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Investigation of the time delay effect on the control of rotating blade vibrations

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ABSTRACT

In this paper, a time-delayed positive position feedback (PPF) controller is applied to reduce the nonlinear oscillations of the dynamical system of a rotating blade. The main system is coupled to the controller whose natural frequency is approximately equal to the natural frequency of the main system. The main system has two oscillatory modes that are found to be powerfully linearly coupled. The approximate nonlinear dynamical behavior is studied and analyzed by applying the multiple time scales method. The effects of the time delay are investigated to indicate the safe region of operation. Time history and different curves are included to show the effectiveness of the controller. Eventually, validation curves are given to estimate the degree of closeness between the analytical and numerical solutions.

1. Introduction

Mechanical vibrations are unwanted phenomena in dynamic structures. They are the reason of nuisance, damage, and sometimes destruction of the industrial systems. Rotating beams are cantilever beams used in helicopter blades, robot manipulators and compressor blades that may suffer from large vibration amplitudes. Those large nonlinear vibrations can cause catastrophic results, especially when operating at a large speed which leads to a huge centrifugal force. Yoo et al. (2001) established the model for pre-twisted rotating blades and made an analysis to clarify the characteristics of vibration in case that a concentrated mass was attached to it. Sinha (2004) investigated the characteristic dynamics of the same model but with a radial blade considering Coulomb damping and a centrifugal force affecting the whole system. Fazelzadeh et al. (2007) adopted a differential quadrature method, first order shear deformation theory, and Galerkin's technique to examine a rotating blade behavior. It was also thin-walled and made of fiber-reinforced composite materials subjected to supersonic gas flow with high temperature. Yao et al., 2012, 2014 utilized Hamilton's principle and isotropic constitutive law to conclude the governing equations of the beam. They analyzed the beam's dynamics at varying speeds under supersonic gas flow and high temperature considering the internal resonance cases of 1:1 and 2:1, respectively.

Theoretical and experimental investigations of the rotating blades response were done to eliminate or suppress the vibrations that could seriously destroy the reported structures. Younesian and Esmailzadeh (2011) reduced the vibrations of a rotating beam by about 50% by applying an internal (time increasing) tensile force. They adopted Hamilton's principle for deriving the bending and longitudinal equations of a rotating blade. Recently, piezoelectric fiber-based sensors and actuators have attracted the attention of researchers. Different kinds of piezoelectric fiber composites have been developed in recent years such as macro fiber composite (MFC). MFC is a combination of an actuator and a sensor offering high performance, durability, and flexibility in a cost-competitive device. Park and Kim (2005) concluded that the active twist rotor blade with a single crystal MFC had an excellent twisting actuation performance. However, the density of a single crystal MFC was slightly higher than that of the active fiber composite and the standard MFC. Therefore the optimal design for a single crystal MFC should be investigated to actuate the structure, efficiently. Choi et al., 2006, 2007 illustrated that an active damping effect could be obtained through a negative velocity feedback control algorithm with Polyvinylidene fluoride (PVDF) sensors and MFC actuators. Accordingly, adequate vibration suppression would be obtained through the suitable arrangement and distribution size of a sensor/actuator pair. Vadiraja and Sahasrabudhe (2009) presented structural modeling of a higher order shearable rotating thin-walled composite cantilever beam using a dynamic modeling method. They applied MFC actuators and sensors to suppress the vibrations of the rotating beam. They also proved that MFC sensors and actuators could be used for vibration sensing and suppression of rotating composite beams.

The authors in (Warminski et al., 2011; Shin et al., 2012; El-Ganaini et al., 2013) studied active vibration control by applying the positive position feedback (PPF) controller, which is a second-order differential

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Nomenclature

$\ddot{p}$, $\dot{p}$, p	Acceleration, velocity, and position of the first mode of the system
$\ddot{q}$, $\dot{q}$, q	Acceleration, velocity, and position of the second mode of the system
$\ddot{y}$, $\dot{y}$, y	Acceleration, velocity, and position of the controller
μ_1, μ_2, μ_{11}	Linear damping factors of the system modes and controller
ω, ω_1	Natural frequencies of the system modes and controller
β_{11}, β_{21}, β_{13}, β_{22}, β_5	Coupling factors between the system modes
β_5, α	Cubic nonlinearity factors of the system modes and controller
β_{14}, β_{24}	Parametric excitation parameters
β_{16}	External excitation parameter
f_0, f	External force amplitudes
Ω	Excitation frequency
c_1, c_2	Gains of both control and feedback signals
σ_1, σ_2	Detuning parameters
τ_1, τ_2	Time delays of the feedback and control signals
ε	Small Perturbation Parameter

equation coupled to the main system, linearly. It has been terrific in suppressing the amplitudes of the studied dynamical systems. They ensured that the maximum benefit of the PPF controller could be fulfilled by tuning its natural frequency in the neighborhood of the measured excitation frequency. Unfortunately, active control techniques exhibited a time delay that resulted from measuring the system states, transport delay, filtering and processing of data, calculation and execution of the control forces. These issues have been considered as sources of instability. Many researchers have studied the stability issue and the performance of delayed control systems. Das and Chatterjee (2002) studied and solved the delay differential equations near Hopf bifurcations by using the multiple scales method. They showed that the obtained solutions provided excellent approximations for the full numerical solutions of the original delay differential equations (DDE). Ahlborn and Parlitz (2005) discussed the utilization of the multiple delay feedback control (MDFC) method with two, three, or four different and independent delay times to stabilize steady states of various chaotic dynamical systems. They compared their work with the delay feedback control methods based on a single (fundamental) delay time. They also showed that the MDFC was more effective for fixed-point stabilization in terms of stability and flexibility, in particular for large delay times. Zhao and Xu (2007) applied the delayed feedback control to suppress the vibrations of vertical displacement in a two-degree-of-freedom nonlinear system subjected to external excitations. With the time delay variations (for a fixed gain), it was seen that the vibrations could be suppressed at a region of time delays called vibration suppression region. El-Ganaini et al. (2016) applied a time-delayed PPF controller to reduce the horizontal vibrations of a magnetically-levitated body subjected to multi-force excitations. That controller was coupled to the main system at 1:1 internal resonance. The effect of time delay magnitude was investigated to indicate the safe region of operation.

In this paper, the adopted model in (Yao et al., 2012, 2014) is our case study as shown in Fig. 1-a,b. The vertical and horizontal deflections of the blade cross section can be measured or sensed via the embedded MFC sensors that are distributed over the bottom surface of the blade as shown in Fig. (1c). The measured signals will be sent back to the computer for analysis and computation of the appropriate control signal as shown in Fig. (1d). Once the control signal is calculated, it is passed through the conditioning circuit to be applied on the embedded MFC actuators that are distributed over the top of the blade in order to modify the blade position and reduce its vibrations. The whole operation continues until the steady state amplitudes become small compared to those before control. The multiple time scales method is performed to derive the steady-state equations and the results are verified through numerical simulations.

2. System model and perturbation analysis

In Fig. (1a), the horizontal (u_0) and vertical (v_0) displacements of the blade cross section have been approximated to the modes and $q(t)$, respectively, via a detailed Galerkin's technique according to Refs. (Yao et al., 2012, 2014). The uncontrolled system model, subjected to a periodic excitation, is as follows:

$$\ddot{p} + 2\mu_1\dot{p} + \omega^2 p + \beta_{13}\dot{q} + \beta_{11}q + \beta_5 pq^2 + \beta_5 p^3 = 2f_0 f\beta_{14}p\cos(\Omega t) + f^2\beta_{14}p\cos^2(\Omega t) + f\beta_{16}\Omega\sin(\Omega t) \tag{1.a}$$

$$\ddot{q} + 2\mu_2\dot{q} + \omega^2 q + \beta_{22}\dot{p} + \beta_{21}p + \beta_5 p^2 q + \beta_5 q^3 = 2f_0 f\beta_{24}q\cos(\Omega t) + f^2\beta_{24}q\cos^2(\Omega t) \tag{1.b}$$

In this research, we have summarized the process of control in Fig. (1c) as applied before in Refs (Choi et al., 2006, 2007; Vadiraja and Sahasrabudhe, 2009; Warminski et al., 2011). depending on MFC technology. When the piezoelectric sensors are used as strain rate sensors, the current can be converted into a sensor voltage output. As long as the blade oscillates, the MFC sensors produce a voltage proportional to the derivatives of the blade coordinates as $V_s(t) = K\begin{bmatrix}\dot{p}(t)\\ \dot{q}(t)\end{bmatrix}$ (Choi et al., 2006, 2007; Vadiraja and Sahasrabudhe, 2009). After that, this voltage signal is passed through a low-pass filter, which acts as an integrator to produce the feedback signal $F_f(t) = K\begin{bmatrix}p(t)\\ q(t)\end{bmatrix}$ inserted into the vibration controller unit as in Ref. (Warminski et al., 2011). Our proposed controller (Eq. (2.c)) processes this signal and produces a control signal $F_c(t)$. The control signal needs to be conditioned through a signal conditioning circuit for providing the MFC actuators with the voltage $V_a(t)$ as stated in Refs. (Choi et al., 2006, 2007; Vadiraja and Sahasrabudhe, 2009; Warminski et al., 2011). We can see that the first mode (Eq. (1.a)) is the only one excited by an external excitation $f\beta_{16}\Omega\sin(\Omega t)$, which is very effective in the primary resonance case. So, we should apply the control signal only on the first mode , and then the second mode $q(t)$ will follow it due to the strong coupling between the two modes thanks to the exact internal resonance of 1:1. After applying the time delayed PPF controller to Eq. (1.a), the overall motion equations will be:

$$\ddot{p} + 2\mu_1\dot{p} + \omega^2 p + \beta_{13}\dot{q} + \beta_{11}q + \beta_5 pq^2 + \beta_5 p^3 = 2f_0 f\beta_{14}p\cos(\Omega t) + f^2\beta_{14}p\cos^2(\Omega t) + f\beta_{16}\Omega\sin(\Omega t) + c_1 y(t-\tau_2) \tag{2.a}$$

$$\ddot{q} + 2\mu_2\dot{q} + \omega^2 q + \beta_{22}\dot{p} + \beta_{21}p + \beta_5 p^2 q + \beta_5 q^3 = 2f_0 f\beta_{24}q\cos(\Omega t) + f^2\beta_{24}q\cos^2(\Omega t) \tag{2.b}$$

$$\ddot{y} + 2\mu_{11}\dot{y} + \omega_1^2 y + \alpha y^3 = c_2 p(t-\tau_1) \tag{2.c}$$

The parameters of Eq. (2) are suitably scaled such that:

$$\alpha = \varepsilon\hat{\alpha},\ \beta_{11} = \varepsilon\hat{\beta}_{11},\ \beta_{13} = \varepsilon\hat{\beta}_{13},\ \beta_{14} = \varepsilon\hat{\beta}_{14},\ \beta_{16} = \varepsilon\hat{\beta}_{16},\ \beta_{21} = \varepsilon\hat{\beta}_{21},$$
$$\beta_{22} = \varepsilon\hat{\beta}_{22},\ \beta_{24} = \varepsilon\hat{\beta}_{24},\ \beta_5 = \varepsilon\hat{\beta}_5,$$
$$c_1 = \varepsilon\hat{c}_1,\ c_2 = \varepsilon\hat{c}_2,\ \mu_1 = \varepsilon\hat{\mu}_1,\ \mu_2 = \varepsilon\hat{\mu}_2,\ \mu_{11} = \varepsilon\hat{\mu}_{11} \tag{3}$$

Applying the multiple time scales method (Nayfeh and Mook, 1995), asymptotic expansions are sought as:

$$p(T_0, T_1; \varepsilon) = p_0(T_0, T_1) + \varepsilon p_1(T_0, T_1) + O(\varepsilon^2) \tag{4.a}$$