Control of a PM-type linear synchronous actuator for an artificial muscle with arbitrary stiffness and damping emulation

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***ABSTRACT* — The aim of this paper is control of a PM-type linear synchronous actuator for an artificial muscle with arbitrary stiffness and damping factor. The authors have supposed to use a linear synchronous actuator for an artificial muscle of a humanoid robot and proposed a thrust control system. Flexible motion has been simulated to a thrust reference and virtual spring and damping factor by controller. A virtual spring and damping has operated using position and velocity information of the mover. The authors have calculated and simulated the system, and performed hardware implementation to actual linear synchronous actuator.**

***Keywords* — Bi-articular muscle, damping factor, humanoid robot, linear synchronous actuator, spring factor**

I. INTRODUCTION

Recently, humanoid robots were intensively developed, e.g., ASIMO from HONDA Co. Ltd. Showed its attractive human-like motions. The mechanisms of many of the conventional robots are quite different from natural biomechanics studies for emulating the natural biomechanics are being active, the purpose of which is to realize kinetic performance of a humanoid robot with the redundancies that natural animals own. Let us think of a robot with two joints operated in a two-dimensional plane. All quadrupled and biped animals have bi-articular muscles. Biceps brachii and tricepts brachii are bi-articular muscles of the parts of arms. A group has studied the reason for and the role of bi-articular muscles, intensively[1].

Fig. 1. shows the arm system of human including bi-articular muscles. It is written by top view. In the figure, f3 and e3 are bi-articular muscles. Bi-articular muscle attaches riding in two adjacent joints. All quadruped and biped animals have the bi-articular muscles. The main characteristics are doing comparable operation and to contribute to output rigidity, and orbit control in the tip of the limbs.

On the contrary, many of conventional humanoid robots have no parts as artificial bi-articular muscles. They have only rotationary motors at their cubital and shoulder joints, which play the roles of mono-articular muscles. With such hardware configuration, one absolutely needs calculating complicated inverse kinematics. However, natural life forms do never execute such complicated calculation in reality. Results of bionic measurements[1] have shown that the motion of our natural arm are controlled by changing the ratio of force divided among mono-articular muscles at cubital and shoulder joints, and a pair of bi-articular muscles linearly (Fig. 2). Fundamentally, robot motion can be operate actuator control as Fig. 2, and the control scheme is much easier than the conventional artificial system. That is to say, a humanoid robot with actuators as bi-articular muscles can move as quickly and flexibly as a natural human without any complex calculation.

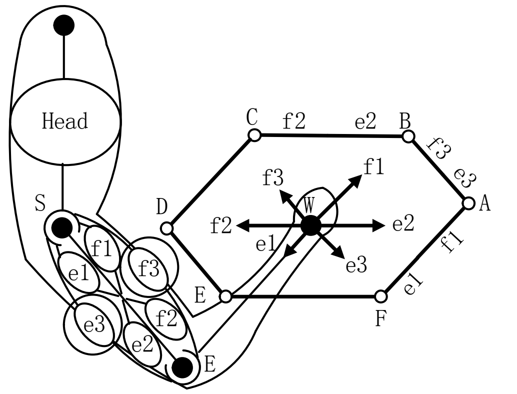

Fig. 1. Unique characteristics of output force distribution[1].

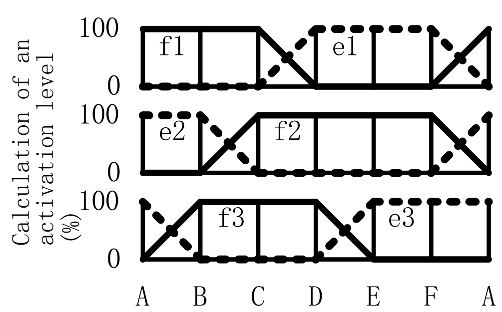

Fig. 2. Simple activation level design among three sets of actuators empirically deduced from bioinstrumentation[1].

This idea has been already realized by using bulky mechanical linear actuators which are combinations of mechanical elements, e.g., wires, springs, dampers, stroke sensors and hydraulic or pneumatic mechanisms.

Especially, we have proposed to use a linear synchronous actuator for an artificial bi-articular muscle. Several reasons have been advanced for it.

1. It can be make the actuator compact by a direct drive of a linear actuator. We can make it without several parts as a mechanical system and the total system can be much simpler and lighter.
2. Flux density using Permanent magnet is high, we can get high thrust with compact composition.
3. High position controllability can be realized using a linear encoder. That is why, a linear synchronous motor is using in a precision machine.

From these reasons, we have described about a control system of a PM-type linear synchronous actuator for an artificial muscle with arbitrary stiffness and damping factor.

II. Algorithm Of Thrust Control System

Muscle generates power after it receives a signal from a brain. A brain sends a thrust reference signal to muscle. In the same way, it is suitable for an actuator to input thrust signal.

A block diagram of thrust control system is shown in Fig. 3. Fundamentally, an actuator generates a thrust F_m depending on input signal of thrust F_{m0}^*. If we assume AC motor, a vector control has been used mainly. In case of a linear motor, we must think about stiffness and damping factor of motor. Different of a rotary motor, a transfer function of a linear actuator is described as follow;

$$\frac{1}{F_m - F_L} X(s) = \frac{1}{Ms^2} \quad (1)$$

x : position of the mover, F_m : Thrust of the actuator, F_L : Disturbance thrust

B. Flexible control with arbitrary stiffness and damping emulation

A linear actuator for the role of an artificial muscle does not go and return simply. And it must move softly and flexible to imitate a biotical motion. To include flexibility, we have proposed a virtual spring and damping factor in Fig. 3.

Actually, virtual spring and damping factor has been simulated by an inertia system. Virtual spring and damping factor can be changed by software. Consequently, a thrust that has flexibility can be generated from a linear synchronous actuator and can be changed the flexibility easily.

A linear actuator using humanoid robot must assume that it use in case of two inertia system. However, we have assumed one inertia system in this paper so that a test machine moves one inertia condition. The transfer function is shown as follows;

$$s^2 MX(s) = -kX(s) - CsX(s) - F_L(s) \quad (2)$$

k : spring factor, C : damping factor

Also, the characteristic equation of second order system which has spring and damping factor is shown as follows;

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \quad (3)$$

ω_n : natural angular frequency (rad/sec), ζ : attenuation factor

We have calculated the transfer function G(s) in Fig. 3. G(s) is shown as follows;

$$G(s) = \frac{F_m(s)}{F_m^*(s)} = \frac{\frac{K_i}{s}\frac{1}{R+L_q s}K_t}{1+\frac{K_i}{s}K_p\frac{K_t}{R+L_q s}} = \frac{K_t K_i}{L_q s^2 + (R+K_p K_t)s + K_t K_i} \quad (4)$$

$$\therefore G(s) = \frac{1}{1 + \frac{R + K_p K_t}{K_t K_i} s + \frac{L_q}{K_t K_i} s^2} \quad (5)$$

And the pole location is calculated in the following simple form.

$$G(s) = \frac{1}{1 + 2T_2 s + 2T_2^2 s^2} \cong \frac{1}{1 + 2T_2 s} \quad (6)$$

$$s = \frac{1}{2T_2}(-1 \pm i) \quad (7)$$

Parameters of the intended model are shown in Table I.

TABLE I. PARAMETERS OF THE TEST MACHINE.

R	0.675 (Ω)
L_d	15.5 (mH)
L_q	18.65 (mH)
M	6.0 (kg)
K_e	10.76 (N/A)
K_t	10.76 (V/msec^{-1})

From Kessler method,

$$T_1 = \frac{R + K_p K_t}{K_t K_i}, T_2 = \frac{L_q}{R + K_p K_t} \quad (8)$$

$$\therefore \frac{T_1}{T_2} = \frac{(R + K_p K_t)^2}{L_q K_t K_i} = 2.0 \quad (9)$$

We have calculated the parameters of the thrust controller: K_p and K_i from table 1. Under the condition of K_p= 1, $T_1$and T_2 are set to 3.2msec and 1.6msec respectively. Also, K_i are set to 325.8.

Actually, we have calculated the position function X(s) in Fig. 3 using these relation.

$$V(s) = sX(s) = \frac{1}{Ms} G(s) - F_m^*(s) - F_L(s) \quad (10)$$

$$F_m^*(s) = F_{m0}^*(s) - CsX(s) - kX(s) + \frac{Cs}{1 + \tau s} X_0(s) \quad (11)$$

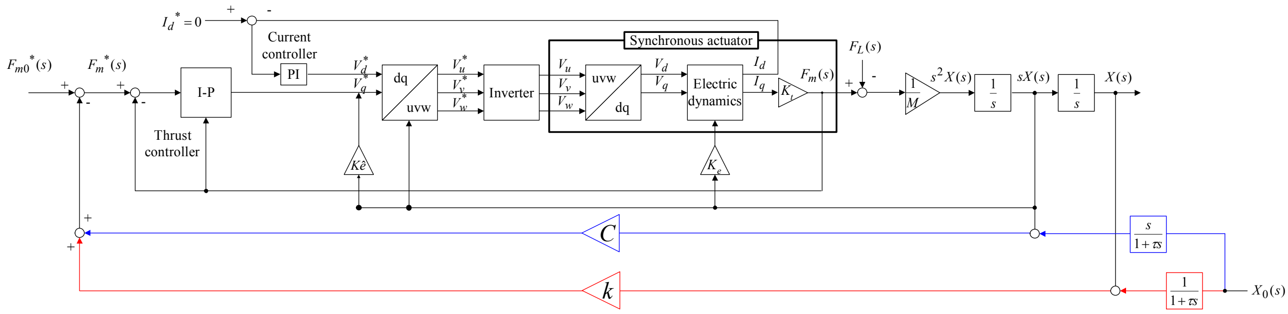

Fig. 3. Block diagram of thrust control system.

$X_0(s)$ means position reference. The proposed system can be used thrust and position reference as input signal. Also, the eq. (11) is sort using follow eq. (12);

$$D_1(s) = \frac{1}{G(s)} \cong 1 + 2T_2 s,\ D_{2(s)} = 1 + \tau s \qquad (12)$$

$$X(s) = \frac{1}{Ms^2}\left[G(s)\left\{F^*_{m0}(s) - (Cs+k)X(s) + \frac{Cs+k}{1+\tau s}X_0(s)\right\} - F_L(s)\right] \qquad (13)$$

$$X(s) = \frac{1}{Ms^2 + (Cs+k)\frac{1}{D_1(s)}}\left\{\frac{1}{D_1(s)}F^*_{m0}(s) + \frac{Cs+k}{D_1(s)D_2(s)}X_0(s) - F_L(s)\right\} \qquad (14)$$

$$\therefore X(s) = \frac{1}{k}\frac{1}{1+\frac{C}{k}s+\frac{M}{k}s^2 D_1(s)}F^*_{m0}(s) + \frac{1}{D_2(s)}\frac{1+\frac{C}{k}s}{1+\frac{C}{k}s+\frac{M}{k}s^2 D_1(s)}X_0(s) - \frac{1}{k}\frac{D_1(s)}{1+\frac{C}{k}s+\frac{M}{k}s^2 D_1(s)}F_L(s) \qquad (15)$$

It is found that position of the actuator depend on thrust and position reference and disturbance thrust from eq.(15). In addition, under the condition of $2\pi/\omega_n$ is sufficiently larger than $2T_1$and τ, $D_1(s)$ and $D_2(s)$ can be set to 1.

Consequently, the characteristic of the actuator can be adjusted by parameters ω_n and ζ.

III. Evaluation of the Control System with Stiffness and Damping Factor

A. Condition of the simulation using MATLAB Simulink

We have calculated the position and thrust of the actuator using MATLAB Simulink. As the simulation condition, we have used the actual linear synchronous motor which has the characteristics as Table I

B. Simulation results

Input signal was thrust reference $F_{m0}^*(s)$. We have simulated a change of mover position when $F_{m0}^*(s)$ was 50 (N). The Characteristics are changed by parameters ω_n and ζ. We have simulated follow the condition of $\omega_n = 10$ or 15 (rad/sec) and $\zeta = 0.1$, 0.5, 0.7 and 0.9 in this paper.

Results of a change of mover position on condition of $\omega_n = 10$ or 15 are shown in Fig. 5, and 6.

Mover position moved oscillatory in Fig. 5. An attenuation factor ζ was too small is the main reason. However, under the condition of natural angular frequency ω_n is 15 (Fig. 6), the mover moved stably.

It was found that we must drive on condition of high attenuation factor when we use a linear synchronous actuator for humanoid robot. Otherwise, the actuator generates an overshoot and humanoid robot cannot operate normally.

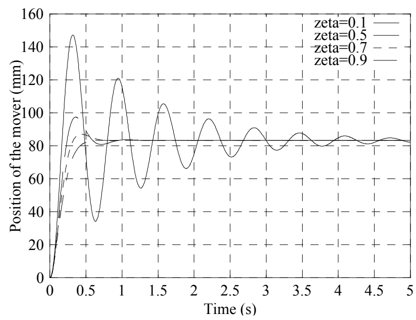

Fig. 5. Change of the mover position to change attenuation factor ζ on Simulink (Natural angular frequency $\omega_n = 10$).

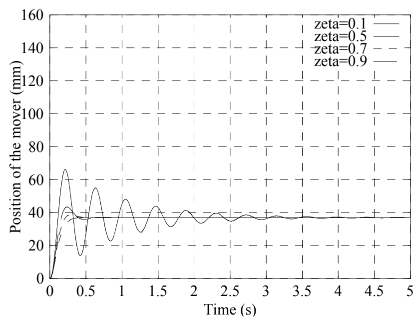

Fig. 6. Change of the mover position to change attenuation factor ζ on Simulink (Natural angular frequency $\omega_n = 15$).

C. Condition of the experiment

We have actualized the thrust control system with stiffness and damping factor to actual linear synchronous actuator (Fig. 7) using servo amp and software to control the actuator thrust. In addition, we have measured the change of the mover position and compared the simulation results. Thrust could be generated correctly when we input the thrust reference to the servo amp. Servo amp can calculate the vector control automatically so that we have added a thrust with spring and damping factor to the thrust reference $F_{m0}^{*}(s)$ using a position and velocity information from the mover.

D. Results of the experiment and comparison with simulation

Same as the simulation using Simulink, we have measured a change of mover position when input signal $F_{m0}^{*}(s)$ = 50 (N). We have experimented follow the condition of ω_n = 10 or 15 (rad/sec) and ζ = 0.1, 0.5, 0.7 and 0.9 in this paper.

Results of a change of mover position on condition of ω_n = 10 or 15 are shown in Fig. 8, and 9.

Actually, the test machine has a considerable viscosity itself so that results of Fig. 5 and Fig. 8 were quite different. It was found that test machine has a big viscosity about 100 Ns/m order. However, very soft damping for example ζ = 0.1 order does not need for an actuator of humanoid robot, and this is not a big problem.

Results of Fig. 6 and Fig. 9 were almost same. In addition, overshoot was generated in Fig. 9 against Fig. 6. It can be thought that composition of the thrust control by the servo amp and thrust controller on Simulink was different.

We thought a I-P controller[2][3] as a thrust controller to prevent the overshoot of an actuator on simulation. On the contrary, we did not consider the overshoot of test machine control. That is why, on the leading edge of thrust of the test machine is higher than the simulation. Although, we have composed the thrust control system from only servo amp, we must consider about the control to prevent the overshoot aftertime.

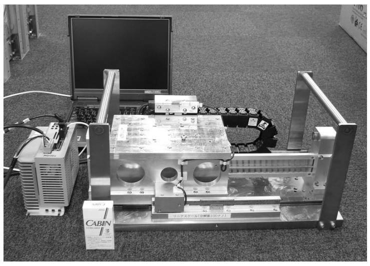

Fig. 7. Overview of the linear synchronous actuator control system.

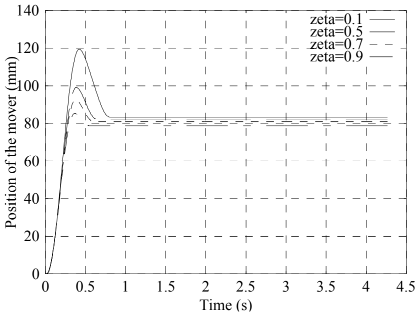

Fig. 8. Change of the mover position to change attenuation factor ζ on experiment (Natural angular frequency ω_n = 10).

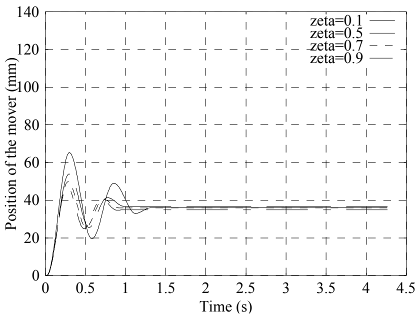

Fig. 9. Change of the mover position to change attenuation factor ζ on experiment (Natural angular frequency ω_n = 15).

IV. Conclusion

We have proposed a linear synchronous actuator for an artificial bi-articular muscle of humanoid robot and designed a control system with arbitrary stiffness and damping factor for the actuator. Parameters of arbitrary stiffness and damping factor can be changed easily using software and the actuator can be moved flexibly.

We have calculated and experimented on condition of soft viscoelasticity in this paper. A linear synchronous actuator has a viscosity about 100 Ns/m order and friction itself so that result of simulation and experiment was different just that much.

As future work, we are going to advance the proposed control system and implement to a humanoid robot.

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