HYBRID ADAPTIVE VIBRATION CONTROL OF SMART ROTOR BLADES

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Abstract

This paper deals with the control strategy and the real time simulation of adaptive vibration control of smart rotor blades. Firstly, the dynamics of a scale BO-105 smart rotor blade is introduced, and described by a recursive MX-filter in which the coefficients have the certain relationships with the blade's modal parameters, e.g. natural frequencies and modal damping, etc. Secondly, based on adaptive feedforward control, a hybrid adaptive control strategy is presented. It is mixed by a conventional feedback controller and an adaptive feedforward controller, and can both increase the modal damping and cancel the disturbance response. Thirdly, evident vibration reductions are observed for single frequency (4Ω, 8Ω), dual-frequency (4Ω and 8Ω), variable frequency (3.83Ω-4Ω-4.23Ω) and variable amplitude harmonic excitations.

List of Symbols

$a'_{l,ij}(k)$, $a''_{l,ij}(k)$	: transversal coefficients of MX-filter
a_0, a_1, a_2	: coefficients of the numerator of the PID controller in z^{-1} polynomial
$b'_l(k)$, $b''_l(k)$	: recursive coefficients of MX-filter
b_1, b_2	: coefficients of the denominator of the PID controller in z^{-1} polynomial
$c_{ij}(k)$	: transversal coefficients of MX-filter
$d(k)$	: response due to disturbance
$D(z)$	: impulse transfer function of the PID controller
$e(k)$	: total response due to disturbance and control
$E(z)$	: z-transform of $e(k)$
f	: disturbance
$f^i_{l,j}$, $f^o_{l,i}$	: l-th shape values at the j-th actuator
	: position and the i-th sensor position
$g(k)$	: response due to control
$h_2(k)$	: impulse sequence of H_2
H_1, H_2	: impulse transfer functions
$\hat{H}_2$	: estimation of H_2
i	: subscript, concerning the i-th output
	: $i=1,2,...,m_o$
j	: subscript, concerning the j-th input
	: $j=1,2,...,m_i$
J	: cost function
k	: k-th sampling interval
K_P, K_I, K_D	: gains of the PID controller
l	: subscript, concerning the l-th mode
	: $l=1,2,...,m$
L	: FIR filter order
m	: number of modes
m_i	: number of inputs of MX-filter
m_o	: number of outputs of Mx-filter
m^d_l	: l-th modal mass
N	: blade number
M	: FIR filter order
P	: FIR filter order
r	: filtered-x signal
$s_{0,i}$, $s'_{l,i}$, $s''_{l,i}$	: states of MX-filter
T	: sampling period
u_b	: control signal due to feedback control
u_f	: control signal due to feedforward control
u	: sum of u_b and u_f
$U_b(z)$	: z-transform of $u_b(k)$
$v_j(k)$	: input of MX-filter
w_k	: sequence in W
W	: weight of adaptive feedforward control
X	: reference signal
y_i	: output of MX-filter
z^{-1}	: time-delay factor
Ω	: nominal rotor speed
ω_l	: l-th modal frequency
ξ_l	: l-th modal damping ratio
μ	: convergence factor

Introduction

Helicopters are susceptible to high vibratory and aeromechanical loads, excessive noise levels, and high dynamic stress. The main source for all those problems is the nonsteady and complex aerodynamic environment in which the rotor must operate. To improve helicopter performances, many design methods and devices are applied. In general, there are two types of methods for reducing helicopter vibrations : passive and active. Passive methods include passive absorbers, passive isolators, and the optimization design of the rotor - fuselage dynamics. These methods and devices have suppressed helicopter vibrations greatly, but it is difficult for them to reduce furtherly. Much attention has been paid to active methods for about a decade[1,2], e.g. Higher Harmonic Control(HHC), Individual Blade Control (IBC), Active Control of Structural Response (ACSR), etc. HHC is realized by driving the swashplate, it is initially used for reducing vibration, but it has some disadvantages such as complex configuration, etc. IBC is a general extension of HHC with each blade controlled individually. Recent works show that HHC and IBC can reduce rotor noise and improve the characteristics of rotors. ACSR has great potentiality for applications, and has been tested in some helicopters (W-30, S-70B, UH-60). It has two types: active isolators located between transmissions and fuselages and servo-inertial force generators located at the floors of the chambers.

In above methods, actuators are separated from blades. Starting from the early 1990s, the integrations of actuators and blades, called smart rotors, attract many researchers[3]. many works have been done on feasibilities, configuration designs and the choices of actuators. Up to now, three kinds of configuration concepts are presented: adaptive nose droop, the trailing-edge flaps driven by smart actuators, adaptive blade twist.

The adaptive nose droop concept studies the local deformations of the leading edge of blades. Lift changes are obtained by changing the aerodynamic contour during operations. Since the airfoil sections are specially designed and can be deformed automatically, the dynamic stall characteristics can be successfully influenced, unfavorable pitching moment peaks and areas of negative aerodynamic damping can completely be avoided. This has been shown by numerical investigations at the DLR[4].

The trailing-edge flap concept has received more attentions because of the inherent advantages of extracting additional powers from the airstream through the servo-aerodynamic effect. Researches are focused on the types of actuations. Piezo-bimorphs[5,6], hybrid stack/tube actuators with hydraulic multipliers[7,8], magnetostractive actuators[9] are under studying. However the efficiency of these flaps is questionable in respect to long blades with low torsional stiffnesses. Additionally, blade torsion due to the rudder moments and the additional vortices leaded by changes in lift distribution due to the flap may cause problems[10].

Adaptive blade twist is an other concept. The blade twist, especially at the outer part of the blades, can be achieved by the following actuation principles:

- Torsion caused by a servoflap [11];
- Torsion caused by 45^0 orientated tension forces [11,3,12];
- Torsion due to torsion-warping coupling[10];
- Torsion due to torsion-tension coupling[3,10]

The last principle is currently being developed at the DLR.

Compared with the configuration designs of smart rotor blades, there are limited works on smart rotor control. Ref.[13] studied the adaptive control in frequency domain, the vibration component of primary passing frequency can be reduced. Ref.[14] used the LQR/LTR and H^{∞} methods for increasing the modal damping ratios of blades, but it is difficult to adapt to the dynamical characteristics of helicopters. Ref.[15] presented some additional control concepts of smart rotors.

In general, there are two kinds of methods to design helicopter vibration controllers: frequency domain methods and time domain methods. Because of the harmonic features of helicopter vibrations, the frequency domain methods are usually used. They can be described by following steps: (a) measuring helicopter vibration; (b) transforming the vibration signal from time domain into frequency domain by FFT; (c) calculating the control signal in frequency domain, according to the vibration and the features of helicopters. In this step, the inversion of matrix is needed; (d) transforming the control signal from frequency domain into time domain by IFFT. But compared with frequency domain methods, time domain methods have some potentials, e.g. fast update rate, recursive algorithm, easy treatment of transient responses, etc.. The comparisons of control methods are listed in Table 1.

Table1 The comparisons of the control methods in frequency domain (FD) and time domain (TD)

	FD	TD
FFT & IFFT	yes	no
inversion of matrix	yes	no
transient response	yes	no
update rate	slower	faster
dimension	same	
reference signal	no	yes
identification	yes	
convergence problem	less	more

The paper deals with adaptive vibration control of smart rotor blades in time domain. It is divided into three sections. Firstly, the dynamics of a scale BO-105 smart rotor blade is introduced, and described by recursive MX-filters; Secondly, based on adaptive feedforward control, the hybrid adaptive control strategy is presented. It is formed by a conventional feedback controller and an adaptive feedforward controller. Thirdly, real time simulations are done by two Digital Signal Processor (DSP) boards, and evident vibration reductions are gotten for different excitations.

Dynamic Modeling of Smart Rotor Blades

Helicopter Vibration Features

Helicopters always suffer from the periodical loads, so long as they fly. The typical vibration source of helicopters is the rotor vibration loads caused by the periodic aerodynamic forces and the blade vibration. If helicopters have horizontal velocities, the tangential velocities of blade sections will periodically vary from the azimuth angles of blades, due to the superimposition of horizontal velocities and the rotating speed. Meanwhile, the induced velocities are not well distributed, because rotor tracks are not symmetrical about the blade spanwise axis.

Because of the periodical environment, the aerodynamic loads must periodically vary. The frequency must be one time per revolution, because the azimuth angle changes one time per revolution. Extending the aerodynamic loads into a Fourier series with the basic frequency of the nominal rotor speed (Ω), it can be found that the aerodynamic loads are of all harmonic components: Ω, 2Ω, 3Ω, 4Ω, $\cdots$, and the higher harmonic components have smaller coefficients. So only the low harmonic components play typical role in vibration excitations.

For a rotor with N blades, the forces and moments at rotor hub are composed of those at each blade root. Though the forces and moments at each blade root contain all harmonic components, parts of them are remained in the rotor hub and transmitted to fuselages, others are canceled. The left harmonic components are those: $N\Omega$, $2N\Omega$, $3N\Omega$, $\cdots$. They are the main vibration excitation sources of helicopter fuselages. The tested BO-105 fuselage vibration feature in the vertical direction showed that predominant frequencies are 4Ω, 8Ω.

One reason for the vertical fuselage vibration comes from the blade flapwise motion. If the blade flapwise vibration is reduced to a low level, the rotor vibration loads will also be low, and the helicopter vibration level will be low. Here the flapwise vibration of each smart blade is therefore modeled and controlled individually.

Basic Features of the Smart Blade

It is assumed that the model blades are scale of BO-105 rotor blades and manufactured by glass-fiber enhanced composite. Piezo-electric materials are integrated to cause their twist motion. The blade and rotor data are listed in Table 2. To get the same blade tip velocity of real BO-105 blades, the nominal rotor speed of the smart rotor is raised. The natural frequencies of the blade can be seen in Table 3.

Table 2 Blade and rotor data

number of blades	4	twist	-6°14'
rotor diameter	4m	pre-coning	2.5°
blade chord	0.121m	design thrust	3900N
lock number	8	scaling factor	2.455
nominal rotating speed	110rad/s	airfoil	NACA 23012 mod.

Table 3 The natural frequencies of the smart blade

	non-rotating in Hz	rotor speed at 110 rad/s. in Hz (1/rev)
first flapwise mode	2.9	19.6 (1.12)
second flapwise mode	17.4	50.3 (2.87)
third flapwise mode	47.4	90.5 (5.17)
first chordwise mode	10.8	13.7 (0.78)
second chordwise mode	66.6	78.9 (4.5)
first torsion mode (infinite control stiffness)	67.9	70 (4.0)

The MX-Filter

The MX-filter is very suitable for modeling structural dynamic features, because of the definite relationships of MX-filter coefficients with respect to the modal parameters of structures, e.g. modal frequencies, modal damping ratios, etc. The MX-filter was named from its modal formulation due to parallel form and its apparent cross-coupled structure[16]. Here, it is extended to the multi-input and multi-output case. In the case of m_o outputs, m_i inputs and m modes, the filter difference equations are as follows:

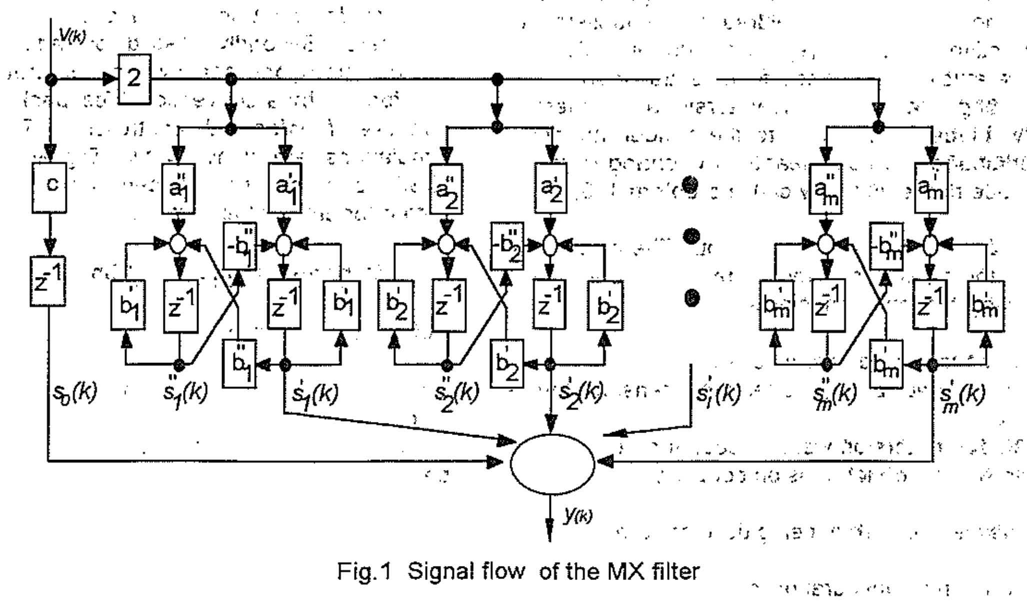

Fig.1 Signal flow of the MX filter

$$s_{0,i}(k) = c_{ij}(k-1)v_j(k-1) \quad (1)$$

$$s^{'}_{l,i}(k) = 2a^{'}_{l,ij}(k-1)v_j(k-1) + b^{'}_l(k-1)s^{'}_{l,i}(k-1) - b^{''}_l(k-1)s^{''}_{l,i}(k-1) \quad (2)$$

$$s^{''}_{l,i}(k) = 2a^{''}_{l,ij}(k-1)v_j(k-1) + b^{'}_l(k-1)s^{''}_{l,ij}(k-1) + b^{''}_l(k-1)s^{'}_{l,ij}(k-1) \quad (3)$$

$$y_i(k) = s_{0,i}(k) + \sum_{l=1}^{m} s^{'}_{l,i}(k) \quad (4)$$

$$i = 1,2,\ldots,m_o, \; j = 1,2,\ldots,m_i, \; l = 1,2,\ldots,m$$

where $v_j(k)$ and $y_i(k)$ are the j-th input and the i-th output of the MX-filte. Otherwise, it has $(2m_o m_i l + m_o m_i + 2l)$ real coefficients: the transversal coefficients c_{ij}, $a^{'}_{l,ij}$, $a^{''}_{l,ij}$ and recursive coefficients $b^{'}_l$, $b^{''}_l$.

The signal flow of a single input / single output MX-filter are shown in Fig.1, in the figure, the subscripts i,j are omitted.

The relationships of coefficients $b^{'}_l$, $b^{''}_l$ with respect to the modal frequencies ω_l, the modal damping ratios ξ_l and the sampling period T are as follows

$$b^{'}_l = e^{-\xi_l \omega_l T}\cos(\sqrt{1-\xi_l^2}\,\omega_l T) \quad (5)$$

$$b^{''}_l = e^{-\xi_l \omega_l T}\sin(\sqrt{1-\xi_l^2}\,\omega_l T) \quad (6)$$

and

$$a^{'}_{l,ij} = -\frac{1}{2}\frac{f^o_{l,i}f^i_{l,j}}{m^d_l}(1 - b^{'}_l + \frac{\xi_l}{\sqrt{1-\xi_l^2}}b^{''}_l) \quad (7)$$

$$a^{''}_{l,ij} = \frac{1}{2}\frac{f^o_{l,i}f^i_{l,j}}{m^d_l}\left[b^{''}_l + (b^{'}_l - 1)\frac{\xi_l}{\sqrt{1-\xi_l^2}}\right] \quad (8)$$

$$c_{ij} = \sum_{l=1}^{m}\frac{f^o_{l,i}f^i_{l,j}}{m^d_l} \quad (9)$$

where $f^i_{l,j}, f^o_{l,i}$ are the l-th shape values of the controlled structure at the j-th actuator position and the i-th sensor position, respectively; m^d_l is the l-th modal mass of the controlled structure.

Modeling of Smart Blade Dynamics by MX-filters

The responses of the smart blades are caused by two factors, disturbances and control signals. Disturbances typically come from unsteady aerodynamics. To model the dynamics of a controlled blade, an MX-filter with 2 inputs and a output must therefore be used. One of inputs is the disturbance, the other the control signal. The total response of the blade is the sum of responses due to the disturbance and the controller. The filter coefficients can be determined by Eqs.(5)-(9).

A local Digital Signal Processing (DSP) board is used to realizing the real-time simulation of the dynamics of the smart blade. The processor is Motorola DSP56002, which is a 24-bit, 40MHz crystal oscillation frequency, 50ns instruction cycle DSP. The local DSP board has two A/D channels and two D/A channels. Its sampling frequency can be programmed from 8K to 48K Hz. By RS-232 serial port, it can communicate with IBM PC-compatible computers to perform debugging and data transmission.

Considering the first three flapwise modes of the smart blades, the spectrum of the flapwise response only excited by white noise is shown in Fig.2. The agreements of the predominant frequencies with the modal flapwise frequencies prove the feasibility of modeling the dynamics of smart blades by MX-filters.

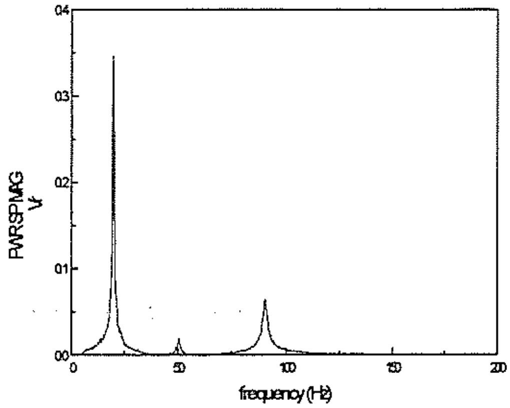

Fig. 2 Response spectrum of white noise excitation

Hybrid Adaptive Control Strategy

Due to the harmonic feature of helicopter vibration, adaptive feedforward control strategy is a very suitable choice.

Adaptive Feedforward Control

Fig. 3 shows the basic principle of adaptive feedforward control. In the Figure, X is called the reference signal at the k-th sampling interval; H_2 is called the impulse response function of the error channel; $\hat{H}_2$ is the estimation of H_2; $d(k)$ and $g(k)$ are the responses caused by the disturbance and the controller at the k-th sampling interval, respectively, and $d(k)$ is called uncontrolled response; $e(k) = d(k) + g(k)$ is called controlled response; W contains the weights of the controller.

Assuming that the H_1, H_2 and W can be described by finite impulse filters (FIR) with the order M, L and P, respectively, then

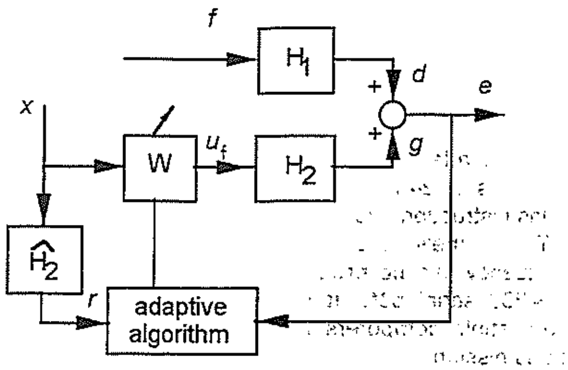

Fig.3 Adaptive feedforward control system

$$e(k)=d(k)+g(k)=d(k)+\sum_{j=0}^{L}h_2(j)u_f(k-j)$$

$$=d(k)+\sum_{j=0}^{L}\sum_{n=0}^{P}h_2(j)w_k(n)x(k-j-n)$$

$$=d(k)+\sum_{n=0}^{P}w_k(n)r_k(n) \qquad (10)$$

where

$$r_k(n)=\sum_{j=0}^{L}h_2(j)x(k-j-n) \qquad (11)$$

is called the filter-x signal.

For single input and single output system, the cost function J

$$J=\mathrm{E}[e^2(k)] \qquad (12)$$

Usually, J is chosen as the square of error at a sample interval for the convenience of real-time processing. According to the Least Mean Square (LMS) algorithm, the weights of the controller can be recursive by the following formulation

$$w_{k+1}(n)=w_k(n)+2\mu e(k)r_k(n) \qquad (13)$$

where μ is the convergence factor. Then

$$u_f(k)=\sum_{n=0}^{P}w_k(n)x(n) \qquad (14)$$

From Eqs. (11) and (13), w_{k+1} depends on w_k, μ, $e(k)$ and $r_k(n)$. Usually, $w_0(n)=0$, $\hat{H}_2$ can be identified off-line or on-line, and $e(k)$ can be measured by sensors. Hence, the weights of the controller will easily be recursive, if the convergence factor μ and the reference signal x are determined.

The adaptive feedforward controller is realized by another local DSP board. The controlled response excited by a 4Ω harmonic disturbance is shown in Fig.4. It can be found that the 4Ω vibration has been controlled, but the lowest flapwise mode of the smart blade is excited, leading to an unstable system.

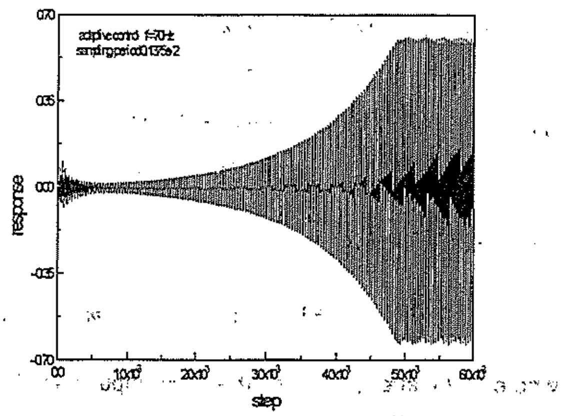

Fig.4 The response of adaptive feedforward control

Hybrid Adaptive Control

In last section, it is shown that the adaptive feedforward control does not give a good vibration reduction, even, it causes an unstable system. This situation would happen while the least modal frequency of the controlled structure is less than the excitation frequency, and the modal damping is small. To solve this problem, there must be an effective method to increase the modal damping of the lowest mode of the controlled structure. Thus, a hybrid control strategy is presented here. It is formed by adding a feedback controller to the adaptive feedforward controller. The feedback controller can increase the modal damping, and the adaptive feedforward controller can cancel the disturbance response. Fig. 5 is the diagram of the hybrid adaptive control. Within the dashed frame of the figure is the feedback control loop.

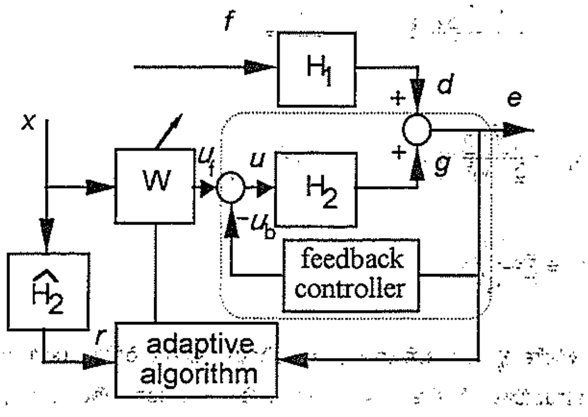

Fig.5 Hybrid adaptive control

From Fig.5, the total control is

$$u(k)=u_f(k)-u_b(k) \qquad (15)$$

where u_b is the feedback control signal, u is the total control signal formed by the feedback and feedforward controllers.

A simple and useful feedback controller is a PID (Proportional-plus-Integral-plus-Derivative) controller. It is special type of the lag-lead controller. Its transfer function is as follows

$$D(z)=\frac{U_b(z)}{E(z)}=K_P+\frac{K_I T}{2}\left(\frac{z+1}{z-1}\right)+\frac{K_D}{T}\left(\frac{z-1}{z}\right) \quad (16)$$

where $U_b(z), E(z)$ are the Z-transforms of $u_b(k)$ and $e(k)$, respectively; K_P, K_I and K_D are the proportional, integral and derivative gains, respectively.

Eq.(16) can also be rewritten in the following type.

$$D(z)=\frac{a_0+a_1 z^{-1}+a_2 z^{-2}}{1+b_1 z^{-1}+b_2 z^{-2}} \quad (17)$$

where

$$a_0=K_P+\frac{K_I T}{2}+\frac{K_D}{T}, \qquad a_1=-K_P+\frac{K_I T}{2}-\frac{2K_D}{T}$$

$$a_2=\frac{K_D}{T}, \quad b_1=-1, \quad b_2=0$$

The PID controller can be simplified in a PI controller or a PD controller. The PI controller can increase the low-frequency gain of the controlled plant, and the PD controller can improve system stability, increase closed-loop system bandwidth.

The Results of the Hybrid Adaptive Control

To evaluate the capability of the hybrid adaptive controller, several excitations are applied to the model of the smart blades, i.e. single frequency excitations(4Ω) with constant frequencies and amplitudes, single frequency excitations with variable frequencies or amplitudes, and dual-frequency excitations(4Ω, 8Ω).

Figs.6 and 7 are the impulse response of the smart blade for the cases without or with the feedback controller, respectively. The least modal damping of the smart blade with the feedback controller is increased to 3.5 times of

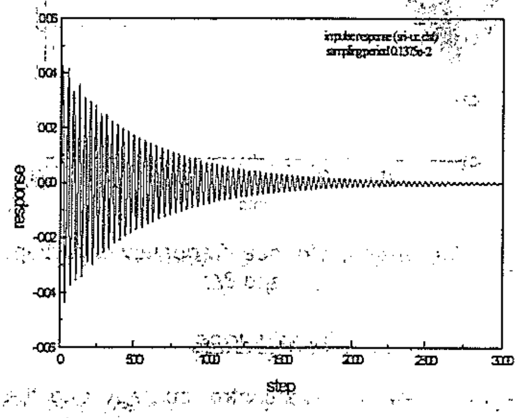

Fig.6 The impulse response of the smart blade (without the feedback controller)

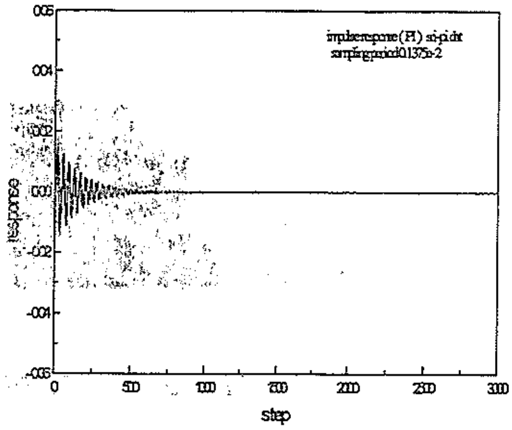

Fig.7 The impulse response of the smart blade (with the feedback controller)

that without the feedback controller.

Figs.8-10 show the response, a controller weight and the control signal of the hybrid adaptive controller for 4Ω harmonic disturbance. They indicate that the lowest flapwise mode are controlled, after the PI controller is added, and the disturbance response are fully controlled.

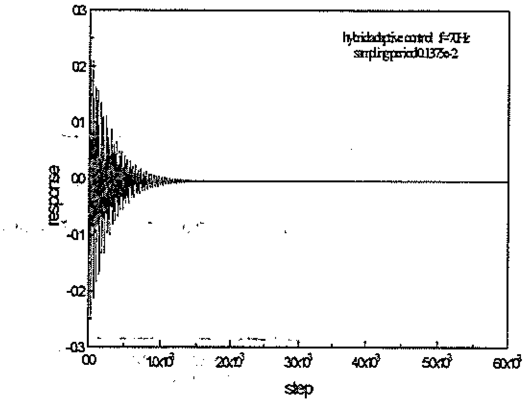

Fig.8 The response for single frequency excitation (4Ω)

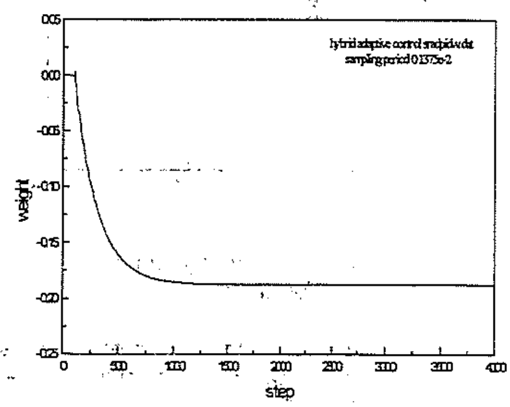

Fig.9 A weight of the hybrid adaptive control

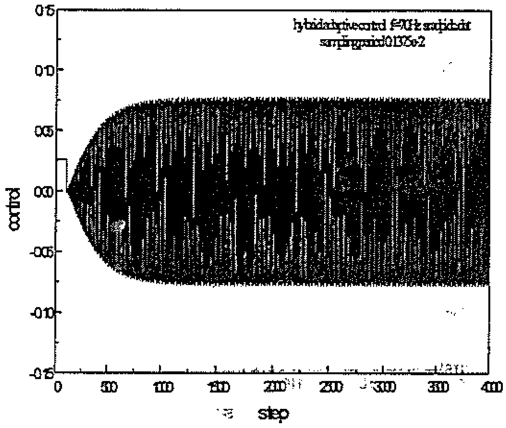

Fig.10 The control signal of the hybrid adaptive control

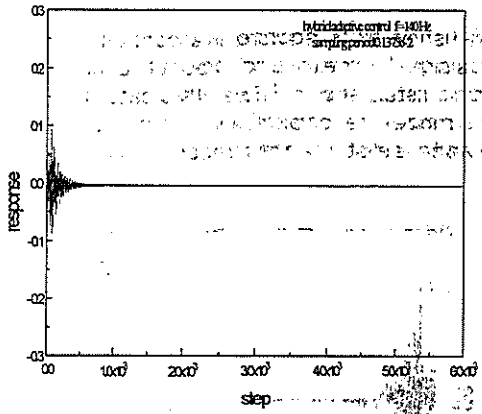

Fig.11 The response for single frequency disturbance (8Ω)

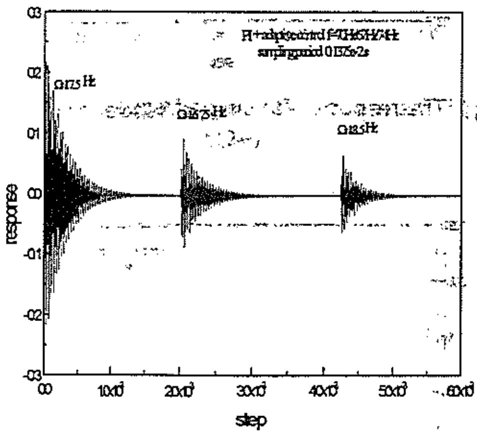

Fig.12 The response due to change of the disturbance frequency

Fig.11 gives the flapwise vibration response of the smart blade with the hybrid adaptive controller for a 8Ω harmonic disturbance excitation.

Fig.12 shows the response of the smart blade with the hybrid adaptive controller for a varied frequency disturbance. This state will happen while the rotor speed changes. The result shows that the hybrid adaptive control works well, even while the rotor speed changes around the normal speed. The rotor speed varies in the range of [0.95Ω-1.05Ω].

Fig.13 shows the response of the smart blade with the hybrid adaptive controller due to the change of the disturbance amplitude.

Fig.14 shows the response of the hybrid adaptive control for a dual-frequency excitation (4Ω and 8Ω). From this figure, it can be seen that the hybrid adaptive control can cancel the 4Ω and 8Ω components of the disturbance.

From above results, it can be concluded that the studied hybrid adaptive control can suppress the flapwise vibration of the smart blade very well, because the higher components of the disturbance are very small.

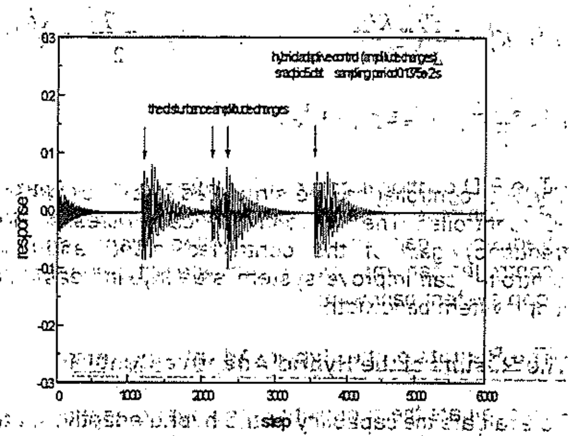

Fig.13 The response due to change of the disturbance amplitude

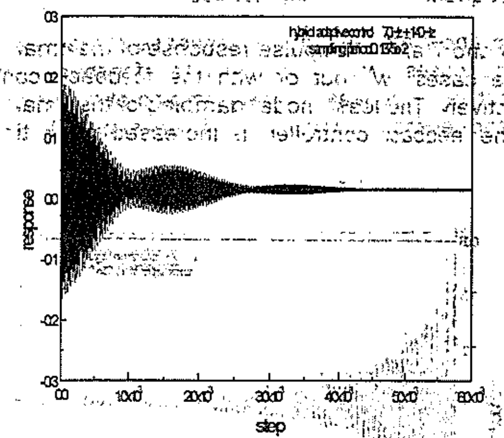

Fig.14 The response for dual-frequency disturbance (4Ω and 8Ω)

Conclusions

This paper deals with the control strategy and the real time simulation of adaptive vibration control of smart rotors. Firstly, the dynamics of a scale BO-105 smart rotor is introduced, and described by a recursive MX-filter in which the coefficients have the certain relationships with the rotor's natural frequencies and modal damping, etc. Secondly, based on adaptive feedforward control, a hybrid adaptive control strategy is presented. It is formed by a conventional feedback controller and an adaptive feedforward controller. The feedback controller increases the modal damping, while the adaptive feedforward controller cancels the disturbance response. Thirdly, Vibration reductions are observed for single frequency, dual-frequency, varied frequency and varied amplitude harmonic excitations.

The future works are as follows: further development of the on-line aero-elastic model and the system realization of the control strategy. After these steps, experiments will be performed on real rotors.

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