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Active Vibration Suppression of an elastic piezoelectric sensor and actuator fitted cantilevered beam configurations as a generic smart composite structure

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ABSTRACT

An efficient analytical method for vibration analysis of a Euler–Bernoulli beam with Spring Loading at the Tip has been developed as a baseline for treating flexible beam attached to central-body space structure, followed by the development of MATLAB© finite element method computational routine. Extension of this work is carried out for the generic problem of Active Vibration Suppression of a cantilevered Euler–Bernoulli beam with piezoelectric sensor and actuator attached as appropriate along the beam. Such generic example can be further extended for tackling light-weight structures in space applications, such as antennas, robot's arms and solar panels. For comparative study, three generic configurations of the combined beam and piezoelectric elements are solved. The equation of motion of the beam is expressed using Hamilton's principle, and the baseline problem is solved using Galerkin based finite element method. The robustness of the approach is assessed.

1. Introduction

Vibration control of light-weight structures is of great interest of many studies and investigations [1–3]. The high cost of sending heavy masses and large volumes into space has prompted the wide utilization of light-weight structures in space applications, such as antennas, robot's arms, solar panels. A model of such set-up is exemplified in Fig. 1 [2]. These kinds of structures are largely flexible, which results in lightly damped vibration, instability and fatigue. To suppress the adverse effect of vibration, sophisticated controller is needed.

Active control approaches are widely reported in the literatures for the vibration control of structures [4–10]. The active control approach makes use of actuators and sensors to find out some essential variables of the structure and suppress its vibration through minimizing the settling time and the maximum amplitude of the undesirable oscillation. This method requires a specific level of understanding about the dynamic behavior of continuous structures via mathematical modeling [4,5]. Selecting adequate sensor and actuator is essential in active vibration control [11,12]. The conventional form of sensor and actuator, such as electro-hydraulic or electro-magnetic actuator, are not applicable to implement on the light-weight space structures. Thus, in recent years, a new form of sensor and actuator has been studied using smart materials, such as shape memory alloys and piezoelectric materials. The definition of smart material may be expressed as a material which adapts itself in response to environmental changes. Among smart materials, piezoelectric materials are widely studied in literatures, since they have many advantageous such as adequate accuracy in sensing and actuating, applicable in the wide frequency range of operations, applicable in distributed or discrete manner and available in different size, shape and arrangement.

Space structures can be simplified using beam and plate. The present investigation is based on the vibration analysis of simple beam as a generic structure. Without loss of generalities, the theoretical development utilizes Euler–Bernoulli beam approximation, which can readily be extended to other refined models. Euler–Bernoulli beam theory is applicable to thin and long span, for which plane sections can be assumed to remain plane and perpendicular to the beam axis, and shear stress and rotational inertia of the cross section can be neglected. Solar panel and antenna are very flexible and slender, so that Euler–Bernoulli beam theory can be considered.

The equation of motion of the beam will be developed using Hamilton's method and Lagrange method [13,14]. Hamiltonian

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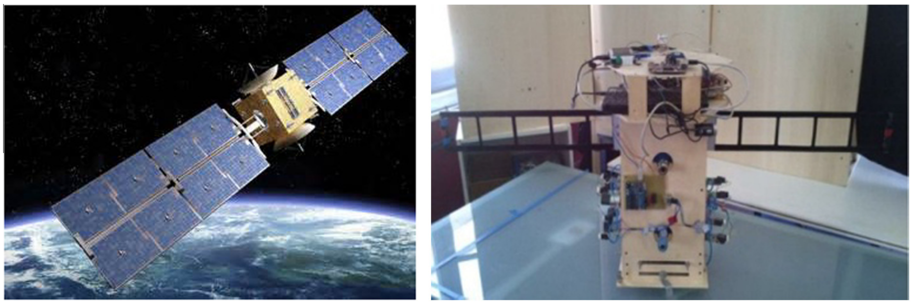

Fig. 1. Solar Panel on a typical satellite (left) and an experimental model of Free-Floating Platform with two flexible appendages designed by Gasbarri et al. [2] (right).

mechanics is an elegant and convenient approach, since scalar equation of motion of the beam and boundary conditions are obtained simultaneously. The partial differential equation of motion of the beam can be solved by analytical methods such as separation of variables, or numerical methods such as finite element method.

Since these structures are flexible, there is a need for Vibration control in these structures is required order not to disturb the functionality of the space structure as a whole as well as to facilitate manoeuvring and attitude control for well-behaved space structural dynamics. There are several ways to control the vibration [15,16]. Then the effort is aimed for devising a simple and effective controller to manipulate the vibration of a flexible structure. One of the adequate and simple controllers is Proportional-Integral-Derivative (PID) controller, which is classified as classic and linear controller [16]. PID controller minimizes the steady state error of the system. Linear Quadratic Regulator (LQR) controller is another convenient method. LQR is expressed as optimal and modern controller, which is based on minimizing the cost function of a dynamic system [16]. To develop a successful operation, most controllers have been developed for a finite number of natural modes where the controllability and observability conditions are met. It is also noted that various recent literature addresses similar issues which are utilized for comparative purposes.

2. Formulation of generic problems

Following a series of previous investigation on the analysis of impact resilient structure [17–20], and vibration analysis of an elastically clamped cantilever beam [21,22], the main aim of this investigation is to design a straightforward and convenient controller for suppressing the transverse vibration in a cantilever aluminum flexible beam through the use of sensing and actuating transducers. The Euler–Bernoulli beam theory is utilized to model the flexible beam with piezoelectric patches. The equation of motion and boundary conditions of the beam are derived by using Hamilton's principle. To validate and assess the analytical as well as the finite element computational schemes, the solution for a cantilevered beam with Spring Loading at the Tip as illustrated in Fig. 2, which has the potential to be expanded in many variations, will be demonstrated. Next, considerations will be given for the active vibration control for Cantilevered Bernoulli Beam. Three different piezoelectric material configurations on the aluminum beam are considered for comparative study. Finite element method is utilized to achieve the natural frequencies and natural modes. Case study one is validated by analytical solution. Previous experimental result is used for validation of case study two.

To design the controller, two first major natural modes of the beam vibration are considered, since other natural modes has insignificant effect [4,12,23,24]. The dynamic equation of the beam is transferred to state space form in order to design controllers.

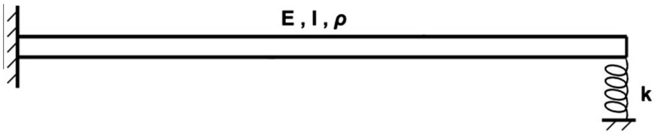

Fig. 2. Assumed model for the beam.

Two controllers are designed for each case study: PID controller and LQR controller with observer. These controllers are easy to perform and effective to suppress the vibration of the beam. The systematic of the problem formulation and the methods of approach including the objective of this study is summarized in Fig. 3.

3. Equation of motion of the Euler–Bernoulli beam using Hamilton's principle

Fig. 4 depicts the cantilevered Euler–Bernoulli beam with spring-loading at the free end. Following Euler–Bernoulli beam model, the shear displacement and the rotation of cross sections are neglected in comparison to the translation; hence the cross sections remain constant after deformation [14,25]. From Fig. 4

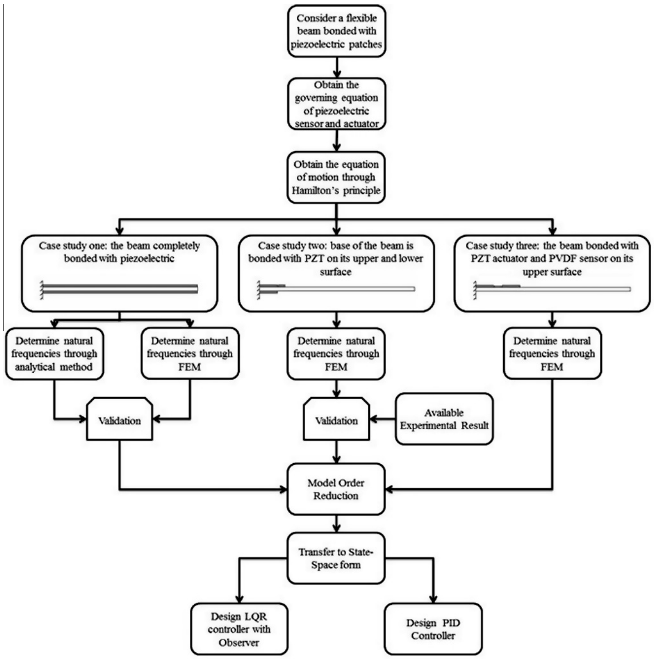

Fig. 3. Systematics of problem formulation.