Active control for performance enhancement of electrically controlled rotor

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Received 31 October 2014; revised 18 May 2015; accepted 16 July 2015
Available online 2 September 2015

KEYWORDS
Electrically controlled rotor (ECR);
Helicopter;
Higher harmonic control;
Performance enhancement;
Swashplateless

Abstract
Electrically controlled rotor (ECR) system has the potential to enhance the rotor performance by applying higher harmonic flap inputs. In order to explore the feasibility and effectiveness for ECR performance enhancement using closed-loop control method, firstly, an ECR rotor performance analysis model based on helicopter flight dynamic model is established, which can reflect the performance characteristics of ECR helicopter at high advance ratio. Based on the simulation platform, an active control method named adaptive T-matrix algorithm is adopted to explore the feasibility and effectiveness for ECR performance enhancement. The simulation results verify the effectiveness of this closed-loop control method. For the sample ECR helicopter, about 3% rotor power reduction is obtained with the optimum 2/rev flap inputs at the advance ratio of 0.34. And through analyzing the distributions of attack of angle and drag in rotor disk, the underlying physical essence of ECR power reduction is cleared. Furthermore, the influence of the key control parameters, including convergence factor and weighting matrix, on the effectiveness of closed-loop control for ECR performance enhancement is explored. Some useful results are summarized, which can be used to direct the future active control law design of ECR performance enhancement.

1. Introduction

The concept of swashplateless rotor was brought forward at the beginning of 21st century. This kind of rotor system applies blade pitch inputs via purely active flap control or blade root indexing and active flap for cyclic control instead of traditional swashplate mechanism. Electrically controlled rotor (ECR) is one kind of swashplateless rotor. For an ECR helicopter, primary flight control is provided by applying blade pitch inputs via integrated active trailing edge flap. Fig. 1 shows the schematic diagram of the ECR helicopter. ECR has many new features, such as simplified mechanical control system, reduced parasite drag caused by the hub, redundant design for more reliable and safer control system, etc. More importantly, ECR can achieve independent blade pitch control absolutely without the restraint of swashplate and any form of the control input can be achieved theoretically. Then taking this advantage appropriately, it is potential to achieve ECR performance enhancement using active control.
During the last two decades, several active control approaches have appeared for rotor performance enhancement, vibration control and noise reduction. Generally, these approaches can be classified into two categories: higher harmonic control (HHC) and individual blade control (IBC). HHC is based on actuators located below the swashplate, the applicable control frequency in the rotating frame is limited for rotor with more than three blades. However, IBC is based on actuators in the rotating frame and therefore overcomes the inherent limit of HHC. Several IBC concepts have been designed and tested, such as blade root actuation and active control flap (ACF). Among these approaches, HHC and IBC based on blade root actuation, especially as the means of reducing vibratory loads and noise, were developed earlier and have been conducted extensively in theoretical analysis, wind tunnel tests and flight tests. While the researches on rotor performance enhancement using these approaches are relatively less. The first investigation on active rotor control approach based on HHC could go back to 1952. Steward focused on changing the lift redistribution through HHC to increase flight velocity. Limited by the available computer hardware, very simple simulation model was used. In his study, an increase at the advance ratio of approximately 0.1 was achieved with an appropriate 2/rev blade pitch control. To evaluate the potential of IBC in improving rotor performance and reducing vibration and noise, a full-scale wind tunnel test of the UH-60A rotor was completed in a 40 × 80 foot wind tunnel in 2009 in the US Ames. Test results showed that up to 5% rotor power reduction was achieved using 2/rev IBC inputs at the advance ratio of 0.4. Germany ZFL company had developed and certified an experimental IBC system for the CH-53G. The flight test results showed that a decrease of about 6% in the total power consumption could be achieved at the flight speed of 232 km/h.

ACF was also specifically used for rotor performance enhancement in a few studies. However, in ACF approach, the trailing edge flaps only offered higher harmonic control. The primary control was still realized with the traditional swashplate system. In 2008, a research of helicopter vibration reduction and rotor performance enhancement using ACF was conducted by Liu et al. The simulation results showed that nearly 4% power reduction was obtained at the advance ratio of 0.35. In 2009, wind tunnel tests of the MD-900 SMART rotor with active trailing edge flaps had been conducted in the US Ames 40 × 80 foot wind tunnel. The tests quantified the effects of open-loop active flap control on rotor performance enhancement and only 1% increase in rotor’s lift-to-drag ratio was seen around 90° of the 2/rev flap inputs phase angle at the advance ratio of 0.3. More recently, several new active control concepts were investigated. Eui and Farhan focused on stall alleviation of a UH-60A Black Hawk helicopter using an active gurney flap. Simulation results showed that appropriate gurney flap actuation was able to achieve 11.3% rotor power reduction at the maximum gross weight of 10.67 tons, at 2348 m altitude and airspeed of 167 km/h. Devesh and Carlos conducted the study on rotor performance improvement using camber actuation in the presence of dynamic stall, in the process of which up to 5/rev camber actuation frequency was used. Optimization results indicated that more than 3.5% rotor performance improvement was achieved for baseline model at the advance ratio of 0.33.

Some researchers have also applied non-HHC control schemes for power reduction, in which the devices were activated over a segment of azimuth only. An optimization effort for non-harmonically deployed active control devices was developed by Frank et al. focused on minimizing the total power required over a designated flight envelope. A peak power reduction of 15.23% is found from a twist optimization study, while a peak power reduction of 9.51% is found from a trailing edge flap optimization study, at the advance ratio of 0.3. German aerospace center conducted numerical investigation on the effects of non-harmonic localized pitch control (LPC). In simulations with BO-105 model rotor blades, with 3.62% rotor power reduction being achieved, LPC was found to be effective. However, when applied to a more modern rotor blade, the margins for power reduction were found to be significantly lowered.

Previous studies show that the effect of active control on rotor performance enhancement for normal helicopter was significant at high advance ratio. However, most of the previous studies were concentrated on the open-loop study. The closed-loop control studies for rotor performance enhancement were relatively less. And both the open-loop and closed-loop study were aimed at normal helicopter. Till now, virtually there is no reference referring to ECR helicopter performance enhancement by active control method.

In one of authors' previous papers, the preliminary open-loop control for ECR performance enhancement using 2/rev flap inputs was investigated, and the efficiency has been verified. It should be pointed out here that the essence of the open-loop control for ECR performance enhancement is to explore the impact of flap inputs on rotor performance through frequency/amplitude/phase sweep by controlling the flap inputs. So, for practical use, the open-loop control here cannot be used directly for the performance enhancement of ECR. For practical engineering application, real-time adjustment of blade pitch and optimum control of rotor performance can only be achieved by closed-loop control. This paper continues the previous work and conducts a study of ECR helicopter rotor power enhancement using closed-loop control. The specific objectives of this paper are summarized as follows. First, establish a relatively precise ECR rotor performance analysis model based on helicopter flight dynamic model, which can reflect the performance characteristics of ECR helicopter at high advance ratio. Second, explore the feasibility and effectiveness for ECR performance enhancement using an active control method named adaptive T-matrix algorithm and the control mechanism is analyzed.
Third, access the influence of convergence factor and weighting matrix on the effectiveness of closed-loop control for ECR performance enhancement, which are the key control parameters of the algorithm.

2. Mathematical model

The present closed-loop control study of ECR performance enhancement is based on the trim state of ECR helicopter, and the control objective is to reduce the rotor power consumption under high speed flight conditions. So the ECR helicopter flight dynamic model is required to provide the necessary simulation environment, among which the ECR aerodynamic model is the basic part and also most important. The fundamental components of the mathematical model are given in the following subsections.

2.1. Aerodynamic model of ECR

In the present study, 2/rev flap inputs are applied to the primary flight control. The flap inputs are given as

\[ \delta = \delta_0 + \delta_{1c} \cos \psi + \delta_{1s} \sin \psi + \delta_2 \]  

where \( \psi \) is azimuth angle; \( \delta_0, \delta_{1c} \) and \( \delta_{1s} \) are flap collective, lateral cyclic and longitudinal cyclic input respectively; \( \delta_2 \) is 2/rev flap inputs, which can be expressed as

\[ \delta_2 = \delta_{2c} \cos 2\psi + \delta_{2s} \sin 2\psi = A_2 \cos(2\psi - \Delta) \]  

where \( \delta_{2c} \) and \( \delta_{2s} \) are respectively cosine and sine components of 2/rev harmonic; \( A_2 \) and \( \Delta \) are respectively the magnitude and phase angle of the 2/rev flap inputs. The equivalent blade pitch can be expressed in a similar form.

Based on rigid blade model, the relationship between equivalent blade pitch and deflection angle of trailing edge flap is derived, in which 2/rev flap inputs are involved:

\[
\begin{bmatrix}
\theta_0 \\
\theta_{1c} \\
\theta_{1s} \\
\theta_{2c}
\end{bmatrix} =
\begin{bmatrix}
\frac{D}{I_1\Omega^2 + k_b} \left( \frac{1}{3} C_3 + \frac{1}{2} \mu^2 C_1 \right) & 0 & -\frac{D}{I_1\Omega^2 + k_b} \left( \frac{1}{3} C_3 + \frac{1}{2} \mu^2 C_1 \right) \\
0 & \frac{D}{k_b} C_3 - \frac{1}{2} \mu^2 C_1 & 0 \\
0 & 0 & \frac{D}{k_b} \left( \frac{1}{3} C_3 + \frac{1}{2} \mu^2 C_1 \right) \\
\frac{1}{I_1\Omega^2 + k_b} \left[ k_b \theta_{pre} + \frac{1}{2} E \left( \frac{2C_3}{3} + \mu^2 C_1 \right) \right] & 0 & \frac{1}{k_b} \left( \frac{1}{3} C_3 + \frac{1}{2} \mu^2 C_1 \right)
\end{bmatrix}
\begin{bmatrix}
\theta_0 \\
\theta_{1c} \\
\theta_{1s} \n\theta_{2c}
\end{bmatrix}

+ \begin{bmatrix}
0 \\
0 \\
0 \\
\frac{E \mu C_2}{k_b} \\
\frac{E \mu C_2}{2k_b} \\
0
\end{bmatrix}
\]

where \( \theta_0, \theta_{1c} \) and \( \theta_{1s} \) are blade collective, lateral cyclic and longitudinal cyclic caused by flap inputs respectively; \( \theta_{2c} \) and \( \theta_{2s} \) are respectively cosine and sine components of 2/rev harmonic blade pitch caused by flap inputs; \( D \) is the constant related to the chord location of the flap; \( C_1, C_2 \) and \( C_3 \) are the constants related to the radial location of the flap; \( k_b \) is the blade root spring stiffness; \( I_1 \) is the blade flap inertia moment; \( \Omega \) is the rotor rotational speed; \( \mu \) is the advance ratio; \( E \) is the airfoil zero lifting moment and \( \theta_{pre} \) the pre-index angle.

The aerodynamic coefficients of the airfoil with trailing edge flap are calculated by CFD method. The results are provided in the form of look-up tables as a function of deflection angle of trailing edge flap, angle of attack and Mach number.

Main rotor inflow is calculated using the finite state wake model suitable for ECR, which yields non-uniform inflow distributions over the rotor disk. Small inflow variations due to the flap deflection are considered here. The final governing equations for the induced velocity coefficients \( \chi_j \) and \( \beta_j \) are given by

\[
M' \left\{ \chi_j \right\} + \mathbf{L}^{-1} \left\{ \chi_j \right\} = \frac{1}{2} \left\{ \tau_{in} \right\}
\]

\[
M' \left\{ \beta_j \right\} + \mathbf{L}^{-1} \left\{ \beta_j \right\} = \frac{1}{2} \left\{ \tau_{in} \right\}
\]

where the superscript \( r \) is harmonics number; the subscript \( j \) is polynomial number; \( M' \) and \( M' \) are respectively cosine and sine components of apparent mass matrix; \( L^c \) and \( L^s \) are respectively cosine and sine components of inflow gain matrix; \( \tau_{in} \) and \( \tau_{in} \) are respectively cosine and sine components of pressure coefficient; \( p \) is harmonics number related to pressure coefficient; \( n \) is polynomial number related to pressure coefficient. \( \tau_{in} \) and \( \tau_{in} \) are both coupled with the blade element thrust force, described by Eqs. (6) and (7):

\[
\tau_{in} = \frac{1}{\pi \rho \Omega R^2} \sum_{q=1}^{B} \sum_{n=1}^{S_q} (L_q^c + \Delta L_q^c) \phi_q^c(r) \cos(p\psi)
\]

\[
\tau_{in} = \frac{1}{\pi \rho \Omega R^2} \sum_{q=1}^{B} \sum_{n=1}^{S_q} (L_q^s + \Delta L_q^s) \phi_q^s(r) \sin(p\psi)
\]
where \( \rho \) is air density; \( R \) is rotor radius; \( B \) is the number of rotor blades; \( q \) is the number of blade elements of a blade; \( N_b \) is the number of blade elements of a blade; \( i \) is the serial number of blade elements; \( L_i^0 \) is the aerodynamic force normal to the rotor plane acting on the \( i \)th blade element of the \( q \)th blade without flap deflection; \( \Delta L_i^0 \) is the corresponding aerodynamic force caused by flap deflection; \( \theta_i^0(r_i) \) is radial expansion shape function and \( r_i \) is dimensionless radius of the \( i \)th blade element.

For the airfoil with trailing edge flap, the effect of flap deflection on the blade element thrust force should be included, just as the equivalent blade angle of attack which is calculated as

where \( z \) is local angle of attack; \( C_{\theta i} \) is a coefficient depending on the length of flap chord.

### 2.2. Flight dynamic model of ECR helicopter

The flight dynamic model of the ECR helicopter is derived from helicopter trim equations based on state space approach. The nine state variables include helicopter velocity components in the body axes \((V_x, V_y, V_z)\); roll, yaw, pitch rates \((\omega_x, \omega_y, \omega_z)\); and roll, yaw, pitch attitude angles \((\Phi, \Psi, \Theta)\). The differential equations of helicopter body motion are described as

\[
\begin{align*}
\dot{V}_x &= V_y \omega_z - V_z \omega_y - g \sin \Theta + F_x/m \\
\dot{V}_y &= V_x \omega_z - V_z \omega_x + g \cos \Theta \cos \Phi + F_y/m \\
\dot{V}_z &= V_x \omega_y - V_y \omega_x + g \cos \Theta \sin \Phi + F_z/m \\
\dot{\omega}_x &= [(I_y - I_z) \omega_z \omega_x + I_z (\omega_y - \omega_z \omega_z) + M_2]/I_x \\
\dot{\omega}_y &= [(I_x - I_z) \omega_z \omega_y + I_z (\omega_x + \omega_y \omega_y) + M_2]/I_y \\
\dot{\omega}_z &= [(I_x - I_y) \omega_x \omega_z + I_y (\omega_x - \omega_z \omega_z) + M_2]/I_z \\
\dot{\Phi} &= \omega_x - \tan \Theta (\omega_y \cos \Phi - \omega_z \sin \Phi) \\
\dot{\Psi} &= \omega_y \sin \Phi + \omega_z \cos \Phi \\
\dot{\Theta} &= \omega_x \sin \Phi + \omega_z \cos \Phi
\end{align*}
\]

where \( I_x, I_y \) and \( I_z \) are the helicopter’s inertia moment; \( I_{xy} \) is the helicopter’s inertia product; \( F_x, F_y, F_z, M_x, M_y, \) and \( M_z \) refer to the combined external forces and moments in the body axes; \( m \) is the mass of the helicopter; \( g \) is the gravity acceleration.

The aerodynamic coefficients of ECR are acquired based on the previous section. The aerodynamic coefficients of the fuselage come from wind tunnel test data, which are provided in the form of look-up tables as a function of sideslip angle and angle of attack. The aerodynamic coefficients of the tail surfaces are obtained by lifting line theory and the aerodynamic coefficient of the tail rotor is calculated with the similar approach used in the main rotor. More details can be found in one of authors’ previous papers.

According to the ECR helicopter’s force and moment equilibrium about the center of gravity, the trim calculation is carried out. The free flight condition is simulated, and the trim variables are the flap collective, lateral cyclic, longitudinal cyclic inputs \((\delta_{\theta b}, \delta_{\theta c}, \delta_{\theta t})\) and tail rotor collective pitch \(\theta_{tr}\).

### 2.3. Rotor power requirement

Rotor power requirement is calculated with or without 2/rev flap inputs under various flight conditions, which includes variations of helicopter flight speed, takeoff weight and 2/rev flap inputs. In all the studies, the helicopter is re-trimmed as 2/rev flap inputs change so as to avoid rotor power change caused by the change of flight condition. For a given flight condition, the “baseline” configuration is the configuration without the 2/rev flap inputs. Rotor required power is calculated by

\[
P_r = \frac{\Omega}{2\pi} \int_0^{2\pi} M_r(\psi) d\psi
\]

where \( M_r \) is the main rotor torque about the hub.

### 3. Active control algorithm

The adaptive T-matrix algorithm, which has been successfully used for both helicopter vibration and noise attenuation, is adopted here as a closed-loop control strategy for ECR power enhancement. Identification of the transfer relation between helicopter response and control inputs is the key process in this algorithm. In the area of helicopter vibration and noise reduction, both off-line and on-line identification methods have been used. However, due to the strong nonlinear relationship between ECR power and flap inputs in the presence of dynamic stall, the off-line identification method for ECR power reduction is inapplicable. So an on-line identification method should be adopted here.

In the present study, the adaptive T-matrix algorithm is used for ECR power reduction, where the objective function is ECR power requirement. The control strategy for ECR performance enhancement is based on the minimization of a performance index, which is a quadratic cost function of the quantities being reduced ECR power \( P_k \) and 2/rev flap inputs \( \delta_{2\phi} \).

\[
J_k = P_k^T W_PP_k + \delta_{2\phi}^T W_{\phi} \delta_{2\phi}
\]

where \( J_k \) is the objective function; \( W_P \) is the weighting matrix for ECR power and \( W_{\phi} \) is the weighting matrix for 2/rev flap inputs. For the right-hand members in this equation, the first represents ECR power term, which will be minimized as the algorithm converges, and the second represents 2/rev flap inputs term, with the effect of restraining the magnitude of 2/rev flap inputs.

2/rev flap inputs are related to the ECR power through local transfer matrix \( T \), given by

\[
T = \frac{\partial P_k}{\partial \delta_{2\phi}}
\]

The relationship between ECR power and 2/rev flap inputs at the \( k \)th control step is given by

\[
P_k = T \delta_{2\phi} + Ww
\]

where \( w \) is the disturbance to ECR and \( W \) is the matrix relating ECR power to disturbance.

Under the initial condition, when \( k = 0 \), the relationship can be written as

\[
P_0 = T \delta_{2\phi} + Ww
\]
Then, the global model of helicopter response is derived by eliminating the influence of disturbance \( w \):

\[
P_k = \Phi_k T
\]

(15)

where \( \Phi_k \) is given by

\[
\Phi_k = [\delta_{2,kc}, \delta_{2,ks}]
\]

(16)

where \( \delta_{2,kc} \) and \( \delta_{2,ks} \) are the cosine and sine components of 2/rev flap inputs; the global transfer matrix \( T \) is given by

\[
T = [T_c; T_s, P_0]
\]

(17)

where \( T_c \) and \( T_s \) are the cosine and sine components of \( T \).

There are two key parts in the adaptive T-matrix algorithm for ECR power reduction. One is the optimal control law, which is determined from the following requirement:

\[
\frac{\partial J(P_k, \delta_{2,k})}{\partial \delta_{2,k}} = 0
\]

(18)

Then the optimal control law can be expressed as

\[
\delta_{2,k, opt} = -(T^T W_p T + W_k)^{-1} T^T W_p P_0
\]

(19)

One thing to note is that the time interval between each control step must be sufficient to allow the system to return to steady state so that the ECR power can be accurately measured.

The other key part is online identification of parameters of the global transfer matrix \( T \). There are several algorithms available for identifying these parameters. The least mean square (LMS) algorithm is adopted here. The corresponding formula is given by

\[
\tilde{T}_{k+1} = \tilde{T}_k + \xi \Phi_k^T (P_k - \Phi_k \tilde{T}_k)
\]

(20)

where \( \tilde{T} \) is the identification matrix of global transfer matrix \( T \), and the subscript “k” denotes the \( k \)th control step; \( \xi \) is the convergence factor, which is a diagonal matrix used for controlling the convergence rate of the LMS algorithm.

4. Results

The results presented in this section are obtained from the simulation calculations based on the sample ECR helicopter. Table 1 shows the main parameters of the sample ECR helicopter. The other parameters can be found in Ref. 22. Considering that the effect of active control on rotor performance enhancement is obvious at high advance ratio, the following simulations are conducted at the advance ratio of 0.34.

The aerodynamic coefficients of the airfoil with trailing edge flap are obtained with CFD method. Fig. 2 shows the typical lift coefficient \( C_{L_k} \) and drag coefficient \( C_D \) variations with respect to both angle of attack and deflection of trailing edge flap, when \( Ma = 0.4 \).

In the following subsections, a typical example is analyzed firstly, in which the control parameters of adaptive T-matrix algorithm are set as the standard, and the physical essence of ECR power reduction is explored. Then, the influences of control parameters on the effectiveness of closed-loop control for ECR performance enhancement are discussed. In the following closed-loop control simulations, the first four steps without 2/rev flap inputs are baseline case; while 2/rev flap inputs are applied beginning with the fifth step.

### Table 1 Main parameters of ECR helicopter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main rotor radius (m)</td>
<td>5.345</td>
</tr>
<tr>
<td>Main rotor speed (rad/s)</td>
<td>40.42</td>
</tr>
<tr>
<td>Blade pre-index angle (°)</td>
<td>16</td>
</tr>
<tr>
<td>Blade root torsional stiffness (N-m/°)</td>
<td>1500</td>
</tr>
<tr>
<td>Blade chord length (m)</td>
<td>0.35</td>
</tr>
<tr>
<td>Flap chord length (m)</td>
<td>0.1</td>
</tr>
<tr>
<td>Flap spanwise length</td>
<td>0.15R</td>
</tr>
<tr>
<td>Flap midspan location</td>
<td>0.8R</td>
</tr>
<tr>
<td>Tail rotor radius (m)</td>
<td>0.93</td>
</tr>
<tr>
<td>Tail rotor speed (rad/s)</td>
<td>213.94</td>
</tr>
<tr>
<td>Takeoff weight (kg)</td>
<td>2080</td>
</tr>
</tbody>
</table>

![Fig. 2](image-url)  

**Fig. 2** Lift and drag coefficients variations with angle of attack and flap angle when \( Ma = 0.4 \).

4.1. Analysis of a typical example

In this section, the effectiveness of the adaptive T-matrix algorithm for ECR power reduction under the basic control parameters is explored. The relationship between ECR power and 2/rev flap inputs is shown in Fig. 3(a). The corresponding sine and cosine components of 2/rev flap inputs variations are shown in Fig. 3(b). The basic control parameters are set as \( \xi = \text{diag} (0.2,0.2,0.2) \), \( W_p = I_{k+1} \), \( W_A = 2000I_{k+2} \).

As shown in Fig. 3(a), about 3% ECR power reduction is achieved by applying the optimum 2/rev flap inputs. This reduction is obtained in the presence of dynamic stall, which
is important under the simulated flight condition. Notice that the adaptive T-matrix algorithm converges to the optimum control in 5 steps, about 4 s. Also the convergence time consumption is similar to the helicopter active vibration control which means the adaptive T-matrix algorithm is feasible for ECR performance enhancement in practical application. These steps are the process of adjusting the parameters adaptively in global transfer matrix $T$, due to the deviation between the initial value and actual value of these parameters. For a well-identified linear system, the algorithm converges to the optimum control in a single step. However, the relationship between ECR power and 2/rev flap inputs cannot be perfectly represented by a linear model, so the optimal control cannot be reached after the first step.

In order to better understand the primary cause of ECR power reduction, the equivalent blade pitch and flap angle in baseline case and optimum 2/rev flap inputs case are provided in Fig. 4.

As shown in Fig. 4, the maximum equivalent blade pitch in retreating blade around $\psi = 300^\circ$ is about $18^\circ$ for baseline case and the corresponding flap angle is about $-10^\circ$. With the optimum 2/rev flap inputs, the equivalent blade pitch in this region is reduced by about $2^\circ$, while the corresponding flap angle is reduced by about $6^\circ$.

The corresponding distributions over the disk of angle of attack in baseline and optimum 2/rev flap inputs case are also provided, as shown in Fig. 5.

As shown in Fig. 5(a), the angle of attack in retreating blade around $\psi = 300^\circ$ is beyond $14^\circ$ for baseline case. According to the nonlinearities of drag coefficient variations with respect to both angle of attack and deflection of trailing edge flap provided in Fig. 2(b), the angle of attack in this region is operated under stall. With the optimum 2/rev flap inputs, the angle of attack in this region is reduced by more than $2^\circ$. Thus a large decrease of drag is achieved.

The underlying physical essence of ECR power reduction can be further identified by considering the drag distributions' variations over the rotor disk. Fig. 6 shows the distributions over the disk of drag coefficient for baseline and optimum 2/rev flap inputs case.

It turns out that with the optimum 2/rev flap inputs, the local drag decreases sharply in out-board region centered on the round of $\psi = 300^\circ$. It is observed that the decrease in angle of attack is due to that the optimum 2/rev flap input reduces the drag coefficient from about 0.10 to about 0.06. This is the primary cause of ECR power reduction. It is also noticed that the local drag remains almost unchanged on the other side of rotor disk.

4.2. Analysis of control parameters

In the process of online identification of the parameters of global transfer matrix $T$, the stability and convergence rate of adaptive T-matrix algorithm are influenced by the
convergence factor $\xi$. ECR power varying with 2/rev flap inputs is shown in Fig. 7(a), when $\xi = \text{diag} (0.4,0.4,0.4)$ and the other control parameters are left steady. The corresponding sine and cosine components of 2/rev flap inputs variations are shown in Fig. 7(b).

As shown in Fig. 7, the ECR power reduction is close to the previous results with basic control parameters. However, the adaptive T-matrix algorithm cannot reach the steady state and ECR power and 2/rev flap inputs are all oscillating, causing an adverse impact on active control. Therefore the parameters in convergence factor $\xi$ should not be chosen too large to avoid divergence of control system.

However, the convergence rate will be affected if the parameters in convergence factor $\xi$ are too small. ECR power varying with 2/rev flap inputs is shown in Fig. 8(a), when $\xi = \text{diag} (0.05,0.05,0.05)$ and the other control parameters are left steady. The corresponding sine and cosine components of 2/rev flap inputs variations are shown in Fig. 8(b).

As shown in Fig. 8, the ECR power reduction and optimum flap inputs are almost the same as previous results with basic control parameters. However, the adaptive T-matrix algorithm converges to the optimum control in about 15 steps. So smaller parameters chosen in convergence factor $\xi$ are not always preferred. These parameters should be set as some reasonable value.

In addition, the effectiveness of the adaptive T-matrix algorithm is also influenced by the weighting matrix. ECR power varying with 2/rev flap inputs is shown in Fig. 9(a), while $W_d = 2500I_{3,3}$ and the other control parameters are left steady. The corresponding sine and cosine components of 2/rev flap inputs variations are shown in Fig. 9(b).

As shown in Fig. 9, the ECR power reduction is almost the same as the previous results with basic control parameters. However, the optimum 2/rev flap inputs are smaller than before.

ECR power varying with 2/rev flap inputs is shown in Fig. 10(a), when $W_d = 1500I_{3,3}$ and the other control parameters are left steady. The corresponding sine and cosine components of 2/rev flap inputs variations are shown in Fig. 10(b).
As shown in Fig. 10, the ECR power reduction is almost the same as the previous results with basic control parameters, while the optimum 2/rev flap inputs are larger than before. It is noted that the magnitude of 2/rev flap inputs are different from various weighting matrix, however the two initial phases are both close to $240^\circ$. The simulation results are consistent with the open-loop control results as well. It is concluded that if a suitable 2/rev flap inputs could delay retreating blade stall, any further increase in magnitude of 2/rev flap inputs would have no obvious effect on ECR power reduction.

5. Conclusions

(1) The simulation results verify the effectiveness of the adaptive T-matrix algorithm for ECR power reduction, and the underlying physical essence of ECR power reduction is further identified by analyzing the angle of attack and drag distribution variations over the rotor disk. For the sample ECR helicopter, about 3% rotor power reduction is achieved with the optimum 2/rev flap inputs at the advance ratio of 0.34. The adaptive T-matrix algorithm can reach the optimum 2/rev flap inputs in about 4 s.

(2) The influences of two key control parameters on the effectiveness of closed-loop control for ECR performance enhancement are analyzed, which are convergence factor and weighting matrix. The stability and convergence rate of adaptive T-matrix algorithm are influenced by the convergence factor $\xi$. If the parameters in convergence factor $\xi$ were too large, the adaptive T-matrix algorithm could not reach a steady state; on the contrary, the convergence rate of the adaptive T-matrix algorithm will be slow. On the other hand, the effect of the weighting matrix on ECR power reduction is not significant. However, it can affect the magnitude of 2/rev flap inputs. The flap inputs would be smaller on condition that the elements in the weighting matrix were larger, which would reduce the power supplied to the flaps. So the control parameters should be set as a reasonable value to improve the effectiveness of the adaptive T-matrix algorithm for ECR performance enhancement.

Acknowledgement

This study was supported by the National Natural Science Foundation of China (No. 51375229).

References


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