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Multi-objective optimization of zero propellant maneuver using hybrid programming

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ABSTRACT

Zero-propellant maneuver is an advanced concept of attitude control. The multi-objective optimization of zero-propellant maneuver using single gimbal control momentum gyroscopes is investigated in this paper. First, the multi-objective optimization model of zero-propellant maneuver is established. Then, a hybrid approach combining pseudospectral method and physical programming is proposed. Finally, the effectiveness of this proposed hybrid method has been validated. It is shown that, using the hybrid programming method, the indexes of the trade-off solution are all desirable. Moreover, the pareto-solution set can be obtained when changing the structure of the preference functions of physical programming, which is examined by 90° and 180° attitude maneuver mission examples. This hybrid programming method provides an effective approach for multi-objective optimal large angle attitude maneuver mission to meet different engineering requirement.

1. Introduction

Zero-propellant maneuver (ZPM) is an advanced concept of space station attitude control using only control moment gyroscopes (CMGs) [1]. On November 5, 2006, the ZPM was first demonstrated on the International Space Station (ISS), when the ISS rotated 90° without consuming any propellant in 7200 s [2]. On March 3, 2007, a ZPM of 180° rotation was achieved [3], saving 50.76 kg propellant at an estimated cost of US$1,100,000 [4]. The environmental torque is exploited to enable large angle maneuver mission to be accomplished, while simultaneously maintaining the CMGs within their operational capability. Mount of propellant can be saved and gas contamination to the solar panel and the exposed device could be avoided, moreover, it can be a backup for the reaction thrusters. This technology will enhance orbiting lifetime of space station, and improve the maneuver security and reliability effectively.

Although ZPM technology has been demonstrated on ISS, most studies concentrate on the single-objective optimization. The energy that the large angle attitude maneuver consumed is treated as the cost function in [1,2]. To test and verify the capacity of double-gimbal CMGs (DGCMGs), the peak magnitude of momentum of DGCMGs is used as the cost function [5]. Moreover, in [6], the cost function is selected as the single momentum of single-gimbal CMGs (SGCMGs) in the process of designing the control system of China's space station. Additionally, the consumed time is another factor of the large angle attitude maneuver mission, and the time-optimal problem of attitude maneuver is also researched [7,8]. However, in engineering practice, several indexes are expected to be optimal during the large angle attitude maneuver mission simultaneously. Thus, the multi-objective optimization of ZPM should be researched. For the multi-objective optimization of ZPM, Zhang [9] introduces sensitivity analysis theory to obtain the relation between the time, momentum and energy. However, the analysis results are only qualitative. Therefore, to obtain the accurate relation between the cost functions, a suitable numerical

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method should be adopted to solve this multi-objective optimization problem.

In this paper, a hybrid programming method is applied to analyze the relation between the objective functions. The persedospectrl method [10–12] is proven to be an effective approach to deal with the optimal control problem, and it is also applied to the ZPM single-objective problem. The physical programming method [13–15] converts a multi-objective problem into a single-objective problem by using preference functions that capture the designer's preferences, and it is widely used in structure design, trajectories optimization and system design. The main goal of this study is to obtain the tradeoff solution and examine the trade relationship between the indexes. A three-objective optimization is established based on the attitude maneuver model. To obtain the tradeoff solution and Pareto-solution set, we introduce a hybrid programming method to solve the multi-objective optimization design problem. The effectiveness of the proposed method is verified by numerical examples.

2. Multi-objective optimization model

2.1. Equations of motion

Consider a rigid-body of the spacecraft with a CMG cluster. It is convenient to define three coordinate system: the inertial frame $\{\mathbf{i}\}$, the orbital frame $\{\mathbf{o}\}$, and the spacecraft principal axis frame $\{\mathbf{p}\}$. The orientation of the $\{\mathbf{o}\}$ frame can be obtained by knowing the orbital elements. The orientation of $\{\mathbf{p}\}$ with respect to $\{\mathbf{o}\}$ is represented by modified rodrigues parameters (MRP).

The kinematic equation of spacecraft defined by Modified rodrigues parameter (MRP) [16], which described the attitude with respect to the orbit frame, is given by

$$\dot{\boldsymbol{\sigma}} = \mathbf{G}(\boldsymbol{\sigma})(\boldsymbol{\omega} - \boldsymbol{\omega}_o(\boldsymbol{\sigma})) \tag{1}$$

where $\boldsymbol{\omega}$ is the angular rate of space station, $\boldsymbol{\omega}_0(\boldsymbol{\sigma})$ is the orbit angular rate. $\mathbf{G}(\boldsymbol{\sigma})$ is defined as

$$\mathbf{G}(\boldsymbol{\sigma}) = \frac{1}{2}\left(\frac{1-\boldsymbol{\sigma}^T\boldsymbol{\sigma}}{2}\mathbf{E}_3 + \boldsymbol{\sigma}\boldsymbol{\sigma}^T + [\boldsymbol{\sigma}^{\times}]\right) \tag{2}$$

where $[\boldsymbol{\sigma}^{\times}]$ represents the skew cross product matrix, and $\mathbf{E}_3$ is 3×3identity matrix.

The attitude dynamics equation is given by

$$\mathbf{I}\dot{\boldsymbol{\omega}} + \dot{\mathbf{h}} + \boldsymbol{\omega} \times (\mathbf{I}\boldsymbol{\omega} + \mathbf{h}) = \boldsymbol{\tau}_d \tag{3}$$

where $\mathbf{I}$ is the inertia matrix of the space station, $\boldsymbol{h}$ is the angular momentum of SGCMGs, $\boldsymbol{\tau}_d$ is the environment torque, which contains gravity gradient torque and aerodynamic torque.

In order to verify the effectiveness of the path planning model and method proposed in this paper, the pyramid configuration, a typical configuration SGCMGs as shown in Fig. 1, is selected. The angular momentum of SGCMGs can be calculated as

$$\mathbf{h} = h_0(\mathbf{A}\ \sin\ \boldsymbol{\delta} + \mathbf{B}\ \cos\ \boldsymbol{\delta})\mathbf{E} \tag{4}$$

The dynamic equation of the SGCMGs momentum is given by

$$\dot{\mathbf{h}} = \frac{\partial \mathbf{H}}{\partial \boldsymbol{\delta}}\dot{\boldsymbol{\delta}} = h_0\mathbf{C}(\boldsymbol{\delta})\dot{\boldsymbol{\delta}} = h_0\mathbf{C}(\boldsymbol{\delta})\mathbf{v} \tag{5}$$

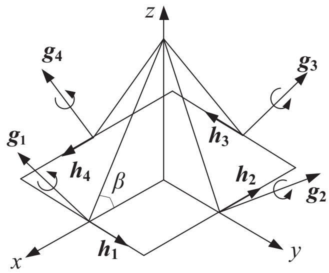

Fig. 1. Pyramid configuration SGCMGs.

where $\mathbf{C}(\boldsymbol{\delta})$ is the torque matrix

$$\mathbf{C}(\boldsymbol{\delta}) = \mathbf{A}\ \cos\ \boldsymbol{\delta} - \mathbf{B}\ \sin\ \boldsymbol{\delta} \tag{6}$$

The singular value of SGCMGs is a parameter to measure the degree of singularity, which is defined as

$$d = \det\left(\mathbf{C}(\boldsymbol{\delta})\mathbf{C}(\boldsymbol{\delta})^T\right) \tag{7}$$

In order to ensure the stability of numerical calculation, the variables should be dimensionless as follows

$$\begin{aligned} &\tilde{\boldsymbol{\sigma}} = \boldsymbol{\sigma}, \quad \tilde{\boldsymbol{\omega}} = \tfrac{\boldsymbol{\omega}}{n_r}, \quad \tilde{\boldsymbol{\tau}}_d = \tfrac{\boldsymbol{\tau}}{I_r n_r^2}, \quad \tilde{h}_0 = \tfrac{h_0}{I_r n_r}, \\ &\tilde{\boldsymbol{\delta}} = \boldsymbol{\delta}, \quad \tilde{\mathbf{v}} = \tfrac{\mathbf{v}}{n_r}, \quad \tilde{t} = n_r t, \quad \tilde{\mathbf{I}} = \tfrac{\mathbf{I}}{I_r} \end{aligned} \tag{8}$$

where n_r is the order of angular rate, and I_r the order of inertia. Eqs. (1)–(6) can be transferred to the dimensionless form as follows:

$$\begin{cases} \dot{\tilde{\boldsymbol{\sigma}}} = \mathbf{G}(\tilde{\boldsymbol{\sigma}})(\tilde{\boldsymbol{\omega}} - \tilde{\boldsymbol{\omega}}_o(\tilde{\boldsymbol{\sigma}})) \\ \dot{\tilde{\boldsymbol{\omega}}} = \tilde{\mathbf{I}}^{-1}\left(-\tilde{\boldsymbol{\omega}} \times \tilde{\mathbf{I}}\tilde{\boldsymbol{\omega}} + \tilde{\boldsymbol{\tau}}_d - \tilde{h}_0\mathbf{C}(\tilde{\boldsymbol{\delta}})\dot{\tilde{\boldsymbol{\delta}}} - \tilde{\boldsymbol{\omega}} \times \left(\tilde{h}_0(\mathbf{A}\ \sin\ \tilde{\boldsymbol{\delta}} + \mathbf{B}\ \cos\ \tilde{\boldsymbol{\delta}})\mathbf{E}\right)\right) \\ \dot{\tilde{\boldsymbol{\delta}}} = \tilde{\mathbf{v}} \end{cases} \tag{9}$$

The continuous control variable $\tilde{\mathbf{v}}$ is select the optimization variable in this optimization model, as it is the control variable that determine all the variables in the optimal control problem as Eq. (9) depicts. The continuous variable $\tilde{\mathbf{v}}$ is treated as dispersed variable in the next section.

2.2. Objective functions

In the multi-objective optimization model, it is most significant to select suitable indexes. In this study, the SGCMGs are applied as the actuator, as this kind of CMGs will be installed to the China's Space Station (CSS) in the future. Thus, to measure the capacity of SGCMGs, the single gyros momentum and the gimbal rate boundary value should be selected as the objective functions. Additionally, the time of flight should be another important objective for design an attitude maneuver mission. In this context, these three objectives are defined as follows.

The momentum of a single gyroscope of SGCMG is the first objective function

$$\min f_1(\mathbf{x}) = h_0 \tag{10}$$