2014 14th IEEE-RAS International Conference on
Humanoid Robots (Humanoids)
November 18-20, 2014. Madrid, Spain

Development of High-Power and Backdrivable Linear Electro-Hydrostatic Actuator*

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Abstract— **Actuator with high power output and durability is a important factor in developing humanoid robots with high mobility. Development of such actuator with force sensitivity is a challenge. We developed linear electro-hydrostatic actuator (EHA) to realize high-power output, high durability, and backdrivability. This paper presents mechanical design of a linear EHA that reduces friction. Low friction piston seal was employed to significantly improve volumetric efficiency while keeping loss of backdrivability minimum. To test this device, a testing device with reaction mass is proposed. This device can be used to give external force to actuator under dynamic movement with high repeatability. Backdrivability, maximum cylinder force, and frequency response were evaluated to show the efficacy of the proposed actuator.**

I. INTRODUCTION

One of the recent demands in robotics is the power capacity of actuators that enable robots to perform dynamic tasks in real world. Robotics Challenge[1] hosted by DARPA is a competition that attempt to develop robots capable of performing heavy-duty tasks for disaster recovery, in outdoor environment. SCHAFT (now a part of Google) developed high power humanoid with liquid motor cooling system marked the best score in competition trial held in December 2013. Atlas [2] developed by Boston Dynamics (also now a part of Google) is a platform robot used in competition, which also have high power capability. It clearly shows high-powerness (as compared to previous humanoid robots) is an important factor in robots for real world.

Hydraulics is one of the ways to deliver powerful and robust actuation to robots. The first industrial robot, Unimate, was hydraulically actuated because the motors back then did not have enough power density to be used for such applications. For the last decades, improvement of power density in motor replaced hydraulic actuators with electric servo motors. However, the gear train lacked impact resistance, and thus the robots were required to move in naive manner.

For legged robots, including humanoid robots, it is very important for them to be impact resistant. CB developed by Cheng et al. [3] and BigDog developed by Raibert et al.[4] are examples of robots with hydraulic actuators, which performed many dynamic tasks successfully. Similar technology is used in fully hydraulic humanoid, PETMAN (Nelson et al. [5]). This technology is used in Atlas [2] mentioned above.

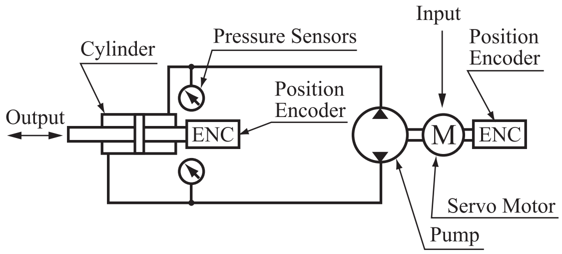

Fig. 1. Structure of Linear Electro-Hydrostatic Actuator

High power robots still need to make safe and stable contact with environment, which imply the importance of capability of sensing and controlling contact forces, or in other word, *force sensitivity*. Force sensitivity is important in both protecting environment and protecting robot itself. Robots that operate in harsh and hazardous environments must behave force sensitive regardless of the control failure. It should be noted that torque sensing performance only shows an aspect of the force sensitivity. Backdrivability plays an important role in force sensitivity in passive sense. Having both the torque sensing capability and the backdrivability is necessary to develop truly torque sensitive actuators and robots.

Friction in an actuator is one of the main causes of losing backdrivability. Gear drives, in general have relatively large friction, which lead to less backdrivable actuators. This is also true for hydraulic actuators. The conventional hydraulic actuators are resistance controlled and lack backdrivability. Although it is reported that the high control bandwidth of servo valves can emulate impedance property at high accuracy [6], the nature of the actuator is still non-backdrivable. The resistance of the valve also have negative effect of lowering the efficiency and heat generation in hydraulic system, that mandate the use of oil coolers, which is usually relatively heavy.

Series elastic actuator [7] and its derivatives [8], [9], [10] are backdrivable gear based actuators, having springs in the output axes or in line with tendons. Their output axes are backdrivable, but the transmission system is still gear based systems. If the external force was so large that the springs get fully extended, then the non-backdrivable part of the actuator may fail.

We aim to develop truly force sensitive actuator with hydraulic actuator called electro-hydrostatic actuator (EHA). EHA is a displacement control type hydraulic actuator that control hydraulic motor motion with the torque supplied to

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*This work was supported by Grant-in-Aid for Young Scientists Category (B)(No.23760219) of the Japan Society for the Promotion of Science.

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978-1-4799-7174-9/14/$31.00 ©2014 IEEE

the pump. We use a combination of a fixed displacement pump, a fixed displacement hydraulic motor, and a servo motor to construct an EHA[11]. In our previous study [11], [12], we developed revolute EHA with low friction. The keys of making system backdrivable were as follows:

1) Low friction design without contact seals
2) Allowance of small internal leakage

We call a flow in pumps and hydraulic motors, from high pressure side to low pressure side, an internal leakage. Internal leakage enhances the backdrivability [13], but at the same time, it reduces efficiency and power output.

Our objective is to develop high-power and backdrivable actuator to realize powerful, robust and force sensitive robot. We chose to use cylinders with low friction seals to improve volumetric efficiency of the actuator to enhance power output. Alfayad et al. [14] developed linear EHA with energy storing accumulator to enhance backdrivability and efficiency. In contrast, we target to extend low friction design of our previous studies. In this paper, mechanical design of the actuator is presented. To show the validity of the concept, we conducted evaluation of backdrivability, maximum force, and dynamic response.

II. LINEAR ELECTRO-HYDROSTATIC ACTUATOR

Electro-Hydrostatic Actuator(EHA) is a displacement control type hydraulic actuator. Unlike conventional hydraulic actuator that use servo valves, EHA control either pump displacement or pump rotation to control amount of pressure supplied to hydraulic motor. Removal of servo valves bring significant benefit to EHAs such as low heat generation, high efficiency, and backdrivability.

Internal leakages exist in all hydraulic systems. They are one of the largest causes of degrading volumetric efficiency of pumps and hydraulic motors. However, in EHAs, internal leakages decouple dynamics of pumps and hydraulic motors, which enhance backdrivability of the actuators[13].

In previous studies, we have developed rotary EHA that consists of a trochoid pump and double vane motor[11]. Most of the joints in robots are revolute and therefore rotary actuator was useful for driving such joints. On the other hand, rotary EHA had large internal leakage at the tip and corner of the vanes, which lead to loss of power. Sealing such sharp corners is difficult.

In this paper, we present linear EHA using hydraulic cylinder instead of a vane motor. Advantages of this design are as follows.

1) Annular section of the cylinder enables the use of precisely machined low friction seals (piston rings) to significantly enhance volumetric efficiency
2) Multiple DOF joints can be driven parallel with multiple cylinders to effectively share actuator power
3) Stroke of the cylinder is unlimited (movable range of double vane motor is 180 degrees at maximum)

Fig. 1 shows composition of linear EHA. Output is replaced from hydraulic motor to cylinder in linear design, but the other components remains identical. EHA requires output axis position encoder due to possible position drift of output axis with respect to input axis cased by internal leakage.

TABLE I
REQUIREMENTS IN LOWER LIMB JOINTS FOR STEPPING

Joint	Power (W)	Torque (Nm)	Speed (rad/s)
Hip-Roll	205	116	1.77
Hip-Pitch	286	48.2	5.93
Hip-Yaw	11.4	5.00	2.27
Knee	476	58.7	8.11
Ankle-Roll	36.9	16.4	2.25
Ankle-Pitch	731	108	6.77
Ankle-Yaw	66.2	29.8	2.22

TABLE II
DESIGN SPECIFICATION OF LINEAR ELECTRO-HYDROSTATIC ACTUATOR

Max. Pressure	5.6 MPa
Max. Thrust	1500 N
Max. Speed	0.23 m/s
Net Weight	1.053 kg

III. REQUIREMENTS ON LINEAR EHA

We aim to use linear EHAs in lower limb of a full-size humanoid robot. We captured human motion and performed inverse dynamics calculation to derive reference data of robot and actuator specification.

Stepping motion of a healthy male with body weight 63kg was captured with optical motion capturing. The movement of markers are then mapped to 34 DOF human figure with same size and weight to solve inverse kinematics and inverse dynamics.

Among the lower limb joints, ankle joint has largest requirement (Table I). Using the inverse dynamics result, size and placement of the actuator were optimized using sequential quadratic programming. The details of the optimization is described in [15].

The result of optimization requires 3 of 200W actuators for the ankle when it is driven in parallel manner. The optimization result, design specification of the linear EHA was calculated as Table II.

IV. MECHANICAL DESIGN OF LOW FRICTION CYLINDER

We aim to develop linear EHA for use in robots. One of the challenge in robot actuator design in the size and weight reduction. They directly affect power density of the robot. For the force sensitive robots, requirement on low friction property also adds up. We designed nondifferential cylinder to realize symmetric and linear actuation.

Fig. 2 shows the cross section drawing of the cylinder developed. Instead of using wear rings to support piston in radial direction, we employed a pair of ball bush to reduce friction and enhance movement precision. Ball bushes are installed in head covers of the cylinder, which are connected with tie rods. Low friction seals were used as piston seal and rod seal to minimize friction while avoiding leak. Use of small diameter piston rod is effective in reducing friction.

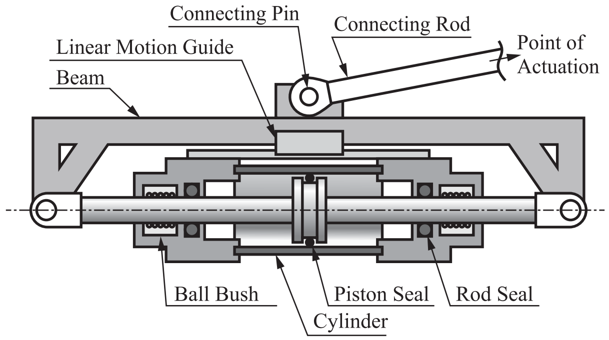


Fig. 2. Cross Section of Developed Cylinder

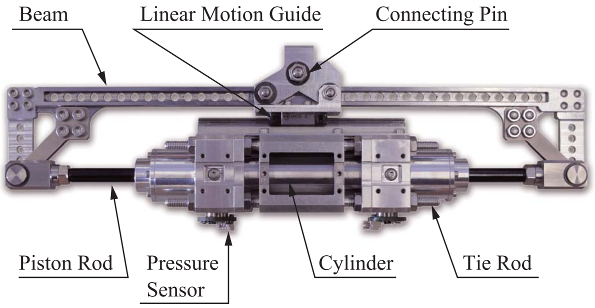


Fig. 3. Outlook of Developed Cylinder

Use of small diameter piston rod in double acting cylinder is difficult since the rod must endure the compressing force and bending moment. In this research, we use supporting beam structure and linear motion guide to support constraint forces. The connecting rod with spherical joint on both end is used to transmit force to joint.

Outlook of the developed cylinder is shown in Fig. 3. The design specification of the cylinder is show in Table III. The cylinder is designed to be driven with the internal gear pump used in [12]. Fig. 4 shows the outlook of whole actuator.

Surface treatment is important in reducing friction of hydraulic systems. For the piston rod, Diamond Like Carbon (DLC) coating was applied. For the cylinder inner surface, Ni-PTFE plating was applied.

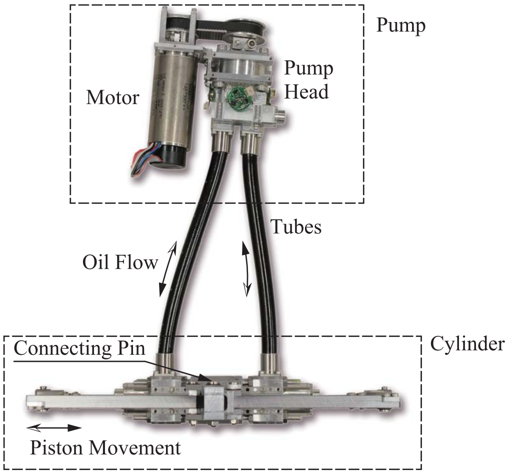


Fig. 4. Outlook of Developed Linear Electro-Hydrostatic Actuator

TABLE III

DESIGN SPECIFICATION OF CYLINDER

Bore Diam.	20 mm
Rod Diam.	6 mm
Stroke	50 mm
Dry Weight	0.444 kg

V. EVALUATION OF ACTUATORS USING REACTION MASS

Our objective of the research is to develop force sensitive robot actuators. Being force sensitive is identical to the actuator being affected by the external force. It is important to know the behavior of such actuator under existence of external force.

To apply external force to the actuator, there are several possible methods.

1) Static push against stationary point
2) Use of gravity
3) Push with other force controlled actuator
4) Use of inertial force

Method 1 is commonly done to measure maximum thrust. Method 2 is also commonly done to measure the (quasi)static force. Interaction force can be calculated from mass and the gravitational acceleration, but the force that can be produced is asymmetric. Method 3 has an advantage that it can produce arbitrary pattern of the force or impedance, but the repeatability and reliability of the evaluation depends on the performance of the actuator that apply the force. Also, accuracy of the measurement of the interaction force determines evaluation accuracy.

We developed an evaluation device using method 4 for dynamic evaluation of the actuator. Method 4 was selected due to following reasons:

1) Dynamic property can be evaluated
2) Both mass and displacement can be measured with high repeatability
3) Push and pull behavior can be symmetrically evaluated

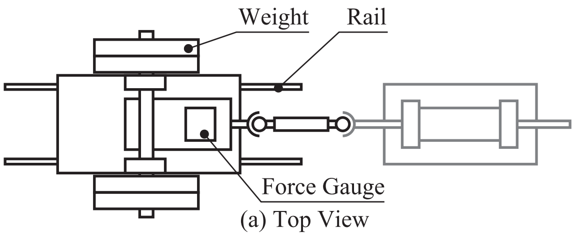
To realize the evaluation, we designed the reaction mass device as in Fig. 5. The weight is fixed on a linear motion guides to support gravity with low friction. Force gauge was put in between the actuator and the weight to measure the interaction force.

VI. EXPERIMENT

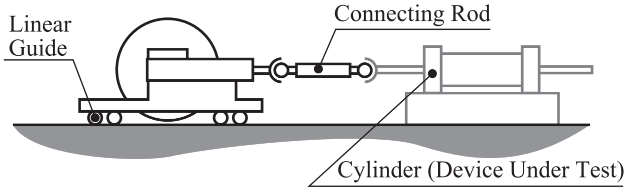
There are several performance measures for robot actuators. To investigate performance of a force sensitive actuator, we chose following measures.

1) Passive backdrivability (friction property)
2) Static properties (maximum force)
3) Dynamic property (frequency response)

Details of the evaluation is shown in following sections.



(a) Top View



(b) Side View

Fig. 5. Structure of Evaluation Equipment using Reaction Mass

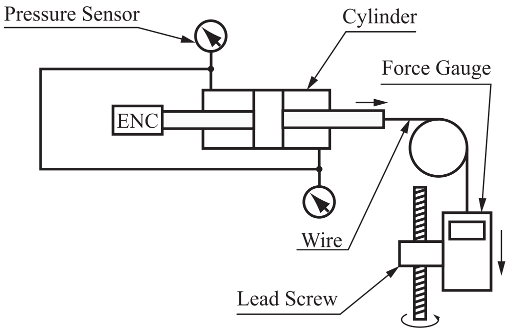


Fig. 6. Evaluation Apparatus of Frictional Properties

A. Backdrivability Evaluation

Backdrivability is one of the most important characteristics of the force sensitive actuators. In this paper, we evaluate passive backdrivability characteristics by applying external force while the control system being turned off.

The testing apparatus shown in Fig. 6 was used to evaluate friction of the piston rod. Pump was removed from the hydraulic circuit to eliminate effect of it. Displacement was applied to the cylinder through a force gauge that measure the interaction force. Displacement of the cylinder is measured with linear encoder attached to the piston rod. Constant speed of $5.285 \times 10^{-3}\mathrm{m/s}$ was applied for the experiment.

We prepared two set of piston rods: one with diamond-like-carbon coating and other with bare titanium surface to compare the friction property.

Fig. 7 shows the time series of the force and cylinder displacement. The reason why the force rises gradually is the slackness of the wire. Table IV shows the friction data acquired from the same experiment. From the result, we observed that the static friction did not make difference but the sliding friction was reduced by 42.8% by DLC coating.

The measured friction force corresponds to output back-driving force [11], which is the force necessary to drive output axis by external force. The output axis can be backdriven with force that is 0.77% of the maximum thrust.

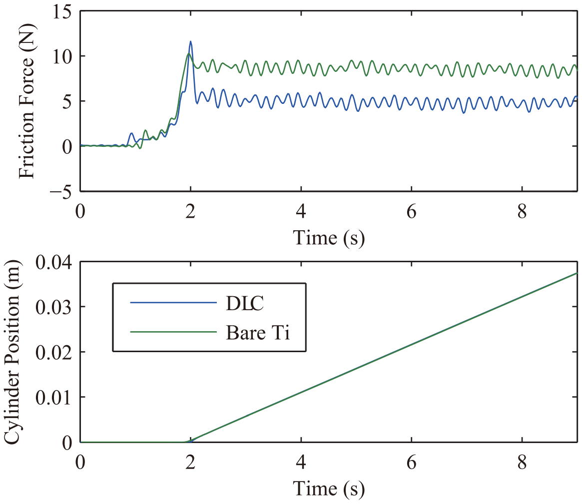


Fig. 7. Friction Comparison Between Bare Titanium Rod and DLC Coated Rod

TABLE IV

FRICTION FORCE OF PISTON ROD WITH DIFFERENT SURFACE COATING

	Sliding	Static
Diamond Like Carbon Coating	4.811 N	11.61 N
Bare Titanium	8.411 N	10.24 N

Similar evaluation was conducted to measure total back-driving force. For this test, pump was attached in place. Total backdriving force is the force necessary to drive whole actuator with external force. The measured total backdriving force was 42.6N, which is 2.8% of the maximum thrust. It is important for the system to be total backdrivable because if the system is total backdrivable, then no matter large external force the actuator receives, the energy can be regenerated at the motor. It avoids the actuator to fail due to over-storage of energy, which is likely to happen in elastic type actuator.

B. Maximum Thrust of Linear EHA

Maximum thrust is one of the important measure of an actuator. We measured maximum thrust with the setting shown in Fig. 8. A force gauge is fixed to the same table that the cylinder is fixed to. We applied 7A to the pump motor and observed the force acting on the force gauge. We pulled the gauge to increase the mechanical stability.

Fig. 9 shows the time-force and time-pump speed plot of the experiment. The current was supplied to the pump at time 0s, and cut off at time 1.5s. The movement of the piston rod is negligible since it is rigidly fixed to the base. The peak of the thrust was 1500 N and average was 1350 N. One of the reason of the decreasing force is suspected to be the decrease of viscosity due to the temperature raise in the pump. When the cylinder is exerting the force, all the mechanical power supplied to the pump is turned into heat. Fig. 10 shows the viscous effect acting on the pump that is calculated by dividing pump torque (derived from pump motor current) by pump speed. If the viscosity is constant, then this value

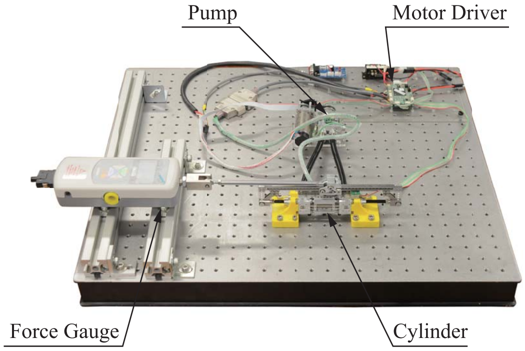


Fig. 8. Evaluation Apparatus of Maximum Thrust with Piston Locked

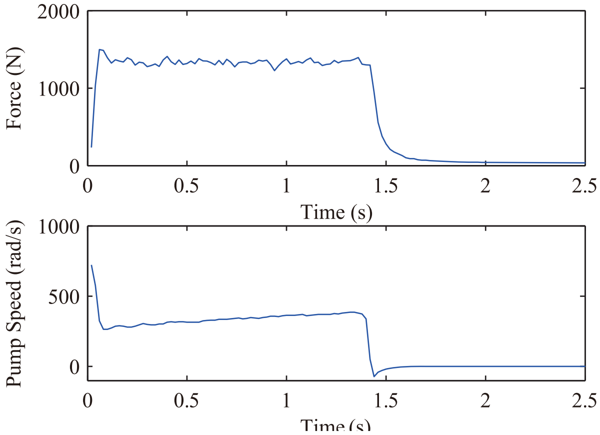


Fig. 9. Time Dependency of Maximum Thrust Force

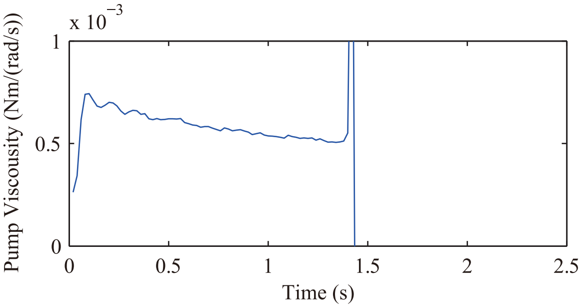


Fig. 10. Change in Viscous Modulus During Maximum Thrust Test

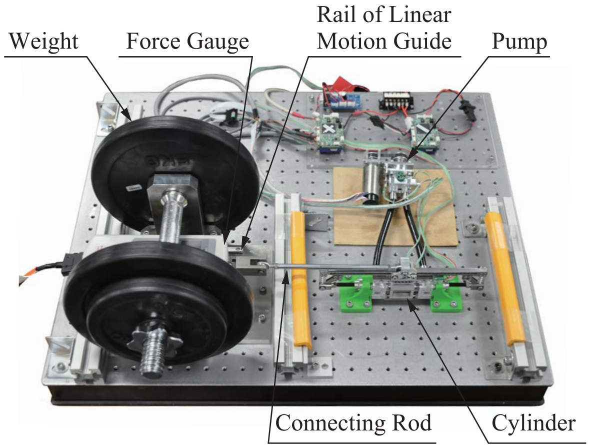


Fig. 11. Evaluation Apparatus of Frequency Response

should be constant. We can observe the decrease in viscosity from this figure.

In Fig. 9 at time 1.5s, we can observe the pump being backdriven with the elastic energy stored in hydraulic circuit (pump speed becomes negative after the motor being powered off), which mainly come from elasticity of tubes. This shows the low friction property of the pump.

C. *Frequency Response of Linear EHA*

First, we identified dynamic characteristics of the actuator. The apparatus for the evaluation is shown in Fig. 11. We applied sinusoidal torque to the pump that corresponds to amplitude of 0.017m at cylinder (34% F.S.) at low frequency. We recorded position of pump and cylinder simultaneously as input and output of the system. Several frequencies were tested. Fig. 12 shows the bode plot of EHA with position input and position output. From the result, with 0kg load, frequency response remains flat throughout the whole range. For the result with 35kg load, we observe slight trend in increasing delay, which shows 40deg phase delay at 6Hz. We can expect the 90deg phase delay between 7 to 8Hz, by extrapolating the result. We expect the difference in behavior with presence of the load due to elasticity in hydraulic system. From these results, we confirmed capability of EHA to transmit large force with frequencies to 6Hz, which is sufficiently higher than main operating frequency of walking robot that is around 1 to 2 Hz.

In order to know the controllability of the actuator under the existence of the external force, we then controlled piston position with PID controller and used position reference as input and actual cylinder position as output. Similar test as above with square wave was performed. Although the results would be dependent on controller tuning, the result would at least show the worst case performance. The test was conducted for amplitudes of 5mm, 10mm, and 15mm.

Fig. 13 shows the position control frequency response. The frequency that the phase lag becomes 90deg is around 2.5Hz in all cases. 35kg is over 330% of its own weight, and shows high power density of the designed actuator. The phase lag at 0.1Hz comes from stick-slip behavior of the system because we are not compensating friction force for this experiment. From this test, we observed maximum speed of 0.27m/s and maximum inertial force of 320N. It implies maximum accerelation observed was $9.1\mathrm{m/s}^2$(0.93g). Maximum speed of the prototype was larger than design specification. The gap between gear and case in the pump is expected to be larger than the design value, which decreased the viscous friction.

The attached video shows the example of the movement with 35kg load dynamic movement using the device ex-

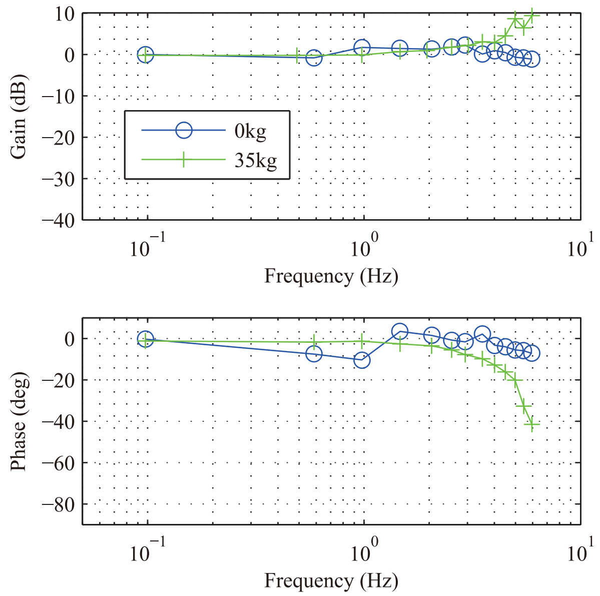


Fig. 12. Open Loop Frequency Response of Linear EHA

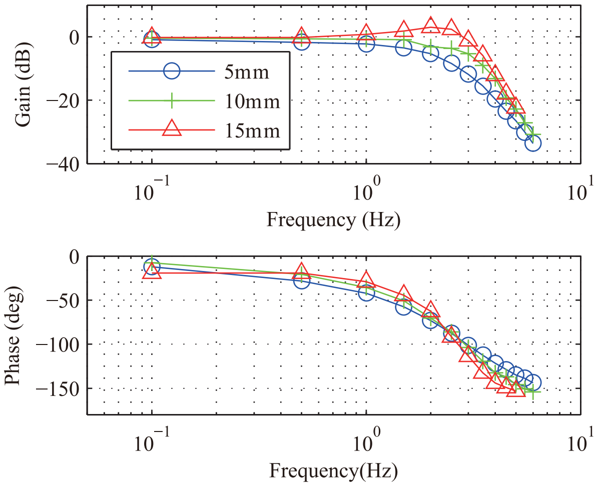


Fig. 13. Frequency Response of Linear EHA with 35kg Load

plained in section V.

VII. CONCLUSIONS

In this paper, we developed a linear electro-hydrostatic actuator for high power purpose, namely targeted for use in lower limb of a humanoid robot. Followings are the conclusions of this paper.

1) Designed low friction, light weight linear EHA. Net weight of the EHA is 1.05kg and motor power is 200W.
2) Low friction design realized low backdriving force as 0.77% of the maximum thrust for output backdriving and 2.8% of the maximum thrust for total backdriving.
3) Maximum force test show the force profile of 1500N at peak and 1350N for continuous.
4) Open-loop frequency response of the actuator showed flat behavior in the range of 0.1Hz to 6Hz with no load. From the elasticity of the system, phase delay becomes 40deg at 6Hz with 35kg load.
5) Position control of the actuator was shown to be 2.5Hz with 35kg load, which is 332% of its own weight. Maximum speed of 0.27m/s with 35kg load was observed.

These results show the efficacy of the low friction design of linear EHA, which significantly enhances backdrivability and force sensitivity of the actuator. Developed linear EHA showed large output force and wide controllable frequency, which would benefit humanoid robot locomotion for real world.

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