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Work Amplification of the Hydraulic Servo Actuator with a Miniature Accumulator *

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***Abstract*— Actuator performance is an important factor limiting the dynamic characteristics of the robot. In this paper, the energy transfer capability of the hydraulic servo actuator is improved by adding a miniature accumulator. We established the dynamic model of the system and obtained the optimal inflation pressure of the gas in the accumulator by numerical method. Both numerical analysis and virtual prototype simulation show this design can enlarge the work of the actuator to about 1.66 times the original. It allows the actuator to maintain high performance while reducing mass and volume.**

***Index Terms*— Hydraulic servo actuator, miniature accumulator, work amplification.**

I. INTRODUCTION

The dynamic movement ability like running and jumping of animals are much better than legged robots. It is of great concern to the muscle-tendon series elasticity of animals as shown in Fig. 1. Compliant elements in muscles and tendons can reduce energy consumption in legged motion [1]. Kubo et al. [2] have noted that the elasticity of tendon has a favorable effect on human daily exercise,such as running and jumping. The researchers found that the frog's excellent jumping ability is due to the elasticity of the skeletal muscle [3], [4]. They use the elastic energy storage capacity of the muscle to redistribute the output power. Galantis and Woledge [5] showed that muscle series elasticity can produce more power than the muscle alone. They found that in the early stages of muscle contraction, the muscle moves faster than the load. At this time, the power of the muscle is mainly used to increase the elastic storage in the tendon. In the later stage, the load moves faster than the muscle, so the muscle and tendon work together on the load. Therefore, the load can get more energy in a limited stroke.

Inspired by biological research, many developers employed mechanical compliance to the robot [6]–[9]. The addition of flexible elements greatly enhances the ability of robots to interact with the environment. Unfortunately, these studies focused on force control, impact-robust and mechanical energy storage. Little attention is given to the effect of elastic elements on the work of the actuator. Paluska and Herr [10] demonstrated that the power and work output of the actuator can be amplified within a limited stroke length via series elasticity. They put forward that series elasticity affects the actuator work output by changing the actuator operating point along its force-velocity curve. Vejdani and Hurst [11] developed a simple model of the throwing mechanism. They proposed that adding appropriate elasticity and damping can improve the performance of the system. Haldane et al. [12], [13] used the power modulating mechanism to amplify the motor peak power to 3.63 times the motor alone. They enhanced the capacity for energy storage through an eight-bar mechanism to achieve greater power amplification.

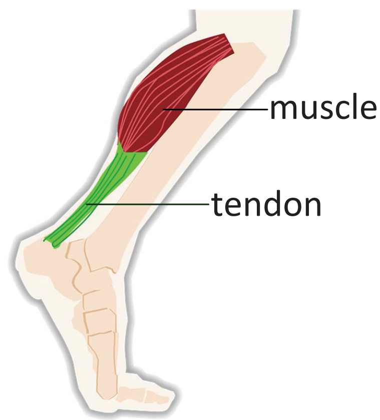

Fig. 1. The muscle-tendon series elasticity system of the human

To the best of our knowledge, there are few people investigating the work amplification mechanism of the hydraulic servo actuator. In this paper, a miniature accumulator is added to the hydraulic servo cylinder for work amplification. Compared with the spring, miniature accumulators have the following advantages. Firstly, The accumulator can be connected to the hydraulic cylinder via hydraulic lines. In this way, the accumulator can be mounted to the torso of the robot through the manifold, reducing the mass and complexity of the leg. This is the golden rule of robot design. Secondly, the air spring stiffness in the accumulator is easier to change. We can easily adjust the pre-inflation pressure of the accumulator according to the actual situation, and then change the stiffness

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of the air spring. Thirdly, air spring is a variable stiffness elastomer. The stiffness increases as the amount of compression increases. This stiffening compliant feature extends the impact time and gains more time for active compliance, resulting in a better buffering effect [14]. A mathematical model of hydraulic servo cylinder with an accumulator was established. We studied the effect of the precharge pressure of the gas in the accumulator and accumulator volume on the work amplification factor and found the optimal precharge pressure of the gas in the accumulator. In order to verify the validity of the design, the virtual prototype is built on the co-simulation platform, where load dynamics is simulated by MSC.ADAMS, and the hydraulic system is performed in AMESim.

The rest of this paper is organized as follows. The dynamic modelling of the hydraulic servo cylinder with an accumulator is introduced in Section II. Results of the numerical analysis and the virtual prototype experiment are described in Section III. Finally, Section IV presents conclusions and our future works.

II. System Modelling

A. Model Description

In order to investigate the effect of the accumulator on the performance of hydraulic servo cylinder, the model in Fig. 2 is considered. An accumulator is added between the servo valve and chamber A of the cylinder. The symbols in Table I describe our model.

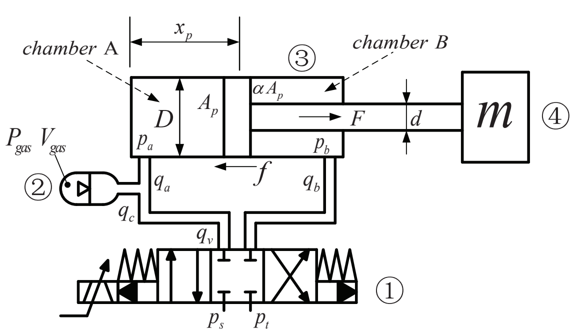

Fig. 2. Schematic of the hydraulic servo cylinder with an accumulator. Servo valve (1); accumulator (2); hydraulic cylinder (3); load (4).

B. System Dynamics

In order to assist the subsequent analysis, this section works to provide a dynamics model of the system. For sake of simplicity, we assume that: (1) pressure loss in the pipe and pipe dynamics are ignored; (2) no internal or external leakage in the hydraulic cylinder; (3) the compression of the hydraulic oil is neglected. According to the basic equation of static pressure, pressure at the outlet of the servo valve

TABLE I

Model Symbols

Symbols	Description
p_s	Pressure at the supply port of the servo valve
p_t	Pressure at the return port of the servo valve
q_v	Flows of the servo valve
q_c [a]	Flows into the accumulator
P_{gas}	Pressure of the gas in the accumulator
V_{gas}	Volume of the gas in the accumulator
D	Piston diameter
d	Rod diameter
p_a	Pressure in chamber A
p_b	Pressure in chamber B
q_a	Flows in chamber A
q_b	Flows in chamber B
A_p	Area of the piston in chamber A
αA_p [b]	Area of the piston in chamber B
x_p	Displacement of the piston
F	Force of the hydraulic cylinder
f	Viscous friction
m	Load mass

[a] When the hydraulic oil flows into the accumulator, it is negative; when the hydraulic oil flows out of the accumulator, it is positive.

[b] α is the ratio of piston area in chamber B and chamber A, $\alpha = \frac{D^2-d^2}{D^2}$

is equal to the pressure of the gas in the accumulator and the pressure in chamber A of the cylinder when the outlet pressure of the servo valve is greater than the precharge pressure of the accumulator. The valve in our system is flow servo valve. We imagine the rated flow of the valve is q_n. The corresponding rated pressure drop is p_n. Furthermore, $C_d, \omega, x_v, x_{vmax}, \rho$ are respectively noted as the flow coefficient, the valve opening gradient, displacement of the spool, maximum displacement of the spool, the density of oil. According to Bernoulli's orifice equation, the flows through the servo valve are expressed as follows.

$$q_v = C_d \omega x_v \sqrt{\frac{2}{\rho}(p_s - p_a)} \tag{1}$$

$$q_b = C_d \omega x_v \sqrt{\frac{2}{\rho}(p_b - p_t)} \tag{2}$$

$$q_n = C_d \omega x_{vmax} \sqrt{\frac{2}{\rho} p_n} \tag{3}$$

Since we want to get the maximum velocity of the load, the opening of the servo valve should always be the largest. Synthesizing equations (1) and (3), (2) and (3), we can obtained the pressure-flow equations.

$$p_a = p_s - \frac{q_v^2}{q_n^2} p_n \tag{4}$$

$$p_b = \frac{q_b^2}{q_n^2} p_n + p_t \tag{5}$$

where

$$q_b = \alpha A_p \frac{dx_p}{dt} \tag{6}$$

The flow into the cylinder chamber A is equal to the sum of the flow of the servo valve and the flow of the accumulator.

$$q_a = q_v + q_c \tag{7}$$

where

$$q_a = A_p \frac{dx_p}{dt} \tag{8}$$

According to Boyle-Mariotte law, the equation can be obtained as follow.

$$P_0 V_0^n = P_{gas} V_{gas}^n = const \tag{9}$$

where P_0 is the initial precharge pressure of the gas in the accumulator, V_0 is the volume of the accumulator. n is the Boyle-Mariotte law gas index. Since the accumulator enters and drains oil quickly, it can be calculated according to the adiabatic process, n=1.4.

Ignoring the throttling effect of the accumulator inlet, the flow continuity equation of the accumulator is as follow.

$$q_c = \frac{dV_{gas}}{dt} \tag{10}$$

Differentiating equation (9) yields

$$\frac{dP_{gas}}{dt} + \frac{nP_{gas}}{V_{gas}} \frac{dV_{gas}}{dt} = 0 \tag{11}$$

Synthesizing equations (10) and (11), we can obtained the equation as follow.

$$\frac{dP_{gas}}{dt} = -\frac{nP_{gas}}{V_{gas}} q_c \tag{12}$$

The hydraulic force F created by the difference of pressures in the cylinder chambers is as follow.

$$F = p_a A_p - p_b \alpha A_p \tag{13}$$

Suppose the load is pushed horizontally by the hydraulic cylinder, the balance equation between the output force and the load force of the hydraulic cylinder is as follow.

$$F - f = m \frac{d^2 x_p}{dt} \tag{14}$$

where $f = B\frac{dx_p}{dt}$, B is the viscous friction coefficient.

III. SIMULATION

A. Numerical Analysis

Due to the mathematical model of the system is relatively complicated, it is difficult to understand the role of each parameter on the behavior of the system. The effect of precharge pressure of the gas in the accumulator and the accumulator volume on system behavior is simulated by numerical method. The simulation parameters are shown in Table II.

TABLE II
SIMULATION PARAMETER

Parameter	Value
p_s	210 bar
p_t	0
p_n	210 bar
q_n	30 L/min
m	200 kg
D	25 mm
d	16 mm
l	0.1 m
B	1000 N/(m/s)

In the simulation, the load is pushed horizontally by the hydraulic cylinder. Fig. 3 showed how the precharge pressure of the gas in the accumulator and the accumulator volume affect the energy transferred from the hydraulic cylinder to the load. As can be seen from the figure, adding an accumulator can amplify the work of the hydraulic servo cylinder. The accumulator can store more energy when the precharge pressure is lower. However, the energy is not completely released during the movement of the cylinder. When the gas in the accumulator has a higher precharge pressure, the accumulator stores less energy. If the gas in the accumulator is too pressurized, the energy in the accumulator is completely released before the hydraulic cylinder is separated from the load. For a certain system, there is an optimal precharge pressure that maximizes the kinetic energy of the load. In addition, the larger the volume of the accumulator, the greater the value of the optimal precharge pressure of the gas in the accumulator. As we have seen, the work amplification factor of the hydraulic cylinder also increases as the volume of the accumulator increases, but it is very limited. Therefore, it is not worthwhile to choose an accumulator with an excessive volume.

Fig. 4 shows the flow versus pressure plots of the cylinder. The green line indicates the maximum flow rate of the valve (30 L/min at 210 bar pressure drop). The supply pressure of the valve is fixed at 210 bar. The precharge pressure of the gas in the accumulator corresponds to the optimum value in Fig. 3. As we can see, when there is no accumulator, the pressure-flow curve of the hydraulic cylinder coincides with the limit of the valve, because the opening of the valve is always set to the maximum. The plots also show that the flow to the hydraulic cylinder can exceed the valve limit when the accumulator is present. This result demonstrates that accumulators enable work amplification of the hydraulic cylinder. Work amplification mechanism allows robots to achieve energetic bounce by reducing the required power of the actuator. In addition, we can use pre-storage of elastic energy in the accumulator to boost the power of the actuator.

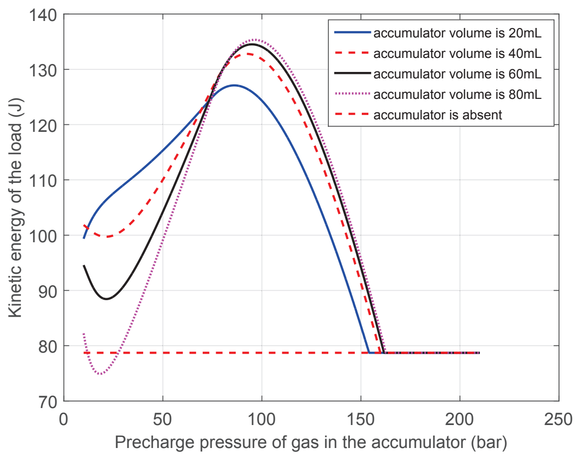

Fig. 3. The effect of the precharge pressure of gas and the accumulator volume on the energy transferred from the hydraulic cylinder to the load.

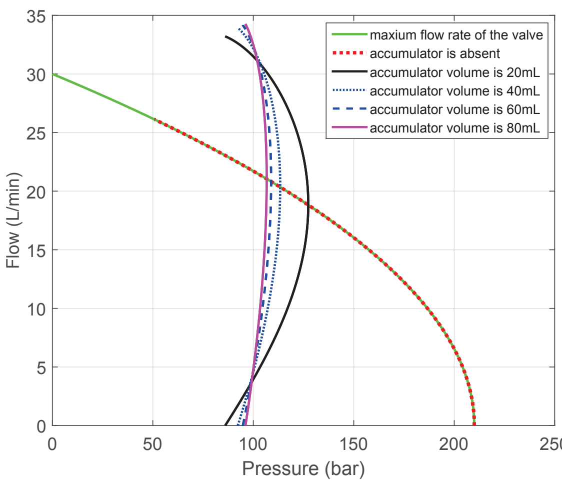

Fig. 4. Flow versus pressure plots of the cylinder. The precharge pressure of the gas in the accumulator corresponds to the optimum value in Fig. 3.

B. Co-Simulation

To verify the accuracy of the numerical simulation, the virtual prototype experiment was conducted on a AMESim and MSC.ADAMS co-simulation platform, as shown in Fig. 5. All parameters in the co-simulation are exactly the same as in the numerical analysis. The control signal keeps the servo valve opening at the maximum from the beginning. The supply port of the servo valve is a constant pressure source of 210 bar.

For the sake of clarity, only the curves of the two typical cases are shown. One is the volume of the accumulator is 40 mL. And the precharge pressure of gas in the accumulator is 92.3 bar, which corresponds to the optimal value

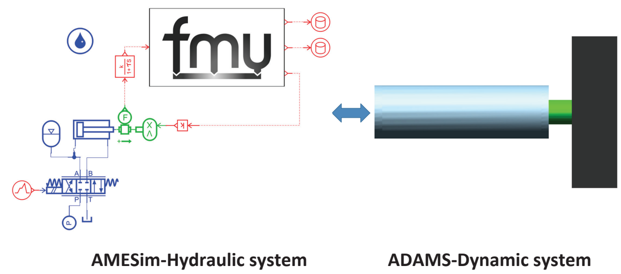

Fig. 5. Co-simulation platform.

in numerical simulation. The another situation is that the accumulator is absent. As shown in Fig. 6, if a miniature accumulator is added, the load will get larger velocity. As we can see, after 0.084 s, the velocity of the load will not change when the accumulator is present. This is because the energy in the accumulator is completely released, which is illustrated in Fig. 7. At this moment, the load is separated from the hydraulic cylinder. It is noted from Fig. 6 that the maximum velocity of the load is 1.144 m/s and 0.887 m/s, respectively, corresponding to the presence or absence of the accumulator. It is easy to know that the kinetic energy of the load is 130.9 J and 78.7 J respectively. The energy delivered to the load by the hydraulic cylinder is amplified by 1.66 times. Both co-simulation and numerical simulation yielded the same results. The correctness of the mathematical model we built in section II is proved.

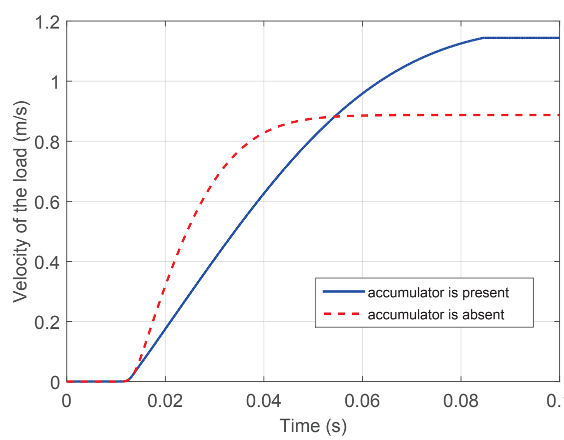

Fig. 6. The variations of the load velocity respect to the accumulator presence or absence.

The power of the hydraulic cylinder is depicted in Fig. 8. Higher peak power can be achieved by the hydraulic cylinder when the accumulator is absent. However, as the hydraulic cylinder moves faster, the power drops rapidly. As shown in Fig. 7, if a miniature accumulator is added, the hydraulic cylinder stores excess energy in the accumulator while accelerating the load. This extends the time the hydraulic cylinder works on the load and thus the energy delivered. This principle can be compared with a catapult [10]. When we need to throw a mass, one way is to throw it out quickly with very large force. A better way is to work with less force for a longer period of time and store energy in the elastomer.

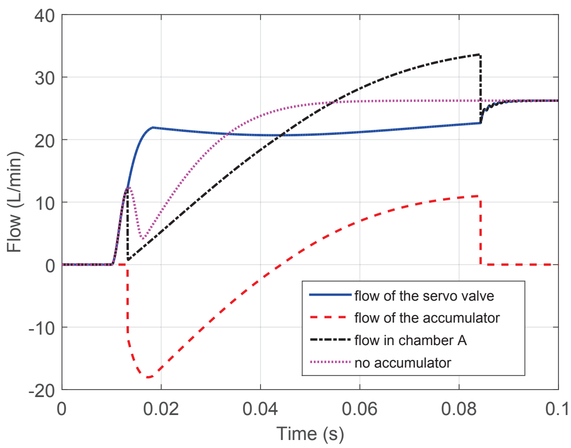

Fig. 7. System flow profiles. The solid line, dashed line, and dash-dotted line correspond to the flow variations of the servo valve, the accumulator, and the chamber A of the hydraulic cylinder in the presence of the accumulator, respectively. The dotted line represents the flow change of the chamber A of the hydraulic cylinder when there is no accumulator. At the beginning, the flow fluctuation in chamber A is caused by the dead volume of the hydraulic cylinder.

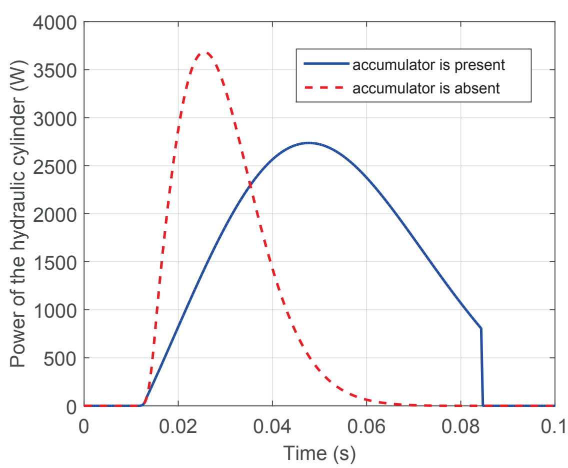

Fig. 8. Power profiles for the hydraulic cylinder.

IV. CONCLUSION

In both numerical simulation and virtual prototype experiments, we show that adding an accumulator to the hydraulic servo actuator can achieve work amplification. The accumulator is not an energy source, it is just an energy buffer, so all the energy used for movement comes from the hydraulic pump [15]. This allows the hydraulic cylinder to work for a longer period in a limited stroke. Therefore, the servo valve and hydraulic pumps required to provide the same energy are less powerful, which can reduce the size and weight of the robot. By properly selecting the precharge pressure of the gas in the accumulator, the work done by actuators can be amplified by a factor of 1.66. We believe this design can effectively improve the bounce performance of the robot. In the future, we plan to investigate how the passive dynamics of the actuator can be combined with active control. And this actuator will be mounted on the robot for hopping.

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