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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.

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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 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[1–5]; 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)[6] or advancing blade concept (ABC)[7,8] 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,[9–12] 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 driving 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.[13] The work done in one drive period of piezoelectric actuator is limited by the tiny work density of piezoelectric material.[14] 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.[15–17] 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.[18,19]