Synchronization of structure and neural oscillator for active mass damper

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SUMMARY:
This paper proposes a new control method for active mass dampers using Central Pattern Generators. The active mass dampers have been applied to structural vibration control of high-rise buildings, bridges and so on. Generally, the mass must oscillate in an appropriate phase in relation to the control object within the limited strokes. On the other hand, on walking of animate beings like mammals, both side feet have an appropriate phase relation. In biological study, the Central Pattern Generators in bodies playing a significant role in the walking have been learned over the last few decades. Moreover, mathematical models of the pattern generators have been proposed, and some researchers have been studying to realize walking of biped-robots using the generators embedded in a computer. In this study, the algorithm is installed into a controller for the active mass damper; furthermore, validation of the controller is performed by numerical simulation.

Keywords: Active mass damper, Central Pattern Generators, Vibration mitigation

1. INTRODUCTION

This paper proposes a new control method for an Active Mass Damper (called AMD for short) using a Central Pattern Generator (CPG) and seeks to evaluate synchronization between a structure and a neural oscillator consisting the CPG. The AMD has been studied with the rapid advancement of computer, in order to reduce the structural vibration of high-rise buildings, long span bridges and so on. In this case, the mass of the AMD might be moved as an appropriate phase in relation to the control object. However, the AMDs controlled by the ordinary linear control theories are valid for only relatively small input like winds or small earthquakes. In the case of large earthquakes happened, the AMD has to be shut down, because the mass of AMD has a stroke restriction due to the limited space. Moreover, the robust performance of the designed controller is of concern when the parameters of the control object changes as a result of being damaged by large earthquakes. To solve the problems, there have been considerable researches on controllers based on the linear control theory and having various functions. As a result of the research, the revised controllers gave better results than that of the ordinary controllers, but the modifications have not been drastic improvements, because of the linearity methods.

On the other hand, some very intriguing studies about biological locomotion, or walking movement have been reported. In the walking of animate beings like mammals or insects, a pair of both side feet has appropriate phase relation. Moreover, it is possible to keep moving on irregular ground. That is, algorithms for the walking would be embedded into the animate beings to control the complicated bodies with ease and robustness. In the biological study, the CPGs in bodies playing a significant role in the walking have been learned over the last few decades (Shik et al., 1976) (Grillner, 1981). Especially, a study about neurophysiology of locomotor automatism by Shik and Orlovsky (Shik et al., 1976) gave us a very interesting result of the generator. The study revealed that a decerebrate animate being could walk on a treadmill by steady electrical stimulation to the midbrain region.

Furthermore, mathematical models of the CPGs of the animate beings have been studied. Matsuoka found that a system consisted by theoretical neuron models could generate steady oscillation (Matsuoka, 1985 and 1987). The study has been inspiring studies of walking robots. Researchers who were interested in locomotive robots have studied to realize walking controllers using the pattern generators (Taga et al., 1991 and 1995) (Hase et al., 1999). Kimura et al. embedded the generator to a quadrupedal locomotion robot and developed the control system, which could walk on the irregular ground without detail data of the ground surface (Fukuoka et al., 2003) (Kimura et al., 2007). The most intriguing characteristic of the CPGs is to harmonize with the input and expressed by the neural oscillator composing the CPGs. Because the oscillator has nonlinear and entrainment properties, the CPGs can generate walking rhythm patterns in response to environment changes.

In this study, the algorithm generating the walking is tried to install into the AMD system. Using the neural oscillator model of first order lag proposed by Matsuoka, a new controller for the AMD is developed. Generally, in the case of vibration mitigation using the AMD, a special phase relation exists between the mass of AMD and the mass of structure. In this paper, the phase relation is analyzed for application of the appropriate control, and a phase controller, which keeps the relation like a biped-walking robot has the relation between the right and left feet, is developed using the CPGs for the AMD. Furthermore, the validation of the controller is performed by numerical simulation.

On the other hand, in order to be tuned into practical application, the controller will have to be analysed in relation to the reliability and robustness along with the vibration mitigation performance. However, there has been no study to evaluate the above-mentioned properties the controller has. Recently, methods, which evaluate synchronization of nonlinear oscillators generated by mutual entrainment, have been proposed. In this paper, a phase reduction theory, which is one of the analysis methods, is also tried to appraise the synchronization between the structure and the CPGs. In this paper, the synchronization between the target structure and the single neural oscillator constituting the CPGs is firstly required to investigate and the synchronization region is expressed using phase response curves.

2. VIBRATION MODEL

In this study, a single-degree-of-freedom structure with an AMD is considered. The structure mass m_S is supported by a spring k_S and a damper c_S, which are connected in parallel. Moreover, x_S and x_A are the absolute displacement of the structure mass and the relative displacement of the auxiliary mass of the AMD, respectively. The mass m_A of the AMD on the top of the structure is driven by an actuator, which generates control force u. The equation of motion of the vibration model is obtained as follow.

$$\begin{aligned} m_S\ddot{x}_S + c_S\dot{x}_S - c_A\dot{x}_A + k_Sx_S - k_Ax_A &= u \\ m_A\ddot{x}_A + c_A\dot{x}_A + k_Ax_A &= -u \end{aligned} \tag{1}$$

3. CENTRAL PATTERN GENERATOR

Central pattern generators are neural circuits that generate periodic commands for rhythmic movements such as locomotion. The mathematical models of the pattern generator of the animate beings have been also studied. Matsuoka found that a system consisted by theoretical neuron models, which are expressed by a pair of first order lag elements, could generate steady oscillation (Matsuoka, 1985 and 1987). In this paper, a new control system for the active mass damper is constructed by using the CPG model proposed by Matsuoka. In this section, the formulation of the CPG model is expressed, and the behaviour and feature are generally stated. First of all, a neural oscillator, which composes the CPG, and a neuron model composing the oscillator are explained.

3.1. Neuron with adaptation

The neural oscillator proposed by Matsuoka is a mitigation type oscillator (Matsuoka, 1985 and 1987), which is composed by mutual inhibition connecting between some neurons with adaptation, or the output increases rapidly at first and then gradually decreases to a lower level, and is expressed as the following equations.

$$\left.\begin{aligned} \tau\dot{x} + x = s - bx' \\ T\dot{x}' + x' = y_N \\ y_N = \max(0, x) \end{aligned}\right\} \tag{2}$$

where, x is a membrane potential of the neuron, x' is the variable that represents the degree of the adaptation of the neuron, s is the steady input to the neuron, y_N is the output valuable of the neuron, τ and T are time constants and b is the parameters that specify the time course of the adaptation. To be sustained oscillation, the condition for the parameters is

$$(T - \tau)^2 \geq 4T\tau b \tag{3}$$

3.2. Neural oscillator

Taking account for connection between the two neurons of the equation (2), a neural oscillator is obtained as follows.

$$\left.\begin{aligned} \tau\dot{x}_{(e,f)} + x_{(e,f)} = ax_{(f,e)} + s - bx'_{(e,f)} \\ T\dot{x}'_{(e,f)} + x'_{(e,f)} = y_{(e,f)} \\ y_{(e,f)} = \max(0, x_{(e,f)}) \end{aligned}\right\} \tag{4}$$

where a is a weighting function for the connection between the neurons. The index e represents an extensor neuron and f is a flexor neuron. The required condition of the parameter to sustain the oscillation is

$$1 + \frac{\tau}{T} < a < 1 + b \tag{5}$$

In addition, the output of the neural oscillator is obtained as the following equation.

$$y = y_e - y_f \tag{6}$$

3.3. Forming of CPG

The CPG in this study is constructed from a connection of the two neural oscillators. Taking account for the mutual entrainment of the pair, the equations (4) and (6) are obtained as the following equations.

$$\left.\begin{aligned} \tau\dot{x}_{(e,f)i} + x_{(e,f)i} = ax_{(f,e)i} + s - bx'_{(e,f)i} + \textstyle\sum_{j=1}^{n} w_{ij} y_{(e,f)j} \\ T\dot{x}'_{(e,f)i} + x'_{(e,f)i} = y_{(e,f)i} \\ y_{(e,f)i} = \max(0, x_{(e,f)i}) \\ y_i = y_{ei} - y_{fi} \end{aligned}\right\} \tag{7}$$

where, w_{ij} is a coefficient for the connection from the output of j-th neuron to the input of i-th neuron, and $n = 2$. Especially, $w_{12} = w_{21} > 0$ give a mutual entrainment in the same phase, and $w_{12} = w_{21} < 0$ give a mutual entrainment in the anti-phase. In this study, the latter is used for the CPG model.

4. AMD CONTROLLER

Referring to control methods of legged locomotion on the basis of neurophysiological knowledge, a new control method for the active mass damper is proposed in this paper. Taga et al. have studied a self-organized system of bipedal locomotion by neural oscillators, which interplayed among the body and environments (Taga et al., 1991 and 1995). The studies showed that the controller composed of mutual connected neural oscillators which had the information of the each leg was able to generate two anti-phased output and give the alternately vibratile motion to the legs. In the system, the rhythm of the neural oscillators and legs, which were affected by the external environments changed, and the all frequencies was going to be synchronized with the relation remaining the anti-phase condition. The phenomenon was called as global entrainment. Fukuoka et al. have studied a quadrupedal robot, which had the legs site-controlled using PD controllers and CPGs, which output applicable rhythms for the controllers, and realized robust quadrupedal locomotion in unpredictable environments (Fukuoka et al., 2003) (Kimura et al., 2007).

On the other hand, for mitigation of structural vibration using the AMD, the mass of AMD have to keep an appropriate phase toward the mass of the structure as the biped robot has the relation between the right and left legs in the locomotion. From the standpoint, it would be possible to apply the CPGs to the phase control of the AMD. Furthermore, if the position of the AMD's mass is controlled according to the output of the CPG, the structural control will be possible to be within the stroke limit the mass has. Then, in this section, firstly, the desired phase relation between the main system and the AMD is clarified from the viewpoint of energy, then, a CPG structure is proposed to generate the phase relation by using the output information from the structure and the AMD, and, finally, a PD controller which uses the output from the CPG for the position of the AMD's mass is explained. However, in this paper, only sinusoidal input is considered as the external disturbance for simplicity.

4.1. CPG part of controller

Giving an appropriate phase relation between the mass of the structure and the AMD is greatly important for mitigation of the structural vibration. In this subsection, the relevant phase relation is clarified from the viewpoint of energy; furthermore, a connection method among the CPG, structure and AMD is proposed for creation of the phase relation.

Adding an external force p to the right side of the equation of motion (1), substituting the second equation into the equation and eliminating the term of control force p give the follow.

$$(m_s + m_A)\ddot{x}_s + c_s\dot{x}_s + k_s x_s = p - m_A\ddot{x}_A \tag{8}$$

Multiplying the equation by the velocity of the structure and integrating as a function of time yields

$$\frac{1}{2}(m_s + m_A)\dot{x}_s^2 + \frac{1}{2}k_s x_s^2 = \int p\,\dot{x}_s dt - c_s \int \dot{x}_s^2\,dt - m_A \int \ddot{x}_A\,\dot{x}_s dt \tag{9}$$

The controllable variable by the control force is the relative acceleration of the active mass damper in this equation. Because the third term on the right is multiplying the variable by the absolute velocity of the main system, the term is going to be always negative, or dissipation energy, if the phase between the velocity and the acceleration is identical. Alternatively, the velocity of the main system is out of phase with the relative displacement of the AMD. Thus, connecting the velocity of the main system and the relative displacement of the AMD to the CPG which has the mutual and forcing entrainment properties as equation (10) gives the CPG part which generates the anti-phase relation and harmonizes to the motion of the main system and the AMD.

$$\tau\dot{x}_{(e,f)i} + x_{(e,f)i} = a x_{(f,e)i} + s - b{x'}_{(e,f)i} + \sum_{j=1}^{n} w_{ij} y_{(e,f)j} + Feed_i \tag{10}$$

$Feed_i$ is feedback term from the absolute velocity of the main system and the relative displacement of the AMD with a gain, and is obtained as the follow, respectively.

$$\left.\begin{aligned} Feed_1 &= k_1 x_A \\ Feed_2 &= k_2 \dot{x}_s \end{aligned}\right\} \tag{11}$$

4.2. Positional control of AMD mass

In this paper, position control applies to the mass of the AMD. In general, the mass of the AMD is confined to move in the space on the top of the structure. The AMD is required to be within the limitation and have the ability to control the response of the structure due to not only small but also large earthquakes. It would be possible to avoid the stroke limit problem if the positional control of the mass of the AMD is employed. Thus, proportional control, which follows desired step values of the mass, is adapted to control the position of the mass in this study. Furthermore, a method, which provides the desired displacement values in synchronized timing based on the suitable phase information from the CPG, is proposed by reference to Kimura et al. (Fukuoka et al., 2003) (Kimura et al., 2007).

If the positional control of the AMD, which has the phase relation explained in the previous subsection, is possible, energy dissipation can be accomplished. To actualize the effectual phase state, the three desired values are considered in synchronized timing of the output y_1 of the CPG; (1) Positive desired value, (2) Negative desired value, (3) Origin point. These values are measured from the reference axis attached to the main system. For the positional control of the mass, proportional control is used as shown in Table 1. Furthermore, to be resistant to rapid change, the controller is embedded an imaginary damper achieved by derivative control. The D control is also switched according to the output y_1 of the CPG as shown in Table 1, also. The damper by the D control is practical only when the desired values of the P control are the minimum and maximum. These control parameters are defined by trial and error. Figure 1 shows the diagram of the proposed controller.

Table 1. PD controller

	Desired value (m)	P-gain
(1) $y_1>0$	X_A	
(2) $y_1=0$	0	K_P
(3) $y_1<0$	$-X_A$	

	Desired value (m/s)	D-gain
(1) $y_1>0$	0	K_D
(2) $y_1=0$	None	0
(3) $y_1<0$	0	K_D

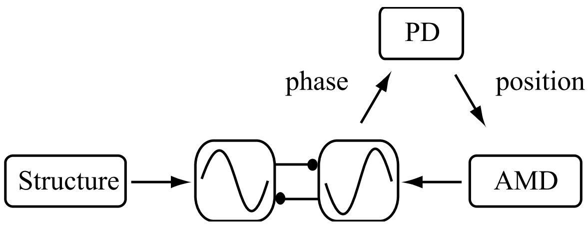

Fig. 1. Proposed controller model for AMD

4.3. Derivation of desired displacement value

The desired displacement value for the mass of the AMD is derived here. For simplicity, assumptions are that the external disturbance acting on the main mass can be measured and the dissipation energy of the damper attached to the main system is very small and can be eliminated. Moreover, the disturbance is assumed as steady vibration. From the energy balance equation (9), the work done on the system by the disturbance is

$$W = \int p\dot{x}_S \, dt \tag{12}$$

To dissipate the energy provided by the disturbance, the term relative to the AMD has to have the following relation.

$$m_A \int \ddot{x}_A \dot{x}_S = \int p\dot{x}_S \, dt \tag{13}$$

Where, the steady vibration of the disturbance is expressed as follow.

$$p = P\sin(\omega t) \quad (14)$$

Furthermore, the AMD is assumed as having the following relative displacement.

$$x_A = -X_A \sin(\omega t) \quad (15)$$

Where X_A is the amplitude of the AMD's displacement. From equation (13), the ideal amplitude of the AMD is obtained as follow.

$$X_A = \frac{F}{m_A \omega^2} \quad (16)$$

5. NUMERICAL SIMULATION OF VIBRATION MITIGATION

The control performance of the proposed controller and the output of the CPG are verified by numerical simulation. The parameters used in the simulation are shown in Tables 2 and 3.

Table 2. Specification of control object CPG

Name	Parameters	Value
Structure's mass	m_S (kg)	1
Structure's spring	k_S (N/m)	1
Structure's damper	c_S (Ns/m)	0.04
AMD's mass	m_A (kg)	0.05
AMD's spring	k_A (N/m)	4.54×10^{-3}
AMD's damper	c_A (Ns/m)	1.216×10^{-3}

Name	Parameters	Value
Constant input	s	1.634×10^{-3}
Time constant	τ	0.212
Time constant	T	2.54
Fatigue coefficient	b	2.54
Connection weight of Neurons	a	2.52
Connection weight of Oscillators	w	1
Feedback gain	k_1	0.4
Feedback gain	k_2	1

Table 3. Parameters of positional control and external disturbance

Name	Parameters	Value
P-gain	K_P (N/s)	0.055
D-gain(imaginary damper)	K_D (Ns/m)	0.02

Name	Parameters	Value
External force's amplitude	F (N)	1
External force's frequency	ω (rad/s)	1

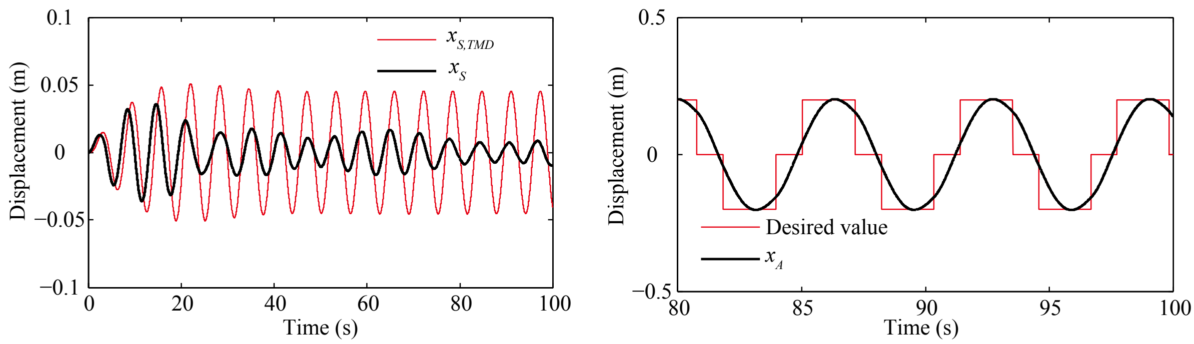

Fig. 2. Comparison of the output responses (left side) and responses of the mass of AMD (right side)

Figure 2 shows the output response of the structure, which has the sinusoidal input acting on the mass of the main system. The specifications of the disturbance are shown in Table 3, also. In comparison with the output of the passive tuned mass damper, the maximum output with the control is clearly smaller than that of the passive system. The right side of Fig. 2 compares the relative displacement of the AMD mass with the desired value. As can be seen, the displacement is like sinusoidal wave due to the proposed switching controller, even though the desired value is not like that wave. The ideal path of the AMD is the sinusoidal path with the limited stroke and out of phase with the velocity of the main system, but not completely realized yet.

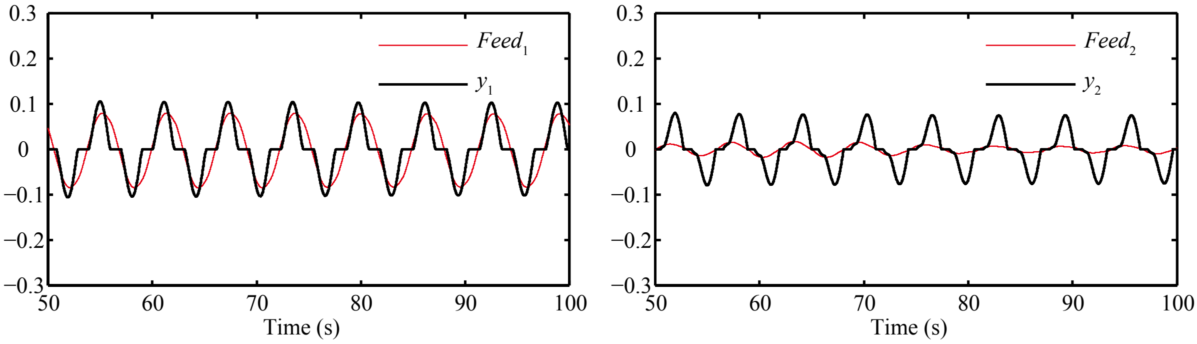

Fig. 3. Input ($Feed_i$) and output (y_i) of the neural oscillator

Figure 3 shows the output y_2 and input $Feed_2$ of the CPG. From the resulting output y_2, it turns out that the neural oscillator is synchronized to the other oscillator due to mutual inhibition connecting.

6. EVALUATION METHOD OF SYNCHRONIZATION REGION

The CPG embedded in the proposed controller consists of the pair of neural oscillators, and the neural oscillator is the key component of the control system. Thus, to obtain the detail characteristics of the neural oscillator is required. A method, called phase reduction method, is one of the theoretical techniques for studying oscillator's dynamics and has been widely and successfully applied to a wide variety of oscillators (Brown et al., 2004) (Pikovsky et al., 2001) (Kuramoto, 2003). A phase equation plays a critical role in the phase reduction methods. Therefore, first of all, the phase equation corresponding to the neural oscillator embedded in our controller is introduced in this section. After developing the expression for the phase, the phase response function, the phase sensitivity function, and the phase coupling function are introduced in series.

6.1. Introduction of phase equation

The state-space expression of the nonlinear oscillator in Eq. (2) is generally expressed as follow.

$$\dot{X}(t) = F(X) \tag{17}$$

To analyse the characteristics of the synchronization of the neural oscillator, a phase equation is introduced, here. The phase is a map to a scalar function $\theta(0\sim 2\pi)$ from the state vector X of the oscillator. The limit cycle of the oscillator can be illustrated as the phase, which has a constant increasing parameter, $d\theta/dt = \omega$. After this operation, the phase equation can be obtained from the Eq. (17).

$$\dot{\theta}\big(X(t)\big) = \mathrm{grad}_X\theta(X)\cdot\dot{X}(t) = \mathrm{grad}_X\theta(X)\cdot F(X) \tag{18}$$

Where, $\mathrm{grad}_X\theta(X)$ express the gradient of the phase.

$$\mathrm{grad}_X\theta(X) = \begin{bmatrix}\partial\theta/\partial x_e & \partial\theta/\partial x_f & \partial\theta/\partial x_e' & \partial\theta/\partial x_f'\end{bmatrix} \tag{19}$$

On the limit cycle and its domain of attraction, $\mathrm{grad}_X\theta(X)\cdot F(X) = \omega$ must be satisfied. Figure 4 shows the introduced phase θ to the Matsuoka's neural oscillator.

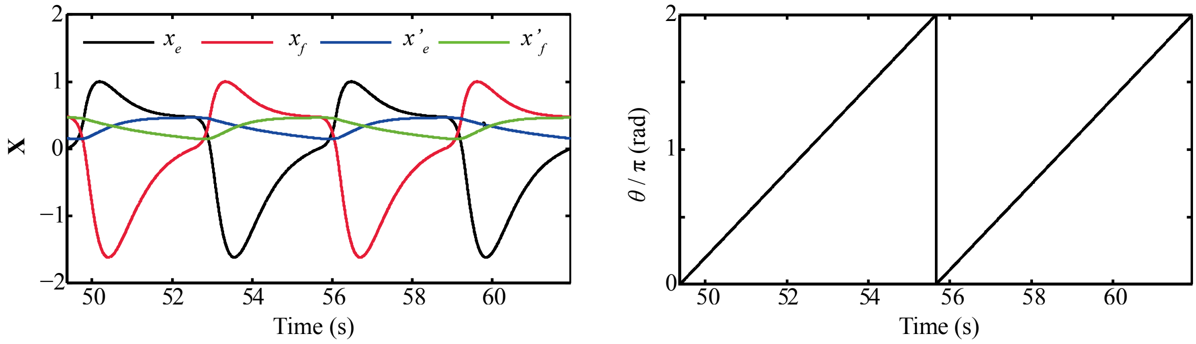

Fig. 4. Time histories of state variables and introduced phase θ (ω=1 rad/s)

6.2. Phase response function and phase sensitivity function

Next, a phase response function of the oscillator is developed. The function illustrates the effect by impulse input I on the phase equation and obtained as follow.

$$g(\theta; I) = \theta(X_0 + I) - \theta = \mathrm{grad}_X \theta(X)\big|_{X=X_0(\theta)} \cdot I = Z(\theta) \cdot I \tag{20}$$

where, $g(\theta; I)$ is the change in θ resulting from the perturbation $X \to X_0(\theta) + I$ from the base point $X_0(\theta)$ on the limit cycle. In addition, $Z(\theta) = \mathrm{grad}_X \theta(X)\big|_{X=X_0(\theta)}$ is called as a phase sensitivity function. Assume that $\dot{\theta}(t) = \omega$ everywhere in the neighbourhood of limit cycle, the phase difference $g(\theta; I)$ is kept. Thus, the function can be obtained in the limit as $t \to \infty$, when the perturbed trajectory has collapsed back to the limit cycle[11]. The following function (Eq. (21)) is used as the perturbation. Where $\varepsilon_p = 10,\ \sigma = 0.001$s.

$$q(t) = \begin{cases} \varepsilon_p, & t_p \le t \le t_p + \sigma \\ 0, & \text{otherwise} \end{cases} \tag{21}$$

The derived phase response and sensitivity functions of the Matsuoka's neural oscillator are shown in Fig. 5.

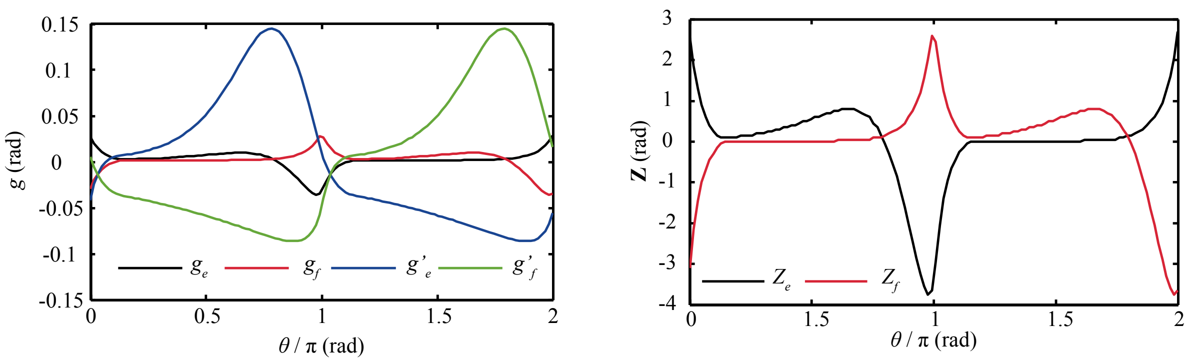

Fig. 5. Phase response functions (left) and phase sensitivity functions (right).

6.3. Phase coupling function

At last, the phase coupling function of the oscillator is developed, here. When the oscillator is subjected to an external periodic signal $p(X, t)$, Eq. (17) becomes

$$\dot{X}(t) = F(X) + \varepsilon p(X, t) \tag{22}$$

Assume that the amplitude ε is sufficiently small. Then, the phase function can be obtained as follow.

$$\dot{\theta}(t) = \omega + \varepsilon Z(\theta) \cdot p(\theta, t) \tag{23}$$

The external periodic signal has a frequency Ω, and the frequency difference and phase difference are defined as $\varepsilon\Delta = \omega - \Omega$ and $\phi = \theta - \Omega t$. Then, the phase difference ϕ is obtained as follow.

$$\dot{\phi}(t) = \omega - \Omega + \varepsilon Z(\phi + \Omega t) \cdot p(\phi + \Omega t, t) = \varepsilon\{\Delta + Z(\phi + \Omega t) \cdot p(\phi + \Omega t, t)\} \tag{24}$$

The right side of this equation is $O(\varepsilon)$, the change of ϕ is slower than the time of external periodic. Thus, doing averaging over the fast oscillation, the phase difference ϕ is constant of the time.

$$\dot{\phi}(t) \simeq \varepsilon\{\Delta + \Gamma(\phi)\} \tag{25}$$

Where $\Gamma(\phi) = 1/2 \int_{2\pi}^{0} Z(\phi + \theta) \cdot p(\theta)\, d\theta$. $\Gamma(\phi)$ is 2π periodic function depends on the form of the limit cycle and the external forcing. The function is the phase coupling function. In this paper, the external input to the neural oscillator can be expressed as $p(\theta) = [\sin\theta \quad -\sin\theta \quad 0 \quad 0]$. Figure 6 shows the resultant function.

The phase coupling function is available to check the synchronization characteristic of the neural oscillator. The frequency mismatch $\Omega - \omega$ of the forcing and phase frequency is within the region $\varepsilon\Gamma_{\min} < \Omega - \omega < \varepsilon\Gamma_{\max}$, then, the frequency entrainment occurs and the oscillator is synchronized with the external forcing. Where, ε is the amplitude of the external force. This region is called a synchronization region. Obviously, the region increases in proportion to the amplitude of the external forcing.

6.4. Synchronization region of neural oscillator

The synchronization region of the neural oscillator is analysed. Resulting of the analysis, a figure, which expresses the region of synchronization, is obtained. The figure is called an "Arnold tongue". Figure 7 shows the Arnold tongue. The colored area is obtained by numerical simulation. Moreover, the synchronization region obtained by the phase reduction method is shown as black dotted lines in fig. 7.

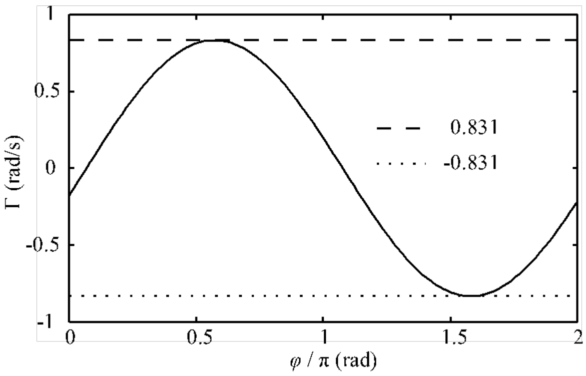

Fig. 6. Phase coupling function

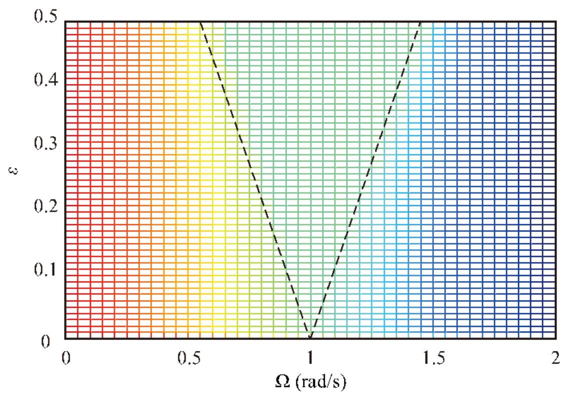

Fig. 7. Synchronized region

The green area is the synchronization region in fig. 7. The edge of the green area and the dotted lines are almost identical. This is, the figure provides enough evidence of effectiveness of the phase reduction method. It is clear that the synchronization region has spread from the oscillator's frequency $\omega = 1$, when the amplitude of the external forcing is increased. The synchronization region depends on the amplitude of the forcing. Increased the coefficient for the external forcing in the neural oscillator, the region can be freely adjusted. For a reason of robustness of the synchronization characteristic, increasing of the coefficient seems to be meaningful. However, the operation also raises the probability to synchronize into an undesired frequency of the external excitation. The appropriate value of the coefficient would be required according to the conditions of the control objects and excitations.

This section showed the evaluating method of synchronization region of the single neural oscillator, but the evaluation of the control system has not done yet. In the future, more general analysis and evaluation for the proposed CPG controller will have to be done.

CONCLUSION

This paper proposed a new control method for active mass dampers using a Central Pattern Generator in the vibration mitigation of structures. An algorithm which can realize an proper phase relation between the main system and the AMD is installed into the controller using the CPG which is expressed as a combination of neural oscillators modeled as the first order lag. Generally, in the case of vibration mitigation using the AMD, an applicable phase relation exists between the auxiliary mass of the AMD and the mass of the structure. In this paper, the phase relation was analyzed for application of a suitable control, and a phase controller, which keeps the phase relation like a biped-walking robot has the relation between the right and left feet, was developed using the CPG. Moreover, another algorithm was proposed that a displacement giving to the auxiliary mass of the AMD is defined by the vibration condition of the main system, and was installed into the controller. Furthermore, the validation of the controller was performed by numerical simulation. The results show the proposed system has the possibility to reduce the structural vibration.

Furthermore, phase response, phase sensitivity and phase coupling functions of the single Matsuoka's oscillator constituting the CPG model were developed by the analysis using the phase reduction method. And from the phase coupling function, the single neural oscillator's synchronization region, which is the important property on the synchronization between the structure and the oscillator, was shown. In the future, synchronize evaluation of the proposed control system will be done.

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