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Fuzzy sliding mode control of flexible spinning beam using a wireless piezoelectric stack actuator

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ABSTRACT

Spinning structures play an outstanding role in aerospace engineering. The vibration caused by eccentric forces or external excitations would damage the structures. Vibration suppression of such spinning structures is necessary, but challenging because of the arrangement of actuators. A new wireless piezoelectric stack actuator spinning in a varying magnetic field is introduced in this paper to avoid the wires winding with large control force. The control voltage on the actuator is generated by the motion of the wires in magnetic field. Besides, fuzzy sliding mode control with universal fuzzy sets based on the wireless actuator is investigated. Numerical simulation demonstrates that the tip displacement response of the spinning beam reduces over 98% compared with that open loop, while the magnitude of the peak in frequency domain decreases from 0.0976 dB to 0.0383 dB. It proved that the proposed actuator is feasible and the fuzzy sliding mode controller could suppress the vibration of spinning beam effectively with a strong robustness to noise.

1. Introduction

Spinning beam is one kind of important structure in aerospace engineering, such as in cyclogyro shown in Fig. 1. Demands for such light structures in aerospace engineering have attracted theoretical analysis and experimental validation on flexible spinning structures worldwide [1,2]. It has been reported in numerous archive papers dealing with spinning structures. Based on Bernoulli-Euler beam theory, Filipich and Rosales [3] studied the crack detection of a spinning beam with measured frequencies. Sheu and Yang [4] investigated the dynamic characteristic of a spinning beam using Rayleigh beam model. The whirl speed, critical speed and mode shape in general boundary conditions were analyzed and discussed. Shiau [5] studied the dynamic behavior of a spinning Timoshenko beam using global assumed mode method. The transient response of the beam was analyzed through Runge-Kutta method. Qian [6]and Pai et al. [7] investigated the motion equations and dynamic characteristics of the spinning Rayleigh beam.

The vibration of spinning beams caused by external excitation and eccentric force is extremely important to structure safety and reliability.

Zhou and Shi [9] reviewed real time active balancing and active vibration control of spinning structures. The work also included a brief evaluation of major difficulties, the basic methodology and future research prospects. Kunze et al. [10] presented the test up and vibration control strategy of spinning shaft of the car. The experiments carried out showed that a reduction of interior sound pressure level of 12 dB was achieved. Horst and Wölfel [11] investigated the structural model of a high speed rotor and developed an active controller to suppress the vibration. Sloetjes and Boer [12] studied a flexible shaft with piezoelectric sheets and strain sensor. Active modal damping and active modal balancing methods were analyzed using frequency domain models, time domain simulations and control experiments.

For the vibration control of spinning beam, piezoelectric lead zirconate titanate (PZT) actuator has been widely studied and utilized during the past decades [13–15]. However, the limited force outputs are the main obstacles of PZT patches in vibration or shape control [16]. PZT stack is an effective alternative with larger outputs. In addition, the existing works do not take the difficulty of implementation of actuators to spinning structures into consideration. As spinning, common PZT actuators may be ineffective for that the actuators are difficult to connect to the voltage supply without slip ring brush. In this study, a wireless PZT stack actuator in varying magnetic field is implemented to overcome these problems.

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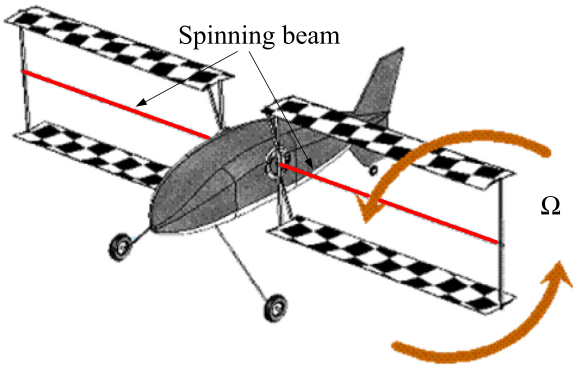

Fig. 1. Spinning beams in cyclogyro [8]

Besides, the dynamic equations of spinning structures contain non-linear terms due to gyroscopic, coriolis and centrifugal effects. Slide mode control is low sensitive to plant parameter variations and disturbances, thus providing an effective way to solve nonlinear problems [17]. It guarantees that the system is asymptotically stable. However, the chattering resulted from unmodeled dynamics or discrete time implementation may lead to undesired results. A fuzzy sliding mode controller with universal fuzzy sets could avoid the chattering phenomenon effectively [18–21].

Thus, a fuzzy sliding mode controller based on wireless PZT stack actuator in the magnetic field is proposed in this paper. This paper is organized as follows. Section 2 gives a finite element model of the spinning beam and formulations of PZT stack actuator in the magnetic field. Design of fuzzy sliding mode controller is presented in Section 3. In Section 4, numerical simulation is conducted to verify the intelligent controller. Finally, concluding remarks are given in Section 5.

2. Modeling of beam and piezoelectric stack

2.1. Finite element model of spinning beam

The finite element model of a spinning flexible beam could be expressed as

$$\mathbf{M}\ddot{\boldsymbol{\eta}} + \mathbf{C}\dot{\boldsymbol{\eta}} + \mathbf{K}\boldsymbol{\eta} = \mathbf{B}u \tag{1}$$

where $\boldsymbol{\eta}$ is the vector of physical coordinates, **M**, **C** and **K** are the mass matrix, damping matrix and stiffness matrix of the spinning flexible beam, respectively. **B** is the input matrix based on the piezoelectric control equation, while u is the control force applied to the beam. The detail of finite element modeling and model reduction of spinning flexible beam system are presented in [22,14]. Eq. (1) can be solved by many methods, such as the homotopy perturbation method, the variational iteration method, the homotopy analysis method, etc. [23].

2.2. The model of piezoelectric stack

As shown in Fig. 2, a beam is spinning along the longitudinal direction with simply supported ends. A piezoelectric stack is consisting of thin PZT layers, and the layers are ceramic laminated together and electrically connected in parallel. The stack is fixed on the beam by rigid brackets. The wire spinning with the beam in magnetic field will generate an electromotive force (EMF) according to the Faraday's Law, and the electromotive force provides control voltage to the PZT stack actuator. As a displacement generating device, PZT stack could provide large control force in response to the control voltage due to piezoelectric effect. Under an external load resisting the deformation of PZT material, a force related to the extensional stiffness of the beam and the stack is generated. The feedback velocity signal is obtained from a wireless sensor placed with the actuator on the beam.

When the PZT stack spins with the flexible beam in the magnetic field B, the generated voltage is given according to the Faraday's Law

$$U = BLv \tag{2}$$

where L is the effective length of the wire moving in magnetic field, $v = [(t/2)\Omega + (t/2 + L)\Omega]/2$ is the effective velocity of the wire.

When the voltage U is applied in z-direction of polarization between the two surfaces of the PZT film, the strain of the film in z-direction is

$$\varepsilon_3 = d_{33}E_3 = d_{33}\frac{U}{t_c} \tag{3}$$

where $E_3 = U/t_c$ is the electric field in the PZT film, t_c is the thickness of a single PZT film, d_{33} is piezoelectric constant of the PZT material in z-direction.

Thus, the displacement of the unconstrained PZT stack actuator induced by U is

$$\delta_U = \varepsilon_3 l = d_{33}\frac{U}{t_c}N_a t_c = N_a d_{33} U \tag{4}$$

where $l = N_a t_c$ is the total length of the PZT stack, N_a is the number of PZT films in the stack.

According to the condition of coincident deformation [16]

$$\delta_U + \delta_f = \delta_b \tag{5}$$

where δ_f is the elastic deformation of the PZT stack, while δ_b is that of the beam.

Thus

$$\begin{cases} \delta_f = Fl/E_s A_s \\ \delta_b = Fl/E_b A_b \end{cases} \tag{6}$$

where F is the resultant induced force in the PZT stack. $E_s A_s$ and $E_b A_b$ are the extensional stiffness of the stack and the beam, respectively. E_s and E_b are the Young's modulus of the piezoelectric material and the beam, respectively. A_s and A_b are the cross-sectional area of the stack and the beam.

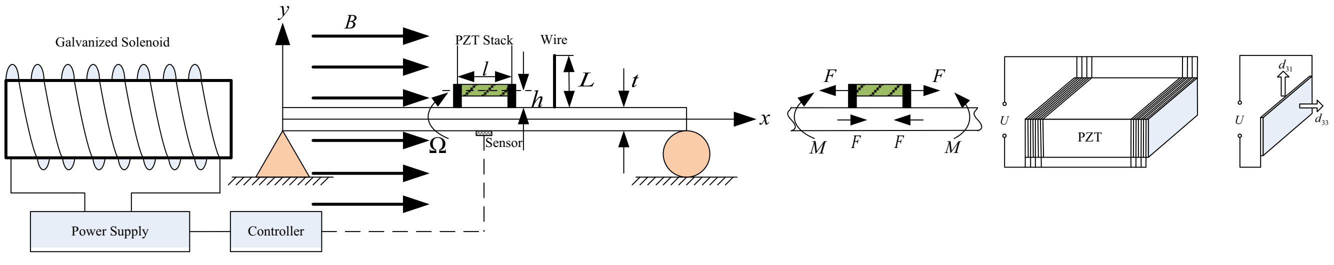

Fig. 2. Smart spinning flexible beam with PZT stack.

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