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DEPARTMENT OF AERONAUTICAL ENGINEERING

CHAIR OF FLIGHT VEHICLE DYNAMICS

Prof. dr. sc. Zdravko Terze

WHAT WE DO?

- ***Flight vehicle dynamics and control, Aerodynamics***
- ***Numerical methods (CFD, FEM, Multi-Body Dynamics, Multi-Physics)***

Faculty Mech. Eng. & Naval Arch., University Zagreb

+ partner institutions:

- *Technische Universität München (TUM), Germany*
- *Institute for Mechanical Systems, ETH Zürich*
- *Politecnico di Milano (POLIMI), Italy*
- *Institute of Mathematics, Martin Luther University, Germany*
- *Beijing University of Aeronautics and Astronautics, China*
- *Institute of Robotics Austria, Johannes Kepler University, Austria*
- *Faculty of Science, Department of Mathematics, University of Zagreb, Croatia*
- *Department of Continuum Mechanics and Structures, UPM, Madrid*

  + TU Delft, Micro Air Vehicle Laboratory

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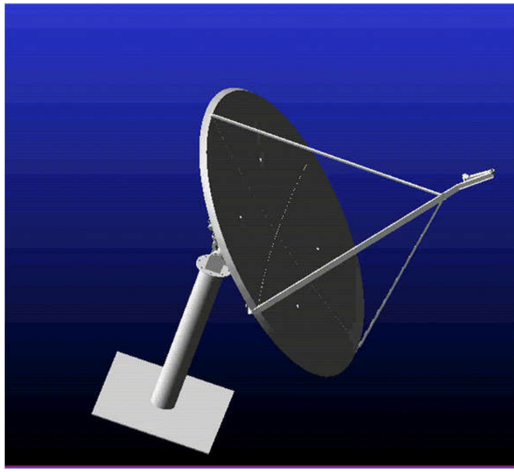
Satellite tracking antenna

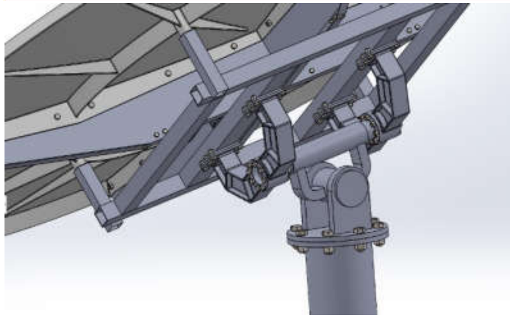
FERSAT (collaboration with FER, Zagreb)

+

‘Pooling and sharing’ - ready Ground station / GOVSATCOM
(collaboration with Amphinicy Technologies)

- Developing novel ground station satellite tracking mechanism with no keyholes
  - high precision ground station simulation and control
  - optimization of the motion parameters during satellite tracking
  - ready and quickly adaptive to different orbits
  - orbit tracking software will be coupled with an optimal control algorithm
  - variety of satellite frequency bands: X (S & X up to Ka/Ku)
  - pointing accuracy < 0.1° (< 0.01 °)
- The solution will be upgraded from a stationary ground station to a mobile station → implementing platform stabilization mechanisms and overall control strategy





Generating az-el tracking trajectory for satellite antenna via STK

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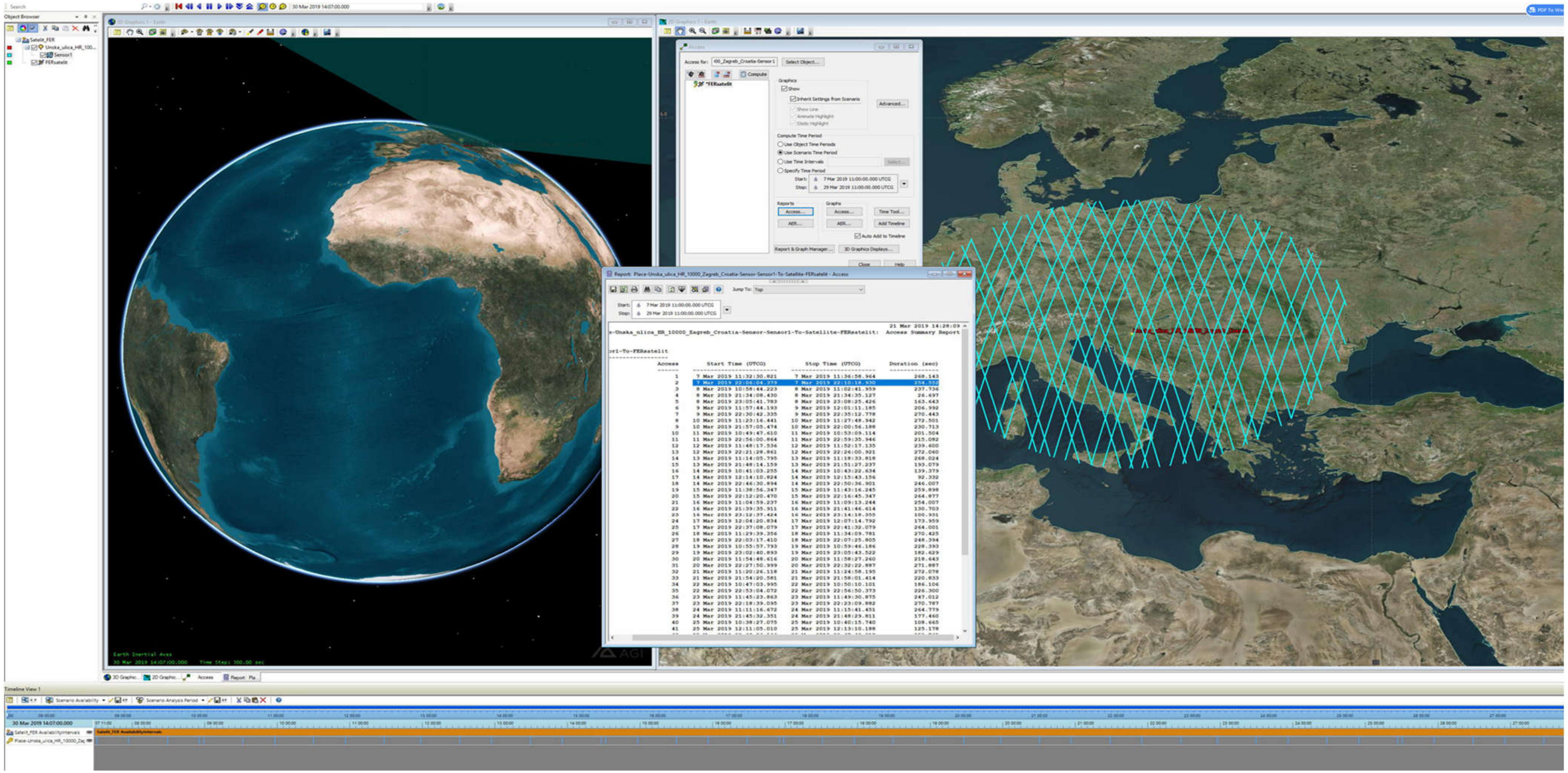

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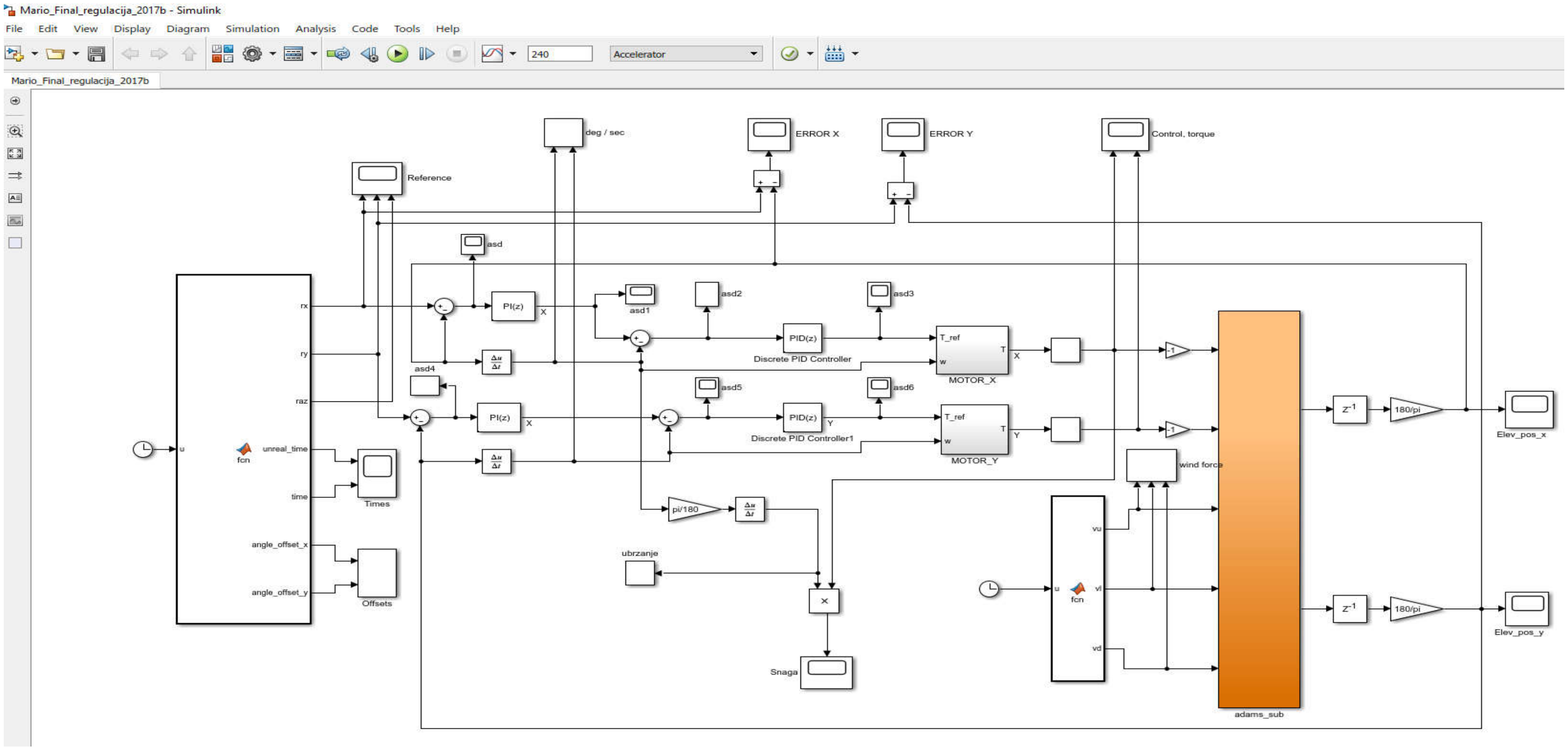
Control scheme:

/...servo-actuators X-Y configuration

/... real antenna digital twin + wind-loads included



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Wind load model is approximated from many different papers and measurements already done across the world.

Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and The 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni

"Characterization of Wind Loading of the Large Radio Telescope"

Sabine Upnere, Normunds Jekabsons, Roberts Joffe (*Engineering Research Institute Ventspils International Radio Astronomy Centre of Ventspils University College*)

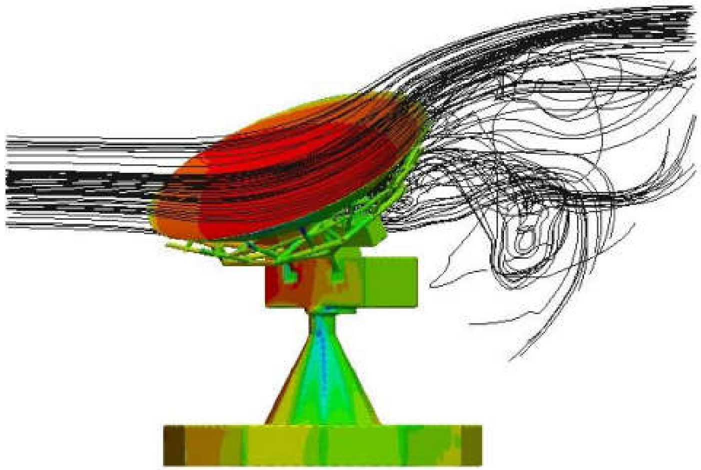


Fig. 11. The distribution of the pressure on a surface and a flow around the radio telescope. The wind direction is 45^0, the elevation angle is 30^0.

Fuerza del Viento sobre la Parabolica

FTApinamar

diametro	150 cm	165 cm	180 cm	200 cm	240 cm	320 cm	400 cm
superficie	1.76715	2.13825	2.54470	3.14159	4.52391	8,04250	12,56637
viento de 20 km/h	3.41	4.12	4.91	6.06	8.73	15.51	24.24
viento de 40 km/h	13.64	16.50	19.64	24.24	34.91	62.06	96.96
viento de 60 km/h	30.68	37.12	44.18	54.54	78.54	139.63	218.17
viento de 80 km/h	54.54	66,00	78.54	96.96	139.63	248.23	387.85
viento de 100 km/h	85.22	103.12	122.72	151.50	218.17	387.85	606.02
viento de 120 km/h	122.72	148.49	176.72	218.17	314.16	558.51	872.66
viento de 140 km/h	167.03	202.11	240.53	296.95	427.61	760.19	1187.79
viento de 160 km/h	210.17	263.98	314.16	387.85	558.51	992.90	1551.40
viento de 180 km/h	276.12	334.10	397.61	490.87	706.86	1256.64	1963.50

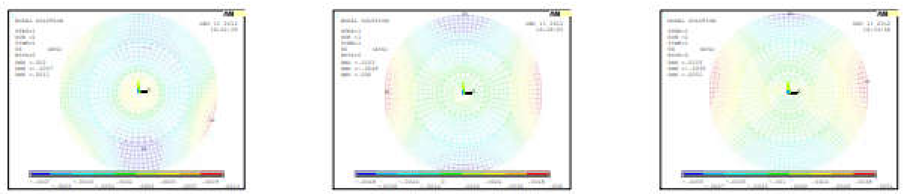
Diametro: ■ Superficie al Satelite: ■ m2 fuerza del viento sobre la parabolica ■ kg

REFLECTOR WIND LOAD CHARACTERISTICS OF THE LARGE ALL-MOVABLE ANTENNA AND ITS EFFECT ON REFLECTOR SURFACE PRECISION

Yan Liu*[,1], Hong-liang Qian[2] and Feng Fan[2]

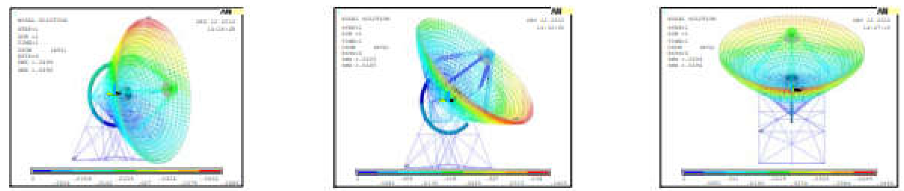
Table 9. RMS of Reflector Surface under the Wind Load

Pitch angle \ Wind angle	0°	90°	180°
5°	0.362	2.092	0.212
30°	2.206	1.715	0.377
60°	2.102	1.785	0.586
90°	2.096	2.092	2.103



a) 5° b) 60° c) 90°

Figure 47. Half Optical Path Error of Reflector Surface



a) 5° b) 60° c) 90°

Figure 48. Whole Displacement of the Structure

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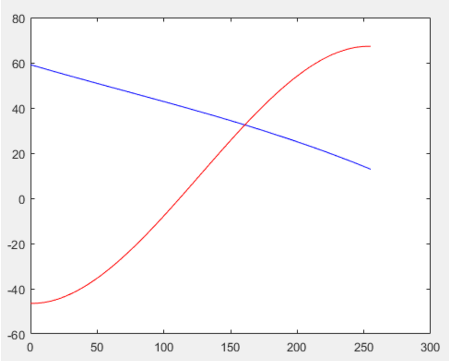
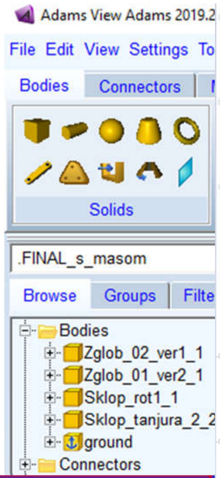
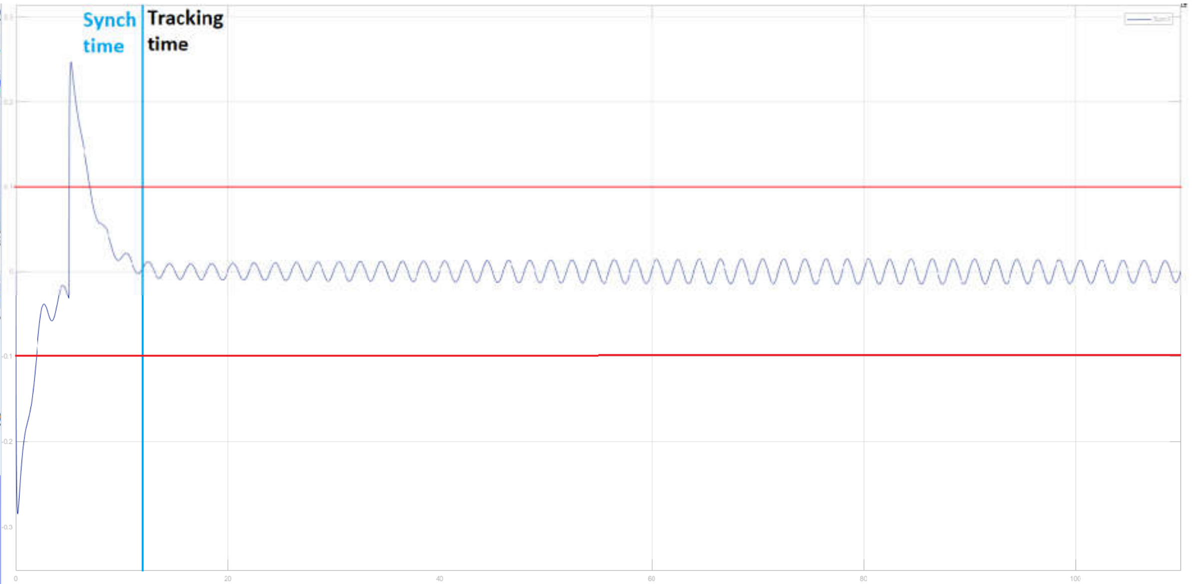
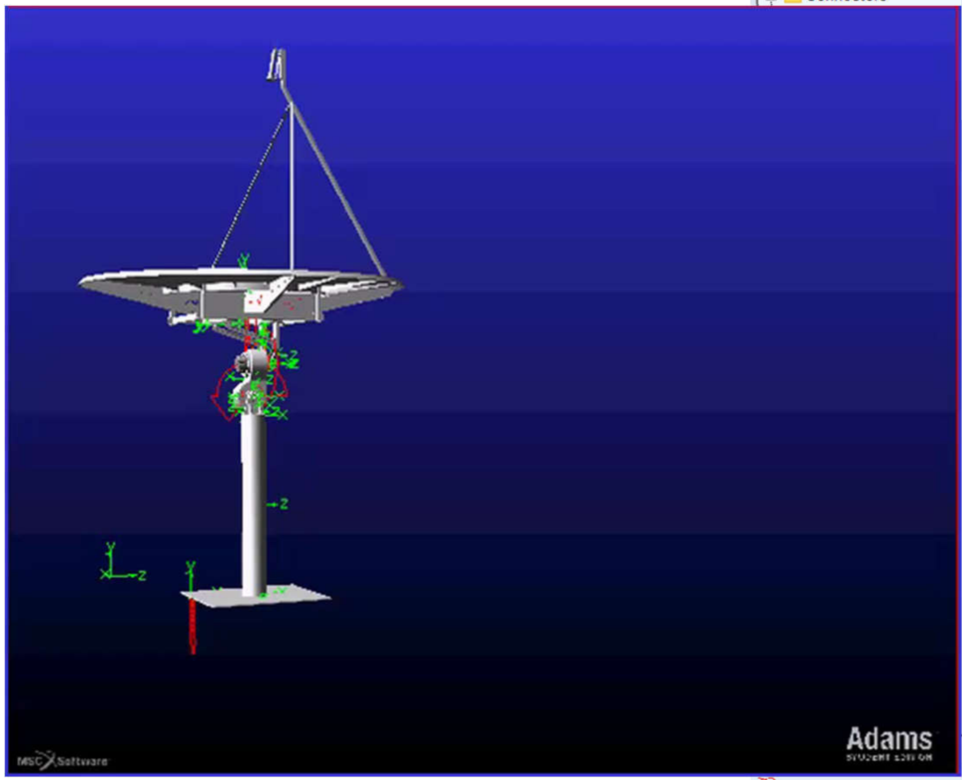
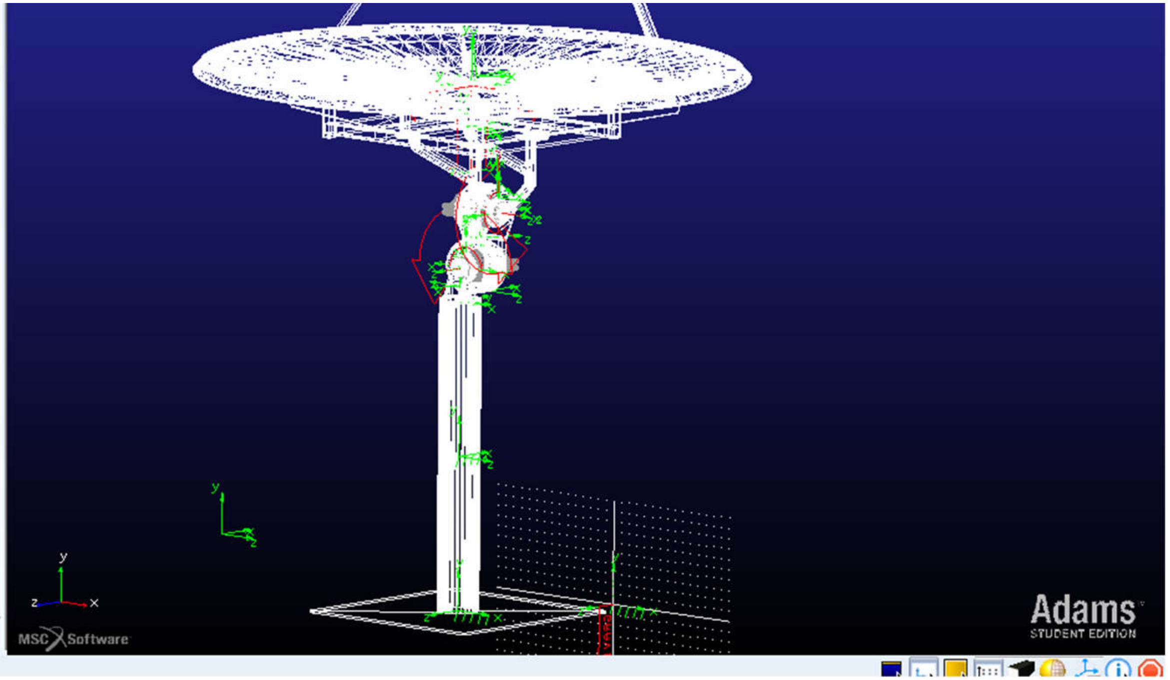
X-Y axis atellite antenna:











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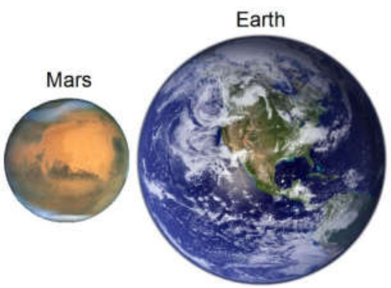
Flapping wing vehicles for Mars exploration



- Low atmospheric density on Mars (air density is 1.3% of that on Earth and gravitational acceleration is 38% of Earth's) → low Reynolds number
  - Conventional aircraft designs have limitation
    - fixed wing vehicles must fly fast to avoid stall (>350 kmph) → passing over regions too quickly, cannot successfully land on uneven terrain for the mission stop or to refuel; 'hard landings'
    - rotary wing vehicles allow for take-off and landing / but rotor tips rapidly exceed the Martian lower speed of sound → rotational speeds insufficient to lift; difficult to manoeuvre
  - Why flapping wings?
    - high lift generating capability at low Reynolds number → allow to fly slow, manoeuvre easily and perform vertical take-off and landing
    - reciprocating nature of flapping wings → resonant operation → energy efficiency; harvesting energy from the ambiental flow
    - should better sustain collisions with hard environment → more robust operation; mission planning activities enhanced

However…can insects actually fly?

„Insects cannot fly, according to the conventional law of aerodynamics: during flapping flight, their wings produce more lift than during steady motion at the same velocity and angles of attack”

Ellington PE, van den Berg C, Willmott AP, Thomas ALR. Leading-edge vortices in insect flight, Nature. 1996; 384: 626-30.

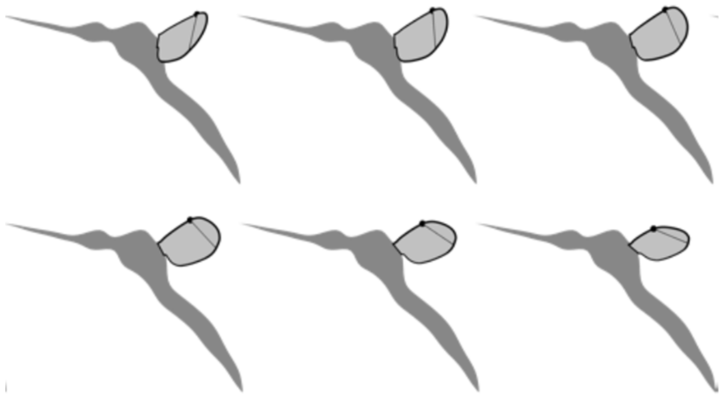
Insect-like flapping:

Hawkmoth

(Ellington et al, 1996)

Mosquito …. (800 Hz !)

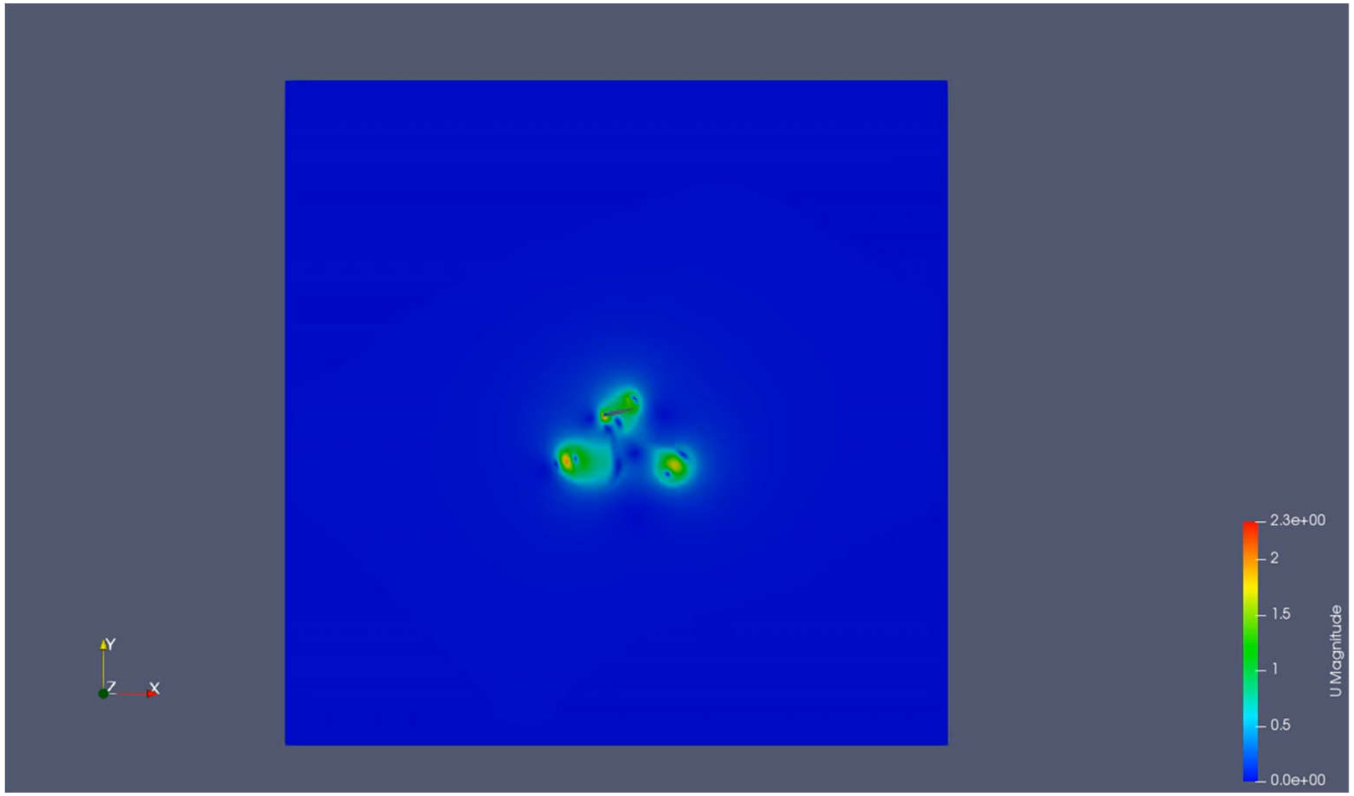
(Bomphrey et al, Nature, 2017)



Fly …TU Delft (DelFly MUAV)

(Guido C. H. E. de Croon et al, Science, 2018)

Numerical example: butterfly wing



- Velocity field distribution for butterfly wing model

Challenges:

How to mathematicaly model such a complex aerodynamic phenomena?

- Standard CFD and FSI numerical co-simulations:

/... very time consumming !

/... problems with accuracy and stability !

/... optimal control ?

/... design optimisation ?

How to design a flapping mechanism?

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UNIVERSITAS STUDIORUM ZAGRABIENSIS MDCLXIX

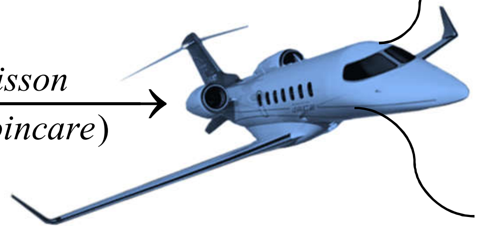
Fluid - Flying vehicle / ‘hybrid’ modelling:

- differential-geometric reductions (Lie groups) + numerical discretisation (BEM)

- **Rigid vehicle**

$$G = \mathbf{R} \in SO(3)$$

$$SO(3) \xrightarrow[(Euler-Poincare)]{Lie-Poisson}$$



$$L(\mathbf{R},\dot{\mathbf{R}}) = tr((\mathbf{R}^{-1}\dot{\mathbf{R}})^T I\, \mathbf{R}^{-1}\dot{\mathbf{R}}) \rightarrow \frac{1}{2}\omega^T I\omega$$

$$\omega$$

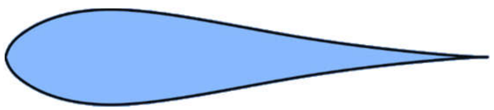
  - Euler equations in Lie-Poisson form:

$$\dot{y} = -\omega \times y, \quad y = I\omega \in so(3)^* \qquad (\; I\dot{\omega} = I\omega \times \omega \;)$$

$$(no\ \mathbf{R}\ !!)$$

- **Rigid vehicle + fluid (planar case)**

$$SE(2) \xrightarrow[(left)]{Poisson}$$



$$\xleftarrow[(right)]{Symplectic\ (\Gamma)} \mathrm{Diff}_{\mathrm{Vol}}(\mathscr{F})$$

$$T^*SE(2) \rightarrow se^*(2)$$

$$(no\ "translations"\ !!)$$

$$\dot{\Pi} = (\mathbf{P} \times \mathbf{v}) \cdot \mathbf{b}_3$$

$$\dot{\mathbf{P}} = \mathbf{P} \times \omega + \Gamma \mathbf{b}_3 \times \mathbf{v}$$

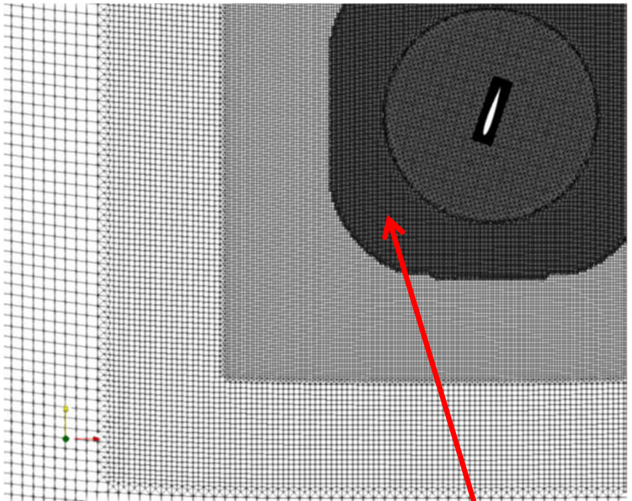
$$\mathbf{P}, \Pi \in se^*(2)$$

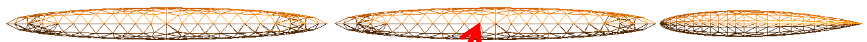
$$T^*Q \rightarrow T^*SE(2)$$

$$(no\ fluid\ variables!!)$$

Fluid volume discretization -> Boundary surface discretization

- Multiple orders of magnitude fewer variables:





$$T_{\mathscr{F}} = \frac{1}{2}\rho_{\mathscr{F}} \int_{\mathscr{F}} \mathrm{div}\left(\phi \nabla \phi\right) dV = -\frac{1}{2}\rho_{\mathscr{F}} \int_{\partial \mathscr{B}} \phi \nabla \phi \cdot \mathbf{n} \, db$$

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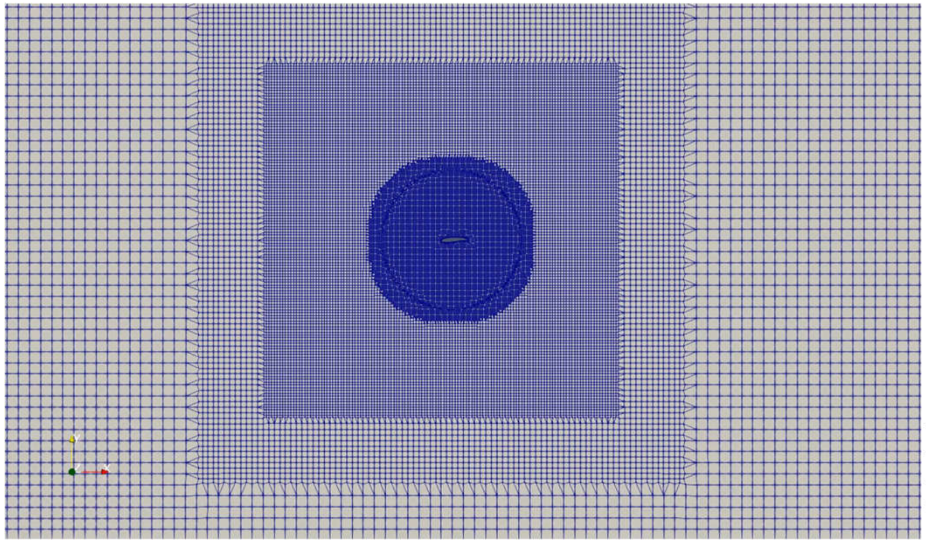
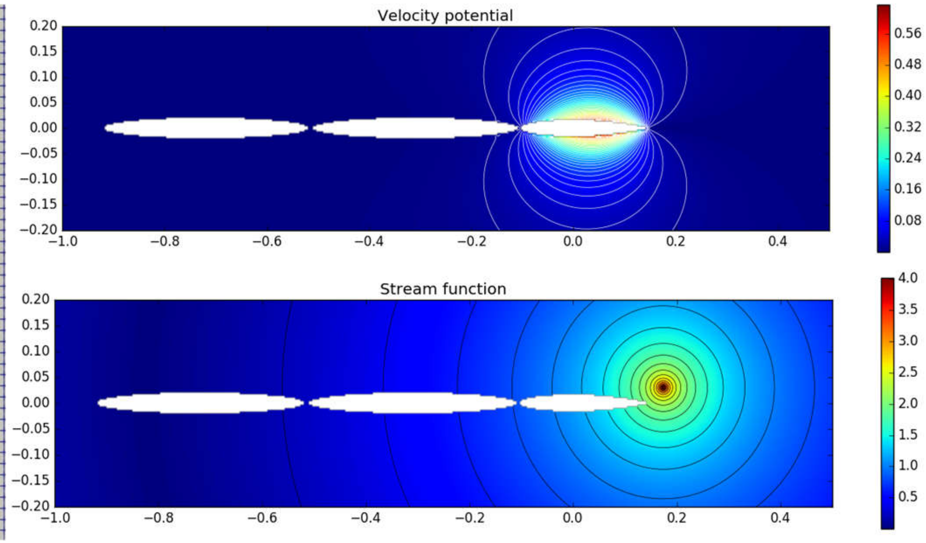
Finite volume method -> Boundary element method

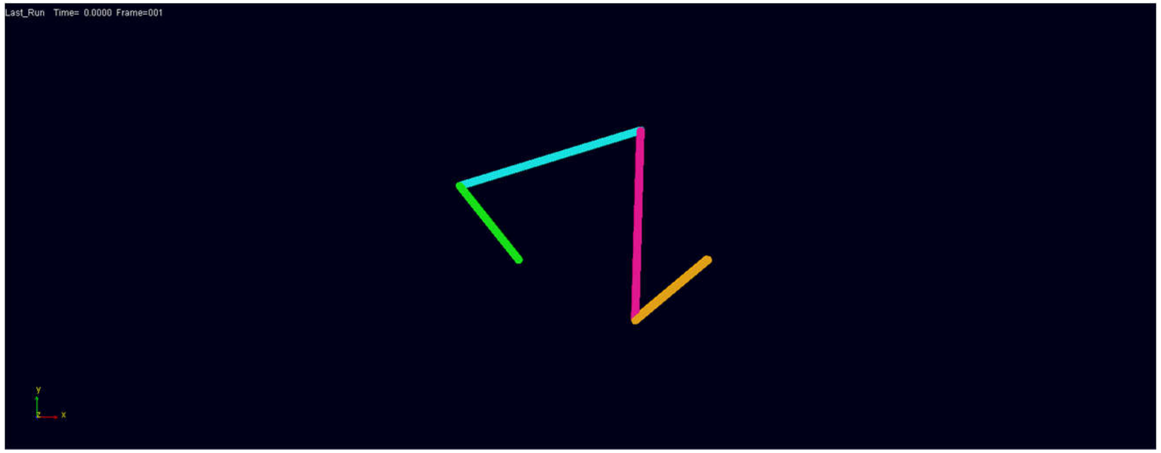


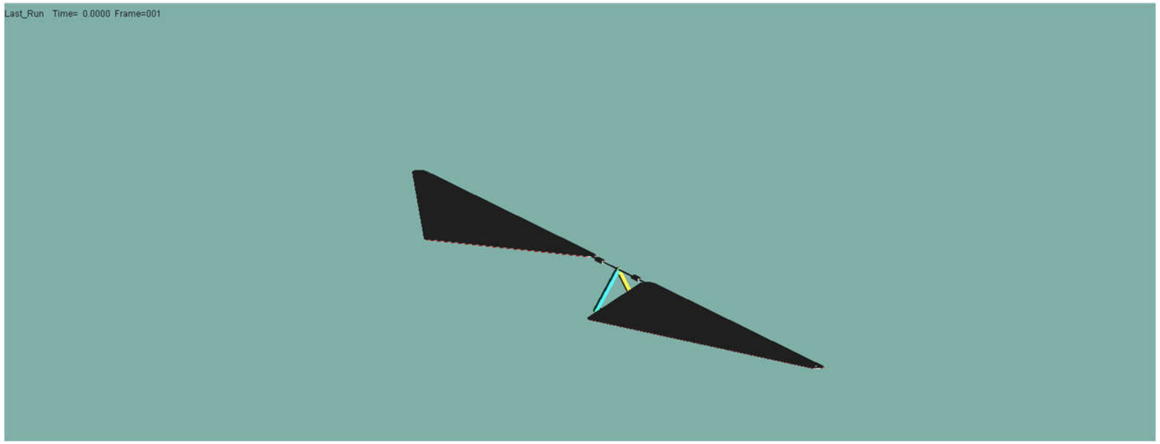


- Problems with mesh deformations
- Stability/convergence problems
- Computation -> large fluid domain
- Computational time measured in days

- Computing only effects of the fluid on the body
- Computational time measured in minutes
- Can be used in optimal control/design loop

Variations of wing mechanism....





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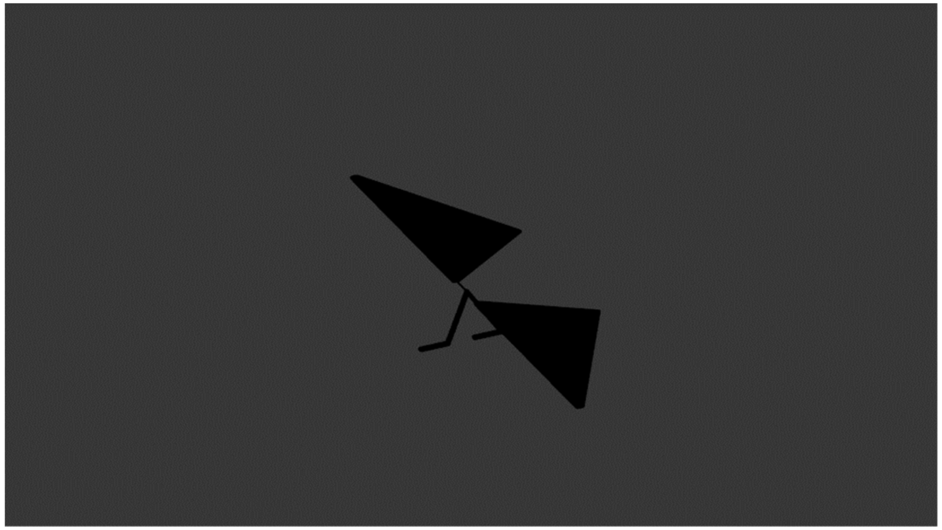
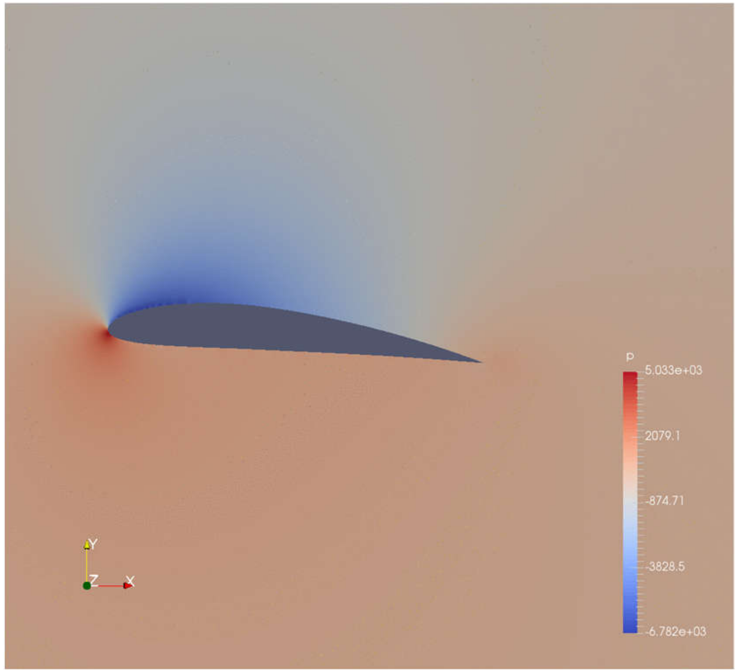
Dynamic coupling with fluid flow:

- MBDyn, OpenFOAM (open source)

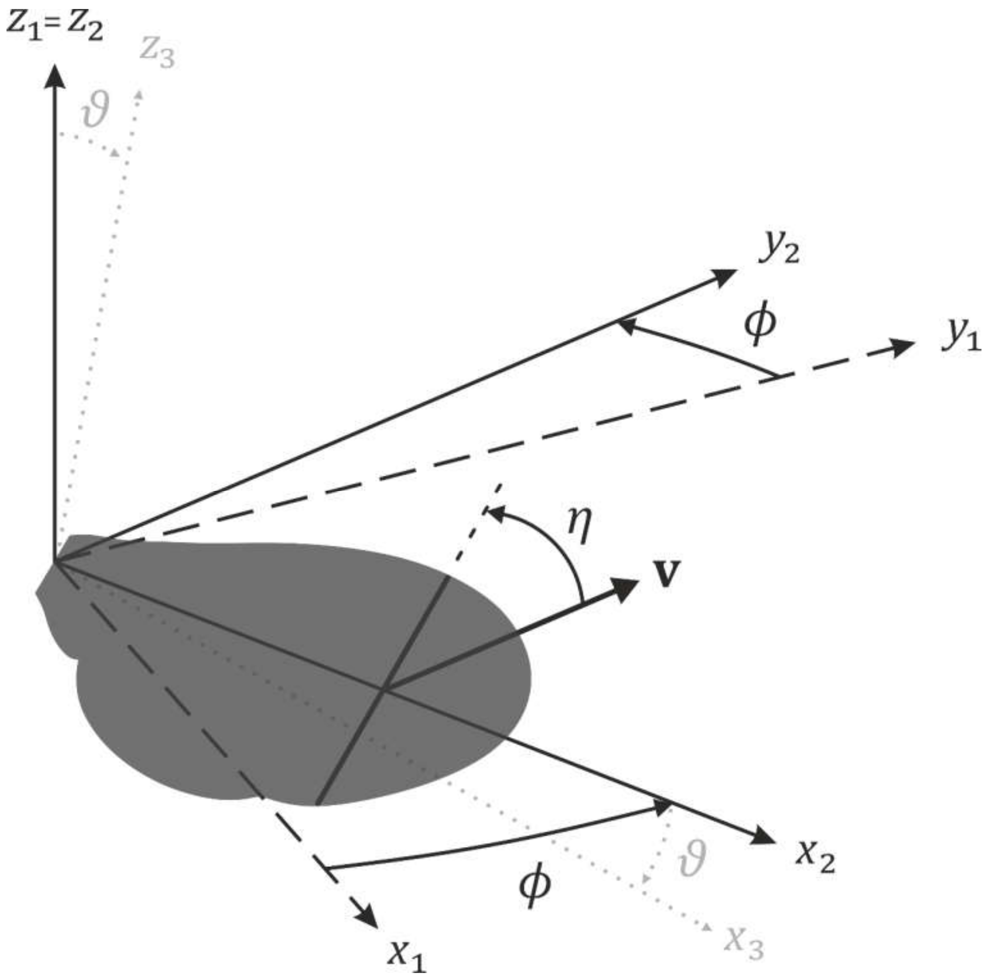




Quasy-steady aerodynamic model

- Dickinson et al. (1993-present) study the fruit fly
- Quasy-steady aerodynamical model based on measures done on the dynamically scaled fruit fly model

Insect wing



ϕ - **Azimuth angle**

ϑ - **Deviation angle (= 0)**

η - **Pitching angle**

Quasy-steady aerodynamic model

$$F = F_\mathrm{a} + F_\mathrm{trans} + F_\mathrm{rot}$$

$$F_\mathrm{a} = {}^1\!/_4\,\rho\pi R^2\bar{c}^2(\ddot{\varphi}\sin\alpha + \dot{\varphi}\dot{\alpha}\cos\alpha)\cdot \int_0^1 \hat{r}\,\hat{c}\,\mathrm{d}\hat{r} - {}^1\!/_{16}\,\ddot{\alpha}\rho\pi\,\bar{c}^3 R\int_0^1 \hat{c}^2\,\mathrm{d}\hat{r}$$

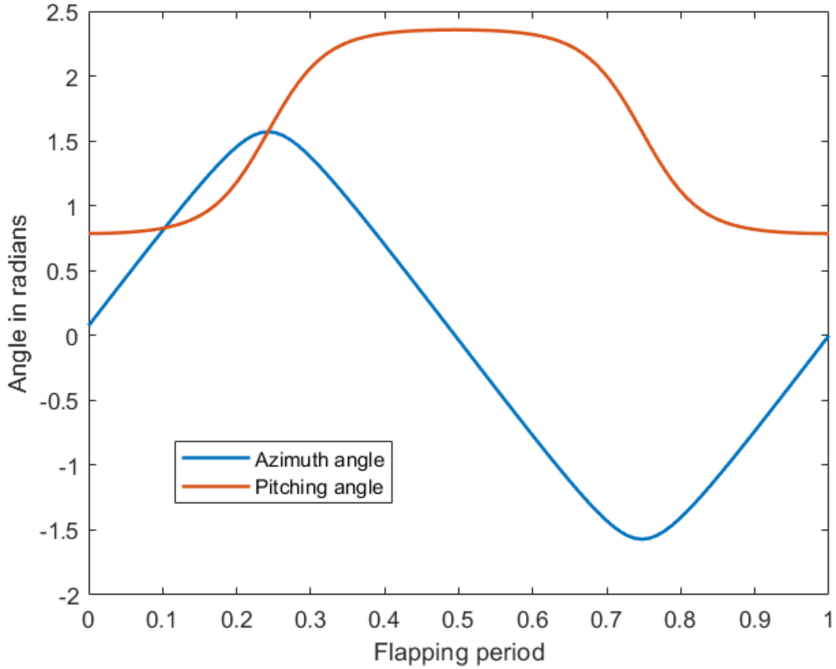
$$F_\mathrm{trans} = \frac{\rho S U_\mathrm{t}^2 r_2^2(S)}{2}\left[C_\mathrm{Lt}^2(\alpha) + C_\mathrm{Dt}^2(\alpha)\right]$$

$$C_\mathrm{Lt}(\alpha) = 0.225 + 1.58\sin(2.13\alpha - 7.2)$$

$$C_\mathrm{Dt}(\alpha) = 1.92 - 1.55\sin(2.04\alpha - 9.82)$$

$$F_\mathrm{rot} = C_\mathrm{rot,exp}\rho U_\mathrm{t}\omega\bar{c}^2 R\int_0^1 \hat{r}\hat{c}^2\,\mathrm{d}\hat{r}$$

Initial angle functions

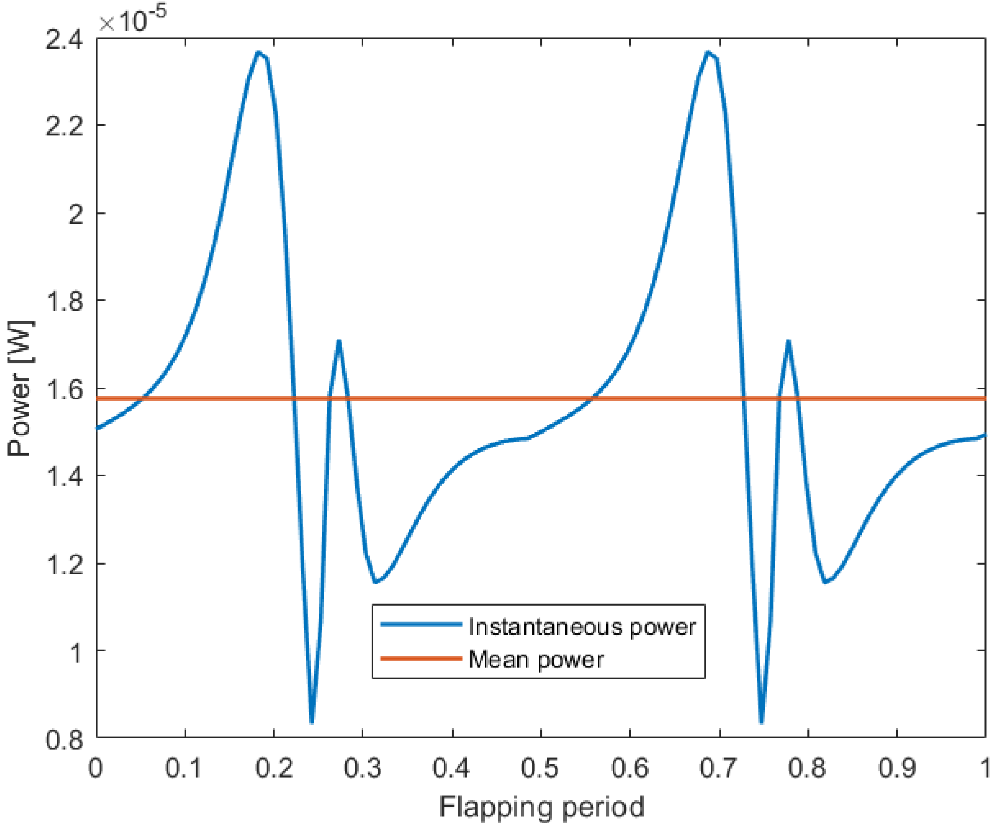


$$\varphi = \frac{\varphi_{\mathrm{m}}}{\sin^{-1}(K)} \sin^{-1}(K \sin(2\pi f t))$$

$$\eta = \frac{\eta_{\mathrm{m}}}{\tanh(C_\eta)} \tanh(-C_\eta \cos(2\pi f t))$$

Initial results

- Frequency: 173 Hz



Optimization

- Optimization goal:

  Reduce power requirement for hovering

- Optimization variables:
  - Frequency
  - Azimuth angle
  - Pitching angle
  - ~~Deviation angle~~

DMOC

- *Discrete mechanics and optimal control*
- Optimization problem defined by using concepts of the variational mechanics
- Discrete solution for a continuous optimization problem

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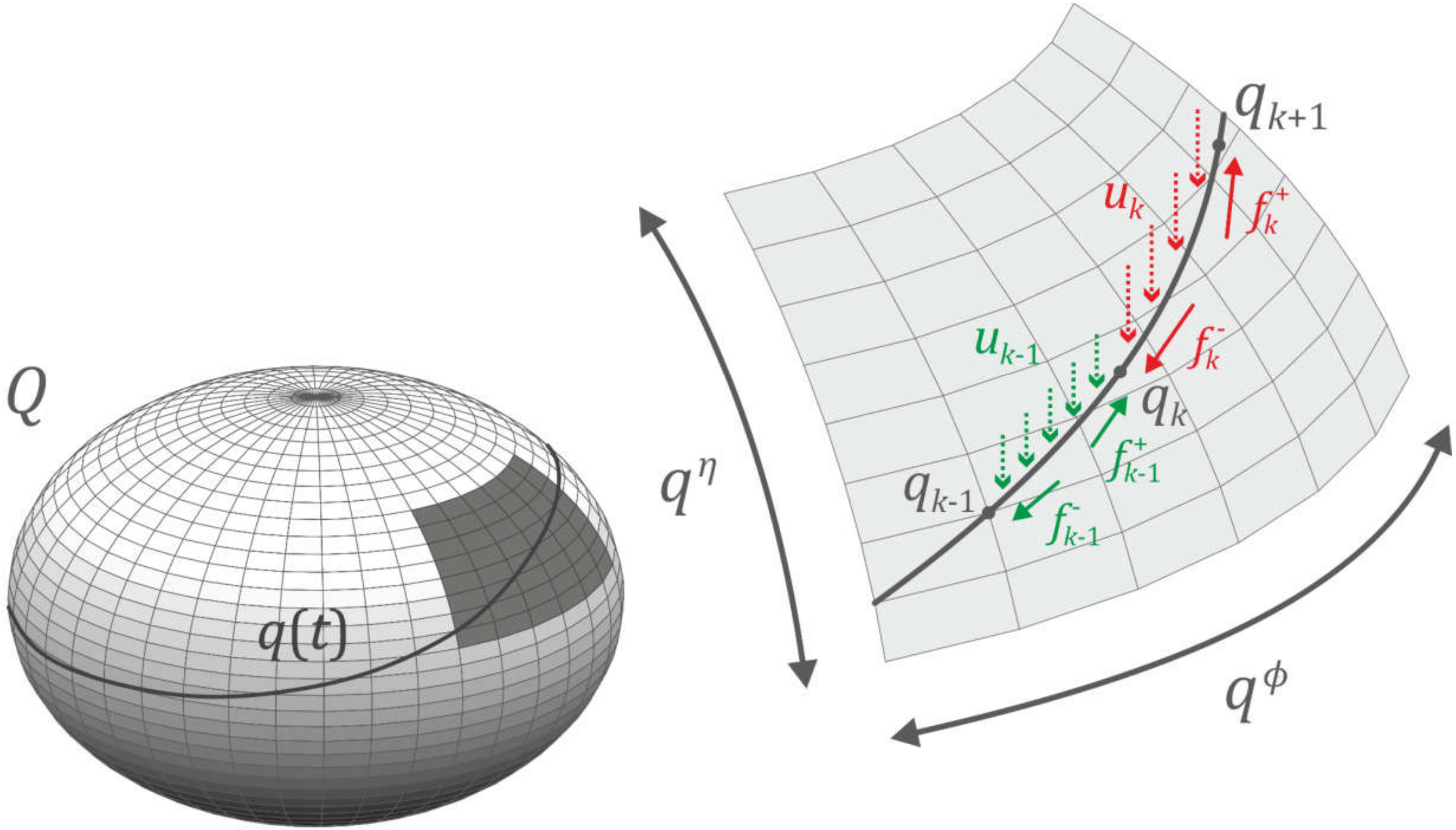
DMOC



DMOC

$$\min_{q_d,\, u_d} J_d\left(q_d, u_d\right) = \sum_{k=0}^{N-1} C_d\left(q_k, q_{k+1}, u_k\right)$$

$$q_0 = q^0$$

$$q_N = q^T$$

$$D_2 L_d\left(q_{k-1}, q_k\right) + D_1 L_d\left(q_k, q_{k+1}\right) + f_{k-1}^{+} + f_k^{-} = 0$$

$$p^0 + D_1 L_d\left(q_0, q_1\right) + f_0^{-} = 0$$

$$-p^T + D_2 L_d\left(q_{N-1}, q_N\right) + f_{N-1}^{+} = 0$$

$$h_d\left(q_k, q_{k+1}, u_k\right) \geq 0$$

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Optimization problem

- Cost function: $\frac{1}{N}\sum_{i=1}^{N} P_i$
- Constraints: $\frac{2}{N}\sum_{i=1}^{N} F_{\mathrm{L}i} = W_{\mathrm{fruitfly}}$

$$P_i \leq P_{\mathrm{max}}$$

- Frequency is sampled in the 150 Hz – 300 Hz range
- Azimuth and pitching angle are used as optimization variables

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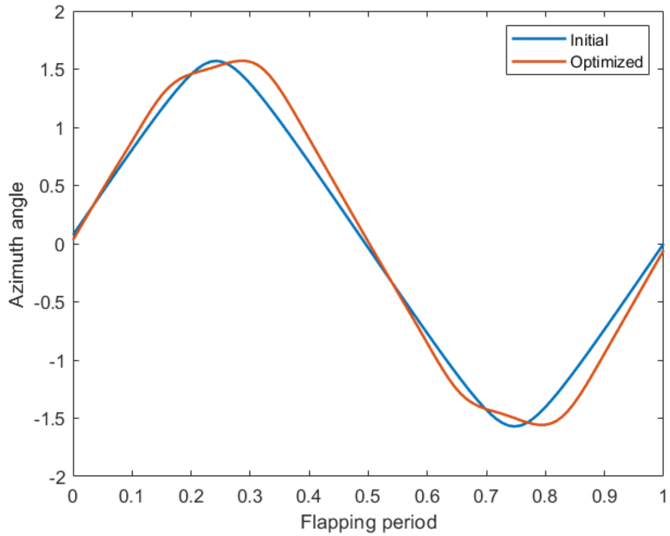
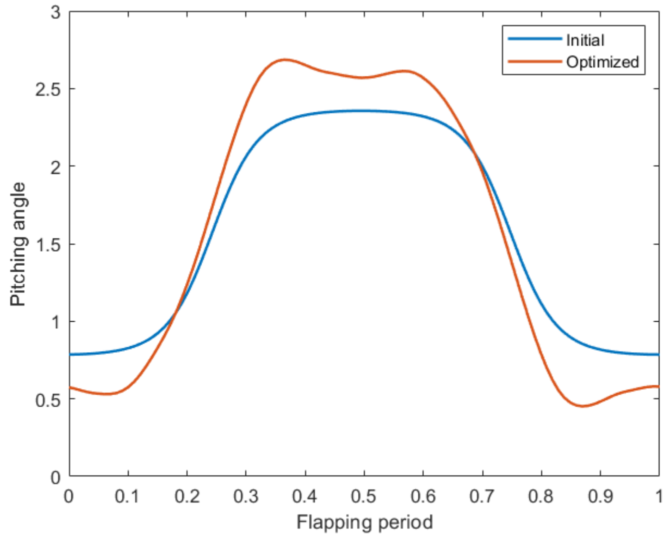
Optimized results

- Initial frequency: 173 Hz
- Optimized frequency: 160 Hz





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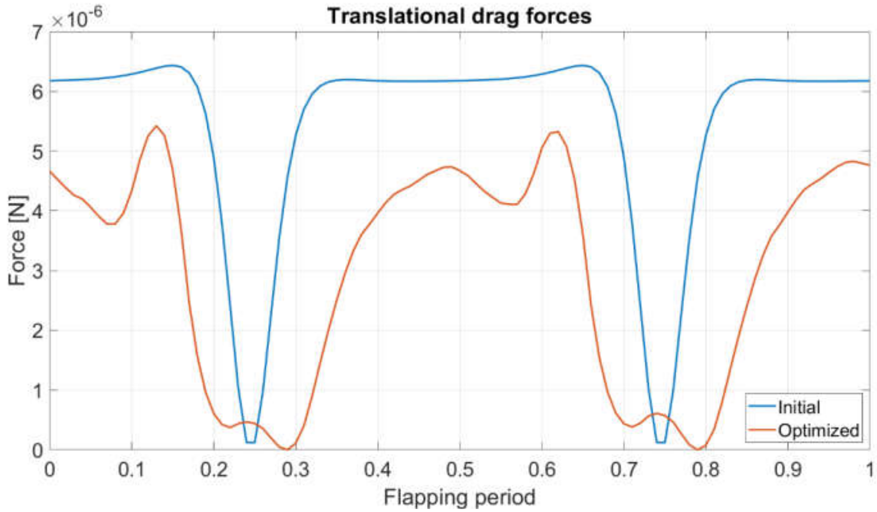
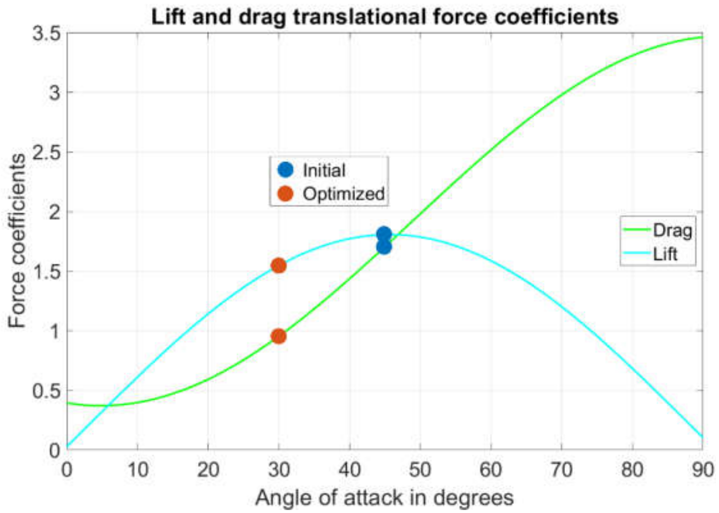
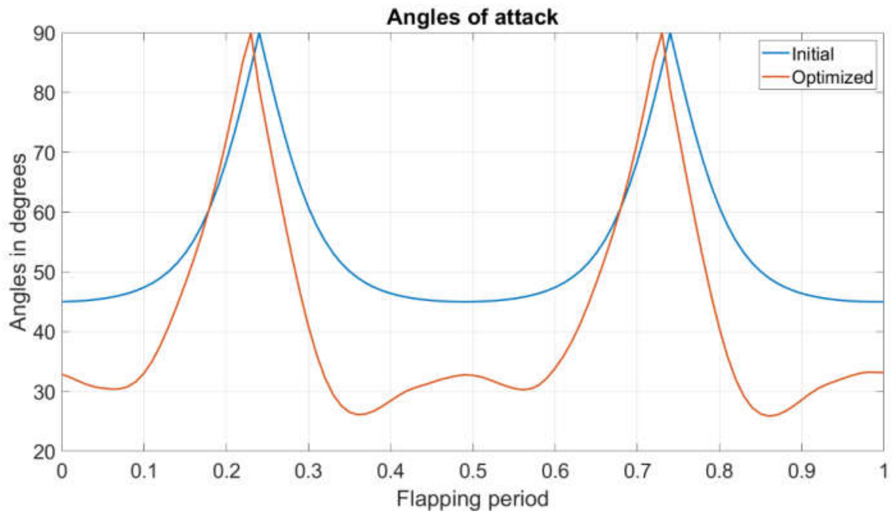
Optimized results







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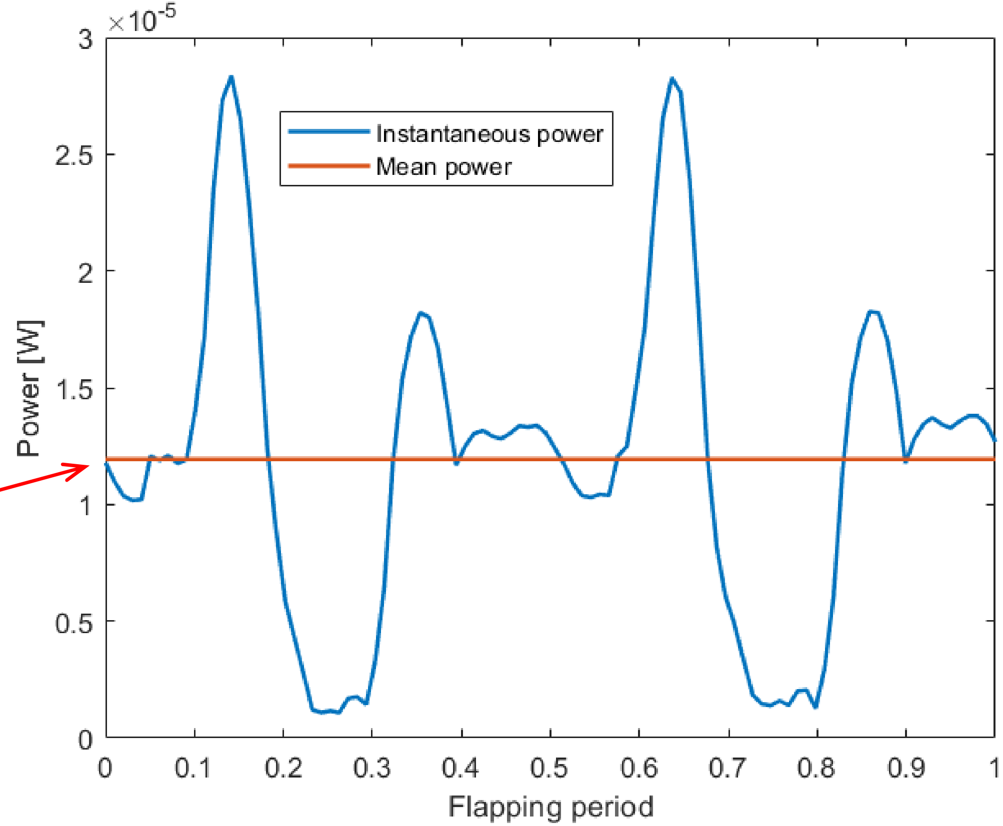
Optimized results

- Frequency: 160 Hz

24 % reduction



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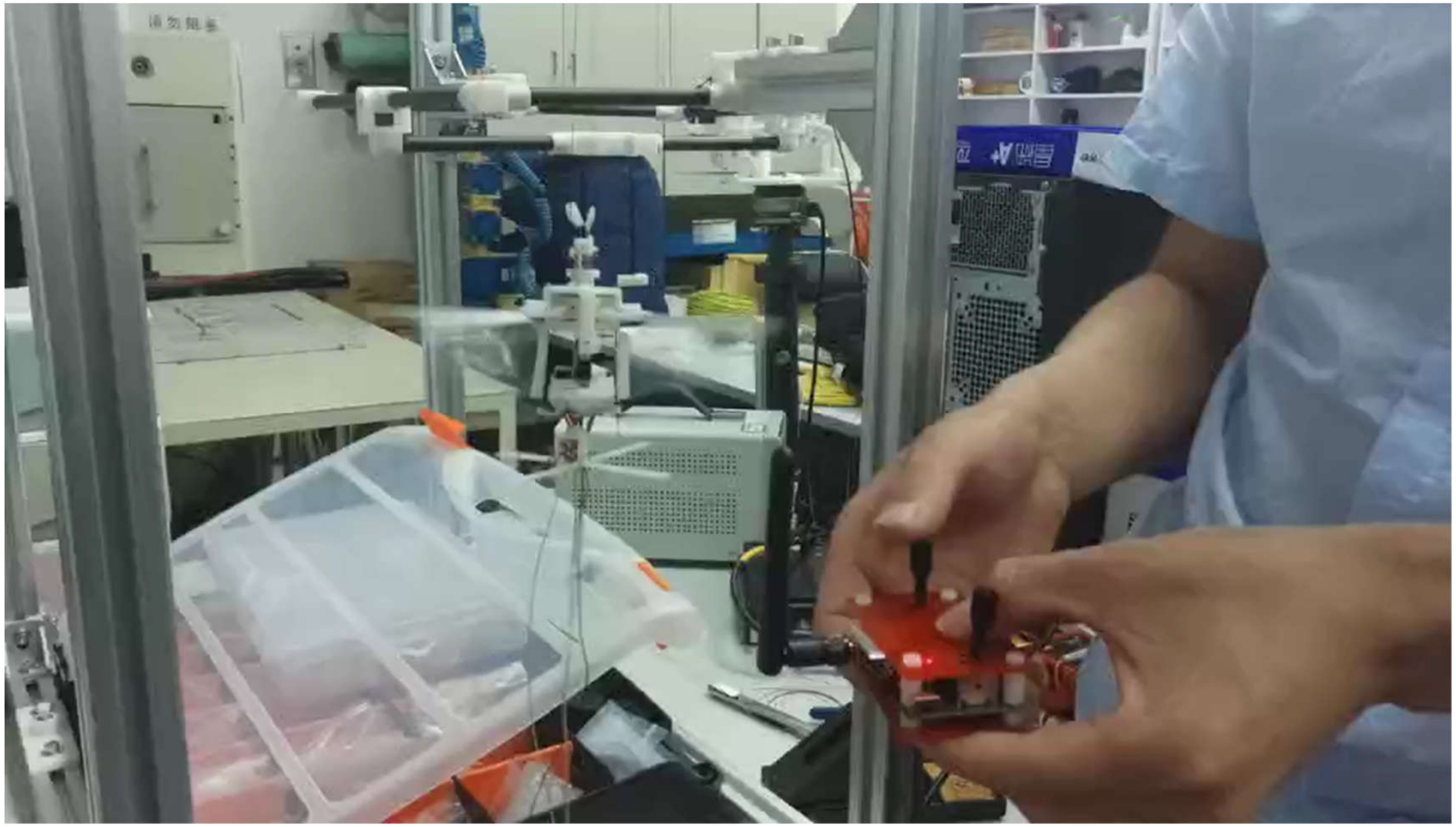
Experiments …/collaboration with:

- Beijing University of Aeronautics and Astronautics (BUAA); Stanford University (USA)
- Harbin Institute of Technology …. / Mars chamber
- ETH Zürich …. / NATO project



- **Thank you for your ATTENTION**