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Attitude control of a flexible launch vehicle using an adaptive notch filter: Ground experiment

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Abstract

Attitude control of a flexible launch vehicle using adaptive notch filtering with real-time control is addressed in this paper. An experimental ground model is developed to verify the stability of the adaptive control technique based upon an adaptive notch filter. The experimental setup simulates the planar motion of a flexible launch vehicle as a coupled dynamics of rigid-body pitch motion and flexible vibration. The adaptive notch filter, which updates the filter parameters continuously from a sensor measurement, is implemented in real-time. The principal purpose of this study is to apply the adaptive notch filter algorithm in a feasibility study to assess its practical implementation. Through this experimental study, it was found that an adaptive controller in the form of an adaptive notch filter successfully stabilizes the uncertain and time-varying launch vehicle model dynamics via a thrust vector control.

Keywords: Launch vehicle; Attitude control; Flexible structure; Adaptive notch filter; Adaptive controller

1. Introduction

A flexible launch vehicle is characterized by complicated dynamics due to structural vibration from such factors as the slenderness of its body, fuel sloshing, uncertain aerodynamics and engine gimbal dynamics (Greensite, 1970). Attitude command is generated from the attitude angles and angular rates measured by an inertial measurement unit (IMU) located at the front of the launch vehicle. This command is delivered to a thrust vector control (TVC) system located at the rear. The IMU signal consists of a rigid-body mode and flexible vibrational modes. Thus, the noncollocated sensor and actuator pair tends to cause instability due to the finite phase difference from the vibrational mode shape. In the design of an attitude control system for a launch vehicle, instability due to structural feedback must be considered carefully.

There have been many papers and technologies associated with the stabilization of a flexible launch vehicle (Choi & Bang, 2000; Clement, Duc, & Mauffrey, 2005; Gaylor, Schaeperkoetter, & Cunningham, 1967; Joshi, 1989; Ljunge & Hall, 1984). Stabilization techniques thus far mostly adopt structural filters such as low-pass, high-pass, band-pass, and notch filters (Wie & Byun, 1989). Also, the dynamic simulation or modulated and demodulated controllers for flexible structures have been conducted (Kojima et al., 2007; Lau, Quevedo, Vautier, Goodwin, & Moheimani, 2007). In addition, an adaptive autostabilization system for airborne vehicles was formulated by Young (1981). This study was concerned with the initial evaluation of a self-adaptive autostabilization system for an airborne vehicle whose dynamic behavior could vary rapidly over a wide range during normal operations. First, the system parameters were estimated using the Kalman filter algorithm, and the state variable feedback gains were then applied to the system. The Kalman filer combined with actual radar data was also used to estimate the prediction of the impact area of a sounding rocket (Ferreira & Waldmann, 2007). Adaptive guidance technology was investigated to expand the potential of adaptive control when applied to autonomous launch systems (Johnson,

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Calise, & Corban, 2001). Their system model consisted only of a rigid body model and did not consider the flexible bending modes (Young, 1981; Johnson et al., 2001). Several papers have investigated the bending modes of the flexible launch vehicles or that of a missile (Cunningham & Higgins, 1970; Gaylor et al., 1967; Oh & Bang, 2005; Ra, 2005). In another study, an adaptive notch filter was applied to a sounding rocket model (Choi & Bang, 2000). Oh and Bang (2005) designed an adaptive filter to estimate the first bending mode frequency of a ground model of a flexible launch vehicle. A practical adaptive notch filter using a H_∞ bending frequency estimator was proposed to remove the time-varying structural mode of a missile from the rate sensor measurements (Ra, 2005). An adaptive notch filter design estimating only a single bending mode was also attempted (Choi & Bang, 2000; Oh & Bang, 2005; Ra, 2005). Gain and phase stabilization were investigated with an adaptive filter to stabilize the first and second bending modes of a SI-B launch vehicle (Gaylor et al., 1967). The favorable features of fixed and tracking filters were evaluated for a variety of bending mode stabilization applications (Cunningham & Higgins, 1970). Tracking filters were employed only in the simulation model of the SI-B launch vehicle and the tracking bending mode frequencies were kept constant (Cunningham & Higgins, 1970; Gaylor et al., 1967). Combinations of filters of different structures were generally used to meet the stability and performance requirement. Research has also been conducted with notch filters in an effort to minimize the effect of vibration and noise (Kim & Park, 1999; Nehorai, 1985; Rao & Kung, 1984; Regalia, 1991; T-Romano & Bellanger, 1988; Wie & Byun, 1989).

In the present study, an attitude control design for an experimental ground testbed is investigated. Generally, gain-scheduled controllers are applied for the attitude control of a flexible launch vehicle. The gain-scheduled controllers can become unstable when the mathematical model of the vehicle differs greatly from the true model. The majority of research relies on a mathematical model that suffers from modeling errors in real applications. In this study, an adaptive controller based upon the adaptive notch filter is designed for the attitude control of a flexible launch vehicle. The primary objective is to examine the adaptive stabilization controller through an experimental real-time ground demonstration. An adaptive notch filter is designed to estimate the multiple bending modes frequencies of the launch vehicle model and to minimize the effect of bending vibration. The experimental setup is a time-varying system with bending modes that vary as time passes. Research concerning the active control for a flexible launch vehicle using ground-based experiments is attractive for its inherent advantages. The basic principles of stabilization techniques that incorporate low-pass, band-pass, and notch filters can be investigated easily through experimental demonstration at a minimal cost. However, it is not straightforward to create an environment that closely matches an actual launch environment. The gravity effect, friction, and other unmodeled error sources hinder ground experiments. Establishing similarity between an experimental ground model and an actual launch vehicle is a further principal requirement for an experimental ground study. Despite such difficulties, preliminary research on the ground provides a huge benefit considering the risks associated with an actual flight demonstration. For the experimental work, a ground-based hardware testbed was developed to model the flexible launch vehicle. An angular rate sensor was used for the angle and rate information, and an air-thruster attached to a DC motor was used as the TVC. The attitude maneuvering and vibration control for the experimental model was handled in real-time. The adaptive notch filter was implemented and tested in conjunction with a feedback control loop.

This paper progresses as follows: Section 2 introduces the mathematical model of a general launch vehicle and the experimental ground model. Section 3 discusses the adaptive notch filter algorithm. In Section 4, the adaptive controller based on the adaptive notch filter is applied to the stabilization of the flexible launch vehicle. The simulation results of the experimental ground model are then presented. In Section 5, the adaptive controller based on the adaptive notch filter is tested on the experimental model, and the experimental results are presented. The concluding remarks are given in the final section.

2. Experimental setup and modeling

2.1. Experimental ground model design

Governing equations for a generic flexible launch vehicle are given in Greensite (1970). The main issues are various dynamic effects due to gravity, thrusters, structural flexibility, fuel sloshing, and engine gimbal inertia. A graphical representation and notations that describe dynamic motions for a flexible launch vehicle are presented in Fig. 1. Under a similar environment with an actual launch vehicle, an experimental ground model is constructed to demonstrate the feasibility of applying an adaptive controller with a real-time adaptation of the controller parameters.

In order to design a model that can simulate the launch vehicle dynamics with the best accuracy possible, the following conditions should be considered:

(a) The friction effect should be minimized to produce structural motion effectively.
(b) Appropriate sensors and actuators should be utilized to implement the real-time control experiment.
(c) External disturbance effects should be generated to cover various disturbance sources.

The schematic description of the experimental setup is presented in Fig. 2. A flexible structure with sufficient flexibility sitting on air-pads serves as a launch vehicle model. The entire structure floats on a granite table to