TAIL ROTOR AERODYNAMIC PERFORMANCE IMPROVEMENT WITH A GURNEY FLAP DESIGN

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Abstract

As per of the effort to increase maximum take-off weight (MTOW) of an indigenous unmanned rotorcraft, increase in tail rotor thrust to compensate resulting higher main rotor torque values is required. Current study summarizes design and analysis of a gurney flap configuration utilized for the present tail rotor of the UAV. Computational fluid dynamics (CFD) analyses are performed for two dimensional airfoil (included Gurney flap) solution with commercial tools. Rotor mathematical model developed with FlightLab operates the generated aerodynamic database of the blade profiles to evaluate rotor total performance improvement. Several Gurney flap designs are constructed on the present blade profiles and configuration that optimizes tail rotor aerodynamic performance according to the desired aspects is evaluated with higher fidelity three dimensional CFD analysis methods. It is evaluated that the designed Gurney flap dimensions are such small that production and assembly may have direct impact on the total performance improvements. Therefore, the geometry of the desired Gurney flap is modified according to the possible manufacturing tolerances and assembly defects and analyses are repeated to investigate the efficiency degradation between analytical design and the product. Current study presents the gurney flap design as well as aerodynamic performance improvements of profile and rotor for both theoretical design and possible product.

1. ABBREVIATIONS

MTOW	:	Maximum Take-Off Weight
UAV	:	Unmanned Air Vehicle
CFD	:	Computational Fluid Dynamics
RANS	:	Reynolds Average Navier-Stokes
MRF	:	Moving Reference Frame
BET	:	Blade Element Theory

2. INTRODUCTION

As being the primary anti torque system of a conventional helicopter configuration, the foremost purpose of a tail rotor is to compensate the torque acting on fuselage generated by main rotor throughout the flight envelope. Moreover, controllability requirements suggest that even during the most critical maneuver or flight condition, additional margin has to remain on control inputs. Consequently, it is evaluated that the thrust range of a tail rotor is required to be compatible with main rotor capabilities, flight envelope of the helicopter and related requirements.

The performed MTOW modification, directly dictated a significant increase in the torque generated by the main rotor. Aeromechanic analyses supported with the ground tests, displayed that the current tail rotor is deficient to generate required thrust to compensate main rotor torque at specific flight conditions.

The main motivation behind this study is to improve tail rotor aerodynamic performance while keeping helicopter configuration and geometry unchanged. Tail rotor thrust performance is desired to be increased in order to counter balance the torque generated by main rotor especially at hot/high or MTOW missions.

Gurney flap attached perpendicularly to pressure surface of the blade trailing edge is one of the candidate solutions in order to increase total thrust produced by tail rotor. Gurney flaps are such small device that increases the camber and enhances the lift characteristic. It is firstly introduced by Liebeck in order to improve down force generation of race cars [1]. Gurney flaps are then applied to airfoils and wings[2] to increase maximum lift coefficient and wind turbines[3] to improve their performances. Moreover, recent studies shows that gurney flap has potential in rotorcraft applications. Potential improvements of articulated gurney flaps on rotors are enhancement in autorotative characteristics[4], reduction in peak to peak variations of hub loads[5], increase in figure of merit in at higher thrust coefficents[6]. Furthermore, gurney flaps are used to improve performance of vertical and horizontal stabilizers on rotorcraft for high powered climbs and high speed level flights[7].

Throughout this study several gurney flap designs are evaluated and analyzed. The

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configuration result in desired thrust levels is determined. In order to evaluate the effect of manufacturing limits, the analysis are repeated for gurney flap geometry with manufacturing tolerances. The blade profile example with ideal gurney flap and gurney flap to be manufactured is demonstrated in Figure 1.

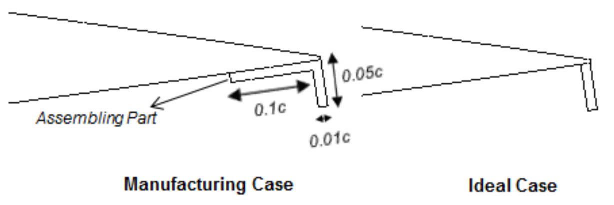


Figure 1 Gurney Flap Geometry For Ideal And Manufactured Case

Two dimensional airfoil analyses are carried out with commercial CFD-RANS tool. Mathematical models developed with Flightlab are then used to calculate rotor total performance with the generated airfoil database throughout helicopter flight envelope. When final geometry yielding the desired rotor thrust is determined, analyses are repeated with three dimensional CFD-RANS tool.

Although total torque and power required of the tail rotor increases, it is evaluated that transmission ratings compensate the increment in power and torque resulted from geometry modification.

3. PROBLEM

Within the scope of increasing MTOW of the discussed UAV, aeromechanics analyses are conducted throughout the flight envelope as well as maneuvers dictated by the standard requirements. It is evaluated that hot & high, MTOW hover out of ground effect flight condition observed to be the most critical case for the current tail rotor with largest thrust requirements. Tail rotor thrust tests at static condition are conducted and compared with aerodynamic evaluation tools with various fidelities. Required thrust level is estimated as 325N. Thrust and torque results are non-dimensionalized with respect to required thrust level and maximum torque which current tail rotor can generate respectively for the following figures. Current thrust result is presented in Figure 2. The tail rotor specification is given in Table 1.

Blade Number	2
Blade Span	0.5 m
Nominal rotational speed	2450 rpm
Tip Mach # Interval	0.4-0.5
Root-Cut Out	16 %

Table 1 Tail Rotor Specification

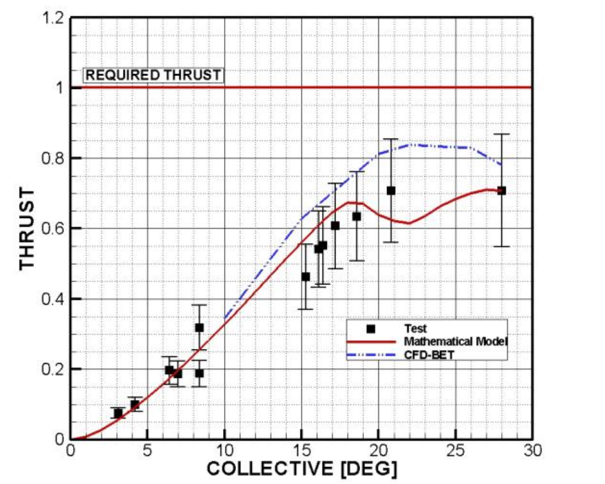


Figure 2 Tail Rotor Current Aerodynamic Performance (w/o Gurney Flap)

4. AERODYNAMIC ANALYSIS

The aerodynamic characteristics of both current and gurney flap installed tail rotor are evaluated using CFD tools having various fidelities. Two dimensional validation studies of tools were performed to calculate lift characteristics of airfoil with available data in literature. Current tail rotor experimental thrust data acquired during the static tests of discussed UAV had furnished another validation case for both two and three dimensional analysis tools. Moreover, the mathematical model and CFD tools used in this study are validated with whirl tower tests. [8],[9]

4.1. Mathematical Model

Aeromechanic modelling of the rotor and helicopter is performed with commercial comprehensive analysis tool Flightlab. Full helicopter model is developed in order to analyze helicopter aerodynamic, stability and maneuver performance throughout the flight envelope. Both main and tail rotors are modeled with blade element method with finite state inflow models. Additionally for a higher order analysis, free wake model is used for tail rotor in order to compare and investigate tail rotor aerodynamic characteristics at various fidelities. Aerodynamic database generated with CFD is used for tail rotor profiles for original and gurney flap configurations. Air loads are predicted with quasi-unsteady approach. Aeromechanic analyses are conducted in order to investigate maximum required thrust levels of the tail rotor as well as induced velocity and effective angle of attack distributions over the rotor disc, total torque, power values and stall characteristics.

4.2. CFD Analysis

CFD analysis are conducted by using commercial tool ANSYS Fluent. Fully turbulent flowfield is assumed and Spalart-Allmaras one equation turbulence model is used in the analysis. Compressible RANS solver utilized in analysis is segregated solver based on SIMPLE pressure-velocity coupling algorithm. Discretization of flow equations is performed by pressure based approach where pressure field is obtained by solving a pressure equation derived from continuity and momentum equations[10]. For the discretization of continuity equation and spatial discretization, Rhie-Chow based method[11] and second order upwind scheme is utilized respectively[12].

A sample view of mesh around airfoil is given Figure 3. Totally 25 boundary layer is composed around airfoil and heights of 1st layer cells is adjusted to satisfy y+ values lower than 1 on airfoil. Farfield mesh is generated by tri mesh type. Mesh refinement is applied to airfoil surrounding for enhancement of the wake resolution. Total volume cell numbers of generated airfoil mesh is around 100000.

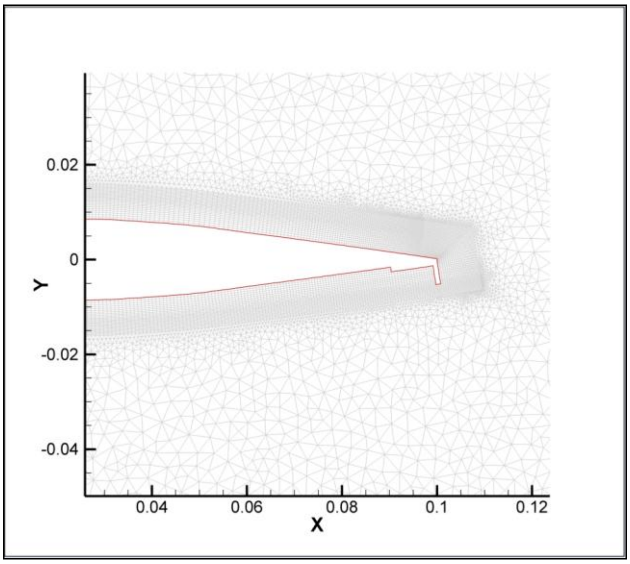


Figure 3 Trailing Edge View of the Tail Rotor Section with Manufacturing Case Gurney Flap Having 5% Chord Height .

Three dimensional RANS hover analysis are carried out by steady moving reference fame method. Periodic boundary condition is applied to lessen the computational cost. Body conforming prismatic cells of 25 layers are constructed around the rotor. 1st prism layer cell heights is set in order to satisfy y+ values lower than 1 on blade surface. Farfield mesh is constructed from tetrahedral mesh type. Upwind and sideway boundaries are located away from rotor centers by 20 rotor radius distance. The below boundary of domain is located 50 rotor radius distance away. Generated mesh includes approximately 3.5 M volume cells. The sample view of mesh topology is depicted in Figure 4.

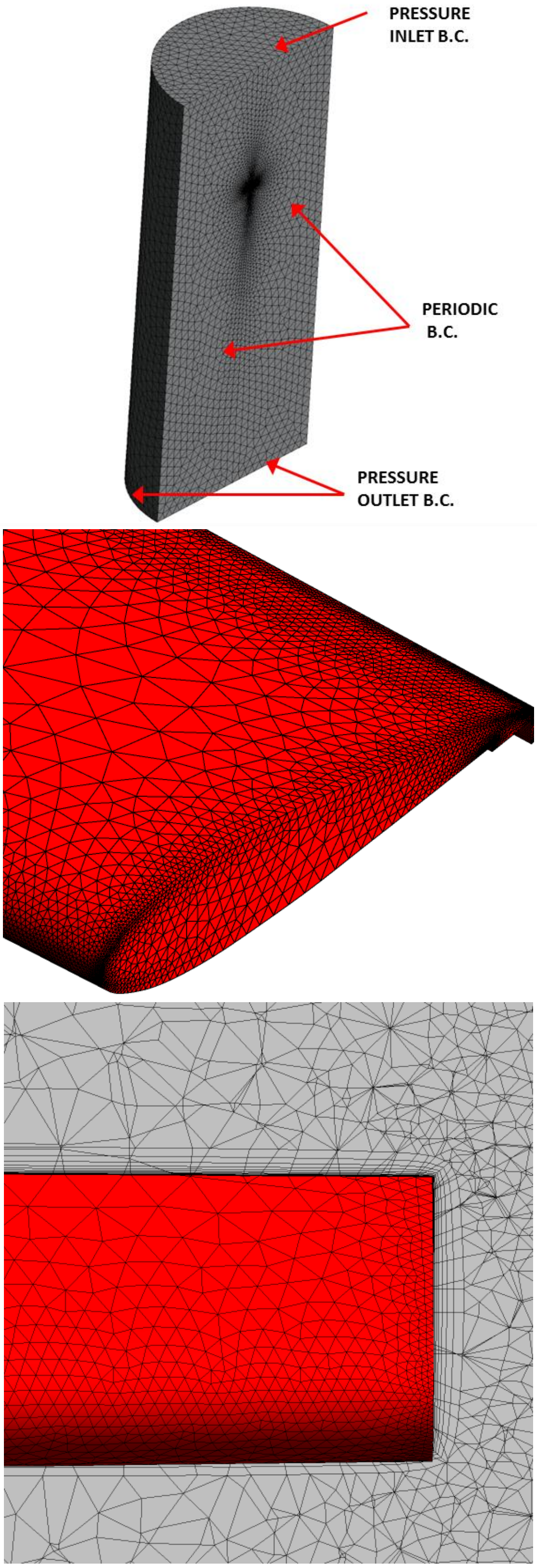
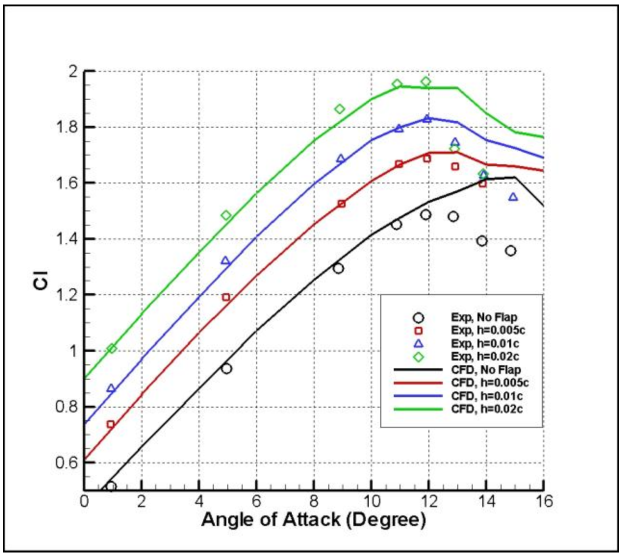
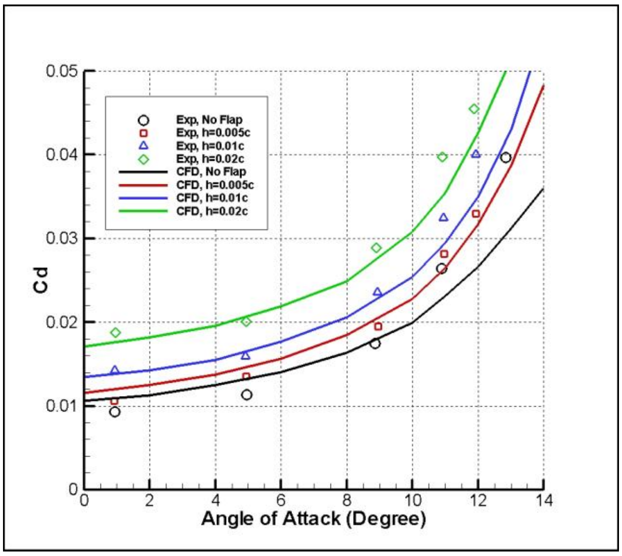


Figure 4 Applied Mesh Topology around Tail Rotor

Storms performed wind tunnel experiments at NASA Ames Research Center for NACA 4412 with varying gurney flap heights [2]. Reynolds number during the experiment is around approximately two millions. Figure 5 presents comparison of the two dimensional CFD analysis results with wind tunnel experiments in terms of lift and drag coefficient. While CFD analysis results are well in agreement with wind tunnel experiments in terms of airfoil with gurney flap, it overestimated maximum lift coefficient, therefore the estimated drag coefficient by CFD differs slightly from wind tunnel experiments after certain angle of attack in concerning with the base airfoil.



a) Variation of Lift Coefficient



b) Variation of Drag Coefficient

Figure 5 CFD-RANS vs. Experiment Comparison for NACA 4412

The CFD analysis results of current tail rotor with MRF is depicted in Figure 6. Thrust results of moving reference frame is given here up to stall angle. CFD results compromised with static tests adequately up to this angle.

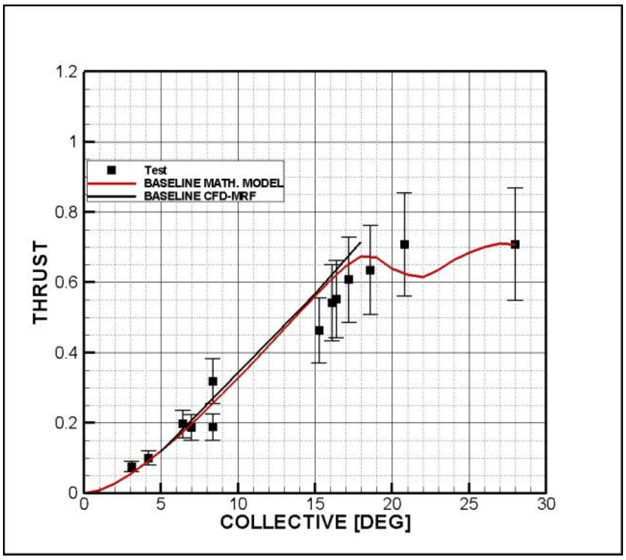


Figure 6 CFD-RANS-MRF vs Experiment Comparison for Current Tail Rotor

5. RESULTS

The lift coefficient variation with angle of attack of tail rotor section including ideal case gurney flap ranging 2 to 5% chord, which is inserted on trailing edge is shown in Figure 7. Figure 8 demonstrate the effect on lift to drag ratio of different gurney flap heights.

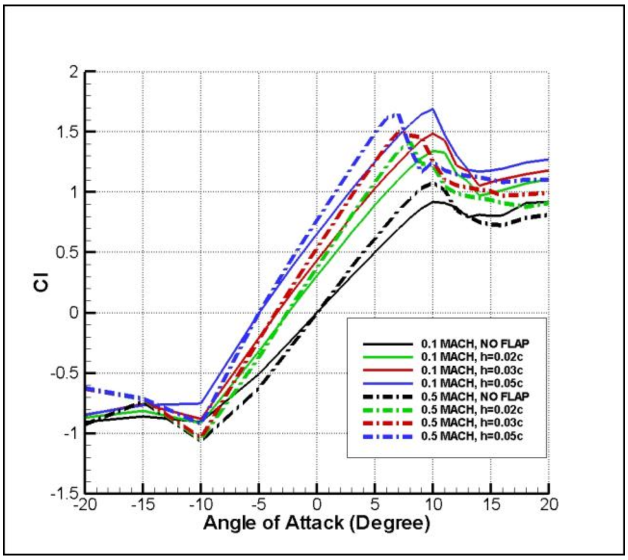
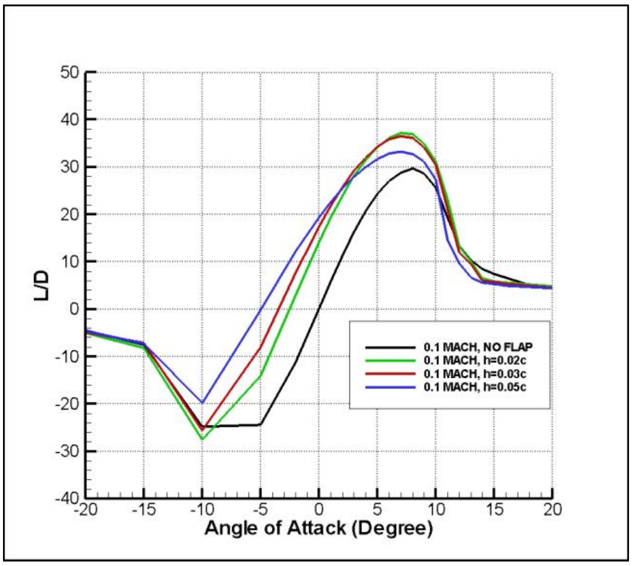
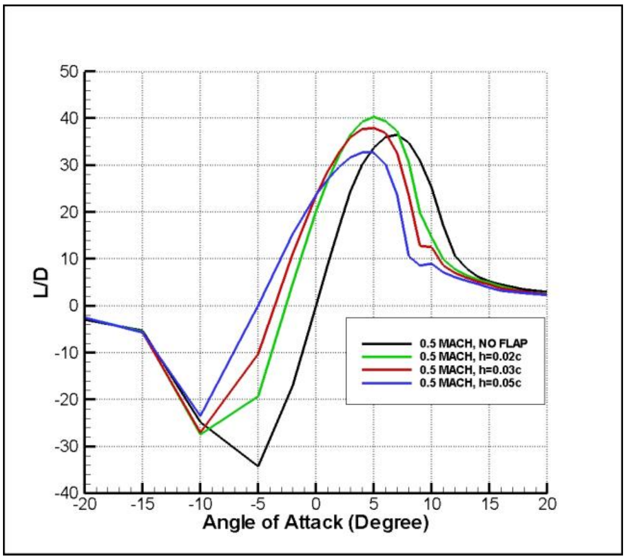


Figure 7 Effect of Gurney Flap Heights on Lift Coefficient at Various Flow Speeds

As a conclusion of experiments conducted by Katz and Largman[13] and Katz and Dykstra[14] , substantial increase in lift coefficient is calculated by numerical analysis, especially for the 5% chord gurney flap height the increment is around 50% over the baseline airfoil. Lift to drag ratio reduced after 2% chord height, since drag increased noticeably beyond this height as stated by Liebeck[1].



a) Variation of L/D at 0.1 Mach



b) Variation of L/D at 0.5 Mach

Figure 8 Effect of Gurney Flap Heights on L/D at Various Flow Speeds

Figure 9 demonstrates the hypothesized flow in the vicinity of trailing edge stated by Liebeck[1] and streamlines computed by CFD-RANS. Flowfield around trailing edge are changed effectively by gurney flap. Two counter-rotating vortices is introduced aft of the flap. CFD-RANS well captured the flowfield around the trailing edge with gurney flap.

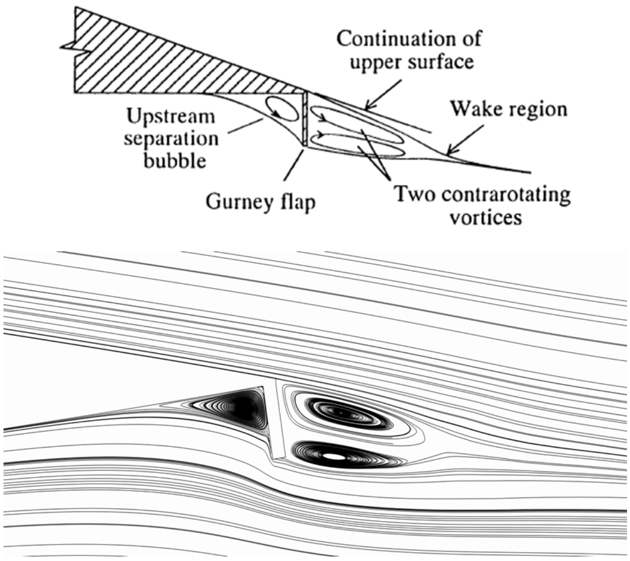


Figure 9 Hypothesized Flow Structure Around Trailing Edge with Gurney Flap[15] [Top], Computed Streamlines at 0° AoA and 0.5 Mach for 5% Chord Height Gurney Flap [Bottom]

Pressure coefficient distribution on the airfoils is indicated in Figure 10 at angle of attack 5° of 0.5 Mach case. Estimated pressure distribution showed that loading increases over the entire airfoil comparing to baseline airfoil. This load increment caused by gurney flap is considerably high at suction peak and near the trailing edge.

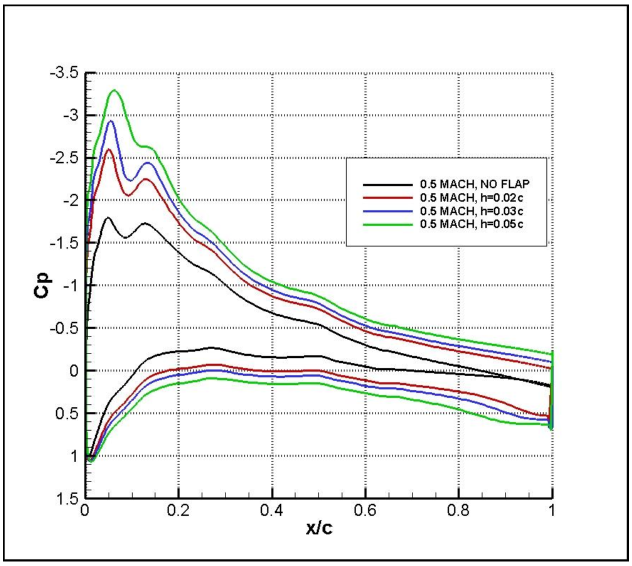


Figure 10 Effect of Gurney Flap Heights on Chordwise Cp Distribution at Angle of Attack 5°

The effect of assembling for manufacturing case is depicted in Figure 11. Loading increment is almost same with ideal case except for near the trailing edge which results in slightly less lift production. Hence, total thrust generated by rotor and total torque required by the rotor with gurney flap heights varying to 3 to 5% chord of only manufacturing case is presented in Figure 12 and Figure 13, respectively. Beside the rotor thrust enhancement by gurney flap, it implies that necessary thrust can be achieved at less collective settings. Analysis shows that 4 and 5% chord height satisfied the required level. However, 5% chord height geometry is selected to apply to tail rotor by the reason of safety in operation and easiness in production.

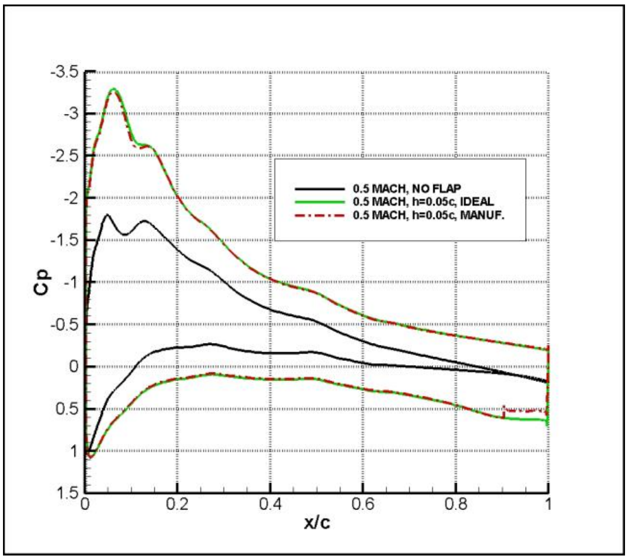


Figure 11 Effect of Assembling Part on Chordwise Cp Distribution at Angle of Attack 5°

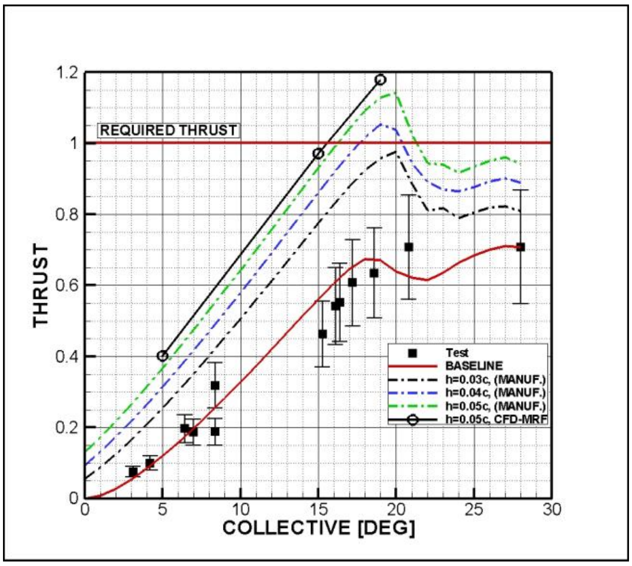


Figure 12 Effect of Gurney Flap Height on Tail Rotor Thrust

Thrust results of gurney flap having 5% chord height by three dimensional CFD-MRF analysis are almost same with mathematical model. Computed velocity magnitude contours of flowfield on plane at constant azimuth (Ψ = 0°) is depicted in Figure 14 for 5 degree collective settings. For the simplicity, upwind side of rotor is given up to 5 rotor radius distance away. Downwash generated by both rotor is extended to farfield boundary located at 50 radius away. Qualitatively it can be stated that tail rotor with gurney flap excited and induced more airflow with higher velocity than current tail rotor. Thus this results in higher thrust values.

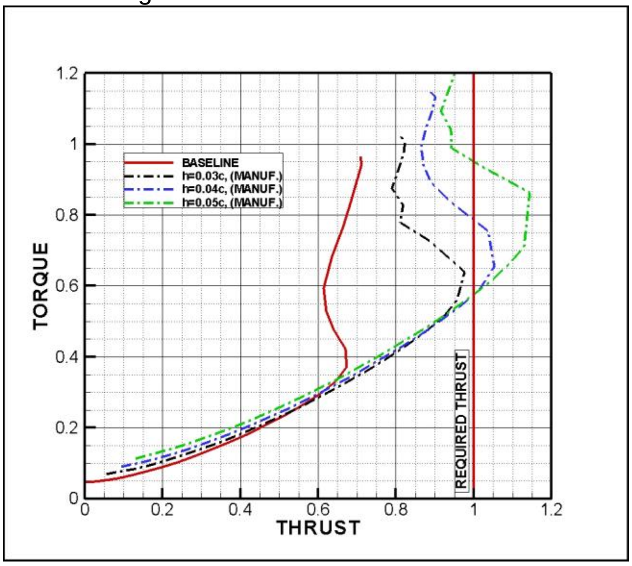


Figure 13 Effect of Gurney Flap Heights on Torque Required for Tail Rotor

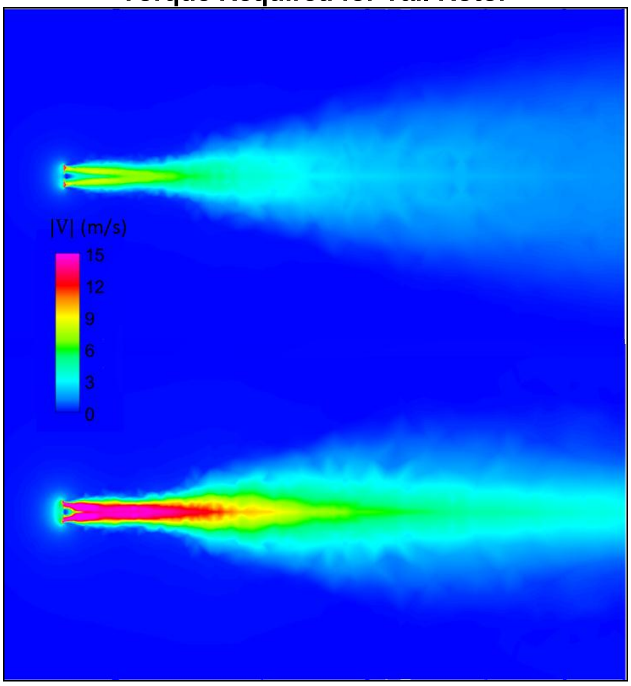


Figure 14 Flowfield for Hovering Rotor by CFD-MRF (Current Tail Rotor [Top], Tail Rotor with 5% Chord Height Gurney Flap [Bottom])

6. CONCLUSIONS

Current study presents a Gurney flap design to improve aerodynamic performance of the tail rotor of an unmanned rotorcraft whose MTOW is increased. Tests are conducted to investigate current performance of the tail rotor. Gurney flap design is accomplished with two dimensional profile CFD RANS analyses and total rotor performance evaluation with developed mathematical model of the rotor. Effect of manufacturing tolerances and assembly of Gurney Flap on rotor total performance is investigated as well. Three dimensional CFD analyses are performed for the candidate gurney flap geometry to estimate rotor performance improvement. Even though applied gurney flap yields increment in required torque and power, it is assessed that this increase is compensated by engine and transmission.

The manufacturing and testing of decided gurney flap geometry will be performed and its effect on rotor performance will be evaluated in future studies.

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