Aerodynamic design of a rotary-wing micro air vehicle for flying on Mars

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retour sur innovation

Overview

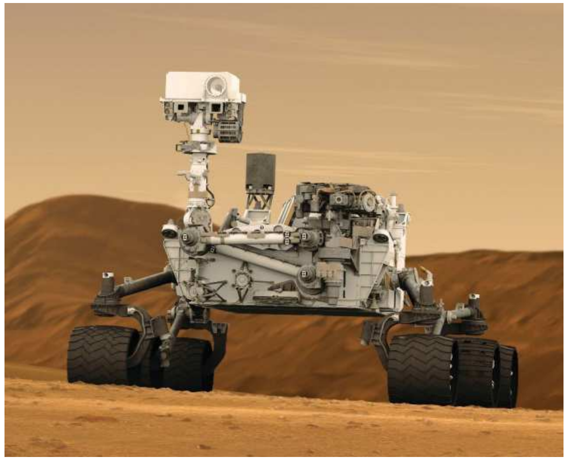
- Introduction
- General trends for flying on Mars
- Airfoil design and evaluation
- Rotor design and configurations
- Conclusions and perspectives

Introduction

- Mars exploration with rovers
  - No real time control: signal Mars ↔ Earth: 3 to 21 min.
  - Human input to analyze immediate surroundings and identifying promising targets and trajectories → low speed, short distances
  - Low accessibility: flat ground, no rocks → only plains

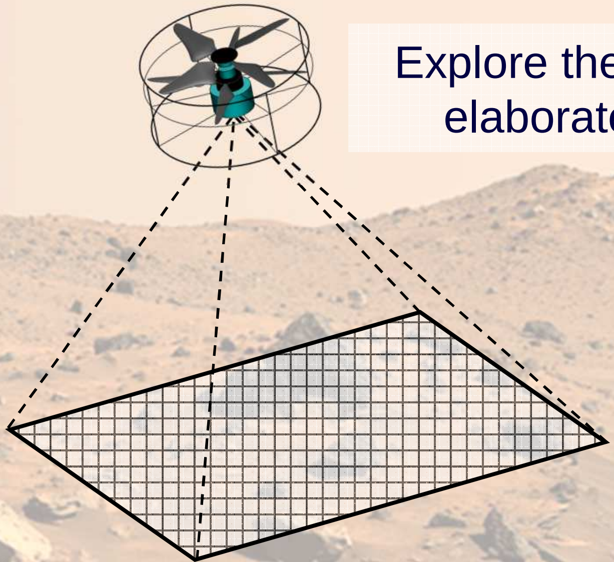
Opportunity
→ 40 km from 2004 to 2014

Curiosity
→ 10 km from 2012 to 2015

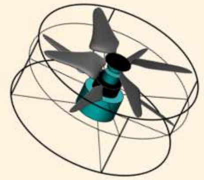


Introduction

- Interest of a micro-UAV associated to a rover

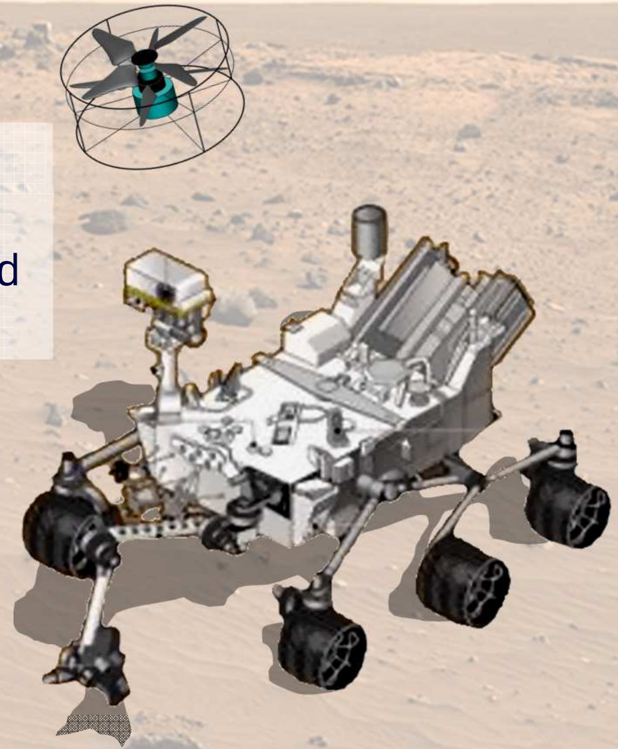


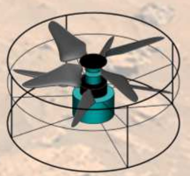
Explore the surroundings to elaborate future routes



Explore inaccessible areas (cliffs, canyons, large rocks)

Multiple take-off and landing on rover to recharge batteries and exchange data





Pick-up soil samples and get back to rover for analysis

Mars atmosphere

- Comparison Earth-Mars

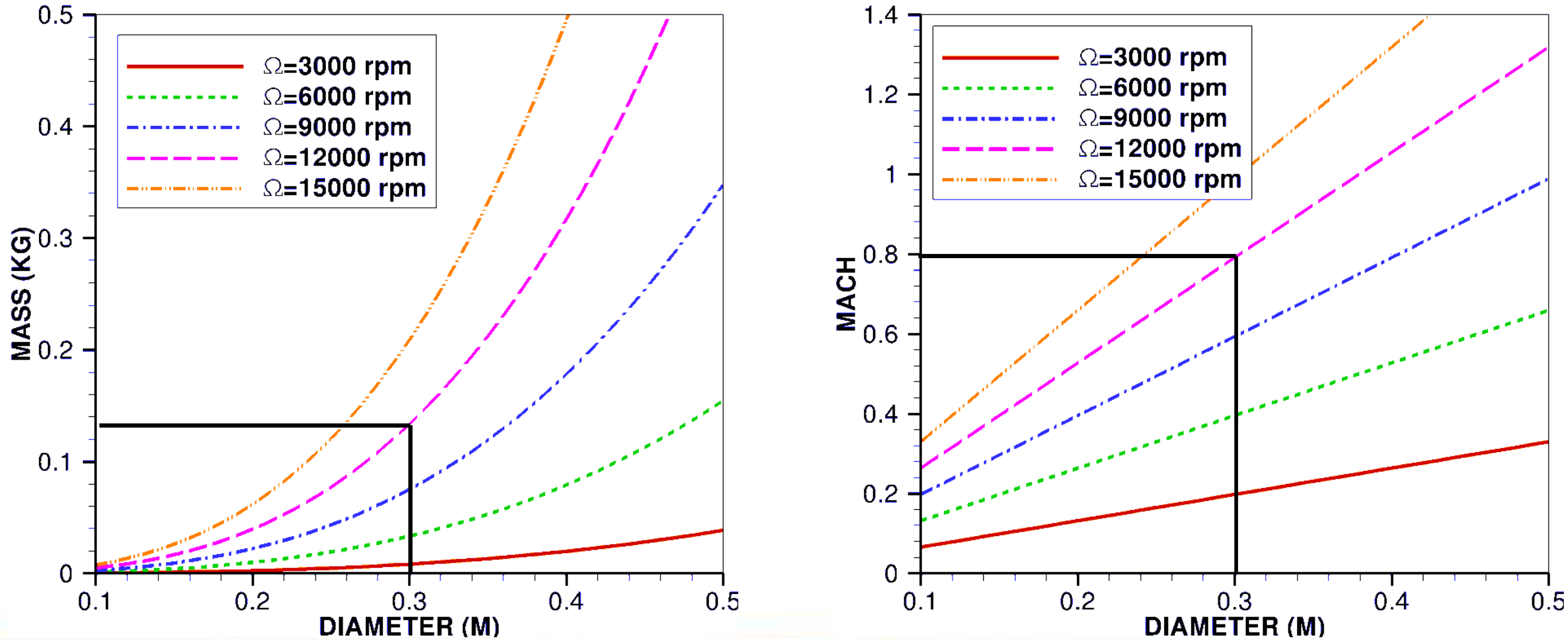
	Earth Ground level	Mars Ground level	Earth Altitude 31.5 km
Gravity (m/s^2)	9.81	3.72	9.71
Density (kg/m^3)	1.225	0.014	0.014
Dynamic viscosity (Pa.s)	$1.8\ 10^{-5}$	$1.04\ 10^{-5}$	$1.4\ 10^{-5}$
Mean temperature (K)	288	213	216
Specific heat ratio γ	1.4	1.29	1.4
Sound velocity (m/s)	340	238	295

- Other features
  - Atmospheric turbulence
  - Strong winds and dust storms
  - High pressure and temperature variation (day/night, mountains/plains)

General trends

- Use of blade element theory
  - Airfoil characteristics representative of ultra-low Re + effect of compressibility up to supersonic
  - Pitch angle adjusted for constant mean lift coefficient $C_L = 0.5$

Effect of diameter and rotational speed on lifted mass and tip Mach number

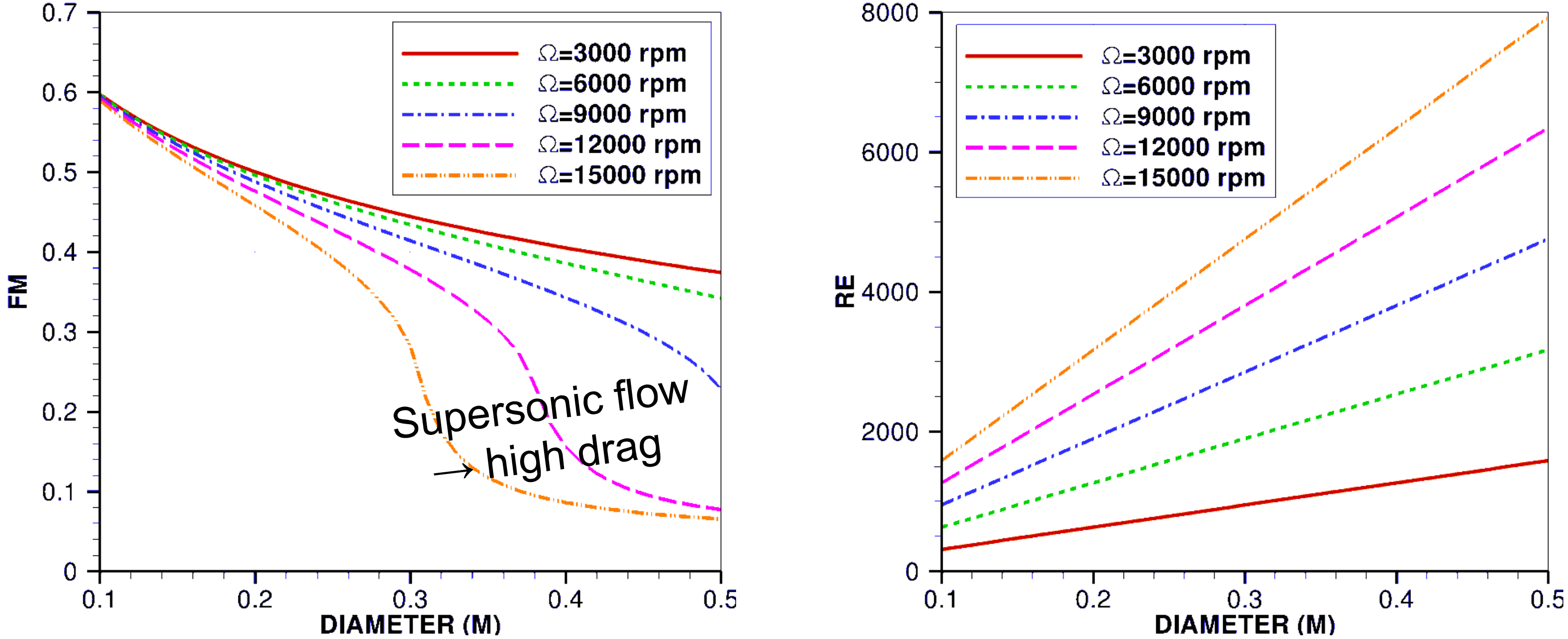


General trends

- Use of blade element theory

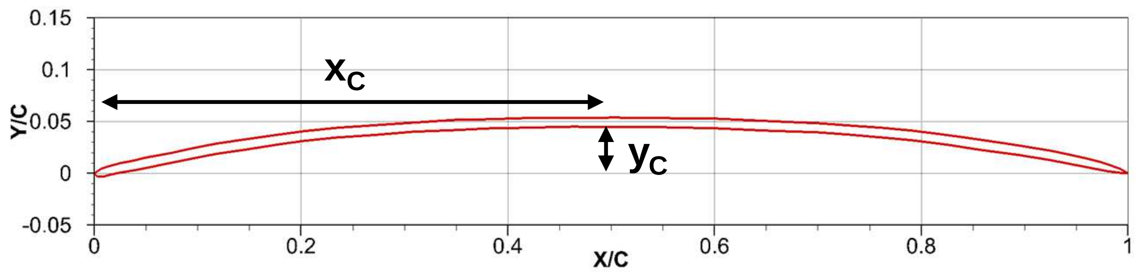
$$\text{Figure of Merit} = \frac{\text{ideal } C_P}{\text{real } C_P} \quad \text{with} \quad \text{ideal } C_P = \sqrt{\frac{C_T}{2}}$$

Effect of diameter and rotational speed on figure of merit and chord Re number

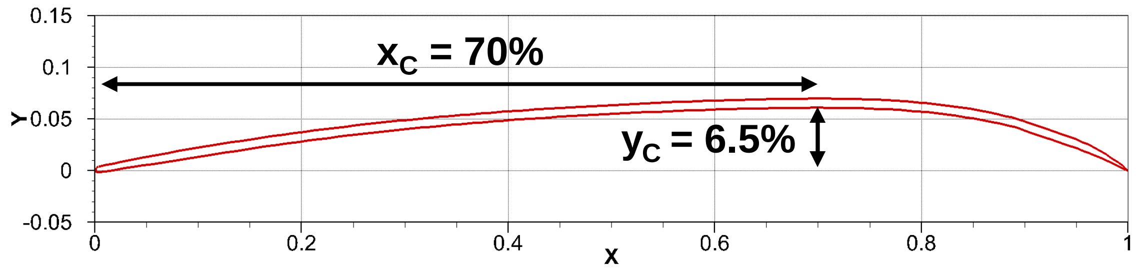


Airfoil design

- Parametric analysis with 2D aerodynamic code (XFOIL)
  - Design conditions: 4 blades, Ø = 30 cm, constant thickness t/c = 1%, lifted mass = 100 g, Re_C = 3000, M = 0.1
  - Analytical camber line with 2 parameters x_C, y_C



  - Optimum in terms of lift-to-drag ratio C_L/C_D and power efficiency $C_L^{3/2}/C_D$



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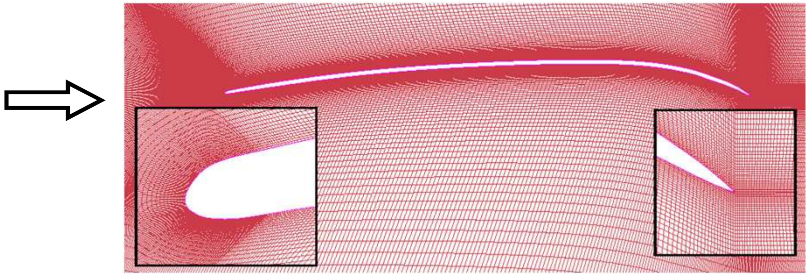
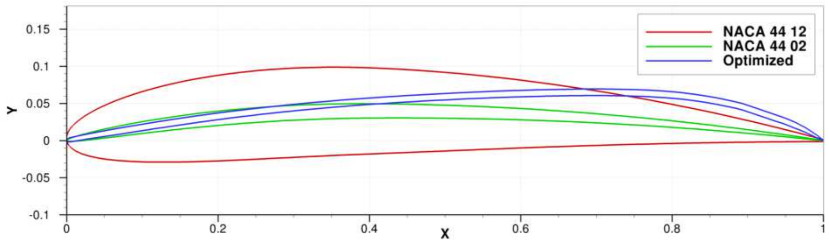
Airfoil performance

- Evaluation of optimal airfoil
  - Laminar Navier-Stokes calculations (*elsA* - ONERA) - M=0.5, Re=3000
  - Comparison with classical NACA 44 airfoils of 12% and 2% thickness

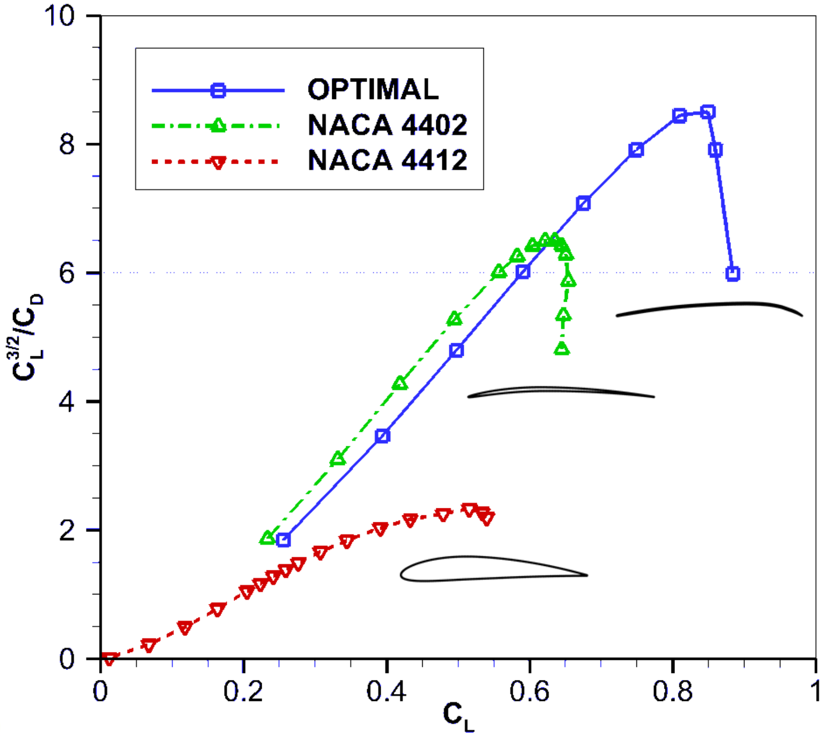
Structured grid 170000 pts



Airfoil geometries

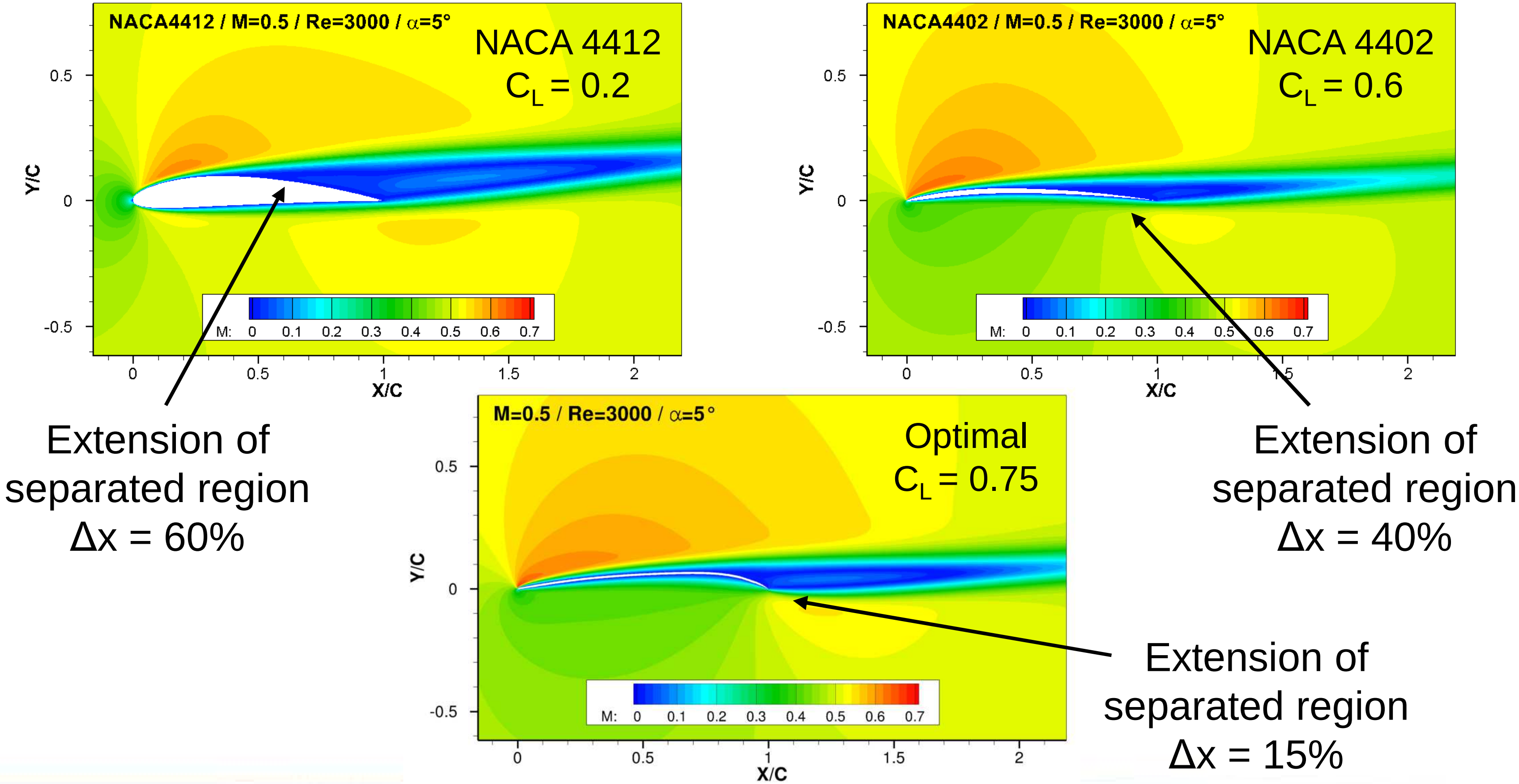


Comparison of performance: $C_L^{3/2}/C_D$ vs C_L



Airfoil performance

- Evaluation of optimal airfoil
  - Comparison of Mach field at M = 0.5, Re = 3000, same α = 5°



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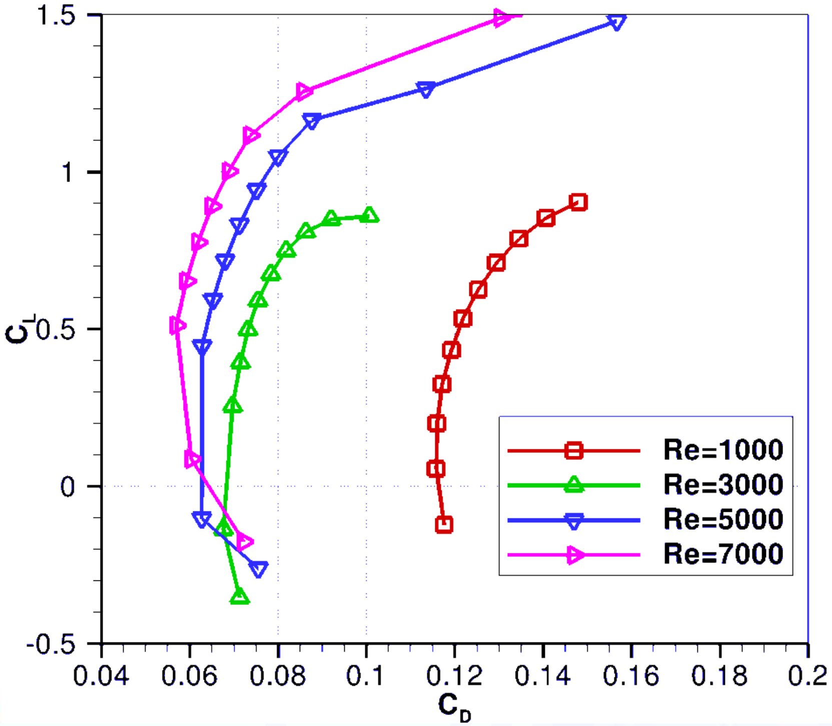
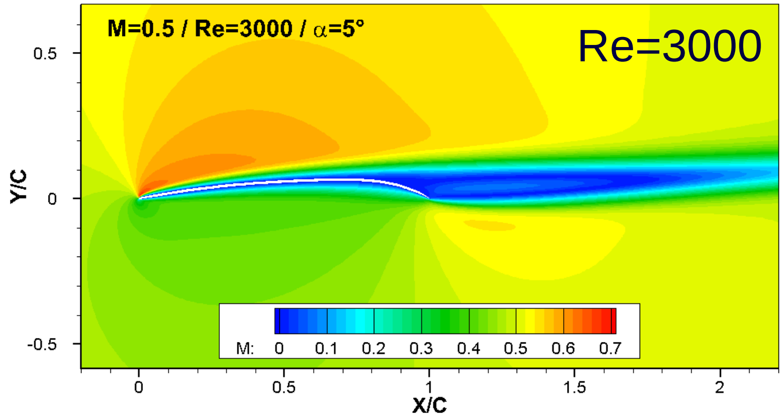
Airfoil performance

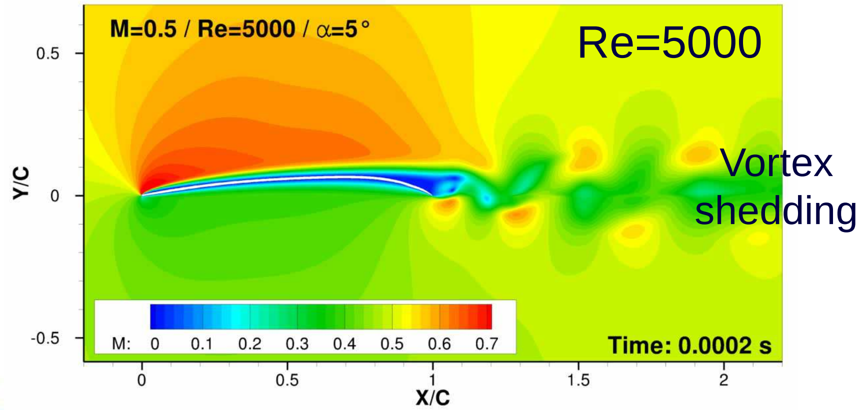
- Aerodynamic characteristics of optimal airfoil
  - Navier-Stokes computations for different M, Re and α conditions

Effect of Reynolds number on C_L,C_D at given M = 0.5



Occurrence of unsteadiness when Re increases (M = 0.5, α = 5°)

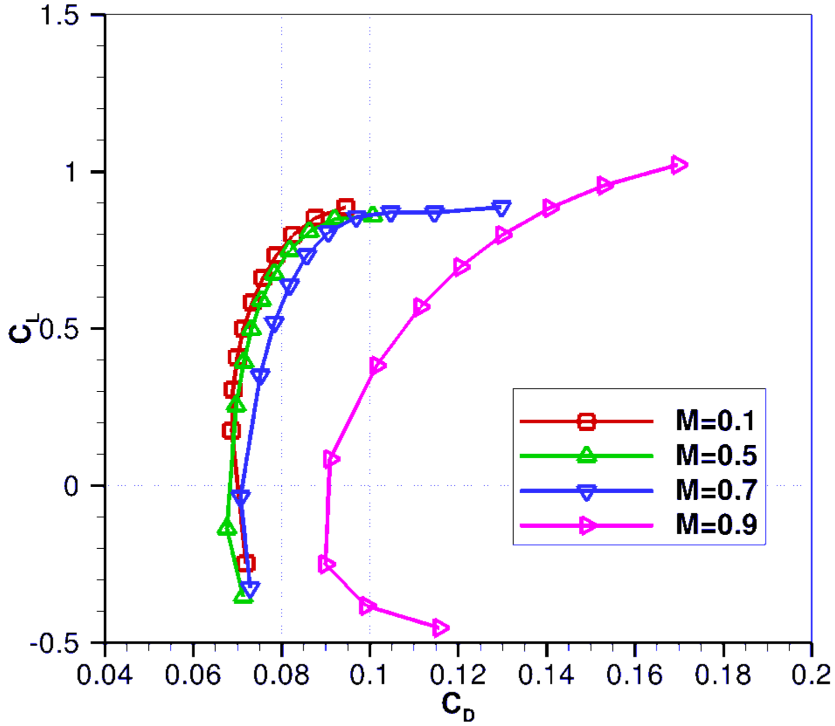




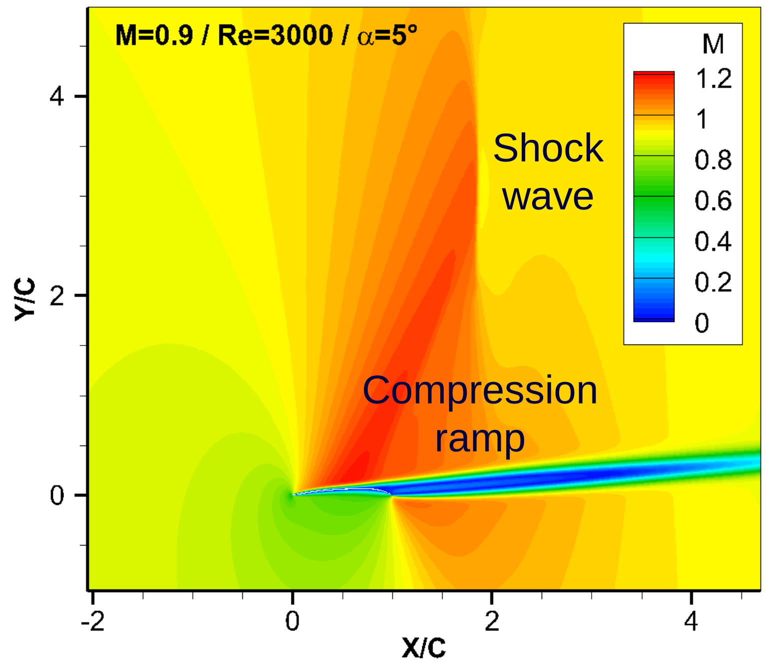
Airfoil performance

- Aerodynamic characteristics of optimal airfoil

Effect of Mach number
on C_L,C_D at given Re = 3000



Occurrence of supersonic flow
when Mach increases
(Re = 3000, α = 5°, M = 0.9)



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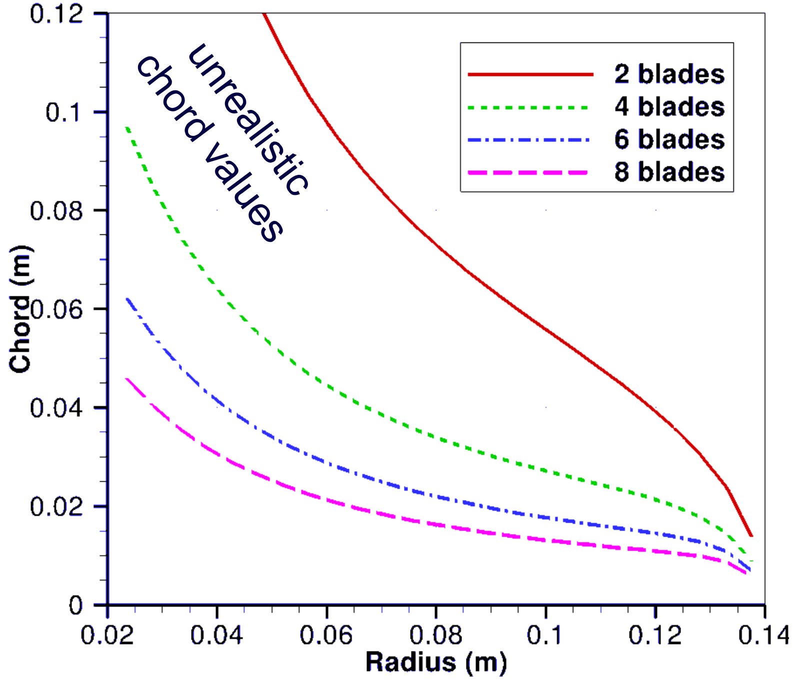
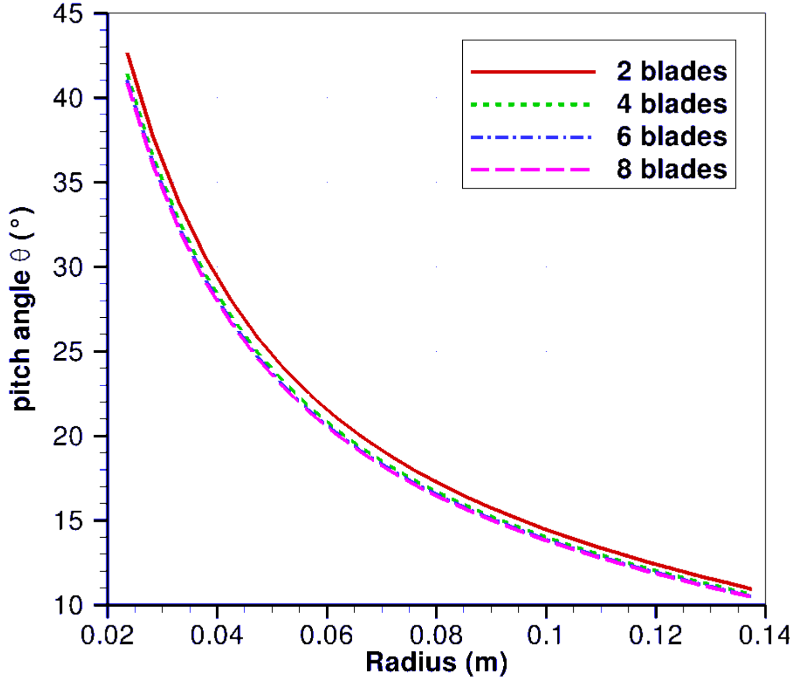
Rotor design

- Optimal design based on optimal airfoil
  - Geometry obtained by minimum induced loss analysis (QMIL)
  - Performance obtained by blade element code (QPROP)

Rotor definition example: Ø = 30 cm, Ω = 9000 rpm, m = 100 g, C_L = 0.7

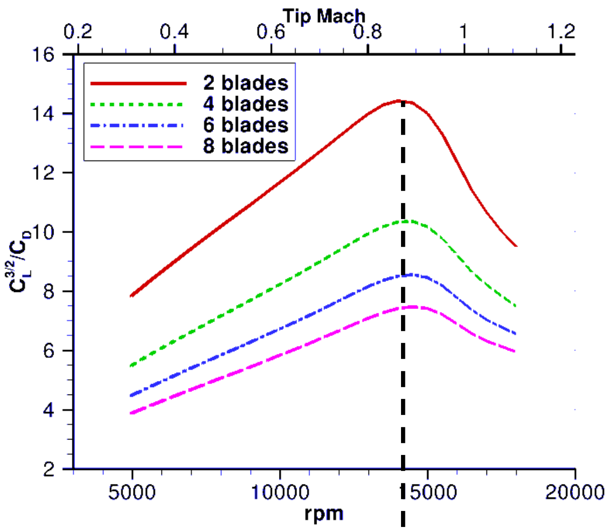




Rotor performance

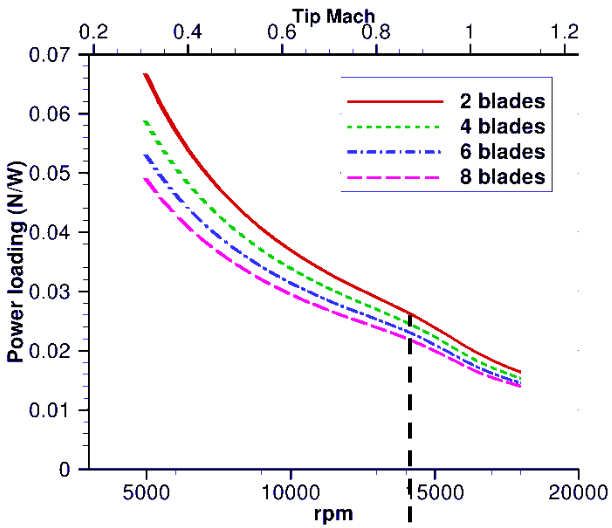
- Performance of optimal rotors
  - Design parameters: Ø = 30 cm, Ω = 9000 rpm, m = 100 g, $C_L = 0.7$
  - Evolution with rotational speed (or tip Mach number)

Rotor power efficiency
$C_L^{3/2}/C_D$



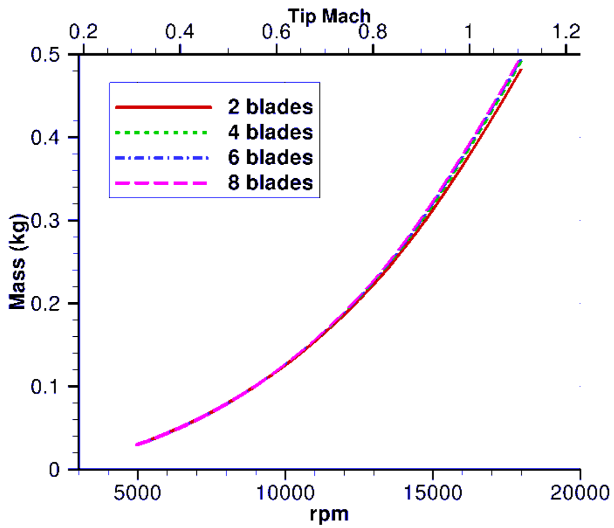
Drag divergence

Power loading
(= Thrust / Power)



Drag divergence

Lifted mass



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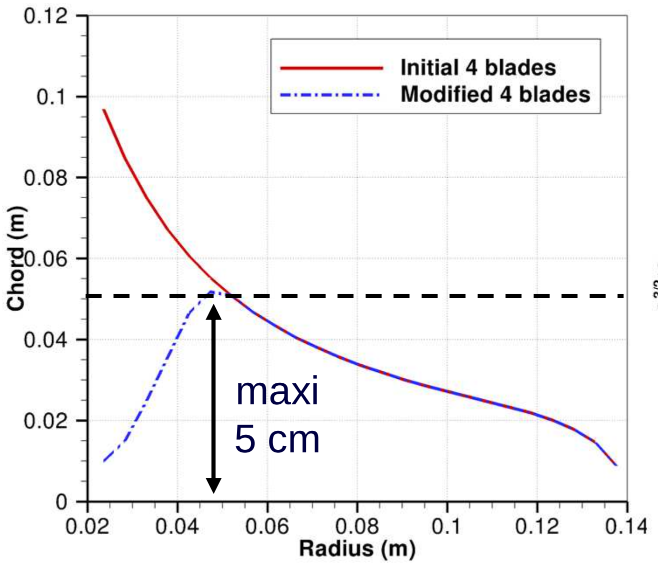
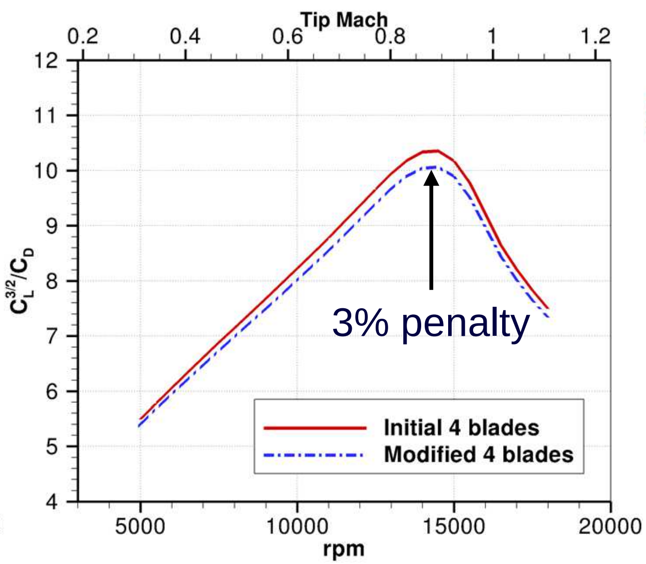
Rotor performance

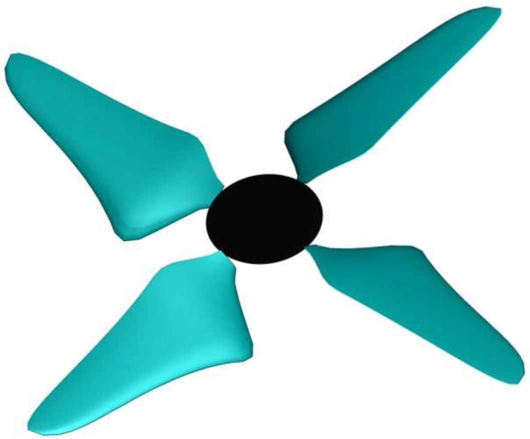
- Realistic geometry: modification close to the hub
  - Example: 4-blade rotor, Ø = 30 cm

Chord distribution



Rotor power efficiency
$C_L^{3/2}/C_D$



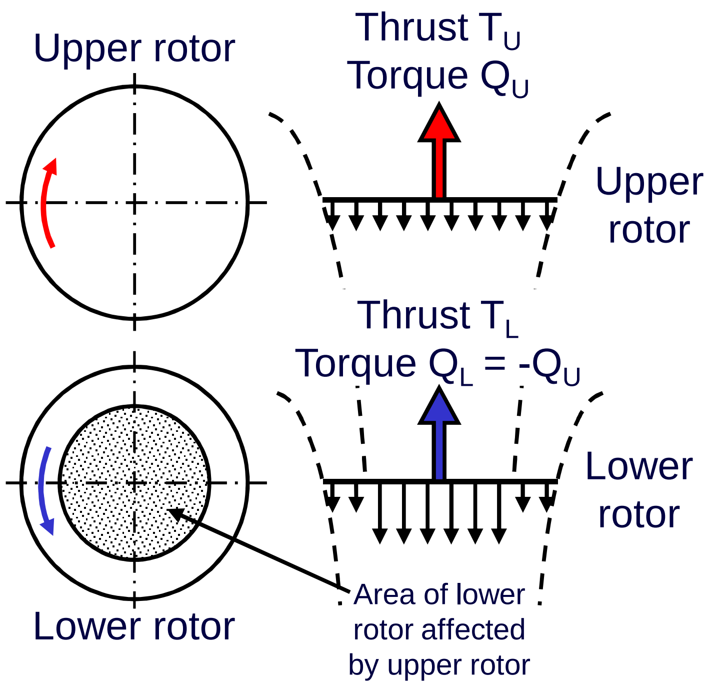


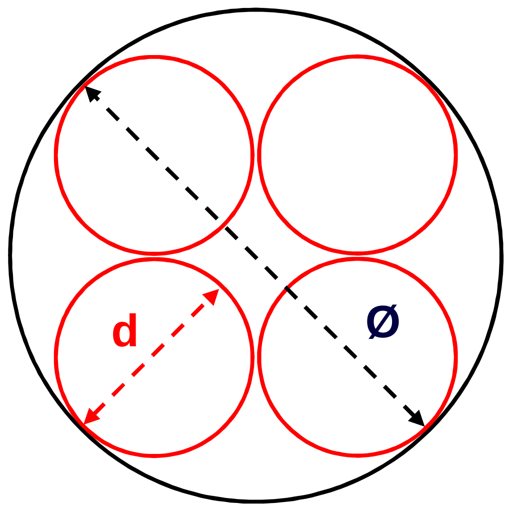
Rotor configurations

- Increase payload: coaxial bi-rotors vs. planar multi-rotors

Coaxial bi-rotors: + larger disk area
- interaction penalty

Multi-rotors: + better control
- lower disk area





Ø = 30 cm
→ 4 rotors of d = 12 cm

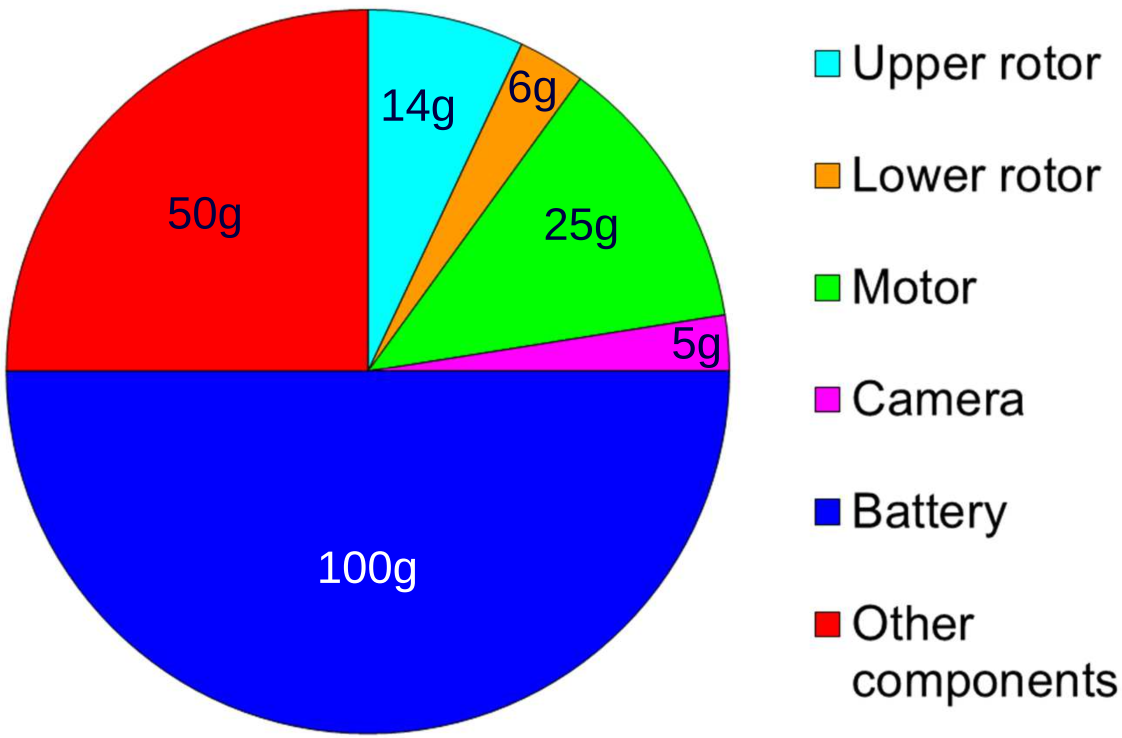
Rotor configurations

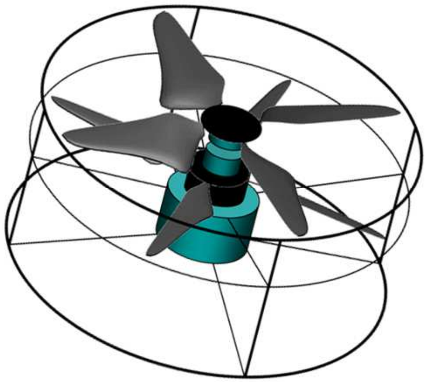
- Comparison of performance
  - Application for Ø = 30 cm, total mass = 200 g, mean C_L = 0.7

	Coaxial bi-rotor	**Co-planar 4-rotors**	
Lifted mass	200 g	200 g	
Lifted mass per rotor	Upper: 114 g Lower: 86 g	50 g	
Total power	**22.8 W**	**32.6 W**	→ **+ 40%**
Rotational speed	9435 rpm	22760 rpm	
Single rotor diameter	30 cm	12 cm	
Tip Mach number	0.6	0.6	

Mass budget

- Application for a coaxial bi-rotor UAV
  - Mass = 200 g, 4 blades per rotor, Ø = 30 cm, flight duration ≈ 30 min.





Conclusions

- Airfoil adapted to low Re and high Mach: low thickness and high rear camber

- Rotor design adapted to high rpm: not in favor of 2-blade rotor (large chords)

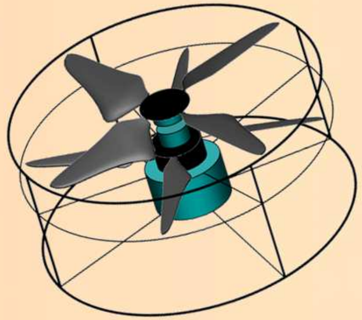
- Coaxial bi-rotor more efficient than planar multi-rotors

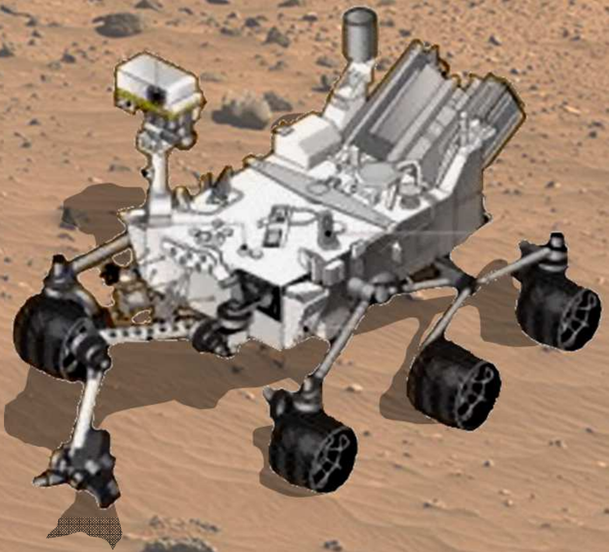
- Designing an helicopter on Mars is challenging but feasible

Perspectives

- Further investigations on airfoil: unsteadiness of laminar separated flow, surface roughness, Navier-Stokes optimization
- Further investigations on rotors: 3D Navier-Stokes computations, upper-lower rotor interaction
- Dynamic response to atmospheric turbulence
- Experiments in low pressure chamber (needs adaptation of existing facility)

Thank you for your attention





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