Airbus Flight Challenge 2024

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Indian Institute of Technology

Kanpur

<u>Team Name</u>

Chakravyuh Squadron
(AIR005)

<u>Team Members</u>

1. Akshat Hemang Jani
2. Vedant Salphale
3. Vanshaj Anand

Abstract

This study investigates strategies to improve the efficiency of propeller systems through a combination of design optimization and performance analysis by researching and analyzing a variety of blade shapes and their performance for corresponding flight phases. The research aims to address the increasing demand for more energy-efficient propulsion solutions in aerospace by emphasizing more on increasing the propeller efficiency and lowering the power consumption. Key factors influencing propeller efficiency, such as airfoil selection, blade geometry, blade orientation, etc. are examined using various optimization techniques and previous studies for the given set of operational constraints. The proposed methodology describes the optimal propeller designs based on performance metrics suitable for given operating requirements, optimization of thrust and power consumption. The study also brings up the idea of energy harvesting capability where the propeller would act as a wind turbine during the phases of flight where the engine power is idled ex. descent, thus, generating and storing power which can boost up the endurance of the flight. The findings offer valuable insights for the development of next-generation propeller systems such as morphing propellers tailored to specific applications, leading to significant improvements in energy efficiency and environmental sustainability.

CONTENTS

Flight Profile

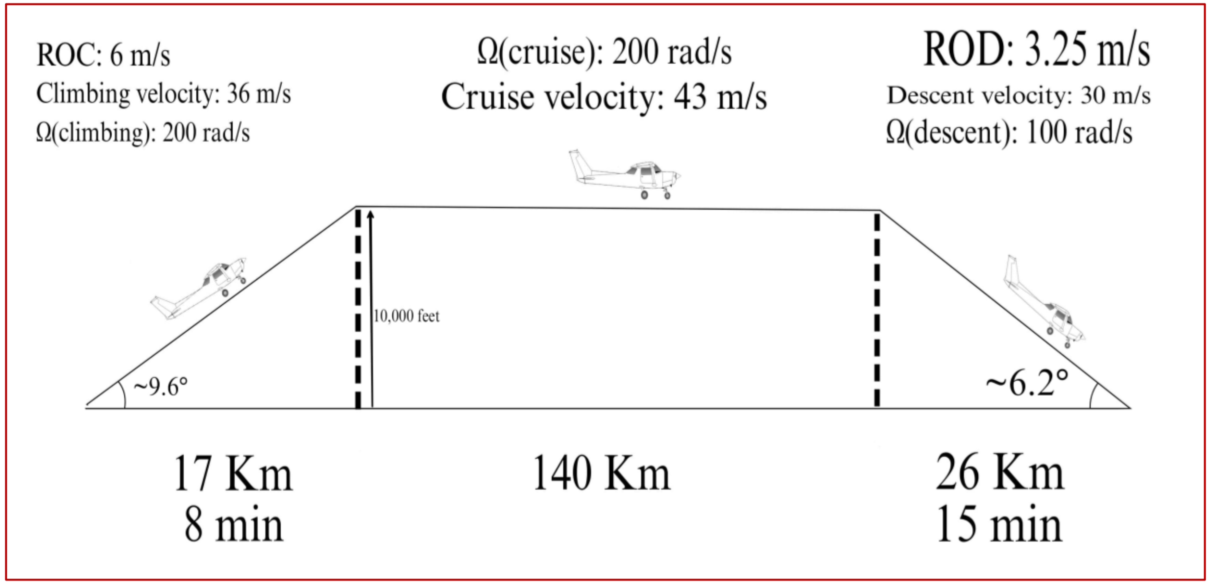


Fig 1.1 Estimated Mission Profile

Ref Aircraft: Pipistrel Alpha Electro

Max Power : 60 kW   Powerplant: Electric   Max RPM: 2240 (cruise)

Weight : 5395.5N   No. of Blades : 3

Cruise Range Distance: 108nm (200km)

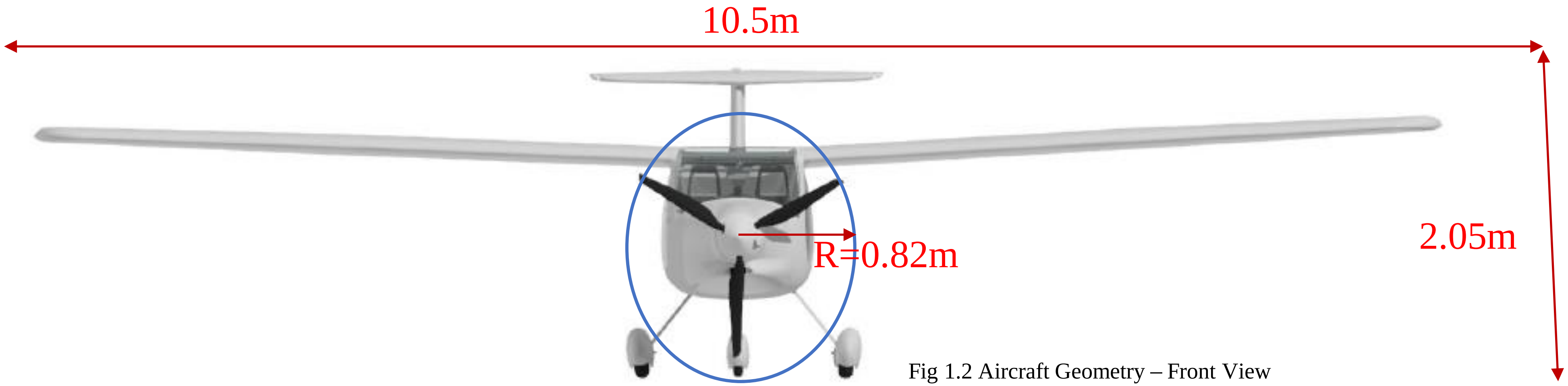
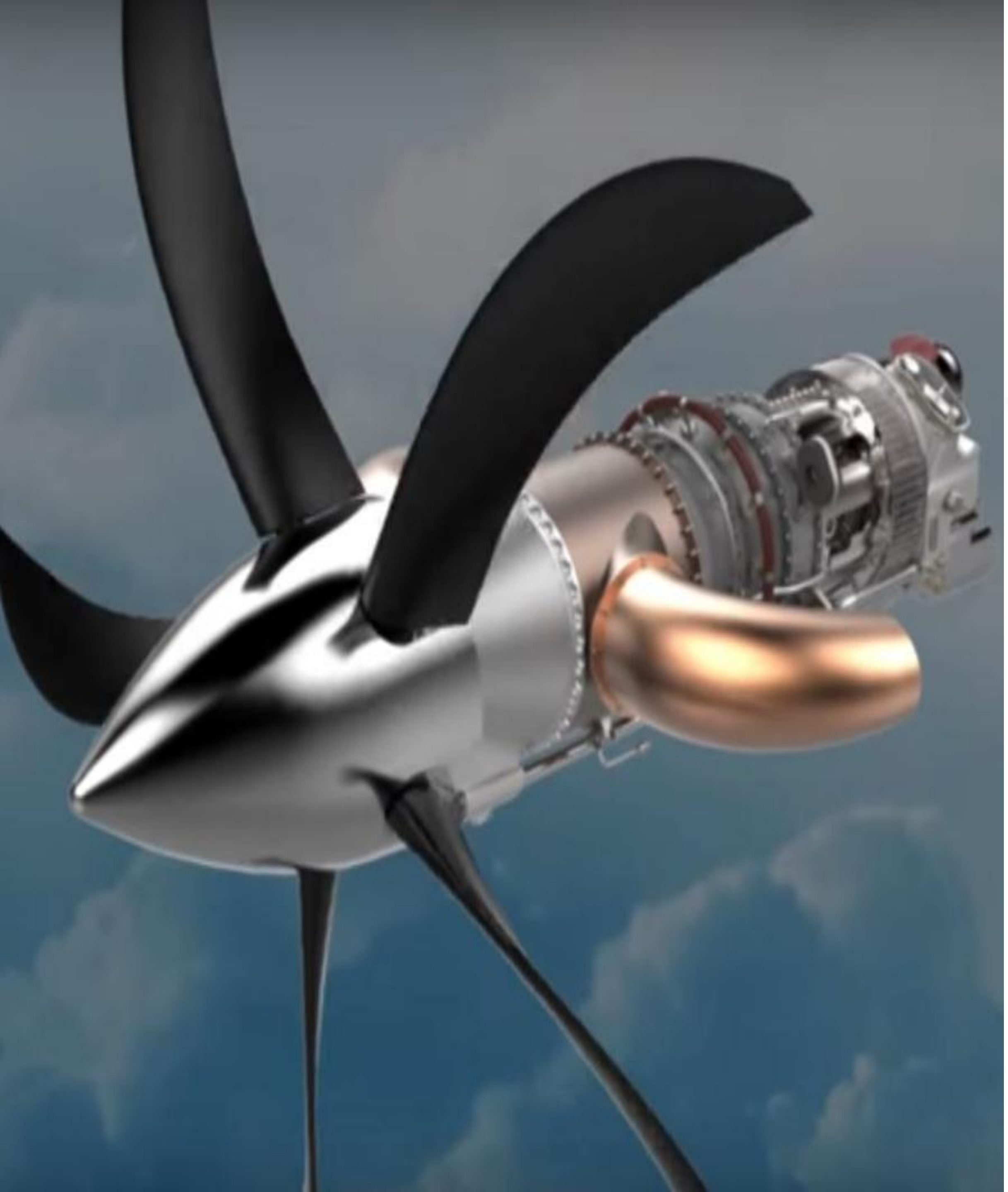


Fig 1.2 Aircraft Geometry – Front View

What is regenerative Flight ?

- The flight time can be increased if necessary, or storage of energy for the subsequent flight becomes possible.
- It is claimed that the technology enables a reduction in energy consumption as well as an extension of the options and flexibility the pilot obtains with the ’extra energy’ that would not be there without in-flight energy recuperation



Is regenerative Flight Practical? (Spoiler Alert YES!)

The main mechanism driving regenerative flight technology is an innovative propeller design that can accomplish a dual function of delivering sufficient power in the most energy-demanding climbing flight phase, while simultaneously regenerating as much energy as possible by windmilling during the descent flight phase.

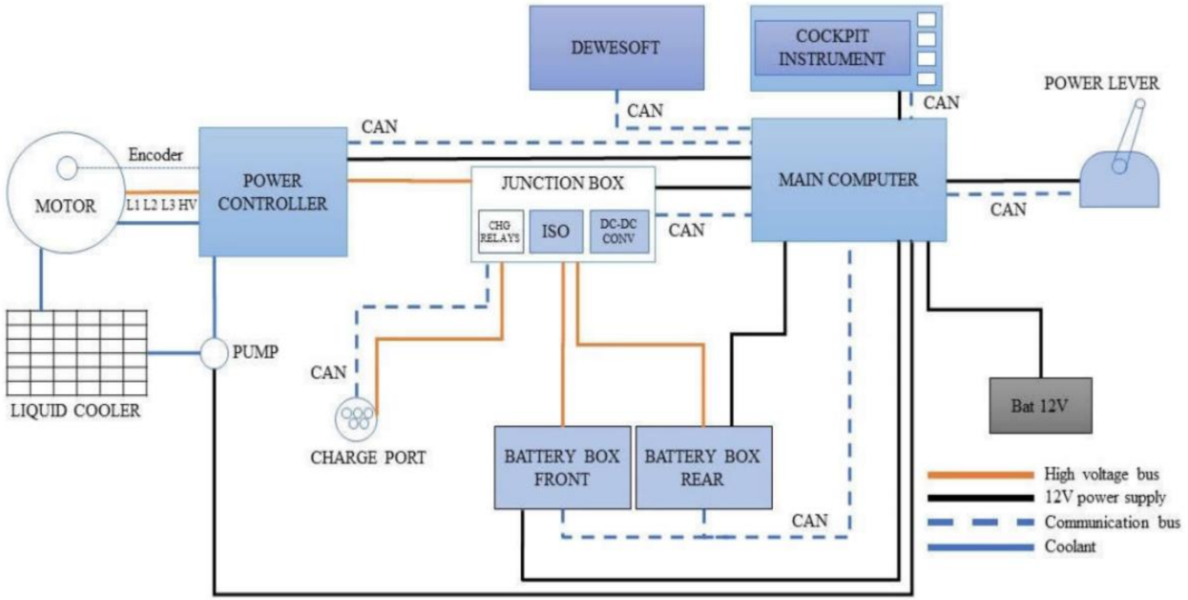


Figure 1.3: Powertrain Architecture

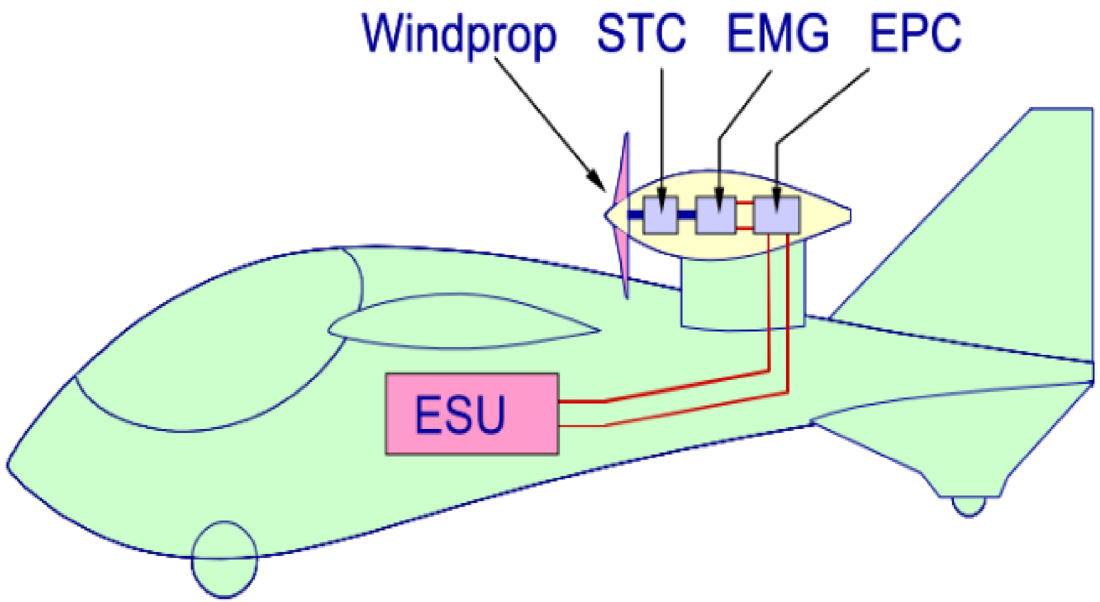


Figure 1.4 : Main components of a regenerative powertrain

ENERGY HARVESTING POWERTRAIN ARCHITECTURE

- Energy is exchanged between the ESU(Electrical Storage Unit) and the electrical-power conditioner (EPC)
- EPC is used to control the Speed of the Electric Motor Generator(EMG)
- Shaft power generated is transmitter to propeller via Speed Torque Controller(STM)
- It has two modes : energy consuming (propelling) or energy extraction (windmilling) mode

Blade Airfoil Selection

- Blade cross section is made up of airfoil and plays a crucial role in performance
- Single airfoil over the entire blade span
- Higher efficiency requires high Lift-to-drag ratio
- Each regime has different characteristics and hence the requirements of the camber
- 3 airfoils were chosen after careful literature review
- L/D plots for Propulsive and Regenerative regimes are plotted in Fig.2.1

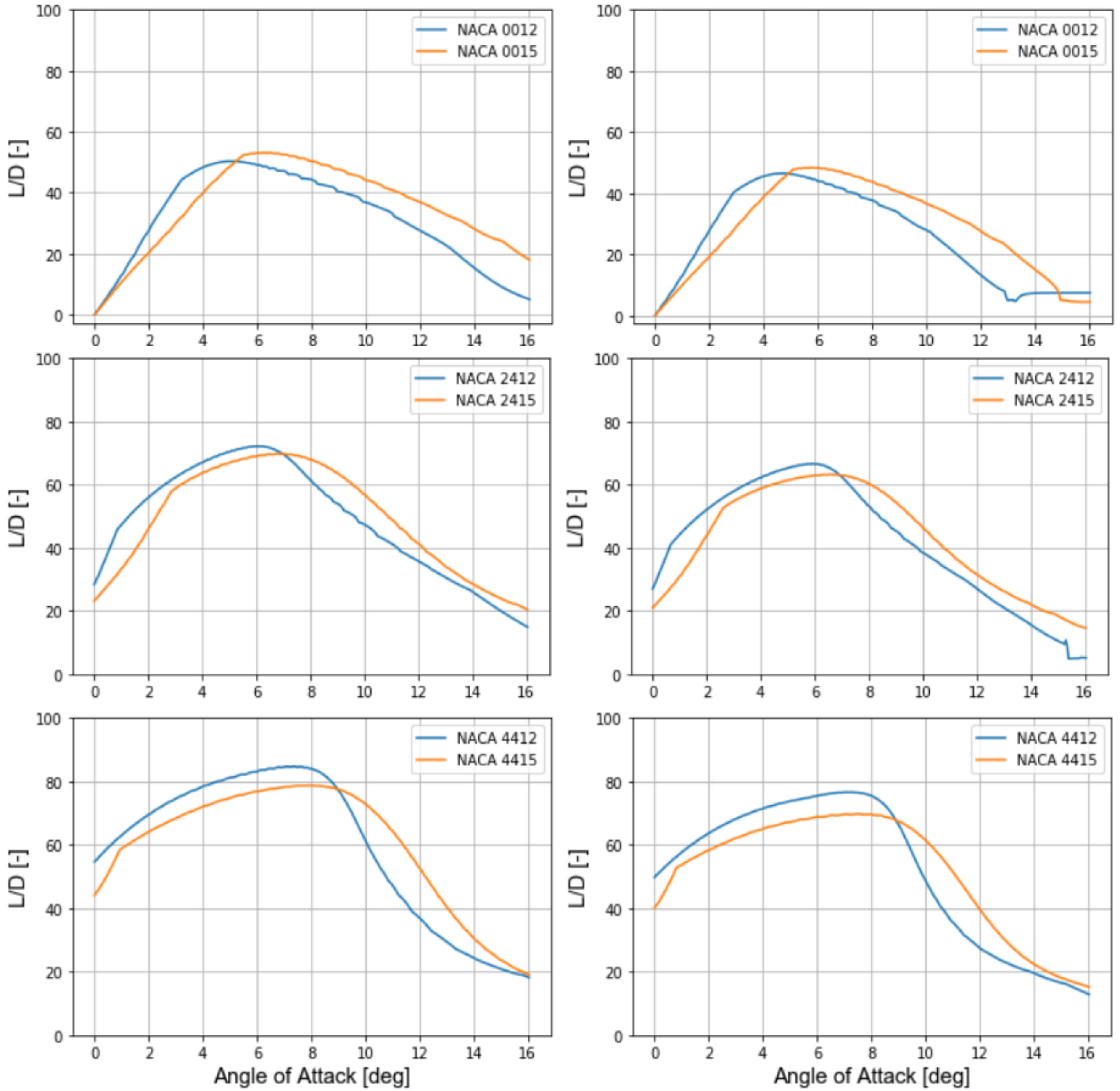


Fig. 2.1 : Lift to Drag ratio for different A.O.A. for propulsive mode[1]

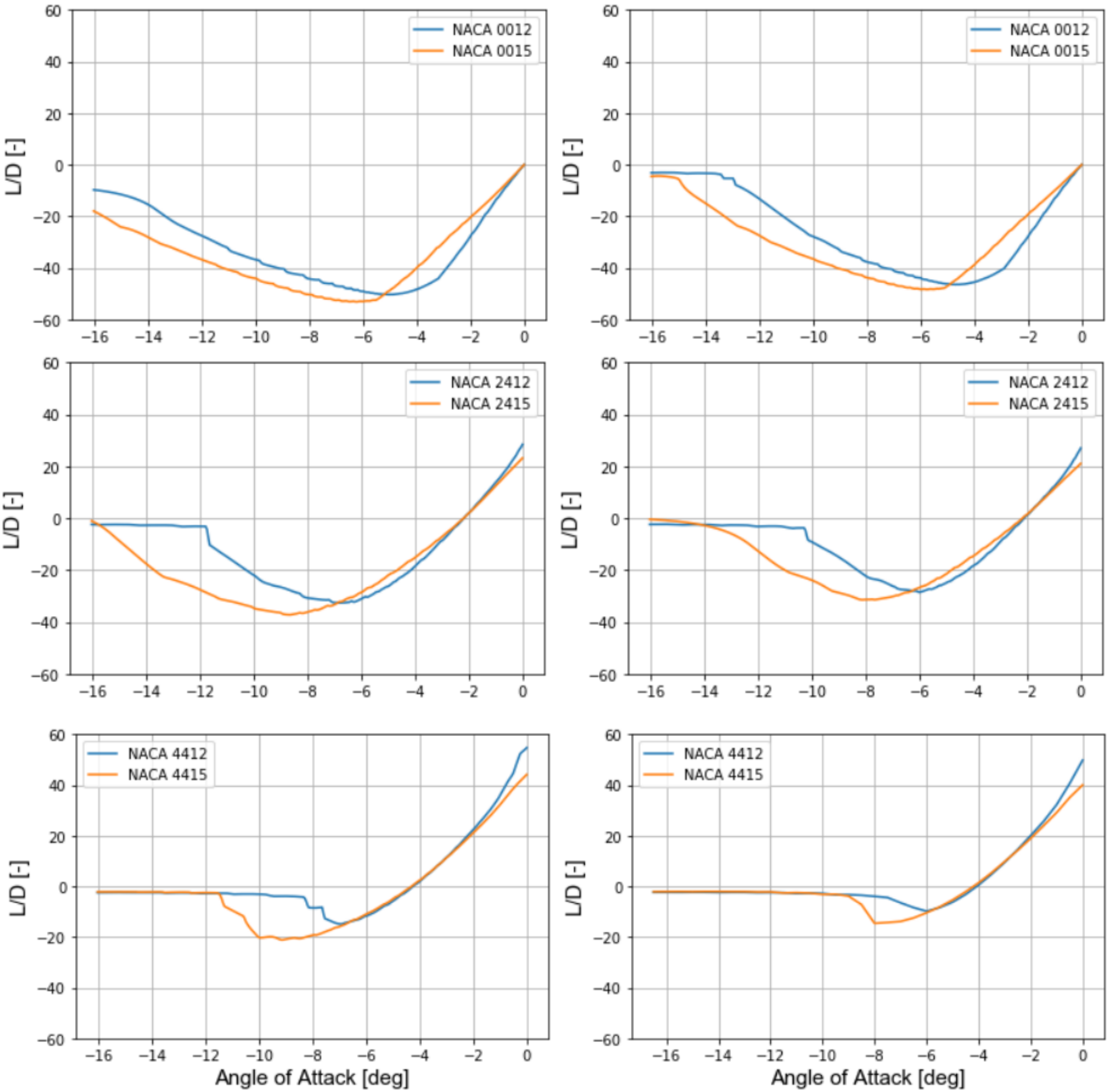


Fig. 2.2 : Lift to Drag ratio at different A.O.A. in regenerative mode[1]

Some important airfoil criteria

- High positive L/D ratio over a wide range of A.O.A. in propulsive mode
- Low negative L/D ratio over a wide range of A.O.A. in regenerative mode
- Thickness-to-chord ratio between 10% and 20%
- Good low and high speed performance
- Benign stall characteristics

Why NACA 4-Series ?

- ➢ It is hard to determine the exact range of Mach and Reynolds numbers on the propeller span
- ➢ Thin airfoil at tip : Higher critical mach number
- ➢ Reduced compressibility drag because of higher velocities seen at the blade tip
- ➢ A compromise as it complies very well with the above listed criteria

Morphing Blades : A Novelty

- **Proposal** is to design a single propeller that can be modified for propulsive and regenerative phases
- Morphing means to undergo transition from one form to another
- Challenge is to put such small actuators in blades
- Shape Memory Alloys (SMA) such as Nitinol is a suitable choice for actuators without increasing weight [2]
- Using micro mechanical actuators inside the blade section for changing camber and thickness
- A flexible yet strong material for blades that can be morphed is Ti-6Al-4V alloy which has a yield strength of upto 1000 MPa and excellent bending capabilities

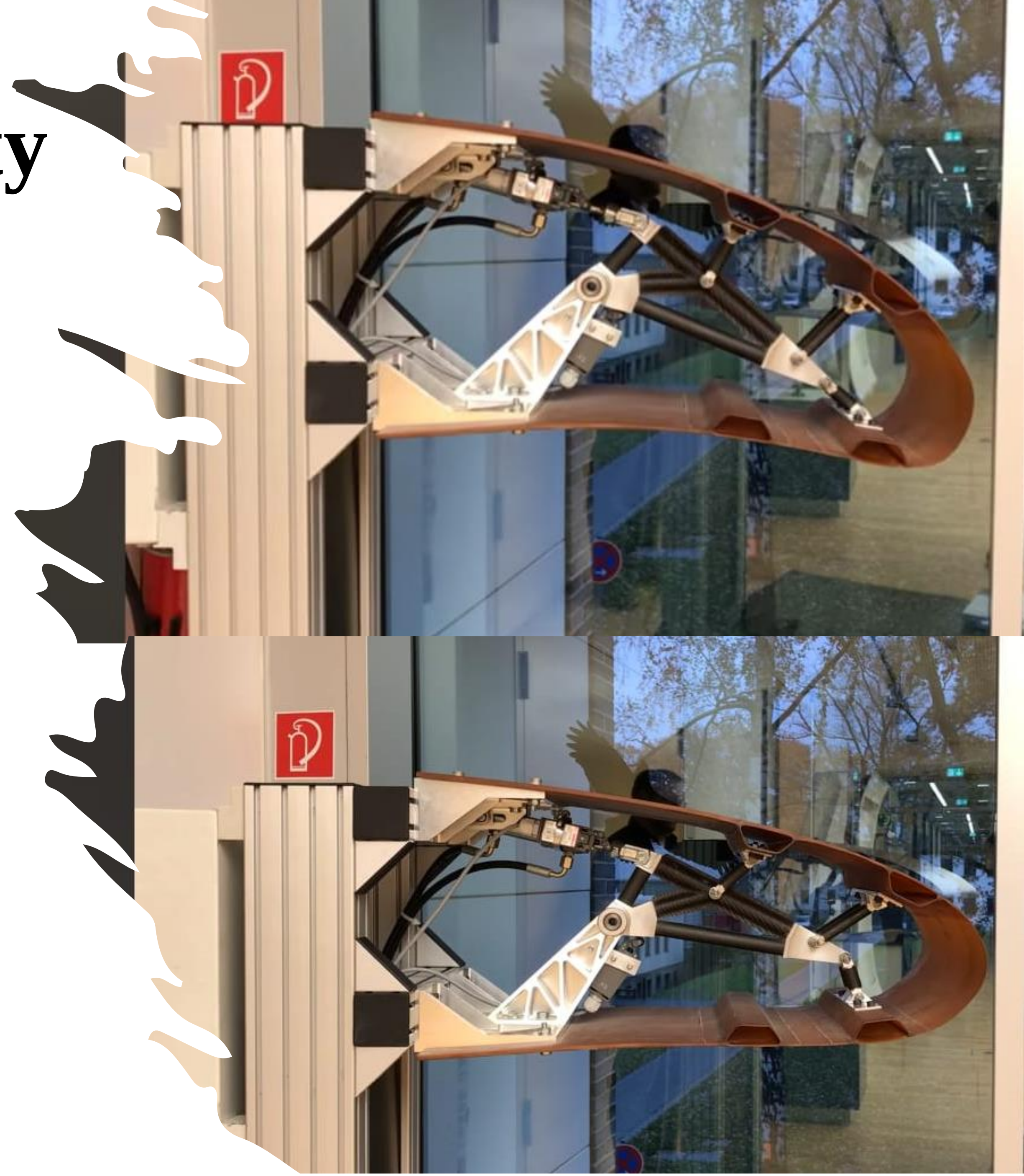


Fig. 3.1 : Pneumatic morphic wing

- First approach is to mount on **SMA strip** to surface
- Upon activation the wire would contract and cause an increase in the blade camber
- Nitinol recovers it's original shape on being heated through it's transformation temperature
- Overall transformation temperature span are about 40 to 70 Deg. C

- **Pneumatic linear actuators** are also a viable option for increasing the camber of the structure
- Actuating the first movable rib segment all the other rib segments would also rotate relative to the segment

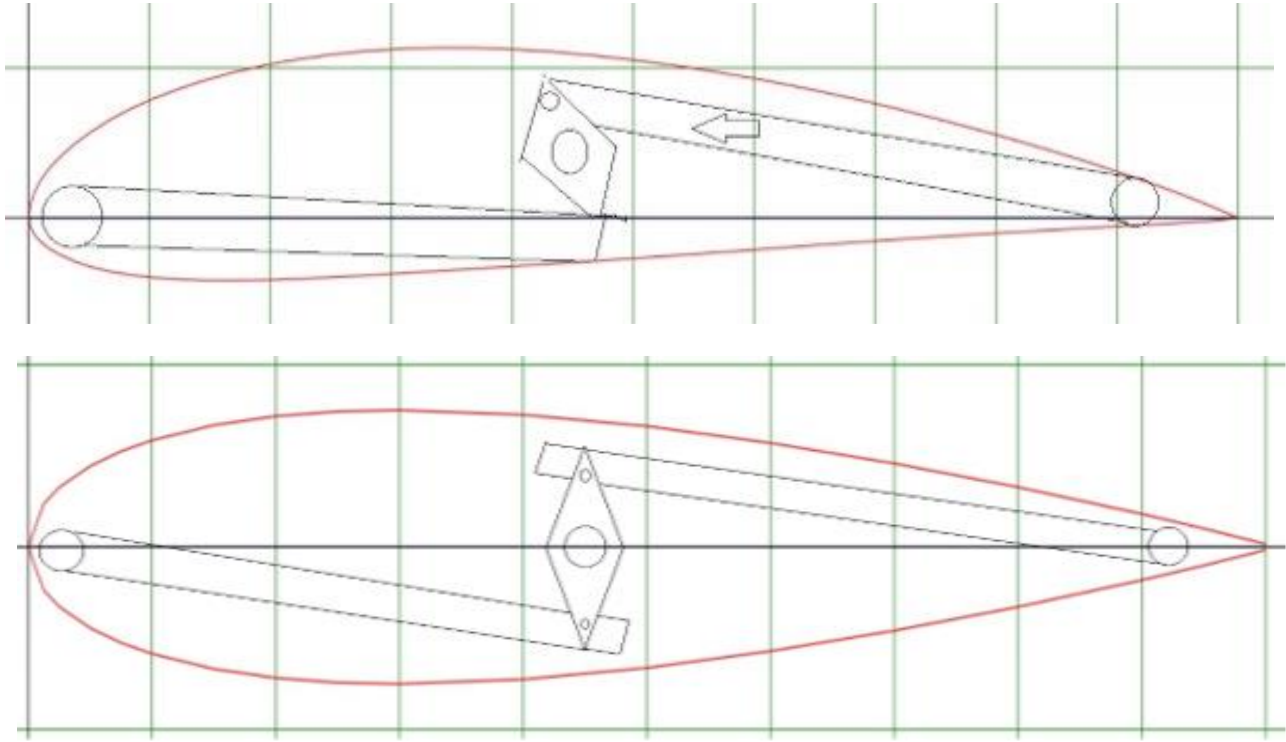


Fig. 3.2 : NACA 4415 and NACA 0015 with actuating mechanism schematic

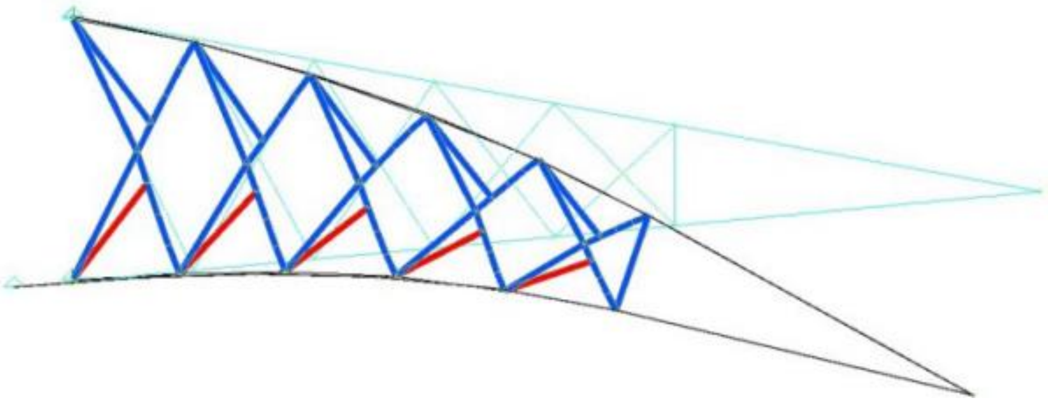


Fig. 3.3 : Pin-connected truss elements

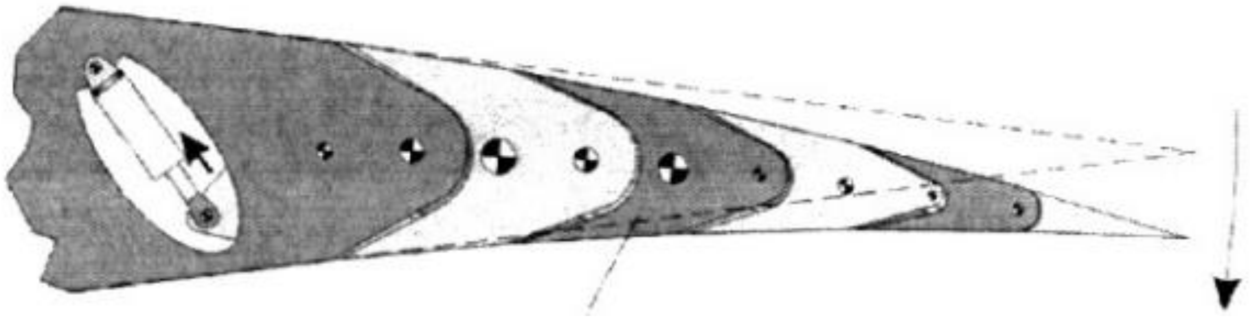


Fig. 3.4 : Movable rib with pneumatic actuator

$\emptyset$ (*Inflow Angle*)
β (*Blade angle*)
V (*Freestream Velocity*)
x_h (*Normalised Hub Radius*)
ρ(*Airflow Density*)
R (*Radius of Blade*)
d (*Flight Distance*)
ω (*Rotational Speed*)
r (*Radial Distance*)

Optimization Results from [1]

Airfoil Database (xflr5)

$$Re = \frac{\rho U_0 c}{\mu}$$

$$\lambda = \frac{V}{\Omega R}$$

$$\sigma = \frac{Bc}{2\pi R}$$

$$\alpha = \beta - \phi$$

$$U_0 = \sqrt{V^2 + (\Omega r)^2}$$

$$K_T = 2\int_{x_h}^{1} (C_l \cos\phi - C_d \sin\phi)\sigma (U_0/V)^2 \mathrm{d}x$$

$$K_Q = 2\int_{x_h}^{1} (C_l \sin\phi + C_d \cos\phi)\sigma (U_0/V)^2 x\mathrm{d}x$$

$$K_P = \frac{K_Q}{\lambda}$$

$$T = K_T \frac{1}{2}\rho\pi R^2 V^2$$

$$P = K_P \frac{1}{2}\rho\pi R^2 V^3$$

$$\eta_p = \frac{K_T}{K_P}$$

$$E_{sh} = P_{sh} \cdot t$$

$$\eta_p = \frac{TV}{P_{sh}}$$

$$E_{sh} = \frac{T \cdot V \cdot t}{\eta_p} = \frac{T \cdot d}{\eta_p}$$

$$\eta_w = K_P = \frac{P_{sh}}{P_w}$$

$$P_w = \frac{1}{2}\rho\pi R^2 V^3$$

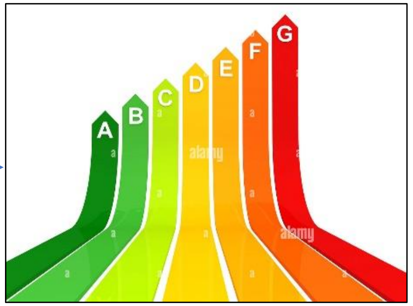
$$K_P = \eta_w = \frac{K_Q}{\lambda}$$

$$E_{sh} = P_{sh} \cdot t = \eta_w \cdot P_w \cdot t$$

Optimization Function

$$E_{tot} = E_{cl} + E_{cr} + E_w :$$

$$= \frac{T_{cl} \cdot d_{cl}}{\eta_{cl}} + \frac{T_{cr} \cdot d_{cr}}{\eta_{cr}} + \eta_w \cdot P_w \cdot t_w$$



Assumptions:

1. Same airfoil along the blade
2. V = const. in each flight phase
3. xh = 0 (xh << R)
4. Steady, Level Flight

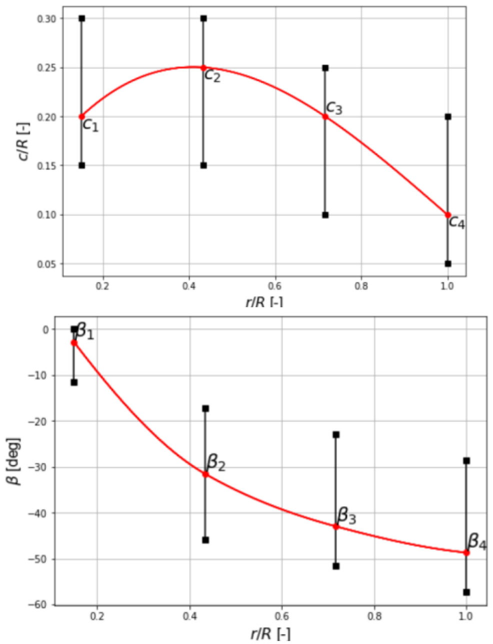


Fig 4.3 Control Points for chord/blade distributions

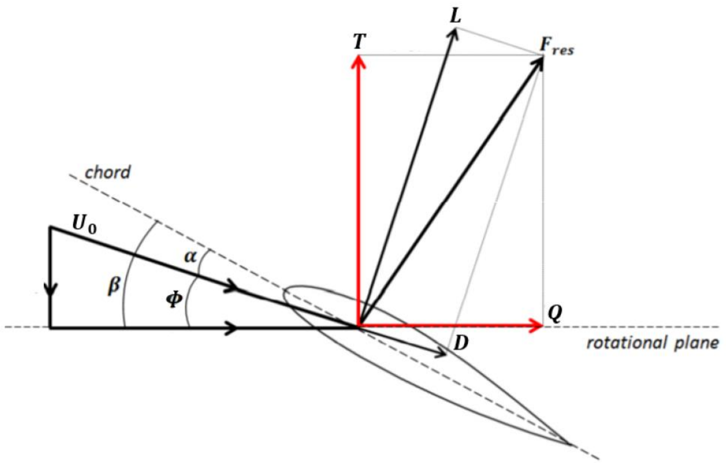


Fig 4.1 Blade Section Schematic

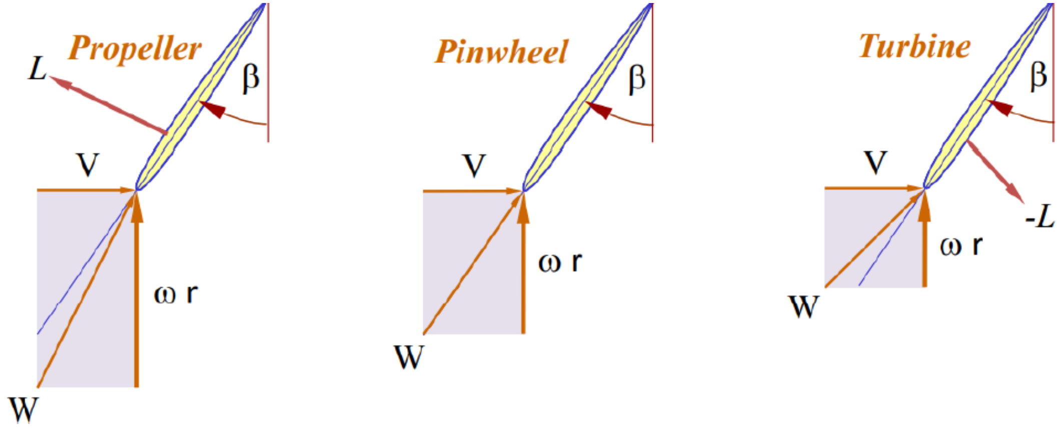


Fig 4.2 F.B.D. of Blade at different modes

Optimization Results (from [1]) for VPVR Propellor

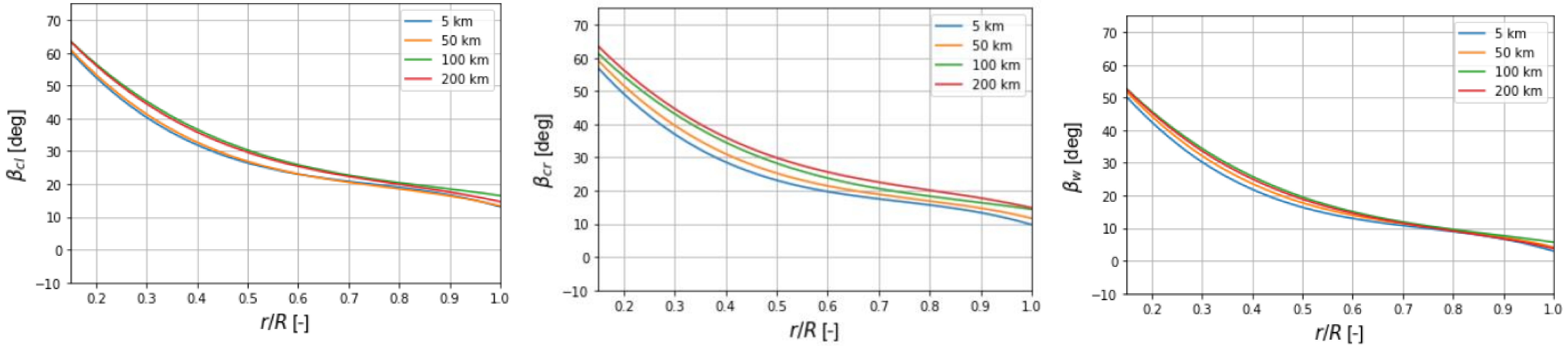


Fig 4.4 Blade Angle distributions for Climb, Cruise & Descent Phases

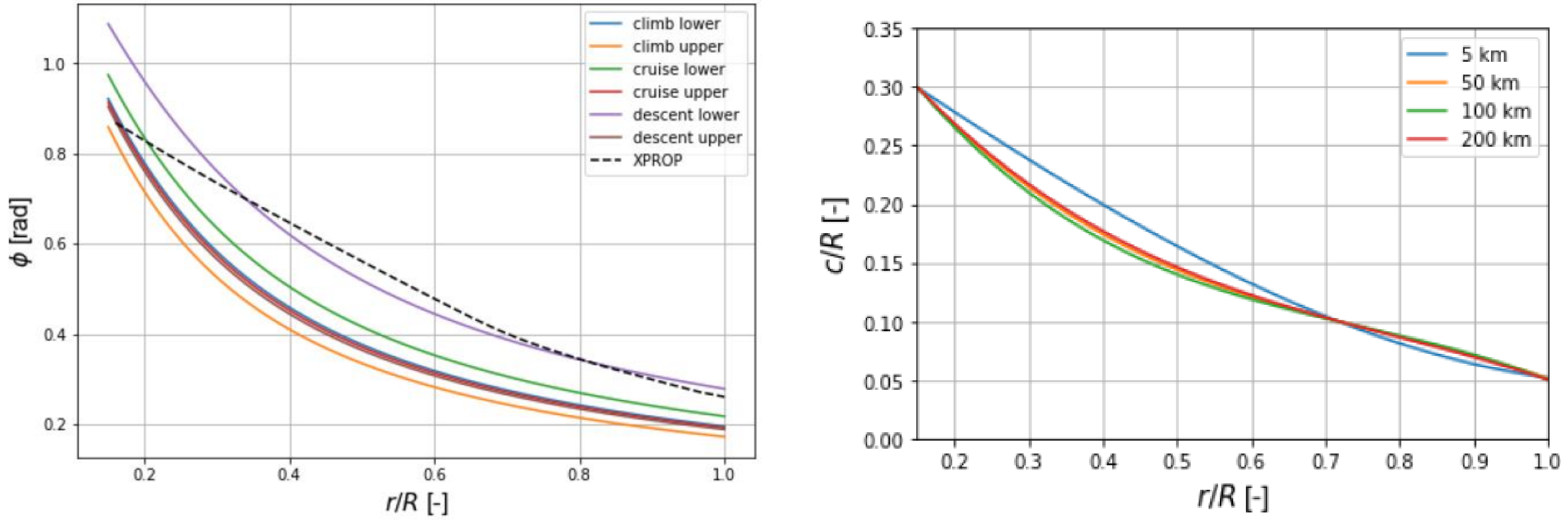


Fig 4.5 Inflow & Chord Distributions

Constraints such as:

1. $3m/s <= RDr <= 5m/s$
2. $Mdd >= U0/A$
3. $\dfrac{c_3}{c_4} - 1 > 0$
4. $\dfrac{\beta_3}{\beta_4} - 1 > 0$
5. $-20^\circ \leq \alpha \leq 20^\circ$

Etc…

```
%% Initialization
clc
clear all
E = zeros(3, 3);
cc_profile = readmatrix('cc_values.xlsx');
des_profile = readmatrix('descent_values.xlsx');
%% Energy Consumption at Climb
clc
%Input Parameters
phi = 0.19; %
beta = 20; %
V = 36; %
xh = 0;
rho = 1.056; %
R = 0.82;
d = 17000; %
omega = 200; %
r = 0.7*R;
%Calculations
phiD = rad2deg(phi);
c = 0.12*R;
U0 = sqrt(V^2 + (omega*r)^2);
l = V/(omega*R);
SR = 3*c/(2*pi*r);
AOA = round(beta - phiD);
i = find(cc_profile(:, 1)==AOA);
k = 4;
    CL = cc_profile(i, k+1);
    CD = cc_profile(i, k+7);
    f1 = 2*((CL*cos(phi) - CD*sin(phi)) * SR * (U0/V)^2);
    f2 = @(x) 2*((CL*sin(phi) + CD*cos(phi)) * SR * (U0/V)^2 *↙
x);
    K_t = f1*(1-xh);
    K_q = integral(f2, xh, 1);
    K_p = K_q/l;
```



```
    T = K_t * (0.5*rho*pi*R^2*V^2);
    n = K_t/K_p;
    Ecl = (T * d)/n;
    E(1, 2) = Ecl;
    E(1, 3) = Ecl;
%% Energy Consumption at Cruise
clc
%Input Parameters
phi = 0.21; %
beta = 22; %
V = 80; %
xh = 0;
rho = 0.905; %
R = 0.82;
d = 140000; %
omega = 200; %
r = 0.7*R;
%Calculations
phiD = rad2deg(phi);
c = 0.12*R;
U0 = sqrt(V^2 + (omega*r)^2);
l = V/(omega*R);
SR = 3*c/(2*pi*r);
AOA = round(beta - phiD);
i = find(cc_profile(:, 1)==AOA);
k = 4;
    CL = cc_profile(i, k+1);
    CD = cc_profile(i, k+7);
    f1 = 2*((CL*cos(phi) - CD*sin(phi)) * SR * (U0/V)^2);
    f2 = @(x) 2*((CL*sin(phi) + CD*cos(phi)) * SR * (U0/V)^2 *↙
x);
    K_t = f1*(1-xh);
    K_q = integral(f2, xh, 1);
    K_p = K_q/l;
    T = K_t * (0.5*rho*pi*R^2*V^2);
```

```
    n = K_t/K_p;
    Ecr = (T * d)/n;
    E(2, 2) = Ecr;
    E(2, 3) = Ecr;
%% Energy Consumption at Descent
clc
%Input Parameters
phi = 0.24; %
beta = 12; %
V = 30; %
xh = 0;
rho = 1.056; %
R = 0.82;
d = 26000; %
omega = 100; %
r = 0.7*R;
%Calculations
phiD = rad2deg(phi);
c = 0.12*R;
U0 = sqrt(V^2 + (omega*r)^2);
l = V/(omega*R);
SR = 3*c/(2*pi*r);
AOA = -5;
i = find(des_profile(:, 1)==AOA);
k = 4;
    CL = des_profile(i, k+1);
    CD = des_profile(i, k+7);
    f2 = @(x) 2*((CL*sin(phi) + CD*cos(phi)) * SR * (U0/V)^2 *↙
x);
    K_q = integral(f2, xh, 1);
    K_p = K_q/l;
    Pw = 0.5*rho*pi*R^2*V^3;
    tw = d/V;
    n = K_p;
    Ew = n*Pw*tw;
```



```
    E(3, 2) = Ew;
k = 2;
    CL = des_profile(i, k+1);
    CD = des_profile(i, k+7);
    f2 = @(x) 2*((CL*sin(phi) + CD*cos(phi)) * SR * (U0/V)^2 *↙
x);
    K_q = integral(f2, xh, 1);
    K_p = K_q/l;
    Pw = 0.5*rho*pi*R^2*V^3;
    tw = d/V;
    n = K_p;
    Ew1 = n*Pw*tw;
    E(3, 3) = Ew1;
%%
E(3, 1) = 0;
clc
names = {'No Renegeneration', 'Conventional', 'Morphing'};
bar(E', 'stacked');
set(gca, 'xticklabel', names)
legend('Climb Consumption', 'Cruise Consumption', 'Descent↙
Consumption');
%%
clc
phi = 0.24; %
beta = 12; %
AOA = round(beta - phiD)
%P1 = E(1, 1) + E(2, 1)
%P2 = E(1, 2) + E(2, 2) + E(3, 2)
```

Overall Power Consumption for CPVR & VPVR Propellors

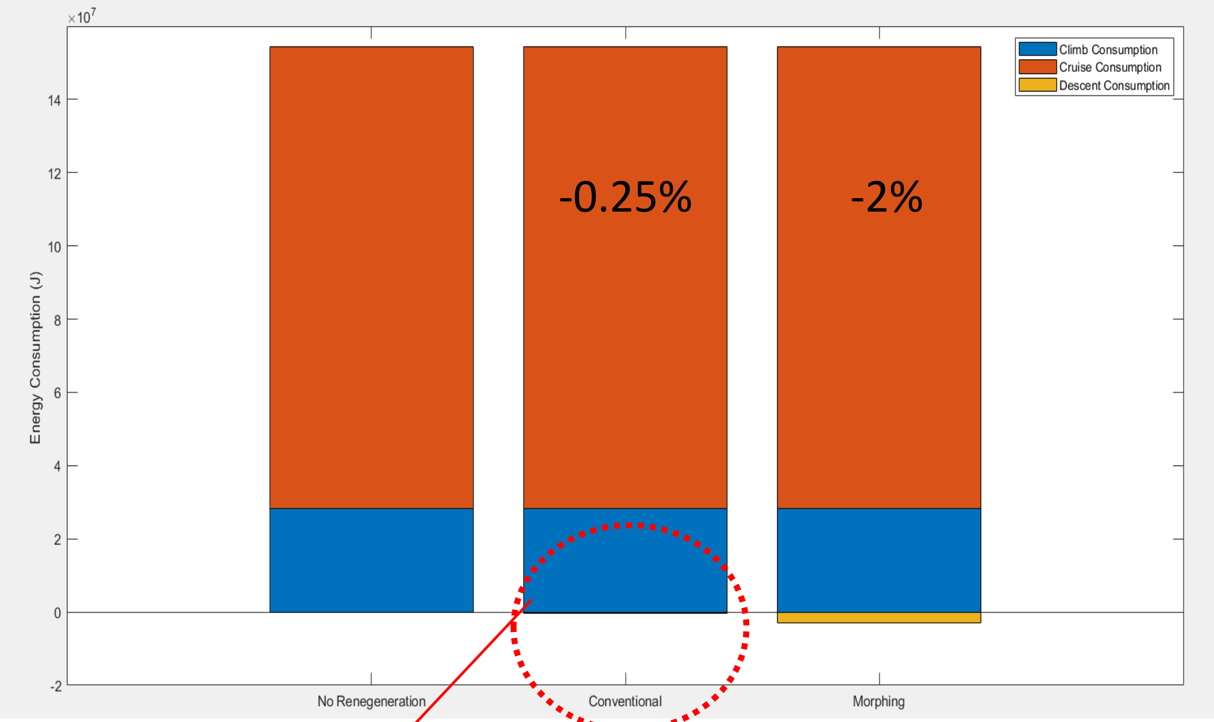


Fig 4.6 Power Consumption for CPVR propellor at r = 0.7R location

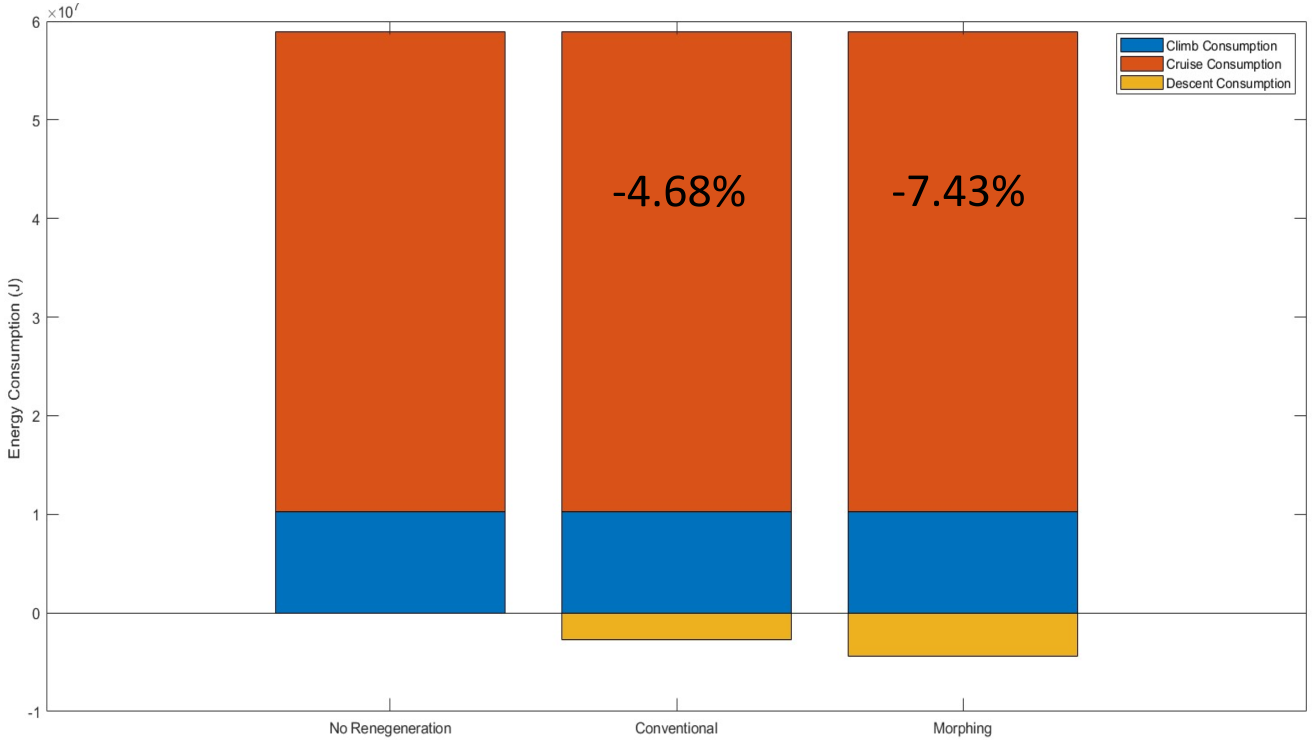


Fig 4.6 Power Consumption for VPVR propellor at r = R (tip) location

Blade Section	Conventional (with Regen.)	Morphing	Daily Savings (2 Legs)
Tip (VPVR)	-4.7 %	-7.4%	-9%, -14%
Tip (CPVR)	-0.2 %	-1.7%	-0.4%, -3.4%
0.7R (VPVR)	-0.22%	-1.56%	-0.44%, -3.12%
0.7R (CPVR)	-0.24%	-1.7%	-0.48%, -3.4%

Fig 4.7 %Savings in various cases

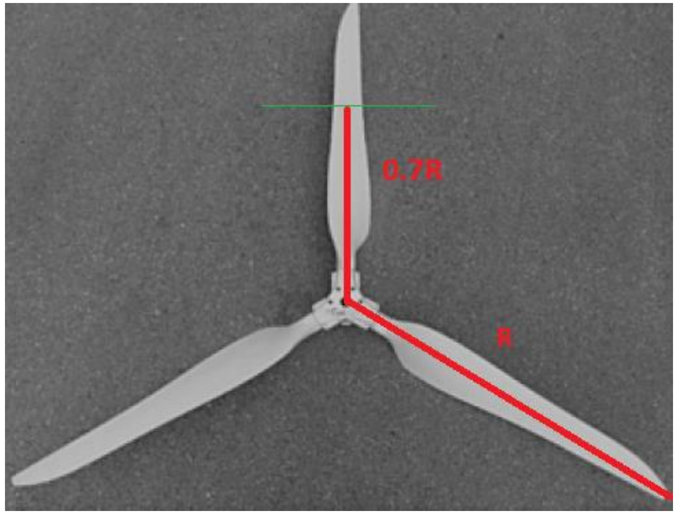


Fig 4.8 Schematic for radial distance r

Conclusions

- Proposal has been made to use the propeller in the descent phase in a windmilling mode to extract energy from the wind and store it in the battery
- An airfoil section is chosen after careful literature review and optimization algorithm
- A novel idea of morphing the propeller geometry to change the cross-section i.e. the camber of the airfoil is proposed along with a suitable blade material
- A Power Consumption study has been performed which predicts considerable power savings in the long term for regenerative propellers (conventional and morphing) compared to ones without energy recuperation capability.

References

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Abbreviations

Greek symbols

Symbol	Definition	Unit
α	Angle of attack	rad
β	Blade angle	rad
γ	Flight path angle	rad
Γ	Circulation	m^2/s
η_p	Propulsive propeller efficiency	-
η_{cl}	Propeller efficiency in climb	-
η_{cr}	Propeller efficiency in cruise	-
η_w	Propeller efficiency in descent	-
μ	Dynamic viscosity of air at 20 deg °C	kg/ms
μ	Mean of values to calculate the standard deviation	-
Ω	Propeller rotational velocity	rad/s
Ω_{cl}	Propeller rotational velocity in climb	rad/s
Ω_{cr}	Propeller rotational velocity in cruise	rad/s
Ω_w	Propeller rotational velocity in descent	rad/s
κ	Airfoil technology factor	-
λ	Wing taper ratio	-
λ	Advance ratio	-
λ_1	Trailing vortex advance ratio	-
λ_2	Trailing vortex advance ratio depending on axial wake displacement velocity	-
ϕ	Inflow angle	rad
ρ	Air density	kg/m^3
σ	Solidity factor	-
σ	Speed ratio	-
σ	Rate of energy consumption per unit of thrust	J/Ns
σ	Standard deviation	-

Subscripts

Subscript	Description
0	At the propeller plane
0	Without energy recuperation
1	At the trailing vortex system
cl	Climb condition
cr	Cruise condition
h	At the hub
p	Propulsive mode
req	Required
sh	Shaft
tot	Total
w	Regenerative mode

Roman symbols

Symbol	Description	Unit
A	Wing aspect ratio	-
a	Asymptotic radius of the source body	m
a	Speed of sound	m/s
B	Number of propeller blades	-
b	Wingspan	m
b	Distance of the plane of the propeller ahead of the nose of the nacelle	m
CR	Crossover constant for differential evolution optimisation	-
C_l	Lift coefficient	-
$C_{l,th}$	Theoretical lift coefficient	-
$C_{l,exp}$	Experimental lift coefficient	-
C_{l_p}	Propulsive lift coefficient	-
C_{l_w}	Regenerative lift coefficient	-
C_d	Drag coefficient	-
C_{D_0}	Zero-lift drag coefficient	-
c	Propeller blade chord	m
c_r	Wing root chord	m
D	Drag	N
D_{ac}	Aircraft drag	N
D_p	Propeller drag	N
D	Propeller diameter	m
d	Flight distance	m
d_{cl}	Climb flight distance	m
d_{cr}	Cruise flight distance	m
d_F	Fuselage width	m
E	Energy	J
E_{cl}	Propeller climb energy	J
E_{cr}	Propeller cruise energy	J
E_w	Propeller descent energy	J
E_{sh}	Shaft energy	J
E_{tot}	Total propeller energy	J
E_{rec}	Fraction of energy recuperated	-
e	Oswald factor	-
F	Mutation constant for differential evolution optimisation	-
F	Vortex sheet tip correction factor	-
F_{res}	Resultant aerodynamic force	N
G	Generation of vectors within the differential evolution optimisation	-
$G(x,\lambda_2,B)$	Goldstein circulation function	-
h	Ratio between the linear vortex sheet pitch and the number of blades	m
h_{cr}	Cruise altitude	m
J	Propeller advance ratio	-
K_T	Thrust coefficient	-
K_Q	Torque coefficient	-
K_P	Power coefficient	-
L	Lift	N
M	Mach number	-
M_{DD}	Drag divergence Mach number	-
N	Number of blade elements	-
N	Number of runs to calculate the standard deviation	-
NP	Population size for differential evolution optimisation	-
n	Revolutions per second	rev/s
P	Propeller power	W
P	Linear vortex sheet pitch	m
P_{sh}	Shaft power	W
P_{max}	Maximum motor power	W
P_w	Regenerative propeller power	W
R	Propeller radius	m
R_1	Trailing vortex radius	m
Re	Reynolds number	-
r	General propeller radial coordinate	m
r_h	Hub radius	m
S	Wing surface area	m^2
T	Propeller thrust	N
T_{cl}	Propeller climb thrust	N
T_{cr}	Propeller cruise thrust	N
T_w	Propeller descent thrust	N
t	Flight time	s
t	Airfoil thickness	m
t_w	Time to descent	s
Q	Propeller torque	N
$\vec{u}_i$	Trial vector	-
u_g	Tangential induced velocity	m/s
$\bar{u}_g$	Normilised tangential induced velocity	-
u_z	Axial induced velocity	m/s
$\bar{u}_z$	Normilised axial induced velocity	-
u_{zN}	Axial velocity contribution of the nacelle	m/s
$\bar{u}_{zN}$	Normilised axial velocity contribution of the nacelle	-
U_0	Resultant velocity at a blade element	m/s
V	Aircraft flight velocity	m/s
V_{cl}	Aircraft climb velocity	m/s
V_{cr}	Aircraft cruise velocity	m/s
V_w	Aircraft descent velocity	m/s
$\vec{v}_i$	Mutation vector	-
w	Axial wake displacement velocity	-
$\bar{w}$	Normilised axial wake displacement velocity	-
W	Aircraft weight	N
x	Normilised radial coordinate at the propeller	-
x_h	Normilised hub radius	-
x_i	Design variable from design vector	-
x_1	Normilised radial coordinate on the trailing vortex system	-
$\vec{x}$	Design vector	-
$\vec{x}_{opt}$	Optimised design vector	-

Acronyms

Abbreviation	Description
RC	Rate of climb
ROD	Rate of descent
RPM	Revolutions per minute
CPVR	Constant pitch, variable RPM
VPCR	Variable pitch, constant RPM
VPVR	Variable pitch, variable RPM

THANK YOU!