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Design of Optimum Torsionally Flexible PropRotors for Tilt-Body MAVs

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Abstract. This paper presents a methodology to design the optimum proprotor for tilt-body micro-air-vehicles (TB-MAV) with efficient global propulsion system and long flight endurance in both cruise and hover modes. The TB-MAV developed at ISAE, which is called MAVion, was used as a baseline in the design process. To acquire maximum performance of TB-MAV's global propulsion system, an efficient optimization process of the proprotor propulsion system was carried out. The optimization process consists of two-step inverse design methods. The first step determines the optimal operating conditions in terms of power and rotational speed of proprotor and the second step designs the optimal blade geometry in terms of twist angle distribution. The optimal blade twist distribution along the blade was computed using the Glauert's strip theory for minimum energy loss condition. Meanwhile, the optimal operating conditions were determined by the motor outputs corresponding to high motor efficiency. A comparison of performance in terms of total efficiency and flight endurance between the optimized flexible proprotor, the optimized rigid proprotor, optimized propeller and optimized rotor is presented.

Introduction

Tilt-body micro-air-vehicles (TB-MAV) have been regarded over the last decade as promising candidates for convertible multi-tasking configuration as they intrinsically combine both vertical and horizontal flight capabilities. Such convertible MAVs can provide better observation abilities during hovering while offering faster forward movement during cruising. However, in these two flight modes the rotor operates under considerably different conditions where using a conventional rotor will require high power consumption or even inability to provide sufficient required thrust in the off-design cases. The substantial variations of blade pitch and twist that are required to offer highest possible efficiency at both flight modes require an active control system to change the shape according to the flight configurations. Nonetheless, the active blade shape modification concept is inapplicable for small-sized rotor (blade ~3mm of thickness) due to its complexity and the unavailability of control devices in the small size range, and requires non-mechanical control system to be used. Structural topology optimization where the mass density distributions along the blade is optimized according to the desired aerodynamic loadings [1] and off-axis carbon fiber composites for blade twisting moment introduction, are among the potential concepts to structurally design the passively adaptive blades. Thus, the idea behind the passive blade shape modification concept is to compute the optimal twist distribution for TB-MAV hingeless proprotor for both cruise and hover mode. The difference of optimized blade twist between these two flight modes and its corresponding resulting aerodynamic loadings to enable twist deformation, can be used as design inputs to structurally design the flexible blade by using inverse methods of blade structural stiffness distribution identification [2].



Fig.1 MAVion (Dimensions: 400mmx220mm) in hover configuration

Blade Twist Optimization

A numerical iterative method for computing the optimal blade twist angle distribution along the blade span in horizontal and vertical flight, with identical chord laws, was developed adapting the inverse design method of proprotor using Blade Element Momentum Theory (BEMT) based on Minimum Induce Loss (MIL) that satisfies the Betz's condition. The systems of equations used were proposed by Adkins and Liebeck [3] and the design procedure is shown as a block diagram in Fig. 2 (lower part). This iterative design procedure determines the optimal blade twist angle along the radius ($\beta(r)$), the characteristics of the designed proprotor (C_T , C_P) and its performance ($\eta_{\text{proprotor}}$, FM). The radial and axial interference factors, Re , and relative Mach number depending on the operating condition are also iteratively computed in the design process. The details are described in [3].

In the classical approach of propeller design and analysis, different assumptions are made, i.e. lift polar is a linear function, in order to obtain a closed loop solution or even to quickly converge the iterative process. Hence, in order to consider non-linear airfoil characteristics prevalent in low Reynolds number regime ($Re < 70,000$), XFOIL, an airfoil design and analysis code developed by Drela [4] was integrated into the iterative process of design to eliminate this assumption as well as to precisely compute the aerodynamic coefficients. The airfoil sensitivity to the turbulence level and Reynolds number variation was eliminated by using cambered plate [5] as a blade profile. The cambered plate profile also promises better performance than other airfoils in MAVs Reynolds number regime [6]. In this respect, the n_{crit} parameter, used to define the turbulence level in XFOIL, was set at 0.1 for both flight modes. The cambered plate with thickness t/c of 2.5%, camber f/c of 3% and camber location xf/c of 30% was used in this study. For optimization, the input parameters are number of blades B , proprotor radius R , operational speed V , rotational speed Ω and mechanical power into the proprotor P_{mech} . Constant non-dimensional chord c/R of 0.15 was used to ensure the activity factor AF of the blade is in the range of practical propeller, $90 \leq AF \leq 200$ [7]. The proprotor diameter D used for MAVion was set at 18cm to ensure the momentum injected into the flow by the propwash covers almost the entire span of the MAVion's body. This will avoid the flow separation on the MAV's body while performing a transition between the two flight modes. To evaluate the performance of proprotor, the computed quantities are the $\eta_{\text{proprotor}}$ in forward flight and the figure of merit FM in hover as defined in Eq. 1.

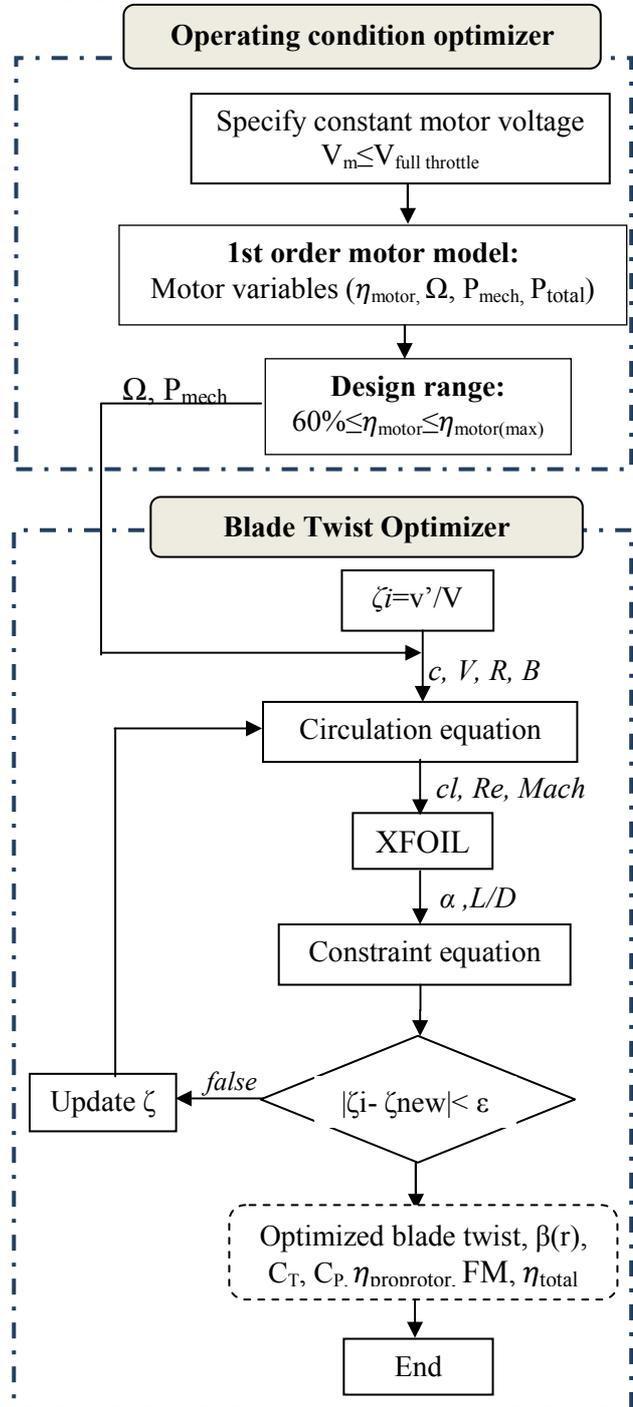


Fig. 2 Proprotor design methodology

$$\eta_{\text{proprotor}} = J \cdot \frac{C_T}{C_P}, \quad FM = \frac{C_T^{3/2}}{\sqrt{2} \cdot C_P} \quad (1)$$

where J is the advance ratio, C_T is the thrust coefficient and C_P is the power coefficient, which are respectively defined in Eq. 2 as:

$$J = \frac{60 \cdot V}{\Omega \cdot D}, \quad C_T = \frac{T}{\rho \cdot \left(\frac{\Omega}{60}\right)^2 \cdot D^4}, \quad C_P = \frac{P_{\text{mech}}}{\rho \cdot \left(\frac{\Omega}{60}\right)^3 \cdot D^5} \quad (2)$$

By knowing the performance of proprotor, the η_{total} in cruise and hover can be respectively computed by using relationships in Eq. 3.

$$\eta_{\text{total(cruise)}} = \eta_{\text{motor}} \cdot \eta_{\text{proprotor}}, \quad \eta_{\text{total(hover)}} = \eta_{\text{motor}} \cdot FM \quad (3)$$

Operating Condition Optimization

In order to control the global propulsion system to be in high performance in both flight modes, the design range of operating conditions was first specified. The operating conditions in the design process of optimal blade twist are the motor outputs in terms of P_{mech} and Ω corresponding to the specified η_{motor} . The motor voltage V_m must be carefully chosen to satisfy the design requirements. In this study, the initial V_m was set up based on the performance data of MAVion which is the motor outputs at 10V with $60\% \leq \eta_{\text{motor}} \leq \eta_{\text{motor(max)}}$ were set, as can be seen in Fig. 4. However, the designed proprotor blade at given operating conditions from the motor outputs is subject to the design requirements. Since two proprotors were used in the MAVion in order to control the yaw direction, the T_{req} at cruise flight was constrained by the half of MAVion's drag at the target cruising velocity $V=16\text{m/s}$. Whereas for the hover flight, T_{req} was constrained by the half of the MAVion's weight of 350 grams. The design requirement for MAVion proprotor at each flight configuration is shown in Table 1.

Table 1 Design requirements for proprotor

Flight configuration	Velocity, V (m/s)	Required thrust, Treq (N)
Hover	0	1.7
Cruise	16	0.31

The design constraint considered in this study is the twist deformation between cruise and hover, $\Delta\beta = |\Delta\beta_{\text{(cruise)}} - \Delta\beta_{\text{(hover)}}|$. The value needs to be as small as possible in order to be able to manufacture the passive control blade, also the desired twist deformation to be possibly adjusted by the aerodynamic loadings. For the design of this study, the $\Delta\beta$ was set as $\leq 8^\circ$. According to the theory of propeller design based on MIL, by increasing the proprotor Ω in the cruise can decrease the optimal blade twist angle. In contrast in the hover flight mode, the optimal blade twist increases as the Ω decreases. This will be advantageous in the design of optimal blades for proprotor where the $\Delta\beta$ can be minimized. From the first order motor model law, higher the voltage can provide maximum η_{motor} at higher Ω as illustrated in Fig. 3. Hence, by freezing the motor outputs at around maximum η_{motor} can promise long flight endurance due to low P_{total} [8]. A direct current motor of AXI2204/54EVP with motor speed constant $K_v = 1400 \text{ rev/min/Volt}$, zero load current $I_0 = 0.35\text{A}$ and internal resistance $R_m = 0.32 \text{ ohm}$, was used in this study. The motor output variables at constant V_m were computed using relationships in Eq. 4 [8] and are plotted in Fig. 3 and Fig. 4.

$$P_{\text{total}} = \left(\frac{V_m - \frac{\Omega}{K_v}}{R_m} \right) \cdot V, \quad P_{\text{mech}} = \left(\frac{V_m - \frac{\Omega}{K_v}}{R_m} \right)^2, \quad \eta_{\text{motor}} = \frac{P_{\text{total}}}{P_{\text{mech}}} \quad (4)$$

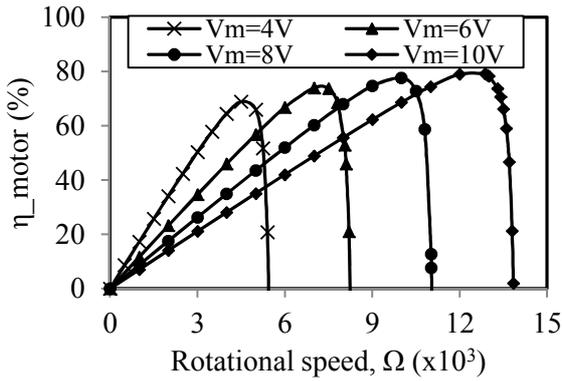


Fig. 3 AXi2808/04 motor efficiency at different voltages

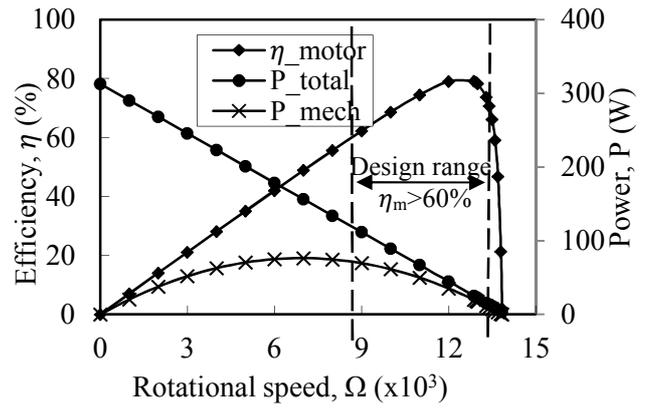


Fig. 4 Motor output variables vs motor speed at 10V of applied voltage

From the known P_{total} supplied into proprotor, the endurance of the flight is computed by the relationship in Eq. 5.

$$\text{Endurance time, } t_{end} = \frac{E}{P_{total}} = \frac{C.K.V_b}{P_{total}} \quad (5)$$

where E is the battery energy stored, C is the battery capacity, K is the number of battery cells and V_b is the nominal battery voltage. For MAVion, three cells of Polymer Lithium Ion battery ($V_b=3.7\text{Volts/cell}$, $C=1000\text{mAh}$) were used in MAVion for its small size and light weight as well as high energy density for long endurance flight.

Results and Analysis

The developed iterative process of proprotor analysis using BEMT method was first validated with the results given by QPROP and corresponding experiment measurement. A 2-bladed rotor with a rectangular planform ($R=0.1\text{m}$, $c=0.02\text{m}$), flat plate blade profile with a thickness $t/c=2.5\%$ and blade pitch of 25° was used in the validation process. From the validation result in Fig. 5, it is found that the BEMT method with the integration of XFOIL shows good agreement with the experimental measurement. QPROP, a propeller analysis tool with simplified and limited lift polar, showed unacceptable correlations due to its incapability to predict aerodynamic coefficients at post-stall region. The design of propulsion system in hover and cruise was done separately. The optimal blade twist within the specified design range of operating conditions was obtained. The results for hover case are shown by Fig. 6 and Fig. 7, and the results for cruise case are shown by Fig. 8 and Fig. 9. To generate the T_{req} in a hover, the rotational speed of $\Omega=12,870$ and the designed blade corresponding to this Ω is shown by a dashed line in Fig. 6. Whereas to attain T_{req} in cruise at $V_c=16\text{m/s}$, the proprotor needs to operate at $\Omega=13,500$ can be observed in Fig. 9. The design at $V_c>16\text{m/s}$ was done to find the maximum V_c that passive control blade can achieve. And it is found that the MAVion is not able to cruise beyond 16m/s using passively flexed proprotor.

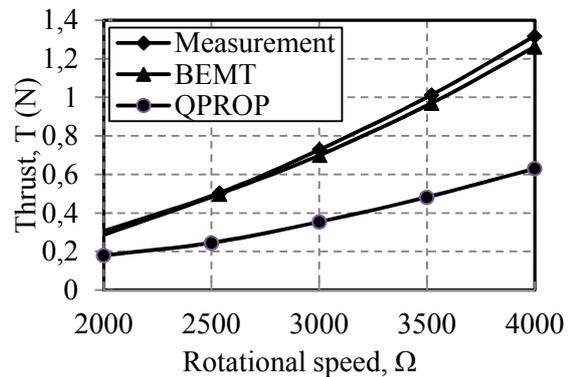


Fig. 5 Comparison of BEMT simulation and the corresponding measurements

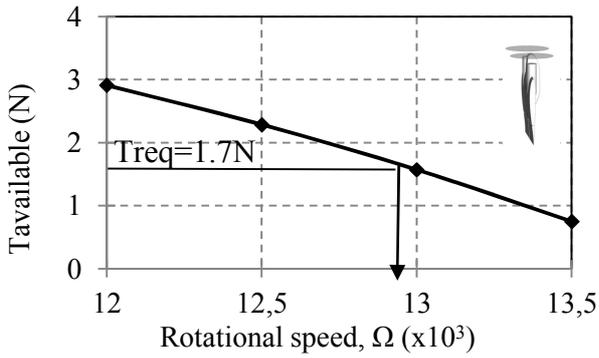


Fig. 6 Thrust available given by the optimized twist blade at different Ω in hover

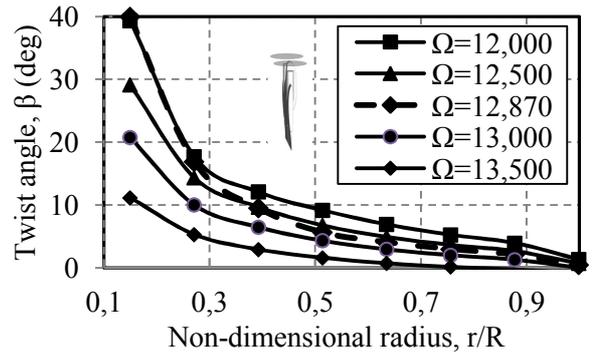


Fig. 7 Optimal twists angle of proprotor blades in cruise at different Ω

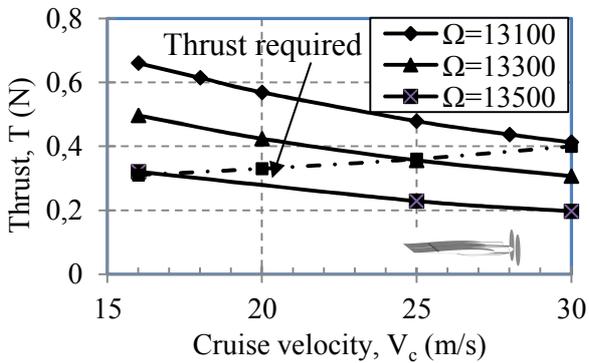


Fig. 8 Thrust available and thrust required at different cruise velocity

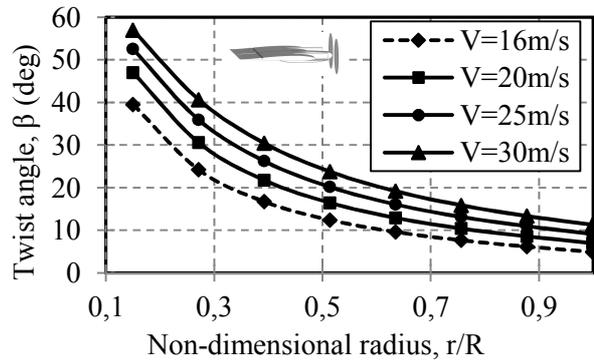


Fig. 9 Optimal twists angle of proprotor blades in cruise mode at different cruise velocity ($\Omega=13,500$)

Fig. 10 represents the optimal blade twist distribution in hover and cruise modes that satisfy the design constraint ($\Delta\beta \leq 8^\circ$) for flexible proprotor. The performance of the rigid proprotor was also computed. As for a rigid proprotor, the optimized blade twist of the flexible proprotor in cruise was chosen as a blade twist of the rigid proprotor, as shown in Fig. 10. The optimized blade geometry of single-point propeller/rotor design in terms of chord and twist angle distribution is shown in Fig. 11. And the performances of the optimized propeller and optimized rotor in cruise and hover respectively were used as a baseline of comparison with the designed proprotor as shown in Table 2.

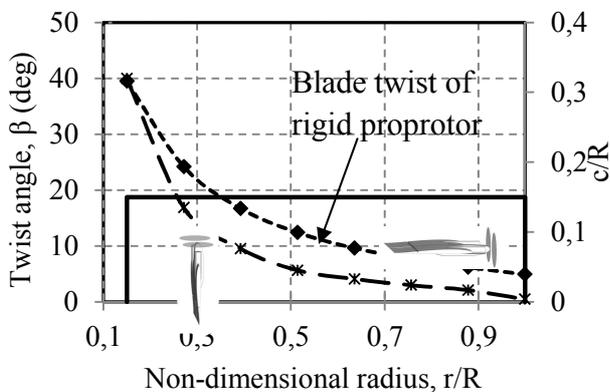


Fig. 10 Blade geometry of flexible proprotor

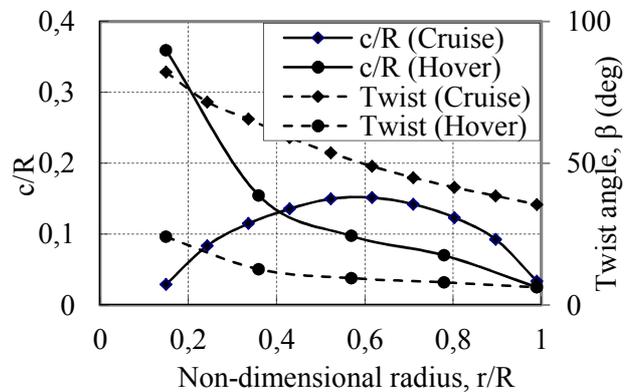


Fig. 11 Optimal blade shapes at single design point in hover and in cruise

Table 2 Results comparison of propulsion performance between propeller, rotor and proprotor

Proprotor type	Flight mode	η_{total} (%)	P_{total} (W)	Endurance, t_{end} (min)
Single design point (Optimized propeller)	Cruise	47.62	10.42	63.89
	Hover	0.058	127.44	5.23
Single design point (Optimized rotor)	Hover	61.74	20.33	32.75
	Cruise (stall)	-	-	-
Flexible proprotor	Cruise	44.57	11.16	59.67
	Hover	31.78	25.22	26.40
Rigid proprotor	Cruise	44.57	11.16	59.67
	Hover ($\Omega=7,850$)	30.19	26.00	25.61

The optimized propeller able to hover the MAVion but consumes very high power which reduces the endurance, meanwhile, the optimized rotor stalls the MAVion in forward flight. The optimized rigid proprotor reduces very slight its performance as compared to the optimized flexible proprotor even though it is needed to be operated at $\Omega=7,850$ to obtain sufficient thrust in hover. The optimized flexible and rigid proprotor offers $\sim 30\%$ increment of η_{total} in hover as compared to the optimized propeller. It also promises flight endurance at both flight modes as long as the optimized rotor and optimized propeller in hover and forward flight respectively.

Conclusions

A practical and reliable methodology to design the proprotor for the application in tilt-body micro-air-vehicles (TB-MAV) with efficient global propulsion system and long flight endurance was presented. To acquire maximum η_{total} , the proprotor blade was optimized in terms of twist angle distribution along the blade using MIL condition to obtain the maximum $\eta_{proprotor}$ while the operating condition was optimized to obtain the maximum η motor. The presented efficient design methodology which combines both proprotor and motor design could be used as a practical design tool for the passive control proprotor development.

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