Design method and fundamental calculation of a light PM-type linear synchronous actuator for producing large thrust

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***Abstract*--The aim of this paper is making a new light PM-type linear synchronous actuator that can produce a large thrust for robot arms. The authors propose a coreless linear actuator using Halbach array for making it come true. The authors have designed a magnetic circuit of a prototype machine and have calculated a static thrust due to the position of the mover by using FEM. The analysis result shows that the proposed model can produce a thrust large enough. In addition, the authors have designed a test machine, and have measured fundamental characteristics. The magnetic flux distribution of the Halbach array matches up to the analysis result. Also, the static thrust increases linearly in size of current, and the authors confirm that the proposed machine can generate sufficient thrust. The authors summarize the design and experimental verification of the possibility of the proposed coreless linear synchronous actuator concretely.**

***Index Terms*-- Bi-articular muscle, Halbach array, humanoid robot, linear synchronous actuator**

I. INTRODUCTION

Recently, humanoid robots have been familiar for human and performance of humanoid robot have been evolving rapidly. Though the mechanisms of many of the present humanoid robots are different to the mechanisms of life, the studies to emulate mechanism of life, especially animals to humanoid robots are active. The aim is in order to evolve the kinematic performance of the humanoid robot and to express a redundancy.

When one observes to a robot arm which has two-joint and operate in a plane, the study on bi-articular muscle is an important one of them. All quadruped and biped animals have such bi-articular muscles. From recent researches, there are some merits for humanoid robots to have bi-articular muscle mechanism.

However, actuators for the role of an artificial bi-articular muscle do not establish now depending on applications.

In this paper, the authors design a new linear synchronous actuator for a humanoid robot arm using strong permanent magnets and research about the fundamental characteristics of the test machine.

II. INTRODUCTION OF BI-ARTICULAR MUSCLE AND THE IMPORTANCE OF THE LINEAR ACTUATOR

A. Characteristics of Bi-articular Muscle

Fig. 1. shows the arm system of human including bi-articular muscles. In the figure, f3 and e3 are bi-articular muscles. Bi-articular muscle attaches riding in two adjacent joints. The main characteristics are doing comparable operation and to contribute to output rigidity, and orbit control in the tip of the limbs [1].

Humanoid robot arms whose equip bi-articular drive mechanism do not need a complex motion algorism as calculate an inverse kinematics, and though the number of actuators, it is possible to use smaller one than the present one. In addition, it can express a redundancy of life from preceding researches [2][3].

In addition, all quadruped and biped animals can generate power in six directions by bi-articular muscles in Fig. 1. However, many of the present humanoid robots can only generate power in four directions. Because they do not have actuators used for an artificial bi-articular muscle. If a robot arm has bi-articular muscle mechanism, it can generate power in six directions. It means that when one motor breaking down and output becomes decrease, entire output distribution characteristic is maintained with output adjustment of the other motors. This is only achieved by having bi-articular muscle mechanism [1].

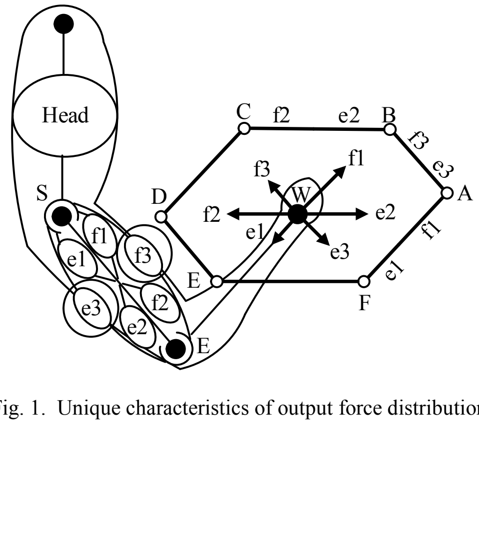


Fig. 1. Unique characteristics of output force distribution.

B. Present Condition of an Actuator for the Role of an Artificial Bi-Atricular Muscle and Proposition of New Actuator

Present bi-articular muscle operation is represented by the combination of a small linear actuator, wire, spring and a stroke sensor or a hydraulic actuator and a pneumatic actuator etc. Respectively, there are some features but it is necessary for an actuator playing the role of an artificial bi-articular muscle to generate a large thrust and being light weight.

TABLE I shows characteristics of an electromagnetic actuator, a hydraulic actuator and a pneumatic actuator.

A pneumatic actuator is difficult to generate a large thrust, and the responsivity is slow. A hydraulic actuator is generally said that it can generate a large thrust compare to the others. However, it needs a hydraulic oil tank and tubes and the device becomes large.

The proposed linear actuator in this paper has the characteristic of direct drive and the device does not become large for the reason of it does not need a hydraulic oil tank and tubes. In addition, even general industrial motors has a responsivity of mm/sec. order by current control and has a position control of mm or μ order and has a repeatability. Also, an electromagnetic actuator can harmonize a microprocessor and easy to control.

Mechanism using a linear actuator is more suitable than mechanism using a rotary motor and pulley when one express linear expansion and contraction motion of bi-articular muscle.

Consequently, a linear actuator, which has a characteristic of direct drive, is suitable as an actuator playing the role of bi-articular muscle. However, it is necessary for a present linear actuator to generate a large thrust and to decrease the weight. Also the reduction of heat, which is generated from a coil, is needed.

The authors propose a new light PM-type linear synchronous actuator for an artificial bi-articular muscle and research about the fundamental characteristics of the test machine.

TABLE I CHARACTERISTICS OF THREE FAMOUS ACTUATORS.

Electromagnetic actuator	
◎**Harmonization** of electronics and digital computers, Easy control, High response and accuracy	×**Heavy weight**, Low power
Hydraulic actuator	
◎**High power** and accuracy, Easy control	×**Large device**, Danger by fire
Pneumatic actuator	
◎**Cheap** device cost, High **safety** & environmental characteristic	×**Low power**, **Low response**

C. Required Conditions as an Actuator for the Role of an Artificial Bi-articular Muscle.

Redundancy is a characteristic for life. Output pattern exists some patterns to each actuator playing the role of muscle when the robot arm operates. Especially, thrust and stroke of an actuator for a robot arm change if the radius of the link and the angular rate change.

Consequently, required thrust and thrust of a linear actuator for an artificial bi-articular muscle have been excerpt from a proceeding research [3]. The specification has been designed for a bi-articular muscle function of a human type robot arm. Fig. 2 and TABLE II are the model and data of the human type robot arm. Except the mass, this data has been based on the arm system of the average adult man in Japan.

In state of the angle θ_2 of link2 is keeping 0 rad, the angle θ_1 of the link 1 moves from 0 rad to $\pi/2$ rad by output of e1 and f1. When the angle θ_1 rotates from 0 rad to $\pi/4$ rad, the arm is accelerated by maximum output of f1. And when the angle θ_1 rotates from $\pi/4$ rad to $\pi/2$ rad, the arm is decelerated by maximum output of e1 and the arm stop. The operating time is $2T$ second.

When parameters are used from TABLE II and T is defined 1.0 second, output is calculated from a moment of inertia and a dynamic rotary equation.

The necessary thrust is calculated 45.0N, and the authors think that the necessary thrust of the proposed machine is more than 50.0N.

Also, the movable angle and the radius of the arm calculate stroke. Stroke is necessary more than 125.0mm from parameters of TABLE II.

The authors design the test machine thinking about these conditions and mass of the actuator that can use as actuator for a robot arm.

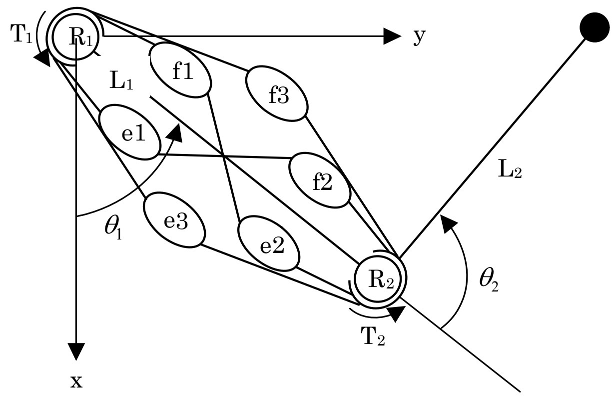


Fig. 2. The arm system of life including bi-articular muscles.

TABLE II PARAMETERS OF THE ROBOT ARM.

	Link1	Link2
Length (mm)	l_{L1}=300.0	l_{L2}=300.0
Width (mm)	w_{L1}=100.0	w_{L2}=100.0
Mass [arm] (kg)	m_{L1}=2.0	m_{L2}=1.0
Radius (mm)	r_{R1}=30.0	r_{R2}=30.0
Mass [joint] (kg)	m_{R1}=0.5	m_{R2}=0.5
Movable angle (rad)	$\pi/2$	$5\pi/6$

III. Specification of the First Test Machine

A. Brief Description on the Proposed Machine

Fig. 3 shows the concept of a new light PM-type linear synchronous actuator. And Fig. 4 shows photos of the test machine.

The field mover is used Nd-Fe-B permanent magnets and the size of a piece of magnet is 10*10*50 mm^3. The field mover is composed of Halbach array in Fig. 4. (b). One can obtain large magnetic field by using it. Also, the Halbach array in the unilateral linear motor is able to generate the large magnetic field one side. The authors are able to make the coreless linear actuator thanks to this advantage. A thin iron plate is placed in the backside of the Halbach magnets. This is for glueing purpose and effect on magnetic flux distribution is negligible.

The Halbach magnet has been wrapped with rigid aluminum in order to bring out thrust and the field mover moves by wheels, which are mounted on the aluminum flame. In addition, the field mover is equipped an optical linear scale. Resolution of the linear scale is 0.5μm. Total mass of the field mover in state of Fig. 4 (b) is 1.13 kg from measurement.

The nonmagnetic materials and a coil compose the armature. Thrust is produced by three-phase alternating currents in the coils wound around nonmagnetic tube located outside of the field mover. Actually, a prototype machine needs support mechanisms and it is formed a complicated mechanism in Fig. 4 (a). Almost support mechanisms including the field mover are made of aluminum. Consequently, those do not pass through the magnetic field. Nominal r.m.s values of three-phase currents in actual driving are defined 3.0 A. The stroke of the test machine is designed to 150.0 mm.

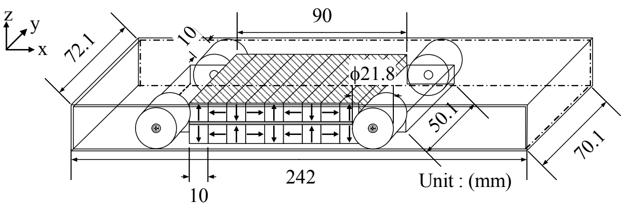
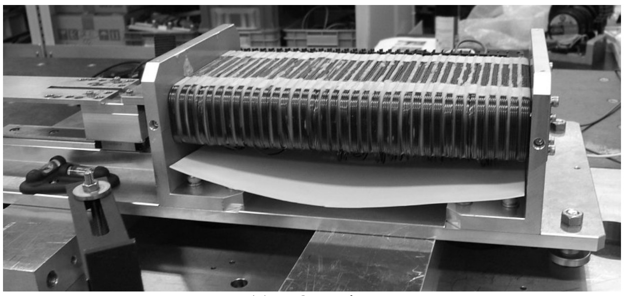
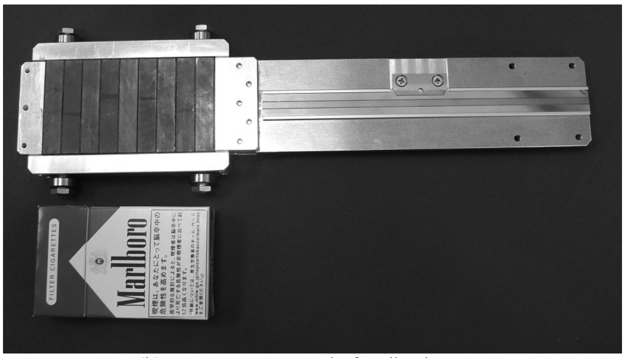


Fig. 3. Concept of the proposed model.



(a) Overview



(b) Mover composed of Halbach array.

Fig. 4. Photos of the test machine.

IV. Comparison with the Electromagnetic Analysis and Measurement of the Test Machine

In this chapter, the authors examine the fundamental characteristics of the proposed machine. To be more precise, the authors analyze whether the field mover, which is composed of the Halbach array, can generate a uniform sinusoidal wave flux density distribution and the proposed model can generate sufficient thrust by using two-dimensional Final Element Method (FEM). The static DC Field is assumed for the calculation. Subsequently, the authors have measured the flux density distribution of the field mover and the static thrust of the test machine, and have compared with the calculated result.

A. Condition of the Analysis Model

Fig. 5 shows a model for a two-dimensional analysis model. The authors have defined that the center point of the field mover is $x = 0.0$ mm and the surface of the upper side Halbach magnet is $z = 0.0$ mm in Fig. 5.

The property of Nd-Fe-B permanent magnet is Br=1.41 T and Hc=1000.0 kA/m. The diameter of the wire ϕ1.0 mm and cross-section for the coil, which is wound and wound 40 Turns per one phase in one pitch. The stroke of the mover is 150.0 mm and twelve parts of coils per one phase are wound. Nominal r.m.s values of three-phase currents are 3.0 A and three-phase currents are set as follows:

$$Iu_{rms} = 3.0\cos(\omega t), \qquad Iv_{rms} = 3.0\cos(\omega t - \frac{2}{3}\pi)$$

$$Iw_{rms} = 3.0\cos(\omega t - \frac{4}{3}\pi) \qquad (1)$$

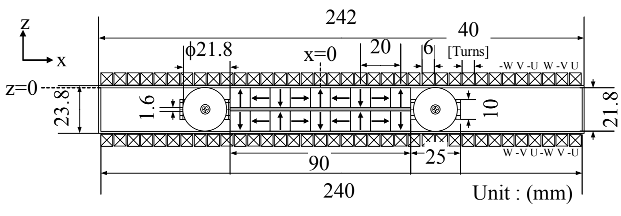


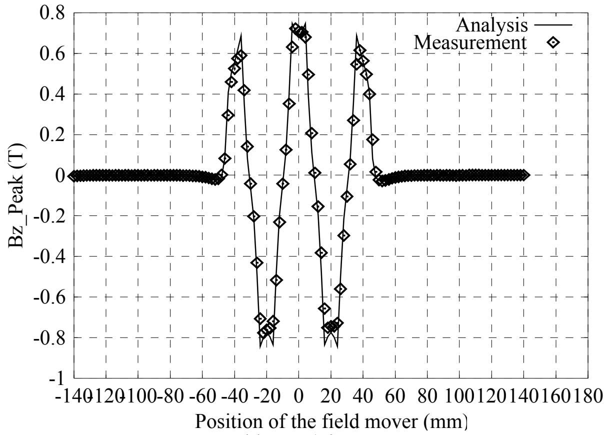
Fig. 5. Two-dimensional analysis model.

B. The Magnetic Flux Distribution of the Field Mover

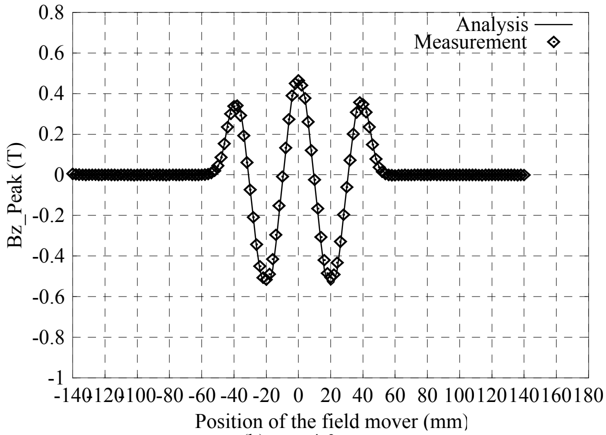
Firstly, the authors have analyzed and measured the flux density distribution of the field mover. The sampled points are on 1.0, 4.0, 7.0 mm from the surface of the Halbach magnet (z=0). Flux density distribution is measured by using a gauss meter. Points of measurement are the center of the magnet regarding y-direction. Also, the field magnet moves slowly to from one edge to another edge under a probe of the gauss meter and the flux density of z-direction are measured and compared with the results of the calculation.

Their results are summarized and compared in Fig. 6. The results of analysis match up to the real measurements. Flux density distribution of the field mover is substantially sinusoidal waveform. Also, flux leakage is negligible. Actually, coil is mainly wound in Fig. 6 (b), (c) and the flux distribution is a uniform sinusoidal waveform.

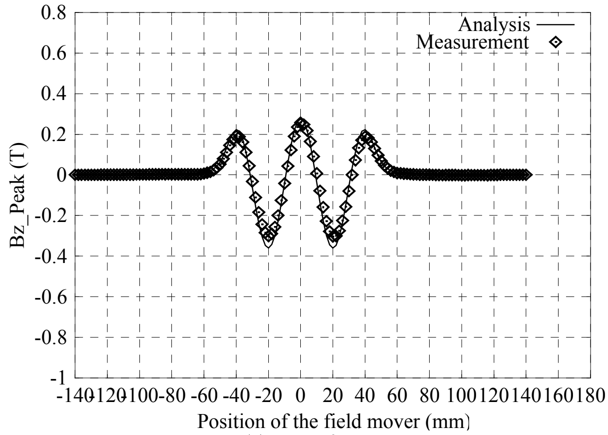
Consequently, the test machine has a characteristic of a simple coreless linear actuator.



(a) z=1.0mm



(b) z=4.0mm



(c) z=7.0mm

Fig. 6. Comparison of analysis and measurement about the flux density distribution of the field mover.

C. The Static Thrust

In this chapter, the authors have compared calculation of the static thrust with measurements.

The static thrust of the actuator is calculated as follows. The nominal r.m.s values of three-phase currents was defined as follows:

$$Iu_{rms} = 3.0\times\cos(\frac{11\pi}{6}), Iv_{rms} = 3.0\times\cos(\frac{7\pi}{6}), Iw_{rms} = 0.0 \quad (2)$$

DC currents are given from Eq. (2) and the static thrust is calculated on every 3.33 mm from x=0.0 to x=40.0 mm. Since coil-pitch is 20.0 mm, the authors have omitted further measurements at platted the extrapolated repeated data assuming periodicity.

The result is shown in Fig. 7. The waveform becomes sinusoidal wave. And, the load angle of A is $\pi/2$ rad and the thrust of point A is 53.0N.

Subsequently, the static thrust of the actuator was measured as follows:

$$Iu_{rms} = \frac{\sqrt{2}}{2}\times 0.5, \frac{\sqrt{2}}{2}\times 1.0, ..., \frac{\sqrt{2}}{2}\times 5.0$$

$$Iv_{rms} = -\frac{\sqrt{2}}{2}\times 0.5, -\frac{\sqrt{2}}{2}\times 1.0, ..., -\frac{\sqrt{2}}{2}\times 5.0, Iw_{rms} = 0.0 \quad (3)$$

Nominal r.m.s values of W-phase current Iw were always held on 0.0 A, and nominal r.m.s values of U and V-phase currents Iu and Iv are adjusted to every 0.5 A varied from 0.50 A to 5.0 A from Eq. (3). The static thrust is measured in state of the field mover moves a constant slow speed.

Fig.8. shows measured instantaneous values of thrust produced by different armature current amplitudes when the field mover is moving under DC current condition. The static thrust is proportional to the amplitude of the armature current in Fig. 8. In addition, the bold line in Fig. 8 is the thrust when the amplitudes of nominal r.m.s values of U and V-phase currents are 3.0 A. The load angle of B is $\pi/2$ rad and the thrust of point B is 52.5N.

Consequently, the results of analysis nearly match up to the real measurements from Fig. 7 and Fig. 8. In addition, the static thrust is calculated as 50.0N using *BIl*-law. The measured data of the flux density of the field mover and the result nearly match up to the real measurements.

Also, a flux leakage is negligible from the results of calculation and measurement in Fig. 6. Flux leakage has no negative thrust. The main reason for the loss is presumed to a kinematic friction. As a result, it can be said that test machine has accomplished the predesigned performance and can generate sufficient thrust as an actuator for the role of an artificial bi-articular muscle in state of nominal r.m.s values of three-phase is 3.0 A.

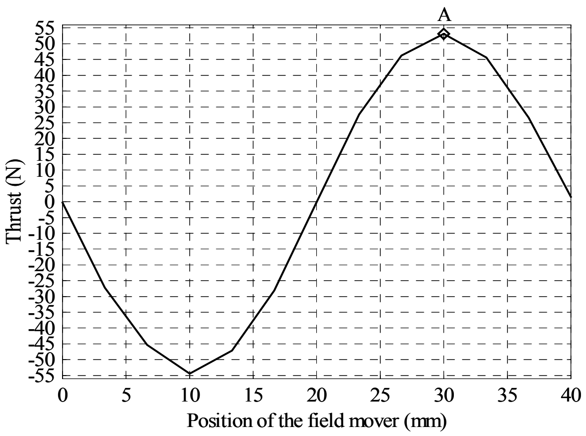


Fig. 7. Change of thrust with the movement of the field mover by two-dimensional FEM.

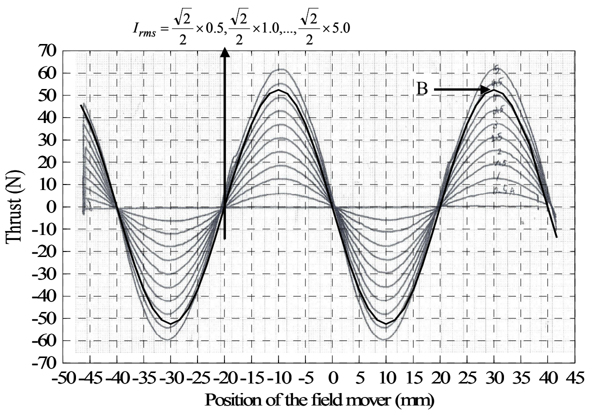


Fig. 8. Change of thrust with the movement of the mover on the condition of a constant current by measurement.

Finally, the authors have calculated the change of thrust with the movement of the field mover in state of a load angle $\pi/2$ rad. Static DC field was assumed for the FEM-calculation; the phase angles ωt is Eq. (1) were given as 0, $\pi/6$, $\pi/3$, $\pi/2$, … , 2π. For example ωt is 0 in state of Fig. 5. When the position of the mover is 3.33 mm from x=0, the corresponding angle ωt is $\pi/6$ rad and when the field mover locates at 20.0 mm, the corresponding angle ωt is π rad. The static thrust is calculated on every 3.33 mm from x=0.0 to x=40.0 mm. Since coil-pitch is 20.0 mm, the authors have omitted further measurements at platted the extrapolated repeated data assuming periodicity. All points of static thrust are calculated on the point of a load angle $\pi/2$ rad.

Thrust of the proposed model becomes average 53.5N from the calculated results in Fig. 9. The thrust ripple is less than 1.3%. The fact that thrust ripple is so small is a merit of the coreless motor.

As a future work, the authors will try to the driving experiment of the test machine and will compare to the analysis result.

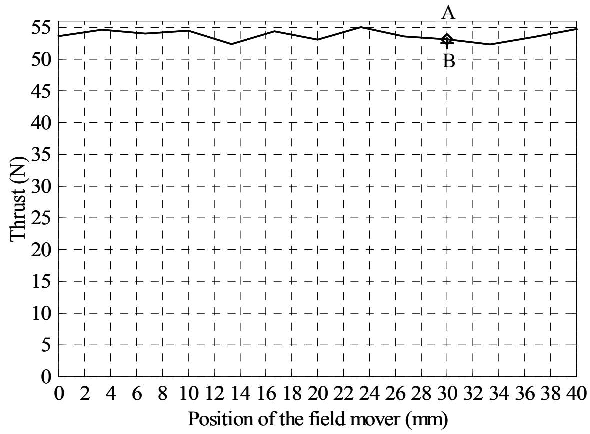


Fig. 9. Change of thrust with the movement of the mover on the condition of a phase difference angle=$\pi/2$ by two-dimensional FEM.

V. Conclusions

Humanoid robots whose actuators and mechanism are similar to the lives do not need a complex calculation of an inverse kinematics, and small and strong electromagnetic actuators are requested for the purpose.

In this paper, the authors have proposed a new light PM-type linear synchronous actuator for human type robot arms whose equip bi-articular drive mechanism. And the authors have designed a magnetic circuit of a prototype machine and have calculated the static thrust due to the position of the mover by using FEM. The authors have measured the flux density distribution and the static thrust where the test machine generates.

The characteristic of the test machine is that the field mover is composed of the Halbach array magnet. Though making the Halbach array is not easy, flux density distribution becomes substantially sinusoidal waveform by the Halbach array magnet. Actually, flux density distribution of the field mover is substantially sinusoidal waveform. And the results of analysis match up to the real measurements. Consequently, the test machine has a characteristic of a simple coreless linear actuator.

The authors have compared calculation of the static thrust with measurements. The results of analysis nearly match up to the real measurements. The static thrust of real measurement is 52.5N in state of Eq. (2) and at the load angle of is $\pi/2$ rad. Also, the static thrust is calculated 50.0N using *BIl* law and the measurement data of flux density of the field mover. Consequently, the calculation using *Bil* nearly matches up to the real measurements.

The proposed model is a simple linear synchronous actuator from the design and the fundamental characteristics, and the thrust where it generate is large sufficient as an actuator for the role of an artificial bi-articular muscle.

As a future work, the authors will test the drive performance of the test machine. In addition, the authors study designing of the control system consideration to drive as an actuator for the role of an artificial bi-articular muscle.

Also, the test machine must be more compact and generate larger thrust as an actuator for the robot arm. Heat generated from coils must be reduced. An actuator playing the role of muscle must be operated in state of the non-horizontal plane. Consequently, the authors will think of ideas about these issues and design the progress model.

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