MANOEUVRABILITY INVESTIGATION FOR TILTROTOR AIRCRAFT WITH AN INTEGRATED SIMULATION ENGINE

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Abstract

The tiltrotor aircraft has unique flight dynamics characteristics because of the extensive aerodynamic interference effects present, the possibility of redundant control strategy, and the unique regime occurring during the conversion process, making its controllability more complex during manoeuvres. Also, these tiltrotor configurations are the basis for many Urban-Air-Mobility (UAM) prototypes, in which formation flight features and airworthiness regulation developments for UAM manoeuvring flight in urban areas should be considered. Therefore, this research developed an inverse simulation embedded manoeuvrability method for the tiltrotor aircraft, and this method was incorporated with the existing MAVERIC multi-agent system for the relevant UAM airworthiness investigation. First, the flight simulation model, the inverse simulation algorithm, and the MAVERIC system were introduced. Then, the Pop-up manoeuvre is utilised for the manoeuvrability investigation. The results indicate that the obtained control input is following the understood flight dynamics characteristics of the tiltrotor aircraft. Furthermore, the tiltrotor aircraft model and associated inverse simulation embedded analysis techniques were adapted into the MAVERIC system, which can be utilised to provide an intuitive demonstration of the manoeuvrability of tiltrotor aircraft. They will be an ideal platform for future UAV vehicles and relevant airworthiness investigations.

1. INTRODUCTION

The tiltrotor aircraft has drawn a lot of research interest due to its outstanding performance characteristics, which combines the advantages of both rotorcraft and fixed-wing aircraft.

However, the flight dynamics characteristics and the manoeuvrability of the tiltrotor aircraft is quite different from the conventional helicopters. First, the nacelle incidence angle has a significant influence on its controllability and stability [1,2]. The nacelle incidence angle changes the lift ratio between the rotor and the wing, altering the manoeuvrability significantly. Second, the aerodynamic interference of the tiltrotor configuration is much complicated and dependent on the nacelle position [3,4], indicating that the nacelle impact on the aerodynamics interference should be considered in the flight dynamics and manoeuvrability investigation. Third, the tiltrotor aircraft needs to combine controllers of both helicopter and aircraft modes to improve the performance and flight dynamics characteristics across the flight range [5,6]. However, the change of the control strategies influences the control power and control coupling characteristics and consequently affects the manoeuvrability of the tiltrotor aircraft.

On the other hand, the advent of Urban-Air-Mobility (UAM) systems will be a revolution for the rotorcraft community [7,8], and the tiltrotor aircraft is one of the mainstream prototype configurations of the UAM designs. The UAM system is envisaged to provide efficient air transportation systems, from package delivery drones to passenger-carrying air taxis, operating above populated areas. Therefore, UAM vehicles will be operating in a formation form in urban airspaces, indicating that they should be investigated using a coordinated system to consider interactions of aerodynamics, flight trajectory, and communication amongst each of these vehicles. However, flight characteristics of the UAM vehicle, such as the tiltrotor aircraft, are complicated, indicating that simulating the UAM system characteristics should be significantly time-consuming and cannot be performed within the real-time requirement using conventional methods.

There has been some research to date focusing on the manoeuvrability and the handling qualities of the tiltrotor aircraft [9–11]. Also, the inverse simulation method is a widely-used approach to investigate the manoeuvrability characteristics of different rotorcraft configurations [12,13]. It is a technique by which the control actions can be calculated for an aircraft to implement a given manoeuvre. This method can be seen as a non-linear equation solution process of the control input following the given manoeuvre trajectory. Also, by using the Automatic Differentiation (A.D.) method [14], the inverse simulation approach could achieve the real-time requirement. This improvement makes the

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manoeuvrability analysis more straightforward, and many other effects, including the lag effect of the actuator, can be taken into consideration.

Thus, an inverse simulation method embedded manoeuvrability investigation method for the tiltrotor aircraft is developed incorporated with the virtual simulation package, MAVERIC (Modelling of Autonomous Vehicles using Robust, Intelligent Computing) [15]. The MAVERIC is developed using the multi-agent system, and consequently, the flight dynamics model of each component can be calculated simultaneously based on the parallel computing algorithm. Meanwhile, the MAVERIC system allows different interactions amongst multiple vehicles to be considered in the simulation process. The tiltrotor flight dynamics model, the MAVERIC system, and the inverse simulation method are first introduced. Then, the simulation results of the tiltrotor aircraft flying Pop-up manoeuvre will be calculated and virtually demonstrated. Also, the wavelet analysis method is utilised to calculate the handling qualities when flying this manoeuvre.

2. METHODOLOGY

The section is divided into four parts, the tiltrotor flight dynamics model, the MAVERIC simulation package, the inverse simulation method, and the mathematic description of the Pop-up Manoeuvre.

2.1. Flight dynamics model

The tiltrotor flight dynamics model contains four parts, the rotor model, the model of pylon and wing, the fuselage model, and the model of the tailplane.

An individual blade method is used in the rotor model to calculate its aerodynamic loads, and the flapping motion is considered in the rotor part. Pitt-Peters dynamic inflow model is used to obtain the induced velocity on the rotor disc, and its average component is utilised to determine the wake effect on the other parts.

In the pylon and wing aerodynamic model, the aerodynamics characteristics are decided based on a look-up table from the GTRS report [16]. The aerodynamic interference of the rotor wake on the wing's force is calculated based on fixed wake theory and the projection relationship between the rotor disc and wing, which is shown in Fig. 1. The wing's surface is divided into two aspects: the freestream area and the interaction area. The position and area of the interaction part are determined by the projection relationship between the rotor and the wing. Meanwhile, the aerodynamic characteristics of the fuselage and tailplanes are obtained using the look-up table according to associated wind tunnel experiments.

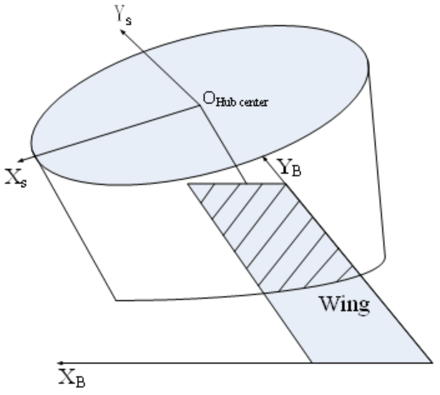


Fig. 1. The schematic diagram for the wing's interference

Therefore, the flight dynamics model of the tiltrotor aircraft is presented within the paper, taking the non-linear form of:

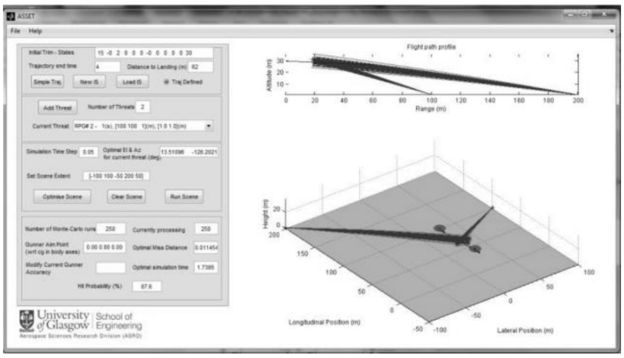
$$\dot{\boldsymbol{x}} = f(\boldsymbol{x}, \boldsymbol{u}, t) \tag{1}$$

where $\boldsymbol{x}$ denotes the state vector of the tiltrotor aircraft, including the vehicle velocities, angular velocities, flight attitudes, blade flapping motions, and induced velocities on the rotor disc. $\boldsymbol{u}$ represents the control vector, which contains the collective pitch, longitudinal cyclic pitch, differential collective, differential longitudinal cyclic, and the nacelle incidence. t is the response time.

The aerodynamic interaction has been considered in the flight dynamics model, and consequently, a range of differential equations are needed to determine this aerodynamic effect, reducing the computing efficiency. Therefore, the Automatic Differentiation (A.D.) method has been added into the flight dynamics model to accelerate the calculation and meet the real-time requirement. The A.D. method is based on the chain rule of the differentiation process. Compared to the traditional numerical differentiation method, automatic differentiation avoids repeatedly calling the flight dynamics model, reducing the calculation duration. The details of the automatic differentiation modelling method can be found in reference [14]. In this research, forward automatic differentiation is utilised to calculate the differentiation process.

2.2. MAVERIC simulation package

The MAVERIC simulation package is a mathematical model based on a multi-fidelity simulation engine, initially for the RPG/Rotorcraft engagement simulation to evaluate the efficacy of various evasion strategies [15]. This simulation engine could handle multiple dynamic agent models of differing fidelity and integrate them to provide an accurate, computational efficiency solution to a user-defined vignette. A Graphical User Interface (GUI) was developed in this software with user-point controls to both the trajectory and display the results, as shown in Fig. 2.



Initial Trim - States: 15 -0 2 0 0 0 -0 0 0 0 0 30
Trajectory end time: 4
Distance to Landing (m): 62
● Traj Defined
Number of Threats: 2
Current Threat: RPG# 2 - 1(a), [100 100 1](m), [1.0 1.0](m)
Simulation Time Step: 0.05
Optimal El & Az for current threat (deg): 13.51096 -126.2021
Set Scene Extent: [-100 100 -50 200 50]
Number of Monte-Carlo runs: 250
Currently processing: 250
Gunner Aim Point (wrt cg in body axes): 0.00 0.00 0.00
Optimal Miss Distance: 0.011454
Modify Current Gunner Accuracy:
Optimal simulation time: 1.7385
Hit Probability (%): 87.6

Fig. 2. MAVERIC Simulation package

It is essential to introduce the flight dynamics model into the MAVERIC simulation package. Firstly, this software provides an intuitive version for the aircraft trajectory, and the inaccuracy in the flight dynamics model can be easily recognised during the simulation demonstration process. Additionally, the actuators, sensors, and other components in the aircraft play a significant role in the flight dynamics characteristics, and the MAVERIC simulation package offers a range of tools to consider those effects and further improve the precision of the simulation results. Also, the autonomous tiltrotor aircraft is rapidly developing in recent years, and incorporating the MAVERIC software with the tiltrotor flight dynamics model could be beneficial for future tiltrotor aircraft and corresponding UAM vehicle developments.

2.3. Inverse simulation method

Inverse simulation is a widely used method for the manoeuvrability analysis of helicopter and fixed-wing airplanes. The so-called integration inverse simulation is utilised in this research, readily available when the flight dynamics model has been constructed. In order to process the inverse simulation algorithm, this article implements the following steps:

1). Calculate the trim control input

The trimmed states correspond to steady level flight with the body accelerations and the attitude rates equal to zero, which is the initial point of the manoeuvres in this investigation.

2). Define the manoeuvre

The manoeuvre can be defined simply by polynomial representations of position or other flight path variables, and it is then discretised into a series of discrete-time points. This investigation utilises the Pop-up manoeuvre to assess the manoeuvrability of the tiltrotor aircraft, and its mathematical description will be introduced later in this article.

3). Calculate the control vector

This inverse simulation model uses a Newton-Raphson technique to calculate the controls required to maintain the tiltrotor's states according to the manoeuvre mathematical description. The Automatic Differentiation method is utilised here to calculate the Jacobian matrix needed in the Newton-Raphson technique to meet the real-time requirement. This process is repeated throughout each time step until the manoeuvre has been completed.

2.4. Pop-up Manoeuvre

Fig. 3 represents an example of the pop-up manoeuvre, where it is assumed that the pilot's task is to clear an obstacle, height h over some distance s. The impediment is located at the end of the manoeuvre.

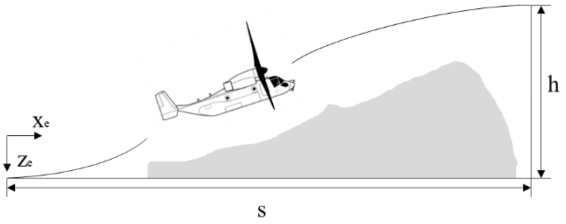


Fig. 3. Pop-up Manoeuvre

A series of boundary conditions are defined based on the trajectory requirement during this manoeuvre to achieve the mathematical description of this manoeuvre. Firstly, the manoeuvre is executed in longitudinal and vertical channels, and consequently, the lateral and yawing channels should be minimum. Hence, the boundary conditions are given as follows:

$$\dot{\varphi}(t) = 0 \tag{2}$$

$$\dot{y}_e(t) = 0 \tag{3}$$

where φ represents the yawing angle; y_e denotes the lateral distance in the earth coordinate. Furthermore, the boundary condition of the altitude change (z_e) is shown as:

$$z_e(t) = -h[6(\frac{t}{t_m})^5 - 15(\frac{t}{t_m})^4 + 10(\frac{t}{t_m})^3] \tag{4}$$

where t_m is the time taken to complete the manoeuvre. With Eq (4), the tiltrotor aircraft could not only achieve the required altitude at the end of the manoeuvre but also guarantee the vertical trajectory and control inputs to be as smooth as possible. On the other hand, the longitudinal displacement $x_e(t)$ can be evaluated numerically by integrating:

$$\dot{x}_e(t) = \sqrt{V_f^2 - \dot{z}_e(t)^2} \tag{5}$$

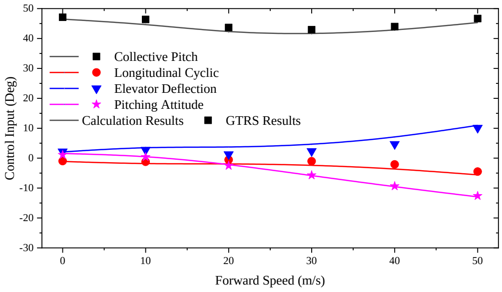
where V_f is the forward speed. Eq (5) is formed to ensure the initial and final forward speeds are equal. Thus, the total track distance is calculated, which is:

$$s = \int_0^{t_m} \dot{x}_e(t)dt \tag{6}$$

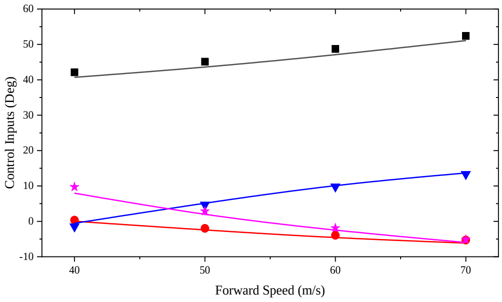
By combining Eq (6) with Eqns (4-5), the relationship among manoeuvre time t_m, track distance s, and initial forward speed V_f is described.

3. RESULTS AND ANALYSIS

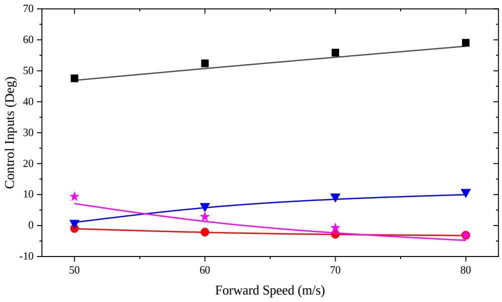
The trim results of XV-15 tiltrotor aircraft are used to validate the model accuracy, and the comparison data is obtained from the related report [17]. The results are shown in Fig. 4.



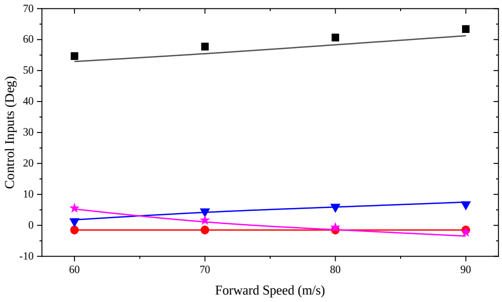
(a) Helicopter mode



(b) Conversion mode (30 Deg)



(c) Conversion mode (60 Deg)



(d) Airplane mode

Fig. 4. Trim results comparison

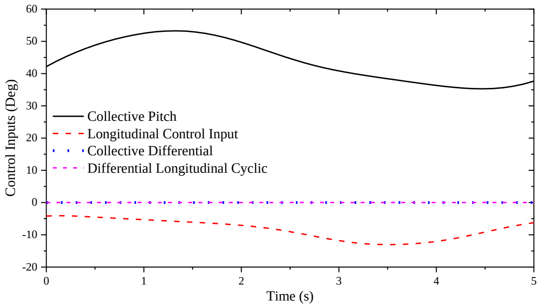
According to Fig.4, the trim characteristics obtained from the proposed model are in line with the GTRS report, demonstrating the accuracy of the proposed model. As shown in Fig. 4(a), the trim characteristics of the tiltrotor aircraft are analogous to the conventional helicopter in helicopter mode. The collective pitch follows the saddle curve. The longitudinal cyclic pitch increases, and the vehicle becomes nose-down to allow rotors to provide the longitudinal thrust needed for trimming. However, as the nacelle tilts forward, the trim characteristics of the tiltrotor aircraft increasingly resemble the fixed-wing aeroplane. When the tiltrotor aircraft is in airplane mode (Fig.4 (d)), the collective pitch increases to provide the propulsive force, and the changes of the longitudinal control inputs due to the forward speed are lower than other flight ranges. This phenomenon arises because the effect of the forward speed increment on the pitching moment reduces as the nacelle tilt angle increases.

The inverse simulation results of the Pop-up manoeuvre in the helicopter mode are used to analyse the proposed method. The pertinent parameters of the manoeuvre and calculation settings are shown in Table 1.

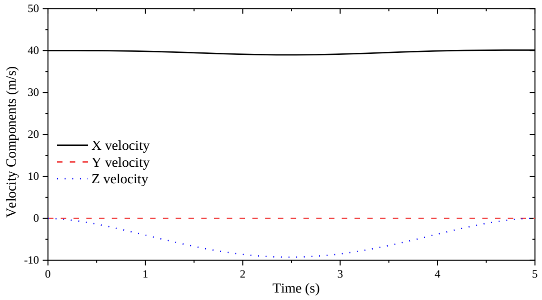
Table 1 Pop-up manoeuvre parameters

Parameters	Values
s	200 m
V_f	40 m/s
h	25 m
t_m	5.06 s

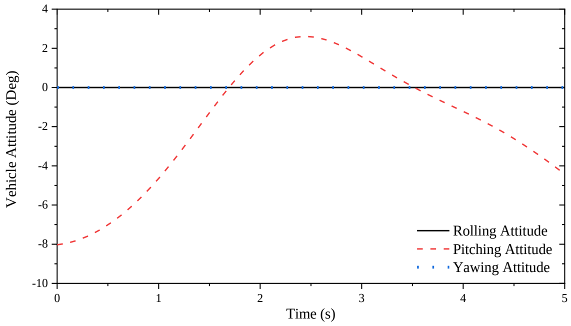
Based on Table 1, the control action, the velocity components in earth coordinate, and vehicle attitudes during the Pop-up manoeuvre are shown in Fig. 5.



(a) Control inputs



(b) Velocity component in earch axis



(c) Attitudes

Fig. 5. Control and state results during the pop-up manoeuvre

According to Fig. 5, the tiltrotor aircraft could achieve this manoeuvre with the given requirements. However, due to the lack of pertinent flight tests or simulation results, the inverse simulation results can only be verified by inspecting and considering the underlying trends and features in the time histories.

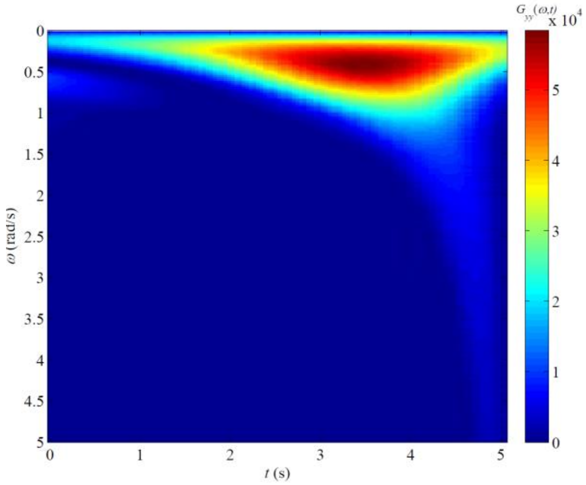
The most evident phenomenon of the inverse simulation result is the amplitude change in the collective pitch, the longitudinal cyclic, and the pitching attitude. According to Fig. 5, the collective pitch has correlated with the vertical acceleration, as it controls the tiltrotor propulsion and consequently the vertical force.

Meanwhile, the longitudinal control input roughly remains at the trimmed velocity when the manoeuvre time is lower than 2.5 s, then increases to a large extent and comes back to the trimmed values during the exit phase of the manoeuvre. The pitching attitude begins to nose up at the beginning and drops down after 2.5 s. This phenomenon arises because of the combined action of the rotor aerodynamics and flapping motion. According to Fig. 5, this velocity needs to reduce at the beginning. The increase of the collective pitch enlarges the drag and nose-up moment provided by the rotor, driving the longitudinal control to remain around the initial value.

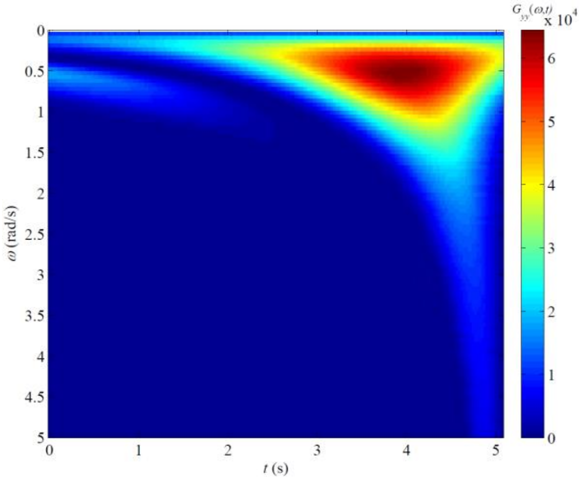
On the other hand, due to the extra pitching moment produced by the collective pitch increment, the pitching attitude becomes nose-up. When the normal velocity starts to drop down, the forward speed needs to increase, according to Eq (5). The collective pitch is reduced and diminishes the rotor drag. However, considering the lag effect of the flapping motion and the pitching attitude, the longitudinal control is forced to increase to balance the pitching moment.

As the configuration of the tiltrotor aircraft is symmetrical and as the Pop-up manoeuvre is longitudinal and vertical, there are no sidewards forces or moments. This accounts for the result that the collective differential (used to provide rolling moment), the differential longitudinal cyclic (used to control the yawing moment), rolling attitude, y-direction velocity, and yawing attitude are all fixed at zero across the manoeuvre.

According to the preceding discussion, the inverse simulation results are in line with understood flight dynamics features of the aircraft. Further, the pilot workload is analysed with the wavelet-based handling qualities method [18], and relevant results are shown in Fig. 6.



(a) Collective pitch



(b) Longitudinal Controller

Fig. 6. Wavelet Analysis for Inverse Simulation Results

According to Figure 6, the primary frequency ranges of the collective pitch and longitudinal cyclic are below 0.8 rad/s, and 1.2 rad/s, respectively, which indicates the pilot workloads in both control inputs are relatively low.

The pertinent handling qualities ratings of collective pitch and longitudinal controller are in Level 1 and Level 2, according to reference [19].

By introducing the tiltrotor flight dynamics model into the MAREVIC system, te calculations mentioned above can be directly obtained using this simulation engine. The MAREVIC interface is shown in Fig. 7.

Fig. 7. The tiltrotor model embedded MAREVIC system

At this moment, one tiltrotor aircraft model is incorporated into the simulation model, which can be utilised to investigate flight dynamics, manoeuvrability, and handling qualities of these aircraft configurations. Furthermore, an intuitive animation of the flight state changes during the manoeuvre can be demonstrated using this system (This demonstration will be shown in the presentation on the forum). Meanwhile, the MAVERIC system will provide an ideal platform to adapt multiple vehicles into one simulation procedure for the relevant formation flight feature and the airworthiness regulation investigation, which is essential for the UAM system development.

4. CONCLUSIONS

This article provides an alternative new method to investigate the manoeuvrability of tiltrotor aircraft using the inverse simulation method. Furthermore, by incorporating the MAVERIC system, the tiltrotor flight simulation model can be performed in a multi-agent system, making this methodology convenient for future formation flight investigation and UAM safety analysis. The main conclusions from the current work are as follows:

1) The trim results of the proposed model are in accordance with simulation results from other research at various forward speeds and nacelle incidence angles, verifying the accuracy of this tiltrotor flight dynamics model.
2) According to the inverse simulation results of the Pop-up manoeuvre, the obtained control input is in line with the understood flight dynamics characteristics of the tiltrotor aircraft, which gives confidence in the likely accuracy of these results.
3) The developed tiltrotor flight simulation model is successfully incorporated with the MAVERIC multi-agent system, providing more opportunities to extend relevant research to rotorcraft swarm flight features and UAM airworthiness development.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] Marr, R. L., and Roderick, W. E. B. “Handling Qualities Evaluation of the XV-15 Tilt Rotor Aircraft.” *Journal of the American Helicopter*

Society, Vol. 20, No. 2, 1975, pp. 23–33. https://doi.org/10.4050/JAHS.20.23.

[2] Padfield, G. D., Brookes, V., and Meyer, M. A. “Progress in Civil Tilt-Rotor Handling Qualities.” *Journal of the American Helicopter Society*, Vol. 51, No. 1, 2006, p. 80. https://doi.org/10.4050/1.3092880.

[3] Gibertini, G., Auteri, F., Campanardi, G., Macchi, C., Zanotti, A., and Stabellini, A. “Wind-Tunnel Tests of a Tilt-Rotor Aircraft.” *Aeronautical Journal*, Vol. 115, No. 1167, 2011, pp. 315–322. https://doi.org/10.1017/S0001924000005790.

[4] Staruk, W., and Datta, A. “Fundamental Understanding, Prediction, and Validation of Tiltrotor Dynamic Loads in Transition Flight Using RANS/FEA.” *58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, 2017*, No. January, 2017, pp. 1–22. https://doi.org/10.2514/6.2017-0859.

[5] Ji, M., Wang, N., and Zhao, C. The Simulation and Analysis of the Tilt Rotor Aircraft Model Transition. No. 130, 2016, pp. 218–221.

[6] Wu, W., and Chen, R. “An Improved Online System Identification Method for Tiltrotor Aircraft.” *Aerospace Science and Technology*, Vol. 110, 2021, p. 106491. https://doi.org/10.1016/j.ast.2021.106491.

[7] Silva, C., Johnson, W. R., Solis, E., Patterson, M. D., and Antcliff, K. R. VTOL Urban Air Mobility Concept Vehicles for Technology Development. 2018.

[8] Vascik, P. D., John Hansman, R., and Dunn, N. S. “Analysis of Urban Air Mobility Operational Constraints.” *Journal of Air Transportation*, Vol. 26, No. 4, 2018, pp. 133–146. https://doi.org/10.2514/1.D0120.

[9] Ye, Y., David, A., and Douglas, T. Use of Uncertainty Quantification to Determine the Impact of Manufacturing Error on the Handling Qualities of Tiltrotor Aircraft. 2021.

[10] Ghiringhelli, G. L., Masarati, P., Mantegazza, P., and Nixon, M. W. Multi-Body Analysis of the 1/5 Scale Wind Tunnel Model of the V-22 Tiltrotor. No. 1, 1999, pp. 1087–1096.

[11] Felker, F. F., Maisel, M. D., and Betzina, M. D. “Full-Scale Tilt-Rotor Hover Performance.” *Journal of the American Helicopter Society*, Vol. 31, No. 2, 1986, pp. 10–18. https://doi.org/10.4050/JAHS.31.2.10.

[12] Yuan, Y., Thomson, D., and Chen, R. “Investigation of Lift Offset on Flight Dynamics Characteristics for Coaxial Compound Helicopters.” *Journal of Aircraft*, Vol. 56, No. 6, 2019, pp. 2210–2222. https://doi.org/10.2514/1.C035190.

[13] Thomson, D. G., and Bradley, R. “Mathematical Definition of Helicopter Maneuvers.” *Journal of the American Helicopter Society*, Vol. 42, No. 4, 2009, pp. 307–309. https://doi.org/10.4050/jahs.42.307.

[14] Yuan, Y., Thomson, D., and Anderson, D. “Application of Automatic Differentiation for Tilt-Rotor Aircraft Flight Dynamics Analysis.” *Journal of Aircraft*, Vol. 57, No. 5, 2020, pp. 985–990. https://doi.org/10.2514/1.C035811.

[15] Anderson, D., and Thomson, D. “Analyzing Helicopter Evasive Maneuver Effectiveness Against Rocket-Propelled Grenades.” *Journal of Guidance, Control, and Dynamics*, Vol. 37, No. 1, 2014, pp. 277–289. https://doi.org/10.2514/1.59318.

[16] Ferguson, S. W. “A Mathematical Model for Real Time Flight Simulation of a Generic Tilt-Proprotor Aircraft.” *Nasa CR 166536*, 1988.

[17] Ferguson, S. Development and Validation of a Simulation For Generic Tilt-Rotor Aircraft. NASA-CR-166537.

[18] Jones, J. G., Padfield, G. D., and Charlton, M. T. “Wavelet Analysis of Pilot Workload in Helicopter Low-Level Flying Tasks.” *Aeronautical Journal*, Vol. 103, No. 1019, 1999, pp. 55–63. https://doi.org/10.1017/S0001924000065106.

[19] Tritschler, J. K., and O’Connor, J. C. “Use of Time-Frequency Representations for Interpreting Handling Qualities Flight Test Data.” *Journal of Guidance, Control, and Dynamics*, Vol. 39, No. 12, 2016, pp. 2772–2779. https://doi.org/10.2514/1.G000401.