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Research article

Compliance control for a hydraulic bouncing system

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ABSTRACT

This paper is to reduce the contact impact, control the leg stiffness and bouncing height. Firstly, the combining position/force active compliance control was involved in the deceleration phase to decrease the impact force and improve the leg compliance capacity. Then a reasonable velocity control of cylinder was addressed to control the bouncing height to the given value in the acceleration phase. Due to the model uncertainties and disturbances in the deceleration and acceleration phase, a near inverse like controller with a proportional and differential control (PD) was added into the velocity control of acceleration phase to compensate the bouncing height control error. Finally, the effectiveness of proposed controller was validated by experiments. Experimental results showed the impact force could be reduced effectively and a significant bouncing height control performance could be achieved. The influences of initial energy, preload of spring and velocity of cylinder on the bouncing height were addressed as well.

1. Introduction

Robotics is a very hot research spot currently, especial for legged robots [1–3]. In fact, a robotic leg can be equivalent to a bouncing system or hopper [4,5], which behaves like a mass-spring-damper system [6]. To analyze the impedance performance of robotic leg directly is complicated, but it is simple to discuss the one of a hopper [7]. Also, due to the high accuracy [8], fast response [9], strong load capacity [10], and high power density [11,12] of hydraulic actuator, it has been a good choice for robotic actuator [1,3]. Hence, a hydraulic bouncing system was chosen as a research subject.

Compliance control is an effective way to detail with robotic environmental interaction [13]. Compliance can be passive or active. Passive compliance can be implemented easily by a spring, but only a spring cannot dissipate impact energy due to its less damping. And the stiffness of passive string is fixed and can not be controlled as required in real time. However, Shen Z H and Seipel J proposed the leg stiffnesses animals use may improve the stability of locomotion [14] and reduce the energetic cost of locomotion [15]. To be more friendly with the environment, robots should be set to be task-based and flexible in stiffness and damping with the changing loads and environments [16]. Thus, active compliance control is added through cylinder control. The impact is instantaneous, but the cylinder control for handling the impact need response time. That means the effect of active compliance control is not in real time but with a delay. The passive compliance of spring provides more response time for cylinder control to reduce the contact impact more, while active compliance control of cylinder makes the impedance tuning more flexible.

The bouncing height controller could be developed based on system model [17]. The model-based solved and numerically [18] or analytically [19] integrated the motion equations in vertical direction to produce an actuator command that allows the robot to regulate its apex height. Another control algorithm that regulates the system's hopping height is designing a near-inverse controller based on a discrete, hop-to-hop model of the plant dynamics with integral error feedback [20]. Therefore, to improve the bouncing height control performance significantly, the proposed velocity controller of cylinder based on analytical solution of model equations were combined with a near inverse like controller with PD control. Nothing that the active compliance control only acts on the deceleration phase, while the bouncing height control only acts on the acceleration phase.

This paper focuses on improving the performance of contact impact, leg stiffness capacity and bouncing height control. The main contributions are concluded as follows:

- The combining position/force active compliance control was involved in the deceleration phase to decrease the impact force and improve the leg compliance capacity. Then a reasonable velocity control of cylinder was addressed to control the bouncing height to the given value in the acceleration phase.
- Due to the model uncertainties and disturbances in the deceleration and acceleration phase, a near inverse like controller with PD control was added into the control of acceleration phase to compensate the bouncing height control error.

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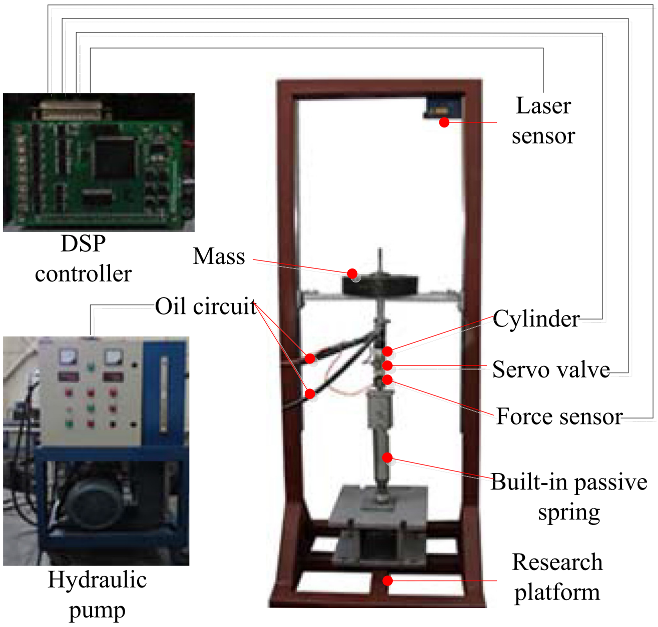


Fig. 1. The hydraulic bouncing system.

- To validate the effectiveness of proposed controller, experiments were implemented and experimental results showed the impact force could be reduced effectively and a significant bouncing height control performance could be guaranteed. Meanwhile, the influences of initial energy, preload of spring and velocity of cylinder on the bouncing height were addressed.

In this paper, Section 2 gives out the system platform and model of a hydraulic bouncing system firstly. In Section 3, the position/force based active compliance controller is addressed for the deceleration phase; the velocity controllers of cylinder for the acceleration and flight phase are designed respectively later. Then, the proposed method is validated through experiments in Section 4. Finally, conclusions are drawn in Section 5 and future work is issued.

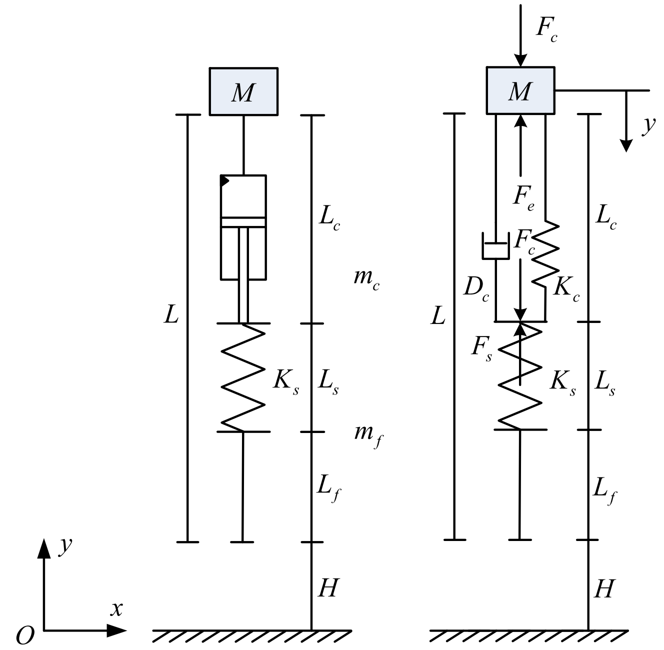
2. System platform and model

2.1. Hardware platform and equivalent system

The research subject is a hydraulic bouncing system, as shown in Fig. 1. This system includes three parts: a hydraulic pump, a controller and a research platform. Here, the hydraulic pump is utilized to provide a constant supply pressure for servo valve. The controller is implemented by a DSP(TMS320F28335: embedded system), which samples the signals of sensors, produces the control signal to servo valve and communicates with a host PC by CAN bus for running data and results showing in the upper monitor. The research platform consists of a position controllable cylinder, a force sensor (EVT-20TH-500KG), a laser sensor (optoNCDT-2200), a built-in passive spring and an inertia load on the top. Notice that the hydraulic bouncing system is one-dimensional and constrained to motion in the vertical direction. The vertical contact impact and motion displacement can be obtained by force sensor and laser sensor respectively. The position controllable cylinder is employed to achieve active compliance. The built-in passive spring is used to provide passive compliance. In this platform, how to deal with the impact contact in bouncing by compliance control can be issued and the bouncing height control can be investigated as well. The basic system parameters are shown in Table 1.

Table 1
System parameters.

Supply pressure	120 bar
Stroke of cylinder	76 mm
Diameter of cylinder piston	25 mm
Diameter of cylinder rod	16 mm
Flow rate of servo valve	16 L/min
Response frequency of servo valve	120 Hz
Range of force sensor	−5 kN ~ 5 kN
Range of laser sensor	1 cm ~ 10 m



(a) The equivalent system of hydraulic bouncing system

(b) The equivalent model of hydraulic bouncing system

Fig. 2. The equivalent system.

The traditional hydraulic drive is rigid in position servo control, as shown in Fig. 2(a), where M, m_c and m_f are the lumped mass of upper body, cylinder and foot, respectively; L, L_c, L_s, L_f and H are respectively the total length of hydraulic bouncing system, the length of cylinder, the length of spring, the length of foot and the bouncing height; K_s is the stiffness of passive spring, which can be taken as the stiffness of environment ($\frac{K_e K_s}{K_e + K_s}$) for the cylinder when the touch terrain is rigid, which means $K_e = \infty$. The stiffness of hydraulic cylinder in the position servo motion displacement is so large that it can be omitted. Thus, the stiffness of the whole system is only dependent on the built-in passive spring. In order to prevent the over compression of passive spring, the stiffness of the spring is chosen to be large enough, which will lead to a large contact impact. In addition, the damping in the position servo hydraulic cylinder system is mainly decided by the frictional damping and throttle damping, which are so small that the cylinder will undergo low damping oscillation.

The active compliance control can be seen as one balance between position servo control and force control, which makes the position servo control change from rigid to compliant by adding force sensing and redesigning an impedance controller and results in reducing the contact impact and oscillation. As shown in Fig. 2(b), the stiffness and damping of active compliance can be set and controlled at the same time, where y is the motion displacement of lumped mass; K_c, D_c is the actual stiffness and damping of the active hydraulic cylinder system