Optimal Segment Control of Active Twist Rotor for Power Reduction in Forward Flight

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Abstract: The segment control of active twist rotor is investigated to evaluate the effectiveness in rotor power reduction. A numerical model for predicting the isolated rotor power and loads in steady level flights is deployed and validated. A parametric sweep of the amplitude and phase angle for uniform single-harmonic active twist control is conducted to demonstrate the mechanism of active twist control in rotor power reduction. The optimal control schedules and segment layouts of the segment twist control for power reduction while considering saturation limits are obtained using an optimization framework based on genetic algorithm. Up to 5-seg configuration is considered. The results indicate that the segment twist control reduces the rotor power more than the uniform twist control by applying divergent control schedules to each segment. The load distribution of the rotor disk is harmonized in both circumferential and spanwise directions. The 2-seg and 3-seg control configurations are appropriate, while the configurations with more segments yield limited benefits and they may be penalized with an increase in system complexity.

Keywords: helicopter; active twist rotor; segment control; power reduction

1. Introduction

In the last decades, the demand for helicopter performance indicators, such as lower required power, greater cargo capacity, lower vibration, higher speed, and lower noise, has been increasing. With the rapid growth of environmental issues and economic needs, aerodynamic performance and efficiency have become the most prominent challenge for helicopter design in the near future. Active control techniques have been investigated for advanced rotor design. Morphing techniques with variable parameters were utilized in order to enhance the rotor performance [1,2]. Extendable-chord rotors [3,4], variable-span rotors [5,6], and variable-speed rotors [7–9] have been examined in order to alleviate the dynamic stall and drag divergence by optimizing the trim states. Higher Harmonic Control (HHC) was originally used for reducing vibration and noise [10,11]. As an improved form of HHC, the Individual Blade Control (IBC) showed significant potential in rotor performance improvement [12,13]. When compared with HHC or IBC, the on-blade control (OBC) requires less power for actuation, and it has less impact on airworthiness. There has been a distinguished progress in OBC with various concepts [14,15]. Active leading-edge slat [16], active control trailing-edge flaps (ACF) [17,18], active twist rotor (ATR) [19–21], active gurney flap [22], active camber [23,24], etc. have been studied. The mechanism of OBC is to change the dynamic response of the rotor and refine the distribution of aerodynamic loads along the circumferential direction.

With the development of active materials and structures, ATR has been studied as an emerging approach for enhancing the helicopter performance and reducing vibration and noise. An illustration of the active twist rotor concept is shown in Figure 1. The lack of independent mechanical parts is the most obvious advantage of ATR. The actuators embedded into the composite skin induce strain to twist the blades. Therefore, the ATR is aerodynamically clean and friendly for manufacture. Chen and Chopra conducted...
earlier research on ATR [25,26]. A 1/8-th Froude-scale bearingless helicopter rotor with embedded piezoceramic elements as sensors and actuators was tested for minimizing the rotor vibrations. Tip twist amplitudes of 0.5° were achieved, which results in maximally 9% thrust changes and 3% and 8% reductions in pitching and rolling moments. The most representative study is the NASA/Army/MIT Active Twist Rotor program, which contains tests in hover and forward flight while using both open-loop and closed-loop control [27]. Vibratory loads were clearly reduced using the 3/rev, 4/rev, and 5/rev active twist control [28]. The benefits from ATR on performance improvement were investigated while using the CFD-CSD approach proposed by Jain et al. [29,30]. Active twist actuations produce additional lift from reducing the negative loads on the advancing side, which increases the performance. The L/D ratio improves by 3.2%, 3.1%, and 8.6% with the 1/rev harmonic twist, 2/rev harmonic twist, and advancing-side-only twist, respectively. In addition to the piezoelectric actuation concept, the novel concept using shape memory alloy has also been studied [31].

Figure 1. An illustration of the active twist rotor.

The precursory studies show the considerable potential of OBC approaches. However, the procurable gain in performance is limited since the actuation concepts were simplified and unoptimized. Because the aerodynamic loads vary along the circumferential direction and spanwise direction, the optimal control deployment schedules and multi-device configurations have been increasingly concerned.

You and Jung [32] investigated several input scenarios of active twist rotor for performance improvement and vibration reduction. Single-harmonic inputs, multi-harmonic inputs, and non-harmonic inputs are optimized with a multi-objective optimization framework. The reduction of both the required power and vibration index can be simultaneously achieved when a suitable twist control input is adopted [33]. Numerical optimization results of localized pitch control from Küfmann et al. [34] show further benefits for the rotor performance enhancement. The maximal power reduction of 7.61% was achieved by a single-objective optimization. With a multi-objective optimization, power reduction of 5.53% and 4/rev vibration reduction of 70.65% were simultaneously achieved.

Komp et al. studied the effect of spanwise varying camber actuation on rotor power and pitch link loads [24]. The spanwise varying camber resulted in a 1.4% improvement in rotor power reduction compared to the spanwise uniform camber. A multi-objective optimization for performance enhancement and vibration reduction while using a dual ACF rotor configuration was conducted [35]. A 6.7% power savings and 68% hub vibration savings are simultaneously achieved. Depailler studied a dual-flap configuration on vibration reduction [36]. The dual-flap configuration was at least 40% better than the single-flap configuration. The optimal deflection schedules of inboard and outboard flaps notably separated. In addition, the dual ACF configuration has been verified to be significant for blade load control. Three configurations of partial span microflaps were studied for the control of noise and vibration [37]. For the vibration reduction at the heavy BVI condition, the single-microflap configuration produced a 2–3 dB noise penalty on the carpet plane. This penalty was reduced with the dual- and five-microflap configurations.
Previous studies demonstrate the superiority of the refined control schedules and spanwise multi-device configuration on the rotor performance improvement. For the ATR configuration, existing studies tend to assume that the active twist control is consistent spanwise. Zhang et al. [38] performed a parameter analysis study on the rotor power reduction with a two-piece twist control rotor while using quasi-steady twist control and 2/rev twist control. The results have raised the prospect of the segment twist control rotor configuration. Because the ATR configuration is implemented by embedding discrete actuators into the composite structure, there is a motivation to consider the optimal segment twist control configuration with refined control schedules in order to improve the rotor performance. This optimal configuration may simultaneously improve the load distribution of the rotor disk along the circumferential and spanwise directions and obtain superior performance gains under limited drive capability of the twist actuators.

The objective of this work is to investigate the effects on the performance of helicopters while using the optimal segment control of active twist rotor. The main contribution of this study is that a novel segment twist control configuration for ATR is proposed and the feasible improvement on the rotor power reduction in forward flight is assessed. The blades are divided into several active twist control segments along the span, and different control schedules are applied to each segment. A numerical model is deployed to predict the isolated rotor power in steady level flights. The mechanism of active twist control on the rotor power reduction is examined. An optimization framework that is based on genetic algorithm (GA) is established to obtain the optimal schedules and segment layouts of the segment twist control for power reduction. The load distribution of the rotor disk has been improved in both circumferential and spanwise directions with the optimal segment twist control, which is introduced in Section 3. The optimal segment twist control achieves a power reduction of 12.42% as compared with the 5.07% that is obtained while using the uniform twist control with single harmonic inputs for a medium-thrust and high-speed flight condition (\(C_W = 0.0083, \mu = 0.35\)).

2. Methodology

2.1. Rotor Loads and Power Prediction Methods

In the present work, a numerical model is deployed to predict isolated rotor loads and power in steady level flights. A fully articulated rotor is modelled with a hinge offset. It is assumed that the bending deformations are small when compared to the flap and lag motions and the elastic torsional deformations are involved in the optimal active twist schedules. A rigid blade model is adopted with flap(\(\beta\)) and lag(\(\xi\)) degrees of freedom, as shown in Figure 2. Four reference frames are used. The non-rotate frame named A is used for solving the trim equations. Rotation frame S is used for the blade load integral. Blade frame F is used in order to calculate the loads of blade. Blade section frame B is used to solve the local velocity and angle of attack.

The aerodynamic model was established based on the blade element method. A look-up table for the airfoils is used to calculate the aerodynamic coefficients (\(C_L, C_D, C_M\)). The quasi-steady correction of the blade element motion is considered. The Pitt–Peters inflow model obtained the induced velocity of the rotor. The motion response of the blades is calculated in the time domain with Euler method.

\[
\begin{align*}
\frac{dF_z}{dt} &= dL\cos(\delta) - dD\sin(\delta) \\
\frac{dF_X}{dt} &= dF_{X-\text{Induce}} + F_{X-\text{Profile}} = dL\sin(\delta) + dD\cos(\delta) \\
\frac{dM_Z}{dt} &= dM_{Z-\text{Induce}} + dM_{Z-\text{Profile}} = (F_{X-\text{Profile}} + F_{X-\text{Profile}})rR \\
C_Z &= C_L\cos(\delta) - C_D\sin(\delta) \\
C_X &= C_{X_l} + C_{X_p} = C_L\sin(\delta) + C_D\cos(\delta)
\end{align*}
\]  

where \(F_Z\) and \(F_X\) are the lift force and drag force of the blade section in frame \(F\), \(F_{X-\text{Induce}}\) and \(F_{X-\text{Profile}}\) are the induced drag and profile drag force of the blade section in frame \(F\), \(M_Z\) is the shaft moment of the blade section in frame \(S\), \(M_{Z-\text{Induce}}\) and \(M_{Z-\text{Profile}}\) are induced
and profile components of the shaft moment of the blade section in frame $S$, $L$ and $D$ are the lift force and drag force of the blade section in frame $B$, $C(\cdot)$ is the coefficient, $r$ is the dimensionless spanwise location of the blade section, $R$ is the radius of the rotor, and the $\delta$ is the induced angle of the blade section.

![Reference frames for the blade load prediction.](image1)

**Figure 2.** Reference frames for the blade load prediction.

The load integral of all blades is performed in order to obtain the forces and moments of the hub transferred by the hinges. The hub load is averaged with the rotation period to obtain the resultant forces and moments of the rotor, which is used for the trim and performance prediction. A propulsive trim is used for the helicopter steady-level flight solution. Three controls (collective and two cyclic controls) and two shaft attitudes (longitudinal and lateral attitudes) are obtained by solving the equilibrium equations of forces and moments with zero sideslip angle in frame $A$. The tail rotor is assumed to automatically balance the torque from the main rotor. The fuselage is modelled as a rigid body. The center of gravity (CG) location of fuselage and the aerodynamic forces and moments that are derived from the attitudes and dynamic pressure are considered for the trim solution, as shown in Figure 3. The Newton–Raphson procedure is used to solve the weak nonlinear trim equations. The simplifying modeling assumptions mentioned above have proved to be sufficient and efficient in rotor power prediction in optimization problems of active control rotors [9,13,20].

![Forces and moments for the trim solution.](image2)

**Figure 3.** Forces and moments for the trim solution.

### 2.2. Modelling and Validation

The UH-60A Black Hawk helicopter rotor is selected as the baseline. The rotor load modelling and power analysis are performed based on the informative experimental data [39]. Table 1 shows the attributes of the UH-60A Black Hawk helicopter. The rotor of the UH-60A helicopter uses two airfoils: SC-1095 and SC-1094R8. The look-up table of aerodynamics coefficients ($C_L$, $C_D$, and $C_M$) for the airfoils is deduced based on wind
tunnel test measurements [40]. Figures 4 and 5 shows the pre-twist distribution, airfoil layout and platform of the blades obtained from Ref. [41].

Table 1. Baseline helicopter attributes.

| Attribute                  | Data          |
|----------------------------|---------------|
| Rotor Radius (m)           | 8.1788        |
| Rotor Speed (rad/s)        | 27.0          |
| Number of Blades           | 4             |
| Blade Chord Length (m)     | 0.5273        |
| Blade Airfoil              | SC1095 & SC1094R8 |
| Hinge Offset (m)           | 0.381         |
| Root Cutout (m)            | 1.39          |

![Figure 4. Pre-twist distribution of the UH-60A blade.](image)

![Figure 5. Layout of SC1095 and SC1094R8 airfoils on the UH-60A blade platform.](image)

The rotor power is the product of the shaft moment and rotor speed.

\[
\begin{aligned}
P &= P_{\text{Induced}} + P_{\text{Profile}} = (M_z - \text{Induced} + M_z - \text{Profile})\omega \\
C_p &= P / \rho \pi R^2 (\omega R)^3 \\
C_{p - \text{Induced}} &= P_{\text{Induced}} / \rho \pi R^2 (\omega R)^3 \\
C_{p - \text{Profile}} &= P_{\text{Profile}} / \rho \pi R^2 (\omega R)^3 
\end{aligned}
\]

(2)

where \( P \) is the rotor power, \( P_{\text{Induced}} \) and \( P_{\text{Profile}} \) are the induced power and profile power, \( C_{p - \text{Induced}} \) is the coefficient of power, \( \rho \) is the density of the atmosphere, and \( \omega \) is the rotor speed.

The validation analysis is conducted. The predictions of rotor power while using established methods are compared with the flight test data of the UH-60A Black Hawk helicopter in Figure 6. Generally, a good consistency is observed for the advanced ratio from 0.05 to 0.35 and weight coefficients \( (C_W) \) of 0.0065, 0.0074, 0.0083, and 0.0091.
Four flight conditions are considered in this study to investigate the generalizability of segment twist control configuration for ATR in rotor power reduction, as shown in Table 2. The weight coefficients of 0.0065 and 0.0083 are determined, representing the typical-thrust flight condition and the medium-thrust flight condition, respectively. The advanced ratios of 0.25 and 0.35 are selected to represent the cruise flight condition and the high-speed flight condition, respectively.

Table 2. Summary of flight conditions.

| Condition | Weight Coefficient ($C_W$) | Advanced Ratio ($\mu$) |
|-----------|---------------------------|----------------------|
| A         | 0.0065                    | 0.25                 |
| B         | 0.0065                    | 0.35                 |
| C         | 0.0083                    | 0.25                 |
| D         | 0.0083                    | 0.35                 |

2.3. Description of Segment Twist Control Configuration

The active twist control schedules and segment twist control configurations are investigated in this study to determine the optimal twist control configuration in order to reduce the rotor power. The segment twist control configuration is determined, as shown in Figure 7. The segment twist control configuration includes the segment layout and control schedule of each segment. The active twist actuator array embedded on the blade is divided into several segments spanwise, and different twist control schedules are applied. It is assumed that, within a control segment, the actuators generate a torsional couple, which results in a linear variation of the twist angle spanwise.

Figure 6. Comparison of the prediction result and flight test data.

Figure 7. Schematic diagram of the segment twist control configuration.
The active twist control model defines the local pitch angle increment that is generated by continuous torsional deformation of the blade, which is derived from the transient active twist rate.

\[ \theta_{A}(r, \psi) = \theta_{Amin} \]

where \( \theta \) is the local pitch angle, \( r_B \) is the location of the concerned blade section, \( \theta_0 \) is the collective pitch angle, \( \theta_{1c} \) is the lateral cyclic pitch angle, \( \theta_{1s} \) is the longitudinal cyclic pitch angle, \( \theta_A \) is the local twist rate derived from active twist control, and \( \psi \) is the azimuth.

The multi-harmonic input of active twist control is described in terms of Fourier series, as follows.

\[ \theta_{A}(r, \psi) = \left\{ \begin{array}{ll}
\theta_{Amin} & \\
A_0(r) + \sum_{i=1}^{5} [A_{ic}(r) \cos(i\psi) + A_{is}(r) \sin(i\psi)] & \\
\theta_{Amax}
\end{array} \right. \]

where \( A_0 \) is the amplitude of the twist rate for the 0/rev twist control, \( A_{ic} \) and \( A_{is} \) are the amplitudes of sinusoidal and cosinoidal components of the twist rate for the \( i/rev \) twist control, and \( \theta_{Amax} \) and \( \theta_{Amin} \) are the upper and lower bounds of the saturation limit of the local active twist rate, respectively. Up to 5/rev of Fourier series is considered.

The segment twist control with a zoned active twist actuator array is structurally feasible. However, too many segments may lead to a proliferation of control system complexity. Selecting fewer segments and applying the optimized segment twist control schedules are the key to obtaining the best benefit. The segment layout is another key factor of segment twist control. Therefore, the present study concentrates on the optimization of the amplitudes of the multi-harmonic input, segment number, and locations of segment points.

2.4. Optimization Framework

With strong robustness and low model dependence, evolutionary algorithms are applicable to optimization problems in nonconvex and discontinuous design spaces with high dimensional variables. The GA is a global optimization method that is constructed by imitating the genetic principles of nature species and it has been widely used in the field of optimization design for aircraft systems [42–46]. A binary string is used in order to simulate the gene sequence of an individual. The optimization evolution of the population genome during reproduction is simulated by processing the binary sequences of the sample group in the iterative process. The primary population is formed with randomly generated binary strings. The binary strings are converted into real values of the variables in the design space by linear interpolation. The response obtained from the analysis is used in order to evaluate the individual fitness value. Evolutionary processes include selection, replication, crossover, and variation. The optimal population is obtained through iterations. The GA optimization framework utilized in this study was established by referring to Matlab toolbox Gatbx [47,48].

The optimization problem in this study is to search the optimal variables to maximize the objective function, which can be formulated as

\[ \max F(v) = \eta = \left(1 - \frac{P_{Active}}{P_{Baseline}}\right) \times 100\% \]

where \( F(v) \) is the objective function (the power reduction), \( v \) is the variable vector, \( \eta \) is the rotor power reduction, \( P_{Active} \) is the rotor power with active twist control, \( P_{Baseline} \) is the power of the baseline rotor, \( v_{i,lower} \) and \( v_{i,upper} \) are the lower and upper bounds of the variables, respectively, and \( n_{dv} \) is the dimension of the variables.

The GA optimization is performed in order to determine the optimal active twist control schedules and the corresponding segment layouts. The optimization variables are
the amplitudes of sine and cosine components of active twist rate and spanwise positions of the segment points. The rotor power in a steady-level flight is predicted, and the power reduction is converted for evaluating the individuals. Figure 8 describes the flowchart of the GA optimization.

A parametric study of active twist control in Ref. [25] shows that the rotor L/D varies linearly with the amplitude of twist control, but the structural loads vary nonlinearly. At high amplitudes, the twist control structural loads significantly increase. Meanwhile, high amplitudes call for high drive power. The twist deformation with existing actuator techniques for active twist rotor is relatively limited. Therefore, an appropriate range of active twist rate should be determined in combination with engineering practice. The maximum achievable active twist rate is approximately 3.0°/m peak-to-peak, as shown in experimental and numerical studies [49]. A parametric study of the amplitudes for uniform twist control is performed in the present study, as shown in following section. There is a linear increase in power reduction with the increase in amplitudes. However, the increase begins to plateau with the amplitude beyond 1.0°/m (2.0°/m peak to peak). Therefore, a saturation limit of the amplitudes of active twist rate is set as 1.0°/m (2.0°/m peak to peak) in this study.

The first type of variables defines the amplitude of the active twist control. The range of coefficients for Fourier series is set from $-1.5°/m$ to $1.5°/m$ with a resolution of $0.1°/m$ in order to obtain a wider fitting capability. Each coefficient is mapped with a 5-bit binary number in the GA.

The second type of variables is used to represent the segment layouts. The positions of the segment points determine the segment layout. For the N-Seg (N is the segment number) configuration, (N-1) segment points are selected from eight points with a resolution of 0.1 L from 0.2 L to 0.9 L, where L is the aerodynamic effective length of the blade. Subsequently,

![Figure 8. Optimization flowchart.](image-url)
types of segment point combinations are mapped to binary variables by arranging the serial numbers. Up to 5-Seg configuration is considered.

The optimization is performed with a determined segment number for the segment twist control. The optimal solution of n-seg configuration is taken as an initial individual for the optimization of (n + 1)-seg.

3. Results and Discussions

The results from uniform twist control and segment twist control studies are presented in this section. The mechanism of uniform twist control using single-harmonic inputs and multi-harmonic inputs to reduce the rotor power in forward flights is investigated. The results for optimal segment twist control are discussed and compared with those that were obtained for uniform twist control.

3.1. Uniform Twist Control with Single-Harmonic Inputs

A parametric sweep of the amplitude and phase angle for the uniform single-harmonic active twist control is performed. Up to 5/rev harmonic inputs were applied. For the 0/rev active twist control, the amplitude of twist rate is varied from $-1.5\degree/m$ to $1.5\degree/m$ in the steps of $0.1\degree/m$. For the 1–5/rev active twist control, the amplitude is varied from $0.1\degree/m$ to $1.5\degree/m$ in steps of $0.1\degree/m$, and the phase angle is varied from $0\degree$ to $345\degree$ in the steps of $15\degree$. The pitch angles of the blade elements for the uniform single-harmonic active twist control are defined, as follows:

$$\theta(r, \psi) = \theta_0 + r\theta_1 \cos \psi + r\theta_2 \sin \psi + r\theta_3 \cos(i\psi + \phi_i) \tag{6}$$

where $\theta_i$ is the amplitude of the $i$/rev active twist control and $\phi_i$ is the phase angle.

In Figure 9 and Table 3, the percentage of rotor power reduction relative to the baseline rotor is shown. For the four selected flight conditions, the 0–3/rev uniform twist control obtains distinct effects. The 0/rev control shows performance gains for larger weight coefficient conditions (2.27% and 3.03% rotor power reduction for condition C and D respectively, $C_W = 0.0083$), while the 1/rev control show benefits for smaller weight coefficient conditions (1.76% and 2.08% rotor power reduction for condition A and B, $C_W = 0.0065$). The 2/rev control shows the most remarkable gains for high-speed flight conditions (4.01% and 5.07% rotor power reductions for condition B and D, respectively, $\mu = 0.35$). The power reductions using 3/rev control for high-speed flight conditions (1.09% and 0.94% rotor power reductions for condition B and D, respectively, $\mu = 0.35$) are higher than those that are obtained for cruise flight conditions.

![Figure 9. Rotor power reduction using uniform twist control with single-harmonic inputs.](image-url)
Table 3. Rotor power reduction using uniform twist control with single-harmonic inputs.

| Condition | 0/rev | 1/rev | 2/rev | 3/rev | 4/rev | 5/rev |
|-----------|-------|-------|-------|-------|-------|-------|
| A         | 0.02%  | 1.76%  | 1.40%  | 0.28%  | 0.13%  | 0.0%  |
| B         | 0.08%  | 2.08%  | 4.01%  | 1.09%  | 0.51%  | 0.0%  |
| C         | 2.27%  | 0.40%  | 1.69%  | 0.19%  | 0.10%  | 0.0%  |
| D         | 3.03%  | 0.45%  | 5.07%  | 0.94%  | 0.34%  | 0.0%  |

Figure 10 shows the results of the parametric sweep of amplitude. In a certain range, the rotor power reduction increases when the amplitude of twist rate increases. However, the larger amplitude results in the penalty of power reduction. The optimal amplitudes and phase angles diverge for different harmonic inputs.
due to the compromised design of conventional rotors are the key factors limiting the rotor performance.

For condition B, the rotor power reductions relative to the baseline rotor that are obtained with 1~3/rev harmonic inputs are 2.08%, 4.01% and 1.09%, respectively. The optimal amplitudes are 0.9°/m, 0.4°/m, and 0.2°/m. The optimal phase angles of the 1~3/rev harmonic inputs are 330°, 225°, and 90°, as shown in Figure 12. The optimal schedules are shown in Figure 13. Generally, the increase in rotor power reduction begins...
to level off with the amplitude beyond 1.0°/m for the 1/rev uniform twist control, while the optimal amplitude for the 0/rev and 2–5/rev control is smaller. Therefore, the saturation limit of the amplitude for active control is set as 1.0°/m in the subsequent analysis and optimization work.

Figure 12. Rotor power reduction of uniform twist control with the 1–3/rev inputs for condition B.

Figure 13. Optimal control schedules of uniform twist control with the 1–3/rev inputs for condition B.

Figure 14 shows the blade shaft moment increments of uniform twist control with 1–3/rev single-harmonic inputs relative to the baseline rotor for condition B. Figure 15 shows the distributions of dimensionless lift load increment ($\Delta C_{L}Ma^2$) and drag load increment ($\Delta C_{D}Ma^2$) relative to the baseline rotor. The increase in angle of attack is the largest at the tip region of the blades due to the uniform twist control, which results in obvious variation of local loads.

Figure 14. Blade shaft moment increments of uniform twist control with the 1–3/rev single-harmonic inputs relative to the baseline rotor for condition B.
For the 1/rev control with the optimal phase angle of 330°, the blades are actuated with pitch up deformations at the rear region on the advancing side and pitch down deformations at the front region on the retreating side. The 1/rev twist control induces loads shifting along the span. The loads on the blades shift towards the tip at the front region of rotor disk and the blade shaft moment decreases from approximately 40° to 250°.
The loads shift towards the tip at the rear region from approximately 250° to 40°, which leads to a penalty in induced drag and increase the blade shaft moment. The negative twist rate is reduced on the advancing side. The angle of attack increases at the tip region and decreases at the root region. The drops of profile drag at the tip region and induced drag at the root region cause a significant decrease of the blade shaft moment at approximately 90°.

For the 2/rev control with the optimal phase angle of 225°, pitch up deformations are generated at approximately 65° and 245°, and pitch down deformations are generated at approximately 155° and 335°. The negative-lift region on the advancing side decreases. The lift loads are alleviated at the front region on the advancing side and rear region on the retreating side. The induced drag loads and the blade shaft moment decreases from approximately 80° to 195° and from 285° to 30°. The shifting of the lift loading zone towards the tip of the blades leads to the increase in blade shaft moment from approximately 30° to 80° and from approximately 195° to 285°.

Under the 3/rev control with the optimal phase angle of 90°, pitch up deformations are generated at approximately 90°, 210°, and 330°, while pitch down deformations are generated at approximately 30°, 150°, and 270°. The lift loads alternately increase and decrease along the circumferential direction. The negative-lift region on the advancing side decreases, which reduces the lift loads at the front and rear region on the advancing side. The profile drag loads at the tip on the advancing side are alleviated as well.

Generally, power reductions are achieved while using the uniform twist control with single-harmonic inputs essentially due to the improved load distribution. However, the effects on the rotor power mitigation are limited due to the simplicity of the single-harmonic input and spanwise uniform twist control.

3.2. Uniform Twist Control with Multi-harmonic Inputs

The uniform multi-harmonic active twist control is obtained with the GA optimization framework established in Section 2. The optimization variables are the amplitudes of sine and cosine components of twist rate ranging from −1.5°/m to 1.5°/m. A saturation limit of the active twist rate is set as 1.0°/m. When compared with the single-harmonic inputs, the multi-harmonic inputs obtain higher power reductions of 3.59%, 6.86%, 5.84%, and 9.89% for the four flight conditions.

For condition B, Figures 16 and 17 show the optimal multi-harmonic input. The components of 0/rev and 1/rev are dominant. Figure 18 shows that the blade shaft moment decreases in majority azimuth, but still increases near 55° and 235°. Figure 19 shows the distributions of load increments with the optimal multi-harmonic input. When compared with the optimal 2/rev input, the multi-harmonic input generates larger pitch up deformations from 20° to 100°. With the further decrease in negative-lift area in the tip region on the advancing side, the induced drag loads in the root region become reduced. The pitch down deformations from 120° to 360° impel a shift of loading zones towards the root region, which averts the increase of drag loads at the tip region and alleviates the blade shaft moment from 180° to 270°.

![Figure 16. Amplitudes of the 0–5/rev harmonic component of the optimal input for condition B.](image-url)
### 3.3. Segment Twist Control

The segment twist control is optimized for selected conditions while using the GA optimization framework. Up to 5-segment configuration is considered, where the uniform twist control is the case when the segment number is 1. Figure 20 shows the percentage of rotor power reduction for the selected flight conditions using optimal segment twist control.

**Figure 17.** Optimal control schedules of uniform twist control with optimal 2/rev input and multi-harmonic input for condition B.

**Figure 18.** Blade shaft moment increments of uniform twist control with optimal 2/rev input and multi-harmonic input relative to the baseline rotor for condition B.

**Figure 19.** Dimensionless load increment distributions relative to the baseline rotor using uniform twist control with multi-harmonic inputs for condition B.

(a) Lift Load Increments, \( \Delta C_{z}M_{a} \)  
(b) Drag Load Increments, \( \Delta C_{x}M_{a} \)
For condition A, the rotor power reductions that are obtained by the 2-, 3-, 4-, and 5-seg control are 4.72%, 5.47%, 5.85%, and 6.39%, respectively. For condition B, the rotor power reductions are 8.95%, 9.49%, 9.52%, and 9.68%. For condition C, the rotor power reductions are 6.54%, 6.90%, 7.05%, and 7.14%. For condition D, the rotor power reductions of 11.52%, 11.91%, 12.20%, and 12.42% are achieved while using the 2-, 3-, 4-, and 5-seg control, respectively. As shown in Figure 20b,c, segment control has little effect on the profile power, while the induced power can be significantly reduced. Even for condition B, segment control has less mitigation on the induced power than the uniform twist control. Regarding the weight coefficient, the power reduction obtained in the case of 0.0083 is higher than that with 0.0065. With respect to the flight speed, the gain that is obtained at an advanced ratio of 0.35 is higher than that at 0.25. Thus, the effect of active twist control on power reduction is more significant for flight conditions with a larger weight coefficient and higher flight speed.

Generally, segment twist control leads to more rotor power reduction than uniform twist control. With the increase in segment number, more power reduction is obtained.
Generally, segment twist control leads to more rotor power reduction than uniform twist control. Taking condition B as an example, 3-seg control increases the power reduction from 6.86% to 9.49% when compared to the uniform twist control, while the 4-seg control has little improvement compared to the 3-seg control.

The following discussion and analysis of rotor loads are performed in condition B. Figures 21 and 22 show the optimal segment layouts and control schedules for 2-, 3-, 4-, and 5-seg control configurations. For 2- and 3-seg control configurations, the optimal control schedules of the adjacent segments diverge. The innermost segment points of these four configurations are all located at 0.6 L. The proportion of the 2/rev component in the control schedules is higher than that of the uniform twist control. The control schedules for these innermost segments are similar. Likewise, all of the outermost segment points of the 3-, 4-, and 5-seg control configurations are located at 0.9 L. The control schedules for the tip segments are similar. Thus, the subdivision of control segments within 0.6 L is not profitable, because the loads are relatively small. Individual control segment at the tip region is of positive significance, with which the negative lift and drag divergence in the transonic region are alleviated.

Figure 21. Optimal segment layouts.

Figure 22. Cont.
For the configurations of 4- and 5-seg control, some adjacent control segments have similar control schedules. For these two configurations, the control schedules from 0.5 L to 0.6 L are similar to that in the innermost segment. Additionally, the control schedule from 0.6 L to 0.9 L are similar to those in the middle segment of the 3-seg control configuration. Figure 23 shows the distribution of the drag load increment relative to the baseline rotor using segment control. The effects of 4- and 5-seg control are basically similar to those of 3-seg control. Some local load distributions are further optimized. Thus, too many control segments may not yield further benefits, but may be penalized with an increase in system complexity. For the four selected conditions of the UH-60A helicopter model, the segment twist control achieves greater power reduction than the uniform twist control, and the 2- and 3-seg control configurations are appropriate.
Figure 23. Dimensionless drag load increment ($\Delta C_{XM}a^2$) distributions relative to the baseline rotor using the segment twist control for condition B.

Figure 24 shows the blade shaft moment increments of the optimal uniform control, 2- and 3-seg control relative to the baseline rotor segment control. When compared with uniform twist control, segment control reduces the blade shaft moment from $80^\circ$ to $200^\circ$ and from $280^\circ$ to $360^\circ$, but it increases the blade shaft moment from $200^\circ$ to $280^\circ$.

Figure 25 shows the induced drag component and profile drag component of the blade shaft moment increment of the 3-seg control relative to the 2-seg control rotor. Figure 26 shows the dimensionless drag load increment distributions of the 3-seg control relative to the 2-seg control. When compared with 2-seg control, 3-seg control applies pitch down deformations from $30^\circ$ to $100^\circ$ on the tip segment and reduces the pitch down deformations at approximately $330^\circ$ on the middle segment, thus gaining a reduction in induced drag loads on both the advancing side and the retreating side. Although there are differences in profile drag distribution between 2- and 3-seg control, they did not cause a significant diversity in profile power, as shown in Figures 25 and 26b. In addition, a slight increase in both induced drag component and profile drag component of the blade shaft moment can be observed at approximately $210^\circ$. The analysis shows that this situation is due to the Fourier series truncation and low precision of the optimization variables, which leads to suboptimal twist actuation in some regions.
3.4. Effects of the Saturation Limit of the Active Twist Rate

In this study, the major assumption is that the twist actuation is modeled as a linear variation of the twist angle within each control segment. The torsional deflections are smaller than the amplitude of twist actuation and they are expected to be involved in the optimal active twist schedules. All of the optimal results presented thus far are obtained with a presupposed saturation limit of the active twist rate. The sensitivity of the saturation limit on the optimal segment twist control configuration is examined. A parametric study of the saturation limit is conducted on the uniform twist control with multi-harmonic inputs and the 2-seg control at condition B. The saturation limit of the active twist rate is varied, from 0.4°/m to 1.0°/m, in the steps of 0.2°/m. The rotor power reductions vary linearly with the saturation limits, as shown in Figure 27. With the saturation limit of 0.4°/m, the rotor power reductions using the uniform twist control with multi-harmonic inputs and the 2-seg control are 4.61% and 5.89%, respectively, at condition B. It shows that the multi-harmonic inputs gain more benefits than single harmonic inputs with the
same saturation limit. The optimal control schedules of the uniform twist control and 2-seg control with saturation limits are demonstrated in Figures 28 and 29, respectively. The optimal control schedules remain in the same patterns. Additionally, the optimal segment layouts also remain the same. Thus, the optimal segment control configurations are less sensitive to the saturation limits of the active twist rate. In other words, the established optimization framework is robust.

![Figure 27](image1.png)

**Figure 27.** Rotor power reductions with saturation limits of active twist rate for condition B.

![Figure 28](image2.png)

**Figure 28.** Optimal control schedules of the uniform twist control with saturation limits for condition B.

![Figure 29](image3.png)

**Figure 29.** Optimal control schedules of the 2-seg control with saturation limits for condition B.

### 3.5. Summary and Comparison of Power Reduction

Table 4 summarizes the rotor power reductions using active twist control over the baseline rotor. The active twist control enhances the rotor performance by reconciling the distribution of loads. When compared to the single-harmonic control, the multi-harmonic increases the power reduction by promoting the control schedule along the circumferential direction. With the increase in segment number, the benefit that is achieved by the segment control configuration increases. However, the increase in rotor power reduction begins to plateau when the segment number exceeds 3.

| Saturation Limit (degree/m) | 0.4 degree/m | 0.6 degree/m | 0.8 degree/m | 1.0 degree/m |
|-----------------------------|--------------|--------------|--------------|--------------|
| Uniform Twist Control      | 0.4          | 0.6          | 0.8          | 1.0          |
| 2-seg Control              | 0.6          | 0.8          | 1.0          |              |
Table 4. Rotor power reductions for the selected flight conditions.

| Active Twist Configuration | Deployment        | CW = 0.0065 \( \mu = 0.25 \) | CW = 0.0065 \( \mu = 0.35 \) | CW = 0.0083 \( \mu = 0.25 \) | CW = 0.0083 \( \mu = 0.35 \) |
|---------------------------|-------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Uniform                   | Single-Harmonic   | 1.76%                         | 4.01%                         | 2.27%                         | 5.07%                         |
| Uniform                   | Multi-Harmonic    | 3.59%                         | 6.86%                         | 5.84%                         | 9.89%                         |
| Segment                   | 2-seg             | 4.72%                         | 8.95%                         | 6.54%                         | 11.52%                        |
| Segment                   | 3-seg             | 5.47%                         | 9.49%                         | 6.90%                         | 11.91%                        |
| Segment                   | 4-seg             | 5.85%                         | 9.52%                         | 7.05%                         | 12.20%                        |
| Segment                   | 5-seg             | 6.39%                         | 9.68%                         | 7.14%                         | 12.42%                        |

4. Conclusions

In this study, the optimal segment control of the active twist rotor is investigated for the power reduction in forward flight. The UH-60A rotor at four selected flight conditions is considered to be the baseline. A numerical model to predict the isolated rotor power in steady-level flights is deployed and validated with experimental data that were obtained from literatures. The optimal schedules and segment layouts of the segment twist control for power reduction are obtained while using a GA optimization framework. When compared with single-harmonic control, multi-harmonic control and segment twist control achieve a further reduction of rotor power. The following are the key conclusions of this paper:

(1) The active twist configurations improve performance by reconciling the distribution of rotor disk loads. The active twist actuations reduce the negative negative-lift area at the tip region on the advancing side, which results in the decrease of the overall induced power.

(2) The established optimization algorithm can effectively obtain the optimal solutions of control parameters and segment layouts for uniform multi-harmonic twist control and segment twist control.

(3) The effects on rotor power mitigation are limited while using the single-harmonic twist control. In contrast, the multi-harmonic twist control obtains more power reduction due to the refined control schedule along the circumferential direction.

(4) The segment twist control reduces more rotor power than the uniform twist control. The load distribution of the rotor disk has been improved in both circumferential and spanwise directions. The segment point of the optimal 2-seg control is at 0.6 L, and divergent control schedules are applied to the inner and outer segments. The optimal 3-seg control includes an individual control segment at the tip region with a schedule that is refined for the wide dynamic pressure range. The 4-seg control and 5-seg control yield limited benefits and they may be penalized with an increase in system complexity.

Finally, the optimal segment twist control configuration with a saturation limit is related to the aerodynamic shape of the initial blade. In this study, the optimal segment layouts of the segment twist control configurations are similar to the airfoil layout of the baseline UH-60A rotor blade. The optimal control configuration and performance improvement levels may vary for a rotor with different platforms, airfoils, pre-twists, etc. Moreover, the aerodynamic shape of the baseline blade is a result of the multi-objective optimization of the conventional rotor system, and it is not optimal for the active twist rotor. In future study, an optimization design of the aerodynamic shape that is targeted for the active twist blade may yield further benefits.

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