Journal of Sound and Vibration 432 (2018) 530–548

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Research on a six-degree-of-freedom disturbance force and moment simulator for space micro-vibration experiments

Xiaoming Wang [a,b], Zhenbang Xu [a,*], Mingyi Xia [a,b], Shuai He [a], Hang Li [a], Qingwen Wu [a]

[a] Innovation Lab of Space Robot System, Space Robotics Engineering Center, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 21 November 2017
Revised 21 June 2018
Accepted 24 June 2018
Available online XXX
Handling Editor: H. Ouyang

Keywords:
Reaction wheel assembly
Disturbance force
Disturbance moment
Iterative control
Simulator

ABSTRACT

A six-degree-of-freedom disturbance force and moment simulator that reproduces the disturbance forces and moments that are generated by a reaction wheel assembly is presented. The simulator has considerable application potential in ground-based micro-vibration experiments. The detailed structure of the proposed simulator is first introduced and the simulator model is then established. Using this model, the dynamic relationships between the actuator forces and the disturbance forces and moments can be derived. Because of parameter uncertainties, a closed-loop iterative control method based on a dynamic model is developed, and the effectiveness of this control strategy is demonstrated through integrated simulations. Finally, the disturbance forces and moments reproduced by the simulator are tested using a six-component test platform, and the experimental results show that the maximum relative error between the measured value and the target value is 3.33%, thus demonstrating that the simulator can reproduce the disturbance forces and moments well.

1. Introduction

Micro-vibration [1] is produced by devices such as the reaction wheel assembly [2], the control moment gyroscope [3], and cryogenic coolers that have been mounted on spacecraft in orbit. Micro-vibrations have characteristics that include wide frequency bands, low amplitudes and complex forms. In high-sensitivity precision devices such as space-based optical payloads, micro-vibrations can affect imaging quality. One of the most common solutions used to attenuate the amplitude of micro-vibrations is vibration isolation [4,5].

Previous researchers [6–8] designed a vibration isolation platform based on a Gough-Stewart platform to attenuate disturbances. Ground experiments must be carried out to test the validity of such a vibration isolation system. For these ground experiments, vibration source equipment is an essential requirement [9–11]. For some of the more common vibration-causing devices, such as the reaction wheel assembly and the control moment gyroscope, it is difficult to use real products in the ground experiments because of considerations including scheduling issues, product assurance activities and safety [12,13]. Among these vibration sources, the effects of micro-vibrations produced by the reaction wheel assembly are generally regarded as being the largest [14]. Consequently, the reaction wheel assembly is generally selected as the vibration device for use in ground experi-

* Corresponding author.
E-mail addresses: wangxm9301@163.com (X. Wang), xuzhenbang@gmail.com (Z. Xu), xiamingyi0619@126.com (M. Xia), 652740868@qq.com (S. He), cicelihang@126.com (H. Li), wuqw@ciomp.ac.cn (Q. Wu).

https://doi.org/10.1016/j.jsv.2018.06.056
0022-460X/

ments. In addition, the disturbance characteristics of real reaction wheel assemblies are regular and cannot be adjusted during an experiment. If a real reaction wheel assembly is used in the ground experiments, the performance of the vibration isolation system will not be tested adequately.

There is thus an urgent need to develop a simulator that can reproduce the disturbance forces and moments that can be generated by a reaction wheel assembly. Some previous researchers set out to develop disturbance simulations. Liu et al. [15] used a single-axis inertial actuator to simulate the disturbance force in a disturbance simulation. Park et al. [13] developed a simulator that used three perpendicular and orthogonal inertial actuators to produce the required disturbance forces in three vertical directions. These studies simulated disturbance forces. However, the simulations involved had fewer than six degrees of freedom, which is an insufficient number for accurate simulation of the micro-vibration disturbance forces. In accordance with the requirements of the ground experiments, the simulator must be able to simulate multidimensional disturbance forces and moments. Therefore, there are problems that must be solved to develop a suitable six-degree-of-freedom (6-DOF) disturbance force and moment simulator (6-DDFMS).

The Gough-Stewart platform has characteristics including high rigidity, a stable structure and good dynamic performance. In particular, the Gough-Stewart platform can provide 6-DOF movement. The Gough-Stewart platform is widely used in the micro-vibration field. Hostens et al. [16] designed a 6-DOF vibration platform for vibration testing of mobile machinery. The University of Pennsylvania [17,18] developed two generations of a micro-vibration simulator that produced a micro-vibration velocity field. Previous researchers have studied various techniques to generate multidimensional vibrations in upper platforms. However, few researchers have used the Gough-Stewart platform to act as a disturbance simulator that can produce the required disturbance forces and moments to act on the mounting surface.

Modeling and control are the main topics of research on the Gough-Stewart platform. Guo [19] and Wang et al. [20] established a complete dynamic model of a 6-DOF parallel platform and derived the relationship between the accelerations of the upper platform and the actuator forces of its legs. Zhang et al. [6] developed dynamic models of a vibration isolation platform that included both perfect joints and joints with clearances, and obtained the relationship between the accelerations and the collision forces. Zhang et al. [7] established a complete satellite dynamic model and obtained the relationship between the accelerations of the upper platform and the disturbance forces and moments that were generated by control moment gyroscopes. In a disturbance force and moment simulator, the most important aspect of the modeling process is to obtain the relationship between the actuator forces of the driving legs and the disturbance forces and moments that are generated by the simulator. The establishment of this relationship is necessary for development of the control strategy for the disturbance simulator, and its development has not previously been described in the literature.

Previous researchers have studied the control strategy required for the parallel platform. Yang et al. [21] proposed a robust proportional-integral controller based on an inverse dynamics model of a micro-vibration simulator. Yan et al. [22] studied an open-closed-loop P-type iterative learning control scheme that was used in trajectory tracking control of mobile robots. Hou et al. [23] designed a control scheme that combines a nonsingular terminal sliding mode control scheme with iterative learning control. Their scheme demonstrated good tracking performance and robustness. Previous researchers also developed control strategies based on theoretical models; however, a control strategy based on the relationships between the disturbance forces and moments and the actuator forces has not been developed to date.

In accordance with the requirements for reproduction of disturbance forces and moments, a 6-DDFMS based on the Gough-Stewart platform is designed and manufactured in this work. The 6-DDFMS described in this paper is used to reproduce the disturbance forces and moments generated by a reaction wheel assembly, and the simulator is applied in ground experiments as a vibration source device. This novel platform is capable of reproducing disturbance forces and moments in six dimensions. In combination with the Newton-Euler method and the Lagrange equation, a theoretical model that considers the inertial masses of the legs and hinges of a parallel platform is established. The complete dynamic equation is derived and the disturbance forces and moments of the mounting surface are then calculated using the developed model. Because some of the model parameters, e.g., the mass and stiffness, cannot be measured accurately, a type of closed-loop iterative control method is proposed to control the disturbance forces and moments that are produced on the mounting surface. The performance of the developed 6-DDFMS is then tested experimentally.

The paper is organized as follows. Section 2 of the paper introduces the 6-DDFMS structure. Section 3 derives the relationships between the actuator forces and the desired disturbance forces and moments. Section 4 proposes a closed-loop iterative control method for the disturbance forces and moments, and validates this control method through simulations. Section 5 presents experimental measurements of the six-dimensional forces and moments that are produced by the 6-DDFMS on a mounting surface. Section 6 draws conclusions about the performance of the 6-DDFMS.

2. Structure of the 6-DDFMS

Figs. 1 and 2 show a model and a physical map of the developed 6-DDFMS, respectively. The 6-DDFMS consists of an upper platform, a lower platform and six driving legs that are connected to the upper platform and the lower platform via gimbals.

The structure of a driving leg is shown in detail in Fig. 3. Within the leg structure, a voice coil motor provides the power to drive the leg. The motor sleeve is a mounting base for a voice coil motor stator (permanent magnet), and this sleeve protects the motor. The leaf spring supports both the voice coil motor mover (coils) and the upper structure of the driving leg. The limiting plate is used to prevent the axial displacement of the driving leg from exceeding its designed index (2 mm) and thus prevents damage to the structure.