Immune Algorithm Based Active PID Control for Structure Systems

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An immune algorithm is a kind of evolutional computation strategies, which is developed in the basis of a real immune mechanism in the human body. Recently, scientific or engineering applications using this scheme are remarkably increased due to its significant ability in terms of adaptation and robustness for external disturbances. Particularly, this algorithm is efficient to search optimal parameters against complicated dynamic systems with uncertainty and perturbation. In this paper, we investigate an immune algorithm embedded Proportional Integral Derivate (called I-PID) control, in which an optimal parameter vector of the controller is determined offline by using a cell-mediated immune response of the immunized mechanism. For evaluation, we apply the proposed control to mitigation of vibrations for nonlinear structural systems, cased by external environment load such as winds and earthquakes. Comparing to traditional controls under same simulation scenarios, we demonstrate the innovation control is superior especially in robustness aspect.

Key Words : Immune Algorithms, PID Control, Structural Vibration

1. Introduction

In recent years, advanced construction techniques have been explored for flexible structural systems which are typically characterized with low stiffness and high strength-to-mass ratio. Such structure usually requires enhanced active control against vibrations by environmental excitations (earthquakes and winds). Rigorous control algorithms have been developed to satisfy the control objective such that various active controls are correspondingly explored in structural engineering fields. High-rise structures possibly in cities are very susceptible to winds or earthquakes (Iemura et al., 1992), which particularly requires significantly robust control strategy to satisfaction of work conditions.

However, such structural systems are involved with complicated dynamics such as uncertainty and system perturbation, which results in difficulty of design of active control systems. Besides, external disturbances against structures are not predictive, which leads hardness of controller design. To overcome these problems, researchers have been focused on advanced control methodology for structural control. Several control approaches

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have been applied for mitigation of structural vibrations: H_∞ control (Masaru and Yoshihito, 1995), a variable structure control (Iemura et al., 1992), and an evolutional computation based controllers such as fuzzy logics (Ishiguro et al., 1990), neural networks (Haykin, 1999), and genetic algorithms (Michalewicz, 1994). It is report that the evolutional controls are outputted in the case of system variations.

In this paper, we consider an immune algorithm based active PID control. An Immune system is one of the biological information processes with self-adjustment by which the human body is adaptively and flexibly controlled under variations and disturbances for environments. The immune system is largely composed of humoral and cell-mediated immunities. Artificial immune networks made from response of both antigen and antibody, which is applied to control behavior arbitration of autonomous robotics, is used in humoral immunities. In addition, well know also as one of evolutional optimization tools, an immune algorithm is widely used in engineering fields due to its superior searching capability and faster convergence rate (Chun et al., 1999).

We present an immunized PID (I-PID) algorithm for vibration control of nonlinear structural systems. This study is an extensive accomplishment from our preliminary work (Lee et al., 2004). This control uses a specific immune response of the biological immune system. We test the proposed controller applying for structure systems embedding with nonlinear dynamics of its stiffness. Computer simulation illustrates our method is obviously more effective than traditional controls.

The remainder of this paper is organized as follows. In Section 2, we present model of a nonlinear structural system. In Section 3, we review an immune algorithm and in Section 4, a controller design is derived, respectively. In Section 5, simulation experiment is provided and lastly, conclusion is given in Section 6.

2. Nonlinear Structural Systems

We consider a simple nonlinear structural system shown Fig. 1.

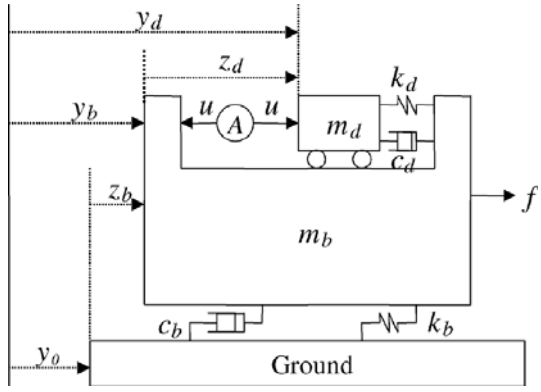


Fig. 1 A nonlinear structural model

In Fig. 1, parameters m_b, k_b, and c_b are a mass, stiffness, and damping for a structure, and m_d, k_d, and c_d are same parameter for a damper system, and f is a wind excitation as an environment disturbance. The mass damper on the top floor in Fig. 1 is an actuator performed as an active controller. System motion equations of the model are given by (Endoh et al., 1998)

$$\ddot{z}_b = -\frac{c_b}{m_b}\dot{z}_b - f_{k_b}(z_b) + \frac{c_d}{m_b}\dot{z}_d + f_{k_d}(z_d) + \frac{1}{m_b}w - \frac{1}{m_b}u - \ddot{y}_0 \tag{1}$$

$$\ddot{z}_d = -\frac{c_b}{m_b}\dot{z}_b + f_{k_b}(z_b) - \left(\frac{c_d}{m_d} + \frac{c_d}{m_b}\right)\dot{z}_d - f_{k_d}(z_d) + \frac{1}{m_b}w - \left(\frac{1}{m_b} + \frac{1}{m_d}\right)u \tag{2}$$

where $\ddot{y}_0$ is a ground acceleration such as earthquakes, u is a control input scalar acted to a damper system, and a system state vector is $z = [z_b\ \dot{z}_b\ z_d\ \dot{z}_d]^T$ in which z_b and z_d are displacements against a structure and a damper and $\dot{z}_b$ and $\dot{z}_d$ are denoted by velocities of them. In (1) and (2), the stiffness nonlinearities f_{kb} and f_{kd} are given as functions of each displacements z_b and z_d. We use the nonlinear stiffness equations referred in (Endoh et al., 1998) for them.

A control goal in this case is to mitigate structure displacement (a system error) occurred due to earthquakes or wind forces disturbance acted to a structure system using a suitable control approach. In general, to construct a controller, some

information about a system is involved in a controller design procedure. But, in this structure control, the environmental disturbance is incompletely known. Hence, this leads to need a robust controller for this case. We should solve this problem by using an adaptive controller whose parameters are optimally determined through an immune optimization algorithm.

3. An Immune system

3.1 Structure of an immune system

An immune system is one of the biological information processing systems such as genetic systems, brain-nervous systems, and endocrine systems. In recent years, numerous researches have considerably been addressed in engineering fields because of its recognition, regulation, and adaptive abilities (Chang and Soong, 1980; Huang, 1999; Lee et al., 2000). The biological immune system in the human body is classified by the first and the second defense system. The first defense is an integument, which is made of a mucus membrane and a skin, and can effectively defend external invasion materials. But, if a first defense system is collapsed, a body achieves to protection functions by secondly constructing a new defense system, i.e. the second defense. As well, the second defense system is separated to a nonspecific defense and a specific defense : a nonspecific defense is directly as well as quickly activated against an external invaded material, and though a chemical and particular Leukocyte are used, these defense materials have feature that can always correspond immediately in stand-by status.

A specific defense system is more complicated and usually need more enough time to prepare defense materials. It is called as a general immune response consisted of Lymphocytes and B cell and classified to a humoral immune response and a cell-mediated immune response. The first one is an antibody secretion phenomenon like a specific chemical reaction (Lee et al., 2000; Dasgupta, 1997). The second one is concerned with T-cells (T lymphocyte) consisted of three kinds of cells : T-helper cell (T_h), T-suppresser cell (T_s), and T-killer cell (T_k) which are produced mostly by thymus. These T-cells do cell-mediated immunity effect that interact directly in the cells invaded by virus or carcinogen material, etc., and T_h-cell activates B cell, and T_s-cell controls immune actions respectively (Dasgupta, 1997; Roitt, 1980; Mohler et al., 1994).

3.2 Cell-mediated immune response

The cell-mediated immune response (CMIR) of the immune system is that the T-cell's stimulate macrophages and other T-cells one another in order to destroy an invaded material. In the T-cell, T_s controls an immune response, T_h helps other parts, and T_k directly destroys pathogenic bacteria. Similarly, macrophages stimulate a humoral immunity by cooperating with T-cells and activated macrophages result in a strong phagocytosis. Except for complement, phagocytes, T-cells and antibodies destroy pathogenic bacteria. The reaction mechanism is shown in Fig. 2.

In Fig. 2, if antigens (Ag) are attacked from external materials, antigen presenting cells (APC) introduce the secreting of interleukin-1 (IL-1) that will pass the information of external material's appearance to T_h and T_s. Then T-helper cell and suppressor cell activated and stimulates the B-cells, T_k cells and T_s cells by secreting Interleukin-2 (IL-2). T_s is also acted as a control mechanism and secrete TSF (T-suppressor factor) which controls the T_h, B-cell, and T_k activity. Through this series of control processes, the immune system's function is to repair the body, and stabilize and protect itself from external invasion the outside (Roitt, 1980). Therefore, we wanted to design an intelligent control system with great adaptability and flexibility in a dynamic environment using a mathematically model-

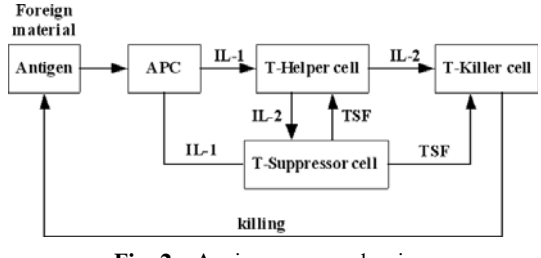


Fig. 2 An immune mechanism

ed self-adjusting process as in the immune system.

4. Design of an I-PID Controller

4.1 Cell-mediated immunity using the cellular molecular kinetics

During the immune response the molecules and the cells of the immune system interact with each other as well as with other cells and molecules of the organism. Therefore, to model immune mechanism we can use the principles of the cellular and molecular kinetics. The cellular molecular kinetics model becomes the basis of all immune responses, and is based on the conservation law or mass action principle of chemistry. From this relationships of the immune response, a general model for a cell-molecule power science (Roitt, 1980; Mohler et al., 1994) is given by

$$\frac{dX_i}{dt}=\text{Source rate}-\text{death rate}+\text{division rate}+\text{rate differentiation to}-\text{rate differentiation from}$$

or

$$\frac{dX_i}{dt}=V_i(t)-\frac{X_i}{\tau_i}+P_i(\cdot)X_i+\sum_{j\neq i}2P_j(\cdot)P_{ji}(\cdot)X_j-\sum_{k\neq i}2P_k(\cdot)P_{ki}(\cdot)X_k \tag{3}$$

where X_i is number of cells, $V_i(t)$ is a source term from outside (through blood from the marrow), τ_i is a death time constant, and $P_i(\cdot)$, $P_{ji}(\cdot)$, and $P_{ki}(\cdot)$ are suitable cell growth coefficients $(\cdot)$ a relevant cells appear. The i, j, and k in (3) refer to different cell types in the cellular and molecular kinetics which can influence each other. For instance, these symbols can be described as T cells which are helper cell, suppress cell and killer cell.

Mathematical models of cancer immunity are reported based on this cellular molecular kinetics. Immune response processes with antigens and T-cells can be modeled from (3). That is, we can get a model such as (4) if we consider the reaction mechanism for T-cells only from (3).

$$\frac{dx_1}{dt}=p_1x_1-\frac{x_1}{\tau_1}-p_{31}x_1 \tag{4a}$$

$$\frac{dx_2}{dt}=p_2x_2-\frac{x_2}{\tau_2}-p_{32}x_2 \tag{4b}$$

$$\frac{dx_3}{dt}=p_3x_3-\frac{x_3}{\tau_3}-p_{33}x_3 \tag{4c}$$

$$\frac{dx_4}{dt}=p_4x_4-\frac{x_4}{\tau_4}-p_{24}x_4 \tag{4d}$$

where x_1, x_2, x_3, and x_4 indicate T_h, T_k, T_s, and antigen respectively. Also, p_1, p_2, p_3, and p_4 are the growth coefficient of each T cells (T_h, T_k, T_s) and antigen. p_{31}, p_{32}, and p_{33} are suppression rate of each T cells (T_h, T_k, T_s) caused by T_s's reaction. P_{24} is destruction rate of antigen caused by T_k's reaction.

4.2 I-PID controller design

We designed an I-PID (Immunized PID) controller using the assumptions in Eq. (4). First, if T_k destroys and removes directly acting antigens, T_h and T_s help or control each other in an actual immune system. Therefore, if antigen $\varepsilon(t)$ is an invasion material from outside and happens t times, the occurrence of external material is informed by APC in the immunocytes in a living body. According to the proliferating function given by (5) and (6) these T_h and T_s stimulate and control the immune response (Mohler et al., 1994)

$$P(\varepsilon)=H_{\max}+\frac{H_{\min}-H_{\max}}{1+\left(\frac{\varepsilon(t)}{C_h}\right)^{g_k}} \tag{5}$$

$$TSF(\Delta T_k)=S_{\max}+\frac{S_{\min}-S_{\max}}{1+\left(\frac{\Delta T_k}{C_s}\right)^{g_k}} \tag{6}$$

where $P(\varepsilon)$ and $TSF(\Delta T_k)$ indicate the cell activation function and the cell control function, respectively. $\varepsilon(t)$ indicate the antigen, and $H_{\max}$, $H_{\min}, S_{\max}$, and $S_{\min}$ that are external invasion material which express the necessary maximum and minimum reaction in cell growth. These can fluctuate according to the amount of external invasion and ΔT_k fluctuates according to the amount of antigen. Also, C_h, g_h, C_s, and g_s are the parameters of cellular growth speed. Each cell, i.e., T_h, T_s, and T_k can consist of immune

response by these two (5) and (6). Also, if the focus to fact that it is T_k acts by directly opposing the antigen, T_k can follow Eq. (7) because it is regulated by $P(\varepsilon)$ and $TSF(\Delta T_k)$.

$$T_k(t)=K_k\{P(\varepsilon)-TSF(\Delta T_k)\} \tag{7}$$

where T_k depends on change amount of $\varepsilon(t)$ and regulates the amount of T_h and T_s as antigen killing cells and K_k indicates the growth element of T_k. Fig. 3 shows the control mechanism of T-cells.

This immune response can control antigens that invade from outside. It is regulated spontaneously in the body, and keeps the body in a stable state. Also, the cell activation function and the control function in Eqs. (5) and (6) can be considered as the design parameters that decide performance of the controller. From Eq. (6), $T_k(t)$ can be considered to control the amount of $U(t)$ that controls the system in engineering field because $T_k(t)$ removes it by fighting directly with the antigens. This time, ΔT_k can be considered to be $\Delta U(t)$, i.e., the control amount of change in the controller, $\varepsilon(t)$ can be thought of as $e(t)$, i.e., the error of the system output, and K_k i.e., the growth element of T_k can be considered to be the scale factor of the controller. From these results, we can design a controller using cell-mediated immunity, as in Eq. (8) from the similarity with the cell-mediated immune response and the PID controller scheme.

$$\begin{aligned} U_{CMIA}(t)=&K_1\{P_P(e)-TSF_P(\Delta u)\}e(t)\\ &+K_2\left\{P_I\left(\int e\right)-TSF_I(\Delta u)\right\}\int e(t)\\ &+K_3\{P_D(\Delta e)-TSF_D(\Delta u)\}\frac{de(t)}{dt} \end{aligned} \tag{8}$$

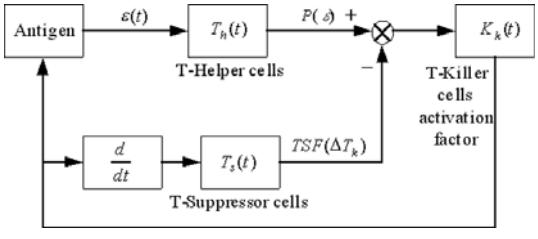


Fig. 3 The T-cells regulation mechanisms based on the CMIR

where K_1, K_2, and K_3 are the scaling elements of the control gains, $P(\cdot)$ is considered to be the proliferating factor of the size of the control, and $TSF(\cdot)$ is considered to be the suppression factor compared with the proportional, derivative, and integral terms in the controller. The next conditions should be satisfied in order for the controller to act within a robust stable area. The conditions $K_1, K_2, K_3>0$, $P(\cdot)>0$, and $TSF(\cdot)\geq 0$ are then satisfied, $H_{\max}, S_{\max}>0$, $H_{\min}, S_{\min}=0$, and $C_h, C_s>0$ should be true. The control system designed in our research can be guaranteed to give convergence and stability under these conditions.

4.3 Optimal selection of I-PID control parameters

The most suitable value for the proposed controller is necessary because the control parameters, which include a nonlinearity element, should be considered at the design stage. Figure 4 shows the auto-tuned structure for the I-PID control parameters using HIA (Humoral Immune Algorithm) (Chun et al., 1999; Endoh et al., 1998). While tuning the control parameters automatically, the generation of HIA reached 100, the individual number for each generation reached 40, and the population number stored in the memory cells reached 10. To create a new individual 50% was used for random sampling, and 50% was used to reproduce an old individual. Then a genetic crossover is used with 0.25% probability of mutation.

For the I-PID controller design, g_s and g_h together are equivalent to 1 to reduce the nonlinear elements as far as possible. All 14 parameters, i.e.,

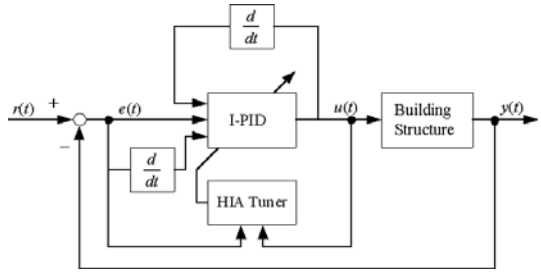


Fig. 4 The tuning diagram of the I-PID controller by HIA

K_1, K_2, K_3, and H_{max} of each function, and C_h, C_s, and S_{max} of the $TSF(\Delta u)$ function, are adjusted using HIA for the most suitable controller design.

5. Computer Simulations

We test our methodology with simulation experiments and compare with traditional approaches, i.e. PID and LQ control. Via repeated simulations, we determined optimal parameters for PID and I-PID as Table 1. To construct LQ control, we used MATLAB© command *lqr* and default values for weighs. However, we adjusted these for better result by HIA (Chun et al., 1999 ; Endoh et al., 1998).

System parameters for the structure in Fig. 1 are as follows : m_b=18,100 ton, k_b=18,100 kN/m, c_b=362 kN·sec/m, and m_d=362 ton, k_d=301 kN/m, c_d=23.8 kN·sec/m. The model of winds excited to the structure in Fig. is mathematically expressed as (Chang and Soong, 1980)

$$f(t) = p(3\sin\omega t + 7\sin 2\omega t + 5\sin 3\omega t + 4\sin 4\omega t) \quad (9)$$

where ω is a fundamental frequency and p is an excitation magnitude of wind forces. We selected ω=1 rad/sec and p=43.4 kN (see Fig. 5).

We referred the record of EL Centro earthquakes shown in Fig. 6, in which the magnitudes

Table 1 Optimal parameter of PID and I-PID

		Kp	Ki	Kd
PID	Earthquake	72.741	52.269	69.421
	Wind force	18.025	9.141	2.868
		K1	K2	K3
I-PID	Earthquake	48.204	0.036	15.643
	Wind force	3.799	0.542	1.380

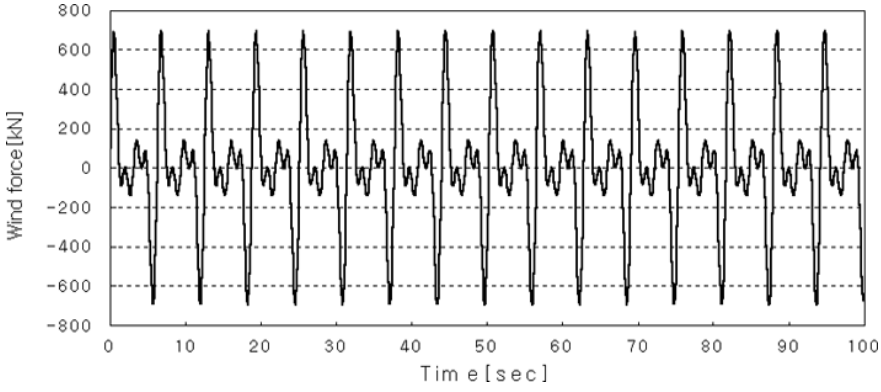


Fig. 5 Time histories of wind forces

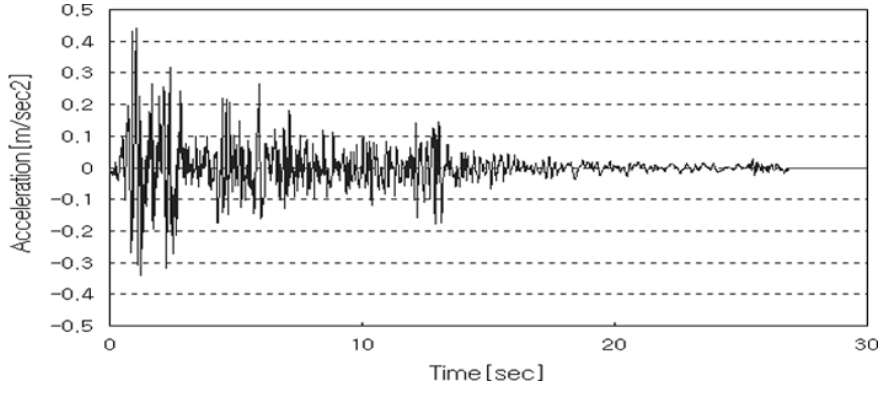
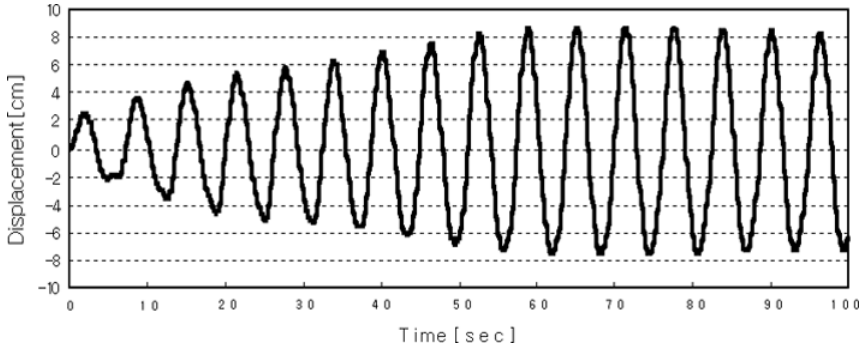
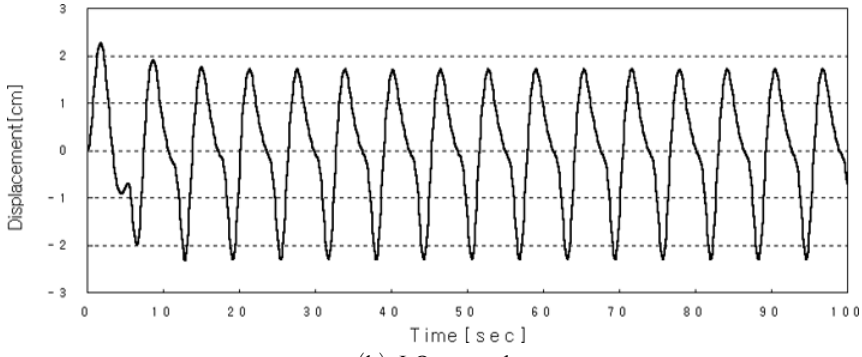


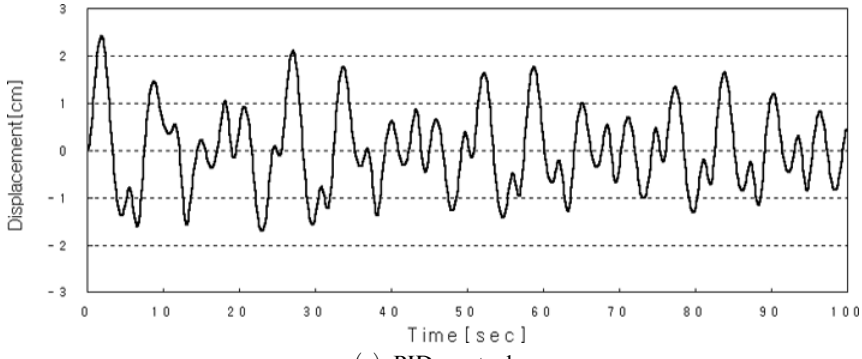
Fig. 6 Time histories of modified EL Centro earthquakes



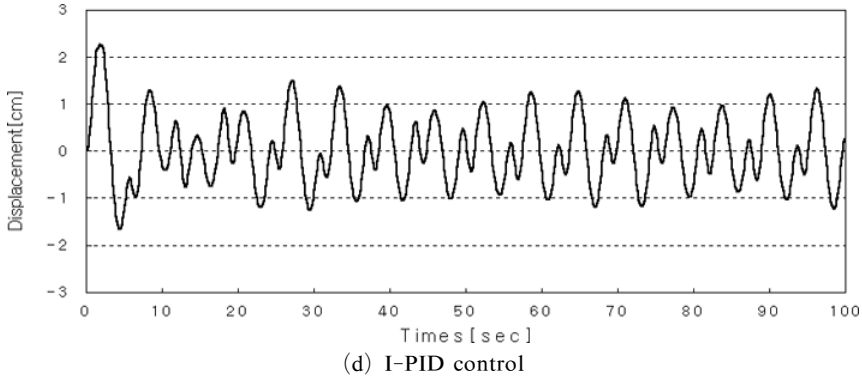
(a) Passive control (no active control)



(b) LQ control



(c) PID control



(d) I-PID control

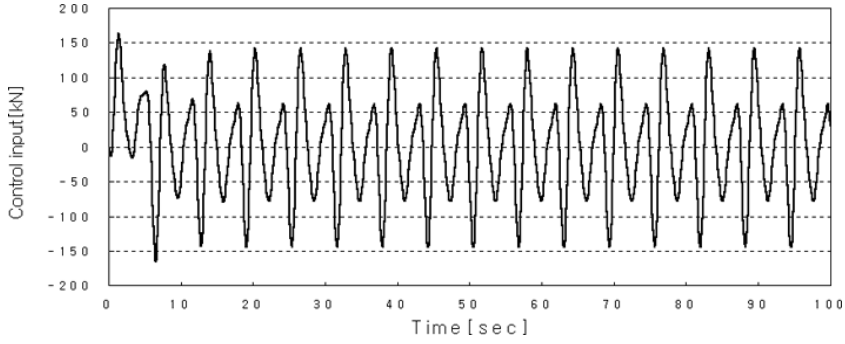
Fig. 7 Displacements of the structure by the wind forces

are modified from the original signal for this simulation. The degree of magnitude of this signal is velocity with the unit of m/s^2.

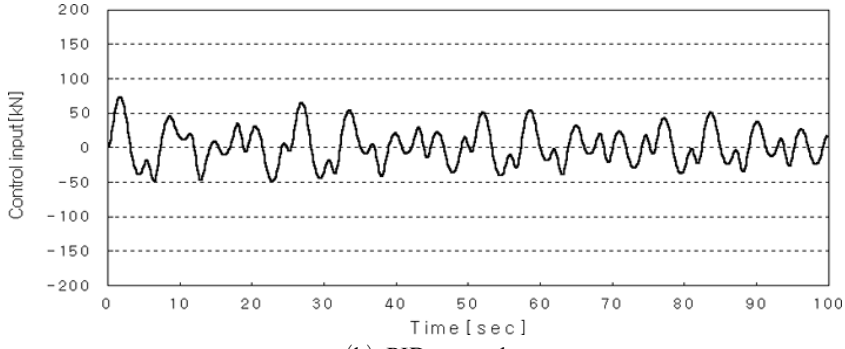
First, we simulated the structure excited by the wind for each control separately and plotted system trajectories illustrated in Fig. 7. Comparing the displacement errors to the result of the passive control, LQ, PID controller and I-PID controller are improved 74%, 82%, and 84% respectively. From this result, we observe I-PID control has the best performance.

Control force is one of importance considerations in structural control. That is, obviously, a large amount of control input is hard to implement in practice. By contrast, small force sometimes involves little satisfying control performance. We also show the control input forces for the controls in Fig. 8. In case of control energy, PID and I-PID controllers have less forces by 64% and 83% than the LQ controller.

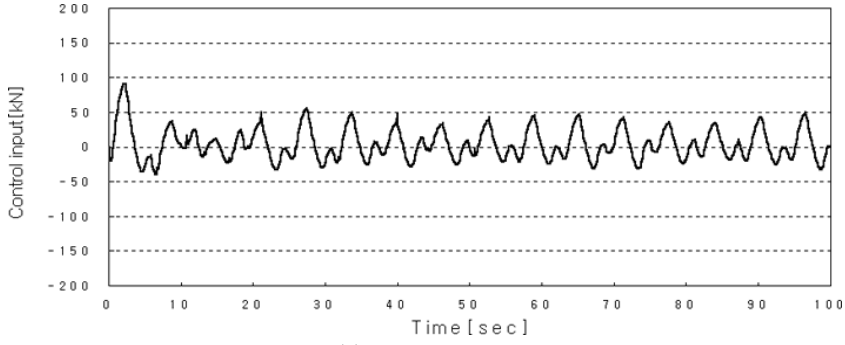
Table 2 contains RMS values for the displacements and control inputs of the results.



(a) LQ control

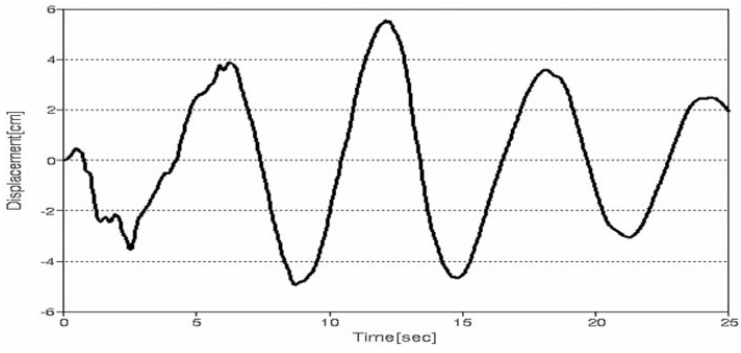


(b) PID control

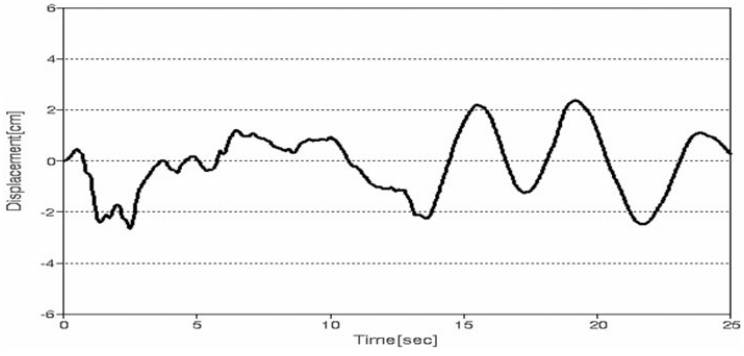


(c) I-PID control

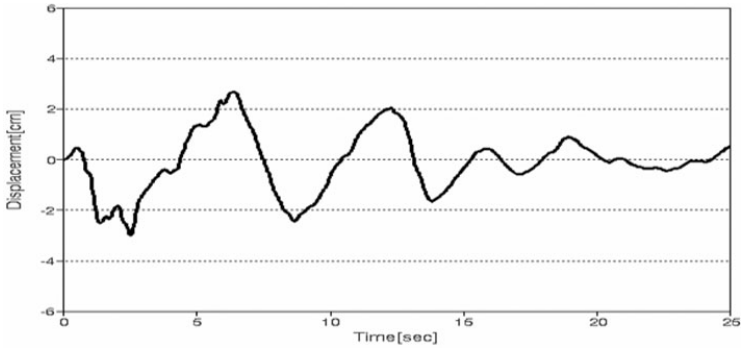
Fig. 8 The control forces



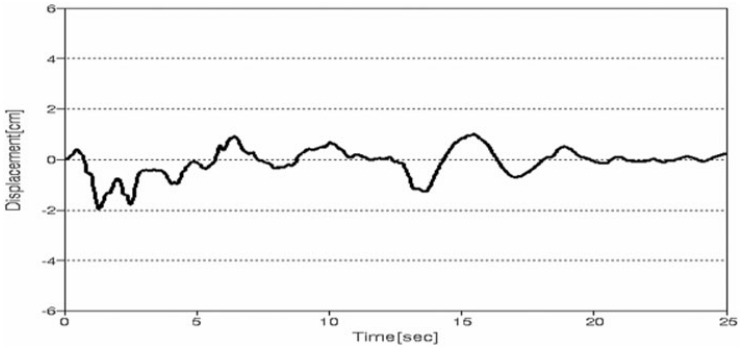
(a) Passive control (no active control)



(b) LQ control



(c) PID control



(d) I-PID control

Fig. 9 Displacements of the structure for the earthquakes

Table 2 RMS values of system errors and control inputs

Controller	Displacement	Control input
	RMS[m]	RMS[kN]
Passive	0.01534	–
LQ	0.00385	42.96
PID	0.00276	15.21
I-PID	0.00239	7.21

Table 3 Peak and RMS values of system errors for earthquakes

Controller	Displacement	
	Peak[m]	RMS[m]
Passive	0.05502	0.02795
LQ	0.02658	0.01257
PID	0.02986	0.01194
I-PID	0.01976	0.00563

Next, we simulated for earthquakes with the controls. Fig. 9 shows trajectories of the structure for each controller.

We measure peak values of the displacements in Fig. 9 that LQ, PID, and I-PID controller are significantly enhanced by 51%, 46%, and 64% than the passive controller. Moreover, LQ, PID and I-PID controllers are improved about 55%, 57% and 80% for RMS error. In the same way, we summarize the simulation results in Table 3.

6. Conclusions

In this paper, we proposed an adaptive controller with PID scheme using cell mediated immune algorithm based on the human body immune reaction system. Our proposed controller is applied to the vibration control of structure and from computer simulations, we prove the proposed methodology is superior to the traditional methods. From this research, we surely contribute an innovation control strategy which is based on an immune algorithm. We extend this mechanism to more complicated control problems for the future work.

Acknowledgements

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