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Active damping control of flexible appendages for spacecraft

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ABSTRACT

Modern spacecraft are usually equipped with various flexible appendages, which bring great challenges to the design of high-performance control systems. This paper proposes a novel approach to provide active damping to spacecraft flexible appendages. Vibrations of flexible appendages are actively attenuated using a base-mounted angular displacement mechanism and tip-mounted non-collocated sensors. Dynamic models are presented and the controller design techniques provided. Effectiveness of the approach is demonstrated through an experimental apparatus, in which the damping ratio of the target beam is increased to be better than 40%. Furthermore, an active damping-control scheme using no extra sensors beyond attitude sensors onboard the spacecraft bus is proposed and demonstrated through numerical simulations.

1. Introduction

Most modern spacecraft are equipped with various flexible appendages, such as solar arrays, deployable antennas, cantilevered truss systems, etc. These flexible structures often have extremely large scale as well as low frequency and lightly damped oscillation modes, which bring great challenges to a spacecraft's precision pointing and agile maneuvering control.

A number of attitude-control techniques have been proposed aimed at reducing the excitation or accelerating the oscillation decay of flexible appendages, especially during attitude maneuvers. Such methods include command input shaping [1,2], optimal control [3], robust control [4,5], adaptive control [6], etc. These methods are usually based on the spacecraft's existing attitude-control actuator and sensor configuration. Although these sophisticated control techniques can improve the control performance of spacecraft flexible appendages, it is still preferable to directly optimize the spacecraft's dynamic characteristics to make them easier to control.

There are usually two ways to reduce the influences of flexible appendages: increasing either the stiffness or the damping level. In general, increasing the stiffness of flexible appendages may often lead to unacceptable mass cost, so enhancing the damping level is a more practical option. Both passive and active damping approaches have been investigated in the past few decades. The Hubble space telescope has extremely high pointing-accuracy requirements. To alleviate dynamic coupling with the pointing control system, passive dampers were developed for the SA-3 solar array that increase the modal damping from 0.5% to approximately 2.25% [7]. Similar designs have been applied to several high-precision spacecraft including AQUA, QURA, ACCESS [8], etc.

Meanwhile, a number of active ways have been investigated to increase structure damping more effectively. In the Mini-Mast experiment, three torque wheel actuators were mounted at the tip of the cantilevered truss structure to achieve 20% active damping ratio for the first mode [9]. In the experiment performed on the ACES testbed, the base-mounted gimbal system (AGS) and the linear momentum exchange devices (LMED) were demonstrated to be able to effectively damp the structural modes of the truss system [10]. In the COFS-I experiment, a tip-mounted proof-mass actuator was used to actively control the flexible structure with collocated and non-collocated sensors [11]. The proof-mass actuators were also applied to suppress the vibration of a lumped mass system and a plane frame structure using acceleration feedback control [12]. There are also a number of studies focusing on the active control of space structures using piezoelectric actuators, either embedded in truss systems [13,14], or bonded to flexible beams [15,16]. A number of controller design techniques were proposed base on piezoelectric actuators, including positive position feedback [17], adaptive positive position feedback [18,19], wave absorbing controllers [20], etc. The piezoelectric-based active damping system

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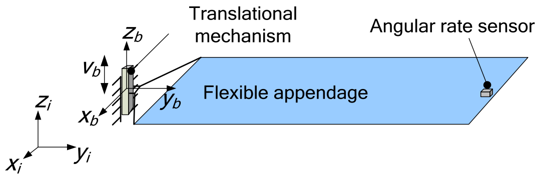
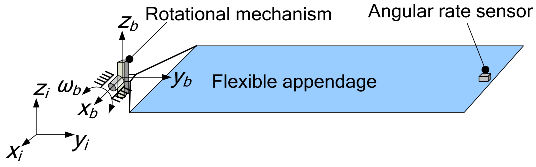


(a) Translational DOF



(b) Rotational DOF

Fig. 1. Optional actuation schemes.

was also applied in reducing the flow-induced vibrations for the aircraft fin [21].

Most of the active damping-control methods require extra actuators attached to the target flexible structure. This configuration may have difficulties for application to spacecraft in practice, especially for appendages that are rotating continuously, e.g., solar arrays, since the cables for the power source and signals must pass through the driving assemblies.

In this paper, we propose a new approach of actively damping flexible appendages. Actuators are mounted at the interface between the spacecraft bus and the deployed flexible appendage. Two measurement schemes are proposed. The first is to use lightweight gyroscope sensors mounted at the tip of the appendage to provide non-collocated measurement for active control. The second is to use the output of spacecraft attitude sensors, based on the dynamic coupling principles between the appendages and the spacecraft bus. The latter measurement approach, together with the proposed base-mounted actuation scheme, can achieve the attractive goal of increasing active damping without any add-ons to the spacecraft flexible appendages.

The dynamic model used in active damping control for flexible appendages is described first. The controller design techniques are then studied, and the experimental apparatus and test results are presented. An active damping method with no extra sensors is also discussed.

2. Dynamic model

The solar array illustrated in Fig. 1 is used to introduce the dynamic model for active damping control. The coordinate system x_i–y_i–z_i is fixed in the inertial space, and the coordinate system x_b–y_b–z_b is fixed to the base mechanism that is able to move in the translational or rotational direction relative to the inertial frame. For clarity, the discussions in this paper will focus on the control of out-of-plane modes of the appendage. The solutions could be easily applied to the other directions when necessary. From an intuitive understanding, in order to control the out-of-plane bending modes via base-mounted mechanisms, both translational and rotational degrees of freedom could be chosen for actuation, as shown in Fig. 1(a) and (b), respectively.

Using the hybrid coordinate method [22], the dynamic characteristics of the appendage about the x axis can be written as Eq. (1):

$$\ddot{\boldsymbol{\eta}}_a + 2\boldsymbol{\zeta}_a\boldsymbol{\Omega}_a\dot{\boldsymbol{\eta}}_a + \boldsymbol{\Omega}_a^2\boldsymbol{\eta}_a + \boldsymbol{F}_t\dot{\boldsymbol{v}}_b + \boldsymbol{F}_r\dot{\omega}_b = 0. \tag{1}$$

$\boldsymbol{\eta}_a$, $\boldsymbol{\zeta}_a$ and $\boldsymbol{\Omega}_a$ represent the appendage's generalized modal displacement, damping ratio, and natural frequencies of the first N normal modes, respectively, where $\boldsymbol{\eta}_a = \begin{bmatrix} \eta_{a1} & \eta_{a2} & \cdots & \eta_{aN} \end{bmatrix}^T$, $\boldsymbol{\zeta}_a\boldsymbol{\Omega}_a = diag\left(\begin{bmatrix} \zeta_{a1}\omega_{a1} & \zeta_{a1}\omega_{a1} & \cdots & \zeta_{aN}\omega_{aN} \end{bmatrix}\right)$, and $\boldsymbol{\Omega}_a^2 = diag\left(\begin{bmatrix} \omega_{a1}^2 & \omega_{a2}^2 & \cdots & \omega_{aN}^2 \end{bmatrix}\right)$. $\boldsymbol{F}_t$ and $\boldsymbol{F}_r$ denote the translational and rotational modal coupling matrices, respectively, with the dimension of N*1. They are determined by the geometry and mass distribution characteristics of the appendages, as in Eq. (287) of Ref. [23]. $\boldsymbol{v}_b$ is the base mechanism's translational velocity along the z_b axis and ω_b the rotational velocity about the x_b axis, with respect to the inertial frame. The base mechanism is designed to be capable of following the translational or rotational velocity command using servo motors and gear assemblies.

Angular rate sensors, such as gyroscopes, are mounted at the selected locations on the flexible appendage, the output of which can be expressed as

$$\omega_a = \boldsymbol{\varphi}_r^T\dot{\boldsymbol{\eta}}_a + \omega_b, \tag{2}$$

where the 1*N vector $\boldsymbol{\varphi}_r^T$ is the appendage's rotational component of mode shapes about the x_b axis at the sensor location. According to the system configuration discussed above, the angular rate at the tip of the flexible appendage is measured via gyroscopes, the output of which contains contents of both flexible vibrations as well as the base motions, as can be seen from Eq. (2). This will result in a non-zero static gain matrix D in the following state-space model. In order to ease the controller design process, a derived output is used in the feedback control,

$$\boldsymbol{y} = \omega_a - \omega_b = \boldsymbol{\varphi}_r^T\dot{\boldsymbol{\eta}}_a, \tag{3}$$

where ω_b is a known variable since it is the output of the controller. The derived output $\boldsymbol{y}$ denotes the angular velocity of the measuring point on the appendage relative to the moving base.

Further study shows that the rotational actuation scheme presents relatively more efficiency in flexible mode control compared to the translational scheme, since it has of some kind amplification-effect. To better understand this, an approximate analysis is conducted as follows. For the flexible appendages shown in Fig., we might consider only the primary out-of-plane bending mode for simplicity. In this case, the coupling vectors $\boldsymbol{F}_t$ and $\boldsymbol{F}_r$ will degenerate into scalars F_t and F_r, which have the following approximate expressions,

$$F_t \approx \sqrt{m}, \qquad F_r \approx \sqrt{J} = \sqrt{\frac{mL^2}{3}} \approx \frac{L}{\sqrt{3}} \cdot F_t, \tag{4}$$

where m is the mass of the appendage, J the inertia of the appendage against the base point, and L the appendage's length. From Eqs. (1) and (4) it can be seen, in order to achieve the same actuation effect, the translational motion v_b should be $L/\sqrt{3}$ times the value of rotational motion ω_b. Although the two quantities have different dimensions, comparisons could be made considering engineering feasibility. For instance, to actively control a solar array 5 meters long, $10°$ of rotational actuation has approximately the same effect with 0.5 meters of translational actuation. Between the two, the rotational actuation scheme is much easier to realize through a compact mechanism under the limitation of tense space on spacecraft.

Accordingly, the following paper will focus on the rotational actuation scheme. Owing to the similar form presented in Eq. (1), the proposed control strategy for rotational actuation could be easily be applied to the translational case when required.

The Eqs. (1) and (3) can be rewritten in state-space form as

$$\begin{aligned} \dot{\boldsymbol{x}} &= \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \\ \boldsymbol{y} &= \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \end{aligned}, \tag{5}$$

where

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