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RESEARCH ON SPACE DOCKING HIL SIMULATION SYSTEM BASED ON STEWART 6-DOF MOTION SYSTEM

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ABSTRACT

This paper presents the research on the experimental testing system of the space docking HIL (Hardware-In-the-Loop) simulation, which is based on a Stewart 6-DOF (Degree-Of-Freedom) motion system. First of all, spacecraft dynamics is analyzed. Because of the under-damping characteristic, stability of the HIL simulation system is analyzed, and control strategy of the 6-DOF-motion system, which is based on the phase compensation, is put forward to improve system stability. The influence created by the frequency characteristics of the 6-DOF-motion system on the accuracy and stability of the HIL simulation system is also analyzed. The characteristics of the spacecraft dynamics and the accuracy and feasibility of the HIL simulation system are verified with a non-damp collision device.

KEY WORDS

HIL simulation, On-orbit docking, 6-DOF Stewart platform, Dynamic simulation

INTRODUCTION

It is great signification to research HIL (Hardware-In-the-Loop) simulation technique for on-orbit docking, because that spacecraft docking technique play very important role in human space program. For the docking mechanism is very complex and the on-orbit docking is a complicated dynamics process, it is necessary to research spacecraft on-orbit docking process dependent on HIL simulation.

In 1964, Langley Research Center of American firstly established a docking simulator [1]; it is employed to test of Gemini-Agena. In March 16th, 1966, NASA accomplished the famous Gemini-Agena on orbit docking, which the first time on-orbit spacecraft docking activity is made by human beings.

In 1969, Langley Research Center established another docking simulator[2],[3], which is employed to research on the complex docking process between the Lunar Excursion Module and Command/Service Module of Apollo. The docking simulator had been made use of to training astronauts.

In 1971, former USSR designed a docking simulator that had been employed to the test of APAS-89 docking mechanism [4].

The docking simulators mentioned above are called physics simulation. With the development of computer technology, mathematics simulation and half-physics simulation has been played more and more important role in human space program. After the Apollo-13 Disaster in 1970, American and USSR began to cooperation in space program, and a new docking mechanism called APAS-75[5] was developed. The composition and dynamics of APAS-75 were much more complex than that of the docking mechanism developed before. To ensure the reliability in space and determine the dynamic parameters of the docking mechanism, an integrated testing system[6],[7] for docking mechanism, shown in Fig.1 and Fig.2, was developed by the American and Russian scientists. Then

Figure1 Integrated testing system for docking mechanism

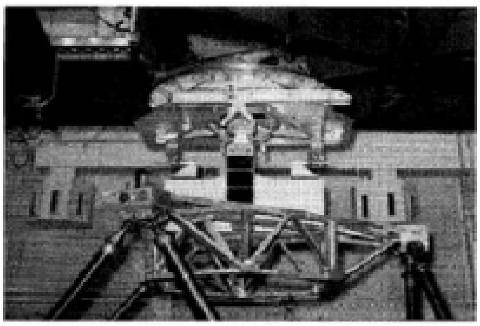

Figure 2 6-DOF contact dynamic simulator

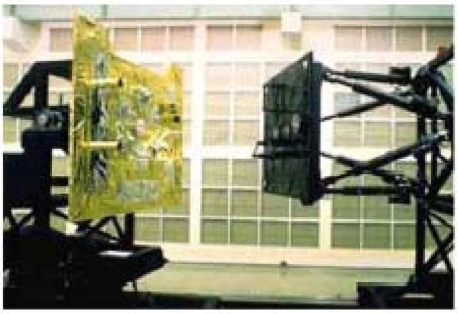

Figure 4 Rendezvous and docking operation test system

Figure 3 European proximity operation simulator

the research on spacecraft docking simulation has come into the time of HIL simulation. Using APAS-75, Union-19 docking with Apollo was realized in July 17th 1975, which is the USA and USSR cooperation on-orbit docking for the first time.

In 1980s, Europe Space Bureau began to research on the unmanned spacecraft rendezvous and docking technology, and a docking mechanism for unmanned spacecraft is developed, which would be employed in Eureca A docking with Eureca B, and Hermes Shuttle docking with Columbus Space Station. Meanwhile, the spacecraft docking simulator[8], shown in Fig.3, was also developed. In the same time, the research on the spacecraft rendezvous and docking technology was put forward in Japan, and a rendezvous and docking operation test system, shown in Fig.4, was developed in NASDA[9], and the docking mechanism was developed too, which is employed in the on-orbit docking of ETS-7 Unmanned Spacecraft.

China began manned space program in 1992. In 2008, an integrated testing system for docking mechanism is developed by HIT and Shanghai Space Bureau. In this paper, firstly the compositions, and the model of system included dynamic model of the spacecraft are given, and secondly the characteristics of the system is analyzed, at last a simply verifying model is employed to research on the effect of 6-DOF Stewart platform frequency characteristics on the system stability and accuracy of the docking dynamics.

SYSTEM DESCRIPTION

Docking mechanisms are employed for docking a spacecraft with another spacecraft. The on-orbit spacecraft is called passive spacecraft, and its docking mechanism name passive docking mechanism. The launched spacecraft is called active spacecraft, and its docking mechanism called active mechanism. To research the docking dynamics, coordinate frames are defined as shown in Fig.5, which includes inertial frame $\boldsymbol{e}$ **(O-XYZ)**, a moving frame $\boldsymbol{e}_1$ **(O_1-$X_1Y_1Z_1$)**, a moving frame $\boldsymbol{e}_2$ ($\mathbf{O}_2$-$\mathbf{X}_2\mathbf{Y}_2\mathbf{Z}_2$), a moving frame $\boldsymbol{e}_3$ ($\mathbf{O}_3$-$\mathbf{X}_3\mathbf{Y}_3\mathbf{Z}_3$), a moving frame $\boldsymbol{e}_4$ ($\mathbf{O}_4$-$\mathbf{X}_4\mathbf{Y}_4\mathbf{Z}_4$). The Euler angles are defined as yaw ψ, pitch θ, and Yaw φ, then the transfer matrix between inertial frame and moving frame is as follows:

$$\boldsymbol{A} = \begin{bmatrix} \mathrm{c}\theta\cdot\mathrm{c}\psi & \mathrm{s}\varphi\cdot\mathrm{s}\theta-\mathrm{c}\varphi\cdot\mathrm{c}\theta\cdot\mathrm{s}\psi & \mathrm{c}\varphi\cdot\mathrm{s}\theta+\mathrm{s}\varphi\cdot\mathrm{c}\theta\cdot\mathrm{s}\psi \\ \mathrm{s}\psi & \mathrm{c}\varphi\cdot\mathrm{c}\psi & -\mathrm{s}\varphi\cdot\mathrm{c}\psi \\ -\mathrm{s}\theta\cdot\mathrm{c}\psi & \mathrm{s}\varphi\cdot\mathrm{c}\theta+\mathrm{c}\varphi\cdot\mathrm{s}\theta\cdot\mathrm{s}\psi & \mathrm{c}\varphi\cdot\mathrm{c}\theta-\mathrm{s}\varphi\cdot\mathrm{s}\theta\cdot\mathrm{s}\psi \end{bmatrix} \tag{1}$$

where $\mathrm{s}(\cdot)=\sin(\cdot)$, and $\mathrm{c}(\cdot)=\cos(\cdot)$. A generalized coordinate vector **q** is defined as:

$$\mathbf{q}=[x,y,z,\varphi,\theta,\psi]^{\mathrm{T}} \tag{2}$$

where *x, y, z* present the varying coordinates of moving frame from inertial frame.

According to Newton-Euler formula, if the mass of the docking mechanism is neglected, the dynamic formula of active spacecraft can be written as

$$\frac{{}^{r}\mathrm{d}^2}{\mathrm{d}t^2}\boldsymbol{r}_1=\frac{\boldsymbol{F}_1+\boldsymbol{F}_3}{m_1} \tag{3}$$

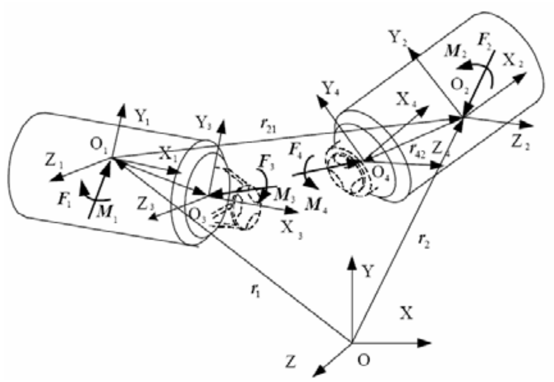

Figure 5 Two On-orbit Docking Spacecraft

$$\mathbf{J}_1 \cdot \frac{{}^{r}\mathrm{d}}{\mathrm{d}t}\boldsymbol{\omega}_1 + \boldsymbol{\omega}_1 \times \mathbf{J}_1 \cdot \boldsymbol{\omega}_1 = \mathbf{M}_1 + \mathbf{M}_3 + \mathbf{r}_{31} \times \mathbf{F}_3 \tag{4}$$

and the passive spacecraft dynamic formula is

$$\frac{{}^{r}\mathrm{d}^2}{\mathrm{d}t^2}\boldsymbol{r}_2 = \frac{\boldsymbol{F}_2 + \boldsymbol{F}_4}{m_2} \tag{5}$$

$$\mathbf{J}_2 \cdot \frac{{}^{r}\mathrm{d}}{\mathrm{d}t}\boldsymbol{\omega}_2 + \boldsymbol{\omega}_2 \times \mathbf{J}_2 \cdot \boldsymbol{\omega}_2 = \mathbf{M}_2 + \mathbf{M}_4 + \mathbf{r}_{42} \times \mathbf{F}_4 \tag{6}$$

If the active spacecraft is defined as reference, and the relative movement $\boldsymbol{r}_{21}$ between active spacecraft and passive spacecraft is

$$\frac{{}^{r}\mathrm{d}}{\mathrm{d}t}\boldsymbol{r}_{21} = \frac{{}^{b}\mathrm{d}}{\mathrm{d}t}\boldsymbol{r}_{21} + \boldsymbol{\omega}_1 \times \boldsymbol{r}_{21} \tag{7}$$

$$\frac{{}^{r}\mathrm{d}^2}{\mathrm{d}t^2}\boldsymbol{r}_{21} = \frac{{}^{b}\mathrm{d}^2}{\mathrm{d}t^2}\boldsymbol{r}_{21} + \frac{{}^{r}\mathrm{d}}{\mathrm{d}t}\boldsymbol{\omega}_1 \times \boldsymbol{r}_{21} + 2\boldsymbol{\omega}_1 \times \frac{{}^{b}\mathrm{d}}{\mathrm{d}t}\boldsymbol{r}_{21} + \boldsymbol{\omega}_1 \times \left(\boldsymbol{\omega}_1 \times \boldsymbol{r}_{21}\right) \tag{8}$$

where $\overset{\circ}{(\ )} = \frac{{}^{b}\mathrm{d}}{\mathrm{d}t}(\ )$ is angular velocity in moving frame, $\dot{(\ )} = \frac{{}^{r}\mathrm{d}}{\mathrm{d}t}(\ )$ is angular velocity in inertial frame, $\overset{\circ\circ}{(\ )} = \frac{{}^{b}\mathrm{d}^2}{\mathrm{d}t^2}(\ )$ is angular acceleration in moving frame, $\ddot{(\ )} = \frac{{}^{r}\mathrm{d}^2}{\mathrm{d}t^2}(\ )$ is angular acceleration in inertial frame. Then on-orbit docking dynamics is shown in Fig.6.

To research on the docking dynamics, a docking simulator is built, and the overall docking simulator system developed by HIT is shown in Fig.7, the system is consisted of the dynamic simulation software, a 6-DOF Stewart platform, a 6-DOF force and torque sensor, and a docking mechanism. When the docking conditions that involves the relative position and relative velocity between active spacecraft and passive spacecraft are given, the passive mechanism driven by Stewart platform impacts the active mechanism that is fixed on the frame through 6-DOF force and torque sensor, the impacting forces and torques effects each other on the passive mechanism and the active mechanism is measured by 6-DOF force and torque sensor. The dynamic simulation software calculates the relative movement between the active spacecraft and the passive spacecraft according to the docking dynamics, the relative movement is replicated by 6-DOF Stewart

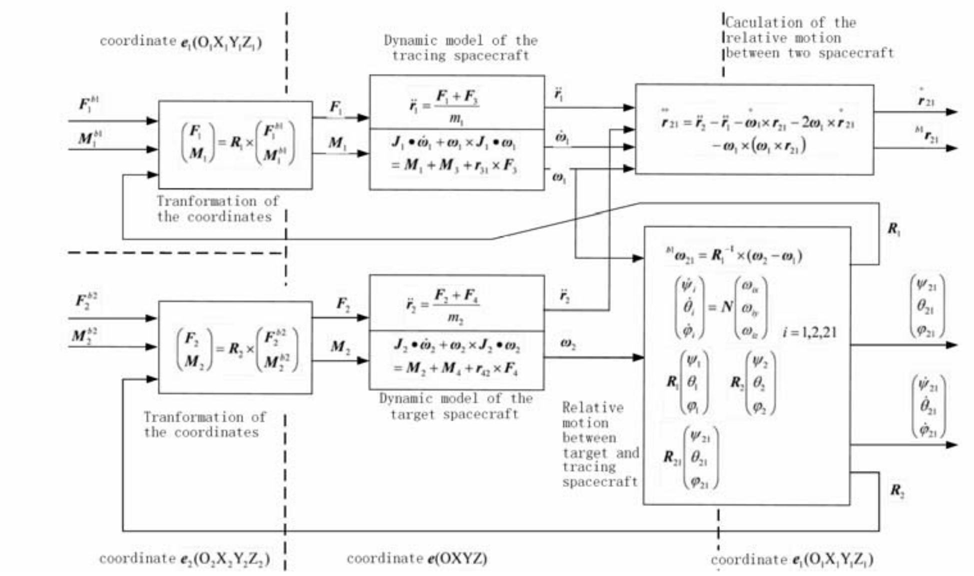

Figure 6 The diagram of docking dynamics

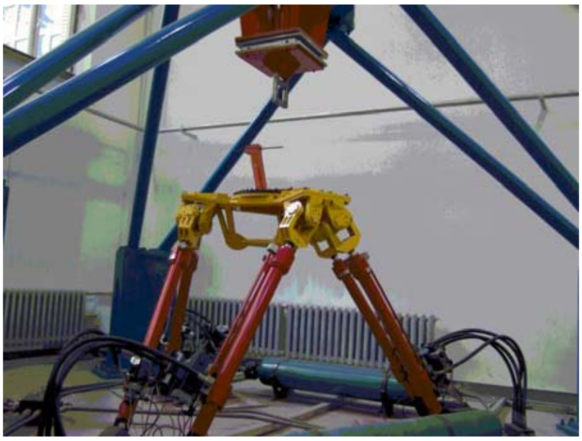

Figure 7 Integrated testing system

platform.

There are several problems for the docking simulation system:

(1) Stability. For the under-damping characteristic of the docking mechanism, the spacecraft dynamics performs under-damping oscillation. Stewart platform has phase lag, which may result in the unstable docking dynamics.

(2) Docking dynamics validation. The docking dynamics presented here is derived from the laws of physics. Where the parameter values were taken from design values or rough approximations of what could be expected in practice. The docking dynamics can be valuable for design and analysis of the spacecraft and docking mechanism. The strengths of the dynamics should, however, be proven by experimental validation.

SYSTEM ANALYSIS

The diagram of the docking simulator is shown in Fig.8, and its the transfer function can be written as

$$G_I(s) = G_M(s)G_D(s)G_S(s)G_T(s) \tag{9}$$

where $G_M(s)$ is the transfer function of docking mechanism, $G_D(s)$ is that of spacecraft dynamics, $G_S(s)$ is that of Stewart platform, and $G_T(s)$ is that of other parts of the simulator. If the transfer functions of Stewart platform and other parts could be seen as

$$G_O(s) = G_S(s)G_T(s) = 1 \tag{10}$$

The docking simulator may replicate the on-orbit docking process with no error. But in fact, $Go(s)$ is not equal to 1, and as result, the docking dynamics replication on the docking dynamics has error. In order to ensure the validation of the docking dynamics replication on the simulator, the attention must be paid to the design of $Go(s)$. Because the docking mechanism and docking dynamics is very complex, to simplifying the analysis, a simple non-damping collision-rebound device, shown in Fig.9 is employed to research on the parameters determination of $Go(s)$.

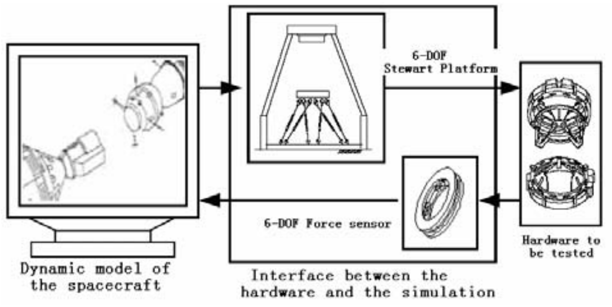

Figure 8 The Schematic diagram of the docking simulator

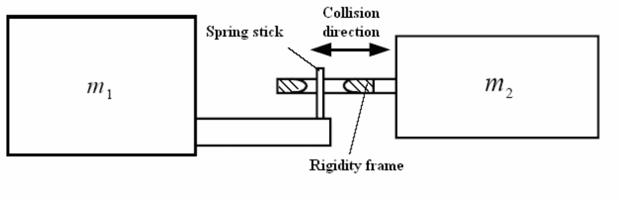

Figure 9 A simplified docking mechanism

VERIFICATION

The simplified docking mechanism as show in Fig.9 is a non-damping collision-rebound oscillation system that is similar with the docking process, the nature frequency of the system is

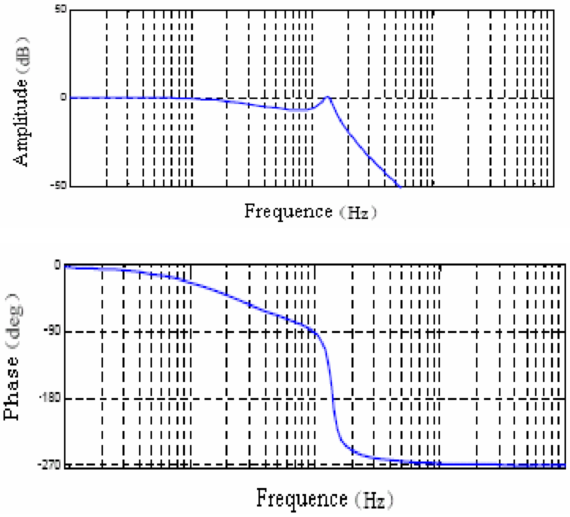

Figure 10 Frequency characteristics of the Stewart platform

$$\omega_n = \sqrt{\frac{K(m_1 + m_2)}{m_1 m_2}} \tag{11}$$

and the rebound coefficient is defined as

$$R_v = \frac{v_i}{v_o} \tag{12}$$

where v_i is input velocity, and the v_o is rebound velocity. If the mass m_1 has a muzzle velocity relative to the mass m_2, the system will oscillation in critical state, and the rebound coefficient is equal to 1. To prove the validation of docking simulator, the simulator is employed to simulation the non-damping collision-rebound oscillation device.

If the frequency error

$$e_f = \left| \frac{\omega_n - \omega_{nc}}{\omega_n} \right| \le 0.05 \tag{13}$$

where ω_{nc} is simulation oscillation frequency, and the rebound coefficient error

$$e_r = 1 - R_{vc} \le 0.05 \tag{14}$$

where R_{vc} is simulation rebound coefficient, the validity of docking simulator can be verified.

ANALYSIS AND EXPERIMENT

The 6-DOF Stewart platform frequent characteristics are shown in Fig. 10, which has phase lag. Without compensation of the phase lag of the Stewart platform, the outputs of non-damping collision-rebound dynamics simulation system are unstable as shown in Fig.11.

A phase compensation controller of Stewart platform is designed as

$$D(s) = k_p \frac{T(s)}{S(s)} \tag{15}$$

Where k_p is the gain of the controller, generally, $k_p = 1$. With the phase compensation, the phase lag from Stewart platform to force sensor is zero, then the simulation outputs of non-damping collision-rebound dynamics, shown in Fig.12, is stabilized. The frequency of the output is greater than theory result, and the rebound coefficient is about 0.97. It is impossible that the damp of the overall system is zero, which result in the rebound velocity attenuation. But what causes the variation of the oscillation frequency?

When the gain k_p of the controller $D(s)$ is decreased, i.e. $k_p<1$, the experiment results is shown in Fig.13, the frequency of the output becomes smaller.

When the gain k_p is increased, i.e. $k_p>1$, the experiment results is shown in Fig.14, the frequency of the output becomes much greater.

From analysis above, it is known that the frequent characteristic of the Stewart platform has great effect on the replicating accuracy of the docking dynamics. The phase lag of the transfer function may cause the docking simulator unstable, and the gain may change the nature frequency of the docking dynamics.

CONCLUSIONS

The docking simulator can be employed to analysis the on-orbit docking dynamics. For the complexity of the docking mechanism, it is difficult to analytically research on the docking dynamics, consequently, experiment research can play important pole on the research job. Then the on-orbit docking simulator is established to carry out the experiment research on docking dynamics. To simplify the research work, and do not lost the generality, a non-damping collision-rebound device that its characteristics is known analytically is employed to verify the validation of the docking simulator. Apart from the stability, two

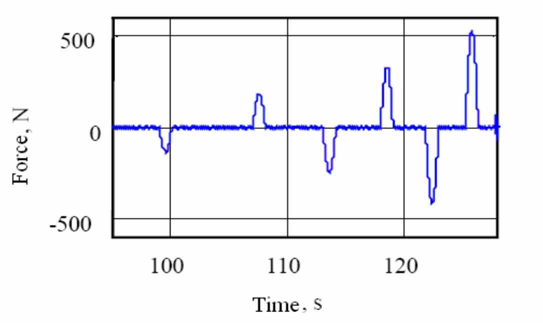

Figure 11 Dynamics output without compensation

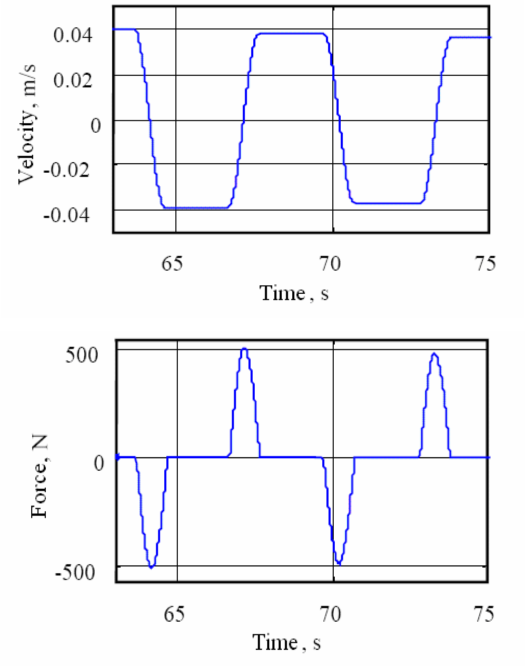

Figure 12 Dynamics output with phase compensation

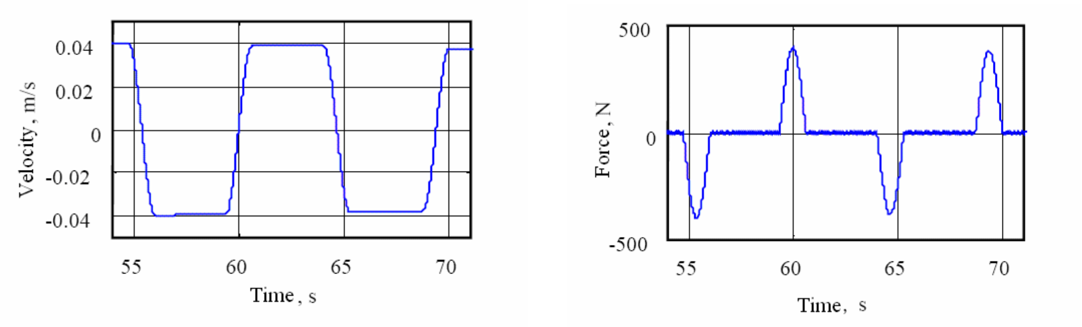

Figure 13 Dynamics output with phase compensation with greater gain

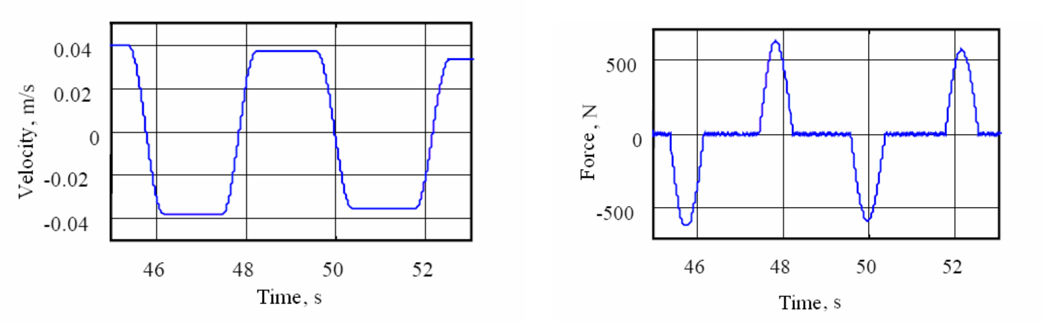

Figure 14 Dynamics output with phase compensation with less gain

other validation indexes are introduced, one is the frequency error, and another one is rebound coefficient. The 6-DOF Stewart platform is used of to replicate the relative movement of the spacecrafts. From the experiment research, it's known that the frequent characteristic of the Stewart platform has great effect on performances of the docking simulator, its phase lag has influence on the stability of the simulator, which will cause the docking dynamics unstable, and its gain may effect on the nature frequency of the docking dynamics. To ensure the validation of research work, a phase compensation controller on Stewart platform is designed. With the controller, the phase lag and the gain of the Stewart platform frequent characteristic is corrected, and the docking dynamics is well replicated consequently.

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