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Dynamic characteristics and performance evaluation for the part strut failure of the vibration isolation platform on satellites

Yao Zhang[a,*,1], Chao Sheng[a,2], Zixi Guo[a,3], Youyi Wang[b,4], Wenbo Li[b,5]

[a] Beijing Institute of Technology, Beijing, PR China
[b] Beijing Institute of Control Engineering, Beijing, PR China

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ABSTRACT

The dynamic characteristics and performance evaluation for the part strut failure of the vibration isolation platform are presented in this paper. The first step provides and mathematically describes two types of strut failure: fractured and stuck. Secondly, the dynamic model of the vibration isolation platform, which considers the part strut failure, is established using the Newton-Euler method and a constraint equation to evaluate its dynamic characteristics and performance. Then, with reasonable assumptions, the dynamic model of the satellite, which has a vibration isolation platform and vibration sources (such as control moment gyros) of three working situations (without and with two types of strut failure), is simplified to analyse the frequency domain characteristic and coupling characteristic with the attitude control system. Finally, a numerical simulation is used to study the effect of the vibration isolation platform with part strut failure on the attitude control and stabilization, and the attitude control performance is evaluated.

1. Introduction

Stewart platform is common used as a type of vibration isolation device to isolate the micro vibration on satellite [1–3]. Zhang et al. [4,5] studied the effect of flexible solar arrays on the vibration isolation platform (VIP). Zhou et al. [6] studied the VIP for momentum wheel assemblies. Some optical satellites such as Worldview [7] and Pleiades-HR [8] have used the VIP.

However, the hostile working environment of spacecraft, such as vacuum with rapid change of temperature and particle flow [9,10] and the micro vibration caused by the operator may cause part strut failure of the VIP, which breaks the symmetry of the VIP, even affects the attitude control mission. This paper mainly discusses two types of strut failure: fractured failure, which indicates that the strut cannot provide any force because of fracturing or other situation; stuck failure, which indicates that the length of the strut is fixed because of a stuck actuator or other situation.

Studies about part strut failure of the VIP are rare. Only Liu et al. [11] and Huang et al. [12] designed a type of octostrut platform for the launch stage whole-spacecraft vibration isolation to add redundancy in case of part strut failure. Sullivan et al. [13] mentioned that the part strut failure may make the active control fail. Mcinroy et al. [14] studied a reconfiguration algorithm for failed struts. Nevertheless, there are few studies about the direct dynamic performance evaluation for part strut failure of the VIP.

Therefore, this paper intends to study the dynamic characteristics and performance of part strut failure of the VIP for control moment gyros (CMGs). The function of the VIP includes passing the control torque that the actuator produces and isolates the disturbance torque between the attitude control system and the satellite bus. The attitude control system usually uses the CMGs [15–18] or the flying wheels [19,20] as the actuator. The disturbance torque results from the static and dynamic rotor imbalances and installation errors of the actuator [21,22]. When the part strut fails in the VIP, those functions may be affected. It is possible that both the attitude control performs worse and the satellite attitude loses stabilization.

To study the effect of part strut failure in the VIP on the attitude control system, the platform must be modelled, and the two types of

* Corresponding author.
E-mail addresses: zhangyao@bit.edu.cn (Y. Zhang), 892263575@qq.com (C. Sheng), guokejie2201@126.com (Z. Guo), wangyouyi502@126.com (Y. Wang), liwenbo_502@163.com (W. Li).
[1] Associate Professor, School of Aerospace Engineering.
[2] Master student, School of Aerospace Engineering.
[3] Doctor student, School of Aerospace Engineering.
[4] Associate Professor, National Laboratory of Space Intelligent Control.
[5] Associate Professor, National Laboratory of Space Intelligent Control.

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strut failure require mathematical expressions. Some studies that model the Stewart platform with actuators can be referenced. For example, Zhang et al. [23] studied the parameter design of a VIP for CMGs. Kamesh et al. [24] designed a low-frequency platform to attenuate micro vibration in spacecraft using reaction wheels. Pendergast and Schauwecker [25] designed a jitter isolation system using a passive reaction wheel to satisfy the imaging performance requirements of the advanced X-ray astrophysics facility.

In the analysis of the dynamic characteristics of the strut stuck failure in the VIP, the dynamics can be considered a type of typical constraint. Thus, the dynamic modelling and analysis can follow the method in modelling with a constraint, which is often a constraint equation with the Lagrange multiplier. Some studies apply a constraint equation to construct a dynamic model. Such as, Estupiñan et al. [26] used constraint equations to construct the model of a reciprocating linear compressor. Qi et al. [27] used constraint equations to model and solve multi-body systems. Choquetbruhat et al. [28] studied the constraint equations for the Einstein-scalar field system on compact manifolds. Estupiñan and Santos [29] studied the modelling of a reciprocating linear compressor using constraint equations. In addition, to prevent the dynamic model with constraints from divergence during the integrals, a method to stabilize the constraint [30] is used in numerical simulations.

This paper discusses the dynamic characteristics and performance evaluation for the part strut failure of the VIP on satellites. Firstly the dynamic models of the entire VIP, which considers CMGs and part strut failure, are established. Then the frequency domain of the VIP and its effect on the attitude control system are analysed based on the simplified models. Finally, with the full models, the attitude angle and attitude angle velocity of the satellite and the disturbance to the satellite are simulated to show effect of the attitude control performance caused by the part strut failure of the VIP.

2. Dynamic model of the entire VIP system

2.1. Reference frames for the VIP system

Some coordinate frames in Fig. 1 are defined as follows:

(1) Inertial frame $f_e(O_eX_eY_eZ_e)$: fixed in the inertial space.
(2) Body frame of the up platform $f_u(O_uX_uY_uZ_u)$: fixed to the up platform of the VIP; O_u is the mass centre of the up platform.
(3) Body frame of the down platform $f_d(O_dX_dY_dZ_d)$: fixed to the down platform of the VIP; O_d is the mass centre of the down platform.
(4) Body frame of the ith strut: $f_{S_i}(O_{S_i}X_{S_i}Y_{S_i}Z_{S_i})$: fixed to the ith strut. O_{S_i} is the connection point between the strut and the up platform. X_{S_i} points outward along the strut. Y_{S_i} satisfies the right-hand rule between X_{S_i} and the install vector of the universal joints. Z_{S_i} is defined by the right-hand rule between X_{S_i} and Y_{S_i}.

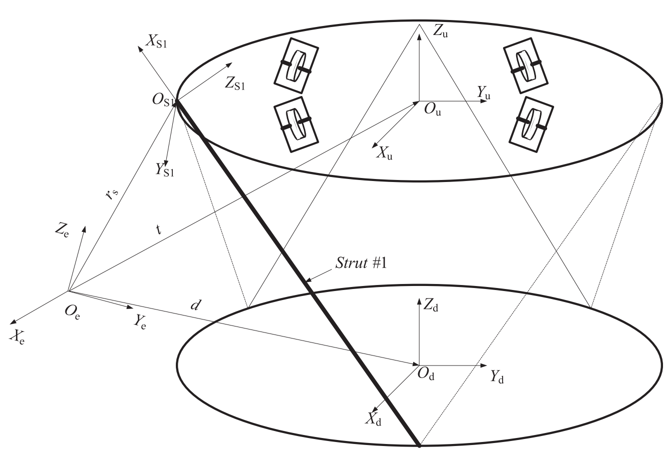

Fig. 1. Reference frames for the VIP system.

A_{mn} represents the transformation matrix from f_n to f_m, which can be any frame.

The dynamic model of the VIP system with CMGs is established using the Newton-Euler method and the constraint equation. The model includes the dynamic equation of the up platform and the down platform, which are connected by the dynamic and kinematic equations of the struts. There is a detailed derivation in the reference [23], so this article does not provide the process; it only shows the result and explains the variables that are used.

2.2. Dynamic model of the VIP without strut failure

As shown in the reference [23], the dynamic model of the VIP is as follows:

$$\begin{cases} \tilde{m}_p \boldsymbol{A}_{ue}\ddot{\boldsymbol{t}} = -\boldsymbol{A}_{ue}\sum_{i=1}^{6}\boldsymbol{F}_{si} + \boldsymbol{F}_{ext} \\ \tilde{\boldsymbol{I}}_p\dot{\boldsymbol{\omega}}_p + \boldsymbol{\omega}_p^{\times}\tilde{\boldsymbol{I}}_p\boldsymbol{\omega}_p = \boldsymbol{T}_{ext} - \sum_{i=1}^{6}\boldsymbol{p}_i^{\times}\boldsymbol{A}_{ue}\boldsymbol{F}_{si} + \sum_{i=1}^{6}\boldsymbol{f}_{pi} \end{cases}$$
$$\begin{cases} m_q\boldsymbol{A}_{de}\ddot{\boldsymbol{d}} = -\boldsymbol{A}_{de}\sum_{i=1}^{6}\boldsymbol{F}_{ui} \\ \boldsymbol{I}_q\dot{\boldsymbol{\omega}}_q + \boldsymbol{\omega}_q^{\times}\boldsymbol{I}_q\boldsymbol{\omega}_q = -\sum_{i=1}^{6}\boldsymbol{p}_i^{\times}\boldsymbol{A}_{de}\boldsymbol{F}_{ui} + \sum_{i=1}^{6}\boldsymbol{f}_{qi} \end{cases}$$
$$\boldsymbol{f}_{pi} = c_{si}(\boldsymbol{A}_{ue}\boldsymbol{\omega}_{li} - \boldsymbol{\omega}_p)$$
$$\boldsymbol{f}_{qi} = c_{ui}(\boldsymbol{A}_{de}\boldsymbol{\omega}_{li} - \boldsymbol{\omega}_q) \quad (1)$$

where $\tilde{m}_p$ and m_q are the masses of the up platform system (including the up platform and the CMGs) and down platform, respectively; $\boldsymbol{t}$ and $\boldsymbol{d}$ are the position vectors of the centres of the up and down platforms, which are expressed in f_e; $\boldsymbol{\omega}_p$ and $\boldsymbol{\omega}_q$ are the attitude angle velocities of the up and down platforms; $\tilde{\boldsymbol{I}}_p$ and $\boldsymbol{I}_q$ are the moments of inertia of the up platform system and down platform; $\boldsymbol{p}_i$ and $\boldsymbol{q}_i$ are the position vectors from the mass centres of the up and down platforms, respectively, to their connection points with the ith strut; c_{si} and c_{ui} are the coefficient of viscous friction in the spherical and universal joints; $\boldsymbol{f}_{pi}$ and $\boldsymbol{f}_{qi}$ are the friction torques of the ith strut to the up platform down platforms; $\boldsymbol{F}_{si}$ is the force of the ith strut; $\boldsymbol{\omega}_{li}$ is the attitude angle velocity of the ith strut; $\boldsymbol{F}_{ext}$ and $\boldsymbol{T}_{ext}$ are the external force and torque on the up platform.

2.3. Dynamic model of the VIP with fractured failing struts

The fractured failing struts cannot provide any force, so the forces of these failing struts are zeroes. The model of the VIP with the fractured failing struts is

$$\begin{cases} \tilde{m}_p \boldsymbol{A}_{ue}\ddot{\boldsymbol{t}} = -\boldsymbol{A}_{ue}\sum_{i=1}^{n}\boldsymbol{F}_{si} + \boldsymbol{F}_{ext} \\ \tilde{\boldsymbol{I}}_p\dot{\boldsymbol{\omega}}_p + \boldsymbol{\omega}_p^{\times}\tilde{\boldsymbol{I}}_p\boldsymbol{\omega}_p = \boldsymbol{T}_{ext} - \sum_{i=1}^{n}\boldsymbol{p}_i^{\times}\boldsymbol{A}_{ue}\boldsymbol{F}_{si} + \sum_{i=1}^{n}\boldsymbol{f}_{pi} \end{cases}$$
$$\begin{cases} m_q\boldsymbol{A}_{de}\ddot{\boldsymbol{d}} = -\boldsymbol{A}_{de}\sum_{i=1}^{n}\boldsymbol{F}_{ui} \\ \boldsymbol{I}_q\dot{\boldsymbol{\omega}}_q + \boldsymbol{\omega}_q^{\times}\boldsymbol{I}_q\boldsymbol{\omega}_q = -\sum_{i=1}^{n}\boldsymbol{p}_i^{\times}\boldsymbol{A}_{de}\boldsymbol{F}_{ui} + \sum_{i=1}^{n}\boldsymbol{f}_{qi} \end{cases}$$
$$\boldsymbol{f}_{pi} = c_{si}(\boldsymbol{A}_{ue}\boldsymbol{\omega}_{li} - \boldsymbol{\omega}_p)$$
$$\boldsymbol{f}_{qi} = c_{ui}(\boldsymbol{A}_{de}\boldsymbol{\omega}_{li} - \boldsymbol{\omega}_q) \quad (2)$$

n is the number of struts without failure, which is less than six. $\sum_{i=1}^{n}X_i$ is the sum of the character X_i of each valid strut. In other words, the characters of struts with fractured failure do not appear in the dynamic model.

2.4. Dynamic model of the VIP with stuck failing struts

The dynamic model of the VIP with stuck failing struts is derived using the Newton-Euler method and the constrain equation. To establish the model, two parts will be discussed: the down platform and the up platform with the stuck failing strut. The terminal point of