Universität Stuttgart
Institute of Aerodynamics and Gas Dynamics

Relying on Dynamically Morphing Blades to Increase the Efficiency of a Cycloidal Rotor

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Introduction - Cycloidal Rotor

What is a cycloidal rotor?

- A rotating wing system
- The rotation axis is parallel to the span

The advantages:

- Provide 360° thrust forces
- Maintain constant flow velocities
- Achieve higher aerodynamic efficiency

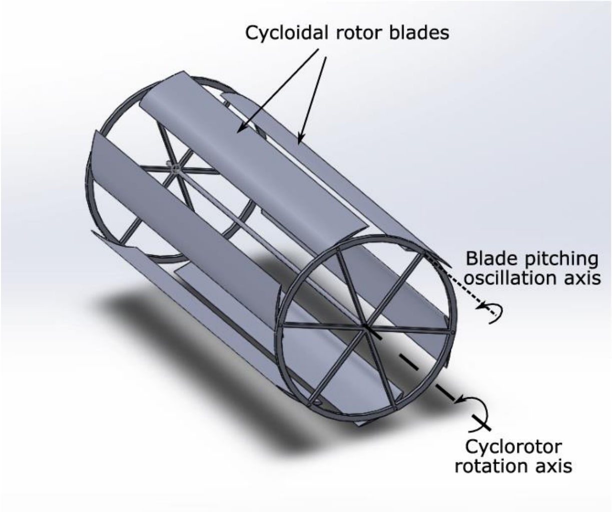


Fig: Schematic of a cycloidal rotor system [1]

[1] F. Rodrigues, M. Habibnia, and J. Páscoa, “Novel propulsion system for VTOL aircraft based on cycloidal rotors coupled with wings,” 07 2020.

Introduction - Project Description

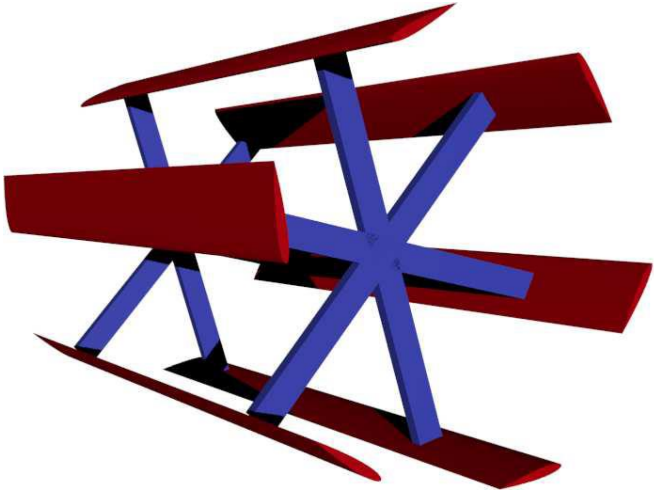


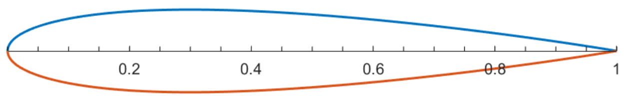
Fig: Example of a cycloidal rotor system [2]

- **Theme**: improve the aerodynamic performance of the cycloidal rotor by utilizing dynamically morphing blades in a CFD model.
- **Objective**: achieve improvements in efficiency by tuning morphing control.

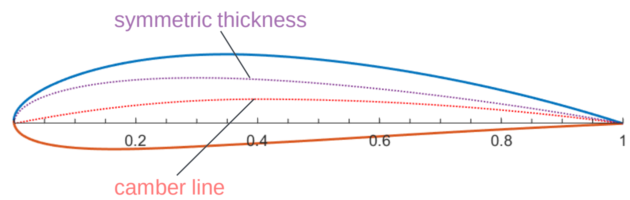
[2] L. Gagnon, G. Quaranta, M. Morandini, and P. Masarati, “Cycloidal rotor aerodynamic and aeroelastic analysis,” 10 2014.

Camber Concepts - NACA Airfoils[3]

Symmetric NACA airfoils:



Cambered NACA airfoils:



Half thickness at a certain location x:

- $y_t = 5t[0.2969\sqrt{x} - 0.1260x - 0.3516x^2 +$

Camber line function:

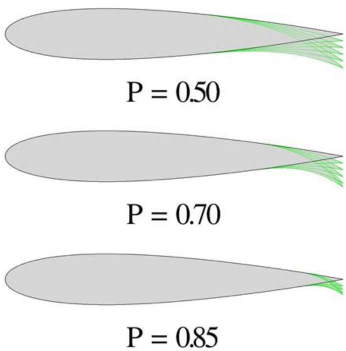
- $y_c = \begin{cases} \frac{m}{p^2}(2px - x^2), & 0 \leq x \leq p, \\ \frac{m}{(1-p)^2}((1-2p) + 2px - x^2), & p \leq x \leq 1. \end{cases}$

- $x_U = x - y_t \sin\theta, \quad y_U = y_c + y_t \cos\theta\,,$
  $x_L = x + y_t \sin\theta, \quad y_L = y_c - y_t \cos\theta\,.$

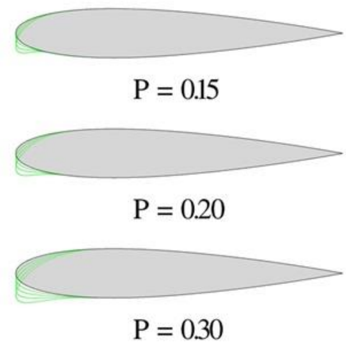
[3] NACA airfoil - Wikipedia

Camber Concepts – Trailing/ Leading Edge Deformation

Trailing edge camber morphing:



Leading edge camber morphing:



Camber line function[4]:

- $$y_c = \begin{cases} 0, & 0 \le x < p, \\ \frac{-m}{(1-p)^3}(x-p)^3, & p \le x \le 1. \end{cases}$$
- p: *start position of TE camber*

Camber line function:

- $$y_c = \begin{cases} \frac{m}{p^3}(p-x)^3, & 0 \le x < p, \\ 0, & p \le x \le 1. \end{cases}$$
- p: *end position of LE camber*

[4] B. K. Woods, J. H. Fincham, and M. I. Friswell, “Aerodynamic modelling of the fish bone active camber morphing concept,” in Proceedings of the RAeS Applied Aerodynamics Conference, Bristol, UK, vol. 2224, 2014.

Case Description

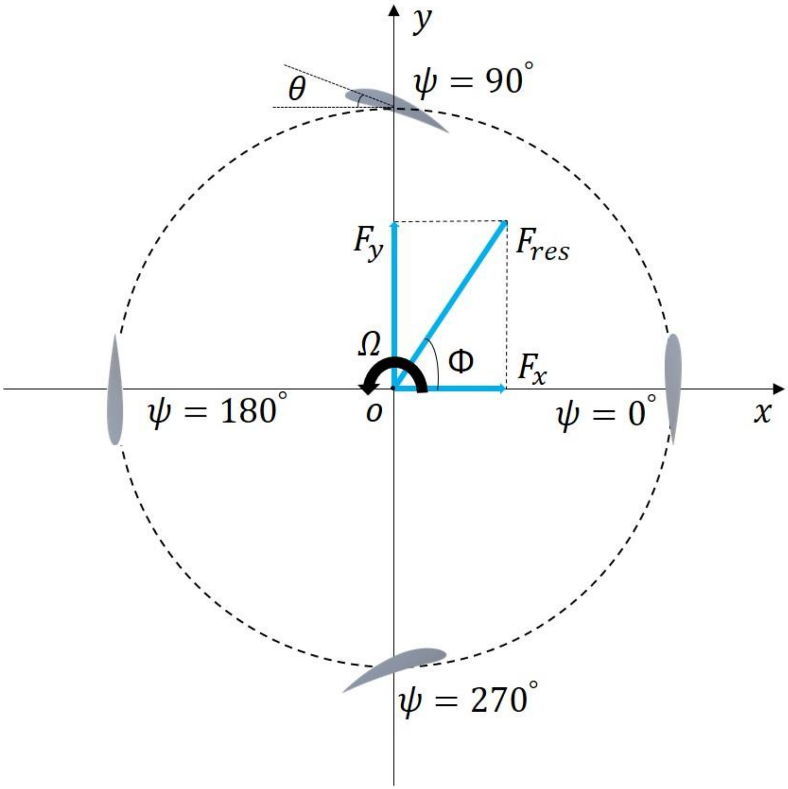


Fig: Definition of coordinate system and parameters

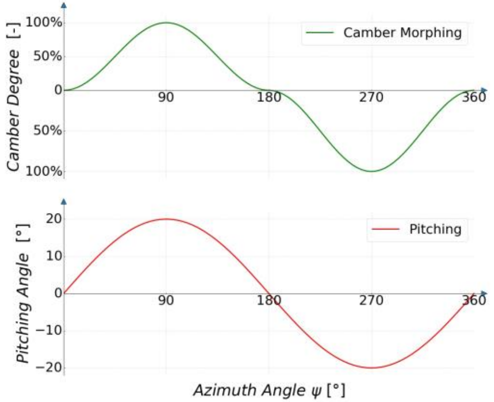
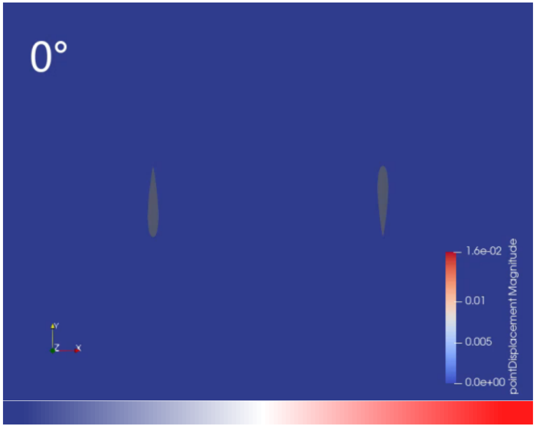


Fig: Periodical pitching and camber morphing



Grid Generation

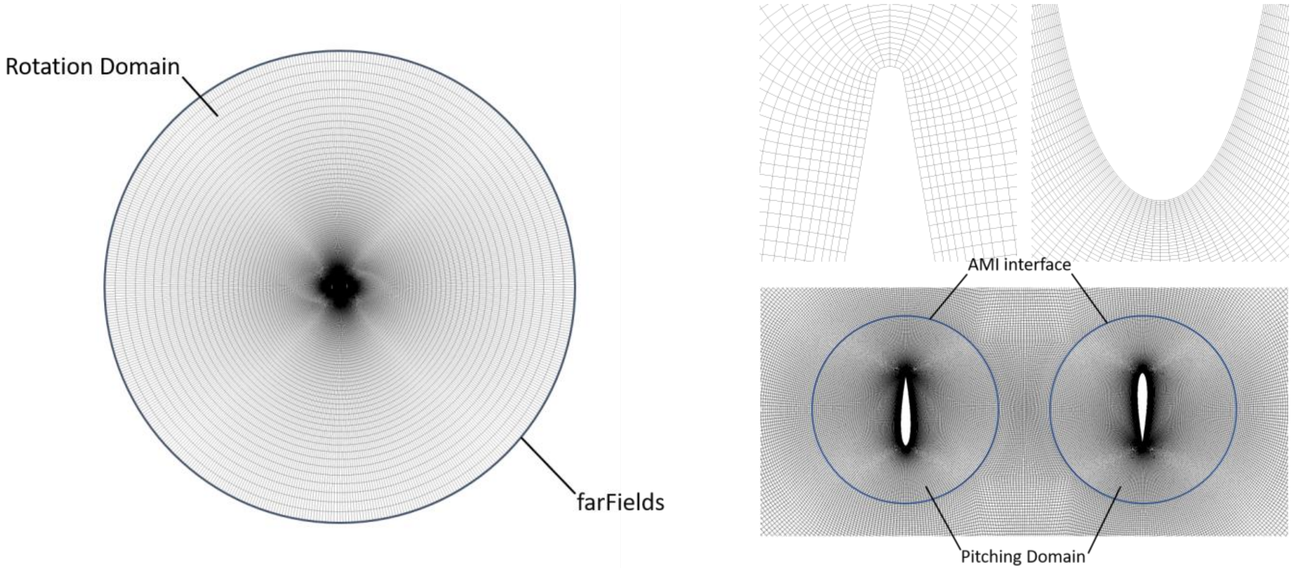


Fig. Mesh topology for the rotor system

Simulation type	$2D\ URANS$	Turbulence modelling	$\boldsymbol{k-\omega-SST}$
Baseline Case	$NACA0015$	Cell Count	$123{,}408$
Number of Blades	2	y^+ Value	< 8
Chord Length	$0.2\ m$	Reynolds Number	$72{,}000$
Blades Span	$0.8\ m$	Courant Number	$(1{,}2)$
Rotational Speed	$17.453\ rad/s$	Pitching Axis	50% of the chord

Tab. Parameters of rotor system in simulations

Aerodynamic Properties

- Thickness Ratio: $\mu = \frac{blade\ span}{actual\ thickness} = \frac{b}{\Delta z}$

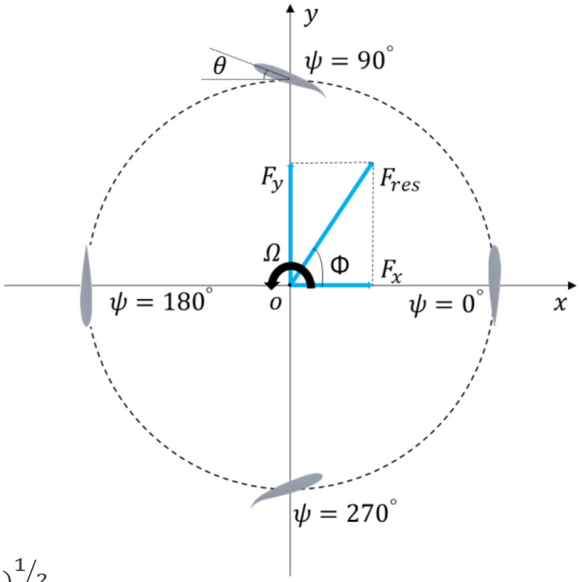
- Resulting Thrust: $F_{res} = \mu \sqrt{{F_x}^2 + {F_y}^2}$

- Thurst Angle: $\Phi = \tan^{-1} \frac{F_y}{F_x}$

- Required Power: $P = \mu M_Z \Omega$

- Power Loading: $E = \frac{F_{res}}{P} = \frac{\mu({F_x}^2 + {F_y}^2)^{1/2}}{\mu M_Z \Omega} = \frac{({F_x}^2 + {F_y}^2)^{1/2}}{M_Z \Omega}$

- Figure of Merit: $FM = \frac{P_{idea}}{P} = \frac{{F_{res}}^{3/2}}{\mu M_Z \Omega (2\rho A)^{1/2}} = \frac{\mu^{3/2}({F_x}^2 + {F_y}^2)^{3/4}}{\mu M_Z \Omega (4\rho R b)^{1/2}} = \frac{({F_x}^2 + {F_y}^2)^{3/4}}{M_Z \Omega (4\rho R \Delta z)^{1/2}}$



Results and Discussion – NACA Camber

Force and Power Analysis

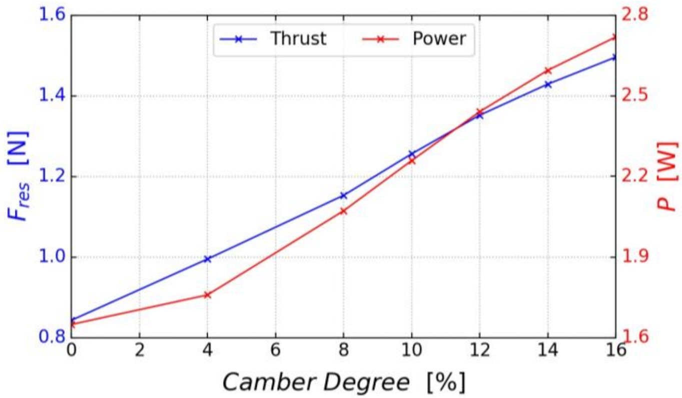


Fig: Thrust and power results, $p = 0.4$

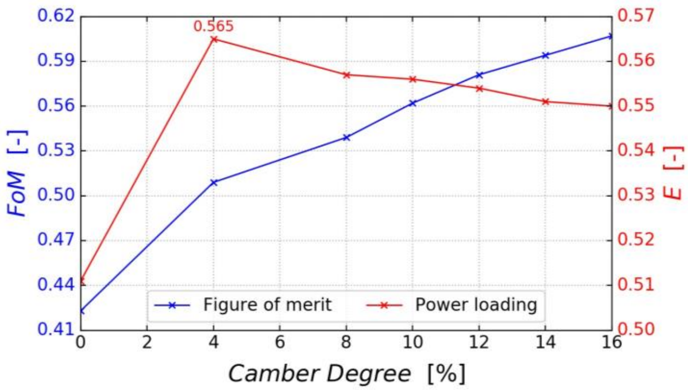
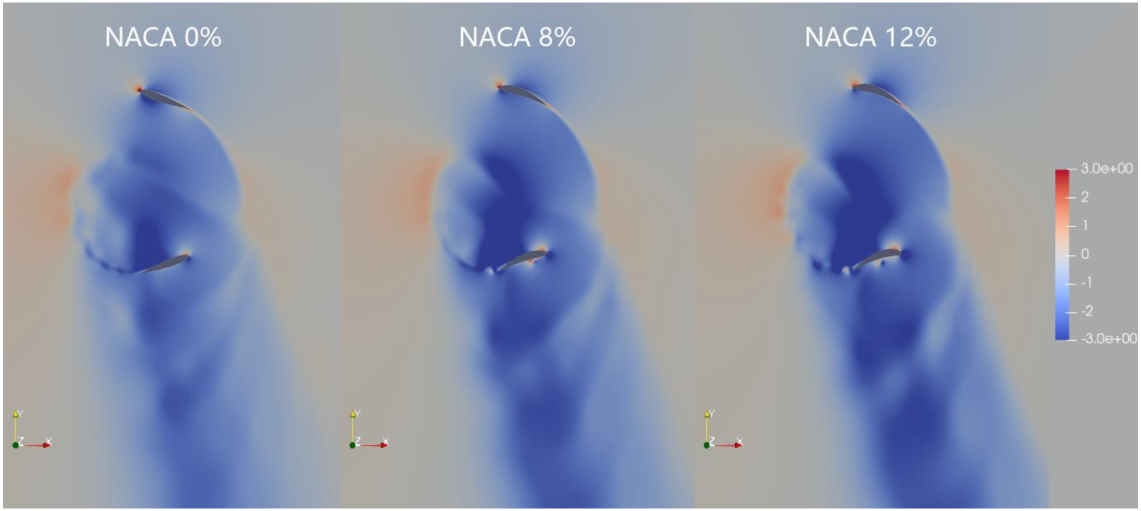


Fig: Efficiency results, $p = 0.4$

- Thrust and power increase with increasing camber degree.
- Thrust grows faster than the power.
- Power loading will decrease while figure of merit continuously increase.
- Figure of merit reaches the value of 0.61 in case of 16% camber.

Results and Discussion – NACA Camber

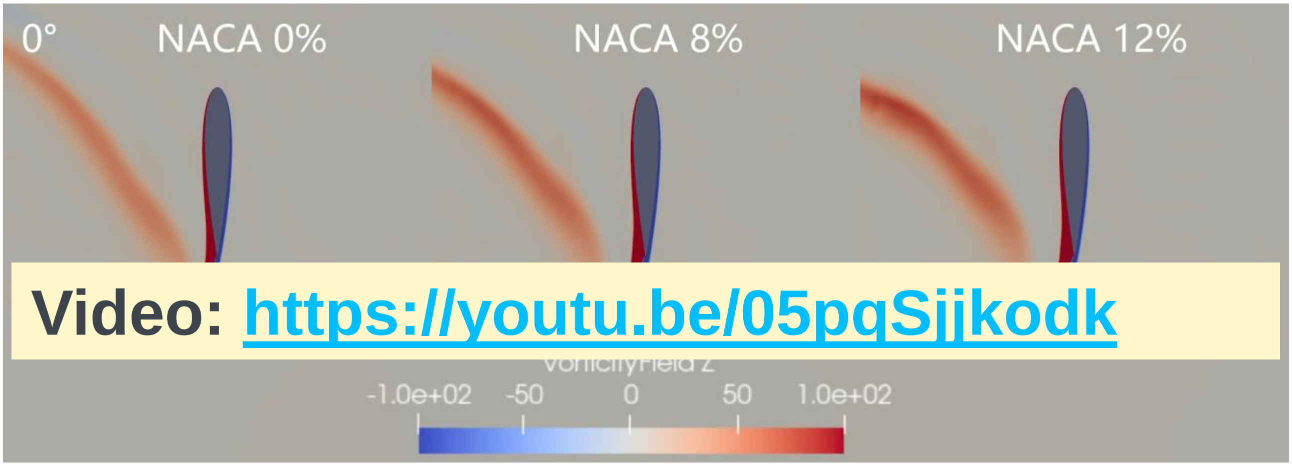
Downwash Velocity



- More intensified down-wash velocity with increasing camber degree.
- Reduction in the effective AOA and changes in inflow velocity.

Results and Discussion – NACA Camber

Vorticity Contour



Video: https://youtu.be/05pqSjjkodk

For the case with cambered NACA airfoils:

- The formation of the leading edge vortex at $\psi = 120°$ is eliminated.
- The presence of vortex at the outer side is observed near the lower end.

Results and Discussion – Leading Edge Deformation

Force and Power Analysis

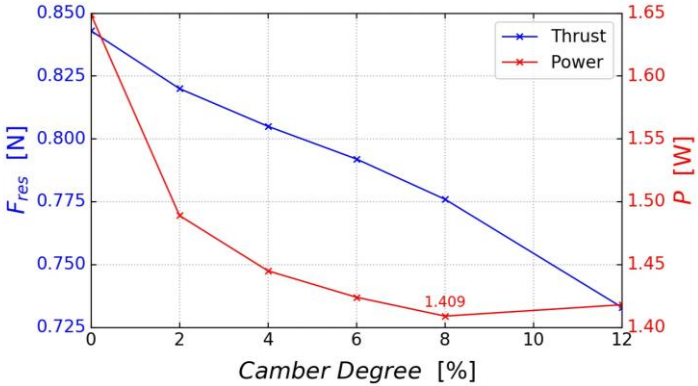


Fig: Thrust and power results, $p = 0.3$

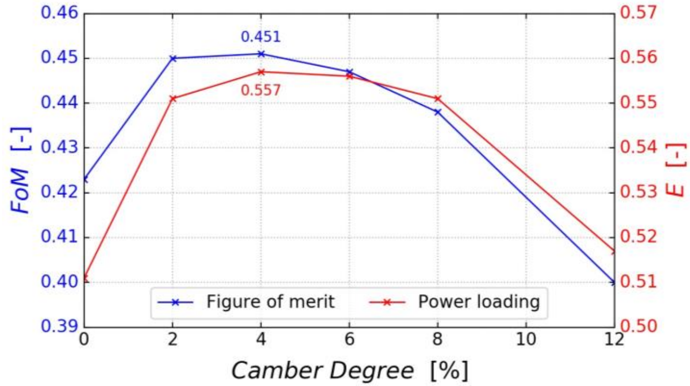


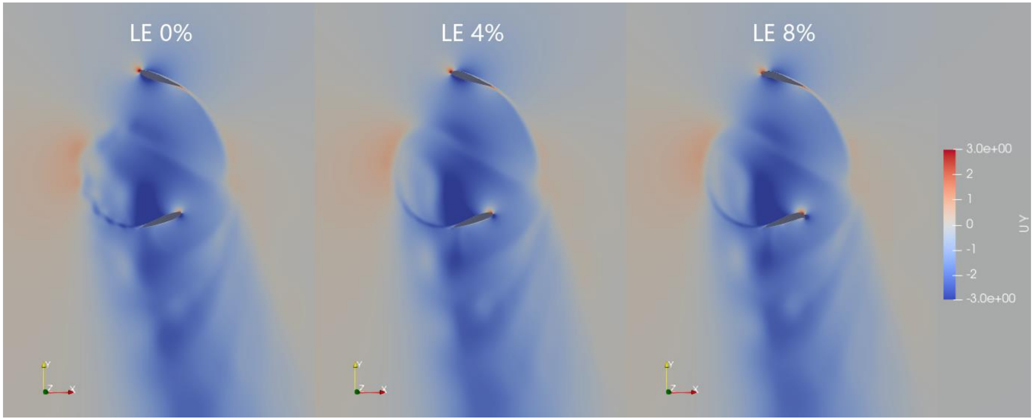
Fig: Efficiency results, $p = 0.3$

- Thrust and required power decrease with increasing camber degree.

- Slight improvements in efficiencies could be achieved when m<8%.
- Best performance in efficiency is obtained in case of 4% LE camber.

Results and Discussion – Leading Edge Deformation

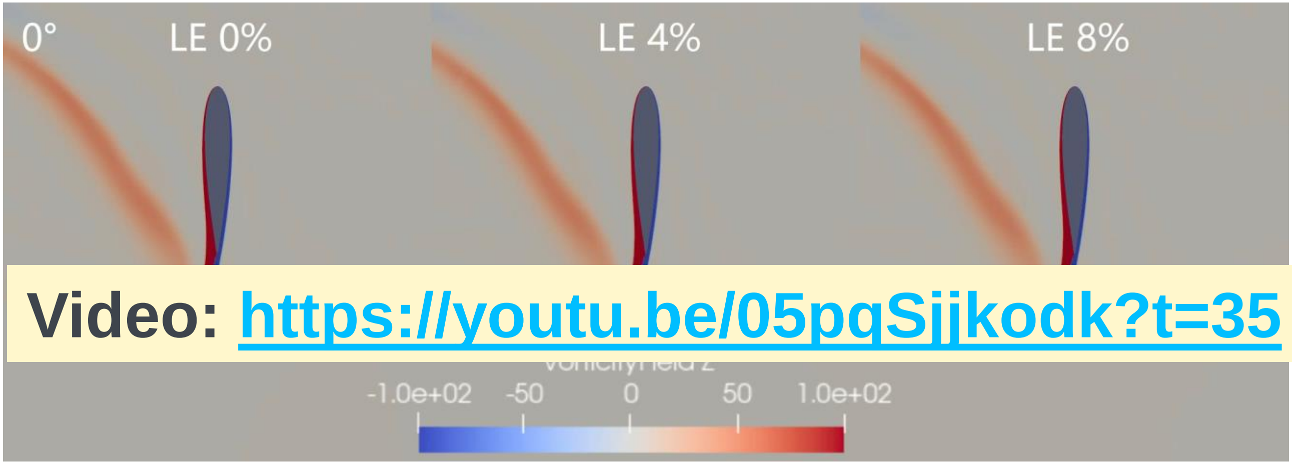
Downwash Velocity



- The thrust angle varies from 96.2° to 93.4° and 92.7°.
- No obvious change in velocity magnitude and a clockwise shift of the area affected by downwash velocity could be observed.

Results and Discussion – Leading Edge Deformation

Vorticity Contour



Video: https://youtu.be/05pqSjjkodk?t=35

For the case with cambered LE:

- The formation and development of LEV at $\psi = 120°$ is eliminated.
- No signs of vortex development or severe flow separation could be seen.

Results and Discussion – Trailling Edge Deformation

Force and Power Analysis

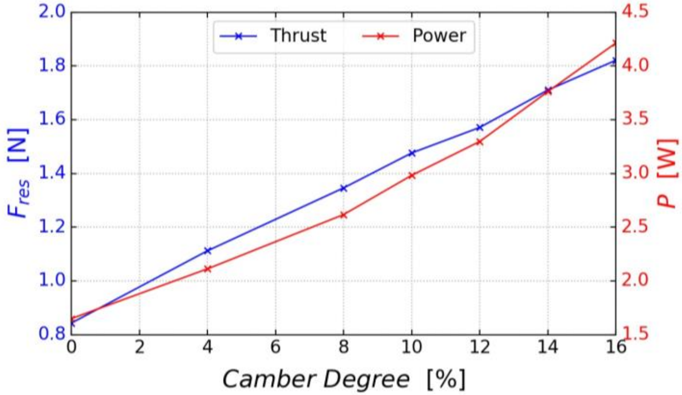


Fig: Thrust and power results, $p = 0.7$

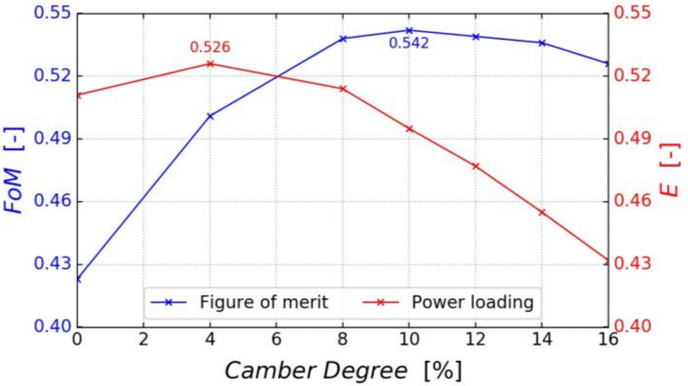


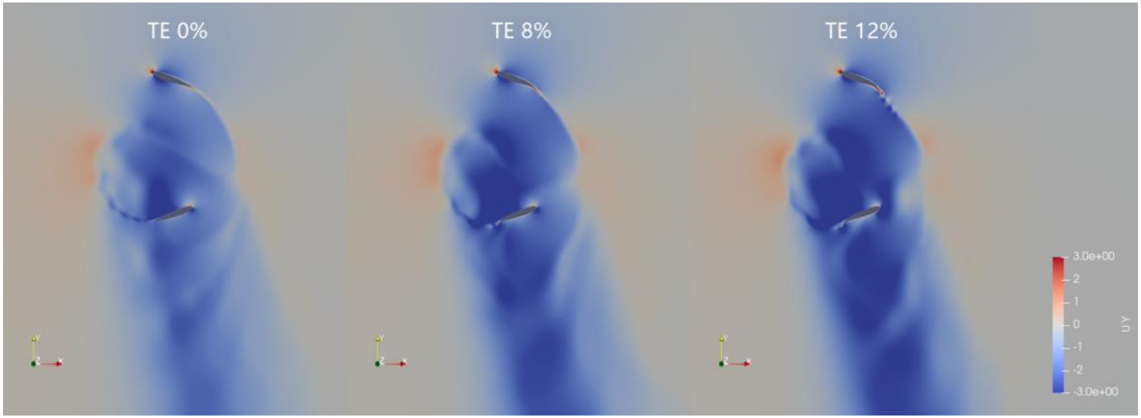
Fig: Efficiency results, $p = 0.7$

- Thrust and required power increase with increasing camber degree.
- Increment in thrust exceeds in power for the case with large camber.

- Efficiency will first increase then decrease as more camber is introduced.

Results and Discussion – Trailling Edge Deformation

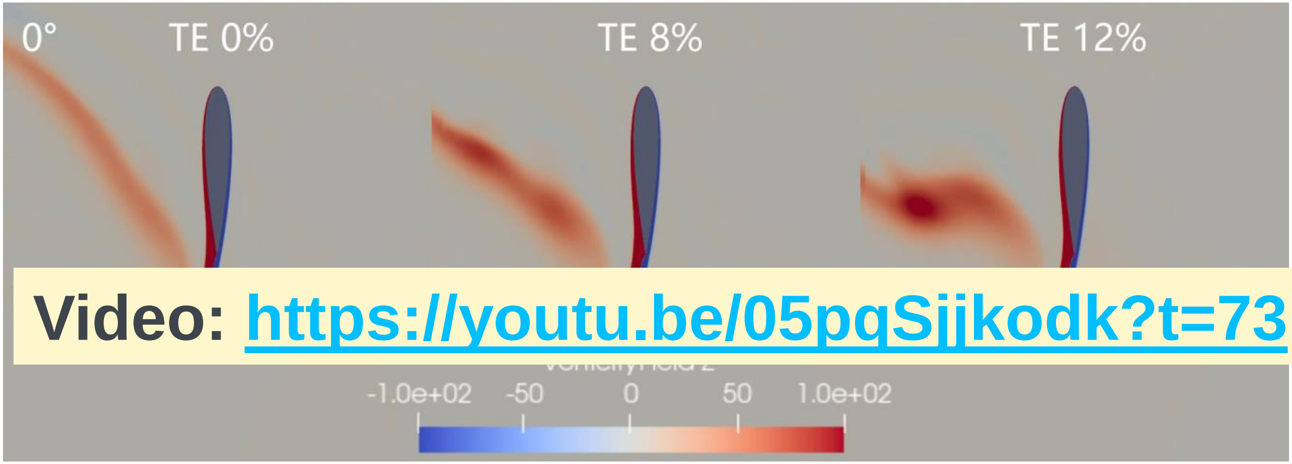
Downwash Velocity



- Intensified down-wash velocity with increasing camber degree.
- More concentrated area affected by downwash velocity.

Results and Discussion – Trailling Edge Deformation

Vorticity Contour



Video: https://youtu.be/05pqSjjkodk?t=73

For the case with cambered TE:

- The size of leading edge vortex at the upper left half is reduced.
- Vortex shedding in the wake region and the blade vortex interaction at the lower end could be observed.

Introduction

Methodology

Results and Discussion

Conclusions

Results Summary

	Resultant Thrust [N]		Thurst Angle [Deg]	Power [W]		Power Loading [N/W]		Figure of Merit [-]	
Baseline case	0.84		96.43	1.65		0.511		0.423	
NACA Camber									
$p = 0.4\ m = 4\%$	0.99	+17.9%	97.05	1.76	+6.67%	0.565	+10.7%	0.509	+20.3%
$p = 0.4\ m = 8\%$	1.15	+36.9%	99.01	2.07	+25.4%	0.556	+8.81%	0.539	+27.4%
$p = 0.4\ m = 10\%$	1.26	+50.0%	100.17	2.26	+40.0%	0.556	+8.81%	0.562	+32.9%
$p = 0.4\ m = 12\%$	1.35	+60.7%	102.23	2.44	+47.9%	0.554	+8.41%	0.581	+37.3%
$p = 0.4\ m = 14\%$	1.43	+70.2%	103.79	2.59	+55.2%	0.551	+7.83%	0.594	+40.4%
$p = 0.4\ m = 16\%$	1.50	+78.5%	105.37	2.72	+64.8%	0.550	+7.63%	0.607	+43.5%

- The highest efficiency is obtained.
- Certain promotion in local flow condition.

Results Summary

	Resultant Thrust [N]		Thurst Angle [Deg]	Power [W]		Power Loading [N/W]		Figure of Merit [-]	
Baseline case	0.84		96.43	1.65		0.511		0.423	
TE Camber									
$p = 0.7 \; m = 4\%$	1.11	+32.1%	98.42	2.11	+27.9%	0.526	+2.93%	0.501	+18.7%
$p = 0.7 \; m = 8\%$	1.35	+60.7%	100.94	2.62	+58.8%	0.514	+0.05%	0.538	+27.5%
$p = 0.7 \; m = 10\%$	1.48	+76.2%	101.00	2.98	+80.6%	0.495	-3.22%	0.542	+28.4%
$p = 0.7 \; m = 12\%$	1.57	+86.9%	101.60	3.30	+100%	0.477	-6.65%	0.539	+27.7%
$p = 0.7 \; m = 16\%$	1.71	+105%	103.42	3.76	+121%	0.455	-11.0%	0.536	+27.0%
$p = 0.7 \; m = 18\%$	1.82	+116%	104.76	4.21	+155%	0.432	-15.5%	0.526	+24.6%

- Highest value of thrust and required power.
- No obvious contribution in flow field.

Results Summary

	Resultant Thrust [N]		Thurst Angle [Deg]	Power [W]		Power Loading [N/W]		Figure of Merit [-]	
Baseline case	0.843		96.43	1.649		0.511		0.423	
LE Camber									
$p = 0.3$ $m = 2\%$	0.820	-2.73%	94.23	1.489	-9.70%	0.551	+7.83%	0.450	+6.38%
$p = 0.3$ $m = 4\%$	0.805	-4.51%	93.36	1.445	-12.3%	0.557	+9.00%	0.451	+6.62%
$p = 0.3$ $m = 6\%$	0.792	-6.05%	92.75	1.424	-13.6%	0.556	+8.81%	0.447	+5.67%
$p = 0.3$ $m = 8\%$	0.776	-7.95%	92.71	1.409	-14.6%	0.551	+7.83%	0.438	+3.55%
$p = 0.3$ $m = 12\%$	0.733	-13.0%	92.43	1.418	-14.0%	0.517	+1.17%	0.400	-5.43%

- No gain in thrust and slight improvement in efficiency.
- Optimized local flow condition.

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Questions?

Thank you for your attention!

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