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SLIDING MODEL VARIABLE STRUCTURE CONTROL FOR MICRO-GRAVITY ENVIRONMENT GROUND SIMULATION TEST SYSTEM

[1]ZHANG WENHUI, [2]JI XIAOMING

[1] Lecturer., Institute of Technology, Lishui University,Lishui, China

[2] Prof., Institute of Technology, Lishui University,Lishui, China

E-mail: [1]hit_zwh@126.com , [2] 715703595@QQ.com

ABSTRACT

A novel spatial microgravity simulation system is proposed for big and middle experimental objects with complex movement. The equipments combine machine transmission、motor drive and air-bearing to realize three-dimension spatial microgravity simulation. Level pane adopts air suspending, upright adopts motor drive, by reducer，ball screw and guide pole. Force feedback control aim gravity real timely as controller. Friction non-linearity of machine system and outside disturbance are considered. Variable Structure controller is employed to reduce disturbance and uncertainty. The experimental result shows that test equipment has light weight, convenience using and higher precision, and compensates non-linearity infection for grasping of robotic manipulator, has important engineering value to three-dimension spatial microgravity simulation.

Keywords: *Variable Structure Control (VSC), Microgravity Environment Simulation (MES), Ground Test System (GTS)*

1. INTRODUCTION

The ground microgravity equipments are adopted in international country recently, the ground simulation authentication is to test the performance and the security of the aircraft. The methods of the simulation spatial environment mainly include: free fall method, parabolic flight method, water float, gas flotation and rope suspension method among the international [1].

The free fall method is making the test target free fall at high attitude or in the drop tower of vacuum. NASDA has carried out the experiments in Japanese microgravity laboratory.

The parabolic flight method is creating the microgravity or weightlessness environment by parabolic maneuvers. Weightless aircrafts are constructed in America, Russia, French and other countries[2].

The rope suspension method is balancing the gravity of the mechanical robot by the vertical tension wire hanging. But the hanging wire tilts and rocks easily. The SM2 test system developed by Carnegie Mellon University adopts this method[3].

Table1 Ground simulation of various micro-gravity test method comparison chart

	Drop Tower	Parabolic Flight	Water Float	Rope Suspension	Gas Flotation
Equipment cost	expensive	expensive	high	higher	low
Construction period	very long	very long	long	short	short
Equipment maintenance	more Expensive	more Expensive	expensive	lowest	lowest
Re-use of equipment	well	well	general	poor	well
3-D spatial simulation	yes	yes	yes	yes	No
Test time limit	only 10s	only 25s	no time limits	no time limits	no time limits
Simulation accuracy	high	high	general	general	high

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The water flotation is balancing the self-gravity of the mechanical robot by buoyancy in the water. The water float is under the influence of the water resistance and the impact of turbulence easily. The tightness is required very well during the trial period. University of Maryland has developed the Ranger test system[4].

Gas flotation is the most widely used method at the simulation spatial microgravity of space aircrafts. The aircraft is asked at the smooth platform using the air bearing. The method is adopted by Canada company and the Stanford University, which has developed the Free-flying space robot system[5].

However, the existing flotation could make two-dimension trails only at the horizontal plane. The attitude motion of the existing aircrafts is complex. The expand parts not only require to complete the expand of the level expand, but at the vertical direction or many degrees of freedom of rotation. The current simulation spatial microgravity methods can't satisfy the ground test requirement. Recently, only Document [6] proposes a method adopting the flotation and cylinder combination for the three-dimension microgravity simulation test. But the scheme ignores the gas source is unstable and the cylinder it-self is very heavy. The scheme is only used for micro satellites. The large additional weight increases the influence of performance test. The use of neural network learning algorithms require a large number of samples, all these affect the value of the engineer project.

For the shortcomings of the above schemes, this paper designs a three-dimension spatial microgravity ground simulation device. The device adopts screw drive, bearing orientation, motor drive and air suspension combinations to complete the complex motion simulation of micro-gravity environment. Force feedback controller counteracts gravity real timely as controller. The scheme dispenses with accurate dynamical model. Friction non-linearity of machine system and outside disturbance are considered. Estimate model is controlled by state feedback. Sliding model controller is employed to compensate uncertainty model to guarantee robust. RBF neural network is used to adaptive study uncertainty up bound to reduce shake. The experimental result shows that test equipment conveniences using and higher precision, has important engineering value to three-dimension spatial microgravity simulation.

2. 3D Microgravity Simulation System

As the complex three-dimensional space movement can be decomposed into horizontal movement and vertical movement. Thus three-dimensional spatial microgravity simulation system is shown in Figure1. The system consists of a motor drive system and a mechanical transmission system, which turns into a constant force servo system through the work of the panel pressure sensor. For the different structure of space robot, it only needs to replace the bracket interface.

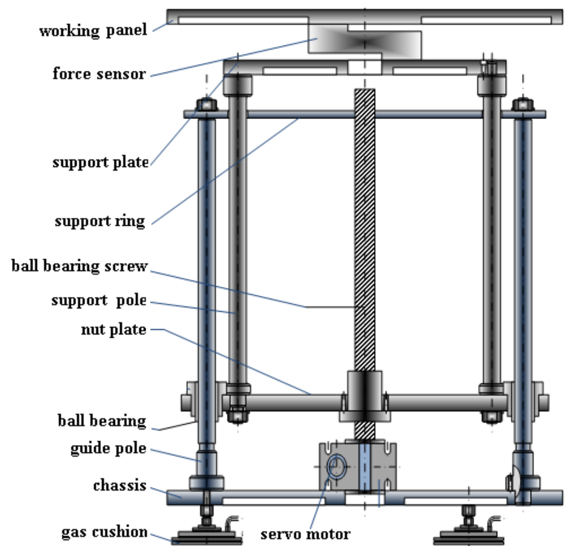

Fig.1 Structure for 3D Spatial Microgravity System

The operating principle of the Three-dimensional Spatial Microgravity Simulation system is as follows, the air feet provide the three-dimensional microgravity environment for the direct push air device[7] ~ [8]; the servo motor controller receives control signals and drive the screw to rotate, which promote the nuts vertical lift; the nut and screw turn spiral movement into straight movement. Supporting makes the upper pallet and screw pallet fixed together, the upper pallet and the screw pallet achieve vertical lift; the pressure sensor measures the pressure information and achieves pressure feedback timely.

The mechanical transmission system, force sensors, the contact specimen (Space Robot) are regarded as mass, damping and stiffness model. The ground simulation equipment and the environment contact can be roughly expressed by Figure 2[9]~[11].

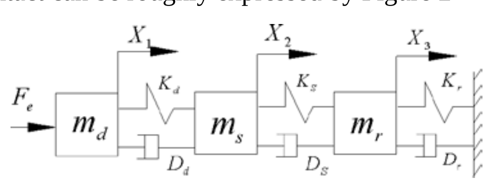

Fig.2 Force system model

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Figure 2 shows the test equipment / sensor / environment model in one direction. m_d 、 m_s 、 m_r respectively are ground mechanical transmission system, sensor and space contact environment mass. $\{K_d, D_d\}$ 、 $\{K_s, D_s\}$ 、 $\{K_r, D_r\}$ are respectively stiffness and damping coefficient.

The input / output equation can be established according Figure2:

$$X_3(s)/F_c(s) = B_3(s)/A(s) \quad (1)$$

$$X_2(s)/F_c(s) = B_2(s)/A(s) \quad (2)$$

Where

$B_3(s) = (D_r s + K_r)(D_s s + K_s)$,

$B_2(s) = [m_r s^2 + (D_s + D_r)s + K_s + K_r](D_d s + K_d)$,

$$A(s) = [m_d s^2 + D_d s + K_d][m_d s + (D_d + D_s)s + (K_d + K_s)][m_r s^2 + (D_d + D_r)s + (K_s + K_r)] - [m_r s^2 + (D_r + D_s)s + K_s + K_r]$$

The output measuring force controlled by the stiffness sensor:

$$F_s(s) = K_s[X_2(s) - X_3(s)] \quad (3)$$

Bring Eq(1)and Eq(2) into the above equation:

$$\frac{F_s(s)}{F_c(s)} = K_s \frac{[m_r s^2 + D_r s + K_r](D_d s + K_d)}{A(s)} \quad (4)$$

Where $D_b = D_d + D_r$, D_b the integrated damping coefficient, D_d the ground transmission speed damping coefficient, D_r the contact environment damping coefficient , K_r the stiffness of the environment, the disturbance d will also need to be considered, the above equation will convert into:

$$\ddot{x} = h(x, \dot{x}) + bu + d \quad (5)$$

Where $h(x, \dot{x}) = -\frac{K_r}{m_d} x - \frac{D_b}{m_d} \dot{x}$, $b = \frac{K_r}{m_d}$;

u the control input.

Making

$M = b^{-1}$， $H = -b^{-1} h(x, \dot{x})$； $D = -b^{-1} d$.

The equation above can be converted into:

$$u = M\ddot{x} + H - D \quad (6)$$

However, at the engineering practice, the mass, stiffness and damping coefficients are not accurately informed, and the disturbance is also unknown as the uncertainty of the test target and environment. The actual system model can only obtain its estimate value, assuming the model consists of estimate value and estimate error. $\hat{M}$ and $\hat{H}$ are estimated value， ΔM and ΔH are estimated error 。 Making $M = \hat{M} + \Delta M$ ； $H = \hat{H} + \Delta H$ 。

Assuming f is the uncertainly model part of the system. $f = \Delta M\ddot{x} + \Delta H - D$， the system dynamics Eq(6) could be amended into:

$$u = \hat{M}\ddot{x} + \hat{H} - f \quad (7)$$

The whole control system is divided into two parts, one is the controller for the estimated model u_1 , the other is the controller for the uncertainty model u_2 .

The system Eq (7) can be converted into:

$$u_1 + u_2 = \hat{M}\ddot{x} + \hat{H} - f \quad (8)$$

As the known of the estimate model, it can be controlled by the state feedback. For the uncertainly model, considering of batter dynamic characters and nonlinear control ability, sliding model controller compensate the uncertainly model for the robust of the system.

Define x_d expect force, $e = x_d - x$, the error of the force track, $e_2 = \dot{e}_1$, $\Lambda \in R^{n\times n}$ is positive definite matrix, don't consider of the uncertain model f ,the error equation of the uncertain model system:

$$\dot{e}_2 = \hat{M}^{-1} u_1 - \hat{M}^{-1}\hat{H} - \ddot{x}_d \quad (9)$$

$$v = \hat{M}^{-1}(u_1 - \hat{H}) - \ddot{x}_d \quad (10)$$

The state equation of the error equatin:

$$\dot{E} = RE + QV \quad (11)$$

Where $E = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}$, $R = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$, $Q = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$.

Assuming $V = KE$， $K = [-k_1 \quad -k_2]$,bring them into state error equation:

$$\dot{E} = ZE \quad (12)$$

Where $Z = R + Qk$,it can be seen, designing the state feedback gain matrix K , using error state Eq(12),the closed-loop poles can be configured at any point. From Eq(10), the control law for the estimated model is designed to:

$$u_1 = \hat{M}(KE + \ddot{x}_d) + \hat{H} \quad (13)$$

From Eq(8), the error of the system:

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$$\dot{e}_2 = \hat{M}^{-1}[u_1 - \hat{H}] - \ddot{x}_d + \hat{M}^{-1}[u_2 + f] \quad (14)$$

From Eq(10) and $V = KE$, the above equation can be converted into:

$$\dot{e}_2 = KE + \hat{M}^{-1}[u_2 + f] \quad (15)$$

Define sliding model plane s ,then

$$s = ce_1 + e_2 \quad (16)$$

Differentiate

$$\dot{s} = c\dot{e}_1 + \dot{e}_2 = ce_2 + \dot{e}_2 \quad (17)$$

The compensated controller for the uncertain model is designed:

$$u_2 = -\hat{M}(ce_2 + KE) - \frac{1}{s\hat{M}^{-1}}\left|s\hat{M}^{-1}\right| f_M \quad (18)$$

Where $\frac{1}{s\hat{M}^{-1}}\left|s\hat{M}^{-1}\right|$ may also be written to $\mathrm{sgn}(s)\mathrm{sgn}(\hat{M})$, f_M is the upper value of the uncertain part f 。

3. Simulation

Complex space motion can be decomposed into horizontal two-dimensional movement and vertical one-dimensional movement.

It is assumed that the weight of the spacecraft is 1000N and it needs to complete the space spin and snatch two movement .The simulation time is 10s. At the starting 0s-2s, the rotary joints of the body rotate, driving rotary aircraft to complete the translation and lift. The component force of the rotation driving force in the vertical direction is $d_1 = 20.0\sin(2\pi t)$. At 2s, the vehicle capture one object of 50N, the total weight becomes 1050N. The whole process is disturbed by $d_2 = 8\sin(\pi t)$. k_r =8 , m_d =5 , D_b =2 。 The simulation results are as follows:

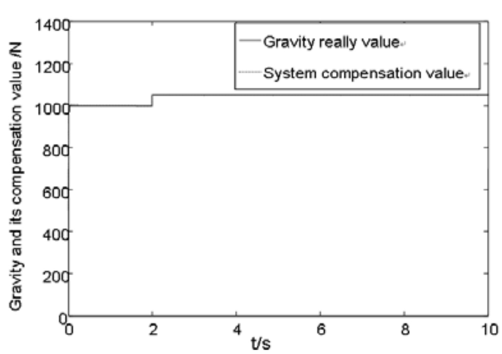

Fig.3 The tensility tracking curve

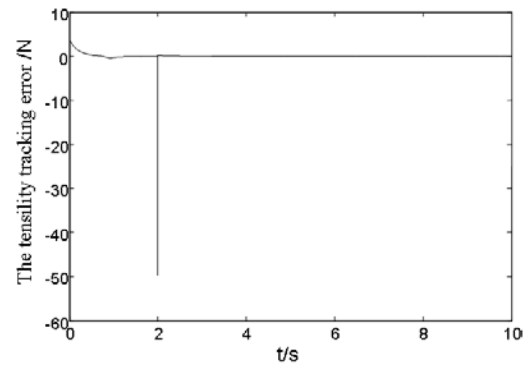

Fig.4 The tensility tracking error curve

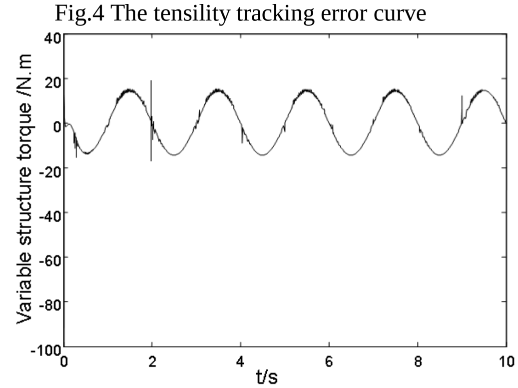

Fig.5 output of sliding model variable structure controller

It can be seen from the figure that the designed control system can achieve better control accuracy in a very short time, the initial error is less than 10N，the simulation accuracy is less than five thousandths. It can be seen from Figure 4 that it can be achieved precise tension track in about 1S, and the initial error is not large, about 50N, the total weight of five thousandth, the microgravity simulation accuracy is higher. After the capture of a 50N objects, the maximum error is about 50N, 5% of the total gravity, tension could achieve to counteract the gravity well in a very short time ,and it could reach the ideal control effect of microgravity. During The whole process, the neural network could estimate the upper value of the uncertainty bound better, reduce the vibration of sliding mode controller, and the total control moment is not large.

4. Conclusion

The paper proposed variable structure control algorithm for three-dimension spatial microgravity simulation device. The device adopts screw drive, bearing orientation, motor drive and air suspension combinations to complete the complex motion simulation of micro-gravity environment. Force feedback controller counteracts gravity real timely as controller. The scheme dispenses with accurate

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