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Contact stiffness and damping identification for hardware-in-the-loop contact simulator with measurement delay compensation

Chenkun Qi [a], Xianchao Zhao [a], Feng Gao [a,*], Anye Ren [b], Qiao Sun [a]

[a] State Key Laboratory of Mechanical System and Vibration, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Institute of Aerospace System Engineering Shanghai, Shanghai 201108, China

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ABSTRACT

The hardware-in-the-loop (HIL) contact simulator is to simulate the contact process of two flying objects in space. The contact stiffness and damping are important parameters used for the process monitoring, compliant contact control and force compensation control. In this study, a contact stiffness and damping identification approach is proposed for the HIL contact simulation with the force measurement delay. The actual relative position of two flying objects can be accurately measured. However, the force measurement delay needs to be compensated because it will lead to incorrect stiffness and damping identification. Here, the phase lead compensation is used to reconstruct the actual contact force from the delayed force measurement. From the force and position data, the contact stiffness and damping are identified in real time using the recursive least squares (RLS) method. The simulations and experiments are used to verify that the proposed stiffness and damping identification approach is effective.

1. Introduction

The simulation of contact dynamics in space is important for the space on-orbit servicing missions, e.g., capturing, docking, berthing, repairing, upgrading and transporting. The active spacecraft carrying the docking system docks with the target spacecraft for subsequent servicing. Due to the high cost and high risk, the docking system must pass the verification on the ground before it is launched [1,2]. The main challenge of the contact simulation on the ground is that the simulator in the one gravity (1-g) environment should reproduce the real contact dynamics of the docking hardware in the zero-gravity (0-g) environment [1,2].

There are three classes of contact simulation approaches, i.e., the full numerical simulation, the full physical simulation and the hardware-in-the-loop (HIL) simulation (also called hybrid simulation). The full numerical simulation uses the software to simulate the contact dynamics as well as the motion of the spacecrafts in the 0-g environment [3–6]. In general, the motion model of the spacecrafts is accurate enough, however the accurate contact model is difficult to obtain due to the unknown and time-varying parameters of the contact process. The full physical simulation tests the contact dynamics of real docking system and the motion of the spacecraft models by using the zero-gravity emulation techniques, e.g., the air-bearing supported floating [7–10], suspension system [11,12] and so on. However, it is very difficult to obtain the six degree-of-freedom (6-DOF) weightless and frictionless motion environment. For the suspension system, it is difficult to preserve the zero-gravity dynamics of the spacecraft when the suspension cables are not perfectly vertical during the test. For the air-bearing supported floating facility, it is inconvenient to change the spacecrafts model or inertial parameters. Moreover, it is difficult and expensive to simulate the spacecrafts with too large mass due to the limited space and payload capability of the supported facility. For the HIL simulation, the numerical simulation software is used to compute the motion of the spacecraft in the zero-gravity environment; the robotic motion simulator is used to reproduce the motion of the spacecraft; the real docking system is installed on the motion simulator to generate the real contact process. Because the HIL simulation integrates the flexibility of the numerical simulation and the fidelity of the physical simulation, it is attractive and effective to verify the complicated contact dynamics in space.

There are some HIL simulators developed to simulate the contact dynamics in space. The serial robots are widely used, e.g., the European Proximity Operations Simulator (EPOS) in the German Aerospace Center [13–15], the Special Purpose Dextrous Manipulator (SPDM) Task Verification Facility (STVF) in the Canadian Space Agency [16–19]. The Shenzhen Space Technology Center [20] and Japan Aerospace Exploration Agency [21] also established the HIL contact simulator using the serial robots. The Stewart parallel robots are also used in the HIL docking simulator,

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* Corresponding author.
E-mail addresses: chenkqi@sjtu.edu.cn (C. Qi), xczhao@sjtu.edu.cn (X. Zhao), fengg@sjtu.edu.cn (F. Gao), ray805s@163.com (A. Ren), semicircle@sjtu.edu.cn (Q. Sun).

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e.g., the six-degree-of-freedom test system (SDTS) in the NASA Johnson Space Center [22], the rendezvous and docking operation testing system (RDOTS) in the Japanese space agency [23]. The McDonnell Douglas Aerospace [24], the NASA Marshall Space Flight Center [25], Harbin Institute of Technology [26], Tohoku University [27–29] also developed the HIL contact simulator using the parallel robots. In fact, the HIL simulation techniques are also very useful in other fields [30–32]. In this study, the parallel robots will be used as the motion simulators because their high stiffness, high precision and high payload are beneficial to simulate the contact dynamics.

For the HIL contact simulator, there is a time delay in the force measurement system. It is known that the time delay results in the simulation divergence. It means that the coefficient of restitution (CoR) (i.e., the ratio of the approach velocity before the contact and the rebound velocity after the contact) will larger or smaller than one. To guarantee the simulation accuracy, the delay compensation is very important for the HIL simulation.

There are several delay compensation approaches for the HIL contact simulator. When the time delay is known and time-invariant, the phase lead model-based force compensation [28,33] is effective to obtain the approximately ideal contact force. The virtual contact model-based force compensation [15,28,29,34] is one method to achieve the expected contact behavior (e.g., contact stiffness or CoR), where the compensated force is obtained by adding the virtual force onto the measured force. When the delay model is known and time-invariant, the model-based feed-forward position compensation [24,26] can be used to compensate the command position in advance, which makes the actual position of the motion simulator approximately equal to the desired position computed by the numerical model.

In this study, the focus is on the contact stiffness and damping identification because it is required for the process monitoring and the compliant contact control. However, due to the time delay of the force measurement system, the contact stiffness and damping identification will be incorrect. Therefore, before the contact stiffness and damping identification, the force measurement delay is compensated by the phase lead. Then, the reconstructed contact force and the measured contact relative position are used to identify the contact stiffness and damping using the recursive least squares method. Simulations and experiments show that the proposed stiffness and damping identification approach can effectively identify the contact stiffness and damping of the HIL contact process.

The rest of this study is organized as follows. The HIL contact simulation system is described in Section 2. The HIL contact simulation modeling is presented in Section 3. The contact stiffness and damping identification is discussed in Section 4. Section 5 reports simulations and experiments. Finally, the conclusions are presented in Section 6.

2. HIL contact simulation system

In the following, the HIL simulation principle and system are introduced.

2.1. HIL simulation principle

In the space 0-g environment, the active spacecraft carrying the active docking mechanism approaches the passive docking mechanism on the target spacecraft. The active and passive docking mechanisms on the spacecrafts are the contact hardwares that refer to the physical model in this study. When two spacecrafts dock through the docking mechanisms, the contact force will be produced. The contact force will change the motion of two spacecrafts according to the dynamics law. Then the new contact force will be produced and two spacecrafts will move to the new position. This dynamic process will continue until the completion of the space task. The docking system in space is shown in Fig. 1.

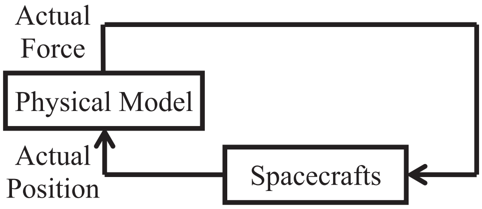

Fig. 1. Docking system in space.

On the ground, the physical model is installed on a motion simulator. The motion simulator is used to implement the relative motion of two spacecrafts. The force sensor is used to measure the actual contact force. By utilizing the measured contact force as the input, the numerical model (i.e., the motion dynamics model of the spacecrafts) is used to calculate the relative position of two spacecrafts (i.e., the desired position of the motion simulator). The motion simulator is controlled to track the desired position. The physical model will produce the actual contact force corresponding to the actual position of the motion simulator. The HIL simulation principle is shown in Fig. 2.

2.2. HIL simulation system

According to the HIL simulation principle, a HIL simulation system is established. Fig. 3 shows the HIL simulation system structure and Fig. 4 is the developed HIL contact simulator. The system consists of a fixed platform, a force sensor, active and passive docking mechanisms (i.e., physical model), a motion simulator and a numerical model. The force sensor is installed between the fixed platform and the passive docking mechanism. The active docking mechanism is installed on the motion simulator. The motion simulator is driven by a servo control system to implement the relative motion of two spacecrafts. The force sensor is used to measure the contact force between the active and passive docking mechanisms. The force acquisition, numerical model computation and motion control are all performed in real-time computers.

The motion simulator is designed by using the novel 3-3 PSS perpendicular parallel mechanism [35]. This novel parallel mechanism guarantees the lower inertia, high stiffness and high precision performances of the motion simulator. The integration of the parallel mechanisms, the differential dual actuators [36] and real-time control systems can realize the high frequency response, high velocity and acceleration of the motion simulator. The upper platform is designed by using the 3-PRS parallel mechanism. In the simulation of the docking process, the upper platform is fixed at a certain position, while in the simulation of the rendezvous process, the upper platform is movable.

The force sensor is based on the piezoelectric quartz measurement technology. The charge produced is proportional to the force acting on the quartz crystal contained in the sensor. A charge amplifier is used to convert the charge into the voltage. The

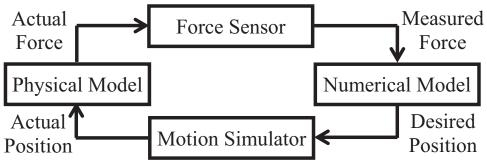

Fig. 2. HIL simulation principle.