Turning flight simulation of tilt-rotor plane with fluid-rigid body interaction

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Abstract
Six degrees of freedom turning flight simulation is presented for a tilt-rotor aircraft represented by V-22 Osprey, considering interaction of fluid and rigid body in a coupled manner. A tilt-rotor aircraft has a hovering function like a helicopter by turning axes of rotor toward the sky during takeoff or landing. On the other hand, it behaves as a reciprocating aircraft by turning axes of rotor forward in flight. The tilt-rotor aircraft is known to be susceptible to instable state compared to conventional aircraft. For realizing Digital Flight of turning flight of the aircraft, combination with the Moving Computational Domain (MCD) method and the multi-axis sliding mesh approach is applied. In the MCD method, the whole of the computational domain itself moves with the bodies included inside the domain, which makes an airplane possible to fly freely in the physical space without any restriction of region size. Moreover, this method is also applied to rotation of rotors. The multi-axis sliding mesh approach is computational technique to enable us to deal with multiple rotating axes of different direction, and it is used to rotate two rotors and change flight attitude of the aircraft. As a result of the coupled computation between flow field and rigid body using above approach, the airplane gained lift and propulsion by rotating the rotor and flew in turning by operating flight control surfaces such as flaperons, elevator and rudders. Moreover, the manipulating variables of flight control surfaces needed for turning flight, flight attitude of the aircraft and generated lift were found. Differences of fluid flow between straight flight and turning flight were also captured.

Keywords: Computational fluid dynamics, Moving grid, Sliding mesh, Tilt rotor, Flight simulation, Coupled simulation

1. Introduction
In computational fluid dynamics, the further goal in the aviation field is the realization of Digital Flight (Salas, 2006). Digital Flight is the simulation of various flights including takeoff and landing of aircrafts in the computer. This is expected to reduce design and development costs and avoid risk in actual flight. For example, it is possible to safely analyze the aerodynamic characteristics of aircrafts that perform dangerous flight such as a sudden turn or a descent without using actual aircrafts. In addition, it will be possible to easily check at low cost whether designed aircraft satisfies required motion performance. In addition, if performance of the computer further improves, it is possible to mount the Digital Flight on actual aircrafts. If this is realized, it will be possible to predict stall of aircrafts by performing Digital Flight under the same conditions as the actual flight, and it can be expected to be used in advance to assist appropriate maneuvering. One of the interesting aircraft is a tilt-rotor aircraft represented by the V-22 Osprey. This is the aircraft capable of switching between the helicopter mode and the airplane mode by switching direction of engine nacelles. As a result, the tilt-rotor aircraft has two advantages. The first is functions of a helicopter that does not require a runway and enables hovering and small-turn flight. The second is functions of a propeller aircraft such as long range and high-speed flight. However, it is known that the aircraft is likely to become unstable, and several accidents
have been reported (O’Rourke, 2009). Thus, it is important to perform fluid flow analysis of this special aircraft by numerical calculation. Also, from the viewpoint of fluid dynamics, the unsteady flow field generated by complex dynamics such as rotation of rotors and mode conversion of a tilt-rotor aircraft is very interesting. However, the computation is difficult because the object is greatly deformed during mode conversion. Therefore, an advanced computation method is required, and the cost is increased. Many of the current reports are partial analysis, such as only for the rotor blade mode (Potsdam and Strawn, 2002) or a prop rotor (Neal, 2012). The aerodynamic interaction phenomenon of a tilt-rotor in helicopter mode was simulated by using overset grids (Liang, et al., 2016), but the aircraft itself didn’t move. There are very few simulations involving the movement of the aircraft. To compute motions and flow fields of aircrafts and simulate the actual flight is useful for design development which improve safety of tilt-rotor aircrafts. Thus, we have conducted moving simulation of the tilt-rotor plane (Yamakawa, et al. 2016). The simulation was, however, symmetrical three degrees of freedom computation. For realizing the Digital Flight of a tilt-rotor aircraft, it is necessary to simulate arbitrary flight motion in three-dimensional space, but a turning flight simulation of the tilt-rotor airplane has not conducted yet.

In this paper, the purpose of this study is to achieve six degrees of freedom turning flight simulation toward the Digital Flight of a tilt-rotor aircraft, using combination of the MCD method and the multi-axis sliding approach. The MCD method is a method for simulating flows driven by a moving body with no restriction of motion. V-22 Osprey was adopted as the simulation model. This simulation is conducted as a coupled computation that integrates both flight dynamics governing motion of the aircraft and fluid dynamics governing fluid flow around that. In other words, the aircraft is treated as a rigid body and flies by receiving forces by interacting with the surrounding fluid. The position and orientation of the tilt-rotor aircraft are automatically determined by force from surrounding fluid flows. The motion of the aircraft is controlled by manipulating its flight control surfaces, just like an actual aircraft. As the result, the amount of operation of flight control surfaces needed for turning flight, flight attitude of the aircraft and generated lift were found. Moreover, differences of fluid flow between straight flight and turning flight were captured.

2. Numerical approach

2.1 Governing equation

Fluid flows around the tilt-rotor aircraft are dealt with as three-dimensional inviscid. Thus, governing equations are written in the conservation form as follows:

\[
\frac{\partial \mathbf{q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \frac{\partial \mathbf{G}}{\partial z} = 0, \tag{1}
\]

where \( \mathbf{q} \) is the conserved quantity vector, \( \mathbf{E}, \mathbf{F}, \mathbf{G} \) are the inviscid flux vectors. As unknowns, \( \rho \) is the density, \( u, v, w \) are the \( x, y, z \) components of the velocity vector and \( e \) is the total energy per unit volume. The working fluid assumed to be perfect gas, the pressure \( p \) is defined as follows:

\[
p = (\gamma - 1) \left[ e - \frac{1}{2} \rho (u^2 + v^2 + w^2) \right]. \tag{3}
\]

where \( \gamma \) is the specific heat ratio and taken as 1.4 in this paper.

2.2 Unstructured moving-grid finite-volume method

The unstructured moving-grid finite-volume method (Yamakawa and Matusno, 2005) was adopted to deal with moving and deforming of grids. In the method, fluxes are evaluated on a control volume in the space-time unified domain \( (x, y, z, t) \) to satisfy the geometric conservation law (GCL) (Obayashi, 1992). Applying the divergence theorem
to tetrahedron space-time unified control volume, the three-dimensional Euler equations are deformed as follows:

\[
\int_{\Omega} \left( \frac{\partial q}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + \frac{\partial G}{\partial z} \right) d\Omega = \int_{\partial \Omega} \left( E, F, G, q \right) \cdot \vec{n} \, d\Gamma
\]

(4)

\[
= \sum_{i=1}^{6} \left( E\vec{n}_x + F\vec{n}_y + G\vec{n}_z + q\vec{n}_i \right)_l = 0,
\]

where \( \Omega \) is the control volume, \( \vec{n} = (\vec{n}_x, \vec{n}_y, \vec{n}_z) \) is the outward unit normal vector on \( \partial \Omega \) and \( l \) indicates boundary face of the control volume.

### 2.3 Moving Computational Domain method

In this paper, the tilt-rotor aircraft makes a turning flight. Thus, it is difficult to calculate fluid flows around the aircraft using a conventional approach which placed it in a uniform flow. Therefore, it is appropriate to apply the Moving Computational Domain (MCD) method (Watanabe and Matsuno, 2009, Yamakawa, et al., 2012, 2016, 2017) in this case. This is the method in which the computational domain itself moves with the aircraft as shown in Fig. 1. In this method, the flow occurs due to the movement of the aircraft: the boundary condition of the moving boundary surface. In addition, this method removes computational space limitation. Therefore, the tilt-rotor aircraft can move freely in the computational space. For rotating two rotors and changing flight attitude of the aircraft to turn, multi-axis sliding mesh approach (Takii, 2019) is adopted. It makes possible to deal with multiple rotation of decomposed domains in different rotation axis. In the approach, propagation of physical quantities between adjacent domains is given by setting interpolated value to ghost cell of boundary of the domain as boundary condition. The interpolated value \( q_{bi} \) of the ghost cell of cell \( i \) is defined as follows:

\[
q_{bi} = \frac{\sum_{j \in l} q_j S_{ij}}{\sum_{j \in l} S_{ij}},
\]

(5)

where \( q_j \) is the physical quantity of cell \( j \), \( S_{ij} \) is overlapping area of faces of cell \( i \) and cell \( j \), and \( \sum_{j \in l} \) means the summation over cells \( j \) adjacent to the cell \( i \). The computational procedure is based on the unstructured moving-grid finite-volume method described in the last subsection. Fluid flow variables are defined at the center of cells in unstructured mesh. The flux vectors are evaluated using the Roe flux difference splitting scheme (Roe, 1981) with MUSCL (Monotonic Upstream-Centered Scheme for Conservation Laws) approach and the Venkatakrishnan limiter (Venkatakrishnan, 1993). The two-stage Runge-Kutta method is adopted to solve implicit equations.

#### 2.4 Coupled simulation

In this paper, the position and orientation of the tilt-rotor aircraft are automatically determined by the interaction with surrounding fluid flows. The aircraft is regarded as a rigid body, and six degree of freedom motion equation including translational and rotational motions in three-dimensional space is used to handle arbitrary motion of the body. Newton's equations are used for translational motion, and Euler's equations are used for rotational motion. Each of equations of motion are as follows:
\[
\frac{m d^2\mathbf{r}}{dt^2} = \mathbf{F},
\]

where \( m \) is the mass, \( \mathbf{r} \) is the position vector, \( \mathbf{F} \) is the force vector, \( I \) is the inertia tensor (written in matrix form), \( \mathbf{\omega} \) is the angular velocity vector and \( \mathbf{T} \) is the torque vector. The force and the torque are calculated by integrating pressure on the surface of the aircraft.

3. Flight simulation of tilt-rotor plane

3.1 Computational mesh and conditions

As a computational model, V-22 Osprey which is a typical tilt-rotor aircraft was adopted. The overall length \( L \) is 17.5 m, the weight is \( 2.15 \times 10^4 \) kg, the wingspan is 13.3m, the rotor diameter is 11.7m. The center of gravity of the model was set at aerodynamic center. The inertia tensor was computed by creating inside mesh in the computational model. The computational domain and surface grid of the tilt-rotor aircraft are shown in Fig. 2. The computational domain is hemispherical and the radius is 15 \( L \). The total number of cells is 3.21 million. The mesh was created by using MEGG3D (Ito and Nakahashi, 2002, Ito, 2013).

In this computation, the whole computational grid consists of nine domains in order to rotate rotors and change flight attitude and altitude. Figure 3 shows domain decomposition. Figures 4-5 show computational meshes for each domain. In this simulation, rotating domains 1-2 themselves perform rotation of rotors of the aircraft. Also, rotating and translating domains 7-9 are used to perform vertical motion and orientation of the aircraft.

![Fig. 2 Computational domain and surface grid](image-url)

![Fig. 3 Domain decomposition](image-url)
In this computation, six degrees of freedom flight simulation coupling with fluid flow and rigid body motion is performed. Therefore, flight attitude of the aircraft is controlled by deforming the shape of surface grid according to the control method that the actual aircraft performs at the time of flight, adjusting the force received from the fluid. Torsion spring method (Murayama and Nakahashi, 2002) is used to smoothly deform spatial mesh around flight control surfaces. The attitude of the aircraft has three degrees of freedom: roll, pitch, and yaw rotation direction. As shown in Fig. 6, the movement of the aircraft is controlled by operating the moving surfaces consisting of flaperons, elevator and rudders. Specifically, rolling is controlled by moving the flaperons mounted on the fixed wings the same angle in the opposite direction. Pitching is controlled by changing the elevator angle at the trailing edge of the horizontal stabilizer. Yawing is controlled by changing the left and right rudder angles in the same direction. Figure 7 shows the deformation of the surface grid to perform motion of flight control surfaces.
3.2 Flight Conditions

The initial conditions of density, pressure and velocity components of air are given as follows: $\rho = 1.0$, $p = 1.0/\gamma$, $u = v = w = 0.0$ normalized by $\rho_{\infty}$ and $U$, where $\rho_{\infty}$ and $U$ are representative values of density and velocity scales for the considered flow system. In this simulation, $U$ is 340m/s and $\rho_{\infty}$ is 1.25kg/m$^3$. As the boundary conditions, the wall boundary condition is set on the ground and surface of the aircraft, and the Riemann boundary condition on outer boundary. The flight is performed under the following conditions.

1. Accelerate to the ground speed toward 200 knots (370km/h): altitude of the body is fixed initially, and after obtaining enough lift, the altitude is tried to maintain by adjusting pitch of the aircraft.

2. After reaching 200 knots, the speed is tried to keep by adjusting collective pitch of rotors. Then, start tilting the aircraft toward target bank angle of 60 degrees by using flaperons.

3. Turn left, keeping 10 degrees pitch angle and 60 degrees bank angle as constant as possible by adjusting elevator and flaperons.

4. After about 90 degrees turning, return the aircraft attitude to horizontal.

During the flight, the rotor speed and change rate of angle of flight control surfaces are constant: 397rpm and 390deg/s, respectively. The flight speed is controlled by linearly changing collective pitch of rotors in response to difference between current speed and target one. The angular velocities of the aircraft in pitch, roll and yaw direction are controlled by linearly moving flight control surface in response to difference between current angular velocity and target one. Flight attitude such as pitch angle and bank angle are controlled by linearly setting target angular velocities of flight control surfaces in response to difference between current angle and target one.

4. Result

Figure 8 shows flight altitude and ground speed of the aircraft in this simulation. The time is normalized by $L$ and $U$, and the starting time of operating flight control surfaces for turning flight is set to $t = 0$. The aircraft started accelerating at $t = -360$ with fixing its altitude. At $t = -70$, the fixation of the aircraft was released, and the computation shifted to coupling simulation between fluid and rigid body. After the speed reached 200 knots, the aircraft started banking at $t = 0$, and then began to return horizontal at $t = 243$. Figure 9 shows the trajectory of the aircraft and the relative horizontal coordinates from $t = 0$ to $t = 350$. It found that the aircraft turned left by taking bank angle.
Next, figure 10(a) illustrates each angle of flight control surfaces and flight attitude (pitch angle and bank angle) of the aircraft from $t = 0$ to $t = 350$. The flaperon angle is positive in the direction where left flaperon tilts upward, the elevator angle is positive in the direction where the elevator tilts upward, and the rudder angle is positive in the direction where the rudders tilt rightward. The pitch angle is positive in the direction where a nose of the aircraft raises, and the bank angle is positive in the direction where right wing of the aircraft lifts. In this computation, the target pitch angle and the target bank angle were set to 10 degrees and 60 degrees, respectively, and then the turning flight started at $t = 0$. The pitching was mainly controlled by the elevator. At first, the elevator instantly tilted to 20 degrees. Then, at about $t = 10$, the pitch angle reached near the target value. During the turn, the pitch angle was maintained at about 7 degrees by controlling the elevator angle in the range of about 2 to 6 degrees. Next, the bank angle was controlled by the flaperons. At $t = 0$, the aircraft started rolling by tilting the flaperons by 20 degrees, and the bank angle reached the target value at $t = 50$. During the turn, the bank angle was maintained at about 60 degrees by setting the flaperon angle to approximately 20 degrees. Therefore, it is considered that the aircraft was receiving the force that make the body return to the horizontal level in the turn. The rudder kept the angle that make the nose to the left during the turn. At $t = 243$, the target bank angle was set to 0 degrees, and the aircraft returned to approximately horizontal state at $t = 300$.

Next, figure 10(b) shows the vertical lift, horizontal lift and gravity acting on the aircraft from $t = 0$ to $t = 350$, where the force is normalized by $\rho \infty U^2 L^2$. The vertical lift is vertical upward component of the force applied to the aircraft. The horizontal lift is horizontal leftward (turning side) component of the force applied to the aircraft. After the start of turn, vertical lift reached a local maximum value greater than the gravity at $t = 10$. And the value decreases to a local minimum value smaller than the gravity at $t = 50$: the time level when the bank angle reached 60 degrees. From $t = 100$ to 243, the vertical lift was almost balanced with the gravity. The flight altitude continued to drop during this time due to descent which have started at about $t = 50$. Then, the vertical lift increased after the bank angle began to return to horizontal, and the aircraft began to climb again at $t = 271$. On the other hand, the horizontal lift increase from the start of the turn, and continued to remain stable between about $t = 90$ and $t = 243$. Considering that the bank angle was stabilized at $t = 50$, a time delay of about 40 was taken until a stable centripetal force was obtained.
Fig. 10 Time-series data in turning flight: (a) each angle of flight control surfaces and flight attitude (pitch angle and bank angle), and (b) vertical lift, horizontal lift and gravity acting on the aircraft.

The surface pressure distribution of the aircraft during turning is shown in Fig. 11. The left side is a view from the top of the aircraft, and the right side is a view from the bottom. On the top surface of the aircraft, a flaperon of left fixed-wing is under high pressure. This indicates that the flaperon receives air resistance strongly by tilting itself upward. Next, on the bottom surface of the aircraft, we can see that the pressure on the flaperon of right fixed-wing is high. Similarly, it indicates that the flaperon receives air resistance strongly by tilting itself downward. Thus, the aircraft rolls with the force to lift the right wing and lower the left wing. We can also see that the bank angle is kept constant by the force during turning flight.

Figures 12 shows isosurfaces of the velocity magnitude ($V = 0.05$) and the second invariant of velocity gradient tensor ($Q = 0.05$), where the values are normalized by $U$ and $L$. At $t = 0$, a symmetrical flow field around the aircraft is confirmed. The main vortices originate from the blade tip, the back of the nacelle and a root of the vertical tail. $t = 9.0$ is the time when flaperons are operated and the aircraft begin to roll. At this time, we can see that the fluid flow on the right side of the aircraft is faster. Moreover, the vortex behind the left nacelle is small and the vortex behind the right nacelle is large. We can also see that vortices are generated from a root of left fixed wing and left vertical stabilizer. To observe the detailed velocity field, the velocity component distribution of air on horizontally sliced plane near the wing at $t = 0$ (straight flight) and $t = 10$ (banking) are shown in Fig. 13: (a) aircraft traveling direction component and (b) upward component of the aircraft. From Fig. 13(b), negative vertical velocity component is observed in wide range behind the right wing as the banking starts. It seems to be because the flaperon inclined downward exerted a downward force on the air. As the result, the lift of right wing increased. The distribution of this negative velocity component is similar to the shape of velocity isosurface in Fig. 12(b). Therefore, it is considered that the change of the velocity isosurface behind wings during banking is due to the change of the lift. On the other hand, Fig. 13 (a) shows that there are positive and negative velocity components in the traveling direction of the aircraft. The positive component is generated by the forward movement of the aircraft, and the negative component is generated by the rotation of rotors. At banking ($t = 10$), the region of the positive component is large behind the right nacelle. The shape of this velocity distribution is similar to the isosurface of Q-criterion in Fig. 12(b). Here, Fig. 14 shows the comparison of velocity direction vectors of the airflow behind nacelles at $t = 0$ and $t = 10$. At $t = 0$, wingtip vortex flows are observed behind the left and right nacelles: counterclockwise behind right nacelle and clockwise behind left nacelle. At $t = 10$, the left vortex becomes weaker and the right vortex becomes stronger. From this, it is considered that, by operating flaperons, the right wingtip vortex was strengthened by increase of the lift of the right wing, and conversely, the left wingtip vortex was weakened by the decrease of the lift of the left wing. Therefore, during left turning, the wingtip vortex flow becomes large behind the right nacelle, and the airflow has positive velocity component in the traveling direction so as to be entrained by the vortex.
Fig. 11 Pressure distribution during turning flight. Left is top view and right is bottom view.
(a) Straight flight ($t = 0.0$)

(b) At the start of banked turn ($t = 9.0$)

(c) Turning flight ($t = 100.2$)

(d) Turning flight ($t = 150.9$)

Fig. 12 Isosurface of velocity magnitude (left, $V = 0.05$) and second invariant of velocity gradient tensor (right, $Q = 0.05$)
Fig. 13 Velocity component distribution of air on horizontally sliced plane near the wing at $t = 0$ (left) and $t = 10$ (right)

Fig. 14 Comparison of velocity direction vectors of airflow behind nacelles at $t = 0$ and $t = 10$ (colored with velocity magnitude)

5. Conclusions

Six degrees of freedom turning flight simulation was computed for the tilt-rotor aircraft represented by V-22 Osprey, considering interaction of fluid and rigid body. To rotate rotors of the aircraft and change its orientation, a combination of the MCD method based on the unstructured moving-grid finite-volume method and the multi-axis sliding mesh method was adopted. As a result of the coupled computation between flow field and rigid body using above approach, the airplane obtained lift and propulsion by rotating the rotor and flew in turning, and the turning motion of the aircraft was controlled by operating flight control surfaces consisting of flaperons, rudders and elevator, and the manipulating variables of flight control surfaces needed for turning flight, flight attitude of the aircraft and generated lift were found. In this simulation, the target angles of bank angle and pitch angle were respectively set to 60 degrees and 10 degrees. In the flight conditions, flight altitude of the aircraft decreased during the turning. Therefore, in order to maintain the flight altitude, it is necessary to reduce the bank angle or increase the pitch angle. In addition,
differences of fluid flow between straight flight and turning flight were captured. During banking, it was confirmed that the flaperon operation increased the lift of the right wing, which extended the isosurface of velocity magnitude to the right aft of the aircraft. In addition, a change of the vortex structure was confirmed in which the wingtip vortex flow behind the right nacelle strengthened, and conversely that behind the left nacelle weakened. These states were always maintained during the turn, not just at the beginning.

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