Helicopter Performance and Vibration Enhancement by Twist-Actuated Blades

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ABSTRACT

This paper investigates potential improvements that can be accomplished by integral twist-actuated rotor blades regarding helicopter performance and its vibration. The twist deformation is obtained using anisotropic piezocomposite actuators embedded in the composite blade construction. A four-bladed fully-articulated Active Twist Rotor (ATR) system was built and tested at Langley Transonic Dynamics Tunnel. From these tests, the integral twist control authority exerted upon the fixed system was determined. Significant control authority in hub vertical shear load component is observed from different blade actuation modes. Similar control authority is found in the other components of the fixed-system loads. Exploiting those authorities, vehicle performance enhancement can be achieved using low-frequency actuation, for example, 0P, 1P and 2P. Payload increase in hover can be obtained with a steady collective actuation of blade twist. Power consumption can be reduced by employing a certain mode of blade actuation at 2P in forward flight. Vehicle pitch and roll moments are generated by longitudinal and lateral blade actuation mode at 1P frequency. On the other hand, actuation at higher frequencies can be used to reduce hub vibratory loads. The closed-loop control algorithm used for this reduction is an improved version of the traditional Higher Harmonic Control. Multi-harmonic and multi-mode controller is designed and tested as part of the present study.

INTRODUCTION

Rotorcraft has been a very important means of aerial transportation due to its capability of vertical take-off and landing. However, it has also been under serious constraints such as relatively poor ride quality associated with high levels of vibration and noise, restricted flight envelope, low fatigue life of the structural components, and consequently high operating cost. The primary source which brings these shortcomings is the complex unsteady aerodynamic environment generated near the rotor blades mainly during forward flight. An instantaneous asymmetry of the aerodynamic loads acting on the blade at different azimuth locations is developed, and such asymmetry becomes more and more adverse as the forward flight speed increases. Such an unsteady aerodynamic environment near the rotor system also imposes constraints on the vehicle performance.

There have been considerable efforts in the helicopter community to improve helicopter performance and vibration, and most of them are based on passive methodologies [1]. During the last two decades, however, active methods to alleviate helicopter vibration based on the idea of directly modifying the unsteady aerodynamic loads on the rotor blades have been pursued. These methods may be broadly classified as higher harmonic control and individual blade control [2, 3]. Higher harmonic control (HHC) is accomplished by manipulating a conventional swashplate to enable blade pitch control at a higher multiple frequency than integral multiple of the rotor rotating frequency, i.e., $(kN \pm 1)/\Omega$ [2, 4, 5, 6, 7, 8]. Classical individual blade control (IBC) uses a feathering actuator in each blade rather than modulating the swashplate, and allows for blade pitch control at arbitrary frequencies [3, 9]. Several outstanding results were obtained in terms of vehicle performance and vibration improvement. Examples include wind tunnel tests with either small or full-scaled model [2, 9, 10], and flight tests [4].

For a closed-loop control implementation based on these methods, the so-called T matrix approach has been used to identify system transfer functions and determine the design of controllers [2, 5, 6]. In that approach, discrete component at target frequency, i.e., $N\Omega$, among the transfer function was only identified from sine-dwell open-loop actuation and used in the

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controller design. More advanced control algorithms were developed based on the basic T matrix approach and tested on an experimental rotor system in the wind tunnel. These controllers in general exhibited satisfactory capability for helicopter vibratory load reduction either in fixed-system or rotating-system loads. Flight test on a modified OH-6A aircraft was also conducted successfully with the higher harmonic control based on the T matrix approach [4]. However, these realizations have shown significant limitations for application in helicopters production. Typical identified problems are adverse power requirement and limitation on excitation frequency in HHC, and extreme mechanical complexity of hydraulic sliprings in IBC.

A variety of actuation mechanisms based on active materials have recently been suggested and tested to overcome the difficulties in the conventional HHC and IBC [11, 12, 13]. These active material-based actuators are embedded or surface-mounted at several locations in rotor blades, or installed inside the blade to drive trailing-edge flaps. By replacing the traditional hydraulic systems with active material-based actuators, potential advantages can be obtained in terms of weight and power consumption. In this study, an integral twist actuation concept is chosen for individual blade control among the various implementations [14, 15]. Although this implementation results in a different physical configuration than the hydraulic-based ones, its control scheme for improved vehicle performance and vibration may be developed from a common HHC or IBC methodology. A control algorithm based on the T matrix approach from the conventional HHC scheme was implemented successfully on an active rotor blade with trailing-edge flap driven by an X-Frame actuator in hover [16]. A similar scheme extended with an optimal control theory was investigated analytically for a possible application on a flap-actuated active rotor system [17].

Regarding vehicle performance improvement, there has been a successful wind-tunnel demonstration of full-scale BO-105 helicopter rotor with traditional IBC actuators [9]. In that experiment, reduced rotor power consumption was achieved during the forward flight by applying a certain prescribed actuation on the feathering actuators, called IBC mode. A preliminary analytical study was conducted on the CH-47D helicopter with integrally twist-actuated rotors [18]. An increase of hover payload was predicted using a steady blade actuation in that study.

NASA/Army/MIT Active Twist Rotor (ATR) program has been investigating the integral blade twist actuation for helicopter vibration in a more comprehensive fashion. It is a collaborative research effort between the U.S. Army Research Laboratory, at NASA Langley Research Center, and the University of Michigan/MIT. Throughout this program, analysis and design capabilities were established for active blades with embedded anisotropic piezocomposite actuators [19]. Using those capabilities, a prototype ATR blade was designed and fabricated for bench and hover tests [20, 21, 15]. After minor design modification, new ATR blades were manufactured and tested in forward flight [15]. During the open-loop forward flight test, significant changes on both fixed- and rotating-system loads were observed from a prescribed blade twist actuation [15]. This culminates to tests demonstrating the vibratory load reduction capability of the ATR concept and the control laws.

This paper evaluates the active blade twist control authority for improvements in vehicle performance and vibration. System identification is conducted experimentally to estimate the harmonic transfer functions [22] of the ATR system in various forward flight conditions. Sine-sweep input signals with varying control phase angles are used with several modes of blade actuation: collective, longitudinal cyclic, lateral cyclic, and differential. From those results, blade twist control authority on the rotor fixed-system can be determined. This control authority can also be translated into additional force (thrust) or moment that the rotor system can generate at a given frequency. Payload increase in hover, rotor power reduction in forward flight, and hub vibratory load reduction are considered here.

**FRAMEWORK**

For analyzing helicopter blades with embedded strain actuators, a framework is needed such that the effects of the active material embedded in the structure are carried throughout all the steps of the analysis. Since there are few analysis formulations available which can properly handle all the peculiarities of an active helicopter blade cross section like the ATR, the authors have worked on creating a general framework for active rotor blade modeling. Here, an asymptotical analysis takes the electromechanical three-dimensional problem and reduces it into a set of two analyses: a linear analysis over the cross section and a nonlinear analysis of the resulting beam reference line. By coupling the active blade formulation with the appropriate unsteady aerodynamics, the aeroelastic problem can then be solved in time and simulations be conducted for control design. A schematic diagram of the established framework is shown in Fig. 1.
Cross-Sectional Analysis

Stiffness and actuation forcing constants for an active anisotropic thin-walled two-cell beam are obtained from a variational-asymptotical formulation [19]. While restricted to thin-walled beams, it yields closed form solutions of the displacement field (which is derived and not assumed), and stiffness and actuation constants. The availability of correct closed form expressions is essential to determine design paradigms on this new type of blade, mainly concerning the tradeoffs between torsional stiffness and twist actuation. These stiffness and actuation constants are then used in the beam finite element discretization of the blade reference line.

Blade Structure and Aerodynamic Analyses

To simulate the active rotor system, a time-domain formulation is needed. The multi-body dynamics code DYMORE, developed by Bauchau and co-workers [23], is based on the geometrically-exact beam equations and it is coupled to the aerodynamics of Peters and He [24]. DYMORE’s original beam formulation is consistent with the one used previously by the authors in studying hover response of the ATR system [21]. The difference now is that the formulation is displacement-based instead of mixed-form. Therefore, the same cross-sectional analysis for active beams can be used. The integral actuation forces and moments existing inside the blade structure are realized in the form of finite element loads to the passive beam in the modified time domain analysis. The solution of the 1-D beam analysis provides blade displacement and generalized stress fields due to external loading and piezoelectric actuation, which are of interest in the analysis of static and dynamic deformations and aeroelastic stability.

The forward flight part of the finite-state dynamic inflow aerodynamics model [24] was already implemented in DYMORE. This aerodynamic theory was originally developed for both hover and forward flight conditions. This model was constructed by applying the acceleration potential theory to the rotor aerodynamics problem with a skewed cylindrical wake. More specifically, the induced flow at the rotor disk was expanded in terms of modal functions. As a result, a three-dimensional, unsteady-induced-flow aerodynamics model with finite number of states was derived in time domain. This model falls on an intermediate level of wake representation between the simplest momentum and the most complicated free wake methodologies. It does not require a severe computational effort, which is usually the case in those that involve the vortex filament theory. Therefore, this model is applicable to the problems of rotor aeroelastic stability, basic blade-passage vibrations, and higher-harmonic control studies [24].

Aeroelastic System in Forward Flight

The aeroelastic system of equations which combines the structural and aerodynamic equations obtained in the previous steps is now solved for forward flight condition to provide the information regarding the transient response. Specifically, the present analysis adopts a direct time integration of the blade response due to an integral actuation during flight. This time integration is required since further analytical tasks are expected to conduct in time domain. DYMORE, the original passive blade dynamics model, adopts a time-discontinuous integration scheme with energy decaying characteristics in order to avoid high frequency numerical oscillation [23]. Such an adverse high frequency oscillation usually occurs during a finite element time integration of a complex multi-body dynamic system.

ATR CHARACTERISTICS

Table 1 summarizes the general dimension and shape characteristics of the ATR blade. The ATR blade employs a total of 24 active fiber composite (AFC) packs placed on the front spar, and distributed in 6 stations along the blade span [15]. Fig. 2 shows basic blade planform and cross section characteristics selected for the ATR prototype blade. The material properties of the passive prepregs and the AFC plies used in the blade are summarized in the appendices of Refs. [19] and [21].
SYSTEM IDENTIFICATION TEST

During forward flight, the helicopter rotor blades are subject to an aerodynamic environment which varies itself with a period corresponding to the rotor revolution. This makes the helicopter rotor a linear time-periodic system during forward flight. Therefore, a methodology considering this periodicity is required for its characterization. In this paper, a method is adopted which results in multi-component harmonic transfer functions [25]. The theoretical background of the adopted methodology and its implementation schemes are described in detail in [25] including additional assumptions imposed on the transfer functions.

Sinusoids are used to determine transfer functions, and more specifically, sine-sweep waves (chirp signals) are used to obtain the system response over a specific range of frequencies. For each test condition, steady-state equilibrium is established first by adjusting the blade trim pitch controls. Sine-sweep signals corresponding to several modes of blade actuation, such as collective, longitudinal cyclic, lateral cyclic, and differential, are generated with varying initial control phase angles. Then, fixed- and rotating-system responses of the ATR system are measured while applying the constructed sine-sweep input signal. Before applying the system identification algorithm suggested in [25], undesirable noise is removed from the acquired measured data using a simple smoothing algorithm. Then, the amplitude of the baseline loads must be subtracted from those under actuation. The amount of loads added to the baseline quantity becomes the object of a transfer relationship. Five harmonic transfer functions are estimated, i.e., $G_{-2}$, $G_{-1}$, $G_0$, $G_{+1}$, $G_{+2}$, at a given condition.

Five harmonic transfer functions estimated for the hub vertical shear load component under collective mode of blade actuation are illustrated in Fig. 3. For the collective mode of actuation, $G_0$ is found to have amplitude which is significantly larger compared with the others. This indicates that the response of the ATR system may be described only by the $G_0$ component, like in a linear time-invariant (LTI) system, under the flight condition and blade actuation mode considered. The other modes of actuation exhibit a similar result with other modes of actuation exhibiting a similar result with $G_0$ as well. Differential mode is excluded from further consideration since it theoretically involves null control authority. Therefore, the fundamental transfer functions, i.e., $G_0$, obtained for the hub vertical shear load component by three blade modes of...
From the harmonic transfer function results, closed-loop controllers can be designed. Since the identified plant can be treated as a LTI system, controllers based on modern control theory methods may be developed. This makes the controller design and preliminary evaluation more effective. Actuation frequency and blade actuation mode used in the control study are selected based on the magnitude and phase of the corresponding transfer function. Also, combination of multiple modes or frequencies must be considered for further performance and vibration enhancement, which results in multi-harmonic or multi-mode controllers.

**PERFORMANCE ENHANCEMENT**

Significant control authority, as observed from the magnitude of the transfer functions of Fig. 4, indicates availability of twist actuation for different potential applications. Improvement in terms of vehicle performance is examined first. By applying steady collective actuation, additional thrust can be generated in hover condition. From Fig. 4 (a), it is expected by extrapolation that approximately 25 lb of the hub vertical shear load is obtained by collective actuation at 0P. This amount of additional thrust is equal to about 10% of the ATR nominal thrust. Similar thrust variation was predicted by analytical simulation conducted on the Mach-scaled CH-47D active integral twist rotor [18].

Results on the ATR hover payload improvement are provided in Table 2 from numerical simulation developed in [21]. As shown in the second column in Table 2, approximately 11.5% increase of thrust is obtained when steady twist actuation is applied to the ATR blades in hover. This level of thrust increase coincides with the prediction that was made based on the transfer function results. However, there is no significant advantage observed in rotor power consumption when adjusting the collective pitch to give the same thrust as in the baseline (shown in the third column of Table 2). Steady twist actuation is expected to modify the blade twist distribution from the built-in twist. Even though it should have a potential for net thrust increase, it could not be seen for the ATR.

While no significant advantage is observed using steady actuation in hover, rotor power consumption can be reduced by higher harmonic blade actuation in forward flight. In general, rotor stall and the accompanying changes in blade loads determine the limit to forward flight speed of helicopters. By employing a combination of longitudinal and lateral cyclic actuation, rotor stall may be postponed. This will result in forward flight performance improvement. The transfer function result in Fig. 4 only illustrates a vibratory component among the ATR hub shear loads or moments response obtained by blade actuation at the respective frequency. Thus it is not straightforward to obtain an estimate
of how much impact the higher harmonic blade actuation exerts upon a steady component of hub moment, such as torque, from those transfer function results. In the full-scale BO-105 wind-tunnel experiment [9], a prescribed actuation signal (IBC mode) was applied at its feathering actuators to demonstrate a considerable rotor power reduction in forward flight. In this paper, numerical simulation is performed to obtain a preliminary estimate in rotor power consumption from higher harmonic blade actuation based on an IBC signal.

The same IBC mode of blade actuation was exploited during the open-loop control test of the ATR system [15]. In that experiment, 3P, 4P, and 5P IBC mode sine-dwell signals were used, and significant impact on both fixed- and rotating-system vibratory loads was observed. From the numerical simulation on the same open-loop control experiment [26], the predicted trend of load variation with respect to its control phase correlated well between simulation and experiment, although discrepancies were found in the amplitude of loads under actuation. In the full-scale BO-105 experiment, various IBC signals (2P, 3P, 4P, 5P, and 6P) were used to demonstrate reduction of hub vibratory loads and acoustic noise, but only 2P IBC signal exhibited a significant advantage in the rotor power consumption. This was due to the more favorable blade angle of attack distribution accomplished by 2P IBC actuation with a specific control phase. Such 2P IBC actuation is applied to the ATR system in forward flight, and numerical results on its torque variation are plotted in Fig. 5. In this plot, ATR torque obtained at the baseline (no actuation) is illustrated by a horizontal solid line. At the control phase of approximately 180°, the lowest power consumption is obtained. This control phase angle coincides with the angle where the minimum power is observed in the full-scale BO-105 experiment.

However, 2P IBC actuation also alters the other components of the rotor force and moment, as exemplified by the thrust change in the second column of Table 3:

<table>
<thead>
<tr>
<th>Component</th>
<th>Baseline (heavy gas, μ = 0.300)</th>
<th>2P IBC actuation (1,000 V, phase 180°)</th>
<th>2P IBC actuation (re-adjusted trim)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust (N)</td>
<td>908</td>
<td>923</td>
<td>908</td>
</tr>
<tr>
<td>Torque (N-m)</td>
<td>104.4</td>
<td>103.3 (1.0% dec.)</td>
<td>102.4 (2.0% dec.)</td>
</tr>
</tbody>
</table>

Figure 5: Variation of the ATR hub torque component for μ = 0.300, α_S = −4°, C_T = 0.0066, and 1,000 V twist actuation at 2P with respect to control phase of how much impact the higher harmonic blade actuation exerts upon a steady component of hub moment, such as torque, from those transfer function results. In the full-scale BO-105 wind-tunnel experiment [9], a prescribed actuation signal (IBC mode) was applied at its feathering actuators to demonstrate a considerable rotor power reduction in forward flight. In this paper, numerical simulation is performed to obtain a preliminary estimate in rotor power consumption from higher harmonic blade actuation based on an IBC signal.

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ble 3. To maintain a specified trim condition, the blade pitch control setting needs to be re-adjusted. Results in Fig. 5 are not corrected for that. Table 3 summarizes the baseline and the ones for the 180° control phase. After re-adjustment to the baseline trim condition, further reduction of rotor power consumption is observed as shown in the third column of Table 3.

On the other hand, the other IBC signals (3P, 4P, 5P) do not exhibit significant benefit in the ATR rotor power reduction. The power reduction from 2P IBC is still obtained through the favorable angle of attack distribution, as mentioned previously. As the flight speed increases, blade stall will become a dominating factor in rotor power consumption. 2P IBC signal is capable of preventing or delaying such blade stall and expected to give an advantage in rotor power reduction in high speed forward flight condition. Since the IBC signal is a combination of the cyclic and collective modes, a closed-loop controller similar to the one described later in this paper can accomplish minimum rotor power. This controller will use 2P collective and cyclic modes of blade actuation, while re-adjusting the blade pitch setting to maintain a desired trim equilibrium.

Significant control authority is observed in the collective mode of blade twist actuation at 1P frequency for the ATR system. This can be used for blade tracking as discussed in further details in the next section. There, the collective mode of actuation at 1P is used as a component of a multi-mode closed-loop controller in the ATR vibration tests.

Additional vehicle pitch and roll moment may be generated by applying longitudinal and lateral cyclic modes of blade actuation at steady and 1P frequency component in combination with the collective mode of actuation. From the ATR system identification test, significant control authority for the vehicle pitch moment is observed from several modes of blade twist actuation. The results are shown in Fig. 6. Here, collective actuation also provides significant vehicle pitching moment due to the forward flight condition. Therefore, it is anticipated that enough vehicle pitching moment can be drawn from the combination of those three modes of blade actuation to assist vehicle’s maneuver ability. For vehicle roll moment, similar result can be achieved by the combination of blade actuation modes.

Another important maneuver capability for helicopters, especially military ones, is the “nap-of-the-earth (NOE)” [27]. This is associated with the closest flight path when a helicopter flies over obstacles in the ground. For this capability, instantaneous pull-up and push-down thrust generated by the rotor system is required. Blade twist actuation may be considered to assist this maneuver capability by the combination of the three actuation modes. For upward or downward negative thrust, collective mode of blade action at steady or 1P frequency is needed. At the same time, to assist vehicle pitching moment in either nose-up before obstacle or nose-down after obstacle, combination of the three blade actuation modes should be considered.

**VIBRATION REDUCTION**

While low frequency actuation is used for the vehicle flight performance enhancement, higher harmonic actuation can be used for hub vibratory loads reduction. Its effectiveness for the ATR vibration reduction has already been demonstrated in the open-loop control test [15]. In the ATR system, the primary vibration happens at 4P since it is a 4-bladed rotor. From Fig. 4, the collective mode of blade actuation is found to have significantly smaller magnitude at 4P frequency when compared to the two cyclic modes. This renders the collective mode of actuation ineffective for 4P vibration reduction, and a combination of the cyclic modes at frequencies between 3P and 5P is the bases for the controller structure used in this study. On the other hand, the collective mode shows a large control authority at 1P, as mentioned before. Thus, 1P collective mode is added to the 4P cyclic modes. Such combination of
different blade actuation modes at different frequencies results in multi-harmonic and multi-mode structure for the controllers. These controllers are generated by cascading single feedback structure based on the traditional T matrix approach \([2, 4, 5, 6, 7, 8]\) corresponding to each mode and frequency as shown in Fig. 7. Notice that by controlling the gain of each actuation mode, the total electric field applied to the individual actuators does not exceed their saturation limit.

Before implementing the controllers, the stability of the closed-loop system should be examined. For this purpose, a loop gain, which is a product of the identified plant transfer function, \(G_0(s)\), and the designed compensator, \(K(s)\), is investigated in frequency domain. Since the ATR transfer function was identified with respect to different blade actuation modes, examination of the closed-loop system stability is conducted for each mode. Among the actuation modes included in the controller (Fig. 7), longitudinal cyclic mode at 4P is exemplified here. Nichols plot of the closed-loop system without any modification on \(K(s)\) is displayed as a dashed line in Fig. 8 for the advance ratio condition of \(\mu = 0.333\). In the same plot, contours of constant disturbance attenuation (or amplification) are also plotted according to the following relation.

\[
\frac{y}{d} = \frac{1}{1 + G_0(s)K(s)}
\]  

(1)

where \(y\) is the plant output and \(d\) is the disturbance, as defined in Fig. 7. To aid in interpreting the level of vibration reduction or amplification, the magnitude of Eq. (1) as a function of frequency is plotted in Fig. 9.

As expected, there exists a significant reduction of disturbance at the target frequency, 4P. However, in the vicinity of 4P, there also appears undesirable amplification of the disturbance. The amount of the amplification present is related to the stability margin of the control system. According to Fig. 8, the present controller with the unmodified \(K(s)\) has a gain margin of approximately 3.2 dB, and phase margin of 70\(^\circ\), a margin regarded sufficient for a general feedback compensator. However, when the gain of the controller is increased, i.e., the closed-loop gain line is shifted upward, the gain margin reduces and a potential instability is nearer. Therefore, a modification on the original controller is desired to improve the gain margin. A solution is to alter the closed-loop gain to have new phase characteristics, that is, shift the phase by \(-40^\circ\) from its original one. Such modification generates a new plot, which is shown as a solid line in Fig. 8. The other modes of blade actuation used in the controller, i.e., 4P lateral cyclic and 1P collective modes, are also modified in a similar way to improve controller performance.

Many different combinations of the blade actuation modes were attempted in the closed-loop control test. In each combination, different relative gain constants are assigned for each feedback structure, and tested at different flight conditions. The combinations used in the test are summarized in Table 4. From the transfer function results, relatively high control authority is observed at 1P for the collective actuation mode. Therefore, a small gain constant, 0.2, is assigned to 1P collective mode controller along with relatively larger constants for the cyclic modes. In the three-mode controller, relative gain constants of \((0.2, 1.0, 1.0)\) for collective, lon-
Table 4: Assignment of relative gain constants in the vibration reduction test

<table>
<thead>
<tr>
<th>Case name</th>
<th>1P collective</th>
<th>4P longi. cyclic</th>
<th>4P lateral cyclic</th>
<th>Advance ratio (μ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyc1</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.333</td>
</tr>
<tr>
<td>Cyc2</td>
<td>0.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.333</td>
</tr>
<tr>
<td>Cyc3</td>
<td>0.0</td>
<td>0.707</td>
<td>0.707</td>
<td>0.333</td>
</tr>
<tr>
<td>Cyc4</td>
<td>0.0</td>
<td>0.9</td>
<td>0.9</td>
<td>0.333</td>
</tr>
<tr>
<td>Cyc5</td>
<td>0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>0.333</td>
</tr>
<tr>
<td>CollCyc1</td>
<td>0.2</td>
<td>0.707</td>
<td>0.707</td>
<td>0.333</td>
</tr>
<tr>
<td>CollCyc2</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.333</td>
</tr>
<tr>
<td>CollCyc3</td>
<td>0.2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.333</td>
</tr>
<tr>
<td>CollCyc4</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.267</td>
</tr>
<tr>
<td>CollCyc5</td>
<td>0.2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.200</td>
</tr>
<tr>
<td>CollCyc6</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.140</td>
</tr>
<tr>
<td>CollCyc7</td>
<td>0.2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.140</td>
</tr>
<tr>
<td>CollCyc8</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>0.140</td>
</tr>
<tr>
<td>CollCyc9</td>
<td>0.2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.140</td>
</tr>
</tbody>
</table>

Among the different flight conditions and different gain constant combinations tested, the greatest reduction of 4P vibration, approximately 40 dB, is obtained at μ = 0.267 with the gain combination (0.2, 0.9, 0.9) for the three actuation modes. Significant attenuation of vibratory loads is observed at each discrete integer/rev frequency, and it is summarized in Fig. 10. Since 1P and 4P components are included in this specific controller, higher reduction is obtained at these two frequencies.

Since 4P is the primary frequency of vibration in the ATR, vibration reduction at 4P is computed and summarized in Table 5. Open-loop and closed-loop 4P peak values are provided in the columns called “open-loop” and “closed-loop” rms (root-mean-square) value. However, due to the slight amplification observed around 4P (see Fig. 9.), a more realistic estimation of vibration reduction is provided by integrating the response spectrum over a short interval around 4P and comparing the results between open-loop and closed-loop conditions. An integration interval of 1 Hz is considered here, and its result is presented in the rightmost column in Table 5.

The closed-loop controller used in the test is designed for the attenuation of the ATR hub vertical shear vibratory load only. However, the other components of the fixed-system loads, such as axial shear force, side-ward shear force, are also reduced by the same controller. The largest simultaneous reduction is obtained in the case CollCyc4, which coincides with the biggest reduction in the hub vertical component. This is illustrated in Fig. 11. The simultaneous reduction is consistent with the ATR open-loop control test results [15]. Further reduction on the different components is expected with multi-component controllers.

Table 5: ATR 4P hub vertical vibration reduction result

<table>
<thead>
<tr>
<th>Case name</th>
<th>Open-loop rms value (lb)</th>
<th>Closed-loop rms value (lb)</th>
<th>Reduction performance (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyc1</td>
<td>22.35</td>
<td>13.77</td>
<td>-4.20</td>
</tr>
<tr>
<td>Cyc2</td>
<td>22.45</td>
<td>15.14</td>
<td>-3.42</td>
</tr>
<tr>
<td>Cyc3</td>
<td>22.52</td>
<td>12.06</td>
<td>-5.42</td>
</tr>
<tr>
<td>Cyc4</td>
<td>22.55</td>
<td>8.87</td>
<td>-8.10</td>
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This paper addresses helicopter performance and vibration improvement using integral blade twist control. First, system identification test is conducted to estimate the control authority exerted upon the rotor system by the blade twist actuation. It is determined that the linear time-periodic system can be represented by a linear time-invariant system under several modes of blade actuation: collective, longitudinal cyclic, and lateral cyclic. Therefore, further controller design and its preliminary evaluation are conducted based on LTI system theory. Significant control authority was observed from the ATR system identification test. Numerical simulation was conducted to study helicopter performance improvement. Steady actuation was used for hover payload increase and 2P IBC prescribed signal for rotor power reduction in forward flight. Traditional HHC and its T matrix approach were used to build a vibration-minimizing controller. Nichols plot is employed for improving controller gain margin by phase shifting. For the ATR hub vertical shear vibratory load control, two cyclic modes at 4P and collective at 1P were used. Different combinations of gain constant for each blade actuation mode were tested at different advance ratios. Significant hub normal shear vibratory load reduction is obtained at the target frequencies (1P and 4P) in all the test conditions. The maximum experimentally verified vibration reduction was approximately 40 dB. The other components in the fixed-system loads are also reduced at 4P although only the vertical component is targeted by the controller.

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REFERENCES


