DRS Drag Reduction System

Study and design and optimize a DRS for F1 cars

Course of Mechatronics Systems Simulation
Academic Year 2021-2022

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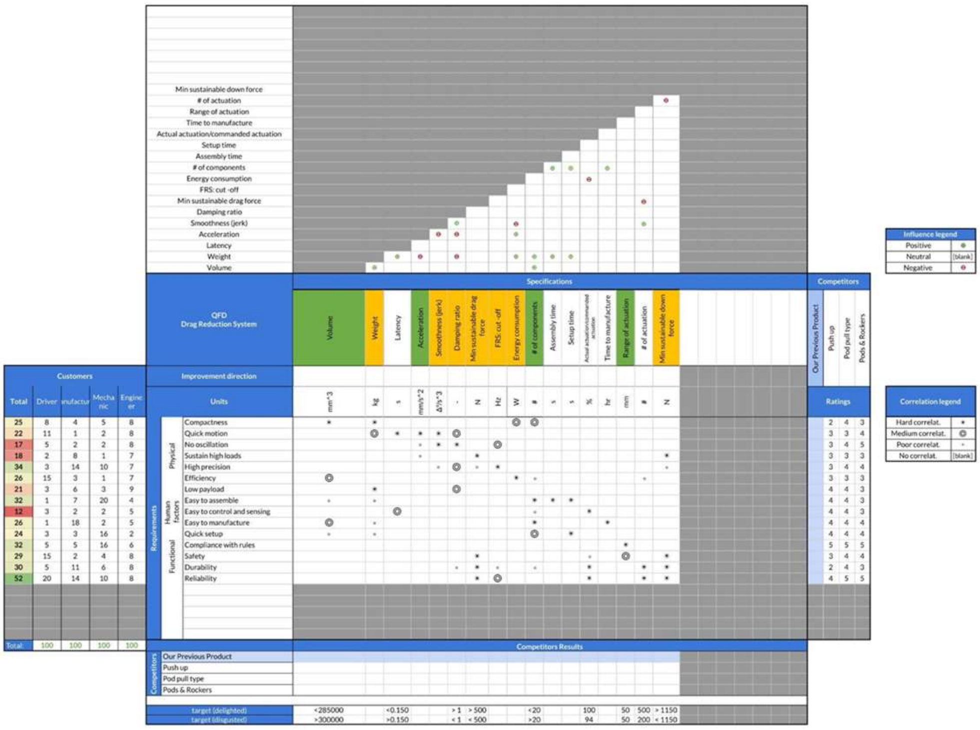
1 - QFD: Quality Function Deployment



In order to better understand the problem we used the QFD.

QFD permits us to listen carefully the voice of the customer and then effectively responding to those needs and expectations

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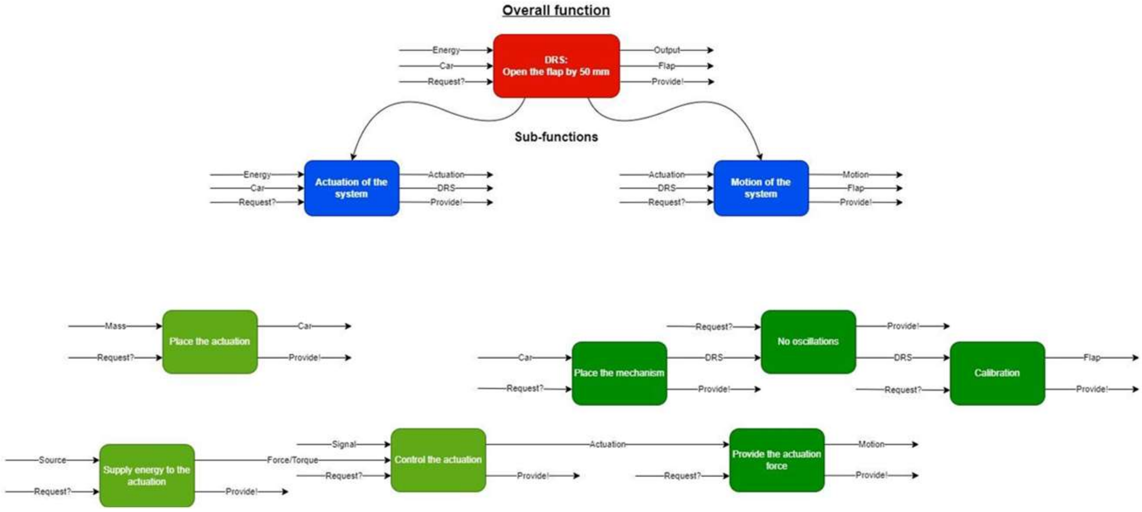
2 - Functional Decomposition

Functional decomposition splits a large complex task into smaller, simpler atomic functions, fostering a better understanding of the overall process.



3 - Robust Decision Making

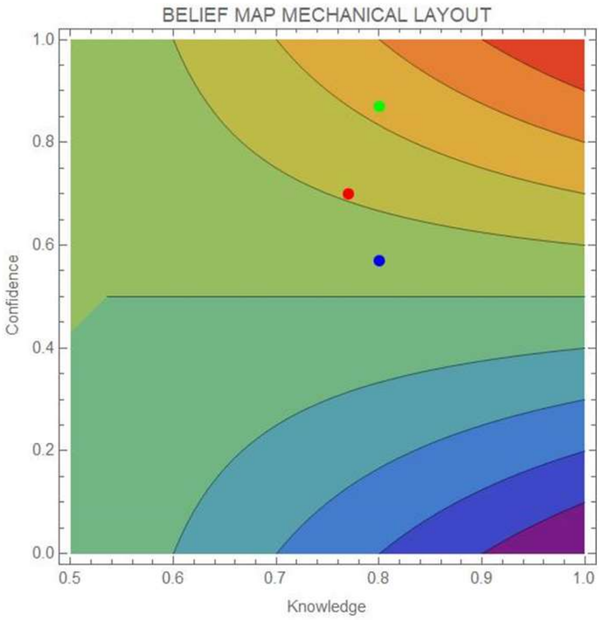
Decisions based on our level of confidence and knowledge

Below are some pros & cons:

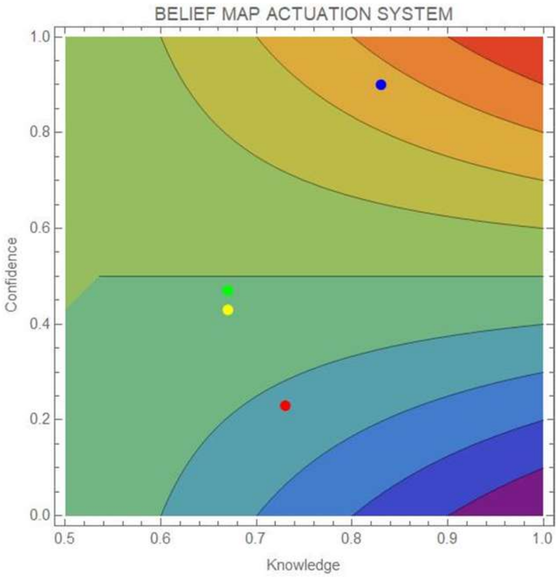
Pods & Rocker mechanism
- No Euler instability
- Less vibrations
- Customize profile of actuation
- Aerodynamic influence
- High number of constraints

Pod pull mechanism
- No Euler instability
- Less vibrations
- Aerodynamic influence

Push up mechanism
- Less aerodynamic influence
- More vibrations
- Euler instability



3 - Robust Decision Making



Decisions based on our level of confidence and knowledge.

Below are some pros & cons:

Electric motor
- Quite energy required to work
- Precise and accurate

Pneumatic actuator
- Lack of precision and accuracy
- Slow response

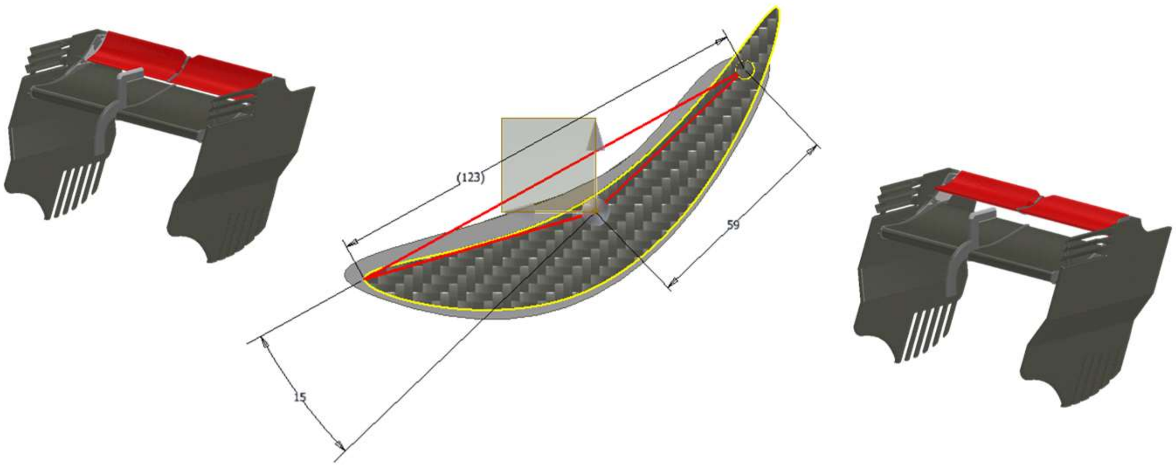
Hydraulic actuator
- Precise and accurate
- Low energy required to work

Electric actuator
- Quite energy required to work
- Precise and accurate

4 - Data

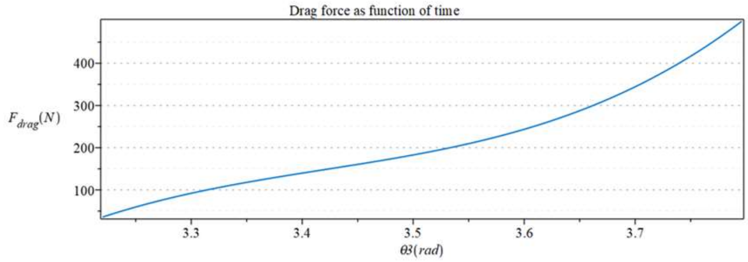
Rear wing 2017 Formula one car

In order to do a more realistic analysis we have considered a real rear wing of a formula one car. It is present in the website.

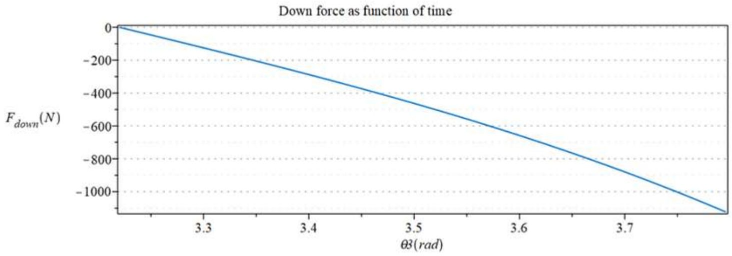


4 - Drag/Down force interpolation (from the paper)

$$drag := -150230.7727 + 3721.386708\,\gamma(t)^3 - 38190.76247\,\gamma(t)^2 + 131055.9937\,\gamma(t)$$

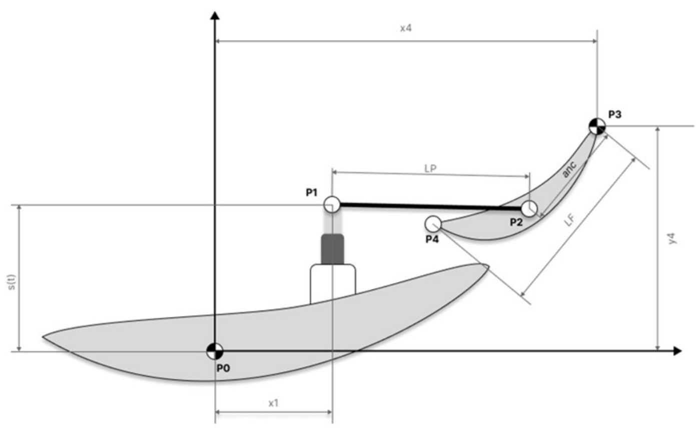


$$down := 42447.20981 - 1131.484001\,\gamma(t)^3 + 10897.17872\,\gamma(t)^2 - 36539.53600\,\gamma(t)$$

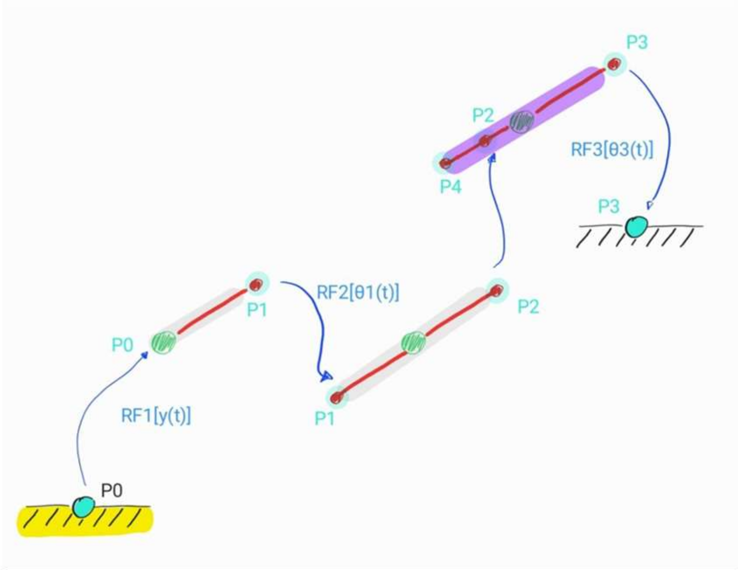


5 - Mechanism analysis

Push-up mechanism



5 - Graph of the push up mechanism



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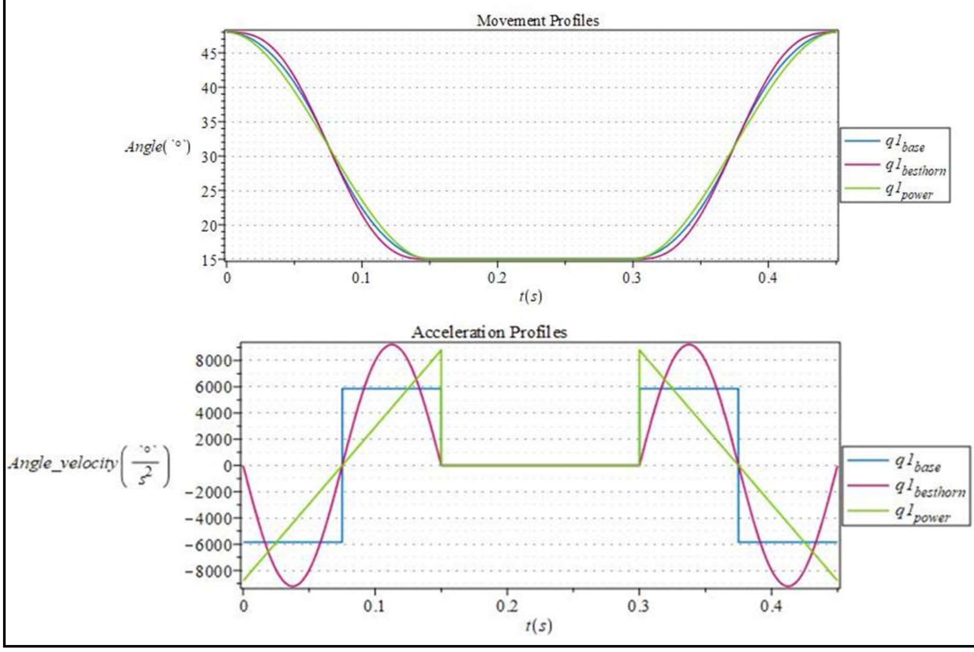
5 - Design specifications: smooth flap movement



- Smooth transitioning
- Forces' jumps avoidance
- Residual oscillations avoidance
- Feasible actuation of the piston

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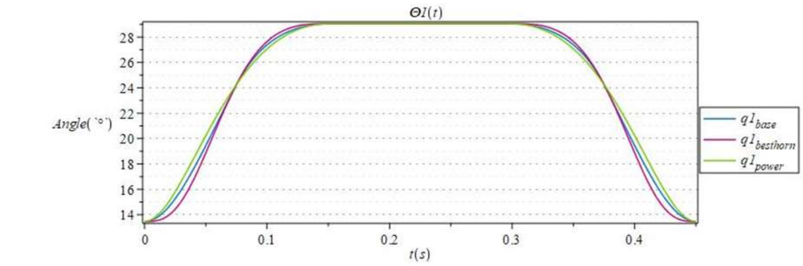
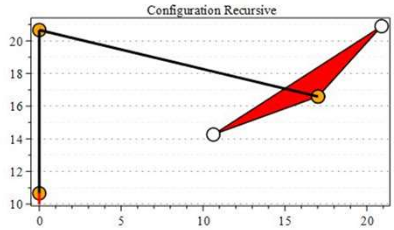
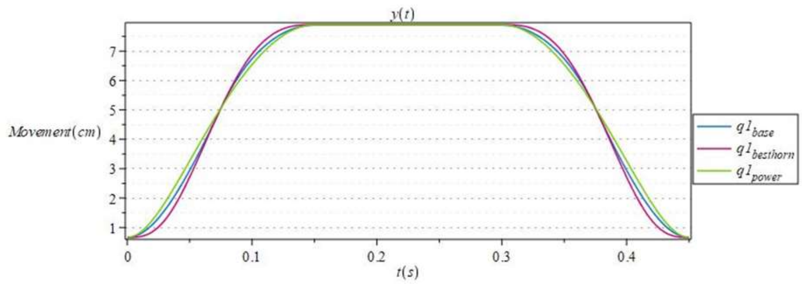
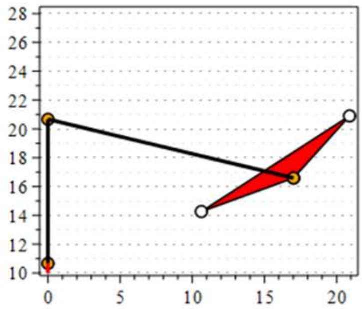
5 - Push-up Position analysis

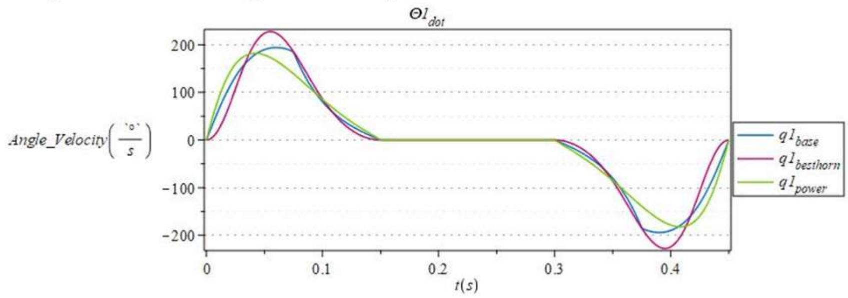


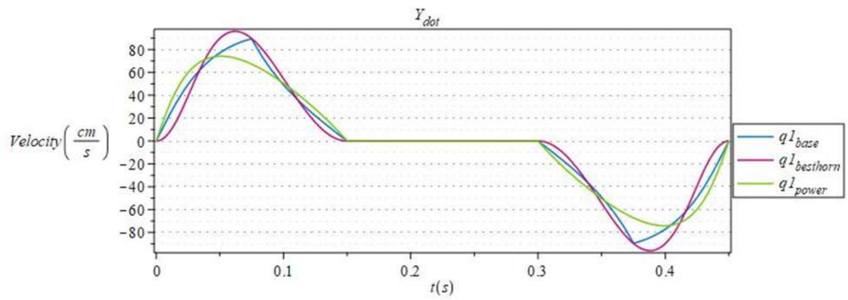




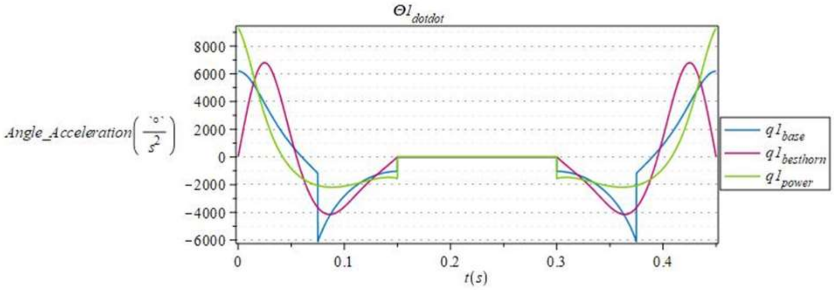


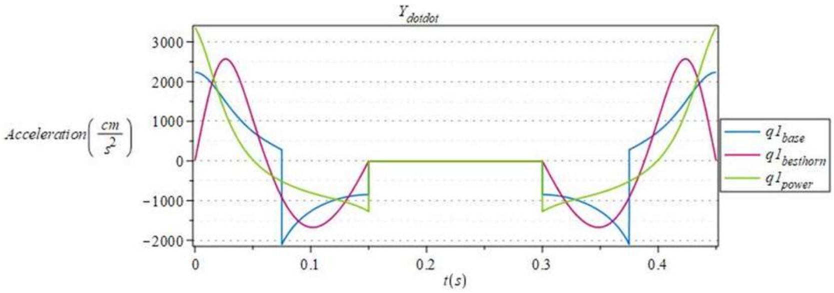
5 - Push-up Velocity analysis





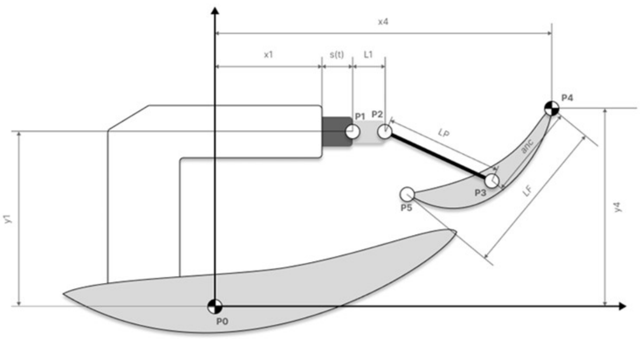
5 - Push-up Acceleration analysis



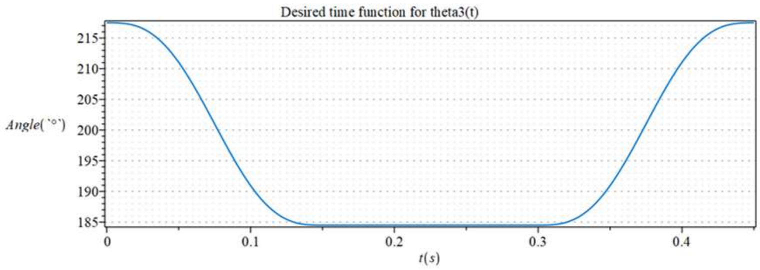


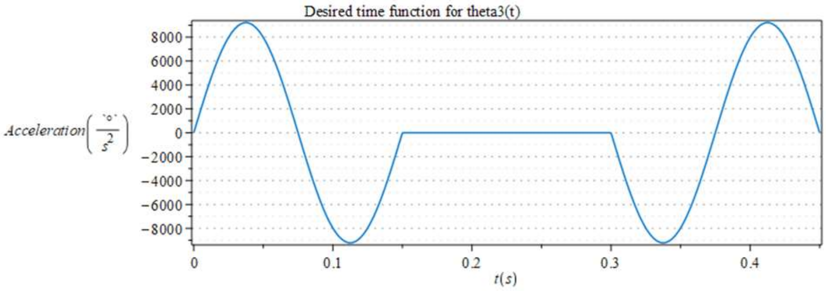
5 - Mechanism analysis

Pod-pull mechanism



5 - From the design specifications: smooth flap movement





5 - Parameters optimization from kinematics

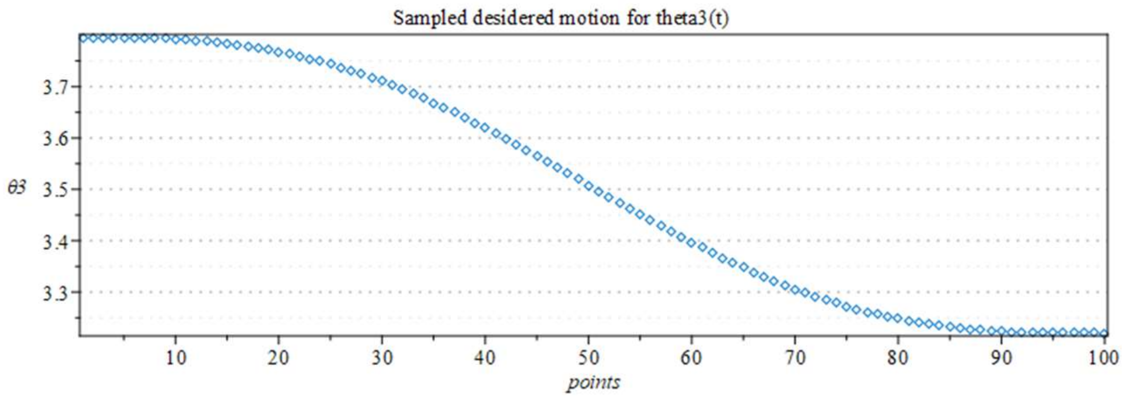
Desidered motion for θ3(t) → Motion for s(t)

Desidered generic and smooth motion for s(t)

→ Estimation of the error (cost function) → **Minimization through optimal parameters values**

$$Fd\_s := \begin{cases} s_{closed} - 88.88888890\, T^2\, s_{closed} & 0 \le T \le 0.07500000000 \\ 88.88888890\,(0.150 - T)^2\, s_{closed} & 0.07500000000 < T \le 0.150 \end{cases}$$

5 - Parameters optimization from kinematics



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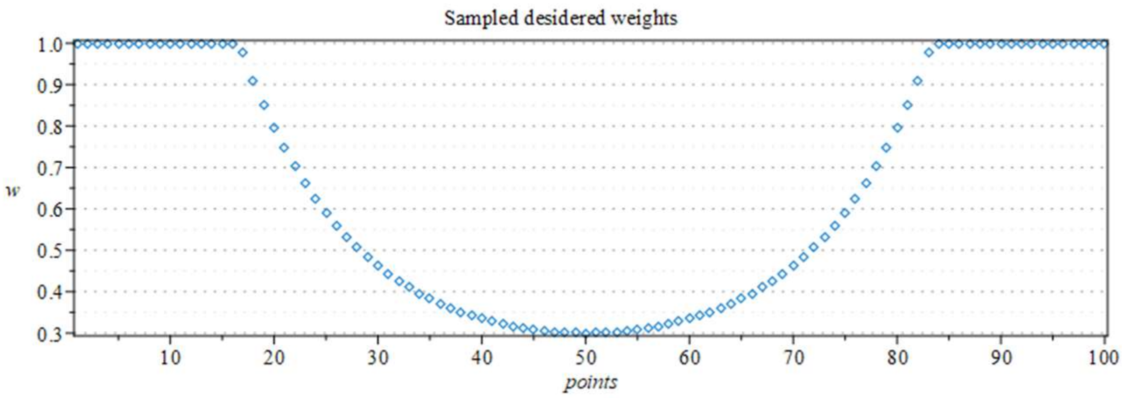
5 - Parameters optimization from kinematics



$$W = \sum_k \delta_{w_k}^{\ 2}$$

$$mygauss := -\frac{(e)^{-\frac{(T-\mu)^2}{2\,\sigma}}\,a}{2\,\pi\,\sigma}$$

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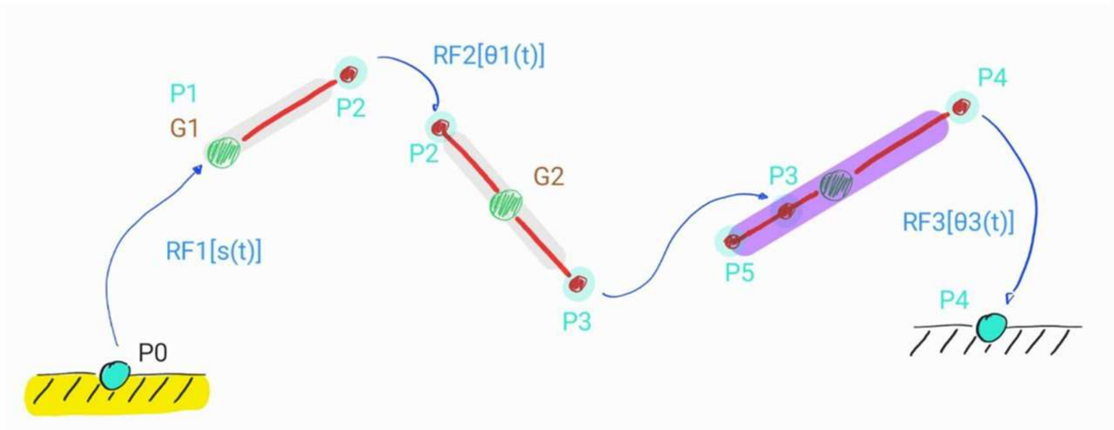
5 - Parameters optimization from kinematics

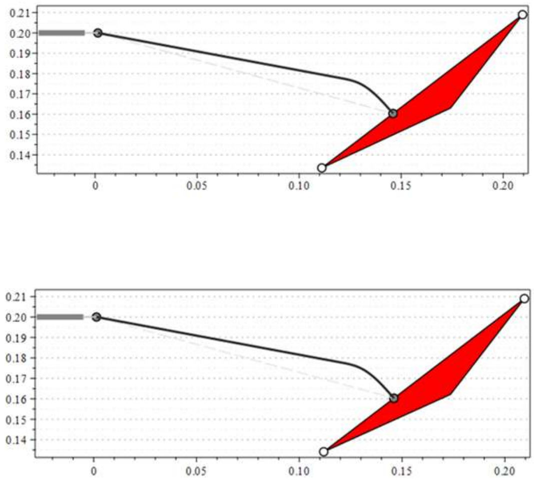
$$cost\_fun = \frac{\sum_k \delta_{w_k}^{\ 2} \left(\delta_{s_k} - s_k\right)^2}{2\,W}$$

Parameters to be optimized: ***L1, LP, anc, x1, y1, s$_{closed}$***

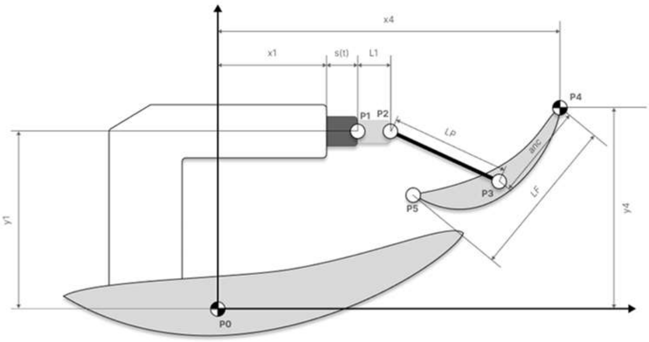
5 - Graph of the pod pull mechanism



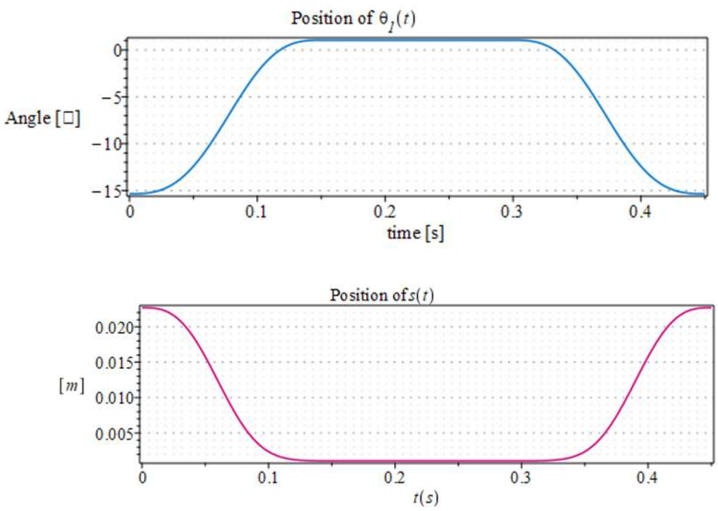
5 - Parameters optimization from kinematics



$$\begin{bmatrix} L1 = 0.00639629816056910 \\ LP = 0.150000000000000 \\ anc = 0.0800000000000000 \\ x1 = -0.0276947859218352 \\ y1 = 0.200000000000000 \\ s_{closed} = 0.0223954420363583 \end{bmatrix}$$



5 - Position, velocity, acceleration analysis



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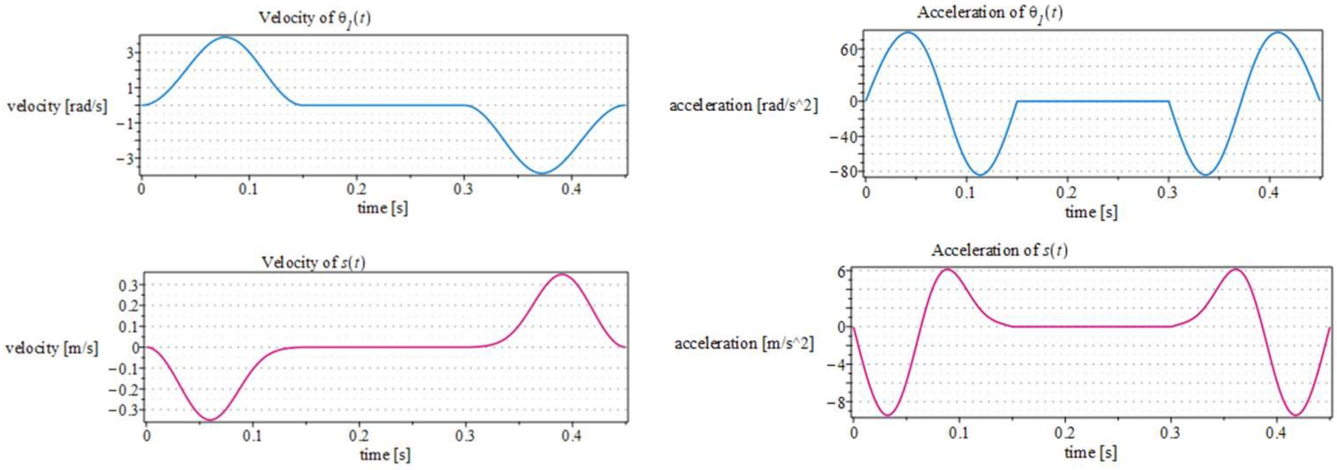
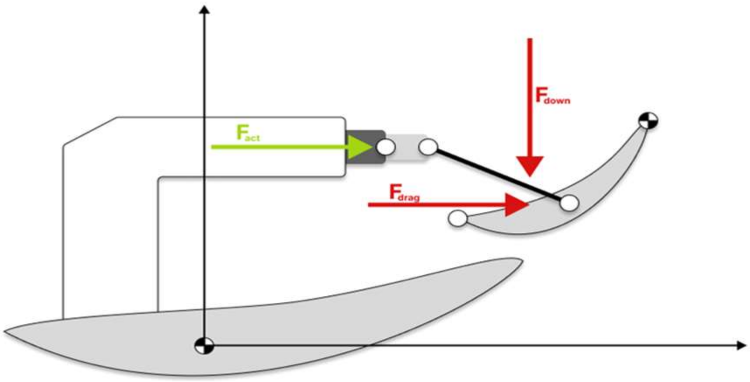
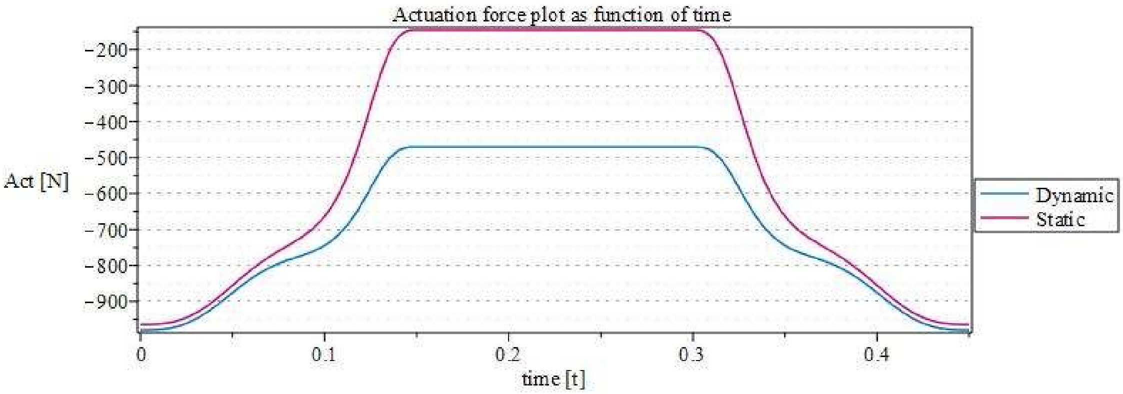


5 - Force definitions: we define the drag force and down force and we suppose that they are applied to the flap center of mass

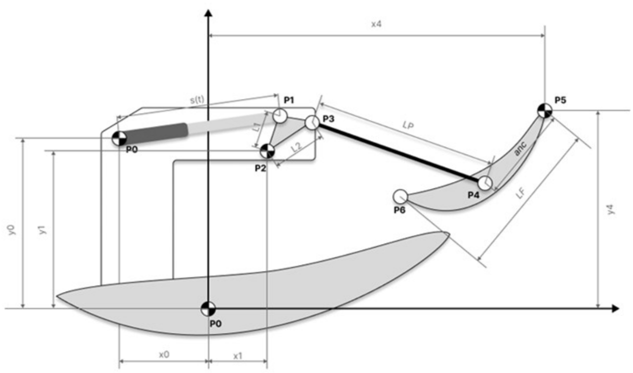


5 - Principle of virtual work

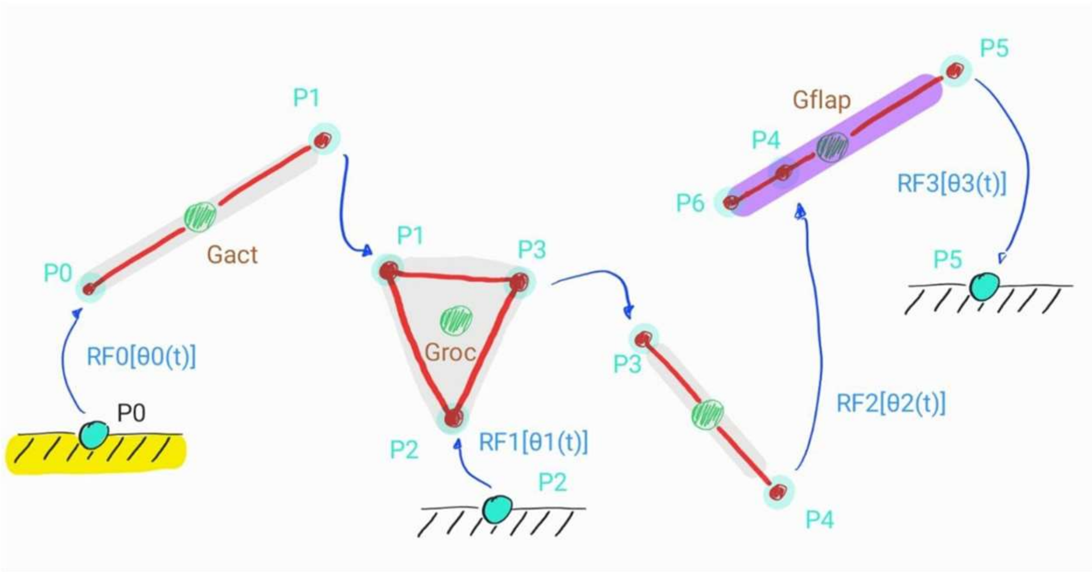


5 - Mechanism analysis

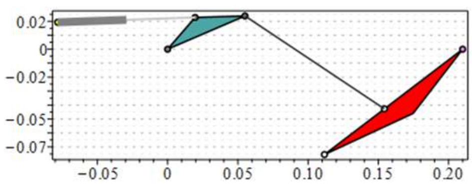
Pods and rockers mechanism

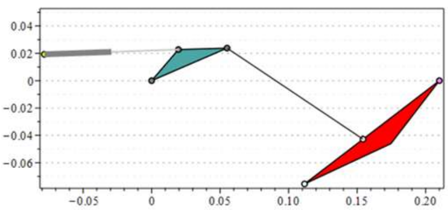


5 - Graph of the pods and rocker mechanism

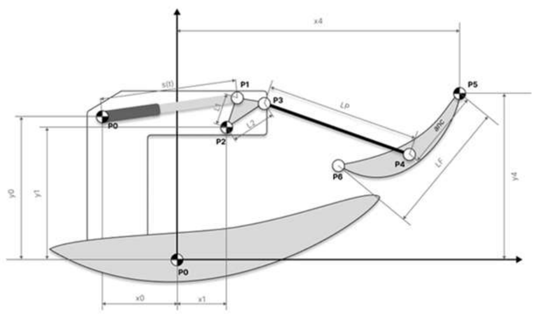


5 - Parameters optimization from kinematics

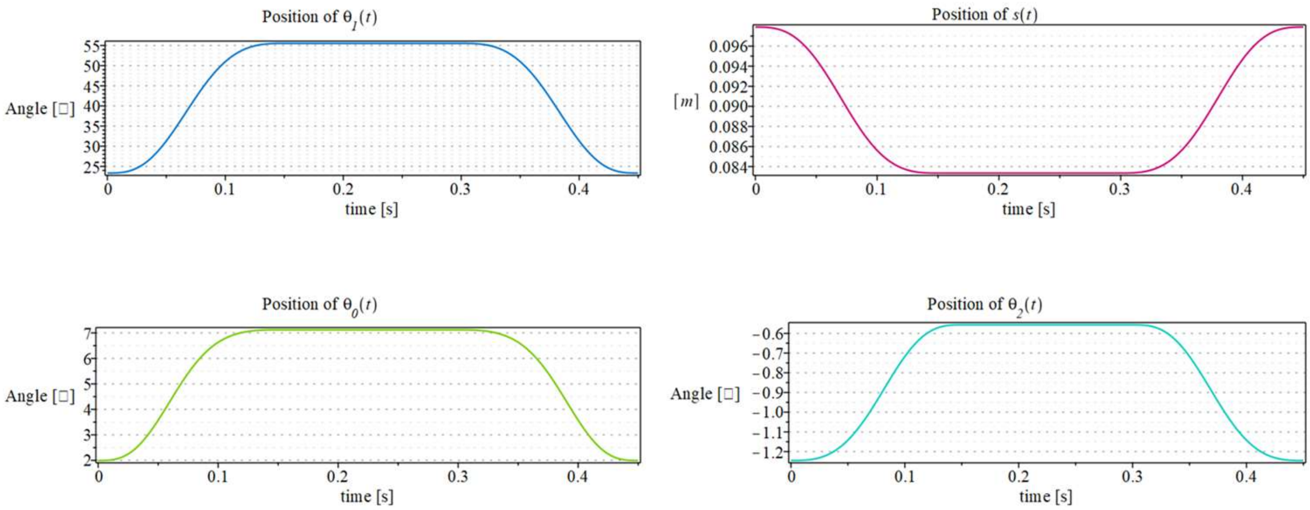




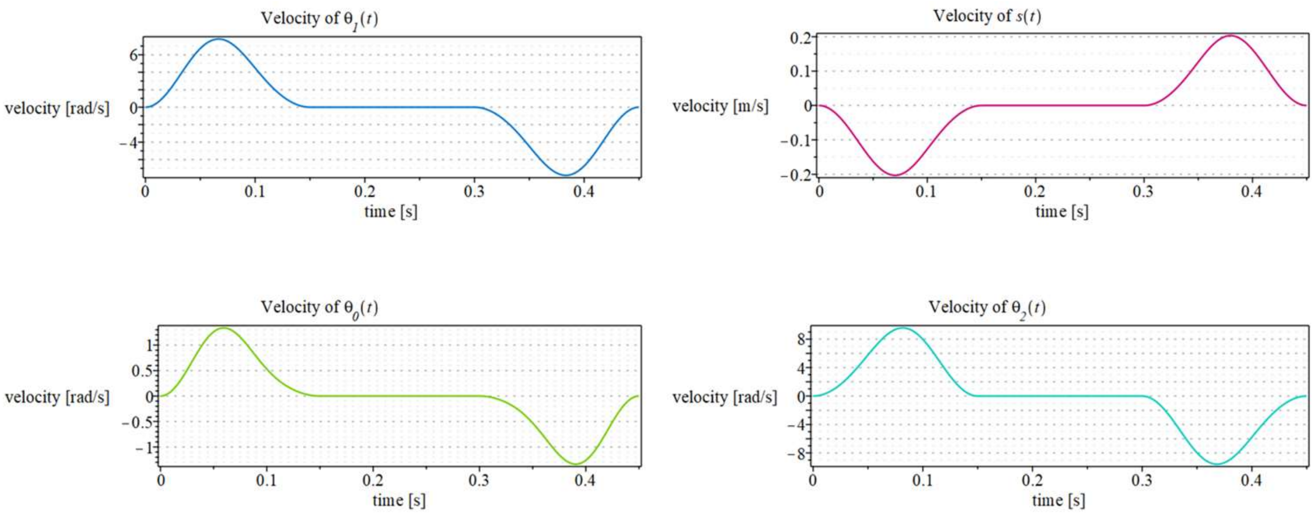
$$
\begin{bmatrix}
L1 = 0.0300000000000000 \\
L2 = 0.0600000000000000 \\
L3 = 0.119451346161947 \\
anc = 0.0702320789119197 \\
s_{open} = 0.0829746576750181 \\
x_0 = -0.0782696135684135 \\
y_0 = 0.0193182452814893 \\
y_3 = -7.82294919842771 \times 10^{-6} \\
s_{closed} = 0.0980584212573635 \\
\theta_r = 0.452909809891713
\end{bmatrix}
$$



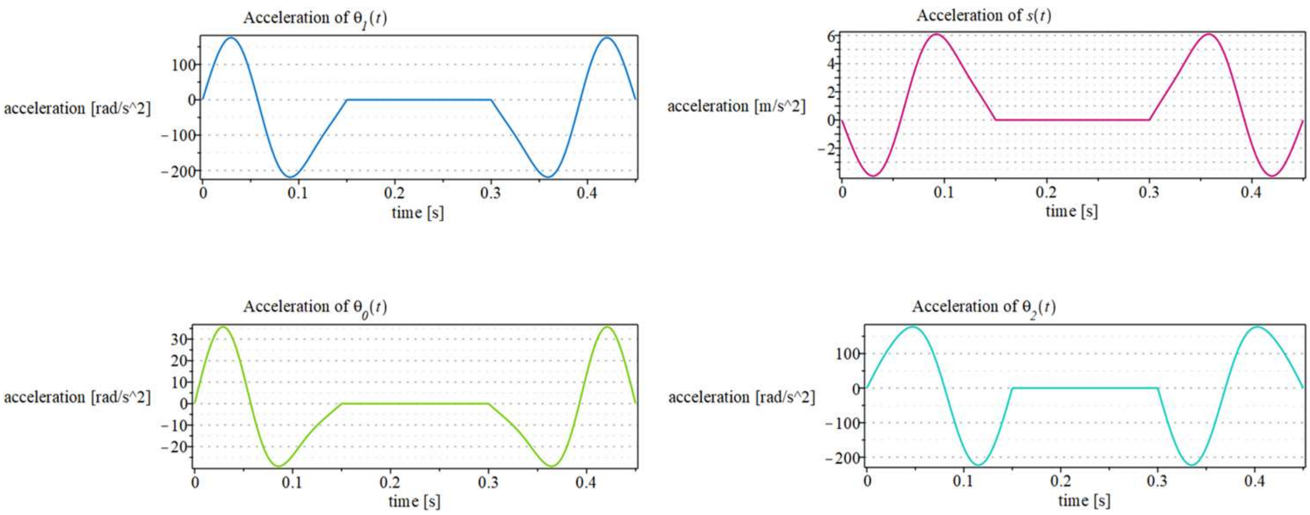
5 - Position analysis



5 - Velocity analysis

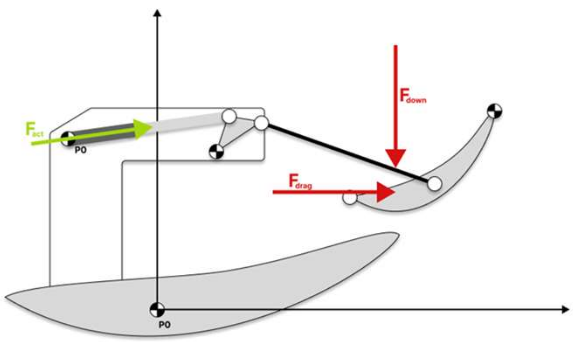


5 - Acceleration analysis



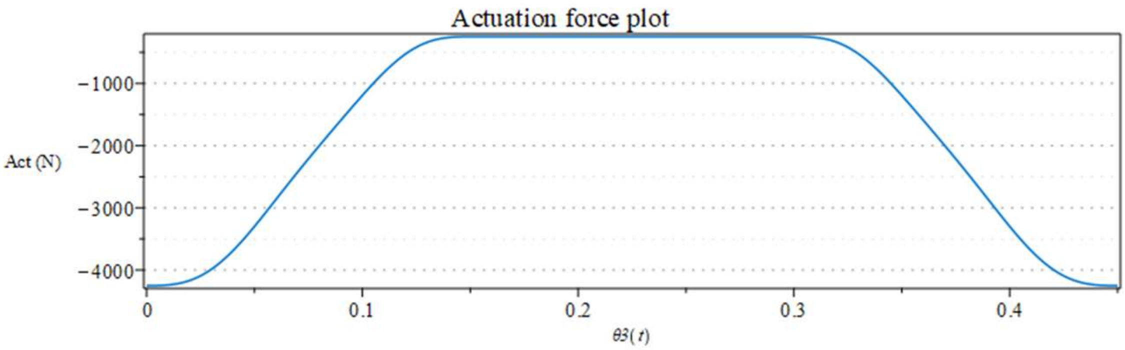
5 - Pods and rockers analysis

Force definitions: we define the drag force and down force and we suppose that they are applied to the flap center of mass



5 - Pods and rockers analysis

Dynamic analysis: Principle of virtual work



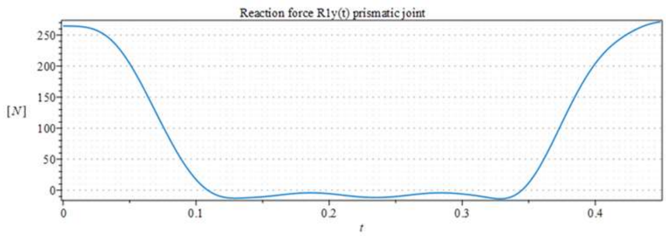
5 - Pod Pull analysis

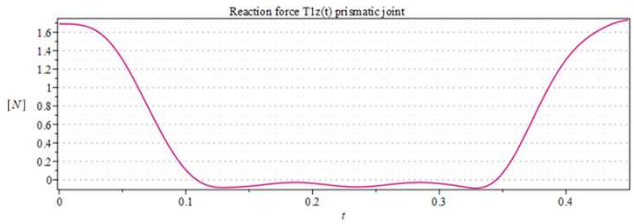
Equation of motion, Newton-Euler formulation

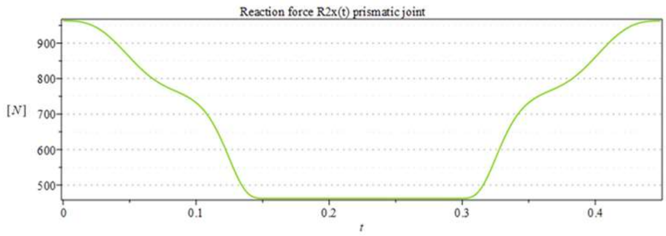
$$\begin{bmatrix}
m1\left(\frac{d^2}{dt^2}s(t)\right) - act(t) - R2x(t) \\
g\,m1 - R1y(t) - R2y(t) \\
-R2y(t)\,L1 - T1z(t) \\
-\frac{m2\left(LP\left(\frac{d}{dt}\theta1(t)\right)^2\cos(\theta1(t)) + LP\left(\frac{d^2}{dt^2}\theta1(t)\right)\sin(\theta1(t)) - 2\frac{d^2}{dt^2}s(t)\right)}{2} + R2x(t) - R3x(t) \\
-\frac{m2\,LP\left(\left(\frac{d}{dt}\theta1(t)\right)^2\sin(\theta1(t)) - \left(\frac{d^2}{dt^2}\theta1(t)\right)\cos(\theta1(t))\right)}{2} + g\,m2 + R2y(t) - R3y(t) \\
Iz2\left(\frac{d^2}{dt^2}\theta1(t)\right) + \frac{\left(\left(-R2y(t) - R3y(t)\right)\cos(\theta1(t)) + \sin(\theta1(t))\left(R2x(t) + R3x(t)\right)\right)LP}{2} \\
-m3\left(\frac{d}{dt}\theta3(t)\right)^2\cos(\theta3(t)+\psi)\,LFb - m3\left(\frac{d^2}{dt^2}\theta3(t)\right)\sin(\theta3(t)+\psi)\,LFb + R3x(t) - R4x(t) - p_drag \\
-m3\left(\frac{d}{dt}\theta3(t)\right)^2\sin(\theta3(t)+\psi)\,LFb + m3\left(\frac{d^2}{dt^2}\theta3(t)\right)\cos(\theta3(t)+\psi)\,LFb + g\,m3 - R4y(t) + R3y(t) - p_down \\
-LFb\left(R3y(t) - R4y(t)\right)\cos(\theta3(t)+\psi) + LFb\left(R3x(t) - R4x(t)\right)\sin(\theta3(t)+\psi) + Iz3\left(\frac{d^2}{dt^2}\theta3(t)\right) + R3y(t)\,LP\cos(\theta1(t)) - R3x(t)\,LP\sin(\theta1(t)) + \left(s(t) + L1 + x1 - x4\right)R3y(t) - R3x(t)\left(y1 - y4\right) \\
-LP\cos(\theta1(t)) + \cos(\theta3(t))\,anc - L1 - s(t) - x1 + x4 \\
-LP\sin(\theta1(t)) + \sin(\theta3(t))\,anc - y1 + y4
\end{bmatrix}$$

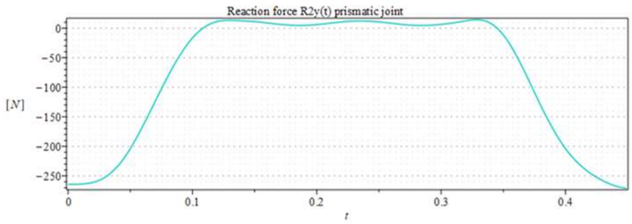
$$y\_vars\_ne := [s(t), \theta1(t), \theta3(t), R1y(t), R2x(t), R2y(t), T1z(t), R3x(t), R3y(t), R4x(t), R4y(t)]$$

5 - Reaction forces

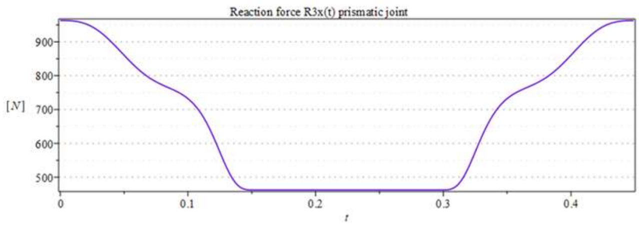


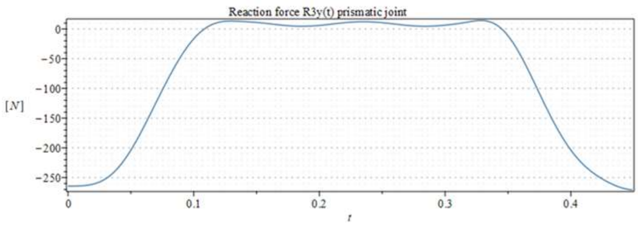


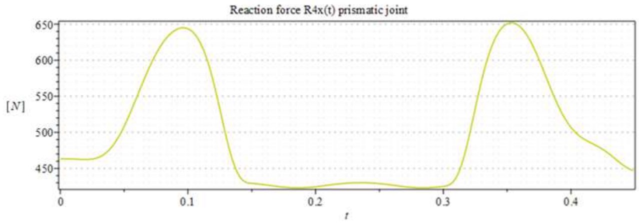


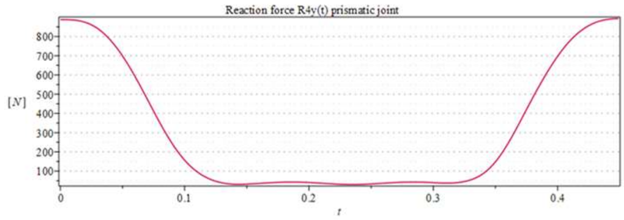


5 - Reaction forces



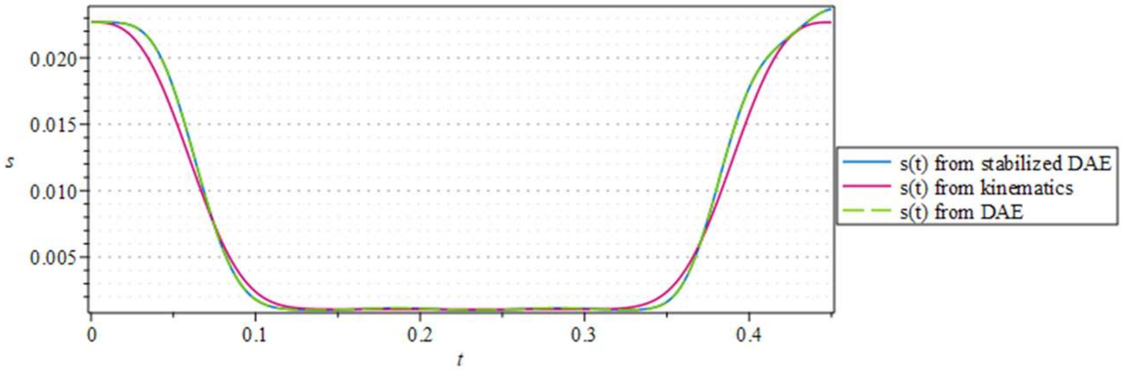






5 - DAE solution

It is shown the plot of s(t) obtained from three different analysis



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5 - Pod Pull analysis

Equation of motion, Lagrange formulation

$$\left[\begin{array}{c}
\frac{(2\,m1 + 2\,m2)\left(\frac{d^2}{dt^2}\,s(t)\right)}{2} - \frac{LP\left(\frac{d}{dt}\,\theta 1(t)\right)^2 \cos(\theta 1(t))\,m2}{2} - \frac{m2\,LP\sin(\theta 1(t))\left(\frac{d^2}{dt^2}\,\theta 1(t)\right)}{2} - \lambda 1(t) - act(t) \\
\frac{\left(LP^2\,m2 + 4\,Iz2\right)\left(\frac{d^2}{dt^2}\,\theta 1(t)\right)}{4} + \frac{LP\left(-\sin(\theta 1(t))\,m2\left(\frac{d^2}{dt^2}\,s(t)\right) + (g\,m2 - 2\,\lambda 2(t))\cos(\theta 1(t)) + 2\sin(\theta 1(t))\,\lambda 1(t)\right)}{2} \\
\left(\frac{d^2}{dt^2}\,\theta 3(t)\right)\left(LFb^2\,m3 + Iz3\right) + LFb\,(g\,m3 - p_down)\cos(\theta 3(t) + \psi) + LFb\sin(\theta 3(t) + \psi)\,p_drag - anc\,(\lambda 1(t)\sin(\theta 3(t)) - \lambda 2(t)\cos(\theta 3(t))) \\
-LP\cos(\theta 1(t)) + \cos(\theta 3(t))\,anc - L1 - s(t) - x1 + x4 \\
-LP\sin(\theta 1(t)) + \sin(\theta 3(t))\,anc - y1 + y4
\end{array}\right]$$

$$y\_vars\_la := [s(t), \theta 1(t), \theta 3(t), \lambda 1(t), \lambda 2(t)]$$

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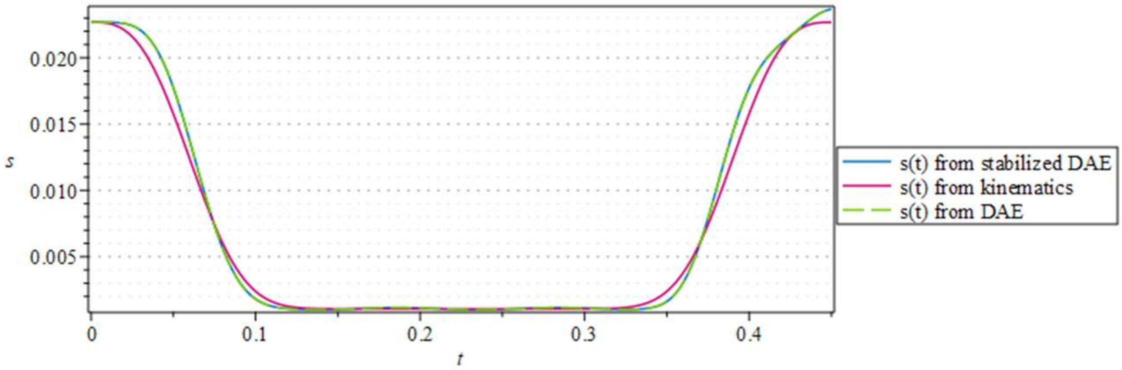
5 - DAE solution

It is shown the plot of s(t) obtained from three different analysis



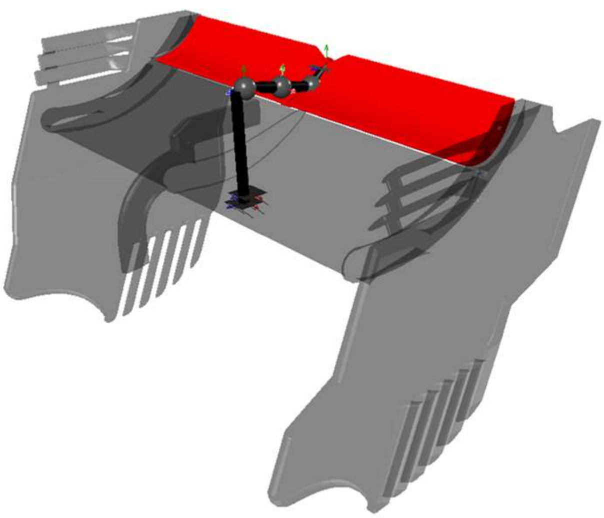
5 - Dynamic Parameters Optimization

Dynamic optimization - NE

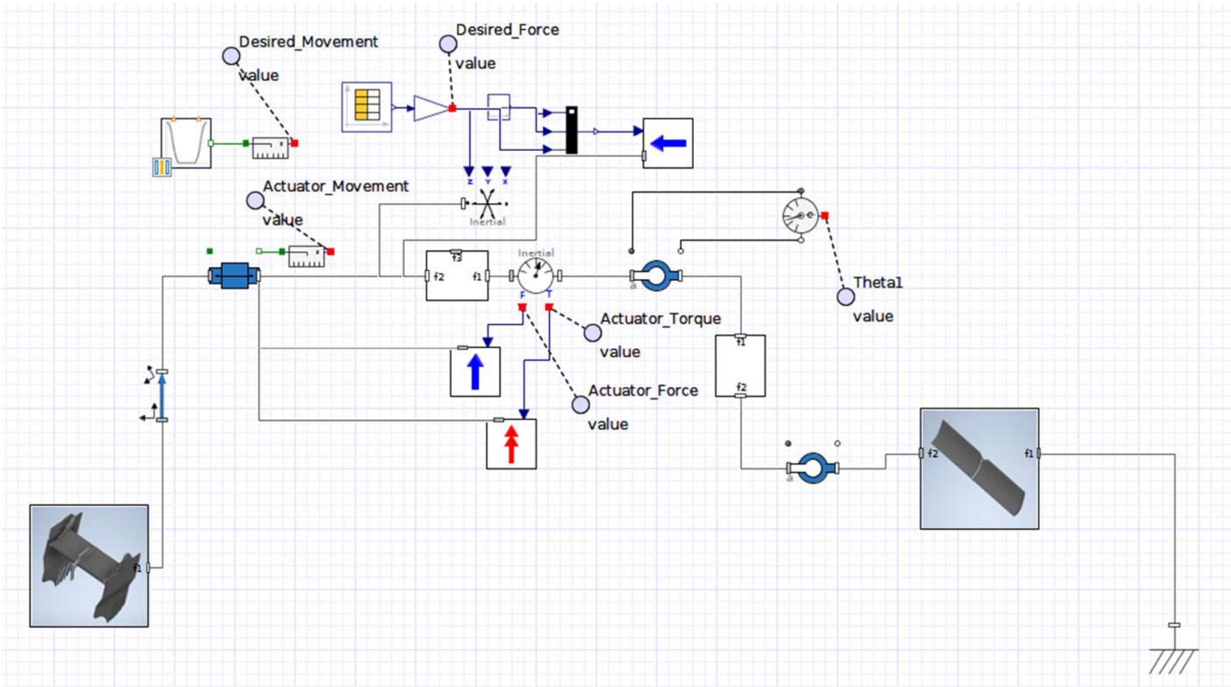
```
> dynam_opt_ne := proc(aaa,bbb,ccc,ddd,eee)
    local param,E,G,NE,NG,r_vars0,dof0,vel_dof0,qD0,vel_qD0,ics0,sol_act_dinam,dae_ics,dae_sys,sol_dae,cost_fun,i,k:

    param := [L1 = aaa,LP = bbb,anc = ccc,x1 = ddd,y1 = eee]:

    #Estimate the initial conditions
    dof0 := theta3(t) = flap_closed:
    vel_dof0 := diff(theta3(t),t) = 0:
    qD0 := op(evalf(subs(dof0, data_dae,param, sol_kine))):
    vel_qD0 := op(subs(vel_dof0, dof0, data_dae,param, [sol_vel])):
    ics0 := [dof0, vel_dof0, qD0, vel_qD0]:

    #Estimate the actuation force
    sol_act_dinam := subs(forcesub,gamma(t)=q1_profile_t,sol_kine,theta3(t)=q1_profile_t,data_dae,param,sol_act):

    #Estimate the reaction forces
    E, G := GenerateMatrix(subs(forcesub,gamma(t)=theta3(t),eqns), diff(q_vars,t,t) union r_vars):
    NE := evalf(subs(subs(forcesub,gamma(t)=theta3(t),sol_act), ics0, data_dae,param, E)):
    NG := evalf(subs(subs(forcesub,gamma(t)=theta3(t),sol_act), ics0, data_dae,param, G)):
    LinearSolve(NE, NG):
    r_vars0 := [seq(r_vars[i] = %[-i],i=1..nops(r_vars))]:

    #Assembling the generic DAE
    dae_ics := subs(t=0,data_dae,convert(convert(ics0,set)  minus {diff(theta1(t),t)=0} ,D) union r_vars0 ):
    dae_sys := convert(subs(sol_act_dinam,forcesub,gamma(t)=q1_profile_t,data_dae, ne_eqns) union dae_ics,set):
    sol_dae := dsolve(dae_sys,numeric,stiff=true,parameters = [L1,LP,anc,x1,y1]):
    sol_dae(parameters = subs(param,[L1,LP,anc,x1,y1])):

    #Cost function
    cost_fun :=1/W*add(subs(data_dae,param,(delta__s[k]-rhs(sol_dae(k/np*actuation_time)[10]))^2),k=1..np);
  end proc:
```

5 - Pod Pull - inventor environment

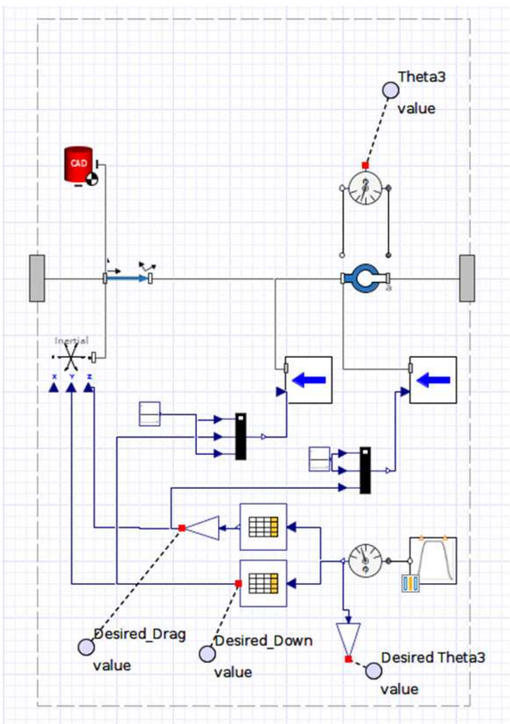
6 - MapleSim analysis



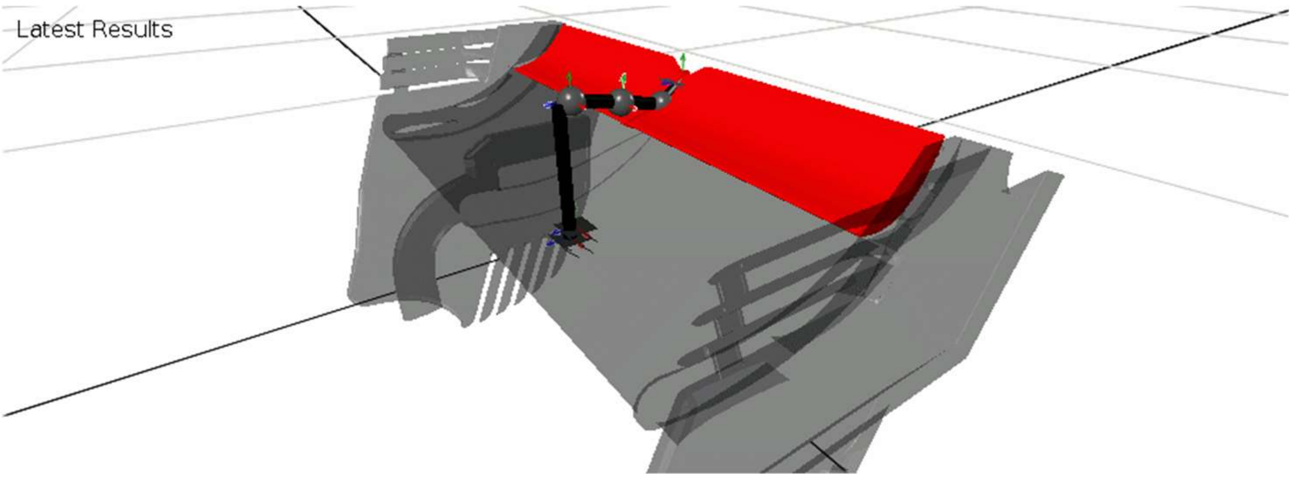
6 - Main File

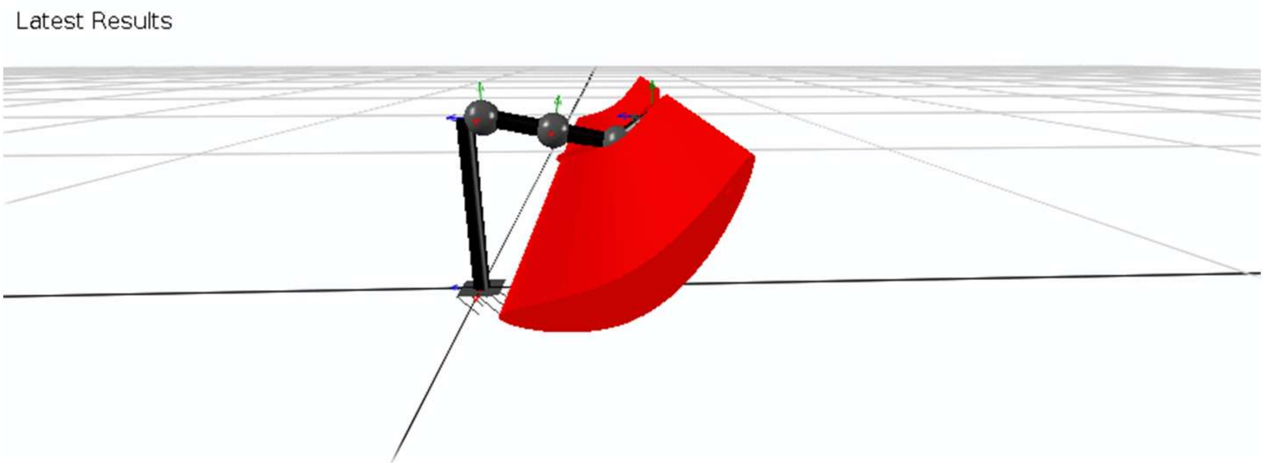


6 - Flap subfile

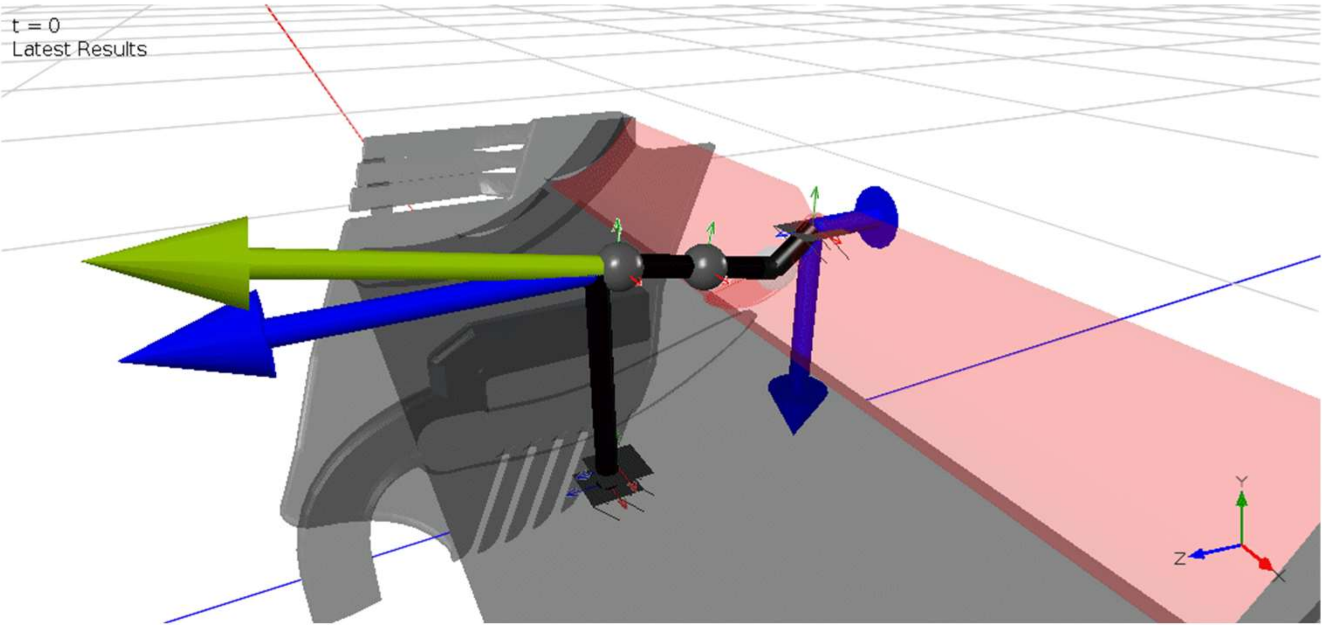


6 - Wing animation

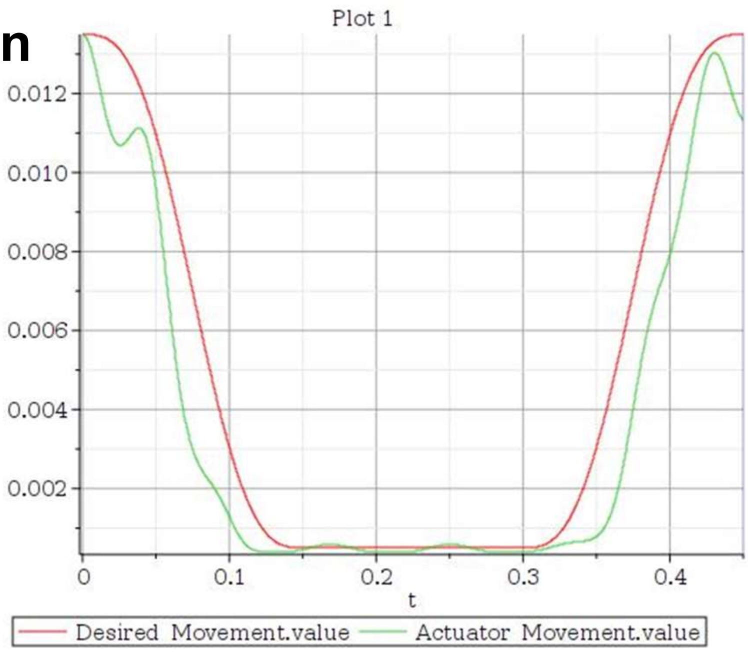




6 - Wing forces



6 - Movements comparison

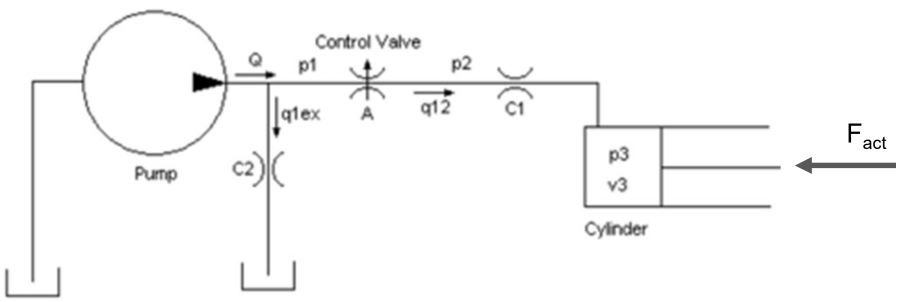


7 - Maple Hydraulics analysis

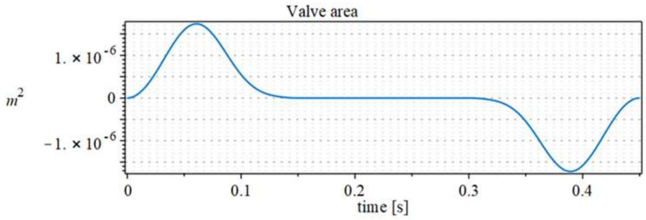
$$D\_eqns\_1 := \left[\beta \left(\frac{d}{dt} V3(t) \right) + V3(t)\, To_{Bar} \left(\frac{d}{dt} p3(t) \right) - q_{12}(t)\, \beta \right]$$

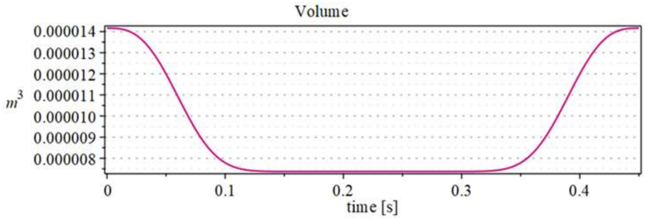
$$AE\_eqns\_1 := \left[\begin{array}{c} q1_{lex}(t) - To_{Bar}\, p1(t)\, C2 \\ q_{12}(t) - \sqrt{2} \sqrt{\frac{\sqrt{\left(To_{Bar}\, p1(t) - To_{Bar}\, p2(t)\right)^2 + \epsilon^2}}{\rho}} \tanh\left(\frac{To_{Bar}\, p1(t) - To_{Bar}\, p2(t)}{\epsilon} \right) A(t)\, Cd \\ Q(t) - q_{12}(t) - q1_{lex}(t) \\ V3(t) - V30 - s(t)\, Ac \\ q_{23}(t) - q_{12}(t) \\ q_{12}(t) - \left(To_{Bar}\, p2(t) - To_{Bar}\, p3(t)\right) C1 \\ \left(\frac{d^2}{dt^2} s(t) \right) mp - Ac\, To_{Bar}\, p3(t) + act(t) \end{array} \right]$$

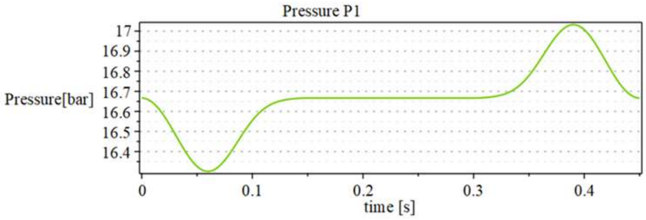
7 - Maple Hydraulics analysis

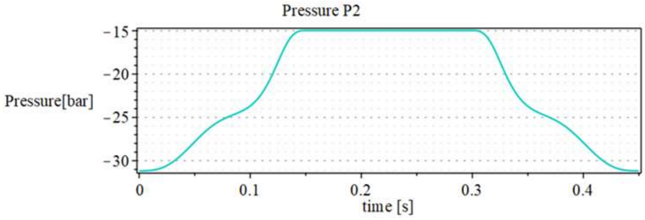


7 - Maple Hydraulics analysis

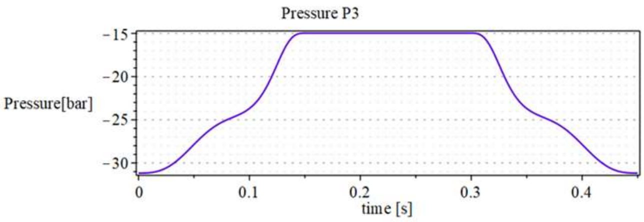


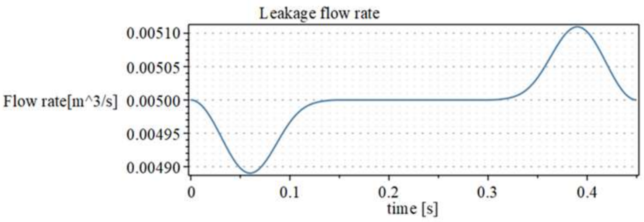


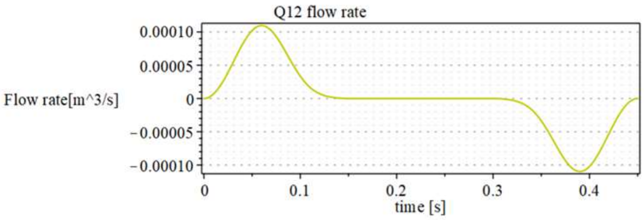


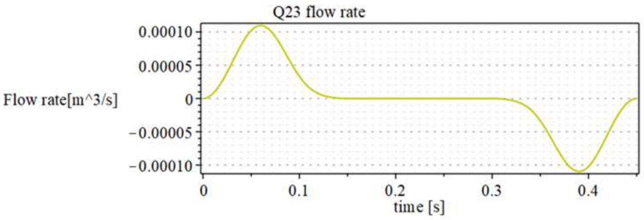


7 - Maple Hydraulics analysis









7 - Maple Hydraulics analysis

Operating Pressure - 207bar (3000psi)
Maximum RPM - 11,000
Displacement - 0 - 2.46cubic centimeters per Rev (0.15inch)
Max Flow Per Minute - 25.7L (6.8USG)
Dry Weight without customer specific mount flange - 1.18KG (2.6lbs)
Length without customer specific mount flange - 90mm - 57mmW - 80mmH

Materials - Customer specific mount flange - Titanium.
Main gold body - 7 Series Aluminium.
Swash plate piston control housing - Cast Aluminum.
Rear Outlet cap - Cast Stainless.
Internals - Steel/Forged steel.

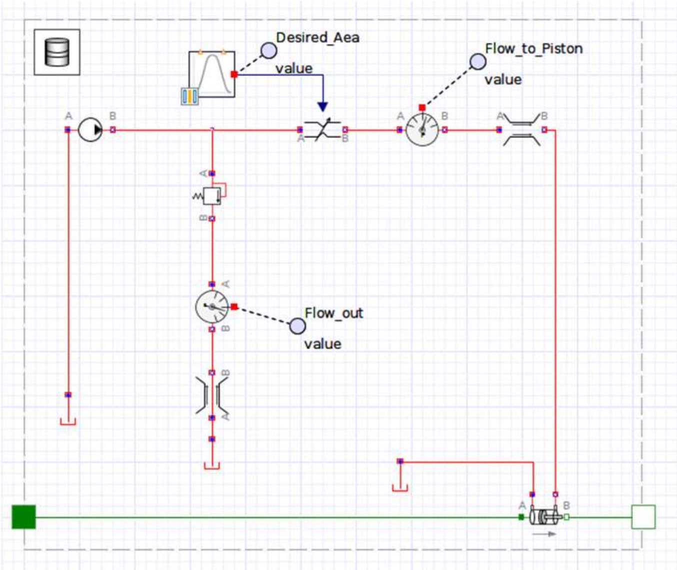
https://www.f1technical.net/forum/viewtopic.php?t=28398

7 - Maple Hydraulics analysis

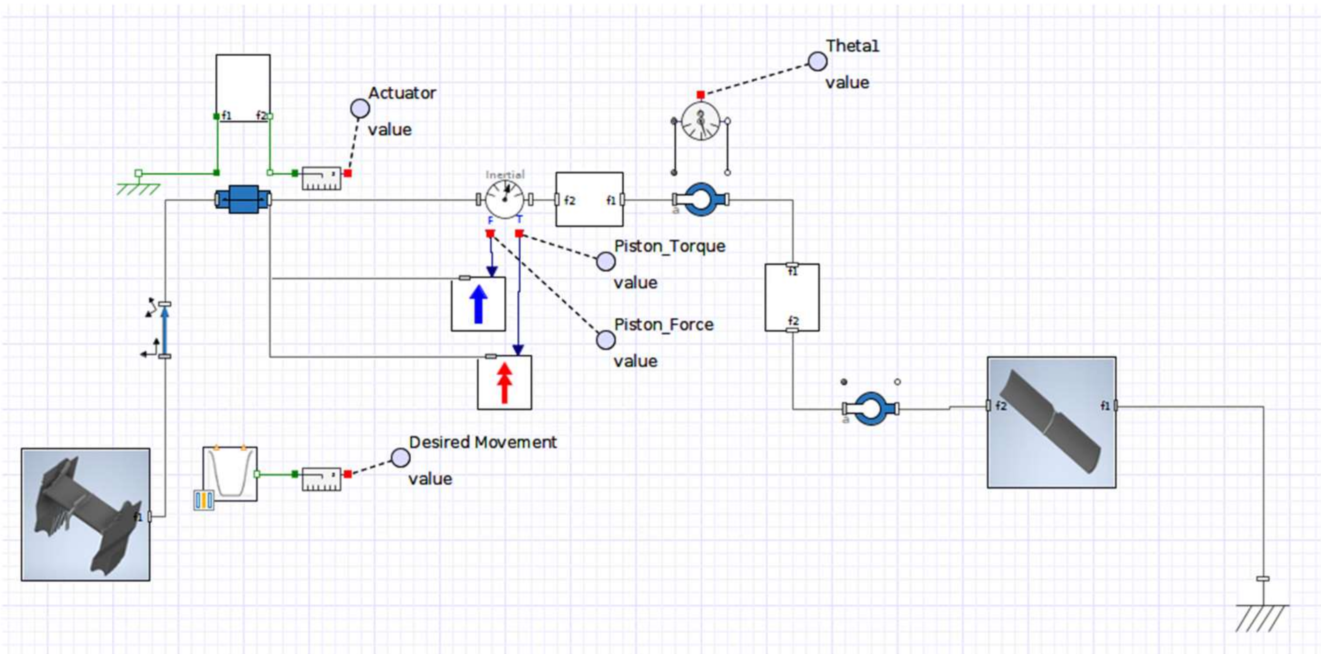
BUCHER
hydraulics

Gear Pumps - AP05

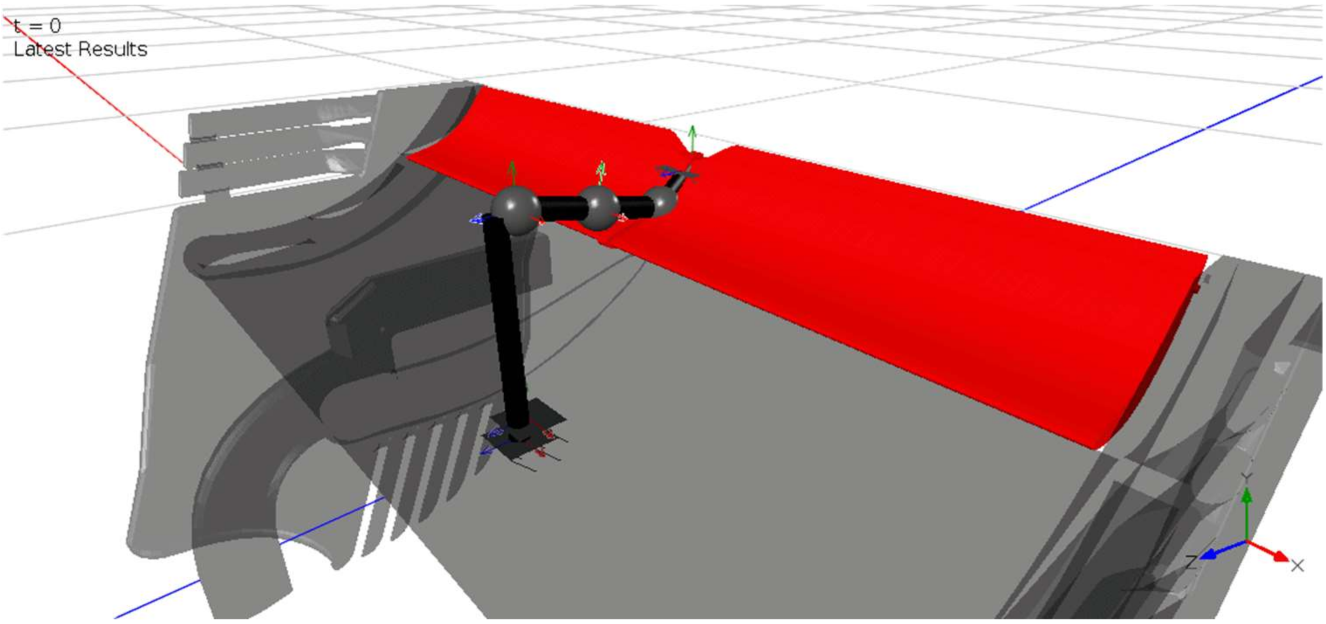
7 - MapleSim Hydraulics analysis, Hydraulic Circuit



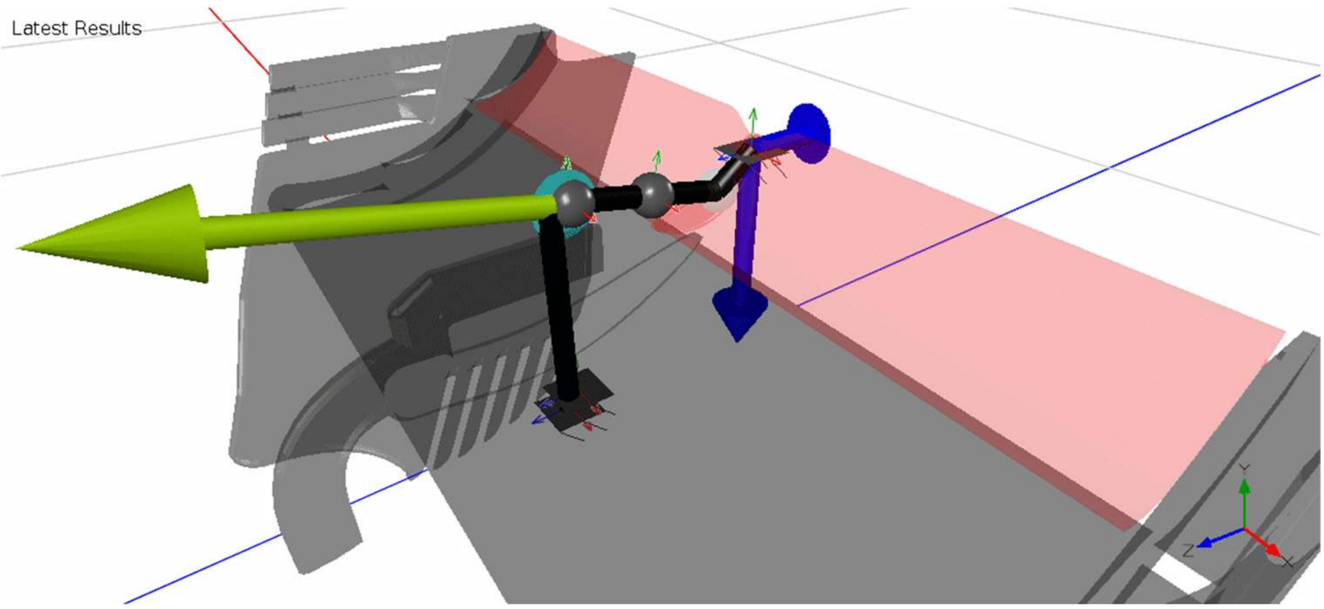
7 - Hydraulic Main File



7 - Wing Movement



7 - Wing Forces



7 - Movements comparison