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Force Control Compensation Method with Variable Load Stiffness and Damping of the Hydraulic Drive Unit Force Control System

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Abstract: Each joint of hydraulic drive quadruped robot is driven by the hydraulic drive unit (HDU), and the contacting between the robot foot end and the ground is complex and variable, which increases the difficulty of force control inevitably. In the recent years, although many scholars researched some control methods such as disturbance rejection control, parameter self-adaptive control, impedance control and so on, to improve the force control performance of HDU, the robustness of the force control still needs improving. Therefore, how to simulate the complex and variable load characteristics of the environment structure and how to ensure HDU having excellent force control performance with the complex and variable load characteristics are key issues to be solved in this paper. The force control system mathematic model of HDU is established by the mechanism modeling method, and the theoretical models of a novel force control compensation method and a load characteristics simulation method under different environment structures are derived, considering the dynamic characteristics of the load stiffness and the load damping under different environment structures. Then, simulation effects of the variable load stiffness and load damping under the step and sinusoidal load force are analyzed experimentally on the HDU force control performance test platform, which provides the foundation for the force control compensation experiment research. In addition, the optimized PID control parameters are designed to make the HDU have better force control performance with suitable load stiffness and load damping, under which the force control compensation method is introduced, and the robustness of the force control system with several constant load characteristics and the variable load characteristics respectively are comparatively analyzed by experiment. The research results indicate that if the load characteristics are known, the force control compensation method presented in this paper has positive compensation effects on the load characteristics variation, i.e., this method decreases the effects of the load characteristics variation on the force control performance and enhances the force control system robustness with the constant PID parameters, thereby, the online PID parameters tuning control method which is complex needs not be adopted. All the above research provides theoretical and experimental foundation for the force control method of the quadruped robot joints with high robustness.

Keywords: quadruped robot, force control system, hydraulic drive unit, force control compensation method, variable load stiffness and damping simulation

1 Introduction

The hydraulic drive has the advantage of small size, high power density, fast and accurate response especially matching the high performance requirement of legged robot, compared with motor drive and pneumatic drive. And the hydraulic drive quadruped bionic robot has good adaptability for the unknown and unstructured environment and can be used in the exploration, transportation and rescue fields, becoming a research focus of many robot scholars[1–4]. In recent years, the Boston Company of America developed the hydraulic drive quadruped bionic robot named Big-Dog, which provided a new idea for the drive and control method of the quadruped robot with heavy load and high performance. The motion performance including gait, trot, jumping, and so on, is outstanding, and especially the adaptability for contacting diversity of environments with different load characteristics including snow, sand, ice, land and rubble is excellent, which enhanced the military and civilian value of the robot and promoted many countries develop the research work of this type robot[5–7].

Generally, each leg of the hydraulic drive quadruped

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robot has three or four active movement joints which are driven by the hydraulic drive units (HDUs)[8]. And the common control of this quadruped robot is mainly the highly accurate position servo control method for HDU to track overall trajectory planning[9–10]. Yet when the foot end hits the ground or barrier, which may lead the position control to cause big impact and even the instability of the quadruped robot to make the damage of the robot frame and electronic device, the highly accurate force servo control or compliance control of HDU should be switched to mitigate the system impact and improve the overall stability of the robot. Thereby, the force servo control of HDU has the same importance with the position servo control to ensure the robot stability. To make the movement performance of the quadruped robot familiar to quadruped mammals and to make the robot better adaptive for the complex and variable environment structure, the fast response ability and the ideal control accuracy are required for HDU. So whether the force control performance is satisfying or not especially when the robot walking on the snow, sand and ice and whether the force control can maintain the ideal stability, response speed and accuracy of HDU or not when the foot end load characteristics are different are the problems that should be solved.

HDU is a highly integrated valve-controlled cylinder which consists of the servo valve and the servo cylinder, and when the valve-controlled cylinder force control system contacts the environment with unknown model parameters and disturbance, many scholars introduced advanced control algorithms. NAMVAR, et al[11] researched the environment factors affecting the robot force control performance, and designed the self-adaptive controller for the unknown environment to ensure the force track control under various environments when the environment stiffness and damping were uncertain. NIKSEFAT, et al[12], introduced quantitative feedback theory to design the robustness controller in order to weaken the effects of model uncertainty and disturbance on the force control performance. XU, et al[13], used time-varying force control method for robot manipulators under uncertain working environment, and the research indicated that a two-link robot manipulator confirm the effectiveness of force control method. XU, et al[14], combined the self-learning control method with the robustness control method to design the robustness-learning controller, using robustness control to ensure the system asymptotical stability and using the self-learning control to eliminate the effects of the system structure uncertainty, which made the robot have good adaptability. ZHU, et al[15], considered the effects of the cylinder friction and the self-adaptive control algorithm was adopted to the force servo control of the cylinder rod. EMRE, et al[16], designed a disturbance observer in the explicit force control systems, and the stability and robustness of the observer were analyzed amply to reveal the relation between the stability and the robustness. IRAWAN, et al[17], researched that the self-tuning impedance control is designed with variable stiffness tuning method using time division method and exponential time reduction and the propose controller is proofed, indicating that the self-tuning impedance control with adaptive element from environment identification could provide compliant body balance for hydraulic drive hexapod robot experimentally. UGURLU, et al[18], adopted a impedance control method was applied to the active compliance controller for the HyQ quadruped robot, and the stiffness and the damping were adjustable online through combining the designed trajectory generator, showing that the method can be efficient in handling environmental interaction. IRAWAN, et al[19], researched single-leg impedance control and center of mass-based impedance control to the hexapod robot named COMET-IV. These two methods had the same schematic, but the online impedance parameters adjustment accorded to the robot legs' configuration and robot body's configuration respectively, and evaluation and verification experiments were conducted with uneven terrain and extremely soft surfaces, indicating that center of mass-based impedance control improved the online impedance parameters adjusting speed and enhancing the impedance control effects. LEE, et al[20], used position-based impedance control of a hydraulic actuator for a legged robot whose hydraulic actuator was simplified as a linearized model and hydraulic parameters were proofed experimentally, while the effects of the impedance control applied to the hydraulic actuator with the lack of the knowledge of the environmental stiffness were also proofed experimentally. IOANNIS, et al[21], researched a novel model-based impedance controller to a 6-degree-of-freedom electrohydraulic Stewart platform, showing that the impedance controller is superior to available PD controller, and that its response is smooth.

The above typical compensation control methods are the advanced control methods where fuzzy, robustness, sliding mode and self-adaption were introduced to tune the control parameter to compensate the time-varying of the HDU force control system natural characteristics. But these advanced control methods are complex and occupy much computing space, which leads the inconvenience in the engineering application and necessity to research a practical force control compensation method with variable load characteristics. Therefore, this paper is organized as follows: firstly，the force control system mathematical model of HDU is established, and the force control compensation algorithm of HDU is presented. Thereby, the load characteristics compensation controller is designed. Besides, the variable stiffness and damping load characteristics simulation of HDU is analyzed. Furthermore, the variable stiffness and damping load characteristics simulation effects are verified experimentally on the HDU force control performance test platform. Finally, the effects of the force control compensation method are analyzed experimentally with the variable stiffness and damping load characteristics.

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2 Force Control System Mathematical Model of HDU

HDU, one of the robot core compositions, is a joint drive of quadruped bionic robot, which can realize the high accuracy force closed loop and position closed loop control. HDU whose three-dimensional assembly drawing is shown in Fig. 1 consists of small symmetrical servo cylinder, flow servo valve, force sensor and displacement sensor. The schematic of HDU is shown in Fig. 2.

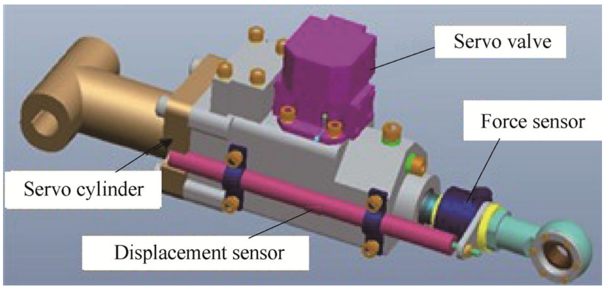

Fig. 1. Three-dimensional assembly drawing of HDU

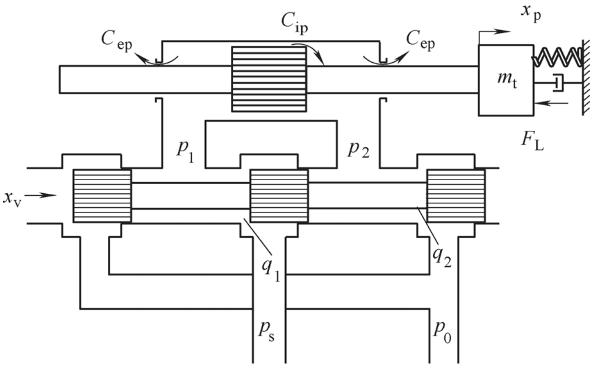

Fig. 2. Schematics of HDU

Based on slide valve flow equation, flow continuity equation and servo cylinder force equilibrium equation, force control system block diagram of HDU shown in Fig. 3 can be established by using mechanism modeling method.

In Fig. 3, ω_{mf} is nature frequency of servo valve, ζ_{mf} is damping ratio of servo valve, K_{vf} is the force feedback loop open-loop gain, $K_d = C_d W\sqrt{2/\rho}$ (K_d is defined as conversion coefficient in this paper), C_d is orifice flow coefficient of spool valve, W is area gradient of spool valve, ρ is density of hydraulic oil, p_s is system supply oil pressure, p_1 is inlet cavity pressure of servo cylinder, p_2 is outlet cavity pressure of servo cylinder, p_0 system return oil pressure, C_{ip} is internal leakage coefficient of servo cylinder, C_{ep} is external leakage coefficient of servo cylinder, L is total piston stroke of servo cylinder, L_0 is initial piston position of servo cylinder, A_p is effective piston area of servo cylinder, β_e is effective bulk modulus, m_t is conversion mass (including the piston, the displacement sensor, the force sensor, the connecting pipe and the oil in servo cylinder), x_r is input displacement, K_F is force sensor gain, PID is PID controller gain including proportional gain K_P, integral gain K_I and differential gain K_D, K_a is the servo valve amplifier gain, K_{xv} is servo valve gain, K is load stiffness, B_p is load damping, F_L is load force, F_r is the input force, F_d is the output force, x_v is servo valve spool displacement, x_p is servo cylinder piston displacement, V_{g1} is volume of input oil pipe, V_{g2} is volume of output oil pipe, F_f is friction, U_r is input voltage, U_f is force sensor feedback voltage, U_g is controller output voltage, Q_1 is inlet oil flow, Q_2 is outlet oil flow.

The force control system parameters and their initial values are shown in Table 1, ignoring the external leakage of HDU.

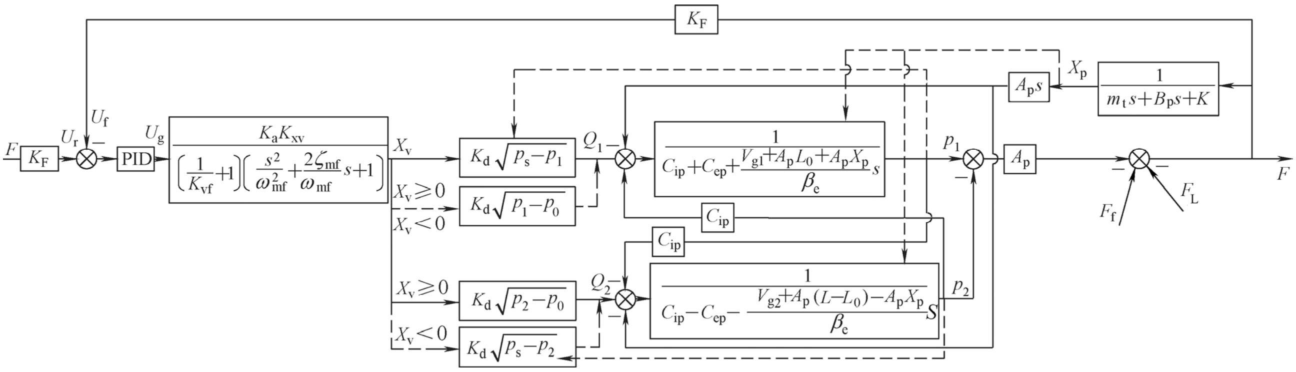

Fig. 3. Force control system block diagram of HDU

3 Force Control Compensation Algorithm of HDU

3.1 Introduction of force control compensation algorithm

Quadruped robot foot end contacts different environmental structure including grass, sand, mud, snow, ice, cement floor, and so on under the practical work condition, and different environment structure corresponds to different force control load characteristics in each joint force closed loop control process. Due to the uncertainty and unrepeatability of environment structure, the complex environment structure is simplified to impedance system by

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many scholars to make system performance analysis and control method research become more convenient.

Table 1. Force control system parameters and initial value

Parameters/Input	Initial value	Unit
K_{vf}	427	rad/s
ω_{mf}	1319	rad/s
ζ_{mf}	0.67	–
K_{xv}	0.05	m/A
K_a	0.009	A/V
A_p	3.368×10^{-4}	m^2
V_{g1}	6.2×10^{-7}	m^3
V_{g2}	8.6×10^{-7}	m^3
L	0.05	m
L_0	0.03	m
p_s	7	MPa
p_0	0.5	MPa
ρ	0.867×10^3	kg/m^3
C_{ep}	0	$m^3/(s \cdot Pa)$
C_{ip}	2.38×10^{-13}	$m^3/(s \cdot Pa)$
m_t	1.1315	kg
β_e	8×10^8	Pa
K_d	1.248×10^{-4}	m^2/s
K_F	7.7×10^{-4}	V/N

In this paper, which compensation control method should be adopted to ensure that the force control performance with the suitable control parameters is not affected as much as possible when the stiffness and damping of HDU changing is a problem need to be solved.

3.2 Design of load characteristics compensation controller

Generally, PID control method is used for HDU of quadruped robot in engineering application, if the selected PID control parameters can ensure that the force control performance is good with the suitable stiffness and damping, then it is better that PID control parameters will not be adjusted with the stiffness and damping changing. In other words, the selected PID control parameters should adapt to the load characteristics variation. Based on the above ideas, the load characteristics compensation controller is designed.

Force control system block diagram of HDU shown in Fig. 3 with the desired stiffness and damping can be simplified as Fig. 4.

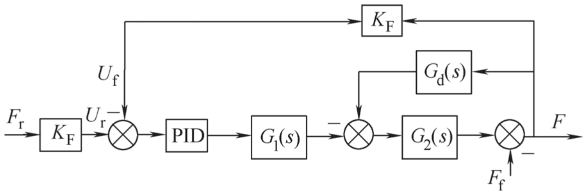

Fig. 4. Simplified force control system block diagram of HDU

In Fig. 4, $G_1(s)$ and $G_2(s)$ are the transfer functions of HDU, $G_d(s)$ is the transfer function of the desired load characteristics.

When the load stiffness and damping vary dynamically, the compensation control block diagram is shown in Fig. 5.

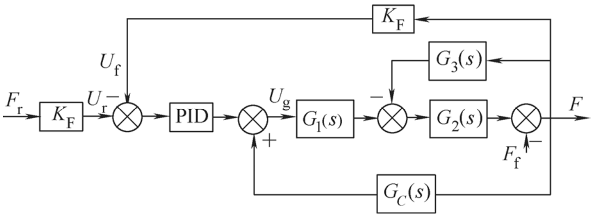

Fig. 5. Compensation control block diagram of HDU

In Fig. 5, $G_3(s)$ is the transfer function of the practical load characteristic and $G_C(s)$ is the transfer function of the load characteristic compensation controller.

Due to the difference between $G_d(s)$ and $G_3(s)$, $G_C(s)$ need compensate the variation between $G_d(s)$ and $G_3(s)$ to ensure the robustness of PID control, and the following equations are derived as:

$$\begin{cases} G_C(s)=\dfrac{G_3(s)-G_d(s)}{G_1(s)}, \\ G_d(s)=\dfrac{1}{B_{pD}s+K_D}, \\ G_3(s)=\dfrac{1}{B_p s+K}, \end{cases} \tag{1}$$

where B_{pD} is the desired load damping, K_D is the desired load stiffness.

In this way, even though the practical load characteristic $G_3(s)$ and the desired load characteristics $G_d(s)$ are different, the introduction of compensation link can make that the load characteristics is still $G_d(s)$, thereby force control system model is no longer affected by load characteristic variation theoretically. The principle of compensation link is that the input voltage of the servo valve is adjusted to change the pressure of two servo cylinder cavities. Load characteristics compensation controller expression $G_C(s)$ can be derived as follows:

$$G_C(s)=\left(\frac{1}{B_p s+K}-\frac{1}{B_{pD}s+K_D}\right)\left(\frac{s}{K_{vf}}+1\right)\times \left(\frac{s^2}{\omega_{mf}^2}+\frac{2\zeta_{mf}}{\omega_{mf}}s+1\right)\bigg/\left(K_a K_{xv} K_d \sqrt{p_s-p_0-p_L}\right), \tag{2}$$

where p_L is the load pressure, $1/(K_a K_{xv})$ is the proportionality coefficient of load characteristics compensation which indicates the relation between servo valve spool displacement and servo valve input current, $[1/(B_p s+K)-1/(B_{pD}s+K_D)]$ is the compensation coefficient which indicates that the load characteristics variation changes to servo cylinder piston displacement

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variation, $1/(K_{\rm d}\sqrt{p_{\rm s}-p_0-p_{\rm L}})$ is the compensation coefficient which indicates that servo cylinder piston displacement variation changes to servo cylinder flow and $(s/K_{\rm vf}+1)(s^2/\omega_{\rm mf}^2+2\zeta_{\rm mf}s/\omega_{\rm mf}+1)$ is used for compensating compensation link lag caused by the dynamic characteristics of servo valve.

For the differential link is difficult to achieve in the real control process and the natural frequency of servo valve outclass the working frequency of HDU under normal working conditions, the dynamic characteristics of servo valve can be ignored in load characteristics compensation controller expression, then the force control system load characteristics compensation control block diagram is shown in Fig. 6.

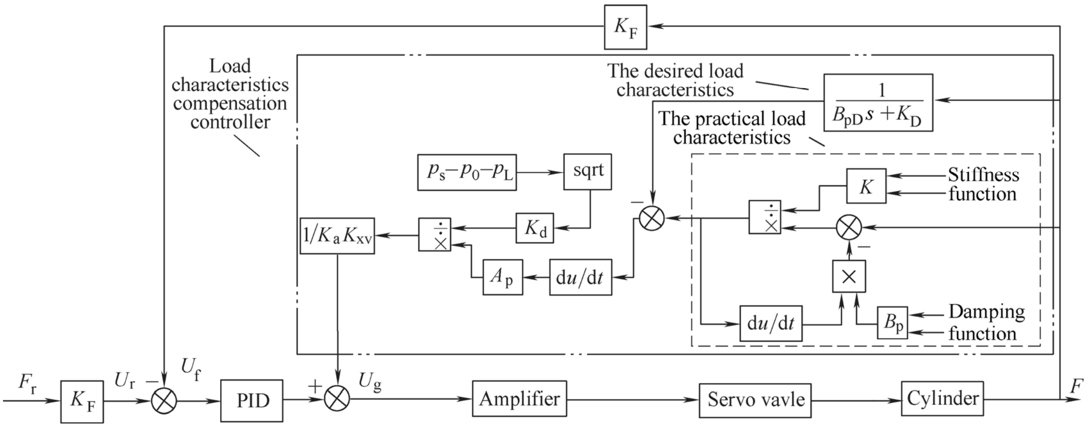

Fig. 6. Force control system load characteristics compensation control block diagram

4 Variable Stiffness and Damping Load Characteristics Simulation of HDU

4.1 Introduction of load characteristics simulation

In the section 3, load characteristics compensation control method with variable stiffness and damping is shown. However, it is difficult to verify the availability of the above method under various real ground environment whose stiffness and damping variation characteristic is hard to simulate. Thereby, it is necessary to research an effective stiffness and damping simulation method applied to the force control system load simulation to quantificationally analyze the compensation control effects under different load characteristics.

4.2 Mathematical model of load characteristics simulation

The schematic of force control system and load characteristics is shown in Fig. 7.

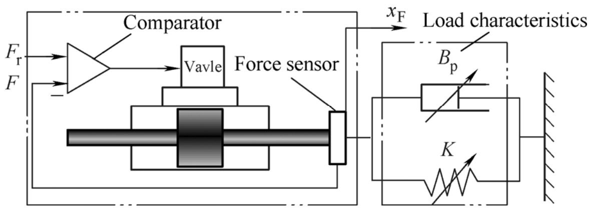

Fig. 7. Schematic of force control system and load characteristics

Accurate simulation of variable stiffness and damping load characteristic is important to research the robustness of force control system with the variable load characteristics. Due to the relatively small mass of force sensor whose mass can be ignored, denote the kinetic equation which takes the force sensor as bary center as follows:

$$F=B_{\rm p}\dot{x}_{\rm F}+Kx_{\rm F}, \tag{3}$$

where $x_{\rm F}$ and $\dot{x}_{\rm F}$ are the force control system cylinder piston displacement and velocity both caused by output force.

Generally, the stiffness and damping increase with displacement decrement increasing in one real environmental structure. Thereby, stiffness and damping can be defined as functions of displacement variation respectively, denote the three order exponential relationship between stiffness K and displacement $x_{\rm F}$ in one environmental structure as follows:

$$K=K_0+Mx_{\rm F}^3, \tag{4}$$

where K_0 is the initial value of stiffness and M is the variable coefficient of stiffness.

Denote the two order exponential relationship between damping $B_{\rm p}$ and displacement $x_{\rm F}$ in one environmental structure as follows:

$$B_{\rm p}=B_{\rm p0}+Nx_{\rm F}^2, \tag{5}$$

where $B_{\rm p0}$ is the initial value of damping and N is the variable coefficient of damping.

Combining Eq. (3) to Eq. (5), then Eq. (3) can be translated as follows:

$$\dot{x}_{\rm F}=-\frac{K_0+Mx_{\rm F}^3}{B_{\rm p0}+Nx_{\rm F}^2}x_{\rm F}+\frac{F}{B_{\rm p0}+Nx_{\rm F}^2}. \tag{6}$$

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Eq. (6) denotes the dynamic relationship between the output force of HDU and displacement with variable stiffness and damping load characteristic shown in Fig. 7.

Combining the variable load characteristic model shown in Fig. 8, the variable stiffness and damping load characteristic simulation schematic is shown in Fig. 9.

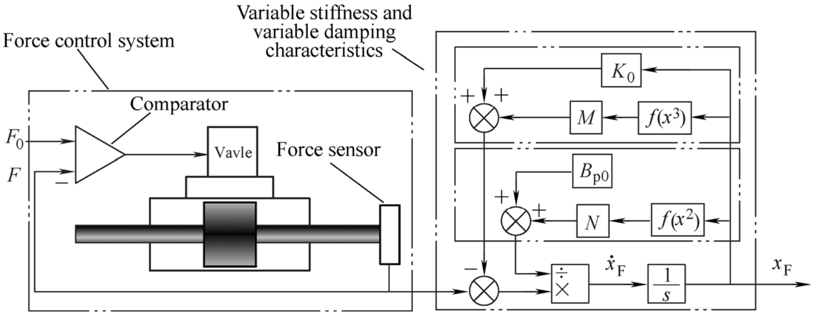


Fig. 8. Dynamic relationship between the output force and variable load characteristic

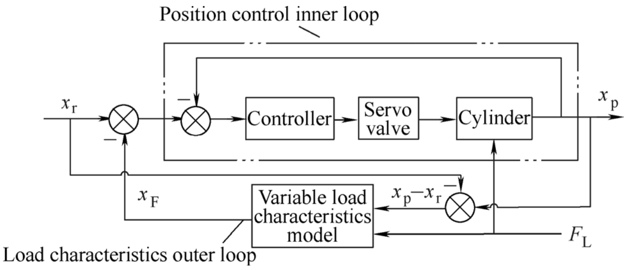


Fig. 9. Variable load characteristic simulation schematic

The simulation method shown in Fig. 9 can simulate the load characteristics variation, and it mainly simulates the two working conditions as follows

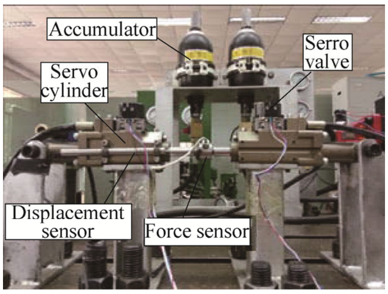
Firstly, if the function relationship between load characteristics and displacement is known under any one robot walking environmental structure, such as sand, mud, and so on, the load characteristics of robot joint end under this environmental structure can be simulated by the simulation method above.

Secondly, if the function relationship between displacement and load characteristics is known under two environmental structures, the load characteristics of robot joint end under these two environmental structures switch process can be simulated by the simulation method above.

5 Force Control Performance Test Platform of HDU

Force control performance test platform photo of HDU and the dSPACE controller photo are shown in Fig. 10.

The force control performance test platform of HDU consists of two same HDU connected by force sensor. The left channel is the tested HDU controlled by the force-loop method, where PI control and load characteristics compensation control method shown in section 3are adopted to verify force control compensation effect experimentally under different load characteristics. While the right channel is the load characteristics simulation HDU controlled by the position-loop method, where load characteristics simulation method shown in section 4are adopted to simulate stiffness and damping. And the control schematic of force control performance test platform of HDU is shown in Fig. 11.



(a) Force control performance test platform

(b) Test system controller photo

Fig. 10. Force control performance test platform photo

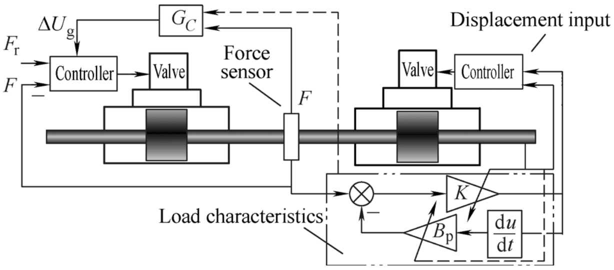


Fig. 11. Force control performance test platform control schematic

In order to verify the availability of load characteristics compensation control method, the coefficient involved in Eq. (6) under one robot walking environmental structure and the working parameters of the load characteristics simulation HDU whose initial value and unit are shown in Table 2.

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Table 2. Initial parameters value and their unit

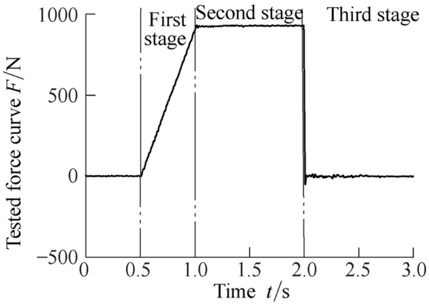
Parameter	Initial value	Unit
K_0	1×10^6	N/m
M	1×10^{15}	–
B_{p0}	5×10^4	N • s/m
N	5×10^{10}	–
L_0	20	mm
P_s	7	MPa
K_P	20	–
K_I	3	–

6 Experimental Analysis of Variable Load Characteristics Simulation

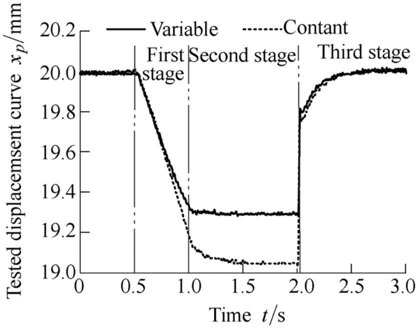
Based on the theoretical method shown in section 4, in this section variable stiffness and damping load characteristics simulation effects are analyzed by experiment to lay the foundation for the experimental verification of force control compensation method.

6.1 Experimental analysis under the ramp and step load force

The displacement curves shown in Fig. 12(b) on load characteristics simulation HDU are tested under the ramp and step load force shown in Fig. 12(a). And in Fig. 12, Variable represents variable stiffness and damping load characteristics, and Constant represents constant stiffness and damping load characteristics.



(a) Tested ramp and step load force curve



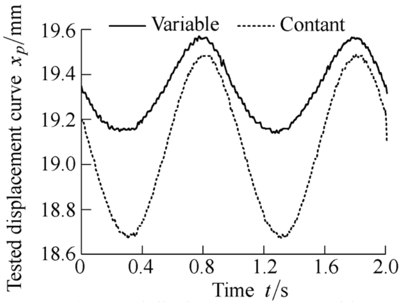
(b) Tested displacement curves

Fig. 12. Variable load characteristics simulation experimental curves under ramp and step load force

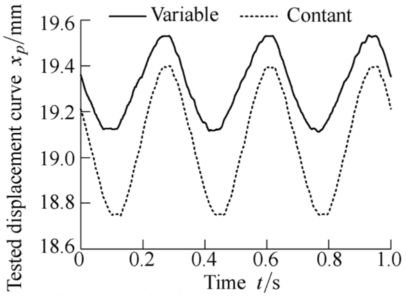
Due to the different stiffness and damping characteristics, the displacement curves shown in Fig. 12(b) change from overlap to separate gradually in the first stage. Furthermore, the displacement curves reach different displacement steady states in the second stage, and the response time reaching the steady states are 531 ms and 1077 ms respectively, and the displacement change reaching the steady states are 0.72 mm and 0.95 mm, respectively. Moreover, based on variable load characteristic simulation schematic shown in Fig. 9, the load characteristic simulation outside loop is useless theoretically so that the stiffness and damping can't be simulated when the step force is removed instantaneously. However, the displacement variation can cause redundant force which lead the force sensor tested value is not zero, so the displacement curves shown in Fig. 12(b) exist difference in the third stage.

6.2 Experimental analysis under sinusoidal load force

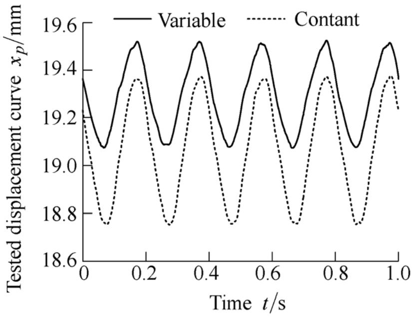
The displacement curves shown in Fig. 13 are tested on load characteristics simulation HDU under sinusoidal load force whose fiducial value is 1000 N and amplitude value is 500 N with frequency 1 Hz, 3 Hz and 5 Hz, respectively.



(a) Tested displacement curves with 1 Hz



(b) Tested displacement curves with 3 Hz



(c) Tested displacement curves with 5 Hz

Fig. 13. Variable load characteristics simulation experimental curves under sinusoidal load force

As it can be seen in Fig. 13, the displacement mean value of the two displacement curves is different under variable stiffness and damping load characteristics and constant stiffness and damping load characteristics, and the detail value is 0.64 mm, 0.67 mm, 0.704 mm and 0.925 mm, 0.934 mm, 0.942 mm respectively, which reflects the

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availability of variable stiffness simulation. Moreover, the displacement fluctuation range of the two displacement curves is different too, and the displacement change at the peak is 0.083 mm, 0.117 mm, 0.152 mm, respectively and the displacement change at the valley is 0.47 mm, 0.37 mm, 0.16 mm, respectively, which reflects the availability of variable damping simulation.

The research above indicates that the variable stiffness and damping load characteristics simulation method can simulate stiffness and damping dynamical variation availably even though the function relation between load characteristics and displacement caused by load force is nonlinearity.

7 Experimental Analysis of Load Characteristics Compensation Control

When the desired stiffness and damping are 1×10^6 N/m and 5×10^4 N • s/m, respectively, the PI control parameters optimization method should be adopted to select suitable PI control parameter to ensure the good force control performance of HDU under this particular working condition. However, the dynamical variation of the stiffness and damping can affect the force control performance necessarily, in order to make the optimized PI control parameters above still suitable, the load characteristics compensation control effects under variable stiffness and damping are the key research content in this section.

7.1 PI control parameters optimization of HDU force control system

According to the critical proportion method empirical formula and many experimental tests, the optimized PI control parameters are $K_P=5$, $K_I=0.12$ respectively, and the tested force step response curve controlled by the above PI control parameters is shown in Fig. 14.

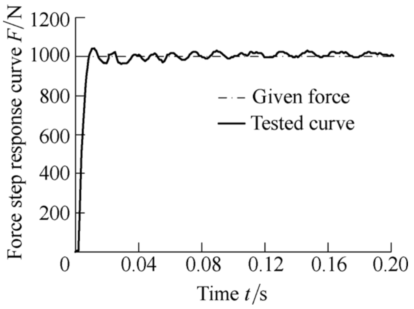


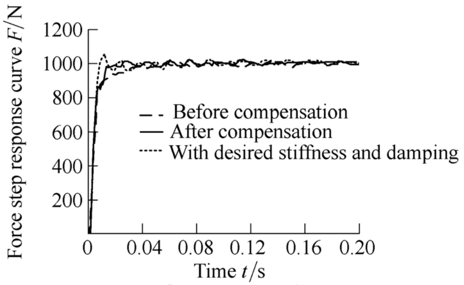
Fig. 14. Tested force step response curve

As it can be seen in Fig. 14, through optimizing the PI control parameters, the rise time of tested force step response curve is 9.63 ms and maximum overshoot is 4.4%.

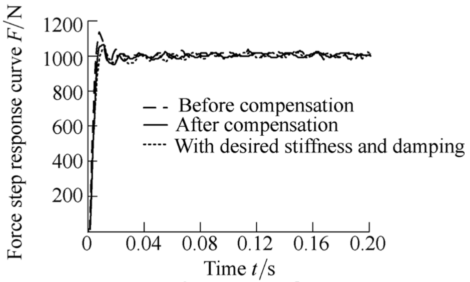
7.2 Experimental analysis of constant load characteristics compensation control

7.2.1 Experimental analysis under step input force

Based on the optimized PI control parameters, tested force step response curves are shown in Fig. 15 with 1000 N input force which indicate the comparison between the two group of practical stiffness and damping parameter whose values are 5×10^5 N/m, 2.5×10^4 N • s/m and 2×10^6 N/m, 1×10^5 N • s/m, respectively and the desired stiffness and damping whose values are 1×10^6 N/m, 5×10^4 N • s/m.



(a) 5×10^5 N/m, 2.5×10^4 N•s/m



(b) 2×10^6 N/m, 1×10^5 N • s/m

Fig. 15. Tested force step response curves with different stiffness and damping

As it can be seen in Fig. 15, with the stiffness and damping increasing, the rise time decreases and the rapidity enhances but the overshoot emerges easily. Whether the stiffness and damping increase or decrease, the force step response curves tested after compensation can approach the force step response curves tested with the desired stiffness and damping, which can reflect the robustness of the HDU force control system.

7.2.2 Experimental analysis under sinusoidal input force

In order to verify the universality of the force control compensation method under sinusoidal load force, the force step response curves shown in Fig. 16 and Fig. 17 are tested under sinusoidal load force whose fiducial value is 1000 N and amplitude value is 500 N with frequency 1 Hz, 3 Hz and 5 Hz, respectively.

As it can be seen in Fig. 16, for the increase of servo cylinder piston displacement caused by the decrease of stiffness can lead the force control system response time extending, the force control response rate under the practical load characteristics is slightly slower than that under the desired load characteristics. Moreover, the load characteristics compensation control method is effective with different sinusoidal force frequency, which indicates that the compensation control link can availably reduce the response rate difference of force control system caused by the variation of load characteristics.

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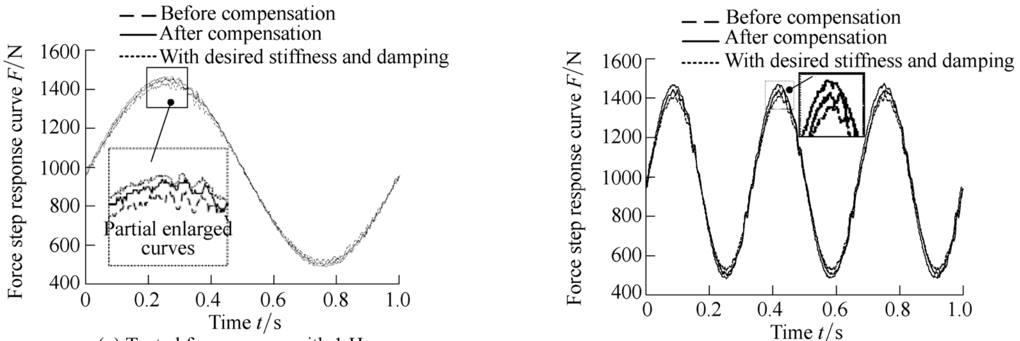
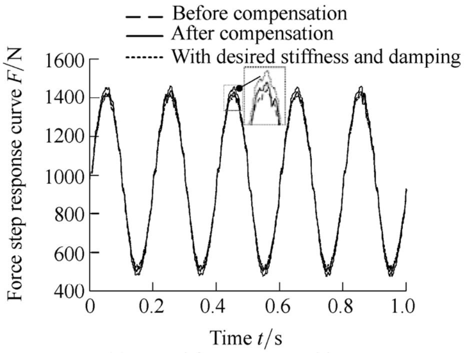
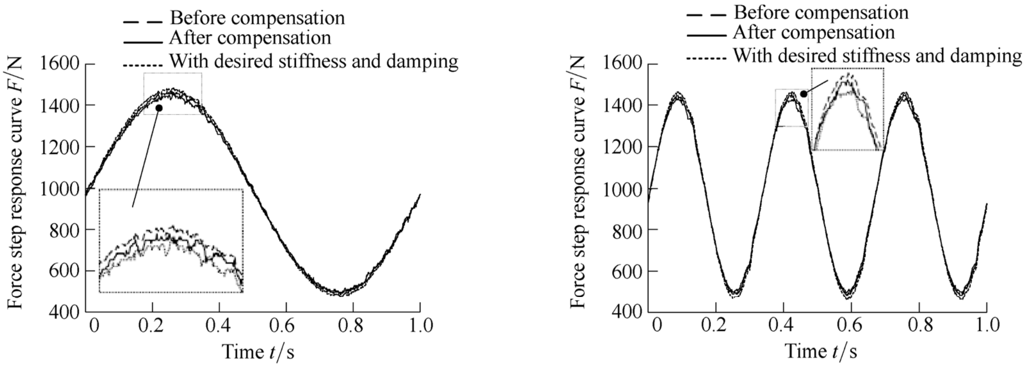


(a) Tested force curves with 1 Hz
(b) Tested force curves with 3 Hz

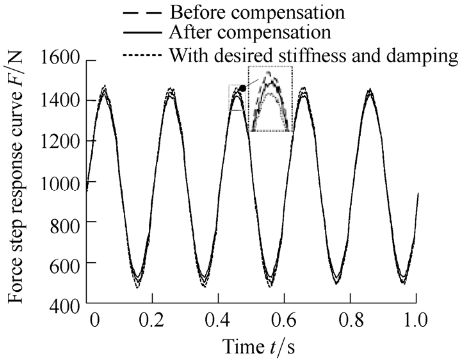


(c) Tested force curves with 5 Hz

Fig. 16. Tested force curves with 5×10^5 N/m, 2.5×10^4 N • s/m



(a) Tested force curves with 1 Hz
(b) Tested force curves with 3 Hz



(c) Tested force curves with 5 Hz

Fig. 17. Tested force curves with 2×10^6 N/m, 1×10^5 N • s/m

As it can be seen in Fig. 17, the force control response rate under the practical load characteristics is slightly faster than that under the desired load characteristics, and the conclusion is the same as that shown in Fig. 16.

7.3 Experimental analysis of variable load characteristics compensation control

In order to verify the compensation control effects under variable load characteristics, the force curves tested by the online change of load characteristics are shown in Fig. 18 and Fig. 19.

As it can be seen in Fig. 18, with the input step force increasing, the maximum overshoot of force control system decreases and the rise time increases. Moreover, the force step response curves tested after compensation can approach the force step response curves tested with desired

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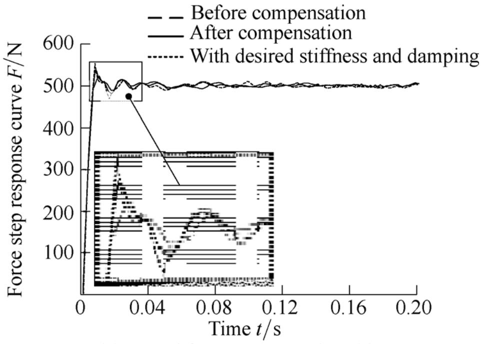
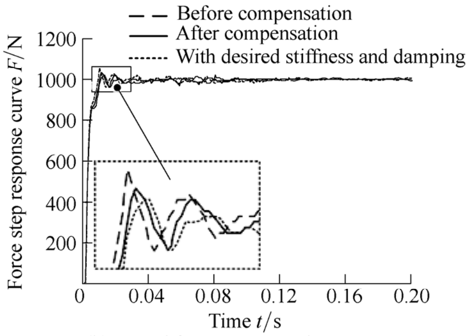
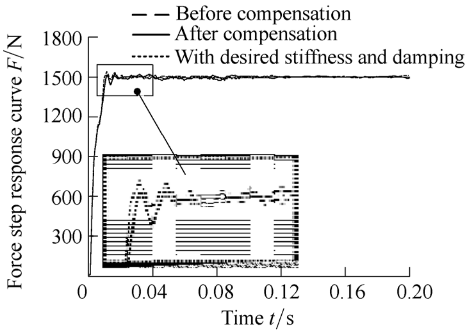
load characteristics even though the load characteristics varies dynamically.



(a) Tested force curves under 500 N



(b) Tested force curves under 1000 N



(c) Tested force curves under 1500 N

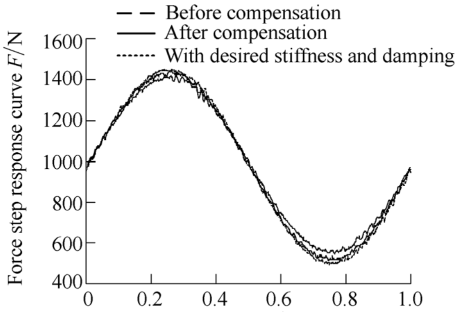
Fig. 18. Tested force curves under different input step force

As it can be seen in Fig. 19, when the input force frequency is relatively small, the compensation control effect is obvious, and the smaller the input force frequency is the better the compensation control effect is.

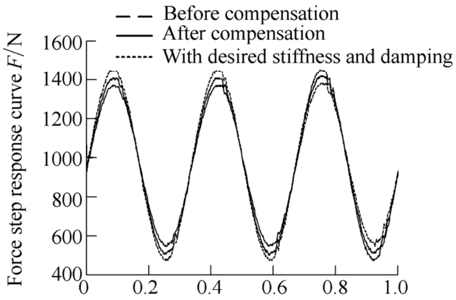
8 Conclusions

In this paper, the HDU force control system of the quadruped robot joint is taken as the research object, and the compensation control method for the variable load stiffness and load damping characteristics is researched to provide a method of improving the quadruped robot joint force control robustness under the different environment structures. Through analyzing the research results, the conclusions are as follows.

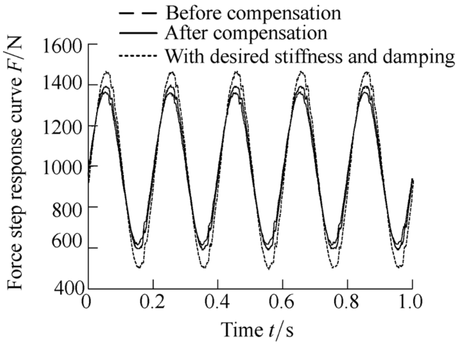
Firstly, the load characteristics of the HDU force control system are equivalent to the stiffness and damping characteristic, and the mathematical model with variable stiffness and damping is established. Then, the load characteristics simulation method is designed, whose availability is verified experimentally. The results indicate that the designed load characteristics simulation method can simulate the dynamical variation of the stiffness and damping accurately under typical load force, though the function relationship between the stiffness and damping and the displacement variation caused by the load force is nonlinear. And the research can provide an effective method for the load characteristics simulation under different contacts between the robot foot end and the environment structure.



(a) Tested force curves with 1 Hz



(b) Tested force curves with 3 Hz



(c) Tested force curves with 5 Hz

Fig. 19. Tested force curves with different frequency

Secondly, a variable stiffness and damping load characteristics compensation control method for the variable load characteristics is designed to apply to the HDU force control system, which is combined with traditional PID controller. The results indicate that if the load stiffness and load damping characteristics are known, the force control compensation method presented in this paper has positive compensation effects on the load characteristics variation which is that this method nearly eliminates effects of the load characteristics variation on the force control performance and enhances the robustness

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of the constant PID control parameters.

More illustrations: the force control compensation method involved in this paper is commonly adaptive with the stiffness and the damping of the load being known and has compensation effects. When the stiffness and the damping of the load are unknown, the control method with more robustness should be developed to make the hydraulic drive quadruped robot apply to more engineering fields.

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