Development of swashplateless helicopter blade pitch control system using the limited angle direct-drive motor (LADDM)

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Abstract

It can be greatly beneficial to remove the swashplate of conventional helicopter, because the swashplate is usually complicated, aerodynamically resistive, and obstacle of more complex pitch control for improving performance. The present technologies for helicopter vibration reduction are usually narrow in effective range or requiring additional actuators and signal transfer links, and more effective technology is desired. Helicopter blade pitch control system, which is removed of swashplate and integrated high-frequency pitch control function for active vibration reduction, is likely the suitable solution at current technical level. Several potential implementation schemes are discussed, such as blades being directly or indirectly driven by actuators mounted in rotating frame and application of different types of actuators, especially implementation schemes of electro-mechanical actuator with or without gear reducer. It is found that swashplateless blade pitch control system based on specially designed limited angle direct-drive motor (LADDM) is a more practical implementation scheme. An experimental prototype of the finally selected implementation scheme has been designed, fabricated and tested on rotor tower. The test results show considerable feasibility of the swashplateless helicopter blade pitch control system using the LADDM.

1. Introduction

The blade pitch control systems of common helicopters are complicated from mechanics perspective, because control inputs must be transmitted from pilot stick or actuators in the non-rotating frame to blades in rotating frame through swashplate, which can usually lead to considerable drag force and high maintenance workload. As a result of mechanical coupling between pitch links of swashplate, more complex pitch control cannot be applied to improving helicopter performance.
The other obvious feature of helicopter compared with fixed wing aircraft is high vibration level, which results in structure fatigue, low system reliability and deterioration of passenger comfort. In order to minimize vibration level, various vibration reduction methods have been studied and tested. These methods can usually be classified into passive vibration control and active vibration control. The latter has attracted much interest in recent years due to the development of microprocessor and actuator technology. The principle of helicopter active vibration reduction can be generally described as that actuators directly or indirectly generate oscillatory forces with proper frequency, amplitude and phase to counteract or decrease vibratory loads in specified locations. Helicopter active vibration reduction methods are usually higher harmonic control (HHC) and active control of structure response (ACSR). In the former method actuators excite rotor blades to generate oscillatory aerodynamic and inertial force, while in the latter method actuators excite fuselage through oscillatory inertial force. Generally, additional actuators and signal links are needed for active vibration control, which brings system complexity and weight penalty. It is obviously beneficial to remove the swashplate and integrate functions of low-frequency pitch control for primary control and high-frequency pitch control for active vibration reduction into helicopter blade pitch control system, and then complex blade pitch control can also be used for performance improvement, while devices for active vibration reduction can be simplified.

2. Preliminary analysis

In swashplateless helicopter blade pitch control system, blades need to be directly or indirectly driven by actuators mounted in rotating frame. In the first implementation scheme, actuator near blade root directly drives the whole blade, while in the latter, actuator generally drives flap mounted in outer segment of blade to mainly generate aerodynamic force to indirectly drive the whole blade. Because the needed driving force to overcome aerodynamic and inertial force of flap is much smaller than that of the whole blade, the actuator needed can be compact and light. Actuators take up a large proportion of the weight of blade pitch control system, so weight cost is smaller for indirect drive scheme than direct drive scheme. Though the weight and volume of actuator of indirect drive scheme is small, the installation space available in blade outer segment is narrow. There had been some attempts to design compact actuators to meet the installation space requirements in which actuators based on piezoelectric stack or bimorph generally were chosen to excite blades or flaps, for their compact size and ability to be integrated into blades; therefore, the installation space problem was solved to some extent. Indirect drive scheme is probably a fine implementation scheme for traditional helicopter, but it is doubtful in blade pitch control ability when the helicopter advance ratio is much higher than common flight condition. The advance ratio can be about 0.8 in helicopters using optimum speed rotor (OSR) or advancing blade concept (ABC) technologies. When the flap in retreating blade is near or in reversed flow region, the aerodynamic force generated by flap is limited for low dynamic pressure and the driving force for pitch control is insufficient. For flight condition of high advance ratio, direct drive scheme is more suitable than indirect drive scheme. Other advantages of direct drive scheme compared with indirect drive scheme are better technical inheritance of rotor blade and shorter signal links for actuators. For more extensive application, implementation scheme of blades directly driven by actuators for pitch control has been studied in this paper.

The widely studied actuators in helicopter field are hydraulic actuators, piezoelectric actuators and electro-mechanical actuators. Actuators for conventional helicopters are mostly based on hydraulic servo technology, which are characterized by large force to weight ratio, small size and agile response. But when taking hydraulic pressure source into consideration, the whole actuation system will be complicated and heavy. In implementation scheme of blades directly driven by actuators, the main problem for using hydraulic actuators is how to provide pressurized hydraulic oil to actuators in rotating frame. Supposing that hydraulic source is mounted in non-rotating frame, there will be hydraulic collector ring needed for supplying oil from non-rotating frame to rotating frame, which has not been practical and doubtful in reliability. The other choice is mounting the hydraulic source into rotating frame. Even without consideration on redundancy for reliability, it would be arduous task for engineers to integrate the whole hydraulic source into rotor hub, which is usually composed of driven motor, hydraulic pump, oil filter, pressure accumulator and high-pressure pipelines.

In helicopter field, piezoelectric actuators have been successfully used as flap actuators and also have been used as pitch control actuators for the whole blade in active vibration reduction. The work done in one drive period of piezoelectric actuator is limited by the tiny work density of piezoelectric material. It is applicable for driving small flap for large amplitude pitch control or driving the whole blade for small amplitude pitch control, in which operating mode the work done in one driving period is small, but unsuitable for driving the whole blade for large amplitude pitch control. It is found that well-designed electro-mechanical actuators have advantage over piezoelectric actuators in the aspect of work density, and the application of electro-mechanical actuators can reduce the weight of actuation system. Even some researchers, which had deeply studied piezoelectric actuators in driving flaps usage, moved some of their interest to electro-mechanical actuators. In this study, the hydraulic actuators and piezoelectric actuators will not be taken into consideration for the above reasons and the following research will focus on electro-mechanical actuators.

3. Determination of actuator performance needed for blade pitch control

The main technical parameters of an existing model rotor system, as shown in Table 1, are used in the calculation for actuator performance, and the following experimental verification will be also based on this model rotor system. Multi-body dynamics model is established to predict moment for pitch control, and the model is composed of rigid body element, flexible blade, force element, and hinge joint. The C81 look-up tables of OA209 are used for steady aerodynamic calculation and the Leishman-Beddoes unsteady/dynamic stall models are used for calculation of unsteady aerodynamic loadings in attached flow and stall. The calculation methodology had been verified through comparing flight test data with calculation results of CAMRAD II.
The strategy for determining actuator performance parameters is that actuator should be available for primary control and active vibration reduction in ordinary state and in critical state the function of active vibration reduction will be phased out to satisfy the requirement of primary control so as to reduce the required weight and power. The other reason of the strategy is that the blade pitch control for active vibration reduction is the combination of higher frequencies with much smaller amplitudes compared with the frequency and amplitude needed for primary control. In case the actuator is available for critical state, it will be feasible for primary control and active vibration reduction in most experiment state. The wind tunnel state at velocity of 50 m/s is selected for calculation, which is the maximum velocity of the wind tunnel planned for further study. Fig. 1 shows the changing process of moment needed for pitch control in one rotation period, and the control inputs for trim are collective pitch \( 7.4^{\circ}/C_0 \) and longitudinal cyclic pitch \( 1.8^{\circ}/C_1 \). According to the above analysis, the peak moment is determined as \( 20 \text{ N-m} \) to provide a margin for calculation error and influence of additional devices in practice. The maximum driving angle \( 120^{\circ} \) is available for blade pitch control in one rotational period.

The required maximum rotational velocity should be no less than \( 1200 \text{ (r/min)} \), which is available for blade pitch control in combination of primary control and active vibration reduction for the rotor system tested. The performance indexes of actuator in practice are complicated and the three performance indexes listed above are simply for experimental actuator design and feasibility verification.

### 4. Analysis of electro-mechanical actuators with and without gear reducer

The electro-mechanical actuators are based on electromagnetic force, which have been widely used in many areas in the form of servo motor. The features of conventional servo motor are high in rotational speed but low in torque compared with the speed and moment needed in blade pitch control, and naturally a gear reducer is usually chosen to amplify torque in this operating mode. A potential problem of this implementation scheme is that the gear backlash cannot be neglected for high-accuracy pitch control of the whole blade required in active vibration reduction, in which operating mode the small amplitude of high-frequency pitch control and the gear backlash can be in the same order. Gear backlash means delay and energy storage and will influence control stability and accuracy. According to the peak moment and rotational speed needed for blade pitch control, a servo motor from Fuji Corporation combined with a precise planetary gear reducer from EISELE Corporation is selected as the research object for backlash influence; the main parameters are listed in Tables 2 and 3.

The backlash influence is studied through simulation in MATLAB/SIMULINK and the simulation model is based on actual parameters with proper simplifications, for the target of simulation is qualitative analysis. The current saturation in motor driver, the torque constant and inertial moment of servo motor, the backlash, torsional stiffness and damping of reducer are considered, while the inertial moment of gears are neglected for tiny in value, little influence on simulation result and the lack of accurate data. Parameters of simplified blade dynamic model are from Table 1 and airfoil data of OA209, and the controller is based on proportion-integration-differentiation (PID) principle. The whole simulation model is shown in Fig. 2; the reference input and results of pitch output in the case of the gear reducer being with and without backlash are compared in Fig. 3.

In case the gear reducer is without backlash and proper configuration of PID parameters, the helicopter blade pitch output will be almost coincident with the reference input, whether the reference input is large amplitude, low frequency pitch control needed in primary control or small amplitude, high frequency pitch control of the whole blade needed in active vibration reduction. When there is backlash in reducer, the pitch output will oscillate around the

### Table 1 Main technical parameters of model rotor system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor diameter (m)</td>
<td>4</td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Blade chord (mm)</td>
<td>131</td>
</tr>
<tr>
<td>Rotor solidity</td>
<td>0.0625</td>
</tr>
<tr>
<td>Airfoil</td>
<td>OA209</td>
</tr>
<tr>
<td>Shape of blade tip</td>
<td>Rectangle</td>
</tr>
<tr>
<td>Blade twist rate (°)</td>
<td>-12</td>
</tr>
<tr>
<td>Weight of blade (kg)</td>
<td>3.0</td>
</tr>
<tr>
<td>Start position of airfoil (mm)</td>
<td>520</td>
</tr>
<tr>
<td>Moment of inertia about pitch axis ((10^{-3} \text{ kg-m}^2))</td>
<td>1.9481</td>
</tr>
<tr>
<td>Moment of inertia about flap axis ((\text{kg-m}^2))</td>
<td>3.2039</td>
</tr>
</tbody>
</table>

Fig. 1 Changing process of driving moment for pitch control in one rotational period.

### Table 2 Parameters of Fuji servo motor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power (W)</td>
<td>400</td>
</tr>
<tr>
<td>Rated torque (N-m)</td>
<td>1.27</td>
</tr>
<tr>
<td>Torque constant (N-m/A)</td>
<td>0.47</td>
</tr>
<tr>
<td>Rated rotating speed (r/min)</td>
<td>3000</td>
</tr>
<tr>
<td>Rated current (A)</td>
<td>2.7</td>
</tr>
<tr>
<td>Inertial moment ((10^{-4} \text{ kg-m}^2))</td>
<td>0.246</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>1.8</td>
</tr>
<tr>
<td>Model</td>
<td>GYS401DC2-T2</td>
</tr>
</tbody>
</table>
reference input, especially when the reference input is high in frequency and small in amplitude, as shown in Fig. 3. If decreasing the width of backlash, the output oscillation will be reduced to same extent, but the improving measures will mean manufacturing cost increase. The practical situation is worse. At high frequency and small-amplitude reciprocating motion operating mode, the backlash in gear reducer means violent crash between driving and driven gears. The situation will be followed by gear abrasion, which will increase the width of backlash and lead to more violent crash and great accuracy decrease. Actually, even in the operating mode of high-precision smooth motion control, such as the motion control in numerical control (CNC) machine, gear reducer for transmission is inclined to be replaced by direct-drive scheme for avoiding motion oscillation and loss of accuracy sourcing from gear abrasion. 24 On conventional aircraft, electro-mechanical actuators with gear reducers are negated in the usage of primary flight control for actuator jamming case.25 It is also important to point out that the pitch control result without backlash reflects the feasibility of implementation scheme of electro-mechanical actuator without gear reducer, for a servo motor combined with reducer without backlash are functionally equivalent to a low speed and high torque servo motor. According to the above analysis, conventional gear reducer is not suitable for long time high frequency and high precise reciprocating blade pitch control, and the implementation scheme of electro-mechanical actuator without gear reducer is selected in the subsequent research, in which there is no gear reducer between blade and servo motor of electro-mechanical actuator.

5. Realization and experimental verification

Based on the selected implementation scheme, a special servo motor has been specifically designed orienting to blade pitch control, a whole helicopter blade pitch control system has been realized, and the system feasibility has been preliminarily verified through experiment.

5.1. Realization

To realize blade pitch control in the way of servo motor directly drive blade without gear reducer, one of the key points is the fabrication of servo motor with high torque and small weight. As has been mentioned above, the conventional servo motor is high in speed but low in torque and it will mean high weight penalty and low efficiency without modification for blade pitch control operating mode. A typical servo motor designed for conventional high-speed and low-torque usage is the Fuji Corporation GYG152CC2-T2 servo motor, whose maximum torque is 21.5 N·m and weight is 9.8 kg. Common servo motor is usually designed for continuous rotation, which is useless for blade pitch control, because the rotational range needed in blade pitch control is very limited. The motor coils, magnets need to be redesigned and devices for coil current switching that are necessary in continuous rotation can be removed to reduce weight and improve the system reliability. Along this line of thinking, the limited angle direct-drive motor (LADDM) has been designed and customized, specifically orienting to the usage of blade pitch control.

In LADDM, there are four magnetic poles on motor rotor and four motor windings on stator, which is different from the conventional servo motor in structure. Fig. 4 shows the magnetic field nephogram of motor in idle state and work state. In conventional servo aircraft, electro-mechanical actuators with gear reducers are negated in the usage of primary flight control for actuator jamming case.25 It is also important to point out that the pitch control result without backlash reflects the feasibility of implementation scheme of electro-mechanical actuator without gear reducer, for a servo motor combined with reducer without backlash are functionally equivalent to a low speed and high torque servo motor. According to the above analysis, conventional gear reducer is not suitable for long time high frequency and high precise reciprocating blade pitch control, and the implementation scheme of electro-mechanical actuator without gear reducer is selected in the subsequent research, in which there is no gear reducer between blade and servo motor of electro-mechanical actuator.

![Fig. 2 Simulation model for gear reducer backlash influence.](image1)

![Fig. 3 Comparison of pitch outputs without and with backlash.](image2)
magnetic poles has been selected to balance torque and effective angle region.

Fig. 5 shows the rotor and stator of the customized LADDM, the magnets in rotor and windings in stator are specially designed for limited angle usage, and there is no motor brush or other devices for current switching. Fig. 6 shows the cutaway view of the LADDM. From inside to outside, the parts shown in the cutaway view are iron core and magnet of rotor, and then coil and shell of stator. The maximum torque of this motor is 21.5 N·m, the rated angle range is from $-15^\circ$ to $15^\circ$, and the weight is 4.0 kg, which is only about 40% of the weight of conventional servo motor with the same maximum torque. The motor stator and rotor are separate parts, which are integrated into a scale helicopter articulated rotor hub as part of its feathering axis, as shown in Fig. 7. For high efficiency of heat dissipation, most of the motor stator shell is exposed to downwash airflow from helicopter rotor. Thrust bearings are usually used in feathering axis for carrying centrifugal force, but the dry friction force will mean violent disturbance in precise blade pitch control. A torsion bar across the hole in motor rotor is used in feathering axis for carrying the huge centrifugal force from rotating blade and providing the rotational freedom needed by pitch control so as to avoid the dry friction force from thrust bearings.

To protect the whole system from being damaged in extreme case that the blade pitch is totally out of control, a mechanical device has been designed to limit the blade pitch in range of $-15^\circ$ to $15^\circ$. Optical grating ruler was firstly used as pitch angle feedback component, but it was found unreliable in this operating mode, for the output of rating ruler was sensible to the distance between optical reading head and ruler, and the distance was inevitably unstable in the vibration environment of helicopter rotor hub. Magnetic railing ruler was finally chosen as the pitch angle feedback component and the experiment proved that it is reliable in the environment of vibration, dust and oil, even being mounted in extreme working conditions.

Table 3 Parameters of EISELE planetary reducer.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated output torque (N·m)</td>
<td>20</td>
</tr>
<tr>
<td>Reduction ratio</td>
<td>3–10</td>
</tr>
<tr>
<td>Backlash (arcmin)</td>
<td>15</td>
</tr>
<tr>
<td>Full load efficiency/%</td>
<td>96</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>1.0</td>
</tr>
<tr>
<td>Torsional stiffness (N·m/arcmin)</td>
<td>1.3</td>
</tr>
<tr>
<td>Model</td>
<td>DPL64</td>
</tr>
</tbody>
</table>
near the motor. Both optical grating rulers and magnetic railering rulers are incremental sensor, which means the zero point should be determined before work and the mechanical device mentioned above for pitch angle limitation is used for determining zero point. As shown in Fig. 8, the magnetic railing ruler and mechanical device for pitch angle limitation are mounted in feathering axis. In the process for determining zero point, the servo motor is set as torque control mode, the torque slowly and gradually increases to 5% of the maximum torque, then the pitch will achieve the maximum angle of the mechanical device, the maximum angle value will be memorized by controller. Next, the torque will slowly and gradually decrease to -5% of the maximum torque, then the pitch will achieve the minimum angle of the mechanical device, the angle value will also be memorized by controller, and median of maximum and minimum angle values is the zero point. The output of magnetic railing ruler will be reset, which bases on the zero point determined, and a corrected value may need to be superimposed for helicopter rotor balance.

An existing direct current (DC) motor driver for brush servo motor has been chosen as the driver for LADDM. Though the LADDM is brushless, the driving principle is similar to DC brush motor, which is much simpler than the driving principles of brushless direct current (BLDC) motor and alternating current (AC) motor, so the driver needed is simple, which means more achievable of high reliability and

![Fig. 6 Cutaway view of LADDM.](image)

![Fig. 7 Articulated rotor hub integrated with LADDM as part of feathering axis.](image)

![Fig. 8 Magnetic railing ruler and mechanical device for pitch angle limitation mounted in feathering axis.](image)
small weight. An industrial four-axis motion controller has been used for blade pitch control, the first axis is used to receive the position signal from the servo motor driving the rotor axis, and the position signal will be converted to rotor azimuth in motion controller. The remaining three axes of motion controller are used for angle control of the LADDM and the angle control commands are generated in real time by motion controller according to rotor azimuth and blade pitch control parameters. A small multichannel slip ring in the through hole of rotor axis is used for transmission of angle signal from magnetic railing ruler in rotating frame to motion controller non-rotating frame. Another multichannel slip ring mounted in the outside of rotor axis is used for transmission of driving current from motor driver in non-rotating frame to LADDM in rotating frame. The two slip rings inside and outside of rotor axis are used to avoid the disturbing of large driving current to small angle signal in case of being transmitted in the same slip ring. Uninterrupted power supply (UPS) modules are used to prevent power failure during the experiment. For the main objective is to verify the feasibility of helicopter blade pitch control system using the LADDM, the existing industrial components are chosen to reduce experiment cost. The architecture of helicopter blade pitch control system is shown in Fig. 9 and the main devices are shown in Fig. 10. The numbers in Fig. 9 are used to mark devices of same type.

5.2. Experimental verification

The fabricated helicopter blade pitch control system has been mounted on rotor tower and has its capability of blade pitch control tested. First, the control parameters for blade pitch control have been adjusted in rotor axis non-rotating state, and the pitch control capability has been tested in the same state for safety. Second, the control parameters adjusted in the non-rotating state are used as the basis for adjusting control parameters in rotating state, and step by step increases the rotational speed from 60 r/min to 720 r/min. Once the rotational speed has been increased, the control parameters may need to be revised according to the pitch control result. The experimental result has shown that the control parameters adjusted in non-rotating state can also produce good control result in rotating state and the control result is better after some modification for rotational state; the main reason of this phenomenon is that the influence of rotational speed on blade torsion modal is small.

Typical pitch control modes are tested in rotor axis non-rotating and rotating state, including large amplitude, low frequency pitch control for primary control, small amplitude, high frequency pitch control of the whole blade for active vibration reduction and the combination of the former two control modes. Experiments in rotor axis non-rotating
Fig. 11  Time history of pitch angle and Blade-1 pitch error during cyclic pitch changing from 3° to 6°.

Fig. 12  Time history of pitch angle and Blade-1 pitch error during cyclic pitch changing from 9° to 12°.

Fig. 13  Time history of pitch angle and Blade-1 pitch error during high frequency, small amplitude pitch control.
state is a transitional state to the final experiment state, so the experimental results listed below (Figs. 11–14) and the corresponding analysis focus on experimental results in rotating state.

According to the experimental results listed above, the pitch outputs in different experimental states are all well coincide with input references. As shown in Figs. 11(a) and 12(a), the changing process of cyclic pitch control for primary control is smooth and without oscillation. Figs. 11(b) and 12(b) show the pitch error of Blade-1 during the change of cyclic pitch. The process of error is approximately periodic, which means the error mainly sources from stable small difference of amplitude and phase that are between the input reference and the actual output, and the effect from error can be compensated by adjusting the input reference in practical primary control. The absolute pitch error increases with amplitude, while the relative pitch error decreases with the increase of amplitude.

Fig. 13(a) shows the typical pitch control for active vibration reduction, which is high in frequency and small in amplitude. Fig. 13(b) shows the process of Blade-1 pitch error during the same control process, which is also approximately periodic. The absolute pitch error is smaller compared with the above primary control process and the relative error is larger, mainly on account of phase delay from high frequency and can be compensated in practical active vibration reduction by adjusting the input reference. Through comparison of results of low-frequency and high-frequency pitch control, it is found that the phase delay increases with harmonic order and the value of phase delay is small.

Fig. 14 shows that the time history of pitch angle and Blade-1 pitch error during the control input is a combination of primary control and typical pitch control for active vibration reduction. The results are similar to the above independent control mode, except for static error caused by collective pitch of rotor, and the pitch error influence can be compensated by adjusting the input reference for desired primary control and active vibration reduction result.

The capability of helicopter blade pitch control system using the LADDM has been preliminarily verified. In the above experiment state, only about 55% of servo motor maximum torque has been used, which can be estimated from the current data that is directly proportional to torque. There are still potential improvements for LADDM performance, the present ferrite magnet can be replaced by sintered NdFeB magnet and the present inner rotor structure can be replaced by external rotor structure; the improving measures will be studied in further research.

6. Conclusions

(1) A swashplateless helicopter blade pitch control system has been designed, fabricated and tested, which can fulfill the requirements for low frequency, large amplitude blade pitch control for primary control and high frequency, small amplitude blade pitch control of the whole blade for active vibration reduction. This indicates the additional actuators and signal transfer links for active vibration reduction can be greatly simplified, and also indicates the potential of using complex pitch control to improve helicopter performance without mechanical restraint of swashplate.

(2) The implementation scheme of servo motor directly drive blade for pitch control has been selected in this research, in consideration of avoiding potential loss of accuracy caused by gear abrasion after long time operation, and avoiding potential instability caused by gear backlash in operating modes that contain high frequency, small amplitude pitch control of the whole blade.

(3) For directly driving blade in pitch control, the LADDM has been designed and fabricated. Without requirement for continuous rotation, the magnet and windings are concentrated on limited angle region to generate larger torque with relatively less weight. The weight of LADDM is about 40% of the weight of conventional servo motor with similar torque.

(4) The swashplateless helicopter blade pitch control system using the LADDM has been tested on rotor tower. The blade pitch outputs in different experiment states are all well coincide with input references, the maximum of average amplitude error is about 0.1° for harmonic pitch changing process. The phase delay increases with harmonic order and the value of phase delay is small in experiments conducted. The results of experiments have
shown typical pitch control capability needed by primary control, active vibration reduction and combination of the two, and the feasibility of swashplateless helicopter blade pitch control system using LADDM has been preliminarily verified.

References


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