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Letter to the Editor

Vibration control of a rotating cantilevered beam using piezoactuators: experimental work

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1. Introduction

During the last few decades, there have been an amount of research activities to actively control unwanted vibration of flexible structures by utilizing piezoelectric actuators. Bailey and Hubbard [1] proposed simple but effective control algorithms; constant amplitude controller (CAC) and constant gain controller (CGC), and proved their efficacies for transient vibration control of a cantilevered beam. Baz and Poh [2] worked on the vibration control of the flexible structure via modified independent modal space control. Choi [3] proposed a hybrid control algorithm to alleviate undesirable vibration chattering of a flexible beam in the settled phase. More recently, Shin and Choi [4] proposed a novel hybrid control scheme to actively and robustly control the end-point vibration of a two-link flexible manipulator using the piezoactuators. Besides the above-mentioned works, there are numerous research works on the vibration control of flexible structures using the piezoelectric actuators. However, most of the piezoactuator-based flexible structures adopted in the previous works are not subjected to rotational motion.

In this work, active vibration control of a rotating flexible structure whose application includes a space boom, a helicopter blade and a wind turbine is considered. In the rotating structures, the variation of vibration characteristics due to the stiffening effect of the centrifugal forces and the resonance problem due to one of disturbance frequencies of multiples of rotating speed need to be carefully considered for active vibration control. Schilhansil and Providence [5] investigated the stiffening effect of the centrifugal forces on the first mode bending frequency of a rotating cantilever beam. Hodges [6] obtained an approximate formula for the fundamental frequency of a uniform rotating beam clamped off the axis of rotation. Vyas and Rao [7] derived equations of motion of a blade mounted on a disc with variable angular velocity including Coriolis forces and higher order terms of shear deflection and rotary inertia. Chandra and Chopra [8] have

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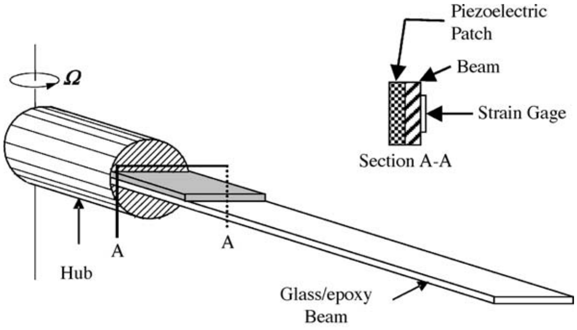
theoretically and experimentally investigated vibration characteristics of thin-walled composite box beams and coupled composite I-beams with bending-twist and extension-twist coupling under rotating conditions. On the contrary to many works on vibration analysis of the rotating flexible structures, a research work on active vibration control of the rotating structure is rare.

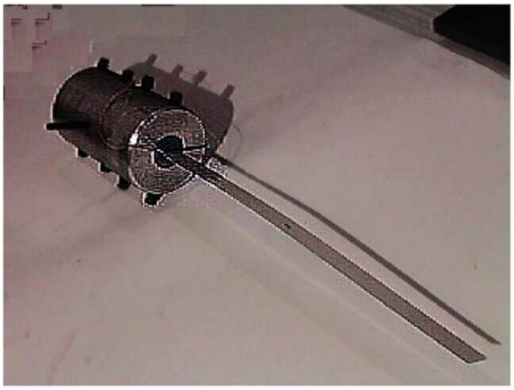
Consequently, the main contribution of this work is to present active vibration control responses of the rotating flexible beam featuring the piezoactuators. A glass/epoxy composite beam is prepared and the piezoceramic actuator is patched at the root of the rotating hub. The variations of the natural frequencies are experimentally investigated with respect to the rotating speed. The critical disturbance frequency is determined by observing the spoke diagram, and the constant amplitude controller (CAC) is experimentally realized. Vibration control responses subjected to two different disturbances (rotational speeds) are evaluated and presented in time domain.

2. Experimental setup

The schematic configuration of a rotating cantilevered beam proposed in this work is shown in Fig. 1(a). The piezoceramic patch (C-9actuator, Fuji Co.) is bonded on top of the host composite



(a) configuration



(b) photograph

Fig. 1. The rotating beam with the piezoceramic actuator.

(glass/epoxy) beam and the strain gage is attached on the other side to measure the deflection of the beam. It is noted that the piezoceramic patch and strain gage have been bonded near the clamped end of the rotating beam in order to take account for the first two bending modes which are dominant for the beam vibration to be controlled. The geometrical and material specifications of the composite beam and piezoceramic are given in Table 1, and the photograph of the manufactured beam attached to the rotating hub is shown in Fig. 1(b).

The hub whose length is 72 mm is directly connected to the shaft of the variable speed DC motor (1 HP) using a few bolts as shown in Fig. 2. The cantilever beam is equipped in a transparent tube to avoid aerodynamic forces. A four-channel slip ring is used for wires of the piezoceramic actuator and the strain gage in the rotating frame. The rotating speed is measured by the tachogenerator, and the deflection of the beam in the flap direction is monitored by means of a strain gage and its signal conditioner. The signal from the strain gage is fed back to the microprocessor (486 IBM PC) via the A/D (analog to digital) converter which has a 12 bits. It is noted that the strain gage signal (voltage) is converted to the tip deflection of the beam by calibration in the feedback process. The velocity component of the beam which is required for the controller implementation is obtained through the numerical derivative of the strain gage signal.

Table 1
Specifications of the beam and piezoceramic actuator

Young's modulus	Density	Thickness	Width	Length
Glass/epoxy beam				
18.5 GPa	1865 kg/m^3	0.6 mm	24 mm	350 mm
Piezoceramic patch				
64 GPa Piezoelectric strain constant: -300×10^{-12} mV	7700 kg/m^3	0.8 mm	23 mm	60 mm

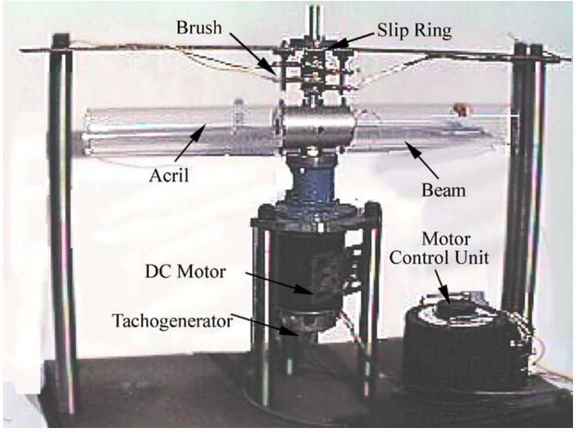


Fig. 2. Experimental apparatus for vibration control.

The control voltage determined on the basis of the sign of the velocity component of the beam is applied to the piezoceramic actuator via both the D/A converter which has a 12 bits and the high-voltage amplifier (Trek 505) which has a gain of 100. The sampling frequency for the controller implementation is set at 1.2 kHz. The sampling frequency is normally determined by considering the vibration signal frequency to avoid aliasing problem as well as spillover problem. The constant amplitude controller (CAC) implemented in this work treats the feedback signal which contains many vibration modes in the control action. Therefore, high sampling frequency is required to treat high vibration modes, and hence to achieve favorable control performance. The sampling frequency of 1.2 kHz is enough to cover high vibration modes of the proposed rotating beam without exhibiting aliasing and spillover problems.

3. Results and discussions

Prior to implementing active feedback controller, the variations of the natural frequencies are experimentally investigated. Fig. 3 presents the natural frequencies of the first three vibration modes at various rotating speeds. As expected, the natural frequencies are increased as the rotating speed increases. This, of course, is due to the stiffening effect associated with the centrifugal force. The first mode natural frequency is increased from 3.25 Hz at 0 rpm to 9.25 Hz at 400 rpm, while the second mode from 22.75 to 32.75 Hz.

In order to determine the disturbance signal to be imposed on the beam, a spoke diagram for the first mode is investigated as shown in Fig. 4. As clearly observed from the figure, the first natural frequency of the system coincides with the second disturbance frequency (2Ω) around 136 rpm. This implies that the structure resonance may occur at this rotating speed. If this disturbance excites the beam, thus, it is required to design an appropriate controller guaranteeing its authority on the system around the resonance speed. In this work, the constant amplitude controller (CAC) proposed by Bailey and Hubbard [1] has been adopted. The CAC has a form of $V(t) = -k\,\mathrm{sgn}$ (velocity). Here, $V(t)$ is the control input voltage, k is the feedback gain, and sgn(●) is the sign function. As mentioned earlier, the velocity component of the beam is obtained by numerical derivative of the strain gage signal (deflection), and the gain k is set at 120 considering

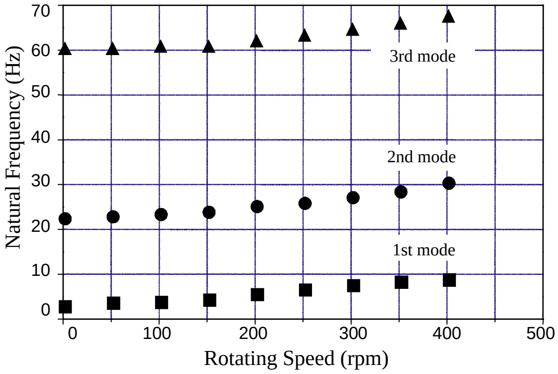


Fig. 3. Measured natural frequencies at various rotating speeds.

the maximum applicable voltage (300 V) of the piezoceramic actuator. The CAC has been experimentally realized and vibration control responses are evaluated in time domain.

Fig. 5 presents the forced vibration control response at the rotating speed of 136 rpm which coincides with the first natural frequency of the beam. The tip deflection of 0.5 mm without control voltage has been well suppressed to almost zero by activating the piezoceramic actuator. It is observed from the input signal that the control voltage has been well supplied to the

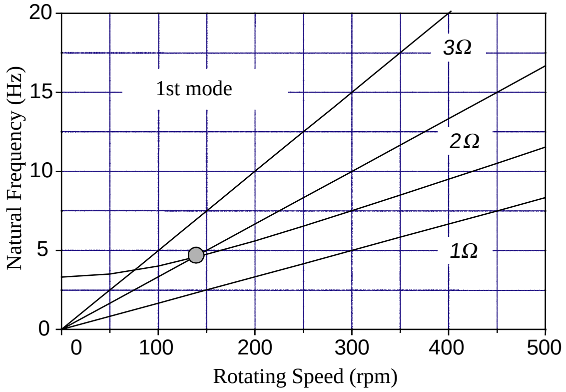


Fig. 4. Spoke diagram of the first mode.

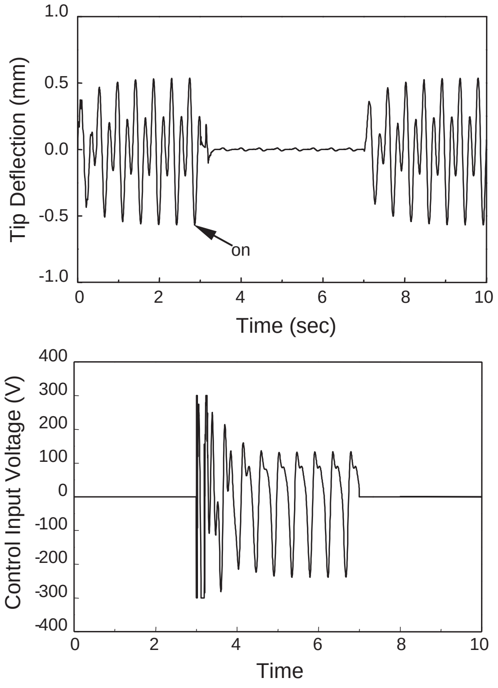


Fig. 5. Vibration control response at resonance speed ($\Omega = 136$ rpm).

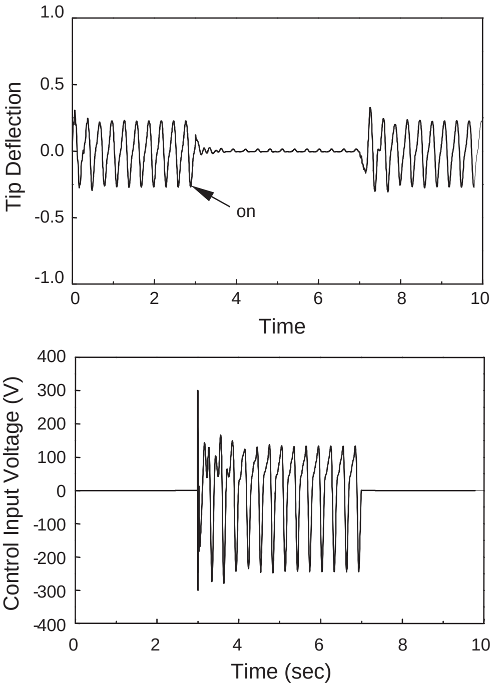


Fig. 6. Vibration control response at non-resonance speed ($\Omega = 200$ rpm).

piezoceramic actuator within the imposed maximum limit of 300 V without any time delay. In order to investigate control effectiveness at the non-resonance speed, the beam is rotated at 200 rpm and control response is evaluated as shown in Fig. 6. It is clearly observed that the tip deflection has been favorably suppressed by activating the feedback controller associated with the piezoceramic actuator. It is noted that the magnitude of the input voltage at the non-resonance speed is smaller than that of the input voltage at the resonance speed shown in Fig. 5. The control results presented in this work are quite self-explanatory justifying that the deflection of the rotating beam can be effectively controlled in both resonance and non-resonance speeds by activating the CAC feedback controller associated with the piezoceramic actuator.

4. Concluding remarks

The vibration of a rotating beam has been actively controlled by utilizing the piezoceramic actuator. After identifying vibration characteristics of the system such as the variation of the natural frequency with respect to the rotating speed, the constant amplitude controller has been experimentally realized. It has been demonstrated that the vibration of the beam caused by rotating the beam at resonance and non-resonance speeds can be substantially suppressed by applying control voltage to the piezoactuator. It is finally remarked that a robust control scheme based on accurate dynamic model will be designed and implemented as a second phase of this preliminary experimental work.

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