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Active control for performance enhancement of electrically controlled rotor

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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 21th century.[1] 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.[2,3] 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,[4,5] 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.

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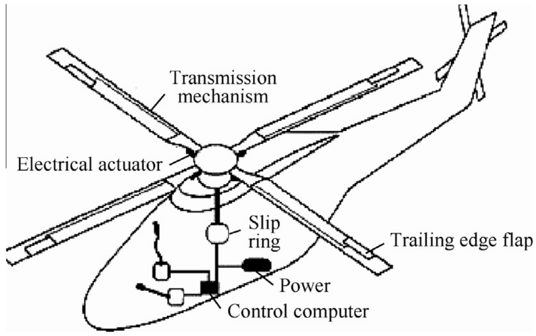

Fig. 1 Schematic diagram of ECR helicopter.

During the last two decades, several active control approaches have appeared for rotor performance enhancement, vibration control and noise reduction.[6–8] 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).[9]

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.[10] 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[11] 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.[12]

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.[13] 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.[14] 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[15] 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[16] 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.[17] 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).[18] 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.[19] 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,[20] 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.