STUDIES ON ACTIVE CONTROL OF STRUCTURES USING HYPER VISION TECHNOLOGY

Hideharu NAKAMURA¹, Tokuo TSUJI², Idaku ISHII³, Ryouichi SATAKE⁴,
Takeshi NAKAYAMA⁴ and Junichiro MOTOYAMA⁴

¹Fellow of JSCE, Professor emeritus, Graduate School of Engineering, Hiroshima University
(1-4-1 Kagamiyama, Higashi-Hiroshima-Shi, Hiroshima, 739-8527, Japan)

²Member of JSCE, COE Researcher, Graduate School of Engineering, Hiroshima University
(1-4-1 Kagamiyama, Higashi-Hiroshima-Shi, Hiroshima, 739-8527, Japan)

³Professor, Graduate School of Engineering, Hiroshima University
(1-4-1 Kagamiyama, Higashi-Hiroshima-Shi, Hiroshima, 739-8527, Japan)

⁴Student Member of JSCE, Graduate School of Engineering, Hiroshima University
(1-4-1 Kagamiyama, Higashi-Hiroshima-Shi, Hiroshima, 739-8527, Japan)

Vibration control technologies, both passive and active, have recently seen significant improvements due to technological advancements in computers, sensors, and actuators. Though passive control methods provide greater advantages in terms of maintenance and reliability, active methods are expected to be adopted for important civil engineering structures since they promise more effective structural response control. In this paper we investigate an active control method using hyper vision technology, and derive recurrence relations for time integration which include controlling forces. The feasibility of the active control method is confirmed by numerical simulations and by shaking table tests.

Key Words : *active control, hyper vision, high-speed camera, shaking table test, numerical simulation*

1. INTRODUCTION

Vibration control is a technology that employs a control mechanism to decrease structural vibration brought on by strong earthquakes and winds. The technology comes in two forms; active control that applies power to the structure to decrease vibration positively, and passive control that applies various types of dampers to decrease structural vibration without applying power. Various studies have been reported on passive control, including the application of tuned mass dampers¹⁾, tuned fluid dampers^{2), 3), 4)} and other dampers with special features^{5), 6)}, as well as research on actual large structures⁷⁾ and experimental methods⁸⁾. Though considerable research has also been performed on active control, such as studies on practical use on the Honshu Shikoku Bridges and on preview control methods, the amount of studies remains far less than that reported for passive control.^{1), 10), 11), 14), 15)}

Recent advancements in sensors, computers and

actuators have helped improve active control methods. Most active control technology is based on the modern control theory, and is designed to calculate controlling force by minimizing the evaluation function which is the quadratic form of the quantity of states and the control force^{12), 13), 14)}. Though the modern control theory is considered to be complete, it is applicable only to linear models. Therefore, it cannot be applied to problems in civil engineering structures that are not suitable for linear modeling. However, depending on progress in sensors, computers, and actuators^{1), 14), 15)}, it is possible to realize new control techniques for non-linear models including bridges and building structures.

One of authors, I. Ishii, developed a hyper vision technology called MmVision. Most conventional real-time vision is limited to 30 fps, since the cameras are designed with an NTSC video signal. Even though several vision chips have been developed for working at more than 1000 fps, their one chip integration limits resolution to thousands pixels.

MmVision employs intelligent pixel selection to achieve mega-pixel resolution at 1000 fps by eliminating the need to record all the pixels in an image at the same moment. Instead, it selects only those pixels required in any given image for transfer to the processor on the PC. This has the added advantage of drastically reducing communication and processing costs¹⁶⁾.

When we apply this hyper vision technology to the active control of civil engineering structures, multi-point displacements of the whole structure and seismic motion (acceleration) at the base of the structure can be measured at a time interval of 1/100 to 1/1000 seconds. The measured values can then be introduced into the controlling system, to calculate and determine the controlling forces at intervals of 1/100 seconds or less, and to act on the structure. The controlling force calculation method suitable for such conditions must be able to quickly calculate by simple calculation formula using the acceleration and displacement data for each short interval. In addition, when nonlinearity appears in the vibration phenomena the calculation method should be able to correspond flexibly to nonlinear control.

As an active control method that meets these requirements, this paper adopts the direct integration of the equations of motion, and shows recurrence relations including controlling force based on analytical derivation^{17),18)}. Integration of the non-homogeneous solution can be accomplished by assuming that earthquake force acceleration is constant or changes linearly during time step Δt . When observed displacements and controlling forces are introduced in the recurrence relation, it is important to appropriately select the dominant natural vibration modes related to the vibration of the whole structure. Precise selection is critical for several reasons; the number of the observed displacement is far less than the degree of freedom in numerical models for structures, displacements of nodal points for the whole structure have to be estimated from the observed displacements, and the relation between the observed displacements and the controlling forces have to be provided accurately. It is possible to correspond to material nonlinearity by selectively using recurrence relations in various nonlinear cases that have been prepared beforehand.

Hereafter, applications of displacement measurement by hyper vision technology to actual problems are described in section 2, and a calculation method of active controlling forces based on the use of hyper vision technology as proposed here is shown in section 3. Furthermore, the system configuration and control procedure using a high speed camera are explained with an example in section 4, and active

control test results using a shaking table are shown in section 5. Finally in section 6, it is confirmed that active control is possible by using the calculated controlling forces based on obtained displacements of structures and earthquake motion at the base measured at intervals of 1/100 seconds or less, as assumed through the comparative study of the test results and analytical results.

2. DISPLACEMENT MEASUREMENT BY HYPER VISION TECHNOLOGY APPLIED TO ACTUAL PROBLEMS

When a hyper vision system is set up in an actual structure and examined for proper adjustment to site conditions, it must basically be capable of meeting the three following requirements:

- 1) Measure the object even when earthquake motion causes the camera to vibrate
- 2) Produce sufficiently high resolution
- 3) Stably measure multi-markers on the same screen

These conditions can be satisfied by the corresponding to the following:

- 1) Positional data of multi-points measured on the same screen are converted into relative displacements to base or near ground measurement points, because absolute displacements cannot be measured when earthquake motion causes the camera to shake, and displacements in the equations of motion also include relative displacements to the ground. Therefore, the camera is set on the base of the structure, or relative displacements of each measurement point from the base point are calculated by setting the camera at other advantageous places for measurement (**Fig.1**). When the camera rotates, the influence can be removed by calculating the rotation from displacement measurement values of two points adjacent to the base of the structure.
- 2) The resolution of high-speed vision is 1280×1024 pixels. The accuracy of displacement of the marker is about one tenth of one pixel width using subpixel estimation¹⁹⁾. Vision accuracy is then 1/10000 of the monitoring range. Greater resolution can be expected as camera image capacity continues to improve. By using multiple synchronized visions, large structures can be measured with greater accuracy.
- 3) By using emission light as a marker, MmVision can track effectively as long as there is no other light source near the marker.

Fig.1 Concept of active control system examined in this paper.

3. METHOD FOR CALCULATING ACTIVE CONTROL FORCE PREMISED ON APPLICATION OF THE HYPER VISION TECHNOLOGY

Based on the current state that analytical evaluation including material nonlinearity effect has been taken into consideration of plasticity to seismic motion ranked level 2, if necessary, in “Specifications for Highway Bridges, Part V: Seismic Design”^[20], and on the assumption of the measurement of multipoint displacements using high speed camera and acceleration on the base of structure, we propose a following active control procedure. Because the control procedure is a single step time integration scheme based on the general solution of simultaneous ordinary differential equations, flexible correspondence is possible by calculating the following recurrence relation matrices beforehand corresponding to various states of elasto-plasticity if the elasto-plastic condition is in a range that can be calculated by a constitutive equation (Mises’s yield criterion, J2 flow rule, isotropic hardening or kinematic hardening) intended for the metal materials.

(1) Solution of the equations of motion

The equations of motion are given by Equation (1) in matrix form.

$$M\ddot{U} + C\dot{U} + KU = P(t) \quad (1)$$

where

M, C, K : Mass, damping, and stiffness matrices,

$\ddot{U}, \dot{U}, U$: Acceleration, velocity and displacement vectors,

$P(t), t$: External force vector, time, respectively.

Equation (1) is transformed into Equation (2).

$$\dot{Y} = AY + Q \quad (2)$$

where

$$Y = \begin{Bmatrix} \dot{U} \\ U \end{Bmatrix} \quad (3)$$

$$A = \begin{bmatrix} -M^{-1}C & -M^{-1}K \\ I & 0 \end{bmatrix} \quad (4)$$

$$Q = \begin{Bmatrix} M^{-1}P \\ 0 \end{Bmatrix} \quad (5)$$

Equation (6) is the general solution of Equation (2), from which the recurrence relation of Equation (7) is obtained.

$$Y(t) = e^{At}Y(0) + e^{At} \int_0^t e^{-As}Q(s)ds \quad (6)$$

$$Y(t + \Delta t) = e^{A\Delta t}Y(t) + e^{A\Delta t} \int_t^{t+\Delta t} e^{-As}Q(s)ds \quad (7)$$

If polynomial approximation is adopted for exponential function, $e^{A\Delta t}$ becomes the next expression;

$$e^{A\Delta t} = I + A\Delta t + A^2 \frac{\Delta t^2}{2!} + A^3 \frac{\Delta t^3}{3!} + \dots \quad (8)$$

If rational approximation is adopted, $e^{A\Delta t}$ becomes the next expression.

$$e^{A\Delta t} = \frac{I + A \frac{\Delta t}{2} + A^2 \frac{1}{2!} \left(\frac{\Delta t}{2}\right)^2 + A^3 \frac{1}{3!} \left(\frac{\Delta t}{2}\right)^3 + \dots}{I - A \frac{\Delta t}{2} + A^2 \frac{1}{2!} \left(\frac{\Delta t}{2}\right)^2 - A^3 \frac{1}{3!} \left(\frac{\Delta t}{2}\right)^3 + \dots} \quad (9)$$

There are many exponential function approximations available, such as continued fraction approximation. However, it is clear that the selection of an approximation method for the exponential function is important for obtaining numerical stability. As a result of investigation comprehensively considering the calculation efficiency, accuracy and numerical stability, we confirmed effectiveness for the rational approximation of Equation (9) to consider up to second order term of Δt of the denominator and numerator.

(2) Time integration^{17), 18), 21)}

To do step-by-step time integration based on Equation (7), some restrictions are necessary for $Q(s)$, such as constant or linear change during time increment Δt . If Δt is shortened, the problem of accuracy decreases and is canceled on practical use.

a) When $Q(s)$ is constant during time increment Δt

This case corresponds when seismic force $P_{t+\Delta t}$ after Δt cannot be previewed. If $Q(s)$ is constant during Δt , Equation (10) is derived from the Equation (7).

$$\begin{Bmatrix} \dot{U}_{t+\Delta t} \\ U_{t+\Delta t} \end{Bmatrix} = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \begin{Bmatrix} \dot{U}_t \\ U_t \end{Bmatrix} + \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix} \{P_t\} \quad (10)$$

where

$\dot{U}_{t+\Delta t}, U_{t+\Delta t}$: Velocity and displacement vectors at time $t + \Delta t$

$\dot{U}_t, U_t, P_t$: Velocity, displacement and seismic force vectors at time t .

Coefficient matrices of the recurrence relations (10) are

$$\begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} = e^{A\Delta t} \quad (11)$$

and

$$B^0 = \int_0^{\Delta t} e^{As} ds = A^{-1}(e^{A\Delta t} - I) = \begin{bmatrix} B_{11}^0 & B_{12}^0 \\ B_{21}^0 & B_{22}^0 \end{bmatrix} \quad (12)$$

$$\begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix} = \int_0^{\Delta t} e^{A(\Delta t-s)} \begin{bmatrix} I \\ 0 \end{bmatrix} ds M^{-1} = \begin{bmatrix} B_{11}^0 \\ B_{21}^0 \end{bmatrix} M^{-1} \quad (13)$$

b) When $Q(s)$ changes linearly during time increment Δt

Due to technical advances in earthquake early warning based on prompt analysis of the epicenter and magnitude using wave form data observed by seismographs, if the following earthquake forces $P_{t+\Delta t}$ can be predicted according to the Earthquake Early Warning system, Equation (14) based on the assumption of linearly varying $Q(s)$ during Δt in Equation (7) can effectively use.

$$\begin{Bmatrix} \dot{U}_{t+\Delta t} \\ U_{t+\Delta t} \end{Bmatrix} = \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \begin{Bmatrix} \dot{U}_t \\ U_t \end{Bmatrix} + \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{Bmatrix} P_{t+\Delta t} \\ P_t \end{Bmatrix} \quad (14)$$

where

$\dot{U}_{t+\Delta t}, U_{t+\Delta t}, P_{t+\Delta t}$: Velocity, displacement and seismic force vectors at time $t + \Delta t$,

$\dot{U}_t, U_t, P_t$: Velocity, displacement and seismic force vectors at time t .

Coefficient matrix of the right side first term of recurrence relations (14) is the same as case a), and the second term is as follows:

$$\begin{aligned} B^1 &= \int_0^{\Delta t} s e^{As} ds = A^{-1} \{ \Delta t e^{A\Delta t} - A^{-1}(e^{A\Delta t} - I) \} \\ &= \begin{bmatrix} B_{11}^1 & B_{12}^1 \\ B_{21}^1 & B_{22}^1 \end{bmatrix} \end{aligned} \quad (15)$$

$$\begin{aligned} \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} &= \int_0^{\Delta t} e^{A(\Delta t-s)} \begin{bmatrix} \frac{s}{\Delta t} I & \frac{\Delta t-s}{\Delta t} I \\ 0 & 0 \end{bmatrix} ds \begin{bmatrix} M^{-1} & 0 \\ 0 & M^{-1} \end{bmatrix} \\ &= \begin{bmatrix} B_{11}^0 - \frac{1}{\Delta t} B_{11}^1 & \frac{1}{\Delta t} B_{11}^1 \\ B_{21}^0 - \frac{1}{\Delta t} B_{21}^1 & \frac{1}{\Delta t} B_{21}^1 \end{bmatrix} \begin{bmatrix} M^{-1} & 0 \\ 0 & M^{-1} \end{bmatrix} \end{aligned} \quad (16)$$

(3) Time integration when controlling forces are introduced

a) When $Q(s)$ is constant during time increment Δt

Adding controlling forces to the right side of Equation (10), though it depends on a mechanical characteristics of the control system, it can be said that Equation (17) is appropriate, because the controlling forces are not necessarily changed ideally as in a step function.

$$\begin{aligned} \begin{Bmatrix} \dot{U}_{t+\Delta t} \\ U_{t+\Delta t} \end{Bmatrix} &= \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \begin{Bmatrix} \dot{U}_t \\ U_t \end{Bmatrix} + \begin{bmatrix} H_{11} \\ H_{21} \end{bmatrix} \{P_t\} \\ &+ \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{Bmatrix} F_{t+\Delta t} \\ F_t \end{Bmatrix} \end{aligned} \quad (17)$$

where

$\dot{U}_{t+\Delta t}, U_{t+\Delta t}, F_{t+\Delta t}$: Velocity, displacement and controlling force vectors at time $t + \Delta t$,

$\dot{U}_t, U_t, P_t, F_t$: Velocity, displacement, seismic force and controlling force vectors at time t .

b) When $Q(s)$ changes linearly during time increment Δt

According to the same idea as a), Equation (18) seems to be suitable.

$$\begin{aligned} \begin{Bmatrix} \dot{U}_{t+\Delta t} \\ U_{t+\Delta t} \end{Bmatrix} &= \begin{bmatrix} E_{11} & E_{12} \\ E_{21} & E_{22} \end{bmatrix} \begin{Bmatrix} \dot{U}_t \\ U_t \end{Bmatrix} \\ &+ \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{Bmatrix} P_{t+\Delta t} + F_{t+\Delta t} \\ P_t + F_t \end{Bmatrix} \end{aligned} \quad (18)$$

where

$\dot{U}_{t+\Delta t}, U_{t+\Delta t}, P_{t+\Delta t}, F_{t+\Delta t}$: Velocity, displacement, seismic force and controlling force vectors at time $t + \Delta t$,

$\dot{U}_t, U_t, P_t, F_t$: Velocity, displacement, seismic force and controlling vectors at time t .

(4) Relations between observed displacements and displacement vector of the whole structure

Using eigen vector $\{u_i\}$, displacement vector U of the whole structure of n -degree of freedom can be expressed as Equation (19).

$$U = z_1 \{u_1\} + z_2 \{u_2\} + \dots + z_n \{u_n\} \quad (19)$$

Though there is no limitation in the number of observed displacements, if we assume the two main eigen vectors that contribute to the vibration to be $\{u_1\}, \{u_2\}$, U is approximated by Equation (20).

$$U \approx [\{u_1\}, \{u_2\}] \begin{Bmatrix} z_1 \\ z_2 \end{Bmatrix} \quad (20)$$

If we assume the observed displacements to be U_A, U_B , they are shown as the next expression.

$$\begin{Bmatrix} U \\ U_A \\ U_B \end{Bmatrix} = \begin{bmatrix} u_{1A} & u_{2A} \\ u_{1B} & u_{2B} \end{bmatrix} \begin{Bmatrix} z_1 \\ z_2 \end{Bmatrix} \quad (21)$$

Taking out only the necessary parts of Equation (21), Equation (22) and (23) are obtained:

$$\begin{Bmatrix} U_A \\ U_B \end{Bmatrix} = \begin{bmatrix} u_{1A} & u_{2A} \\ u_{1B} & u_{2B} \end{bmatrix} \begin{Bmatrix} z_1 \\ z_2 \end{Bmatrix} \quad (22)$$

$$\begin{Bmatrix} z_1 \\ z_2 \end{Bmatrix} = \begin{bmatrix} u_{1A} & u_{2A} \\ u_{1B} & u_{2B} \end{bmatrix}^{-1} \begin{Bmatrix} U_A \\ U_B \end{Bmatrix} \quad (23)$$

Though it is clear that the displacement of the whole structure can be provided from the limited observed displacements by Equation (24), it is no wonder that the selection of appropriate eigen modes is very important.

$$U = [\{u_1\}, \{u_2\}] \begin{bmatrix} u_{1A} & u_{2A} \\ u_{1B} & u_{2B} \end{bmatrix}^{-1} \begin{Bmatrix} U_A \\ U_B \end{Bmatrix} \quad (24)$$

(5) Estimation method of controlling forces

The number of control points and directions are also limited as well as the number of measurement points. Excessive controlling forces not only demand excessive power from the control system, but also excite the higher-order vibration modes and cause unstable vibration, therefore, parameter α is intro-

duced as the controlling force adjustment. As shown in **Fig.2** conceptually, without control, displacement U_t at time t reaches B and moves $(B - U_t)$ during Δt . However, displacement is controlled to $\alpha(B - U_t)$ ($0 < \alpha \leq 1$) by adding the controlling forces. If α is appropriately set, steady control can be achieved for the noise because the control forces are added so that the kinetic energy is reduced.

a) When $Q(s)$ is constant during time increment Δt

Equation (17) can be transformed to the next expression.

$$U_{t+\Delta t} = E_{21}\dot{U}_t + E_{22}U_t + H_{21}P_t + G_{21}F_{t+\Delta t} + G_{22}F_t \quad (25)$$

We define B as Equation (26).

$$B = E_{21}\dot{U}_t + E_{22}U_t + H_{21}P_t + G_{22}F_t \quad (26)$$

Equation (27) is obtained from Equation (25).

$$U_{t+\Delta t} - B = G_{21}F_{t+\Delta t} \quad (27)$$

B is displacement vector $U_{t+\Delta t}$ at the next step without controlling forces. The controlling forces are the components of the controlling force vector $F_{t+\Delta t}$. If the controlling forces are f_1 and f_2 , Equation (27) can be written as in Equation (28):

$$\begin{Bmatrix} U_{t+\Delta t,A} \\ U_{t+\Delta t,B} \end{Bmatrix} - \begin{Bmatrix} B_A \\ B_B \end{Bmatrix} = \begin{bmatrix} g_1 & g_2 \\ g_3 & g_4 \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} \quad (28)$$

If we assume α ($0 < \alpha \leq 1$) is the coefficient to determine the ratio of displacement with the controlling force in time step $t + \Delta t$ to displacement without the controlling force as shown in **Fig.2**, Equation (28) can be written as in Equation (29):

$$(1 - \alpha) \begin{Bmatrix} U_{t,A} \\ U_{t,B} \end{Bmatrix} - \begin{Bmatrix} B_A \\ B_B \end{Bmatrix} = \begin{bmatrix} g_1 & g_2 \\ g_3 & g_4 \end{bmatrix} \begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} \quad (29)$$

Taking out only the necessary parts of Equation (29), Equation (30) is obtained:

$$\begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} = (1 - \alpha) \begin{bmatrix} g_1 & g_2 \\ g_3 & g_4 \end{bmatrix}^{-1} \left(\begin{Bmatrix} U_{t,A} \\ U_{t,B} \end{Bmatrix} - \begin{Bmatrix} B_A \\ B_B \end{Bmatrix} \right) \quad (30)$$

Though the value of the best α cannot be set uniformly, because it differs depending on a structural form or the capacity of the controlling system, it is confirmed, even if α is about 0.8-0.9, that remarkable control effects are found under the high amplification condition by resonance, as described later (Fig.16).

In addition, $\dot{U}_t$ in Equation (25) is calculated in the previous step as $\dot{U}_{t+\Delta t}$ using Equation (31) derived from Equation (17).

$$\dot{U}_{t+\Delta t} = E_{11}\dot{U}_t + E_{12}U_t + H_{11}P_t + G_{11}F_{t+\Delta t} + G_{12}F_t \quad (31)$$

Alternatively, when we apply this control method to a shaking table test or an actual structure, $\dot{U}_t$ also can be provided by the finite difference approximation based on the displacement measurement values before several steps.

b) When $Q(s)$ changes linearly during time increment Δt

Equation (18) can be transformed to the next expression,

$$U_{t+\Delta t} = E_{21}\dot{U}_t + E_{22}U_t + G_{21}(P_{t+\Delta t} + F_{t+\Delta t}) + G_{22}(P_t + F_t) \quad (32)$$

We define B as Equation (33).

$$B = E_{21}\dot{U}_t + E_{22}U_t + G_{21}P_{t+\Delta t} + G_{22}(P_t + F_t) \quad (33)$$

Equation (34) is obtained from Equation (32).

$$U_{t+\Delta t} - B = G_{21}F_{t+\Delta t} \quad (34)$$

The controlling forces can be calculated according to a procedure similar to a). Likewise, $\dot{U}_t$ in Equation (32) is calculated in the previous step as $\dot{U}_{t+\Delta t}$ using Equation (35) derived from Equation (18).

$$\dot{U}_{t+\Delta t} = E_{11}\dot{U}_t + E_{12}U_t + G_{11}(P_{t+\Delta t} + F_{t+\Delta t}) + G_{12}(P_t + F_t) \quad (35)$$

Alternatively, when we apply this control method to a shaking table test or an actual structure, $\dot{U}_t$ also can be provided by a procedure similar to a).

Fig.2 Definition of coefficient α ($0 < \alpha \leq 1$).

4. COMPOSITION OF THE CONTROL SYSTEM AIDED BY HYPER VISION TECHNOLOGY AND THE CONTROL PROCESS

(1) The overview of system

According to the control method previously described in 3., the proposed control system is composed of three main parts as below (Fig.1):

- 1) Measure multi-point displacements using a high speed camera and acceleration of the structure base using an acceleration meter.
- 2) Calculate controlling forces using the acquired displacement and acceleration data.
- 3) Transmit the signal to actuators and having the controlling forces act on the structure.

The active vibration control is done by repeating these procedures performed within about 1/100 seconds.

(2) Control process

The trigger acts if acceleration at the base of the structure exceeds the specified value, the control system starts, and the control progresses according to the following procedures:

- 1) Obtain measurement displacements $U_{t,A}, U_{t,B}$ at time t , if measurement points are assumed to be A and B, by high speed camera.
- 2) Calculate the displacement vector of the whole structure using Equation (24).

$$U_t = \begin{bmatrix} \{u_1\}, & \{u_2\} \end{bmatrix} \begin{bmatrix} u_{1A} & u_{2A} \\ u_{1B} & u_{2B} \end{bmatrix}^{-1} \begin{Bmatrix} U_{t,A} \\ U_{t,B} \end{Bmatrix} \quad (24)$$

- 3) Calculate the load vector to act on the whole structure using the earthquake acceleration obtained on the base at time t .
- 4) Obtain B of Equation (26) or Equation (33) by using $\dot{U}_t$ led by calculation one step ahead or by using $\dot{U}_t$ approximated by finite difference using the displacement measurement values. In the first step of the control, unknown values are all assumed to be zero.
- 5) Obtain controlling forces f_1, f_2 for the next step by Equation (30), and determine the controlling force vector $F_{t+\Delta t}$. In the first step of the control, unknown values are all assumed to be zero.

$$\begin{Bmatrix} f_1 \\ f_2 \end{Bmatrix} = (1 - \alpha) \begin{bmatrix} g_1 & g_2 \\ g_3 & g_4 \end{bmatrix}^{-1} \left\{ \begin{Bmatrix} U_{t,A} \\ U_{t,B} \end{Bmatrix} - \begin{Bmatrix} B_A \\ B_B \end{Bmatrix} \right\} \quad (30)$$

- 6) Obtain $\dot{U}_{t+\Delta t}$ using Equation (31) or Equation

(35), however, no calculation is needed for $\dot{U}_{t+\Delta t}$ if $\dot{U}_t$ is provided by the finite difference approximation in the next step based on the displacement measurement values from the high speed camera.

- 7) Send the control signal and apply the controlling forces to the structure.
- 8) Return to 1) when the control is continued. Alternatively, discontinue the control and to terminate when the measurement displacements and observed acceleration drop below the definite values.

5. ACTIVE CONTROL TESTS USING SHAKING TABLE

(1) Test procedures

A framed structure model composed of four columns and multi-floors as shown in **Fig.3** and **Fig.4** was used for the active control tests. Under the condition in which a mass of 30kg is placed on the top floor of the framed structure model, the first and second natural periods of the horizontal direction of the long side are 0.51 and 0.067 seconds, and the damping ratio is 0.02. The lowest part of the framed structure model is inserted in a 30mm long pipe welded to the steel plate, and in addition, fixed with two or more screws perpendicularly installed the pipe.

Fig.5 shows conditions to set up the wire to make the controlling forces act on the framed structure model, and **Fig.6** shows the situation in which LED (Light Emitting Diode) lights are set up in the displacement measurement points as markers. Two wires shown in **Fig.5** are set between the markers (Marker 3 $\leftrightarrow$ Marker 5 $\leftrightarrow$ Motor 2, and Marker 6 $\leftrightarrow$ Marker 2 $\leftrightarrow$ Motor 1), and it is possible to make the controlling forces act on the framed structure model only by the resulting tension.

Servo motors 1 and 2 (**Fig.5**) set up on the shaking table are used as high-speed actuators as shown in **Fig.7**. The motors rotate and strain the wire in the arrow direction as shown in **Fig.5**. The motor specifications are 100V voltage, 50W output power, 0.159N-m rated torque, 0.48N-m maximum torque, 3000rpm rated rotation speed and 5000 rpm maximum rotation speed.

The high speed camera shown in **Fig.8** measured marker displacement from a position on the concrete floor approximately 2m from the shaking table. Marker displacements of the framed structure model related to the motion of the shaking table were obtained by subtracting the displacement of Marker 1 on the shaking table. This image displacement

measurement system was able to measure several marker points simultaneously at 100 frames per second or faster with a maximum error factor of 0.05cm. Though placement of the camera on the shaking table would allow direct measurement of the relative displacements of Marker 2 - 6 to Marker 1, dimensional limitations of the shaking table and the framed structure model made it necessary to place the camera on the concrete floor adjacent to the shaking table.

Acceleration of the shaking table was measured using an ordinary accelerometer which obtained values every 1/100 seconds. This data was then transmitted to the PC as shown in **Fig.9** and **Fig.10**, and the controlling forces were calculated using the values as earthquake motions. The accelerometer was not fixed to the framed structure model.

(2) Seismic waves used for shaking table tests

In the shaking table tests, the control effect of the framed structure model was confirmed by using sine waves and two kinds of earthquake waves with different characteristics. The sine waves used had the same natural frequency (1.9Hz) as the structure model and were assumed to provide a high amplification ratio.

Earthquake waves recorded at Kobe Marine Observatory during the Hyogoken-nanbu Earthquake (1995, M7.2, NS) and at the Ushita filtration plant in Hiroshima during the Geiyo Earthquake (2001, M6.4, NS)^{22), 23)} were adopted for the shaking table tests. The Geiyo Earthquake was an inslab seismic event occurring within the plate and demonstrated a mechanism of earthquake generation that differs from plate boundary and inland active fault type earthquakes. The presence of short period elements is a common feature of inslab earthquake movement.

The acceleration of these earthquake waves was integrated and after the displacement shift was corrected by a low-order polynomial, the displacement waveform was converted into voltage waveform with a maximum displacement of one volt, and was used as an input signal to the shaking table. Hereafter, these reproduced earthquake waves are referred to as the Experiment Kobe wave and Experiment Geiyo wave, respectively.

Fig.9 shows the acceleration waveform and displacement waveform for the Experiment Kobe wave. These waves are measured on the shaking table. Similarly, **Fig.10** shows corresponding values for the Experiment Geiyo wave measured on the shaking table. Though these amplitudes depend on the excitation power of the shaking table, it was confirmed that the reproduced waveforms corresponded to the original waveforms. **Fig.11** shows the acceleration response spectrums of the earthquake waves made

through such a process. The spectrum peak was observed at about 0.1 seconds for the Experiment Geiyo wave and at 0.3-0.7 seconds for the Experiment Kobe wave with several short period elements. Therefore, since the Experiment Kobe wave and the Experiment Geiyo wave have a different resonance frequency area, they constitute an effective earthquake wave pair to compare the effects of the active control.

Fig.4 Uniaxial shaking table used in the test.

Fig.7 Motor to apply controlling force.

Fig.5 Test setup.

Fig.6 Marker (LED) position.

Fig.8 High speed camera.

(a) Reproduced accelerogram on the shaking table

(b) Displacement on the shaking table

Fig.9 Experiment Kobe wave used for shaking table tests (Reproduced wave recorded at Kobe JMA station (N-S) during the 1995 Hyogoken-Nanbu earthquake).

(a) Reproduced accelerogram on the shaking table

(b) Displacement on the shaking table

Fig.10 Experiment Geiyo wave used for shaking table tests (Reproduced wave recorded at Ushita Water Purification Plant in Hiroshima (N-S) during the 2001 Geiyo earthquake²³⁾).

Fig.11 Acceleration response spectra of two seismic motions (Experiment Kobe and Geiyo waves, Damping ratio: 0.02).

(3) Addition of controlling forces

When wires are attached as shown in **Fig.5**, horizontal forces f_A, f_B shown in **Fig.12** are caused by the wire tension acting on the nodes of the framed structure model as controlling forces. The vertical direction force is considered to have no influence on the horizontal vibration.

Assuming the condition of non-deformation, f_A, f_B are led by geometric relation. However, in actual application it is necessary to operate the motor after additional tension is applied because the model inclines and additional tension is generated in the wire. Meanwhile, nodal points A, B, C, D and E in **Fig.12** (a) correspond to the position of Markers 3, 6, 2, 5 and 1 in **Fig.12** (b).

Fig.13 shows the section within nodal points A, B, C, and D. If the length of the wire in the original condition is assumed as W_1 , the length of the wire in the inclined condition is assumed as W_2 , the distance between node A and node C is assumed as h , and the distance between node A and node B is assumed as b , the change of the length of the wire ΔW can be obtained from the geometrical relation by Equation (36) by disregarding the displacement in the vertical direction and the expansion and contraction of the structural member is negligible.

(a) Wire drawing (b) Controlling forces by wire
Fig.12 Forces to act on nodes by tension of wire.

Fig.13 Expansion of diagonal wire according to shearing deformation of framed structure model.

$$\Delta W = W_2 - W_1 \approx \frac{b}{\sqrt{h^2 + b^2}}(X_1 - X_2) \quad (36)$$

where

X_1, X_2 : Horizontal displacements of nodal points A and C measured with the high speed camera

In addition, if the following relation 1) and the value 2) are confirmed by a preliminary experiment, the relation between the wire tension corresponding to the controlling force and the motor rotation factoring the model deformation during excitation can be obtained.

- 1) Relation between the rotation of the motor and the roll length of the wire
- 2) Spring constant of the wire

Though these tests dealt primarily with the first natural vibration, the control method proposed here is capable of controlling the second or further higher-order natural vibrations by arranging two or more actuators.

(4) Results of the shaking table tests

Vibration behaviors of the framed structure model during excitation by the sine wave and the two types of earthquake waves are shown in **Fig.14** with attention to the response displacement in the direction of the excitation axis at the top position (Marker 4). Under the condition without control, the maximum response values were 1.9 cm for the sine wave, 1.4 cm for the Experiment Kobe wave and 0.93 cm for the Experiment Geiyo wave, respectively, and hereafter, the effects of active control are clarified based on these values.

In the following tests, parameter α used in Equation (30) is assumed to be $\alpha = 0.8$ and the controlling forces are made to act at time intervals of $\Delta t = 1/100$ seconds.

Fig.14 (a) shows a comparison of results for cases with and without control using the sine wave (1.9Hz). Similarly, **Fig.14** (b) shows the same data for the Experiment Kobe wave, and **Fig.14** (c) for the Experiment Geiyo wave.

In the case of excitation by the sine wave, the maximum response horizontal displacement for the top position (Marker 4) was 0.41 cm with control, and 1.9 cm without control, showing that the maximum response displacement can be reduced up to about 22%. Moreover, though there is no corresponding data for the middle position (Marker 2) relative to the top position (Marker 4), approximately the same level or somewhat larger horizontal displacement was caused at Marker 2. This phenomenon appears to have been caused by excitation introduced to the

second mode by the controlling force. When the proposed control method is applied to a small number of controlling force, it is necessary to weaken the control force moderately by α of Equation (30) to avoid excessive effects from higher-order modes. Such problems can be naturally mitigated by increasing the number of controlling force.

During excitation by the Experiment Kobe wave, the maximum response horizontal displacement of the top position (Marker 4) was 0.40 cm with control, and 1.4 cm without control, showing a reduction to approximately 29%. As with the sine wave excitation, Marker 2 may undergo larger displacement than Marker 4. During excitation by the Experiment Geiyo wave, the maximum response horizontal displacement of the top position (Marker 4) was 0.33 cm with control, and 0.93 cm without control, showing a reduction to approximately 35%. The same tendency was found as with excitation by sine wave and the Experiment Kobe wave.

Next, horizontal displacement and the controlling forces of Marker 4 are considered. **Fig.15** (a) shows the relation among displacement and controlling forces f_A, f_B , which confirms that the controlling forces were effective in suppressing the vibration amplitude. Similar results are shown in **Fig.15** (b) and (c) for the Experiment Kobe wave and the Experiment Geiyo wave.

These results confirm that we can depend on the control effect when vibrating at a large amplification ratio. However, it was also confirmed that when the framed structure model is controlled at the time increment of $\Delta t = 1/100$ sec., the control effect was large whether a large amplification ratio is assumed for the resonance area or a low amplification ratio is assumed for the non-resonance area.

In addition, because the capacity of the control mechanism is also very important in investigating the control system, the maximum response displacement values to $\alpha = 0.0 - 1.0$ (not controlled) shown in Equation (30) were examined by using Experiment Kobe wave in order to understand the tendencies of the control effect. **Fig.16** shows the effect of active control on the ratio of the maximum response displacement corresponding to $\alpha = 1.0$. It can be understood that the effect of active control increases rapidly when α changes from 1.0 to about 0.8, and afterwards the effect increases gradually as α decreases further than 0.8.

The rate between the motor rotation angle and the wire tension force is obtained in a preliminary experiment. Achievement of the targeted controlling force is then evaluated using a rotary encoder. **Fig. 17** shows target encoder values and real encoder values from 10sec. to 15sec.. These terms are selected since

the controlling force is larger than the other terms. The target force is achieved quickly and there is no obvious phase lag with consideration of the natural period of the framed structure model. The actuator dynamics show sufficient response and the target controlling force is achieved.

Moreover, it can be pointed out that measuring displacement directly by hyper vision technology does not require strong noise suppression. Also, while integral error accumulates when velocity and displacement are obtained by an accelerometer, when obtaining these data from displacement, numerical error does not accumulate and steady measurements are possible though some numerical error accompanying the differentiation does exist.

6. COMPARISON OF TEST AND COMPUTATION RESULTS

The shaking table tests confirmed our theoretical assumption that the vibration control can be attained by using the calculation method of controlling forces and the control system proposed in this paper. We carried out a comparative analysis of the computational simulation and the shaking table test results to verify the proposed method. For purposes of the analysis, 0.02 was adopted for the critical damping ratio based on observed values, 0.8 was adopted for coefficient α , and 1/100 sec. was adopted for time increment Δt .

Data comparing the test results and the computational results on the excitation direction displacement of marker 4 for the case without control is shown in **Fig.18**. Sine wave (1.9Hz) and the earthquake acceleration waves shown in **Fig.9** and **Fig.10** were used for the analysis. Computational results and test results corresponded well for both the phase and the response displacement.

Fig. 19 shows corresponding data for the case with control. When applying the Experiment Kobe wave both phases and response displacements corresponded well when the response displacement was large, though a fast periodic component was observed in the overall test results (See **Fig.19** (b)). The same results were found for the Experiment Geiyo wave tests, except that in this case the effect of the control was remarkable (See **Fig.19** (c)).

As a cause of the difference, it was a possibility that the vibration caused in the wire when the controlling forces were added, and the vibration caused in the wire was not handled in the analyses. Anyway, the effects of active control could be confirmed enough from both results of experiment and analysis.

7. CONCLUSION

Acting on the premise that hyper vision technology that can produce megapixel resolution at a speed of 1000 fps, we investigated an active control method using multipoint displacement measurement values. The following conclusions were obtained:

- (1) Features of the use of the hyper vision technology are as follows:
 - a) Displacements of the structure are measured directly.
 - b) Multipoint displacements are simultaneously recorded by a single high-speed camera.
 - c) Data is obtained at megapixel resolution in each frame every 1/100-1/1000 seconds.

The use of hyper vision technology presents the potential for active control methods to achieve performance levels equal to those found in conventional control methods.

- (2) In this paper we presented one such possibility. By extending the time integration scheme previously presented by one of the authors, we proposed two types of single-step calculation methods for controlling forces. The equations used herein were derived on the assumption that seismic force is constant or linearly varying during incremental time Δt , and are based on general solutions of simultaneous second-order ordinary differential equations. If Δt is about 1/100 seconds, the influence on accuracy in calculating the assumption of constant during Δt is negligible. Equations that assume linear change can be effectively used for earthquake forces that can be predicted by the Earthquake Early Warning system. In addition, using such a single-step control force calculation method allows the application of active control that considers material nonlinearity, thus paving the way for applications to civil engineering structures that experience the nonlinear vibration phenomena during strong earthquakes.
- (3) To confirm the actual feasibility of the proposed active control techniques, we developed an active control system comprised of the following segments, and the system was evaluated by shaking table tests.
 - a) Displacement measurement is carried out by high-speed camera.
 - b) Controlling forces are calculated.
 - c) The signal is sent to the actuators and the motors are rotated.

By observing the behavior of the structural model while controlling vibration in time-steps of 1/100 seconds, we were able to confirm that the system provided adequate control power during both earthquake wave and sine wave excitations,

(a) Sine wave (1.9Hz)

(b) Experiment Kobe wave

(c) Experiment Geiyo wave

Fig.14 Comparison of the displacement of marker 4 under controlled and not controlled conditions.

(a) Sine wave (1.9Hz)

(b) Experiment Kobe wave

(c) Experiment Geiyo wave

Fig.15 Comparison of phase relation between the displacement of Marker 4 and controlling forces.

Fig.16 Relations between α in Eq.(30) and the maximum displacement of Marker 4 in case of the Experiment Kobe wave.

Fig.17 Target value and actual value of motor rotation
(Ordinate axis: One rotation of the motor is shown by 2000 counts).

(a) Sine wave (1.9Hz)

(b) Experiment Kobe wave

(c) Experiment Geiyo wave

Fig.18 Comparison of the displacement of marker 4 when not controlled with analysis and experiment.

(a) Sine wave (1.9Hz)

(b) Experiment Kobe wave

(c) Experiment Geiyo wave

Fig.19 Comparison of the displacement of marker 4 when controlled with analysis and experiment.

and that it was capable of decreasing the structural response remarkably.

(4) In addition, we compared the computational results concurrently with the shaking table test results, and confirmed that they corresponded well.

These results confirm that the proposed method using hyper vision technology is effective as an active control method. While we did not target specific structural forms or structures, the ability to use this method with various actuators such as rotation pendulums, gives it wide application that would include, in addition to buildings, tower-like structures or bridges with wide clearance.

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