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Force Holding Control of a Finger Using Piezoelectric Actuators

Z.W. Jiang*, S. Chonan*, M. Koseki* and T.J. Chung**
* Department of Aeronautics and Space Engineering
Tohoku University, Sendai, 980, JAPAN
** Department of Mechanical Design & Production
Kunsan National University
Kunsan, 573-360, KOREA

Abstract

A theoretical and experimental study is presented for the force holding control of a miniature robotic finger which is driven by a pair of piezoelectric unimorph cells. In the theoretical analysis, one finger is modeled as a flexible cantilever with a tactile force sensor at the tip and the mate of the finger is a solid beam supposed with sufficient stiffness. Further, the force sensor is modeled by a one-degree-of-freedom, mass-spring system and the output of sensor is then described by the sensor stiffness multiplied by the relative displacement. The problem investigated in this paper is that two typical holding tasks of the human finger are picked up and applied to the robotic finger. One is the work holding a stationary object with a prescribed, time-varying force and the other one is to keep the contacted force constant even if the object is in motion. The simple PID feedback control scheme is used to control the minute gripping force of order 0.01 Newton. It is shown both experimentally and theoretically that the artificial finger with the piezoelectric actuator works well in the minute force holding of the tiny object.

1 Introduction

Demands for higher function and precision of robot hands lead to the wide study and rapid development of robotic fingers. In the future, the robot hand would be used in various environment, and its finger is need to operate and grip various things or materials, for instance, to grip and operate a soft and delicate tiny object without damage. So there is a necessity to develop a high-response actuator and a sensitive tactile sensor for the minute tip force control of robotic finger.

It was shown in the previous papers[1-3] that the piezoelectric bimorph cell works well as an actuator to control actively the position and the vibration of a flexible robotic miniature arm. The work reported in this paper, is a further study on the force holding control of a miniature robotic finger which is driven by a pair of piezoelectric unimorph cells. In the analysis, one finger is modeled as a flexible cantilever with a tactile force sensor at the tip and the mate of the finger is treated as a solid beam supposed with sufficient stiffness. Further, the force sensor is modeled by a one-degree-of-freedom, mass-spring system and the output of sensor is then described by the sensor stiffness multiplied by the relative displacement. The behavior of the force control of the finger is discussed in detail both theoretically and experimentally.

2 Theoretical Analysis

Figure 1 shows a flexible cantilevered finger of length l with a force sensor of mass m attached at the tip. A pair of piezoelectric unimorph cells of length a are glued on both sides of the finger as shown in the figure. An applied voltage signal to the cells causes one cell to expand while the other to contract which results in a constant continuous bending moment M_p in the range $x = 0$-a and deforms the finger in the xy-plane. The mate of the finger is a solid finger with adequate stiffness and it is assumed to be rigid. In the following, one investigates the problem of gripping a tiny object with the fingers then holding it with the minute commanded force even if the object is in motion.

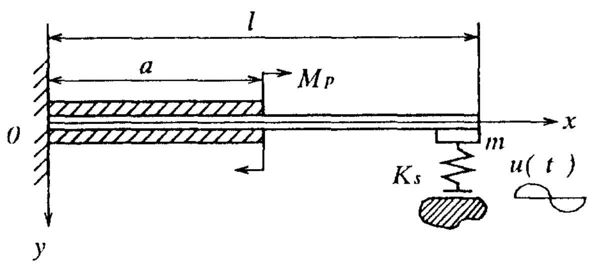

Fig. 1 Geometry of problem and coordinates.

Considering the equilibria of moments and forces that are acting on the flexible finger, one has the equation of motion of the finger as

$$[\rho(x)A(x)+m\delta(x-l)]\frac{\partial^2 y}{\partial t^2} + \frac{\partial^2}{\partial x^2}[E(x)I(x)(1+\gamma\frac{\partial}{\partial t})\frac{\partial^2 y}{\partial x^2}] = M_p[\delta'(x-0)-\delta'(x-a)]-F_s^*, \quad (1)$$

where

$$\rho(x)A(x) = \begin{cases} \rho_b A_b & \text{for } a \le x \le l, \\ (\rho A)_{bp} & \text{for } 0 \le x \le a, \end{cases}$$
$$E(x)I(x) = \begin{cases} E_b I_b & \text{for } a \le x \le l, \\ (EI)_{bp} & \text{for } 0 \le x \le a, \end{cases} \quad (2)$$

and

$$(\rho A)_{bp} = \rho_b A_b + \rho_p A_p ,$$
$$(EI)_{bp} = \frac{b h_b^3 E_b}{12} + \frac{b[(h_b+2h_p)^3 - h_b^3]E_p}{12}.$$

Here, ρ_b are the mass density, A_b the cross-sectional area, E_b the Young's modulus and I_b the moment of inertia of the beam respectively; ρ_p, A_p, E_p, I_p the corresponding parameters of the piezoelectric cell; further c is the coefficient of structural damping coefficient and $\delta(\cdot)$ the Dirac delta function. F_s is the finger tip force measured by the sensor and it is represented theoretically in the form

$$F_s^* = F_s(l,t)\delta(x-l) = K_s[y_L(t)-u(t)] = K_s[y(x,t)-u(t)]\delta(x-l), \quad (3)$$

where K_s is the stiffness of the force sensor, y_L the deflection at the finger tip and $u(t)$ the fluctuation of the object.

Substituting Eq.(3) into Eq.(1) one has

$$[\rho(x)A(x)+m\delta(x-l)]\frac{\partial^2 y}{\partial t^2} + \frac{\partial^2}{\partial x^2}[E(x)I(x)(1+\gamma\frac{\partial}{\partial t})\frac{\partial^2 y}{\partial x^2}] + K_s y(x,t)\delta(x-l) = M_p[\delta'(x-0)-\delta'(x-a)] + K_s u(t)\delta(x-l). \quad (4)$$

The solution of Eq.(4) is assumed to be of the form

$$y(x,t) = \sum_{n=1}^{N} W_n(x) f_n(t). \quad (5)$$

When the piezoelectric cells are perfectly bonded on both sides of the beam, the system can be modelled as a stepped beam with two uniform sections, having a laminated structure in part. The mode function W_n in the i-th uniform section is then obtained by the Laplace transform method as

$$W_n^i(x) = A_n^i S(\xi_n^i x) + B_n^i T(\xi_n^i x) + C_n^i U(\xi_n^i x) + D_n^i V(\xi_n^i x) + \frac{\beta_n^4}{(\xi_n^i)^3} X_n^i(l) V[\xi_n^i(x-l)] H(x-l)$$
$$i = \mathrm{I},\ \mathrm{II}, \quad (6)$$

where

$$S(\xi x) = \frac{1}{2}[\cosh(\xi x)+\cos(\xi x)],$$
$$T(\xi x) = \frac{1}{2}[\sinh(\xi x)+\sin(\xi x)],$$
$$U(\xi x) = \frac{1}{2}[\cosh(\xi x)-\cos(\xi x)],$$
$$V(\xi x) = \frac{1}{2}[\sinh(\xi x)-\sin(\xi x)], \quad (7)$$
$$(\xi^i)^4 = -\frac{(\rho A)^i p_n^2}{(EI)^i(1+\gamma p_n)},$$
$$\beta_n^4 = \frac{m p_n^2 + K_s}{E_b I_b (1+\gamma p_n)}. \quad (8)$$

The eigenvalue ξ^i and the unknowns A^i through D^i in the above equations are determined by substituting Eq.(6) into the system boundary conditions. Further, substituting Eq.(5) into Eq.(4) and then applying the Galerkin method to the resulting equation, one has the equation of motion in the matrix form

$$\mathbf{M}\ddot{\mathbf{F}}(t) + \mathbf{\Gamma}\dot{\mathbf{F}}(t) + \mathbf{K}\mathbf{F}(t) = \mathbf{Q}M_p(t) + \mathbf{U}u(t), \quad (9)$$

where

$$m_{ij} = \int_0^l [\rho(x)A(x)+m\delta(x-l)]W_j(x)W_i(x)dx,$$
$$\gamma_{ij} = \int_0^l \gamma E(x)I(x)\frac{\partial^4 W_j(x)}{\partial x^4} W_i(x)dx,$$
$$k_{ij} = \int_0^l [E(x)I(x)\frac{\partial^4 W_j(x)}{\partial x^4} + K_s W_j(x)\delta(x-l)]W_i(x)dx,$$

$$q_i = \int_0^l [\delta'(x) - \delta'(x-a)] w_i(x) dx,$$
$$u_i = \int_0^l K_s \delta(x-l) W_i(x) dx, \quad (10)$$
$$i, j = 1, 2, \ldots N.$$

Next, one introduces the discrete variable method to Eq.(9). In this case, the state equation discretized in time is

$$\mathbf{x}(i+1) = \mathbf{A}\mathbf{x}(i) + \mathbf{B}_1 M_p(i) + \mathbf{B}_2 u(i),$$
$$y(i) = \mathbf{C}\mathbf{x}(i), \quad (11)$$

In the following analysis, the PID control scheme is introduced to drive the finger so that the tip produces the desired magnitude of force. To this end, the commanded tip force is compared with the sensor's measurement of actual tip force, and the difference (tip-force error) is used, together with the integrated and differential error signals, as a basis for applying control moment, i.e.,

$$\begin{aligned} M_p(i) &= G_p[F_d(i) - F_s(i)] \\ &+ G_v[(F_d(i) - F_d(i-1)) \\ &- (F_s(i) - F_s(i-1))]/T \\ &+ \frac{1}{2} G_I \sum_{k=0}^{i} [F_d(k) - F_s(k) \\ &+ F_d(k-1) - F_s(k-1)]. \end{aligned} \quad (12)$$

Here, $F_d(i)$ is the commanded force, $F_s(i)$ is the actual force between the finger tip and the object, and G_p, G_v, G_I are the proportional, derivative and integral feedback gains.

3 Experimental Setup

Figure 2 shows the whole experimental setup. The physical parameters of the cell-arm system measured are given in Table 1. The damping coefficient γ was determined from the logarithmic decrement of a freely vibrating cantilevered beam laminated in part by the bimorph cells. The force sensor on the finger tip is made up of a semiconductor strain gauge mounted on a square copper frame of thickness 0.1mm.

In the experiment, the contact force measured was digitized through a 12bit A/D converter (ADTEK AB98-05) and then sent to the computer (NEC PC9801VX) every sampling time T (=3 ms) in order to construct the system feedback signal. The output from the computer was transformed to a voltage signal through a 12bit D/A converter (ADTEK AB98-06) and then applied to the bimorph cells through the power amplifier to produce the control moment.

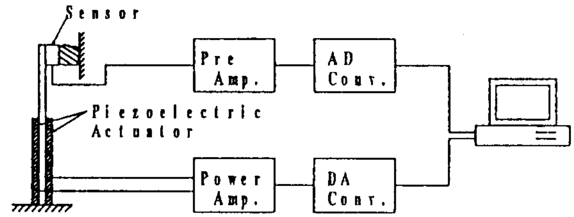

Fig.2 Experimental setup.

Table 1 Physical parameters of finger.

	Beam	Piezo Cell
Lenght(mm)	51.9	33.3
Width(mm)	12.2	12.2
Thickness(mm)	0.3	0.65
Density(Kg/m^3)	8670	8300
Young's modulus(GPa)	102.5	58.03
Damping coefficient(s)	4.05×10^{-5}	
Mass of sensor(g)	5.05	
Stiffness of sensor(N/m)	2110	

The feedback signal constructed in the computer is given by

$$\begin{aligned} V &= f_{gp}[V_r(j) - V_y(j)] \\ &+ f_{gv}[V_r(j) - V_r(j-1) - V_y(j) + V_y(j-1)] \\ &+ \frac{1}{2} f_{gi} \sum_{k=0}^{j} [V_r(k) - V_y(k) \\ &\quad + V_r(k-1) - V_y(k-1)], \end{aligned} \quad (13)$$

where $V_r(k-1) = V_y(k-1) = 0$ for $k = 0$; $V_r(j)$ and $V_y(j)$ are the digitized commanded and measured forces at time j; f_{gp}, f_{gv} and f_{gi} are the feedback gains in the computer.

For the experimental setup assembled here, the feedback gains in the computer, f_{gp}, f_{gi} and f_{gv}, and the gains in the theoretical analysis, G_p, G_I and G_v, are related each other through

$$(G_p, G_I) = (fgp, fgi),$$
$$G_v = 110.6 T fgv, \quad (14)$$

which was obtained from the comparison of the calculation based on the theory of elasticity and the experimental results of calibration.

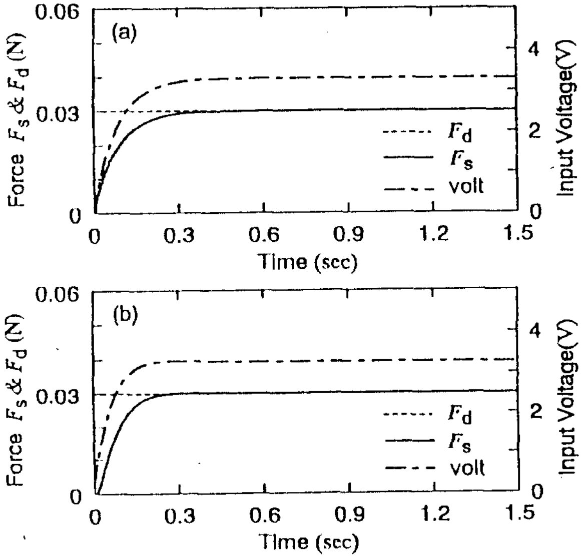

Fig. 3 Force response of finger tip tracking a step signal; (a) Numerical, (b) experimental results with $G_p = f_{gp}$=0.07, G_v=0.001(f_{gv}=0.003), $G_I = f_{gi}$=0.05.

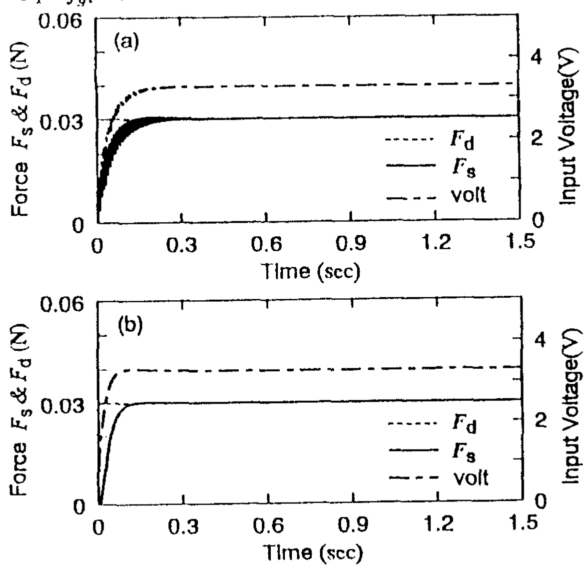

Fig. 4 Force response of finger tip tracking a step signal; (a) Numerical, (b) experimental results with $G_p = f_{gp}$=0.3, G_v=0.001(f_{gv}=0.003), $G_I = f_{gi}$=0.1.

4 Results and Discussions

Considering the motions of the human finger working, two basic holding tasks are picked up and studied in detail in the following. One is the work in which the finger operates a stationary object with a prescribed, constant and time-varying force. The other one is the task that the finger is needed to holding a time-fluctuating, i.e. a living object with a constant force for preserving it from any injury. In both cases the theoretical and experimental results have been obtained and discussed in the following.

In the first case, tow kind of commanded forces, a step force with amplitude 0.03N and a sinusoidal force of amplitude 0.01N, are introduced to operate the stationary object. Since the object is stationary its fluctuation $u(t)$ in equations (3) and (4) is set to zero in the following theoretical simulation.

Figures 3 and 4 are the results when the finger tip was controlled to produce a step commanded force of amplitude 0.03N to the stationary object. In the figures, the dashed line shows the commanded constant force of 0.03N, the solid line is the output from the tip force sensor and the one-dotted chained line is the input control voltage to the piezoelectric actuator. Fig.(a) shows the theoretically simulated result and Fig.(b) the corresponding result obtained experimentally. The force feedback gains used in figure 3 are $G_p = f_{gp} = 0.07$, $G_v = 0.001(f_{gv} = 0.003)$ and $G_i(f_{gi}) = 0.05$. Comparison with Figs.3(a) and (b), it is found that the experimental result is in good correspondence with the theoretical one and the tip force produced comes to the desired value F_d rapidly within 0.3 seconds. Figure 4 shows the results when the feedback gains are increased as $G_p = f_{gp} = 0.3$, $G_v = 0.001(f_{gv} = 0.003)$ and $G_i(f_{gi}) = 0.1$, the maximum value tested in stable, in order to get high speed of response. In this case the rise time of the response is reduced to a value of 0.1 seconds and the theoretical and the experimental results agree again each other well although some slight vibration appears on the theoretical response shown in Fig.(a).

Figures 5 through 7 show the results when the finger tip was operated to produce a sinusoidal force of amplitude 0.01N with initial pressure of 0.03N. Here the one-dotted chained line shows the commanded sinusoidal force of amplitude 0.01N and the solid line is the output from the force sensor. Fig.(a) is the theoretical result and Fig.(b) the experimental one. The frequencies of the commanded sinusoidal force are tested by 2Hz in the case of Fig.5, 10Hz in Fig.6 and 15Hz in Fig.7 respectively, and the feedback gains in each figures are selected in such a way that the finger has the best control response as desired. Comparing each figures it is shown that the tip force produced tracks the commanded target in a satisfactory manner, especially in the case of Fig.5. When the target frequencies are increased to 10Hz or 15Hz it is found that a

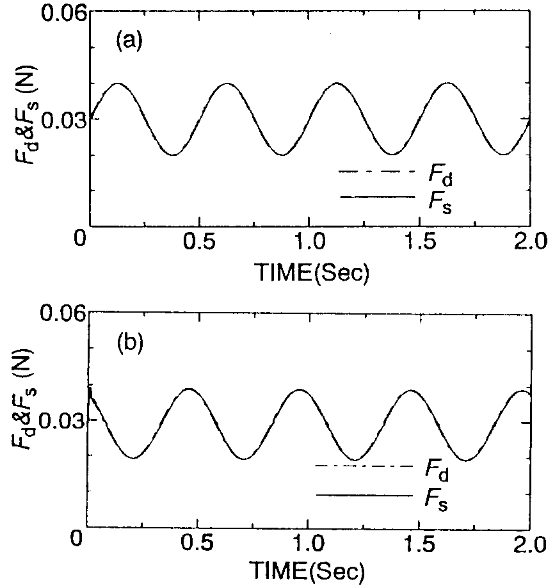

Fig. 5 Force response of finger tip following a 2Hz sinusoidal signal; (a) Numerical, (b) experimental results with $G_p = f_{gp} = 0.1$, $G_v = 0.04(f_{gv} = 0.12)$, $G_I = f_{gi} = 0.8$.

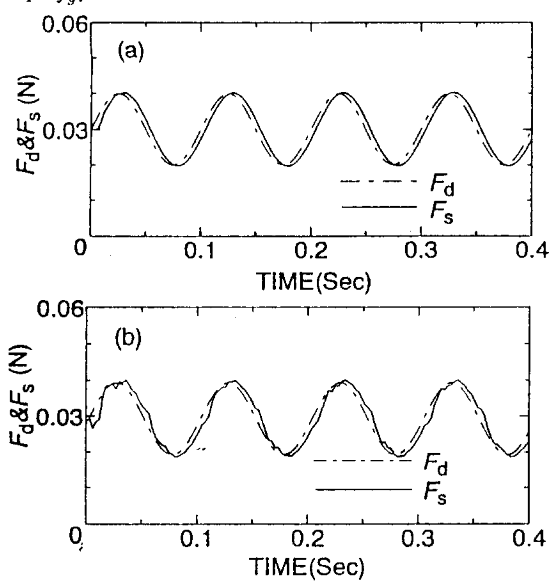

Fig. 6 Force response of finger tip following a 10Hz sinusoidal signal; (a) Numerical, (b) experimental results with $G_p = f_{gp} = 0.2$, $G_v = 0.05(f_{gv} = 0.15)$, $G_I = f_{gi} = 1.0$.

small phase delay appears between the produced force and commanded force as shown in Figs.6 and 7. This is the reason caused by the sampling time in the digital feedback control. It is also noted that the theoretical and the experimental results are in good agreement with each other. This means that

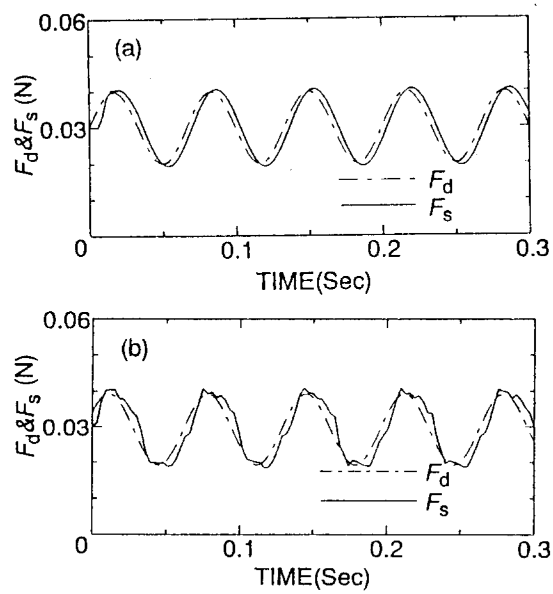

Fig. 7 Force response of finger tip following a 15Hz sinusoidal signal; (a) Numerical, (b) experimental results with $G_p = f_{gp} = 0.2$, $G_v = 0.05(f_{gv} = 0.15)$, $G_I = f_{gi} = 1.2$.

the theoretical analysis mentioned above is valid for this kind of force controlled flexible finger system. Some experimental results are also shown when the frequency of the commanded force is higher than 15Hz the phase delay increases significantly so that the tip force becomes uncontrol within the sampling time of 3msec.

Next suppose that the object is in motion and the finger is operated to keep a constant force, say 0.03N, when the object is being held. Since the control ability of the finger is mainly investigated here, the motion of the object is simply supposed as a sinusoidal time-fluctuating with various frequencies which causes to react against the finger with the force of amplitude 0.01N. The results obtained are shown in Figures 8 through 10.

Fig.8 shows the results when the object is fluctuating sinusoidally with frequency of 2Hz, Fig.9 is the case for 10Hz and Fig.10 for 15Hz. It is said both the simulation and experimental results compare favorably. In figures, the one-dotted chained line shows the commanded constant force of amplitude 0.03N, the solid line is the output of the tip force sensor and the dashed line only in Figs.(a) is the simulated force of tip sensor obtained if the finger is not in control. The feedback gains in these cases were so selected that the finger works satisfactorily to keep a constant force even if the object is in motion. It is also shown from these figures that the

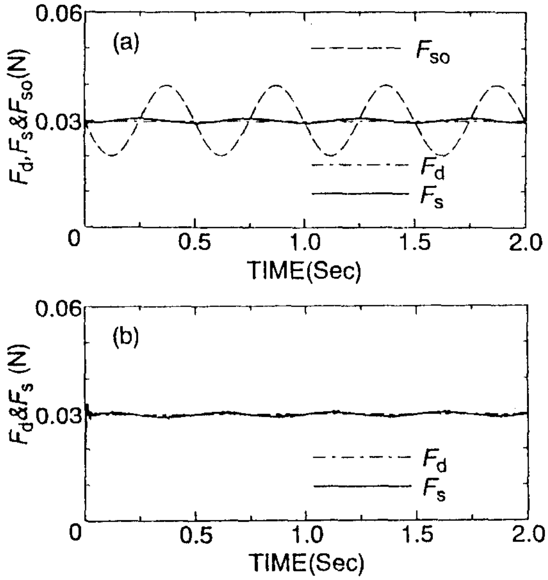

Fig. 8 Force holding control of a 2Hz sinusoidal fluctuating object; (a) Numerical, (b) experimental results with same feedback gains of Fig.5.

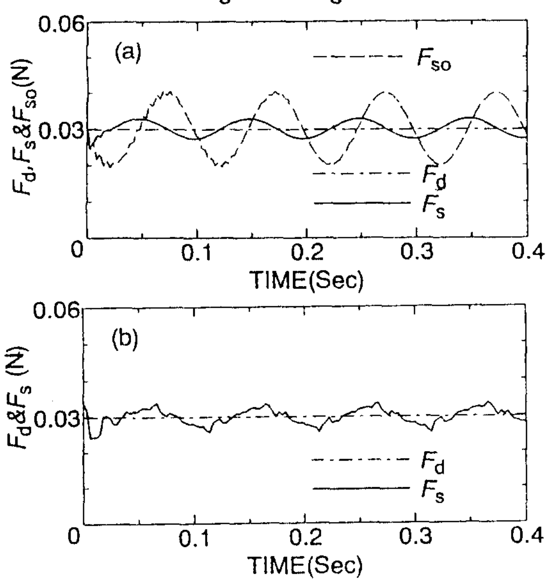

Fig. 9 Force holding control of a 10Hz sinusoidal fluctuating object; (a) Numerical, (b) experimental results with same feedback gains of Fig.6.

deviation between F_s and F_d increased gradually as the fluctuating frequency increased. It is predicted that the response of the finger will be improved by shorten the sampling period in the digital feedback control system. Further, the above results are noted that the simple PID control scheme works satisfactorily for the tip force control of the finger system under consideration.

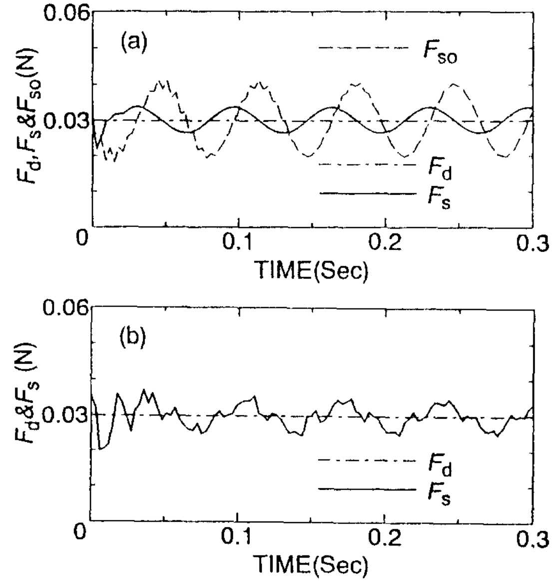

Fig. 10 Force holding control of a 15Hz sinusoidal fluctuating object; (a) Numerical, (b) experimental results with same feedback gains of Fig.7.

5 Conclusions

(1) The piezoelectric bimorph cell works well as an actuator for a miniature finger holding a small object with a prescribed minute force.
(2) Theoretical results are in good correspondence with the experimental ones, which means that the analytical method for the miniature gripper using the piezoelectric bimorph cell as an actuator is valid and can be used to design the the miniature gripper systematically with the aid of the computer simulation.
(3) The simple PID control low is satisfactory for the force control of the bimorph finger.

6 References

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