Chinese Journal of Aeronautics, (2015),28(1): 93–102

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Numerical study on flow fields and aerodynamics of tilt rotor aircraft in conversion mode based on embedded grid and actuator model

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Received 22 January 2014; revised 20 June 2014; accepted 3 September 2014
Available online 26 December 2014

KEYWORDS

Actuator disk;
Conversion mode;
Embedded grid;
Grid assembling;
Tilt rotor aircraft

Abstract A method combining rotor actuator disk model and embedded grid technique is presented in this paper, aimed at predicting the flow fields and aerodynamic characteristics of tilt rotor aircraft in conversion mode more efficiently and effectively. In this method, rotor's influence is considered in terms of the momentum it impacts to the fluid around it; transformation matrixes among different coordinate systems are deduced to extend actuator method's utility to conversion mode flow fields' calculation. Meanwhile, an embedded grid system is designed, in which grids generated around fuselage and actuator disk are regarded as background grid and minor grid respectively, and a new method is presented for 'donor searching' and 'hole cutting' during grid assembling. Based on the above methods, flow fields of tilt rotor aircraft in conversion mode are simulated, with three-dimensional Navier–Stokes equations discretized by a second-order upwind finite-volume scheme and an implicit lower–upper symmetric Gauss–Seidel (LU-SGS) time-stepping scheme. Numerical results demonstrate that the proposed CFD method is very effective in simulating the conversion mode flow fields of tilt rotor aircraft.

1. Introduction

Tilt rotor aircraft is a flight vehicle which can land and take off vertically, as well as convert to propeller mode to achieve high-speed cruise performance. Extensive researches, covering a number of areas including aerodynamic interactions, performance, aeroacoustics and dynamics, have been conducted on it in recent years due to its unique advantages and technical complexity. In the aspect of experimental research, various experiments have been carried out by NASA Ames Research Center, Bell Helicopters Inc.[1–3] and other institutions. Abundant experimental data has been obtained, which provides great assistance to the tilt rotor aircraft design and manufacture. In the aspect of computational research, due to the complexities of tilt rotor flow fields and its aerodynamic characteristics, more and more researchers started to study tilt

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2014.12.028

rotor aircraft aerodynamics by solving Navier–Stokes equations instead of using conventional methods. For example, in the mid-1990s, the flow field of V-22 rotor/wing configuration in hover was simulated by Meakin[4] with the unsteady thin-layer Navier–Stokes equations, and rotor motion and rotor/airframe interference were simulated directly using moving body overset grid methods. The flow over a wing-fuselage-nacelle configuration of the V-22 tilt rotor aircraft in forward flight was simulated by Tai[5] with a multi-zone, thin-layer Navier–Stokes method, and major flow features including the three-dimensional flow separation due to viscous-vortex interactions observed experimentally were captured. After the year 2000, overset-grid Reynolds Averaged Navier–Stokes (RANS) solvers, OVERFLOW and Fun3D, were used by Gupta and Baeder[6] and Lee-Rausch[7] respectively to numerically simulate the flow fields of a simplified Quad Tilt Rotor (QTR) in forward flight and an isolated tilt rotor in hover. Aerodynamic characteristics of tilt rotor in hover were computed by Potsdam and Strawn[8] by solving the governing equations in rotation reference frame. More detailed investigations on tilt rotor aircraft were presented in the doctorate thesis of Gupta.[9] In his paper, flow fields around a simplified Quad Tilt rotor, both in and out of ground effect, were simulated; rotor was modeled by both actuator disk and body conforming meshes method, the results obtained by these two methods were then compared.

A feature of tilt rotor aircraft is the existence of conversion mode. In this status, the manipulation and dynamic response of its blades are more complex than those of conventional helicopter rotors or propeller because of the more severe wake distortion and unsteady blade loads. Research on tilt rotor aircraft in conversion mode is still a challenge until now, although extensive research works on this aircraft in helicopter or propeller mode have been conducted. Challenges to the research work on tilt rotor aircraft arise from the complexity of flow physics in conversion mode, which is reflected in the following two aspects. One is that the rotor wake is intensely distorted due to the blade manipulation for aerodynamic balance and the other is that flow fields induced by wing and rotors are closely coupled and severe aerodynamic interference phenomenon appears, with the reason that the forward flight speed is usually not very high and the space between rotor blades and wings is quite narrow.

Considering the importance and complexity of the research on conversion mode, this paper mainly focuses on numerical methods to be used for conversion mode simulation. In general, accurate modeling of flow around individual rotor blades is a complex task even for a conventional helicopter configuration, which means much more time and resource requirements for tilt rotor aircraft conversion mode calculation. As the first step of the research plan, this paper proposes a new approach by combining rotor actuator disk model with embedded grid technique, aimed at providing a rapid, effective and universal method, which can be conveniently transplanted to the rotor blade body-fitted flow field calculation in future. The work in this paper can be described as follows: rotor is modeled as an actuator disk in order to ameliorate computational time costs and make simulation works possible, and transformation matrixes among different coordinate systems are deduced so that the actuator model can be used at different tilt angles. Meanwhile, embedded grid system is designed to describe relative movement among the rotors and wing/fuselage, and a new method is presented for ‘donor searching’ and ‘hole cutting’ during grid assembling. Grids generated around fuselage and actuator disk are regarded as background grid and minor grid respectively, and the influence of actuator disk on flow fields at different tilt angles is simulated by the location change of minor gird.

A CFD solver is put forward after comprehensively analyzing the requirements of flow field calculation for tilt rotor configurations in conversion mode, by combining methods mentioned above and Navier–Stokes equations solving technique. Three-dimensional Navier–Stokes equations are discretized using a second-order upwind finite-volume scheme and an implicit LU-SGS scheme. Induced velocity fields of experimental rotors are simulated firstly for validation purpose, and then flow fields of a tilt rotor aircraft model are calculated. Results indicate that the present CFD method is very effective and has the ability to capture essential flow field characteristics and to predict aerodynamic interactions of tilt rotor aircraft in conversion mode.

2. Methodology

2.1. Grid system

An embedded grid system with the rotor modeled as actuator disk is adopted in the present work. Considering the relative movement among different components of tilt rotor configurations, a minor grid with the rotor modeled as actuator disk and a background grid enclosing unmoving bodies (fuselage) are generated separately, and the minor grid is fully embedded inside the background grid. Taking the universality into consideration, topology of grid cells is not restricted (although the pure hexahedron cells are used in the following illustrations).

Preprocessing of overset grid conventionally involves two steps: ‘hole cutting’ and ‘donor searching’. The related previous investigations are extensive and various methods are developed, such as explicit and implicit methods for hole cutting,[10–12] inverse map,[13] neighbor-to-neighbor (N2N)[14] and alternating digital tree (ADT) searching algorithm[15] for donor cell searching. Based on these previous studies, a more adaptable scheme is designed and applied in the present work to meet the requirements for tilt rotor aircraft calculation as described in detail as follows.

(1) For each grid block, cells which are directly adjacent to body surface or actuator disk are marked as layer 1; those unmarked cells which are adjacent to layer 1 are then marked as layer 2. Then, the left cells will be marked with different layer numbers according to the method, and these layer numbers will be used as adaptable parameters for adjusting range of ‘hole cutting’.
(2) For each cell (noted as C) in one grid block, cell in other grid blocks which contains the cell center of C is searched and noted as donor cell (D). If the layer number of cell D is less than or equal to a given constant, cell C will be regarded as ‘Hole Cell’, which should be blanked out during computation. Those cells which do not have donor cells are temporarily considered as normal cells. Neighbor-to-Neighbor (N2N) searching algorithm is adopted for donor cell searching and the