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Time-varying modal parameters identification of a spacecraft with rotating flexible appendage by recursive algorithm

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ABSTRACT

The rotation of spacecraft flexible appendage may cause changes in modal parameters. For this time-varying system, the computation cost of the frequently-used singular value decomposition (SVD) identification method is high. Some control problems, such as the self-adaptive control, need the latest modal parameters to update the controller parameters in time. In this paper, the projection approximation subspace tracking (PAST) recursive algorithm is applied as an alternative method to identify the time-varying modal parameters. This method avoids the SVD by signal subspace projection and improves the computational efficiency. To verify the ability of this recursive algorithm in spacecraft modal parameters identification, a spacecraft model with rapid rotational appendage, Soil Moisture Active/Passive (SMAP) satellite, is established, and the time-varying modal parameters of the satellite are identified recursively by designing the input and output signals. The results illustrate that this recursive algorithm can obtain the modal parameters in the high signal noise ratio (SNR) and it has better computational efficiency than the SVD method. Moreover, to improve the identification precision of this recursive algorithm in the low SNR, the wavelet de-noising technology is used to decrease the effect of noises.

1. Introduction

For the spacecraft identification problem, most structures are still mainly processed as the time-invariant system, such as the in-orbit identification experiments of the Hubble space telescope [1] and the Engineering Test Satellite VI (ETS-VI) satellite [2]. If the structure is slow time-varying, caused by rotation of the solar panels in the identification experiment, the solar panels can be temporarily locked at certain angles in the identification process due to the relatively slow speed of solar panel rotation [2,3]. Therefore, the time-varying system can be degraded into a time-invariant system. However, from the perspective of actual operations, we hope that in-orbit identification can be implemented without affecting the normal work conditions of the spacecraft, such as by using the input and output (I–O) signals (control torque signal/satellite attitude signal/appendage vibration signal, etc.) during spacecraft attitude adjustment to perform the corresponding in-orbit identification experiment. In this case, the identification of the time-varying parameters may be considered. In addition, because the rotation appendage carried by the spacecraft becomes increasingly large, the huge appendage may lead to the structural parameters varying with time [4]; for example, the solar panel rotation of the Engineering Test Satellite VIII (ETS-VIII) can cause a maximum 25% change in the structure parameter [5]. This type of effect is sometimes impossible to ignore.

In this paper, a spacecraft with large rotational appendage, the Soil Moisture Active/Passive (SMAP) satellite, is

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selected as our research model. The SMAP mission is an observation mission proposed by the U.S. Jet Propulsion Laboratory to survey global soil moisture and freeze-thaw states. The launch of this satellite can help to improve the accuracy of weather forecasting, flood warning, and drought monitoring [6–8]. The Delta II rocket sent the satellite into a near-circular orbit at perigee 660 km and apogee 685 km on January 31, 2015, U.S. Eastern Standard Time. To maximize the scope of earth observation during the satellite's in-orbit operation and obtain high-resolution global soil moisture maps, the on-board large deployable antenna can rotate at a speed of 4 s/r after deployment. Because the satellite structural configuration is changing during in-orbit operation, which has led to changes in the corresponding system modal parameters, the satellite can be studied as a time-varying system.

The identification methods of modal parameters for some spacecrafts have been performed in other studies [1,9,10]. In these methods, the eigensystem realization algorithm (ERA) method has been successfully applied to the parameter identification experiments of time-invariant systems many times [11–13], such as the identification of the Galileo spacecraft and the Hubble space telescope by Juang [14] and the ETS-VI/VIII satellite in-orbit parameter identification [3–5,15]. The ERA method is a typical system realization method. By constructing a Hankel matrix corresponding to the I–O data and performing singular value decomposition (SVD) on the Hankel matrix at each time step, the system observability matrix is established to determine the state-space model parameters $\{\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}\}$, and the corresponding modal parameters are obtained from the state-space model [13]. If the system is time-varying, then the repeated-experiments methods can be used, such as the pseudo modal method proposed by Liu [16] and the time-varying ERA (TV-ERA) method proposed by Majji [17]. These methods can be considered the improvement of time invariant identification methods, and the multiple sets of I–O data are applied in these repeated-experiments methods. Because the in-orbit spacecraft often has periodic characteristics, the repeated-experiments methods are reasonable for identifying the time-varying spacecraft system. However, because these methods require the SVD, the computational cost of the identification procedure is still very high. Some control problems, such as the self-adaptive control, often need to obtain the latest dynamical parameters for updating the controller parameters in real time. In addition, the identified system parameters can help to track and monitor the on-orbit working condition of spacecraft. Consequently, a faster identification method is required.

To avoid the SVD and implement the on-line identification, a recursive subspace method called projection approximation subspace tracking (PAST) was proposed by Yang [18]. The PAST algorithm is based on the theory of signal subspace projection. By tracking the signal subspace matrix from the I–O data, this method avoids the SVD computation and thus improves the computational efficiency. The PAST method has already been applied to the modal parameter identification experiments of some time invariant/variant mechanical systems, but few studies have investigated in spacecraft parameter identification.

The primary purpose of this paper is to study the recursive identification problem of the time-varying modal parameters of the SMAP satellite caused by the rotation of large flexible antenna. With the control torque during satellite attitude motion as the input signal, the attitude angle/angular velocity and appendages vibration signals as the output signal, the PAST algorithm is used to provide an alternative identification approach for the commonly used pseudo modal method to identify the time-varying modal parameters recursively. Because the SVD has been avoided and the required data decrease in the recursive identification procedure, the computational speed has been improved. In the numerical simulation, the time-varying frequencies are identified by designing the I–O signals. A comparison of the frequency values under different signal noise ratios (SNRs) proves that the recursive algorithm can identify the time-varying modal parameters of the SMAP satellite effectively under the higher SNR. Besides, when the SNR is lower, the wavelet de-noising technology is employed to process the output signal with noise to improve the identification precision. Finally, the numerical results also illustrate that the recursive algorithm has faster computation speeds than the frequently-used SVD methods for time-varying spacecraft system.

The contents of this paper are organized as follows: Section 2 reviews the spacecraft modeling principle for the rigid-flexible coupling structure, and the state-space equation of the SMAP satellite is provided. Section 3 briefly introduces the basic procedures of the PAST recursive algorithm, and the satellite time-varying modal parameters are identified using PAST method. By designing the I–O signals, the results of the numerical simulation verify the effectiveness of the recursive algorithm in Section 4. Finally, some conclusions are presented in Section 5.

2. Establishment of the satellite state-space model

This section describes the establishment of the SMAP satellite model. First, the satellite structure is simplified, and the coordinate system is defined. Next, the problem of finite element modal analysis on appendages (such as the antenna and solar panels) is considered. Then, the system's rigid–flexible coupling dynamical equation is established [19]. Finally, the system state-space equation is developed by considering the selection of the satellite I–O signals.

2.1. Description and simplification of the satellite structure

The SMAP satellite has a deployable antenna with a diameter of 6 m. The antenna consists of the front/rear net, tension tie, rim trusses, and metallic fittings. The antenna is connected to the body of the satellite by two fixed support rods. To increase the ground scanning surface area during in-orbit operations, the structure formed by the antenna and the two connection rods can rotate quickly at a speed of 4 s/r.

The definition for the satellite coordinate system is shown in Fig. 1. The Earth's center of mass is selected as the origin O of the inertial coordinate system O-XYZ. The X-axis is on the equatorial plane and points to the spring