Development of Piezoelectric Actuator Control System using FEM

*Daigoro Isobe[1)], Hiroshi Nakamura[2)], Ryuta Shimizu[2)] and
Hisashi Nakagawa[3)]

Institute of Engineering Mechanics, University of Tsukuba, Ibaraki 305-8573, Japan

ABSTRACT

In this paper, the Finite Element Method (FEM) is proposed for application to a real-time control system of connected piezoelectric actuators, assuming an actuator as finite elements, which are mainly used in the field of computational mechanics. The FEM is capable of expressing the state of an entire system by stiffness equations, and can cope flexibly with lack or disability of constituent elements of the system by controlling the stiffness matrices. An inverse analysis program using the FEM, combined with the empirical formulae considering time-dependent characteristics of the piezoelectric material, is implemented into a parallel control system. The system is verified by the experiments on quasi-static displacement control of connected piezoelectric actuators. The results show the possibility of highly accurate, real-time control of the actuators using the FEM.

INTRODUCTION

Parallel control of robotic systems, which is an adaptive control scheme involving the reassembly of hardware systems into different configurations while still using the same software, has been progressively developed in recent years. The concept of robotic systems with high adaptability to their environment is called Parallel Robotics, and is expected to be applied in space, under the sea, mining, and construction, where environments tend to change rapidly. Hamlin and Sanderson (1997), for example, had made a prototype of robotic architecture which is capable of reassembling into many different patterns of platforms consisting of linear actuators and multi-link spherical joints.

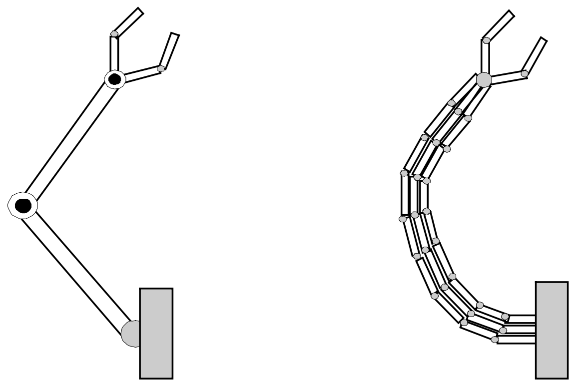
In this paper, a parallel control system for a continuous architecture formed by bimorph

1) Assistant Professor
2) Graduate Student
3) Kajima Construction Co. (Ex-undergraduate Student)

piezoelectric actuators has been developed and verified, as a part of the research project by Fujii *et al*. (1997), with the goal of constructing more human-like robots from a biological point of view (see Figure 1). The conventional control system necessitates the change of state equations depending on the shape of a system or the quantity of the linked members. On the other hand, the Finite Element Method (FEM), a generally used computational tool in analyzing structures, fluids, etc., is capable of expressing the behaviors of each discrete element, as well as the whole continuous system, by evaluating the stiffness equations derived from the energy principle. Flexible control can be achieved simply by changing the material properties of the finite elements expressing the actuators, in case of disorder. Therefore, the FEM, when used as a control scheme, may achieve a higher redundant parallel control system.

Several steps are taken to enable real-time control by FEM. First, a simple inverse theory, which is obtained by considering the linearity of voltage distribution in bimorph piezoelectric actuators, is applied for calculating the control voltage. The algorithm using this theory consumes less computational memory. Second, a noncompatible four-node element is implemented into the FEM program. The finite element allows the in-plane bending mode by considering a noncompatible mode in shape functions. Although the continuity of displacement along the elemental boundary is not satisfied in the element, practical accuracy can be achieved by a minimum number of elements. Third, to minimize the effect of time-dependent characteristics of a piezoelectric material, empirical formulae for creep deformation and residual strain are evaluated, and are combined with the FEM inverse analytical algorithm.

In this paper, the inverse analysis program using the FEM combined with the empirical formulae, is implemented into a parallel control system. The system, which consists of a PC, a bipolar DC unit and a signal-distributing controller, is examined and verified by experiments on quasi-static displacement control of connected piezoelectric actuators.



(a) Conventional robotic system》 (b)Piezoelectric actuator robot

Fig.1 Robotic systems

INVERSE THEORY USED IN PIEZOELECTRIC ACTUATOR CONTROL

When no external force is applied to the material, the stiffness equation under static condition considering piezoelectricity (Allik and Hughes, 1970) is:

$$[K_{uu}]\{u\} = -[K_{u\phi}]\{\phi\} \tag{1}$$

where $[K_{uu}]$ is the stiffness matrix, $[K_{u\phi}]$ the piezoelectric stiffness matrix, $\{u\}$ the displacement vector and $\{\phi\}$ the voltage vector. Displacements are calculated by multiplying the inverse matrix of the $[K_{uu}]$ matrix from the left on both sides of the equation above. On the contrary, the voltage required for achieving target displacement can not be simply calculated from the equation, since the $[K_{u\phi}]$ matrix has no inverse matrix. Thus a simplified inverse theory using the linearity of voltage distribution in a bimorph piezoelectric actuator is employed (Isobe and Nakagawa, 1999).

By assuming the thickness of bimorph piezoelectric actuator to be t mm, the voltage at top and bottom planes to be ϕ_0V, the voltage at the central plane to be 0 V, and the distance of a node point (No. i) from the central plane to be d_i mm, the voltage applied at the node point ϕ_iV is:

$$\phi_i = \frac{2d_i}{t}\phi_0 = C_i\phi_0 \tag{2}$$

By using the above equation, the right hand side of Eq.(1) can be expressed as:

$$-[K_{u\phi}]\{\phi\} = -[K_{u\phi}]\{C\}\phi_0 \tag{3}$$

When target displacement is given to the tip of an actuator by the pseudo-force scheme, a certain reaction force is calculated at the freedom. By comparing the reaction force f_b (>0) and the corresponding components of Eq.(3), the relation between control voltage ϕ_0 and reaction force f_b is obtained as:

$$f_b = \alpha_{ne}\{k_{b1}C_1\phi_0 + k_{b2}C_2\phi_0 + \cdots + k_{bn}C_n\phi_0\} = \alpha_{ne}\sum_{i=1}^{n} k_{bi}C_i \cdot \phi_0 \tag{4}$$

where k_{bi}(i=1,…,n) are the (freedom No. of target displacement, node point No.) components of the $[K_{u\phi}]$ matrix. α_{ne} is a coefficient connecting the mechanical and electrical quantities, and it shows a dependence on elemental size. It is calculated by carrying out a direct analysis and an inverse analysis. From Eq.(4), we can derive

$$\phi_0 = \frac{f_b}{\alpha_{ne}\sum_{i=1}^{n} k_{bi}C_i} \tag{5}$$

and the control voltage of the actuator can be obtained. Furthermore, the control voltage, considering the reaction force from other objects in the case of contact, can be evaluated by adding the corresponding value to the equation.

EMPIRICAL FORMULAE USED FOR TIME-DEPENDENT CHARACTERISTICS

A piezoelectric material shows time-dependent characteristics such as creep deformation and residual strain (see Figure 2). Some empirical formulae are derived to consider such nonlinearlity, which also has a strong dependence on applied voltage.

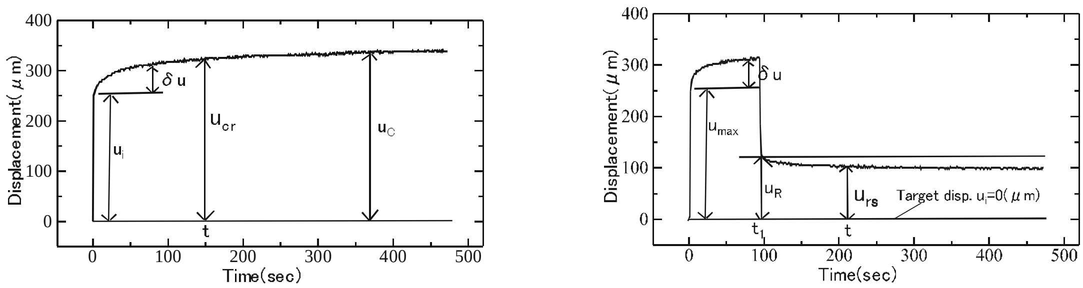


Fig.2 Creep deformation and residual strain of piezoelectric actuator

Empirical formulae considering creep deformation

As seen in Figure 2, the actuator tip displacement after a certain time lapse can be expressed by the sum of the time-independent component u_i and time-dependent component δu. Therefore, the displacement at time t can be determined by approximating the time-dependency of δu by the asymptotic exponential function:

$$u_{cr} = f_{inc}(\phi_P)(u_i + \delta u) = f_{inc}(\phi_P)\{u_i + (u_C - u_i)(1 - a^{t^c})\} \tag{6}$$

where a and c are the constants for convergence. The function expressing dependence on the applied voltage can be written in the same manner against u_i and u_c as:

$$f_{inc}(\phi_P) = 1 + s_{inc}\phi_P^m \tag{7}$$

where s_{inc} and m are the constants of voltage dependence. Displacement including creep deformation after convergence can be expressed as:

$$u_C = c_{cr}u_i \tag{8}$$

where c_{cr} is the mean ratio of u_c and u_i in a low-voltage area.

Empirical formulae considering residual strain

As also seen in Figure 2, a large amount of residual strain can be observed after the electrical charge is reduced. The displacement at time t can be determined by approximating the time-dependency of u_R by the asymptotic exponential function:

$$u_{rs} = f_{inc}(\phi_P)u_i + f_{dec}(\phi_P)u_R b^{(t-t_{i-1})^d} \tag{9}$$

where b and d are the constants for convergence. The same function f_{inc} from Eq.(7) is used as the voltage dependency function for u_i. Since crystal grain in a reduced electrical field acts differently, another function for the second component is defined as:

$$f_{dec}(\phi_P) = \frac{s_{dec1}}{(\phi_{Pmax} - \phi_P)^q} + s_{dec2}\phi_P^n \tag{10}$$

where s_{dec1} and s_{dec2} are the constants of voltage dependency, q and n the exponents, and ϕ_{Pmax} the maximum voltage applied in the control process. Displacement considering residual strain after a complete discharge can be expressed as:

$$u_R = c_{rs}(u_{max} - u_i) \tag{11}$$

where u_{max} is the maximum target displacement in the process, and c_{rs} is the mean ratio of u_R and u_{max} in a low-voltage area.

DEVELOPMENT OF REAL-TIME CONTROL SYSTEM USING FEM

A GUI application using FEM inverse analysis combined with the empirical formulae is implemented into a parallel control system. The system consists of a PC, a bipolar DC unit and a signal-distributing controller as shown in Figure 3. Figure 4 shows the algorithm used in the GUI application. The GUI application starts by initializing the element subdivision followed by the calculation of a global stiffness matrix, to minimize the CPU time during the control process. The application moves to the next step if target displacements are provided by the user, and starts time loop calculation of the inverse analysis. One cycle of calculation by a 270 MHz clock CPU takes only 30 ms. The output data of the control voltage is provided every 200 ms, and is sent via a serial wire to the controller. The controller supplies independent DC power to each actuator.

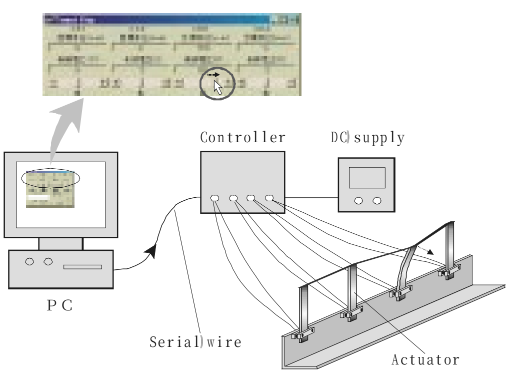


Fig.3 Control system using FEM

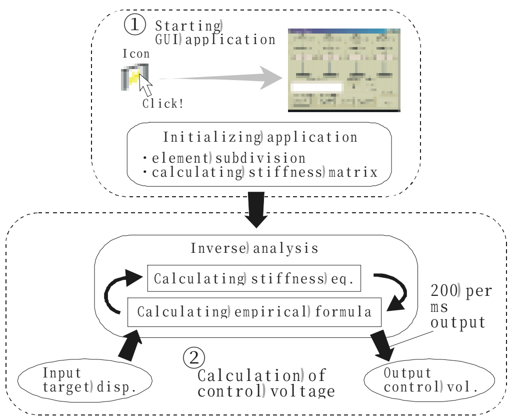


Fig.4 Algorithm in GUI application

Four piezoelectric actuators (each with six finite elements) clumped at one end and connected at the other end with elastic material (natural rubber, two finite elements), is selected for the experimental model of quasi-static displacement control. Figure 5 shows the control voltage applied to each actuator, which is obtained from the FEM control system. The control voltage changes with time to minimize the effect of time-dependent characteristics. As seen in Figure 6, the creep deformation and residual strain are effectively reduced, and practically accurate control is achieved. The experimental data suggest that the FEM control system handles the effect of the material connecting the actuators, since the control voltage varies when the property data of the connecting material are changed.

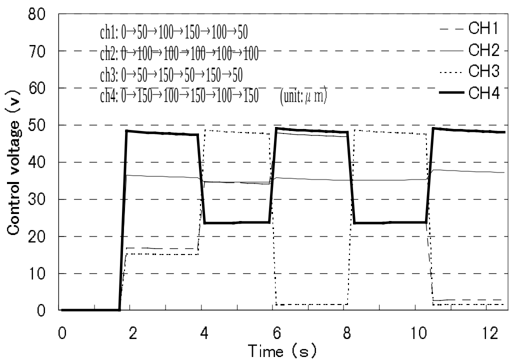


Fig.5 Applied control voltage

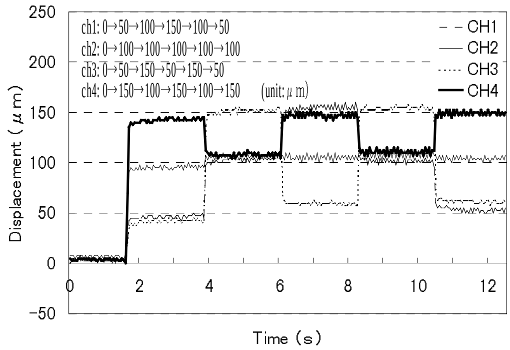


Fig.6 Attained displacement by FEM control

CONCLUSION

Although some steps must be taken to minimize the calculation time, there is a possibility of using the FEM as an effective control scheme. Most control schemes handle an entire system in series, which becomes a drawback when some elements lose their function. On the other hand, the FEM can handle the system in parallel by subdividing it into discrete finite elements, and can cope with flexibility in the change of form and material properties. This kind of approach may be applied to other fields of robotic control.

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