17^{th} World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

ACTIVE PREVIEW VIBRATION CONTROL WITH THE ESTIMATED FUTURE SEISMIC WAVEFORM GENERATED BY AN AI-BASED ESTIMATION SYSTEM

K. Hiramoto(1), T. Matsuoka(2)

(1) *Professor, Mechanical Engineering Program, Niigata University, Niigata, Japan, hiramoto@eng.niigata-u.ac.jp*
(2) *Associate professor, Department of Mechanical Engineering Informatics, Meiji University, Kawasaki, Japan, matsuoka@meiji.ac.jp…*

Abstract

We propose a new active preview vibration control strategy based on the information of seismic waveform observed in remote observation sites. The observed waveform information of the remote site is transmitted by a waveform transmission network to the structure under control. The waveform transmission network is realized by interconnecting multiple controlled structures and observation sites. With recent development of information and communication technology (ICT), e.g., internet of things (IoT) and the wireless high-speed wide-bandwidth data transmission such as 5G technology, etc., the real-time data acquisition of the complete seismic waveform in remote places by using above observation systems is presently getting realistic. By using the future waveform information obtained through the network, we propose an active vibration control method for structural systems that achieves fairly higher control performance over conventional methodologies. A preview control consisting of the state-feedback and feedforward control (preview action) is adopted as the control law. For the preview action, a future seismic waveform in some time interval is needed. Since the future seismic waveform is not available, the preview action contributing the performance improvement is generally impossible. Some studies exist on active vibration control with the preview of the incoming seismic waveform, e.g., Refs. [12] and [15], showed that the control performance on vibration suppression was improved by introducing the preview action with a single recorded seismic wave. However, the soil dynamics between remote and the place of the controlled structure is ignored in [12] and the control law in [15] is an approximated version of the optimal control problem that must be solved a continuous time matrix differential equation a time backward manner from the final time of the seismic event. To get over the difficulties in above studies, we have proposed a preview control of the structural systems subject to seismic disturbance[3]. That is, the preview control that can be implemented as a real-time digital control algorithm without any non-causalities employing the accurate prediction of the future seismic disturbance with the measurement of the remote observation site(s) while taking into account the nonlinear soil dynamics. A small-scale simulation study with a recorded seismic event in Japan, we showed that the proposed control method achieved much higher control performance over the conventional linear quadratic optimal control. In this study, a more intensive parameter optimization of the proposed control system in the AI-based waveform estimation system and the preview control law is carried out to evaluate how much the proposed control system is effective and beneficial for vibration control of structural systems compared to standard feedback-based control methods.

Keywords: vibration control; preview control; waveform transmission network; waveform estimation system

1. Introduction

Seismic waves are observed in real time at numerous points such as structures that are under vibration control and observation sites in various countries that suffer from severe seismic events frequently, e.g., Japan, Mexico and USA etc.. In Japan, observed seismic data are used not only for the vibration control of the controlled structure, but as a real time web-based seismic intensity monitor service[1] and as an earthquake early warning[2]. Similar observation system has been realized also in the USA[3] for the earthquake early warning in the west coast region of the country. Those systems provide the real-time information on the seismic intensity over the area of interest and have been put to practical use effectively.

A lot of buildings have been controlled by various types of vibration control laws, e.g., the active and semi-active methods etc., based on the state of the art control methodology and most of such control is a feedback control law.

To obtain further performance improvement of the vibration control system, we propose an idea to connect the buildings with a network and share some data about the seismic disturbance. A similar idea is found in [4]. They use the information of the seismic waveform in the form of its dominant frequency before it reached to the structure under control. A kind of semi-active control that changes structural natural frequencies with the information on the dominant frequency is proposed.

With recent development of information and communication technology (ICT), e.g., internet of things (IoT) and the wireless high-speed wide-bandwidth data transmission such as 5G technology, etc., the real-time data acquisition and sharing of the complete seismic waveform in remote places by using above observation systems is presently getting realistic. The MeSO-net (the dense Metropolitan Seismic Observation Network) system[5] in Japan and a wireless smart sensor platform for high-fidelity data acquisition, e.g., [6], for structural health monitoring and control, e.g., [7] in the USA, are some examples of the effort to realize such *data-rich* environment.

We propose a new active vibration control strategy based on the future seismic waveform information observed in the remote site(s) with the forthcoming data-rich envronment. The waveform of the remote site is assumed to be transmitted by a waveform transmission network to the structure under control. The waveform transmission network can be realized by interconnecting multiple controlled structures and observation sites via a network.

A preview control law consisting of the state vector feedback control and the feedforward control is adopted as the control method to obtain the high performance control systems [8-11]. The state vector data required for the feedback control part can be obtained with sensors installed in the structure currently under control. On the other hand, the future value of the seismic disturbance for the preview action is unknown.

Some studies exist on active vibration control with the preview of the incoming seismic waveform[12-16]. However, those studies have some problems, e.g., igonoring the soil dynamics[12], the accuracy of the estimation of the future seismic disturbance [13], difficulty in the real-time implementation [14] and too long preview time interval [15].

In this study, we propose a preview control of the structural systems subject to seismic disturbance overcoming above difficulties and drawbacks of existing studies. That is, the preview control that can be implemented as a real-time digital control algorithm without any non-causalities employing the relatively short time range prediction of the future seismic waveform with the measurement of the remote observation site(s) while taking into account the nonlinear soil dynamics.

To realize such high performance preview control system, an wave estimation system to predict the future seismic waveform based on artificial intelligence (AI) is proposed. The waveform estimation system is a dynamic system with a multi-layered artificial neural network (ANN) at its central core.

The ANN proposed in the study has three external input signals, i.e., some samples of the waveform in the remote seismic observation site(s), those of the disturbance shaking the structural system itself after its arrival, and those of error between the estimated and real waveform data. The output of the system is the estimate of some samples of the future disturbance waveform enough to carry out the preview action.

We use the genetic algorithm (GA) for optimizing design parameters in the waveform estimation system and the preview control law. Through a small scale simulation study with a recorded seismic event in Japan, we show that the proposed control method achieves much higher control performance over the conventional and popularly used LQ feedback control methodology. Also, we test some cases of the preview control with the different preview length, i.e., the sample number of the future seismic waveform and find out that there exists a reasonable preview length to achieve good control performance.

Notations are as follows: t: time, $0_{m\times n}$: an $m \times n$ zero matrix, I_n: an n-dimensional identity matrix, A^T: transposition of a matrix A, $\mathbf{R}^{m\times n}$: the set of $m \times n$ real matrices, $\mathrm{trace}(A)$: the trace (sum of diagonal elements) of a matrix A, $\mathrm{diag}(a_1, \dots, a_n)$: A diagonal matrix whose diagonal elements are $a_1, \dots, a_n$.

2. Concept of the control system

The block diagram of the proposed control system to show the concept of the present study is depicted in Fig. 1. A structural system is actively controlled with sensor measurements of the structural response, the seismic disturbance at the location of the structural system itself and that of the remote place(s). The sensor measurement in the remote place is transmitted with a network. The authors hope that the transmission of the remote seismic waveform is carried out with the standard Internet protocol because it is easily realizable without large amount of additional costs. The realizability of such data transmission will be examined in the future study. Note that the remote site transmitting the waveform information is assumed to be located closer from the epicenter than the structure under control. This assumption becomes almost true if relatively large number of observation sites exist over a region and the measurement of each site is shared by all the sites through the network. At least in Japan, such condition is satisfied since observation sites are located over 1,000 points nationwide[1].

With the sensor measurements, the control effort, i.e., the command signal for the actuator to produce the active control force, is generated by the preview control law consisting of the feedback and feedforward control parts. The feedback control law uses sensor measurements of the structural response, e.g., the displacement and the velocity of each floor. The feedforward control is obtained with the future value of the seismic waveform of some time interval (defined by the control system designer) from a current time. The output of the feedforward control part is referred to as the preview action.

Several studies have shown that the preview control with the preview action greatly improves the control performance with the known future value of the external input, such as a reference value of the controlled output[8-11]. However, in the present situation, we generally cannot obtain the future value of the seismic waveform that is necessary to realize the preview action because of the law of causality.

To realize the preview action, the measured seismic disturbance in the remote area is used. Because of the above assumption, i.e., the remote site is located closer from the epicenter than the structural system, the seismic waveform of the remote site contains the information on the future waveform of the disturbance in the location of the structural system. We propose an AI-based waveform estimation system to predict the waveform of the future seismic disturbance with the disturbance waveform data obtained in the location of the structural system and the remote site. With those subsystems, *a quasi-preview action* with the estimated future value of the seismic disturbance becomes possible.

3. Model of the structural system

The equation of motion of a n-dof structural system to be controlled is given by

$$M\ddot{q}(t) + D\dot{q}(t) + Kq(t) = G\ddot{w}(t) + Hu(t) \qquad (1)$$

where $M = M^T > 0$, $D = D^T \geq 0$, $K = K^T > 0 \in R^{\boldsymbol{n}}$ are the mass, damping and stiffness matrices of the structural system respectively. The vectors $w(t) \in \mathbf{R}^{n_w}$, $q(t) \in \mathbf{R}^{n}$ and $u(t) \in \mathbf{R}^{n_u}$ are the displacement of the seismic disturbance, the relative displacement between the absolute displacement of each floor and $w(t)$ and the active control force generated by the actuator, respectively. In the following, the number of disturbances n_w is assumed to be $n_w = 1$ to retain brevity. Matrices $G \in \mathbf{R}^{n\times n_w}$ and $H \in \mathbf{R}^{n\times n_u}$ are constant coefficient matrices. By taking the state-vector $x^c(t)$ as $x^c(t) = [q^T(t) \quad \dot{q}^T(t)]^T$, the state-space form of the structural system is given as the following:

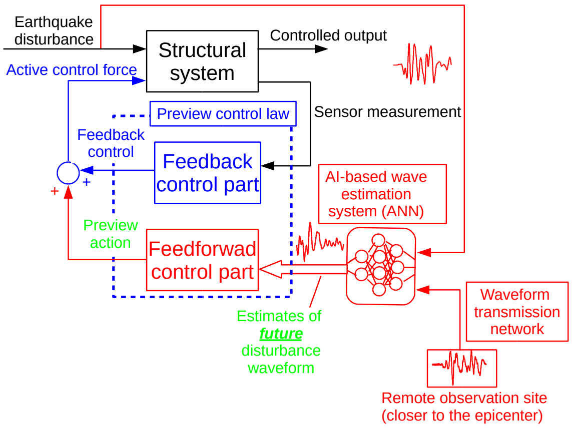

Fig. 1 – Concept of the proposed vibration control system

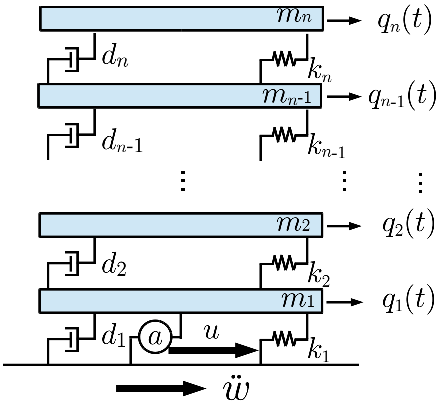

Fig. 2 – n-dof structural system with a force actuator in the base

$$\begin{cases}\dot{x}^c(t) = A^c x^c(t) + B_1^c \ddot{w}(t) + B_2^c u(t)\\ z^c(t) = C^c x^c(t) + D^c u(t)\end{cases} \tag{2}$$

$$A^c = \begin{bmatrix} 0_{n\times n} & I_n \\ -M^{-1}K & -M^{-1}D \end{bmatrix},\ B_1^c = \begin{bmatrix} 0_{n\times 1} \\ M^{-1}G \end{bmatrix},\ B_2^c = \begin{bmatrix} 0_{n\times n_w} \\ M^{-1}H \end{bmatrix}$$

where $z_c(t) \in \mathbf{R}^{n_z}$, $C^c \in \mathbf{R}^{n_z\times n}$ and $D^c \in \mathbf{R}^{n_z\times n_w}$ are the controlled output vector and coefficient matrices respectively.

In the present study, the discrete time model of the structural system is necessary to apply the preview control law. The discrete time state-space form with the sampling interval T is given as the following:

$$\begin{cases}x(k+1) = Ax(k) + B_1\ddot{w}(k) + B_2 u(k)\\ z(k) = Cx(k) + Du(k)\end{cases} \tag{3}$$

where $k = 0, 1, 2, \ldots$ is the sample number. As an example, a schematic figure of the actively controlled n-dof structural system with an actuator in the base is shown in Fig. 2.

4. Preview control with the waveform estimation system

The preview control[8-11] is adopted as the control law in the study. As depicted in the blue part of Fig. 1, the preview control law is composed of the feedback and feedforward control parts. The control force $u(k)$ in Eq. (3) is given as

$$u(k) = u_{ff}(k) + u_{fb}(k), \tag{4}$$

$$u_{ff}(k) = K_{ff} w_p(k),\ u_{fb}(k) = K_{fb} x(k), \tag{5}$$

$$w_p(k) = \begin{bmatrix}\ddot{w}(k) & \ddot{w}(k+1) & \ldots & \ddot{w}(k+h_p)\end{bmatrix}^T \tag{6}$$

where $K_{ff} \in \mathbf{R}^{n_u\times h_p}$ and $K_{fb} \in \mathbf{R}^{n_u\times 2n}$ in Eq. (5) are the feedforward and feedback gain matrices respectively. The vector $w_p(k)$ is a time series of the predicted seismic disturbance where h_p is the amount of the sample number of the preview (preview length). The preview length h_p is determined as a design parameter so that the preview control system achieves the best control performance. The control force $u(k)$ is a sum of the state-feedback (structural response $x(k)$) control and the feedforward control of the predicted future disturbance $w_p(k)$. The feedforward control part $u_{ff}(k) = K_{ff} w_p(k)$ is referred to as the preview action. The control gain matrices K_{ff} and K_{fb} are obtained with following steps[9].

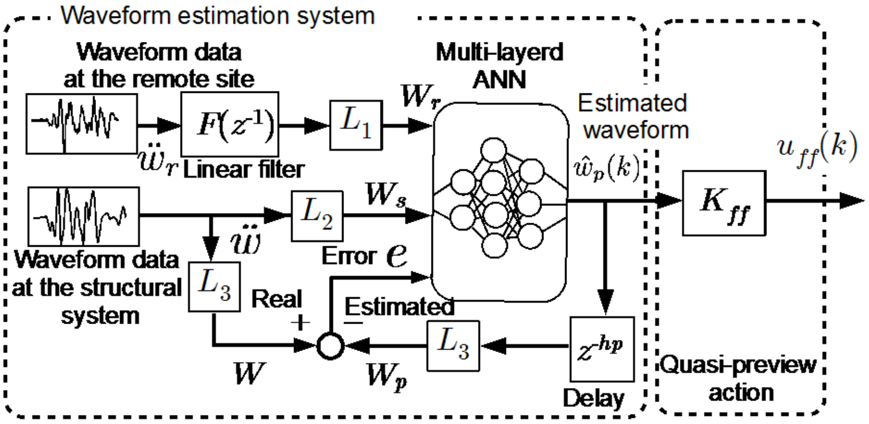

Fig. 3 – Block diagram of the AI-based estimation system

Step 1: Determine the preview length h_p and define an augmented system given by

$$\begin{cases} x_a(k+1) = A_a x_a(k) + B_{aw_p}\ddot{w}\big(k+h_p+1\big) + B_{au}u(k) \\ z(k) = C_a x(k) + D_{au}u(k) \end{cases} \tag{7}$$

$$x_a(k) = \begin{bmatrix} x(k) \\ w_p(k) \end{bmatrix}, A_a = \begin{bmatrix} A & B_1C_d \\ 0_{(h_p+1)\times 2n} & A_d \end{bmatrix}, B_{aw_p} = \begin{bmatrix} 0_{2n\times 1} \\ B_d \end{bmatrix}, B_{au} = \begin{bmatrix} B_2 \\ 0_{(h_p+1)\times n_u} \end{bmatrix}$$

$$A_d = \begin{bmatrix} 0_{h_p\times 1} & I_{h_p} \\ 0_{1\times(h_p+1)} \end{bmatrix}, B_d = \begin{bmatrix} 0_{h_p\times 1} \\ 1 \end{bmatrix}, C_d = \begin{bmatrix} 1 & 0_{1\times h_p} \end{bmatrix}$$

Step 2: For the augmented system, obtain a stabilizing state-feedback control law $u(k) = K_a x_a(k)$ satisfying some control criteria. Then, the control force as shown in Eq. (5), i.e., the state-feedback control with the structural response and the feedforward control with the predicted seismic disturbance can be obtained as the following:

$$u(k) = K_a x_a(k) = \begin{bmatrix} K_{fb} & K_{ff} \end{bmatrix} \begin{bmatrix} x(k) \\ w_p(k) \end{bmatrix} = K_{ff}w_p(k) + K_{fb}x(k) \tag{8}$$

The preview action in Eq. (5) is possible if the future h_p samples of seismic disturbance given by Eq. (6) are available. In the servomechanism control problem, the reference value of the controlled output is defined as the disturbance (external input). Because the reference value of such systems is generally determined before control system design[9], in other words, the control system design of the servomechanism is carried out so that the controlled output tracks the predetermined reference value, we can use the reference value of any time interval during the control action. However, in the present situation, we cannot get the future value of the seismic waveform because of causality in general.

To apply the preview control law to the vibration control of structural systems subject to seismic disturbances, we propose an AI-based waveform estimation system drawn with the red line in Fig. 1 to reproduce the feedforward term $u_{ff}(k) = K_{ff}w_p(k)$ in Eq. (8).

The detailed block diagram of the waveform estimation system is shown in Fig. 3. The waveform estimation system consists of a multi-layered artificial neural network (ANN) for the waveform estimation, a linear filter $F(z^{-1})$ for signal processing where z^{-1} is the unit delay operator yielding $z^{-1}w(k) = w(k-1)$, a pure delay element z^{-h_p} and L_i, $i = 1,2,3$ that is given as

$$L_i = \begin{bmatrix} 1 & z^{-1} & \dots & z^{-n_i} \end{bmatrix}, i = 1,2,3 \tag{9}$$

where n_i, $i = 1,2,3$ is a natural number specified by the control system designer. The input signals of the ANN for the future waveform estimation are described as follows:

- $W_r(k) = L_1 F(z^{-1})\ddot{w}_r(k) = \left[\ddot{w}_r^f(k) \quad \ddot{w}_r^f(k-1) \quad \dots \quad \ddot{w}_r^f(k-n_1)\right]^T$, $\ddot{w}_r^f(k)$: n_1 samples of the seismic waveform at the remote site through the filter $F(z^{-1})$.
- $W_s(k) = [\ddot{w}(k) \quad \ddot{w}(k-1) \quad \dots \quad \ddot{w}(k-n_2)]^T$: n_2 samples of the seismic waveform at the structural system to be controlled.
- $e(k) = W(k) - W_p(k), W(k) = [\ddot{w}(k) \quad \ddot{w}(k-1) \quad \dots \quad \ddot{w}(k-n_3)]^T$,
- $W_p(k) = [\widehat{w}_p(k) \quad \widehat{w}_p(k-1) \quad \dots \quad \widehat{w}_p(k-n_3)]^T$: n_3 samples of the error between the estimated future seismic disturbance and the observed real one. A pure delay element z^{-h_p} is inserted to match the timing of the real and estimated seismic waveform data.

The output of the ANN is the estimate of the future value of the seismic disturbance from $k+1$ to $k+h_p$ samples, denoted by $\widehat{w}_p(k) = \left[\widehat{\ddot{w}}(k) \quad \widehat{\ddot{w}}(k+1) \quad \dots \quad \widehat{\ddot{w}}\left(k+h_p\right)\right]^T$ where $\widehat{\ddot{w}}(k)$ is the estimated seismic acceleration. With the time series of the estimated future seismic disturbance $\widehat{w}_p(k)$, the *quasi-preview action* is realized as the following:

$$u_{ff}(k) = K_{ff}\widehat{w}_p(k) \tag{10}$$

5. Optimal design of the control system

The adjustable design parameters to optimize the control performance exist in two subsystems, i.e., the preview control law and the waveform estimation system. The detail is described below.

Preview control law: We define the controlled output $z(k)$ in Eq. (3) as

$$z(k) = C_a x_a(k) + D_{au}u(k) = \begin{bmatrix} Q_w x_a(k) \\ R_w u(k) \end{bmatrix}, \tag{11}$$

$$C_a = \begin{bmatrix} Q_w \\ 0_{n_u \times (2n+h_p)} \end{bmatrix}, D_a = \begin{bmatrix} 0_{(2n+h_p)\times n_w} \\ R_w \end{bmatrix}, Q_w = \mathrm{diag}\left(q_1^w, \dots q_2^{2n+h_p}\right), q_w^i \geq 0, i = 1, \dots, 2n+h_p$$

$$R_w = \mathrm{diag}(r_w^1, \dots, r_w^{n_w}), r_w^j > 0, j = 1, \dots, n_u$$

We set $q_w^i \geq 0, i = 1, \dots, 2n+h_p$ and $r_w^j > 0, j = 1, \dots, n_u$ that are the weighting factors for each element of the augmented state vector $x_a(k)$ or the control input vector $u(k)$ as the design parameters of the control system because those parameters realize trade-offs between the control performance on vibration suppression and the energy consumption of the actuators in the active vibration control.

Waveform estimation system: Design parameters in the waveform estimation system exist in the filter $F(z^{-1})$ and the multi-layered ANN generating the estimate of the future waveform to carry out the quasi-preview action.

- Filter $F(z^{-1})$: The coefficient parameters in the pulse transfer function in $F(z^{-1})$
- Multi-layered ANN: Values of weight and bias in the multi-layered ANN are design parameters to be optimized. Also, some hyper-parameters, e.g., the number of hidden layers and its units, the number of samples n_i, $i = 1,2,3$ in Eq. (9) to form the input layer and the length of the preview h_p that determines the dimension of the output layer.

The objective function to be minimized with the optimization of the above design parameters is defined as the weighted sum of three performance indices given by

$$J = \rho_1 J_c + \rho_2 J_e + \rho_3 J_p \tag{13}$$

where $\rho_i > 0$, $i = 1,2,3$ are weighting factors. Each component of the objective function J is defined as follows:

J_c: The performance index to evaluate the control performance of the closed-loop system defined by

$$J_c = \sum_{l=1}^{n} \frac{\mathrm{RMS}(\ {}^{l}r_c)}{\mathrm{RMS}(\ {}^{l}r_{off})} + \sum_{l=1}^{n} \frac{\mathrm{Peak}(\ {}^{l}r_c)}{\mathrm{Peak}(\ {}^{l}r_{off})} + \sum_{l=1}^{n} \frac{\mathrm{RMS}(\ {}^{l}a_c)}{\mathrm{RMS}(\ {}^{l}a_{off})} + \sum_{l=1}^{n} \frac{\mathrm{Peak}(\ {}^{l}a_c)}{\mathrm{Peak}(\ {}^{l}a_{off})} \tag{14}$$

where ${}^{l}r_*$ and ${}^{l}a_*$, and $* = c$ or off are the relative displacement between adjacent two floors and the absolute acceleration of each floor of the actively controlled closed-loop system (subscript c) and the system without active control (subscript off) respectively. The superscript l, $l = 1, \dots, n$ is the floor number of the structural system.

J_e: The error between the real and quasi-preview actions defined as

$$J_e = \mathrm{trace}(E_{est}E_{est}^T),\ E_{est} = \overline{K_{ff}} \sum_{k=0}^{k_f} \{w_p(k) - \widehat{w}_p(k)\}, \tag{15}$$

k_f: Final sample of the simulation

where $\overline{K_{ff}}$ is the normalized feedforward gain matrix K_{ff} given by

$$\overline{K_{ff}} = K_{ff}S^{-1},\ S = \mathrm{diag}(\alpha_1, \dots, \alpha_{nu}),\ \alpha_i = \sqrt{K_{ff}(i)\left(K_{ff}(i)\right)^T},\ K_{ff}(i)\text{: } i\text{-th row of } K_{ff} \tag{16}$$

J_p: The penalty function to evaluate the peak control force defined as the following:

$$J_p = \sum_{i=1}^{nu} \mathbf{1}\left(\mathrm{Peak}\left(u_i(k)\right) - \bar{u}_i\right),\ \mathbf{1}(a) = \begin{cases} a & (a \geq 0) \\ 0 & \text{otherwise} \end{cases} \tag{17}$$

where $u_i(k)$ and $\bar{u}_i > 0$, $i = 1, \dots, n_u$ are the control force of the i-th actuator and its allowable peak control force respectively.

For a given design parameter set, all the control signals to compute J (J_c, J_e and J_p) are obtained with the simulation of the structural system with and without active control for a recorded or simulated seismic disturbance.

In this study, all the design parameters in the control system are optimized with the genetic algorithm (GA) with the recorded seismic event(s) data by the offline manner.

6. Simulation example

4.1 Simulation setting

We use data of a recorded seismic event (Niigata Chuetsu Earthquake, M6.8: 17:56 (JST) October 23, 2004) for the simulation study. The system arrangement of the simulation example is shown in Fig. 4.

The epicenter of the earthquake is Kawaguchi Town (Nagaoka City in the present), Niigata Prefecture.

We assume that an actively controlled structural system is located in Niigata City and the state variables of the structural system and the seismic disturbance there are observed. The recorded acceleration of Niigata City is shown in the lower-right part of Fig. 4. The structural system is a 3dof system with an actuator in its base. The coefficient matrices in Eq. (1) of the 3dof system is given as follows:

$$M = \mathrm{diag}(6000, 6000, 6000)\ \mathrm{kg},\ D = \begin{bmatrix} 2.700 & -1.712 & 0 \\ -1.712 & 2.796 & -1.084 \\ 0 & -1.084 & 1.084 \end{bmatrix} \times 10^4\ \mathrm{Ns/m},$$

$$K = \begin{bmatrix} 2.359 & -1.148 & 0 \\ -1.148 & 2.514 & -1.366 \\ 0 & -1.366 & 1.366 \end{bmatrix} \times 10^6\ \mathrm{N/m},\ G = -\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix},\ H = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}, \tag{18}$$

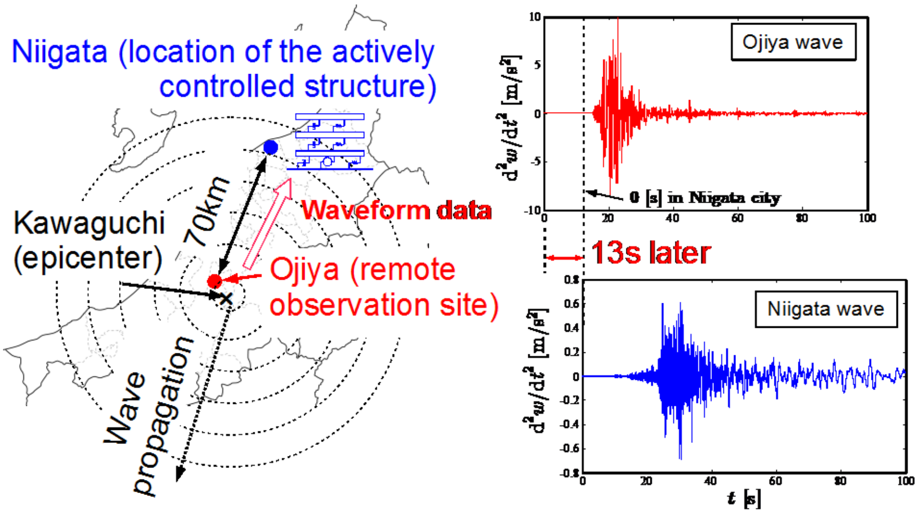

Fig. 4 – System arrangement of the simulation study

Coefficient matrices in Eq. (18) are taken from the model of the 3dof benchmark building of NCREE (National Center for Earthquake Engineering), Taiwan[16]. As the remote seismic wave in the proposed AI-based waveform estimation system, we employ the disturbance observed in Ojiya City (away 70km from Niigata City) located closer from the epicenter than Niigata City. The recorded acceleration waveform of Ojiya City is given in the upper-right part of Fig. 4. We assume the seismic waveform observed in Ojiya City is transmitted to Niigata City where the actively controlled structure located immediately through the network. Note that at 13s of the recorded data in Ojiya City, shown in the broken line of Fig. 4, the record of the waveform in Niigata City is started, i.e., there is a 13 seconds' gap of the onset time of recording between two cities.

4.2 Results and discussion

Under the above simulation setting, design parameters shown in the previous section are optimized with the GA. The sampling period of the control system is $T = 0.01$s. In the ANN of the wave estimation system in Fig. 3, ten samples (0.1s, $n_1 = n_2 = 10$) of the seismic disturbance in both cities are taken as the input accelerations. We set two hidden layers whose number of units are 50 and 40 respectively.

To see the effect of the preview length h_p on the performance of the control system, we consider three different preview length $h_p = 10, 20, 30$ to form $\hat{w}_p(k)$. Those three values of h_p correspond to the time interval of the future waveform estimation 0.1s, 0.2s and 0.3s respectively.

The augmented state feedback gain matrix $K_a = [K_{ff} \quad K_{fb}]$ in Eq. (8) is obtained as

$$K_a = (B_{au}^T X B_{au} + R_w^T R_w)^{-1} B_{au}^T X A_a, \tag{19}$$

where $X \in \mathbf{R}^{(h_p+2n)\times(h_p+2n)}$ is the positive semi-definite solution to the algebraic Riccati equation given by

$$A_a^T X A_a - X - A_a^T X B_{au} (B_{au}^T X B_{au} + R_w^T R_w)^{-1} B_{au}^T X A + Q_w^T Q_w = 0. \tag{20}$$

The upper-bound of the control input $\bar{u}$ in the penalty function J_p in Eq. (17) is $\bar{u} = 4500$N.

For three values of the preview length, $h_p = 10, 20, 30$, design parameters in Section 3 are optimized with GA. The optimized values of the objective function J are summarized in Table 1. Although the obtained values are locally optimal by the property of the objective function J and the stochastic GA optimization, the result indicates that there exists a reasonable preview length in the formulated design problem involving the quasi-preview action in Eq. (10).

Also, for comparison purposes, the LQ optimal state-feedback control law is obtained. The weighting factors are defined similar to Eq. (11) and they are optimized so that the objective function

$$J_{fb} = \rho_1 J_c + \rho_3 J_p \tag{21}$$

Table 1 – Values of the objective function J for tested preview lengths

h_p	10	20	30
J	10.93	5.61	6.94

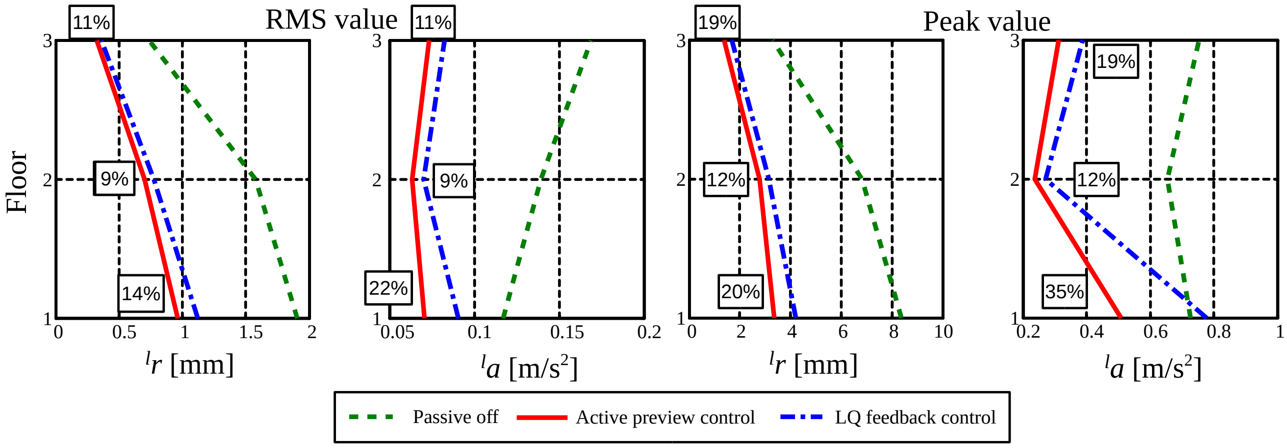

Fig. 5 – RMS and peak values of $^l r(k)$ and $^l a(k)$, $l = 1,2,3$, where Passive off, LQ feedback control and Active preview control are cases without control, optimized LQ state-feedback control, and the proposed quasi-preview control, respectively ($h_p = 20$). The amount of the performance improvement (in percent) of the proposed quasi-preview control compared to the LQ feedback case in each item is also depicted.

where J_c and J_p are defined in the previous section is minimized with the GA.

In the following, we show the result in the case of $h_p = 20$. The results of the optimization are summarized in Fig. 5. The preview control with the waveform estimation system shows the best result. About 10-20 % improvement of the control performance is achieved in the proposed method, in the sense of the averaged RMS and peak values of the relative displacement $^l r(k)$ and the absolute acceleration $^l a(k)$, $l = 1,2,3$ over the optimized LQ state-feedback control law.

Moreover the peak value of the control input denoted by Peak(u) of the proposed preview method is almost same as that of the optimized LQ state-feedback control because the both performance indices J in Eq. (13) and J_{fb} in Eq. (21) contains the penalty function J_p to regulate the peak value of the actuator force. In summary, the proposed preview control method with the AI-based waveform estimation system accomplishes the fairly good control performance compared with the optimized LQ state-feedback control which is one of the most popular and frequently used method for active vibration control.

To see the performance of the waveform estimation system, the time histories of the quasi-preview action using the estimate of the predicted seismic disturbance and the real one using the recorded waveform are shown in Fig. 6. The form of the quasi-preview action with the estimated seismic waveform captures general waveform of the the real preview action. Therefore, the AI-based waveform estimation system proposed in this study works well to realize the quasi-preview action.

7. Conclusion and future research subject

In this study, a new structural vibration control system that consists of the preview control law and

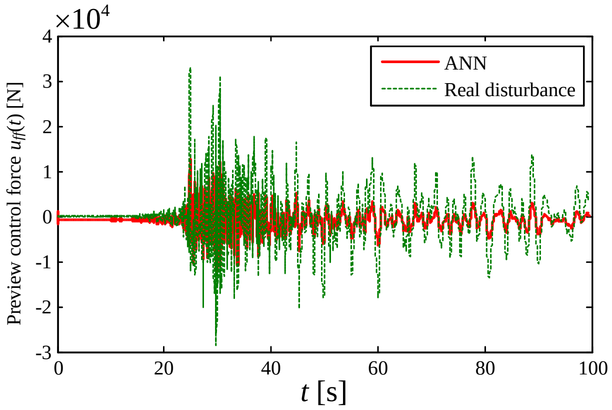

Fig. 6 – Feedfroward control input $u_{ff}(t)$ in cases of the quasi and real-preview actions.

the AI-based waveform estimation system is proposed. With the quasi-preview action using the of the performance improvement becomes possible. A GA-based optimization method of the design parameters in the preview control law and the waveform estimation system is proposed. A small scale estimate of the predicted future seismic disturbance, the preview control that achieves a large amount simulation example with a recorded seismic event in Japan is carried out. The preview length is optimized in the simulation. The proposed control system with the preview control and the AI-based waveform estimation system achieves fairly superior control performance over that of not only the case of the without control, but also the conventional LQ state-feedback control with the weighting factor optimization.

Future research subjects are as follows:

- Feasibility of the wave transmission network with exiting Internet protocol should be examined
- Parameter search of the ANN to achieve the best performance, e.g., the number (samples) of input signals and the output signal (length of the prediction), the number of hidden layers and units in each layer including the structure of the ANN, must be carried out.
- Extension of the present approach to the semi-active control, e.g., [17], or the passive control with adjustable devices having slow dynamics. It is quite important in applying the proposed method to wide range of existing buildings under control.

6. Acknowledgements

The authors used K-NET and KiK-net strong motion data (http://www.kyoshin.bosai.go.jp/) of National Research Institute for Earth Science and Disaster Resilience (NIED), Japan.

This work was partly supported by JSPS KAKENHI Grant-in-Aid for Scientific Research (C) 19K04254.

8. References

[1] Realtime ground-motion monitoring system. Available at: www.kmoni.bosai.go.jp

[2] What is an earthquake early warning? Available at www.jma.go.jp/jma/en/Activities/eew1.html

[3] ShakeAlert: An earthquake early warning system for the west coast of the United States. Available at www.shakealert.org/.

[4] Kuyuk HS and Motosaka M (2009): Forward spectral forecasting of ground motion with the nformation of earthquake early warning systems for structural control. *Journal of Japan Association for Earthquake Engineering*. **9**(3), 14-27.

[5] Sakai S and Hirata N (2009): Distribution of the metropolitan seismic observation network. *Bulletin of the Earthquake Research Institute*, *University of Tokyo*, **84,** 57-69 (in Japanese).

[6] Fu Y, Mechitov K, Hoang T, Kim JR, Lee DH and Spencer BF Jr (2019): Development and full-scale validation of high-fidelity data acquisition on a next-generation wireless smart sensor platform. *Advances in Structural Engineering*, DOI: 10.1177/1369433219866093.

[7] Sun Z, Li B, Dyke SJ, Lu C and Linderman L (2016): Benchmark problem in active structural control with wireless sensor network. *Structural Control and Health Monitoring*, **23,** 20-34.

[8] Tomizuka M and Rosenthal DE (1979): On the optimal digital state vector feedback controller with integral and preview actions. *Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control*, **101**(2), 172-178.

[9] Katayama T, Ohki T, Inoue T and Kato, T (1985): Design of an optimal controller for a discrete-time system subject to previewable demand. *International Journal of Control*, **41**(3), 677-699.

[10] Akbari A and Lohmann B (2010): Output feedback H_∞/GH_2 preview control of active vehicle suspensions: a comparison study of LQG preview. *Vehicle System Dynamics*, **48**(12), 1475-1494.

[11] Birla N and Swarup A (2015): Optimal preview control: a review. *Optimal Control Applications and Methods*, **36,** 241-268.

[12] Marzbanrad J, Ahmadi G and Jha R (2004): Optimal preview active control of structures during earthquakes. *Engineering Structures*, **24,** 1437-1471.

[13] Tateisi A and Nishioka T (2002): Control of structural response by using information on predicted external force. *Journal of Japan Society of Civil Engineers*, **I-58**(696), 21-29 (in Japanese).

[14] Tsuji T, Nakamura H, Kagimura S (2012): Studies on an active preview control of structures and applicability if predicted earthquake motions. *Journal of Japan Society of Civil Engineers*, **A1-58**(1), 110-123 (in Japanese).

[15] Nagashima I, Maseki R (2012): Study on feed-forward control of base-isolated buildings using predicted propagation of seismic waves. *15th World Conference on Earthquake Engineering*, 9820-9820, Lisbon, Portugal.

[16] Nakamura Y, Fukukita A, Tamura K, Yamazaki I, Matsuoka T, Hiramoto K and Sunakoda K (2014): Seismic response control using electromagnetic inertial mass dampers. *Earthquake Engineering and Structural Dynamics*, **43,** 507-527.

[17] Dyke SJ, Spencer BF, Sain MK and Carlson JD (1996): An experimental study of MR dampers for seismic protection. *Smart Materials and Structures*, **7,** 693-703.