by the proposed neural oscillator system.

In this subsection, the viability of the proposed system is tested in numerical simulation. In the numerical simulation, we use the Runge-Kutta method, and the step time is 0.001s. Table 2 shows the parameters of the designed FitzHugh oscillators to synchronize with the sine waves, and Table 3 is the specification of the control object. Moreover, the specification of the dual frequency base input is shown in Table 4. The gain for the damping is set to $\alpha_f = 0.08$. The initial values of the oscillators are $x_{f0,1} = x_{f0,2} = x_{f0,3} = [100 \ 0]^T$.

Table 2 Oscillators' parameters.

Parameters	Value		
	$n=1$	$n=2$	$n=3$
a_n	0.95	0.95	0.95
b_n	0.01	0.01	0.01
c_n	1.103	36.3	25.2
I_n	95	95	95
ε_n	1	1	1

Table 3 Structure's parameters.

Parameters	Value
ω (rad/s)	1
ζ_{DC}	0.25

Table 4 Specification of the base input.

Parameters	Value
Z_1	1
ω_1 (rad/s)	1
γ_1 (rad)	0
Z_2	1
ω_2 (rad/s)	6
γ_2 (rad)	0

Figure 4 shows the time history of the input displacement. We can see two frequency in the base-input, one frequency is the eigen-frequency of the structure, and the other is the higher than the eigen-frequency.

Fig. 4 The dual-frequency base-input to the structure. One of the frequencies is identical to the eigen-frequency of the structure, and the other is higher than the eigen-frequency.

Fig. 5 The output of the neural oscillators synchronizing with the dual-frequency input. (a) This oscillator is for frequency 1, which is identical to the eigen-frequency of the structure and induces resonance. (b) This oscillator is synchronizing with frequency 6, which is higher than the eigen-frequency of the structure and have little or no effect on the structure.

Figure 5 shows the output of the neural oscillators, which have the dual-frequency input. Figure (a) shows the output of the Neuron 1 synchronizing with frequency 1, which is identical to the eigen-frequency of the structure. Figure (b) shows the output of the Neuron 2 synchronizing with frequency 6. As can be seen, the both output consists principally of the single frequency, it is found that the neural oscillators have the function as filter. In this study, the higher frequency component is used to reduce the amplitude of the resonating structure by modulating the frequency using the parametric excitation of damping.

Figure 6 shows the modulation results using oscillator output. (a) shows the product of output from Neuron 1 and 2. The frequency components of the product includes mainly two frequencies 5 and 7 as shown in Fig. 7(a). As can be seen, however, Fig (b), which is the output of Neuron 3, has mainly the single frequency 7 as shown in Fig. 7(b), because of the filter function of Neuron 3.

Fig. 6 The input-output of Neuron 3. Figure (a) is the input, which is the product of the output from Neuron 1 and 2. And figure (b) is the output of Neuron 3. The input is more complex than the output, because of the frequency modulation. The output data is filtered by Neuron 3.

Fig. 7 The results of Fast Fourier Transformation of the input-output of Neuron 3. The input has mainly two frequencies 5 and 7, and the output consists principally of the single frequency 5, because of the filter effect of the neural oscillator. The peak at frequency 7 of the output is about 80% down.

Fig. 8 The variable damping ratio and damping force generated by the variable damper. The frequency component of the damping ratio is the same as the output of Neuron 3, which is mainly frequency 5. Because one of the input frequencies is 6, then, the frequency of resulting frequency modulation is 1, which is identical to the eigen-frequency of the structure.

Figure 8(a) shows the variable damping ratio controlled by the output of the Neuron 3. The damping ratio is greater than equal 0, so the DC offset is given to the ratio. The DC offset is the 0.25, which is the same as the damping ratio of the passive system. Obviously, the main frequency of the damping ratio is 5. Figure 8(b) shows the damping force generated by the variable damper.

Figure 9 shows the displacement responses of the structure with and without the proposed semi-active control. As can be seen, the amplitude of the controlled response is smaller than the amplitude of the passive system. The frequency modulated damping force has the same frequency component of the eigen-frequency of the system, the interaction between the components is occurred. In the case of the comparison of the maximum amplitude of the semi-active system with that of the passive system, the cancellation effect is 79.8% down as shown in Fig. 10.

Fig. 9 Dimensionless displacement amplitude of the structure with or without the semi-active system. The blue solid line is the response of the passive system for comparison. The green solid line shows the response of the semi-active controlled system. The amplitude of the response is gradually reduced.

Fig. 10 Comparison of the maximum amplitude. In the bar figure, the left side bar is the input amplitude of dual frequency, the middle is the amplitude of the passive system, and the right one is the amplitude of the proposed semi-active control system. The amplitude of the semi-active system is down to 79.8% in the simulation.

5. Conclusion

We proposed a new semi-active base-isolation system using harmonically varying damping and having a filter of the FitzHugh oscillators. Especially, extracting the specify frequency component from complex wave is the core technology of the system. In this paper, we used FitzHugh oscillators as a filter to extract the frequency component, because such nonlinear oscillators have synchronization property with periodic external input in a frequency region close to the natural frequency of the oscillator. We showed the special configuration of the neural oscillators for frequency modulation using harmonically varying damping. The viability of the proposed system was tested in numerical simulation. As a result of the simulation, it was found that the proposed system could extract the designated frequency for the frequency modulation from the input wave, and reduce the amplitude of the single-degree-of-freedom structure with a variable damper using harmonically varying damping method.

Acknowledgement

The authors gratefully acknowledge the support by the Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Scientific Research (C), 24560260.

References

- FitzHugh, R., Impulses and physiological states in theoretical models of nerve membrane, *Biophysical Journal*, Vol. 1, (1961), pp.445-466.
- Hirohata, S and Iba, D, Semi-Active Vibration Control with Harmonically Varying Damping (Application to Serial TDOF system and Filtering using the Stuart-Landau Equation), *Proc. SPIE 8692, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2013*, (2013), 869244, pp.1-11.
- Iba, D., A. Masuda and A. Sone, Resonance by parametric excitation of variable damping, *Journal of System Design and Dynamics*, Vol.2, No.1, (2008), pp.331-341.
- Iba, D. and Spencer JR., B. F., Vibration control using harmonically-varying damping, *Journal of System Design and Dynamics*, Vol. 5, No. 5, (2011), pp.727-736.
- Iba, D. and Hongu, J., Structural vibration control by tuned mass damper using central pattern generator, *Proc. SPIE 7981, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2011*, 79814Q (April 18, 2011); doi:10.1117/12.880406.
- Kimura, H., Fukuoka, Y., and Cohen, A., H., Biologically inspired adaptive walking of a quadruped robot, *Philosophical Trans. of Royal Society in London*, Vol.365 (2007), No.1850, pp.153-170.
- Kuramoto, Y., *Chemical Oscillations, Waves, and Turbulence*. Dover Books on Chemistry Series Dover Publications, (2003).
- Matsuoka, K., Sustained oscillations generated by mutually inhibiting neurons with adaptation, *Biological Cybernetics* 52 (1985), pp. 367–376.
- Pikovsky, A., Rosenblum, M., Kurths, J., *Synchronization (A universal concept in nonlinear sciences)*, Cambridge University Press, (2003).
- Shik, M. L. and Orlovsky, G. N., Neurophysiology of locomotor automatism, *Physiol. Rev.*, 56 (1976) , pp. 465-501.
- Shinoda, K., Iba, D., Hongu, J., Nakamura, M. and Moriwaki, I., Filter Characteristics of FitzHugh Oscillator for Semi-Active Vibration Control, *Proceedings of Motion and Vibration Control (MOVIC) conference 2013*, (2013), pp. 1-9. (in Japanese)