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Verifications of Delay Compensation for a Hybrid Motion Table *

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***Abstract* - This study considers the time delay problem of the hybrid motion table. A motion table is designed using the 3-3 parallel mechanisms to guarantee the static stiffness and dynamic performance. The time delay in the system loops is compensated to guarantee the hybrid simulation accuracy. The effects of the table parameters (sensor delay and dynamic response frequency) and the contact parameters (contact natural frequency, contact stiffness and initial velocity) on the hybrid simulation results are investigated by simulations and experiments. They show that the simulation instability can be compensated by the approach under different table parameters and contact parameters.**

Index Terms* - *motion table, parallel mechanism, hybrid simulation, delay compensation

I. Introduction

The motion tables using the parallel mechanisms are very useful to generate the required simulation motion of the heavy payload, e.g., spacecraft, aircraft and rocket. The dynamic process of contact between two spacecraft must be simulated on the ground in order to guarantee the safety and reliability of the on-orbit operations in the space, including space docking, space capturing, space robot operations and so on [1]. During the space docking, the contact dynamic process happens between the active contact device and passive contact device on the spacecraft. The main challenge is how to simulate the zero gravity (0-g) space contact on the one gravity (1-g) ground.

Full numerical simulation [2] is often used in the contact device design stage. It cannot verify the real contact device. Moreover, the contact simulation accuracy is limited due to complicated and uncertain contact parameters. Full physical simulation applies 0-g emulation system to eliminate the effect of gravity, e.g., suspension system [3] and air bearing supported floating platform [4], and calculates the contact kinematics and dynamics by experimenting on real hardware. However, the full physical simulation requires complicated mechanisms. And changing the spacecraft model for simulation is inconvenient. Differently, hybrid simulation system rebuilds the contact process in the space by using the real docking hardware, and calculates the kinematics of spacecraft by using its mathematical model. Therefore, the hybrid simulation is suitable for the complicated space contact simulation with good fidelity and flexibility.

In the hybrid simulation system, time delay will generate simulation instability, which will destroy the stability and accuracy of the simulation. Therefore, the time delay should be compensated. The delayed force signal can be phase leaded using a first-order phase lead compensator [5] when the value of time delay is time-invariant and measurable. If the model and frequency of the contact process are known, the force compensator can also be designed analytically [6-8]. The required movement signal of the motion table can also be phase leaded when the value of time delay is time-invariant and measurable [9]. In practice, the dynamic response model of the motion table, contact model and contact frequency are often unknown. The sensor delay and motion delay of the motion table are considered individually in [10]. The model-based phase lead is used to compensate the known sensor delay. The force compensation based on the response error is used to compensate the unknown motion delay of the motion table.

In this study, the sensor delay and motion delay compensation is further investigated. The effects of table parameters (e.g., dynamic response frequency and sensor delay) and contact parameters (e.g., contact natural frequency, contact stiffness and initial velocity) on the hybrid simulation results are studied and verified by simulations and experiments. They indicate that the approach can effectively compensate the time delay and eliminate simulation instability under different table parameters and contact parameters.

II. Modeling of Hybrid Simulation System

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The hybrid contact table is shown in Figure 1. The table includes a motion table (a lower motion table and an upper motion table), a force/torque measurement sensor, and a numerical simulation model. Specially, the lower motion table is designed using the 3-3 parallel mechanisms to guarantee the static stiffness and dynamic performance. The real contact devices or contact device (e.g., the stiff frame and elastic rod) are able to rebuild the real contact process. To study the time delay problem of the hybrid simulation system, four parts of the system models are established as shown in Figure 2.

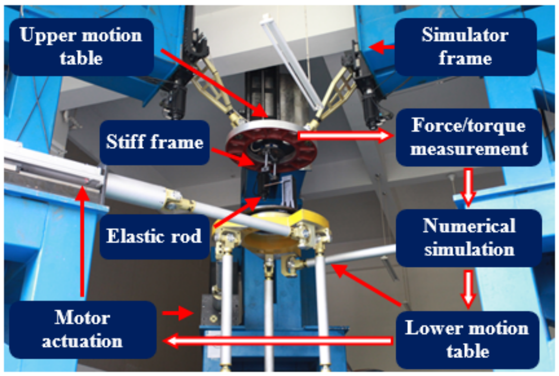

Figure 1: The hybrid simulation system

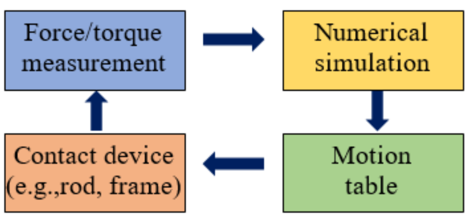

Figure 2: The system models

Though the contact of real contact devices is six-dimensional, for easy formulation we only study one-dimensional contact. The damping and friction of the contact model is assumed to be ignorable. The contact model is stiffness dominant. Therefore, let us define $f_{act}(t)$ be the actual contact force, $p_{act}(t)$ be the actual relative position, k_{con} be the contact stiffness which may be constant or time-varying. When two contact devices just contact without force, $p_{act}=0$. Note that with some revisions, the studied method can be extended to the cases with damping or in the six-dimensional space.

Considering the noise filtering and force sensor, the measured force $f_{mea}(t)$ lags behind the actual force $f_{act}(t)$. The time delay value is defined as T_{fms}.

The expected relative position $p_{des}(t)$ of two spacecraft under the contact force can be described by

$$m_{spac}d^2p_{des}(t)/dt^2=f_{sim}(t) \tag{1}$$

where m_{spac} is the mass/inertia of the spacecraft, $f_{sim}(t)$ is the contact force for numerical simulation. $f_{sim}(t)$=$f_{mea}(t)$ when the measured force is not compensated and $f_{sim}(t)$=$f_{comp}(t)$ when the measured force is compensated.

The actual position $p_{act}(t)$ of the motion table dynamically lags behind the desired position. Here, a linear second-order model is used to estimate the dynamic response of the motion table. We use ξ_{resp} to represent the damping ratio, ω_{resp} to represent the undamped natural frequency (rad/s). The formula $f_{resp}=\omega_{resp}/2\pi$ is used to calculate the response frequency in Hz. A higher-order model can also be used when the motion table is a higher-order dynamical system. In the divergence analysis, the above model emulates the motion table.

III. Simulation Instability and Compensation Approach

A. Instability Phenomena

Figure 3 gives the simulated velocity with sensor delay only. The results show that a larger time delay in force measurement makes the hybrid simulation more divergent. Here, the initial velocity is 0.1m/s, the contact frequency is 1Hz and the contact stiffness is 1E5N/m. These parameter values are selected referring to a kind of contact process in space. Other reasonable parameter values can also be used, while they do not change the conclusions.

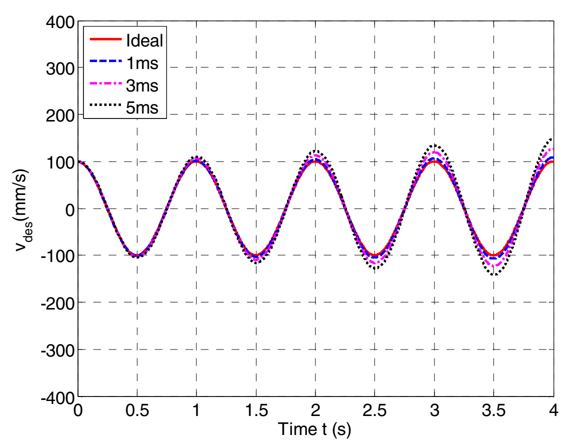

Figure 3: Simulated velocity with sensor delay

Figure 4 gives the simulated velocity with the motion delay only. Without compensation, the divergence of the hybrid simulation is getting more severe while the frequency response of the motion table is getting worse. The response frequency of the motion table is selected as 100Hz, 50Hz and 25Hz, while the damping ratio is set as 0.8. In practice, the damping ratio is tuned to balance the overshoot and fast response. A 25Hz frequency response is practical, while an ideal frequency response is impossible.

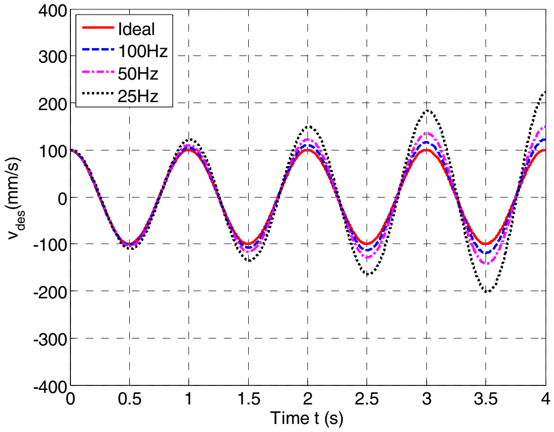

Figure 4: Simulated velocity with motion delay of the motion table

Figure 5 shows the simulated velocity with 25Hz frequency response and 5ms sensor delay. The hybrid simulation becomes more divergent, compared with individual sensor delay or motion delay as shown in Figure 3 and Figure 4.

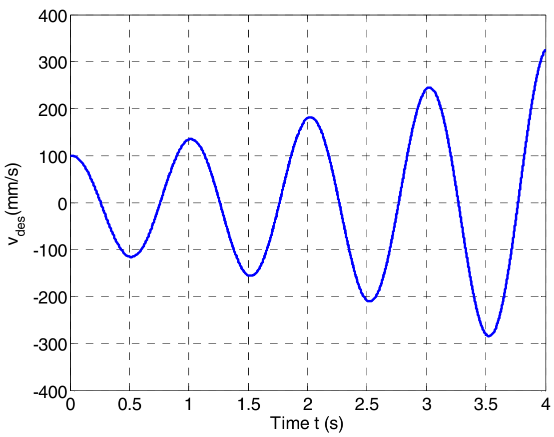

Figure 5: Simulated velocity with time delay both in dynamic response and force measurement

B. *Compensation Approach*

In this study, a sensor delay and motion delay compensation approach is used. The approach is called as SDMDC because the sensor delay compensation (SDC) and the motion delay compensation (MDC) are both used.

For the SDC, the measured force is phase leaded. A first-order compensator is used to estimate the actual force from the measured delay force

$$\hat{f}_{act}(t) = (1 + T_{lead}s) f_{mea}(t) \tag{2}$$

where T_{lead} is the lead time. In the time domain, this compensator is implemented as

$$\hat{f}_{act}(t) = f_{mea}(t) + T_{lead} df_{mea}(t)/dt \tag{3}$$

This phase lead compensation is widely used in the hybrid contact table. The compensation performance is satisfactory as shown in the simulations and experiments.

For the MDC, the contact force corresponding to the motion delay is compensated as follows

$$\Delta f_{resp}(t) = k_{con}(t) \Delta p_{resp}(t) \tag{4}$$

from the position response error

$$\Delta p_{resp}(t) = p_{des}(t) - p_{act}(t) \tag{5}$$

When the contact mechanism has no damping, $k_{con}(t)$ is the contact stiffness matrix. When the contact mechanism has damping, $k_{con}(t)$ is the contact stiffness and damping matrix, and the compensation force can be expressed by

$$\Delta f_{resp}(t) = k_{con}(t) \begin{bmatrix} \Delta p_{resp}(t) \\ \Delta v_{resp}(t) \end{bmatrix} \tag{6}$$

Note that the contact stiffness should be identified in real time from several past sampled contact force and position data points.

Finally, the compensated force inputted to the numerical simulation of the spacecraft dynamics model is obtained as follows

$$f_{comp}(t) = \hat{f}_{act}(t) + \Delta f_{resp}(t) \tag{7}$$

III. Effects of Table and Contact Parameters on Divergence Compensation

A. *Simulation Studies*

As an example, the parameters of simulation are set as follows: contact stiffness $k_{con} = 1\text{E}5 N/m$, contact frequency $f_{con} = 1Hz$, initial velocity $v_{spac}(0) = 0.1m/s$, response frequency $f_{resp} = 25Hz$, time delay $T_{fms} = 5ms$. These parameter values are selected because they can represent a typical contact process and motion table.

Figure 6 gives the simulated velocity with the SDC, MDC and SDMDC. The compensation performance of SDMDC is much better than the SDC or MDC. The coefficient of restitution (CoR) is shown in Table 1. The CoR with the SDC or MDC is still larger than 1, while the SDMDC achieves a close ideal CoR. The compensated force is shown in Figure 7. The SDMDC achieves an approximate ideal compensated force. Because the time delay in the hybrid simulation system is compensated, the simulation instability is prevented.

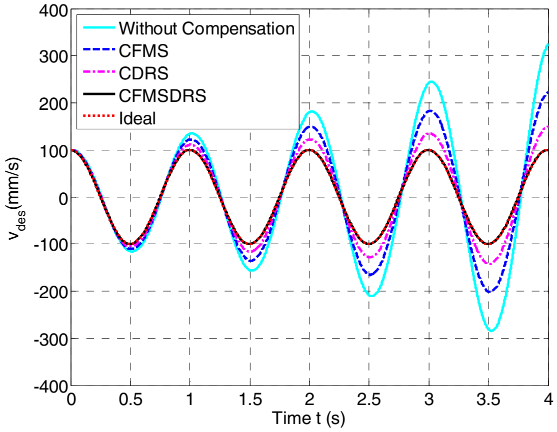

Figure 6: Desired velocity with SDC, MDC and SDMDC

Table 1: CoR with SDC, MDC and SDMDC

	Without compensation	SDC	MDC	SDMDC	Ideal case
CoR	1.1611	1.1057	1.0508	0.9999	1.0000

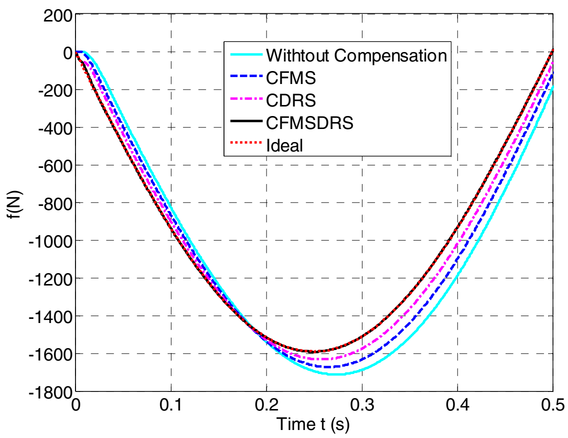

Figure 7: Compensated force with SDC, MDC and SDMDC

Then, various simulations with different sensor delay (1ms, 3ms and 5ms), different frequency response (100Hz, 50Hz and 25Hz) of the motion table, different contact frequency (1Hz, 3Hz and 5Hz), different contact stiffness (100N/mm, 300N/mm and 500N/mm), and different initial velocity (100mm/s, 300mm/s and 500mm/s) are performed to further verify the performance of the SDMDC. From the CoR as shown in Table 2, it can be seen that satisfactory hybrid simulation performances are obtained with these parameters. It means that the SDMDC approach works well for different parameters.

Table 2: CoR with SDMDC at different time delay, response frequency, contact frequency, contact stiffness, and initial velocity

Time Delay (ms)	Resp Freq (Hz)	Contact Freq (Hz)	Contact Stiffness (N/mm)	Initial Velocity (mm/s)	CoR with SDMDC
1	25	1	100	100	1
3	25	1	100	100	1
5	25	1	100	100	0.9999
5	100	1	100	100	1
5	50	1	100	100	1
5	25	1	100	100	0.9999
5	25	1	100	100	0.9999
5	25	3	100	100	0.9999
5	25	5	100	100	0.9999
5	25	1	100	100	0.9999
5	25	1	300	100	0.9999
5	25	1	500	100	0.9999
5	25	1	100	100	0.9999
5	25	1	100	300	0.9999
5	25	1	100	500	0.9999

B. *Experimental Studies*

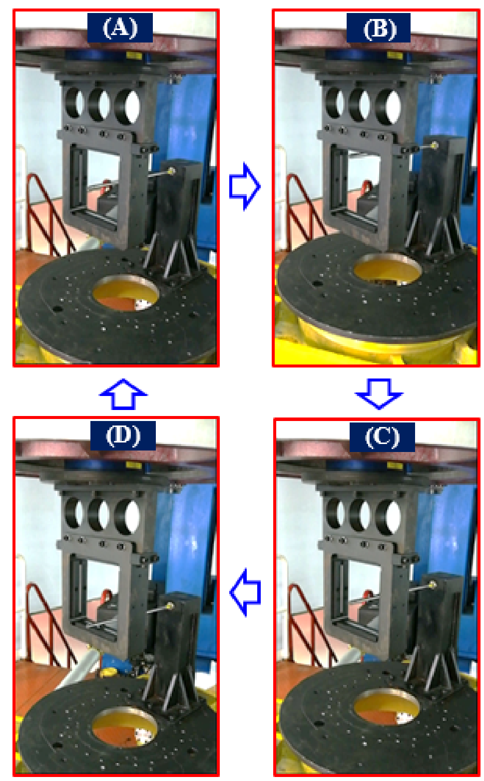

Figure 8: Contact experiments

The experiments on the developed hybrid table in Figure 1 are used to verify the divergence compensation performance. The sensor delay is about 3ms, which mainly comes from the signal processing. Figure 8 shows some pictures in the experiments.

Figure 9 shows the simulated velocity with the SDC, MDC and SDMDC. The CoR is shown in Table 3. The hybrid simulation is divergent much significantly without the force compensation. There is only a little convergence with the

SDMDC, which is much better than the SDC or MDC. In fact, a little convergence is expected to guarantee the stability margin and the accuracy.

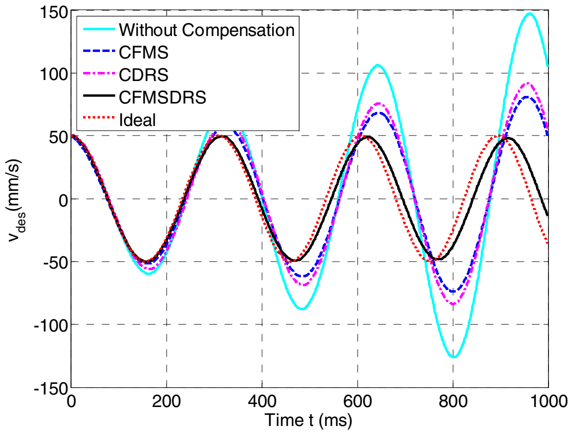

Figure 9: Simulated velocity with SDC, MDC and SDMDC

Table 3: CoR with SDC, MDC and SDMDC

	Without compensation	SDC	MDC	SDMDC	Ideal case
CoR	1.1887	1.0831	1.1	0.9801	1

Figure 10 shows the desired and actual position, desired velocity, measured force, the force f_{CFMS} that compensated with the SDC and the force $f_{CFMSDRS}$ that compensated with the SDMDC. Since the compensated force has a shift to the left side, the time delay between the compensated force and the desired position is reduced. Compared with the SDC, the time delay with the SDMDC is smaller. This is the reason why the better simulation performance is achieved with the SDMDC.

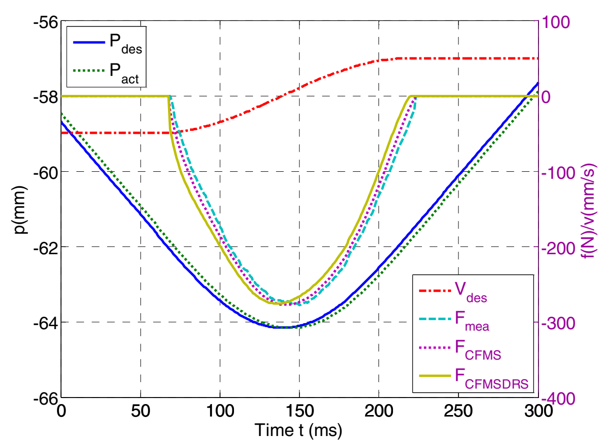

Figure 10: Desired position, actual position, desired velocity, measured force and compensated force with SDMDC

Then, various simulations with different contact frequency, different contact stiffness, and different initial velocity are performed to further verify the performance of the SDMDC. From Table 4, it can be seen that the CoR has a little variation for different cases. Compared with the ideal CoR value, the obtained CoR error is less 5%, which is satisfactory for engineering applications.

Table 4: CoR with SDMDC at different contact frequency, contact stiffness, and initial velocity

Contact Freq (Hz)	Contact Stiffness (N/mm)	Initial Velocity (mm/s)	CoR with SDMDC	CoR idea value
2	48.68	50	0.99	1
2	75.75	50	0.98	1
3	103.57	50	0.98	1
3	264.68	80	0.97	1
4	264.68	100	0.98	1
4	301.50	100	0.97	1
5	301.50	120	0.99	1
5	384.51	120	0.97	1

Note that the design of the hybrid table depends on the contact natural frequency range required in the real spacecraft docking task. If the contact natural frequency range is tight and much smaller than the bandwidth of the motion table, the phase delay in that range can be approximated as a pure time delay with a fairly well accuracy. Then the phase lead compensation for the motion delay of the motion table can be used. If the contact natural frequency range is wide and only smaller a little than the bandwidth of the motion table, the compensation approach in this study will be helpful to achieve a satisfactory simulation accuracy.

IV. CONCLUSIONS

The hybrid motion table can simulate the six-degree-of-freedom motion of the spacecraft and regenerate the force between contact devices. The time delay existing in the system loops is the main factor of the hybrid simulation error. A time delay compensation is introduced to compensate the sensor delay and motion delay. The effects of table parameters (e.g., dynamic response frequency and sensor delay) and contact parameters (e.g., contact natural frequency, contact stiffness and initial velocity) on the hybrid simulation results are investigated by using simulations and the hybrid simulation experiments. They indicate that the simulation instability can be compensated effectively by using the approach under different table parameters and contact parameters.

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