STUDY ON CONTROL EFFECTIVENESS OF A DUCTED-FAN UAV

Adnan Maqsood, Yi Xiang Tan, Tiauw Hiong Go
School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Republic of Singapore

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Abstract

The paper discusses the aerodynamic performance of a ducted fan UAV during hover flight. The design refinement is carried out through the analysis of the experimental data of various control surface configurations of the ducted fan UAV. The effects of various arrangements as well as the positioning of control surfaces on the control effectiveness of the ducted fan UAV are discussed. Moreover, comparisons between the single propeller motor and the twin propeller motor (counter-rotating) configurations are drawn from various aspects such as the thrust, control power and slipstream velocity. It is observed that the single propeller configuration of the ducted fan UAV possess inadequate control authority whereas, the twin propeller configuration exhibit desired controllability for hover mission segment and improved thrust performance.

1 Introduction

Changes in the aircraft configuration in the design and development phase are common in aerospace industry. These changes are typically motivated by design refinement requirements. There has been an increasing interest in ducted-fan configuration for Unmanned Air Vehicle (UAV) application. Ducted- fan configuration combines the advantages of both the fixed-wing and rotary wing. It possesses both the cruising ability and long flight time of the fixed wing, as well as the maneuverability and hovering ability of the rotary wing. In addition, a ducted fan configuration offers advantages such as high propulsive efficiency and high static thrust.

Recently, AVID LLC[1, 2] has successfully designed and commissioned the ducted-fan UAV platforms in US Army for military applications. Nieuwstadt [3] has done the seminal work on the application of annular wings for UAV applications. Aurora Flight Sciences have come up with the unique design of the clandestine UAV called Goldeneye[4]. It is a ducted fan configuration with the control surfaces submerged in the prop-stream. The vehicle is claimed to have a good hover gust rejection response and transition performance as a result of its unique torsionally-decoupled outer wing panels.

Ducted-fan UAVs are popular because they produce high static-thrust for a given diameter than the open propeller counterparts. Typical mission profile of such UAVs include maneuvers like vertical takeoff and landing, hover, efficient forward cruise and multiple transitions between hover and forward flight. The UAV is supposed to fly in closed cluttered terrains and is subjected to rough air patches and cross-winds. Due to the presence of large turbulent eddies created by buildings, hills, trees and other obstacles, the stable operation of such aircraft becomes more difficult. Across this velocity spectrum, the aircraft must have sufficient control authority to avoid such disturbances.

In this paper, a systematic alteration is carried out in the UAV control surfaces distribution for hover conditions. For this purpose, experimentation in the wind-tunnel facility is carried out. Initially the baseline configuration is evaluated. It is found that stator plus elevator configuration or elevon configuration provide inadequate control authority for anti-torque moment. The position change is also not a viable solution. The existing single-propeller motor is then interchanged by twin propeller motor such that both propellers are counter-rotating. It is found that the lateral control authority is adequately addressed. Moreover, the high thrust generation for relatively lower RPM is also made possible. The changes in slip-stream velocity profile are also compared.

2 Experimental Setup and Procedure

2.1 UAV Model

The front, top, side and oblique views of the baseline configuration of the UAV model are shown in Fig. 1. It has a single propeller ducted-fan configuration, payload box in front and short wings. The unique feature of the wings that the angle of incidence is dealt as an independent control variable to utilize the feature of 'aerodynamic vectoring'. The control surfaces are submerged in the slipstream aft of the duct. The maximum dimensions of the aircraft are 0.65 m axially and 0.5 m laterally. The duct has an Eppler-180 airfoil cross-section with the chord length of 15 cm and inner diameter of 20 cm.

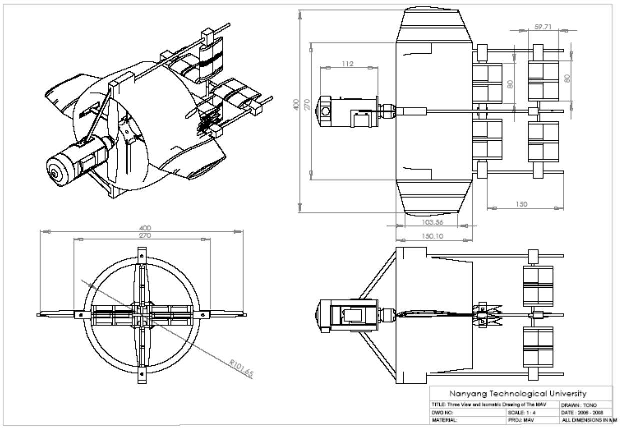

Fig. 1. Three-view drawing of the ducted fan UAV

The zoomed view of the control surfaces arrangement aft of the duct is shown in Fig. 2. It consists of six stators (three on each side), two rudder and two elevator surfaces respectively. The vertical and horizontal control surfaces have NACA-0018 airfoil sections and rectangular platforms. The wings of the UAV are hinged with the duct at quarter-chord length. The airfoil section for wings is also of the Eppler-180 class. During the initial conceptual design, the stators were installed to cater for the counter-torque produced by the propeller. The slipstream effect is calculated based on Leishman[5] approximations for fan-tail design. The positioning of the elevator and rudder surfaces was carried out based on the preliminary investigations by Fleming [2] at AVID LLC.

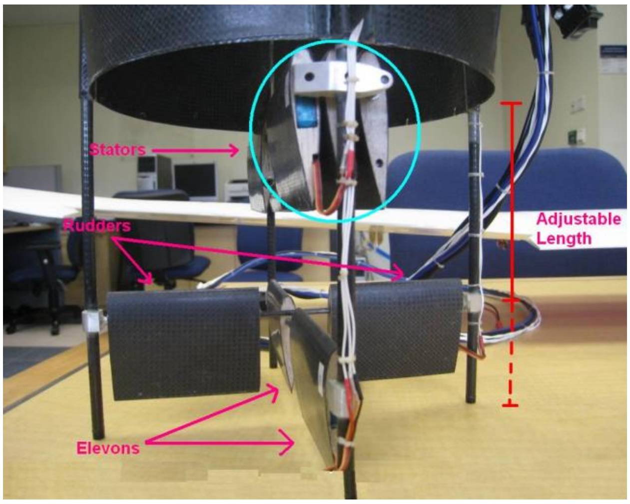

Fig. 2. Existing control surfaces distribution

2.2 Wind Tunnel Facility

The wind tunnel testing is performed in the Nanyang Technological University (NTU) low speed closed-circuit wind-tunnel. The dimensions of the internal surfaces of test-section are 0.72x0.78x2.00 meters. A six-component sting balance is used to measure all forces and moments. The model positioning system is of quadrant type and is equipped with a sting model support. It is capable of allowing the model to perform rotations in three axes, namely roll, pitch and yaw. The data acquisition system is based on National Instruments (NI) platform and Lab-View based software to graphically view and records the data. It is known as Data Acquisition, Reduction and Control System (DARCS).

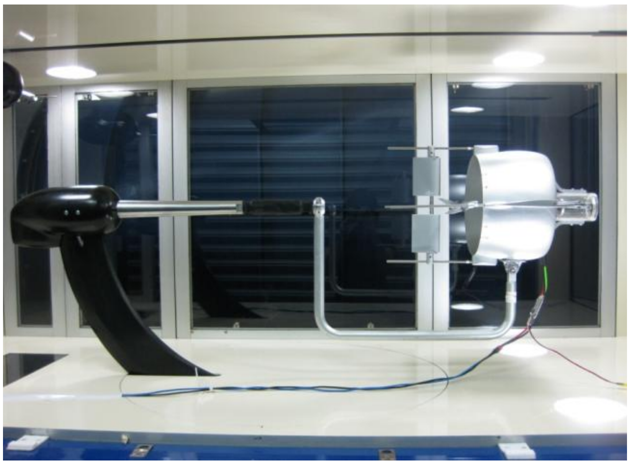

Fig. 3. Mounting of ducted fan UAV in wind-tunnel test section

2.3 Electronic Equipment

Beside the wind-tunnel facility and wind-tunnel model to be tested, the complete experimental setup is a combination of several electronic components. For the single-propeller configuration, Tahmazo® ER2822/1100 is used whereas, for the twin propeller system Himax® CR2816-1100 motor is used. The Electronic Speed Controller (ESC) is different for both configurations based on the recommendations by motor manufacturers. Pololu® serial 8-servo controller is used for the controlled actuation through MATLAB®. In this case, the RPM of the motors is controlled through computer using Simulink®. In order to power up the system with sustained current supplies, two power supplies are used: one for the motor and second for the servo controller. The servo controller can be powered through ordinary power supply as the current demand is quite low. The power supply used for the motor will be GW® Instek PSH-3630A, a single output 36V/30A 1080W programmable switching power supply with significantly low ripple noise. A tachometer is also used to calibrate the motor RPM with the control signal.

3 Single Propeller Configuration

In this section, the effect of elevator effectiveness in the presence or absence of stators is evaluated for single propeller configuration. Beside that the effectiveness of stator itself is evaluated and an alternate configuration with the stators absent and elevators working as elevons is also evaluated.

3.1 Elevator Effectiveness

3.3.1 Effect of Stators

The effect of stators on the elevator effectiveness is shown in Fig. 4. The gradient of this graph can be referred as stability derivative $M_{\delta e}$ associated with the control vector. It is observed that with the positive deflection of elevator, more pitch down moment can be generated and that is consistent with the standard axes rotation. It can be inferred that the absolute magnitude of M_{δ_e} is higher without stator presence. This clearly shows that there is a strong interference factor of stators on the elevator effectiveness. Generally a steeper slope is desired because with minimal control effort, higher moments may be generated. M_{δ_e} with stators is *0.235 kgf-m/rad* and without stators is *0.271 kgf-m/rad*. It is predicted that the removal of stators in this configuration will increase the elevator control power but will also increase the higher elevator trim angle during hover.

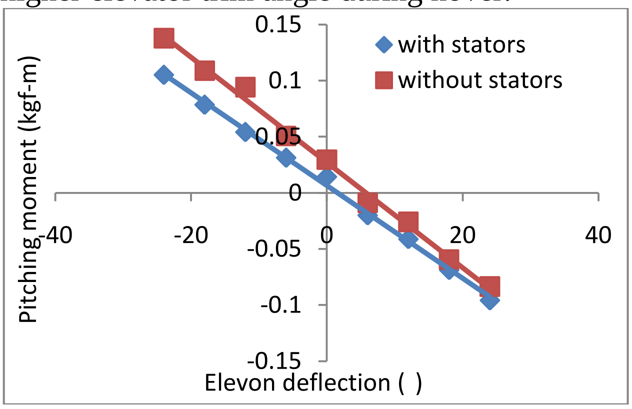

Fig. 4. Pitching Moment Comparison

3.3.1 Effect of Position

The effect of position on the elevator effectiveness is evaluated in Fig. 5 with the stators present. The positions are shown in terms of percentages of duct length. For example, the position of the leading edge of elevator just at the trailing edge of the duct is referred as 0% of duct length whereas, the original position of the elevator is 65.5% of duct length. It is observed that the trim elevator angle is 2^o for the 65.5% duct length and 10^o for the

115.2% duct length behind duct. Moreover, it is observed that the position of the elevators behind duct does not change the slope of the graph and therefore, it can be said that M_{δ_e} is independent of the position of elevators behind duct. It is also observed that as the distance is increased, higher deflection angle is required to trim the aircraft thereby indicating that there is a possible decrease in slipstream velocity. The effect of slipstream velocity will be discussed ahead.

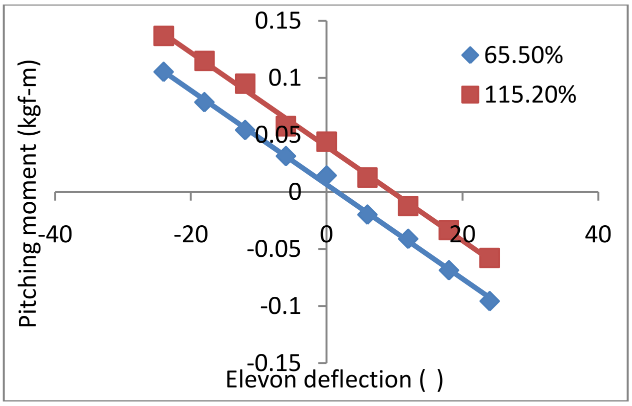

Fig. 5. Pitching Moment Comparison (Position of Elevators)

3.2 Stator Effectiveness

The control effectiveness of the stators in countering the induced rolling moment from the single propeller configuration is studied in this section. The net rolling moment produced by the UAV at various RPM and stator deflections is shown in Fig. 6. In addition to that, the net induced rolling moment in the absence of stators solely contributed by the single propeller is also plotted. It can be seen that the induced rolling moment is not counter-rotated by the stator deflection at various angles of stators deflection for all the RPM. The rolling moment experienced is therefore for a large amount and is nowhere near to zero and problem worsens near hover condition. Therefore, it can be concluded that the stators of the ducted fan UAV are not fulfilling its responsibility of counter-rotating the spiral air flow caused by the propeller of the motor and the insufficient control authority of the stators to counter the induced rolling moment can be deduced.

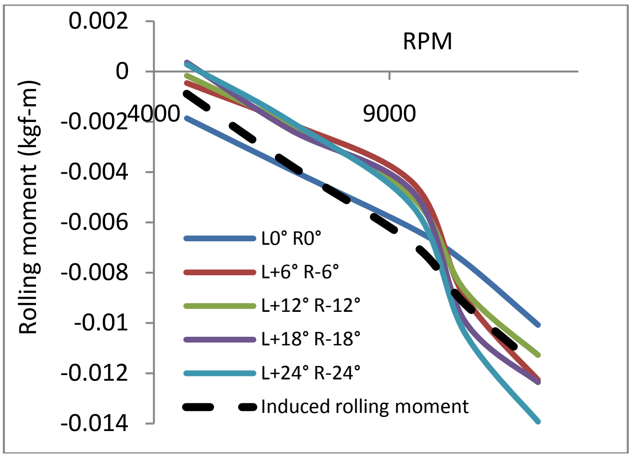

Fig. 6. Comparison of control effectiveness of stators against induced rolling moment

3.3 Elevons Effectiveness

After the realization of the fact that stators fail to counter the induced rolling moment, the next approach is adopted to remove the stators and use elevators as elevons. The effect of position on the differential deflection of the elevator is also evaluated. In Fig. 7, the differential deflection of elevators (working as ailerons) is plotted against the net rolling moment of the UAV in hover condition. Moreover, the effect of position is also shown for three points behind duct. It can be clearly seen that none of the three trend pass through horizontal axis thereby clearly indicating that the trim angle cannot be achieved within the specified range. Therefore, it can be said that because of the significant amount of the torque generated by the single propeller configuration, stators as well as elevons have failed to provide roll trim condition. The position change is also insignificant for the remedy. A subsequent design strategy is to change the single propeller motor to contra-rotating twin propeller motor to overcome this discrepancy. .

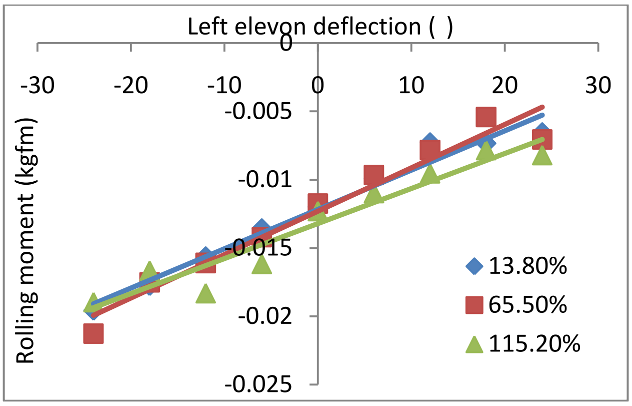

Fig. 7. Rolling Moment Comparison (Position of Elevons)

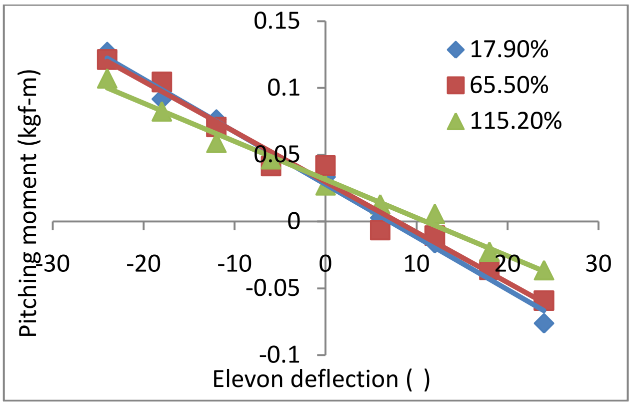

Fig. 8. Pitching Moment Comparison (Position of Elevons)

4 Twin Propeller Configuration

In this section, the twin propeller configuration is discussed. The effect of elevator positioning on its effectiveness is analyzed. The problem of rolling moment as mentioned in section 3 is discussed explicitly in section 5.

4.1 Elevator Effectiveness

The effect of elevator position for the twin-propeller configuration is also studied and plotted in Fig. 8. It can be observed that the pitching moment stability derivative M_{δ_e} is sensitive to the position of elevator in prop-stream. The results reveal that M_{δ_e} starts to reduce as the elevators are located far downstream. The value of M_{δ_e} reduces by 30% as the position of elevators is moved from 17.9% to 115.2% of duct length inside propstream. This means that in order to trim the aircraft at higher angles, substantial amount of control effort is required if the position of the control surfaces is farthest from the duct trailing edge. Moreover, the difference between first two locations is relatively less as it clearly indicates that the prop-stream energy starts to reduce significantly after this position. Therefore, as a design rationale, it can be concluded that the elevators must be placed as near as possible to the propeller.

5 Comparative Results and Discussion

5.1 Thrust Comparison

One of the key objectives of the study is to increase the thrust at reduced RPM so that with lesser current drawn, high thrust can be generated. The comparative analysis of thrust generation between single propeller and twin propeller is shown in Fig. 9. It can be observed that the thrust produced by the twin propeller is greater than the single propeller across a certain RPM. Therefore, in order to fly the aircraft at hover position, the RPM required by the twin propeller is significantly less than its counterpart. The expansion of thrust envelope gives the leverage to the field operators to put additional payload in the form of sophisticated cameras for critical missions.

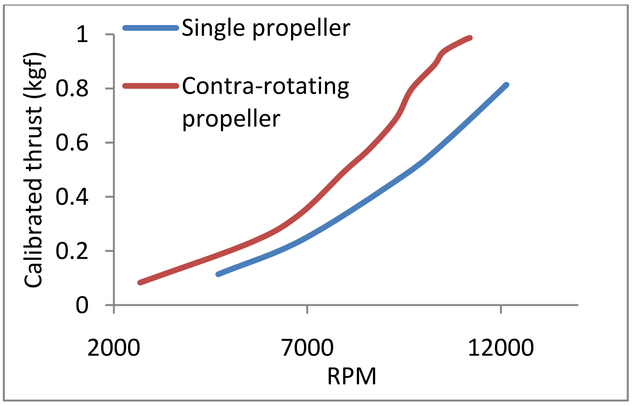

Fig. 9. Thrust comparison between two motor configurations

5.2 Rolling Moment Comparison

As discussed in the previous sections, single propeller configuration does not have sufficient control effectiveness to remove induced roll rate because of propeller. For twin propeller configuration, intuitively, this problem should be diminished. The comparison between rolling moments of the two different configurations is shown in Fig. 10. The net rolling moment at a certain RPM is plotted and it can be clearly observed that at lower RPM, the twin propeller is generating no induced torque at all. However, at high RPM, there is a mild offset in resultant rolling moment but of negligible nature. There can be two techniques to cater for this minor offset. One of the techniques is to use the differential drive. This is more trivial and easy technique and can be done in the control design phase. Second technique is to resize the two propellers so that the net result for the static case is zero. This is more time demanding and is considered to be out of the scope of the paper.

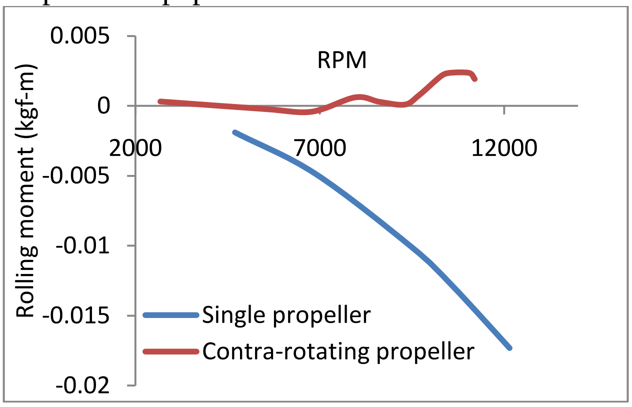

Fig. 10. Rolling moment comparison between two motor configurations

5.3 Slipstream Velocity Comparison

In this section slipstream velocity profile is studied for single and twin propeller configurations behind duct.

The slipstream velocity profile of single propeller configuration at several locations is shown in Fig. 11. The slipstream velocity distribution is shown at 13.8%, 65.5% and 115.2% duct length behind trailing edge of duct is plotted. Comparing the three profiles, it is apparent that a position of 13.8% duct length behind duct, the slipstream profile is in the process of buildup and is in pre-mature stage. The slipstream velocity varies drastically from 13.5 m/s to 28 m/s from 0 to 5.5 cm radius and then drops from 28 to 11 m/s from 5.5 to 7.5 cm radius. The profile trend at 13.8% and 65.5% duct length positions show in close agreement with Akturk [6] for ducted fan configurations.

The profile contour for 13.8% and 65.5% positions is almost similar and it can be said the slipstream profile is in the process of buildup and by the position 115.2%, the flow is fully matured and slipstream profile is more similar to theoretical shape. The significant decrease at the periphery of the duct shows a strong presence of shear layer and may be studied computationally in detail in future.

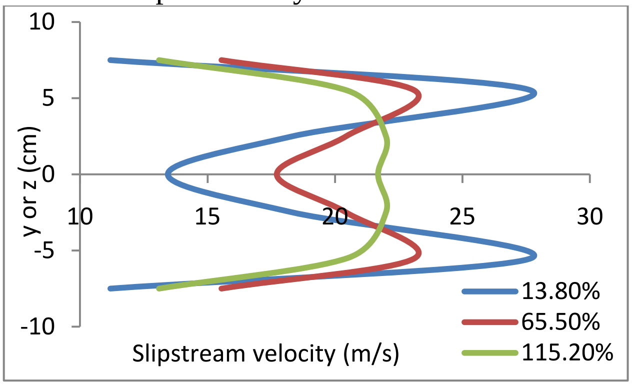

Fig. 11. Slipstream velocity behind duct for single propeller configuration

The slipstream velocity profile for twin propeller configuration follows similar trend of single propeller configuration and has not been discussed here explicitly for brevity. Fig. 12 shows the comparison of average slipstream velocity aft of the trailing edge of the duct between single and twin propeller configurations. It can be seen that for all the positions of the control surfaces behind the duct, the slipstream velocity of the twin propeller configuration is higher than the slipstream velocity of the single propeller configuration. Moreover, difference between average slipstream velocities for 13.8% and 65.5% duct-length behind duct are negligible for both configurations. The difference for single and twin propeller configurations is approximately 3.1% and 1.8% respectively thereby indicating that the difference is smaller for latter.

On the other hand, the average velocity comparison between 65.5% and 115.2% duct-length behind duct indicate the significant decrease. The difference for single and twin propeller configuration is approximately 6.1% and 6.3% respectively. Thus it can be inferred that the decrease in control power of the control surfaces for the single and twin propeller configurations is of the same extent.

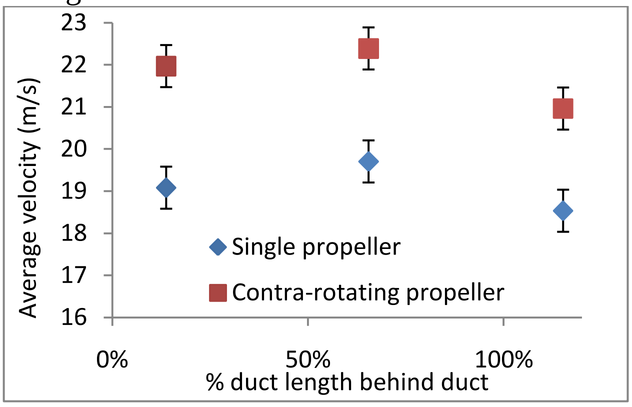

Fig. 122. Slipstream velocity comparison between two motor configurations

Based on the discussion above, it can be concluded that twin propeller configuration is better in terms of overall average velocity at all locations behind duct. It is obvious from the fact, that the two propellers will energize the slipstream velocity better than the single propeller of the same diameter.

6 Conclusion and Future Work

The study aims at the improvement in performance of a ducted fan UAV during hover flight. The effects of various configurations on the overall control effectiveness are discussed. Moreover, comparisons between single propeller and twin propeller configurations are drawn from various aspects such as the thrust, control power and slipstream velocity. It is concluded that for the single propeller configuration, the elevators are more effective once the stators are removed. Moreover, stators show inadequate control authority over roll moment. Therefore, the single propeller configuration is replaced by twin propeller configuration which in return gives clean air to the elevator and rudder surfaces (in absence of stators) with high prop-stream velocity. Moreover, the trim roll moment can be achieved across the range of RPM. The twin propeller configuration also results in better thrust properties. The change of motors has not increased the weight, in fact the removal of stators has reduced the overall weight of the vehicle.

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7 Contact Author Email Address

Adnan Maqsood
adnanmaqsood@pmail.ntu.edu.sg

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