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Attitude control and sloshing suppression for liquid-filled spacecraft in the presence of sinusoidal disturbance

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ABSTRACT

The attitude regulation for a liquid-filled spacecraft in the presence of low frequency sinusoidal disturbance is considered in this paper. The liquid-filled spacecraft is modelled as a rigid body attached with a simple pendulum. A novel control scheme is proposed, which is composed of Active Disturbance Rejection Control (ADRC), Positive Position Feedback (PPF), Extended State Observer (ESO) and Singular Spectrum Analysis (SSA). The unknown sloshing mode could be estimated from the combined ESO and SSA, and accordingly ADRC and PPF controller is designed for the stabilization of the spacecraft. Particularly, the parameters of the disturbance are not required as long as its frequency is lower than the sloshing one. The proposed approach could provide stabilization for the spacecraft, rejection for the disturbance, and active damping for the sloshing. Its effectiveness is validated by numerical simulations.

1. Introduction

Sloshing is usually considered as the motion of a free liquid surface inside its containers. In the presence of attitude or trajectory maneuvers of partially filled spacecraft, liquid sloshing often imposes significant effects on the motion of spacecraft, and sometimes even induces instability [1]. In order to reduce these effects, modelling and control for partially liquid-filled spacecraft are required to be studied.

It is well known that an analytical solution for the general liquid-filled spacecraft motion problem is too difficult to solve [2]. Moreover, it is usually the force and torque of liquid on the rigid body that demands concern [1,3]. Thus, some mechanical equivalent models are presented to replace liquid part, especially for the analysis and design of controller. Pendulum and mass spring are adopted as mechanical equivalent models in [2,4], and they are still widely used because of their effectiveness and simplicity. Of these equivalent models, pendulum model is more suitable and received more attention for launch vehicles. Although a nonlinear and complicated model might have more accurate prediction for the sloshing dynamics [5,6], the dynamics model become too challenging for the controller design. In this article, the sloshing dynamics are modeled by a simple pendulum.

Even if the liquid-filled spacecraft is modelled using mechanical equivalent model, it is still a challenging problem for the control design for such a system. Apparently, it is an underactuated system since the sloshing mode is unable to be directly controlled. Controller for planar and three-dimensional spacecraft was designed in [7] and [8] respectively based on underactuated system control design approach. Although theoretical stability results were given in their works by Lyapunov

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functions, such controllers are difficult to be implemented in practical applications, because it requires exact dynamics and states of the system, which are usually hard to obtain. With the consideration of unknown sloshing mode, an estimator for the sloshing mode was presented in [9], but it requires an additional laser sensor in the fuel tank, which adds much complexity to the whole system. A wave-based control was designed in [10], but disturbance is ignored in the analysis.

Instead of dealing with rigid and sloshing modes together, they are controlled separately in some works. Nonlinear Dynamic Inversion is a common control method for rigid spacecraft, and it has also been implemented in various applications of liquid-filled spacecraft to deal with the rigid part [11–13]. However, for the sloshing mode different methods were implemented. A slosh observer was designed and additional thrusts were used for the slosh damping in [11]. Neural network was adopted for handling the uncertainties in the dynamics in [12]. Command input shaping approach was used for the reduction of sloshing in [13,14]. Additional thrust would increase the complexity of the system and the other methods fail to add active damping to the sloshing mode.

For the control of rigid spacecraft, uncertainty and disturbance are among the primary concerns in the design. Active Disturbance Rejection Control (ADRC) is one of the control schemes that could maintain tracking performance under uncertainties and disturbances [15–17]. It first implements an Extended State Observer (ESO) to estimate the total disturbance, which is usually composed of internal uncertainties and external disturbances [15]. Then a disturbance rejection controller is used for stabilization. The theoretical stability results of ADRC could be found in [18]. Although the total disturbance estimate brings much convenience in disturbance rejection, the internal part and the external part should be separated in some special applications. However, to the best knowledge of the authors, a general separation approach is not found yet.

As for the active damping for the sloshing mode, Positive Position Feedback (PPF) is a promising method. It was first proposed by [19] and mainly implemented for the active control of flexible structures [20–22]. It has the advantage that it could provide sufficient damping for the considered frequency signal and insensitive to spillover [23]. However, PPF is not applied in the suppression of sloshing and the sloshing state is required in this approach, which is unknown in our application.

Singular Spectrum Analysis (SSA) is one of the useful approaches to separate the sloshing mode from the extended state. SSA is a time series analysis method, which is capable of decomposing the original series into several independent components by using singular value decomposition (SVD) [24,25]. While it has been investigated in forecasting economics data [26], tool wear detection [27], signal separation filter [28] and structural damage detection [29], less attention was paid for its application in a feedback control loop. The online implementation experiences some particular problems, and one of them is to identify each decomposed components. Eigensystem Realization Algorithm (ERA) is able to identify the frequency of each component [30]. It has been applied in the modal parameter identification of spacecraft [30] and bridge [31]. Either SSA or ERA requires less information on the original system, and they own robustness herein.

Moreover, sinusoidal disturbances are commonly suffered in the control of spacecraft, so that they should be imposed particular attention [32,33]. One of the usual causes of low frequency sinusoidal disturbances is due to the liquid rocket motor [34,35]. To the best knowledge of the authors, they have not been handled in the control of liquid-filled spacecraft.

In this paper, we aim to propose a control scheme which could stabilize the rigid body with low frequency sinusoidal disturbances and suppress the liquid sloshing at the same time. ADRC, PPF and SSA are coordinated in the control design. Our contribution mainly contains two parts. First, a novel control scheme that combined ADRC and PPF is proposed for the stabilization of the rigid body and the attenuation of sloshing mode at the same time. Second, a novel signal separation

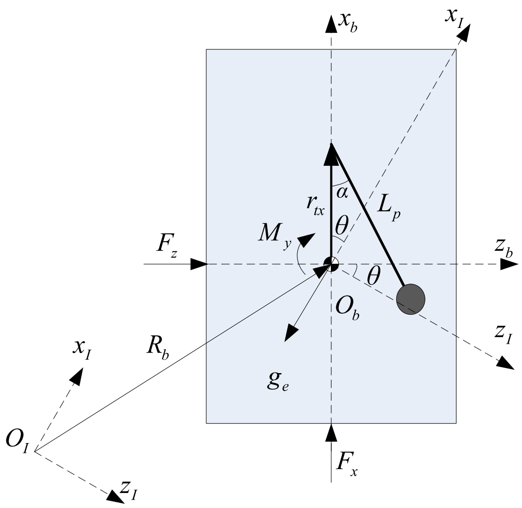

Fig. 1. Spacecraft model with pendulum.