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Control Optimization of Tiltrotor Aircraft Autorotation after One Engine Failure

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Abstract

The tiltrotor aircraft combines the capabilities of helicopter vertical takeoff and landing as well as the fixed wing aircraft high speed and range. Like the conventional helicopter, the safety is one of the critical issues for tiltrotor aircraft encountering one engine failure during the takeoff and landing procedures.

Some works have studied the control optimization to investigate the tiltrotor aircraft autorotation during power failure situations [1-3]. The rotor thrust, pilot’s longitudinal stick displacement and nacelle angle are determined to perform the autorotation procedure for One Engine Inoperative (OEI) situation based on a longitudinal rigid body model by using collocation and nonlinear programming. This method has been applied to the tiltrotor aircraft autorotation for the OEI conditions of runway takeoff, vertical takeoff as well as the determination of OEI H-V diagrams. On this basis, it seems worthwhile to investigate the application of control optimization to determine a more practical control strategies, *i.e.* the pilot’s collective and longitudinal stick displacements in cockpit and nacelle angle as well as their rates, in the attempt to provide pilots more accurate references to perform the autorotation procedure so that the limits of mechanical characteristic of aircraft control system can be considered.

Therefore, the control optimization of tiltrotor aircraft autorotation in the event of OEI is studied by applying the nonlinear optimal control theory. To the end, an augmented longitudinal three-dimensional rigid body flight dynamic model is developed with pilot controls and corresponding control rates, described in terms of a set of nonlinear differential-algebraic equations. Considering safety-related requirements and tiltrotor aircraft performance limits as well as selecting the appropriate cost function, the control optimization problem of tiltrotor aircraft autorotation landing is then formulated into a nonlinear optimal control problem (NOCP). To improve computational efficiency and rate of convergence of numerical optimization methods, the NOCP is normalized and scaled well. Finally, the NOCP is directly transcribed into a discrete nonlinear programming problem (NLP) using a collocation method. The optimal solution of the NOCP is approximated by interpolation of the discrete NLP optimal solution obtained by solving the NLP using sequential quadratic programming method.

XV-15 tiltrotor aircraft in the event of one engine failure during short takeoff is taken as the sample for the investigation. The takeoff conditions from reference [2] is set to conduct the calculation in order to compare the results with those from reference [2]. These conditions include: 1) the aircraft, with weight of 13000lbs and flap setting of 40/25, accelerates from rest on the runway with nacelle angle of $70°$ to a constant acceleration of 0.2g. 2) the aircraft lifts off at the speed of 40 knots and maintains a constant flight path angle of 8^o. 3) OEI occurs at

the moment with the speed of 44 knots and the altitude of 10ft. Based on these conditions and the same optimal cost function in reference [2], the optimal control inputs and autorotation landing trajectory which minimize the runway length during the autorotation landing are conducted. The optimal solutions are compared with those of reference [2] as shown in Fig. 1.

It can be found that there is a good agreement between the results and those of reference [2]. The difference is that the variations of optimal solutions are more relatively gentle with the present method. This is the contribution of the present method adding the control rates in the augmented flight dynamic model.

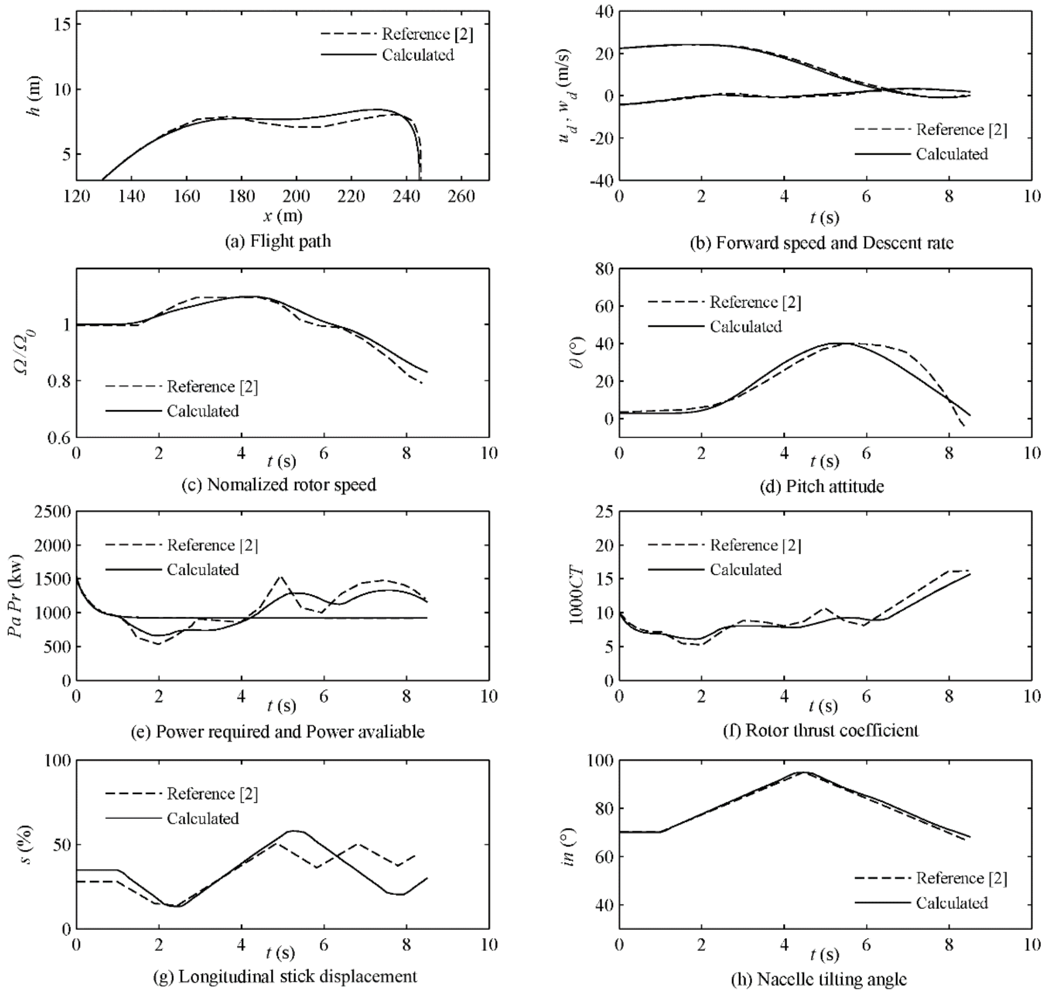

Fig. 1 Comparison of present solutions with reference [2]

In addition, the present optimal solutions involve more control information, such as the time histories of collective stick displacement in cockpit and its rate, rotor collective and longitudinal cyclic pitch angles as well as the rate of nacelle tilting angle, as shown in Fig. 2. It is obvious that the present solutions are more practical to pilot as reference during autorotation operation. It is also the contribution of the augmented flight dynamic model.

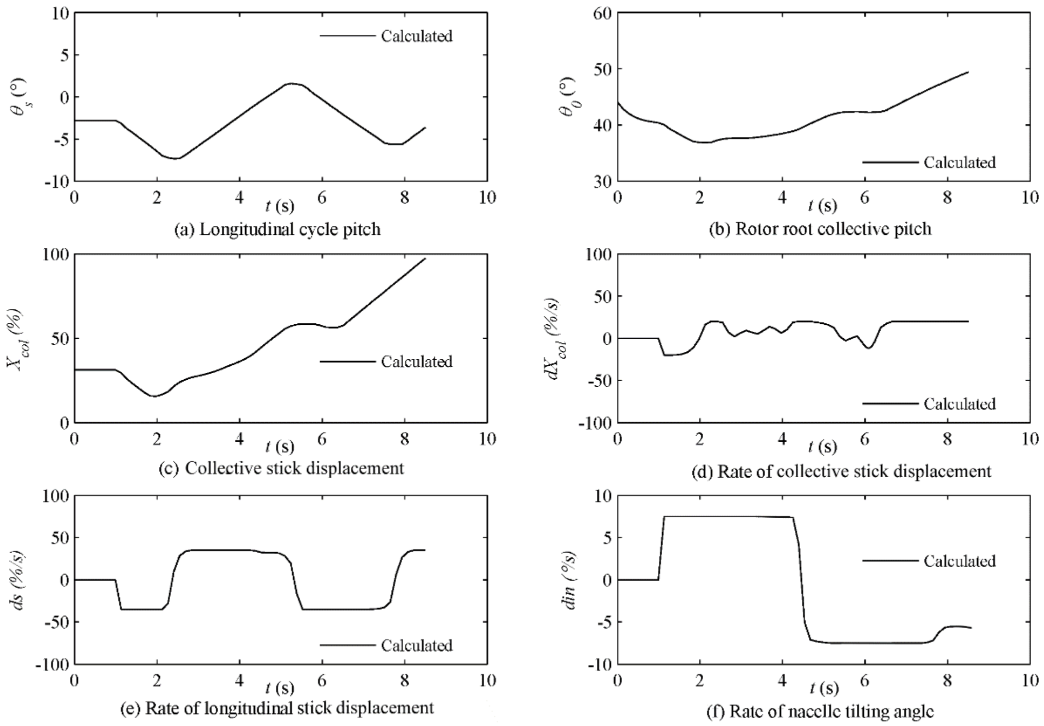

Fig. 2 Additional control information obtained with the present control optimization

The paper includes the development of the augmented longitudinal three-dimensional rigid body flight dynamic model, path constraints, boundary constraints and cost function, the formulation of the optimal control problems and the numerical solution techniques of the NOCP. This is intended as a contribution to a practical control strategies for pilot to product safe autorotation when tiltrotor aircraft encountering one engine failure during the takeoff.

References

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