Dynamics of mechanical press

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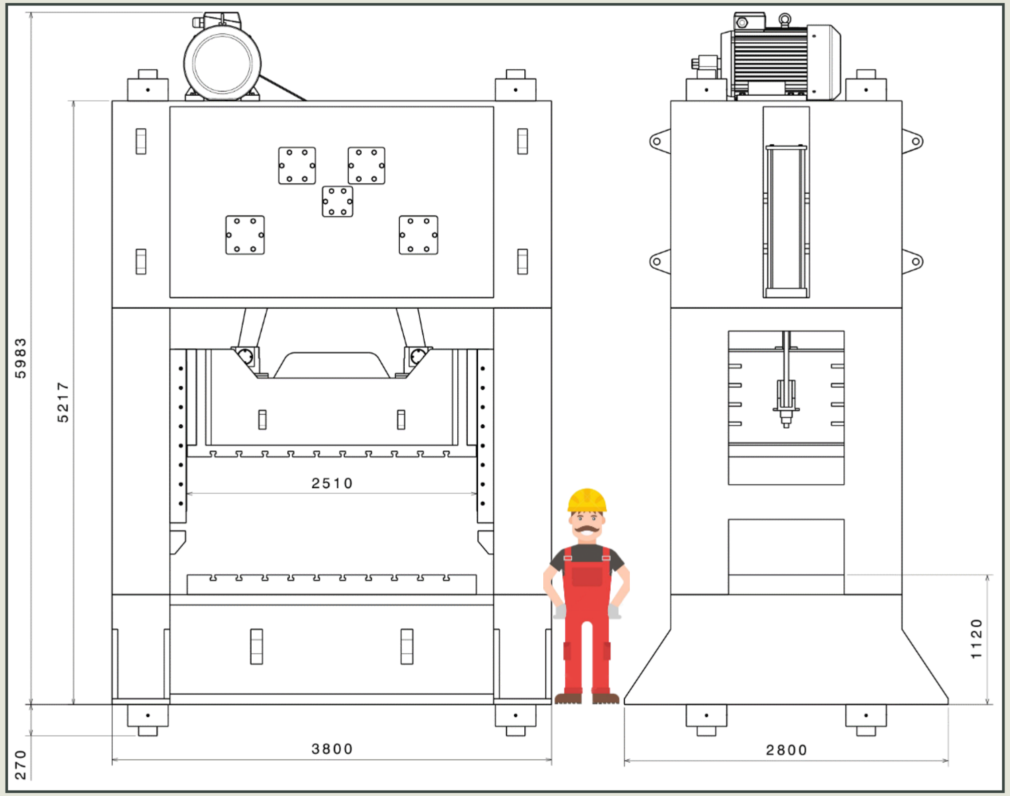
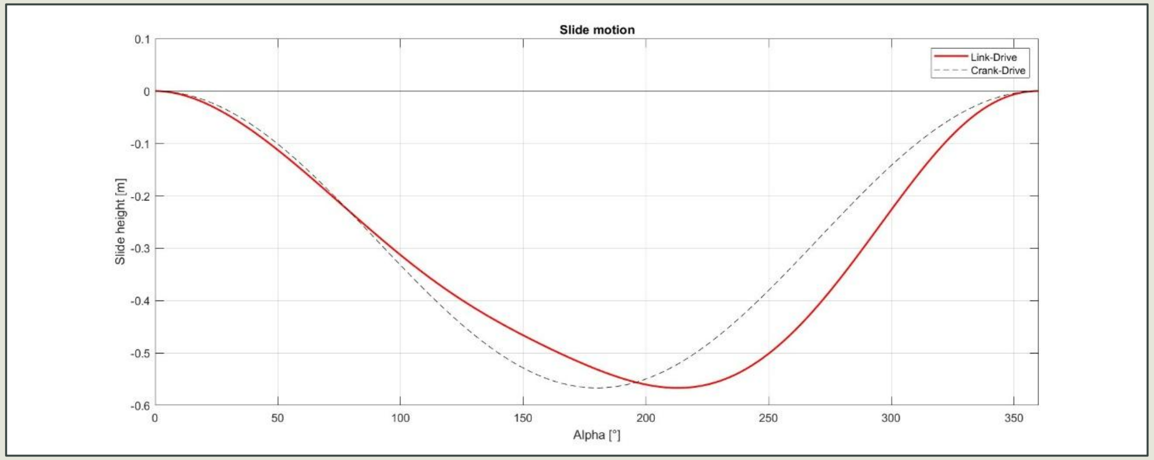
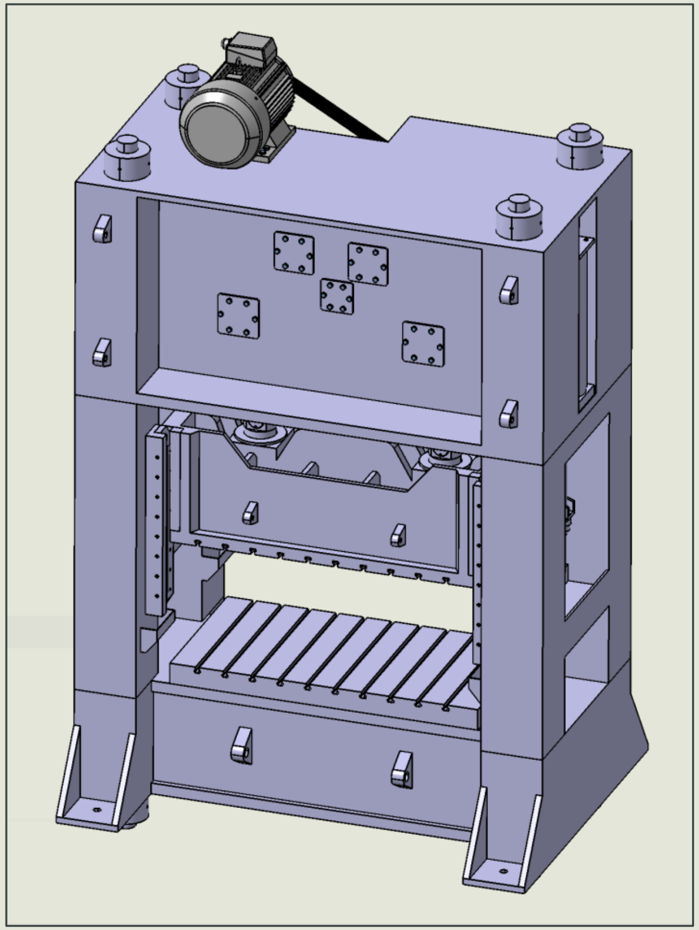
POLITECNICO
MILANO 1863



- Frame dimensions: 5.2 x 3.8 x 2.8 [m]
- Total weight: 90T (8400kg only the slide)
- Tonnage: 300T (e.i. 3MN)
- Frequency: 20 Hits/min
- Engine: three-phase asynchronous electric (315kW)
- Link drive motion

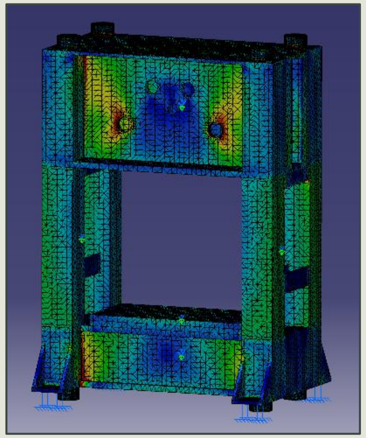


The aim of the project

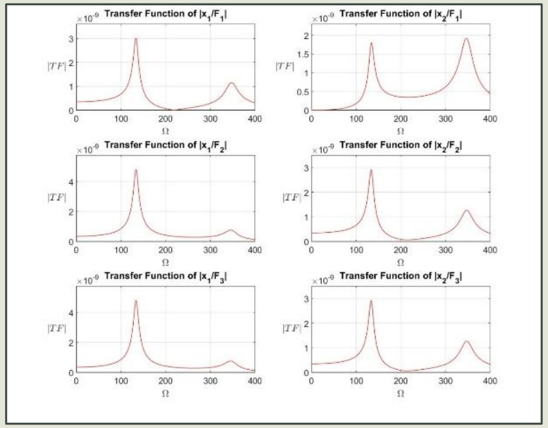


Forces (t)
Torques (t)

Static dimensioning of frame



Vibration analysis



Dynamics equations

- Lagrangian mechanics

From **Virtual Work** to **Lagrange's equations** (I° kind)

- Virtual Work

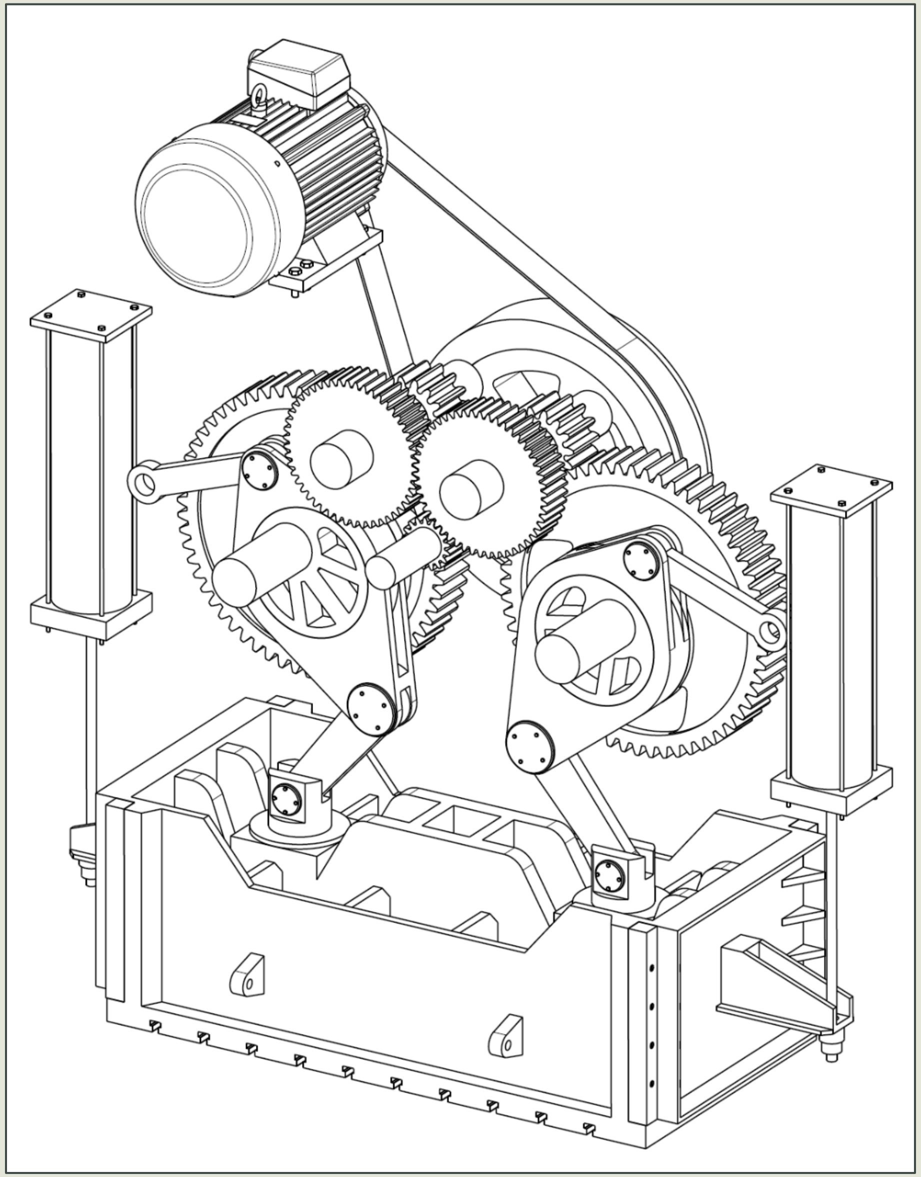
$$\delta W = \sum_{k=1}^{n} (Q_{in,k} + Q_k)\delta q_k = 0$$

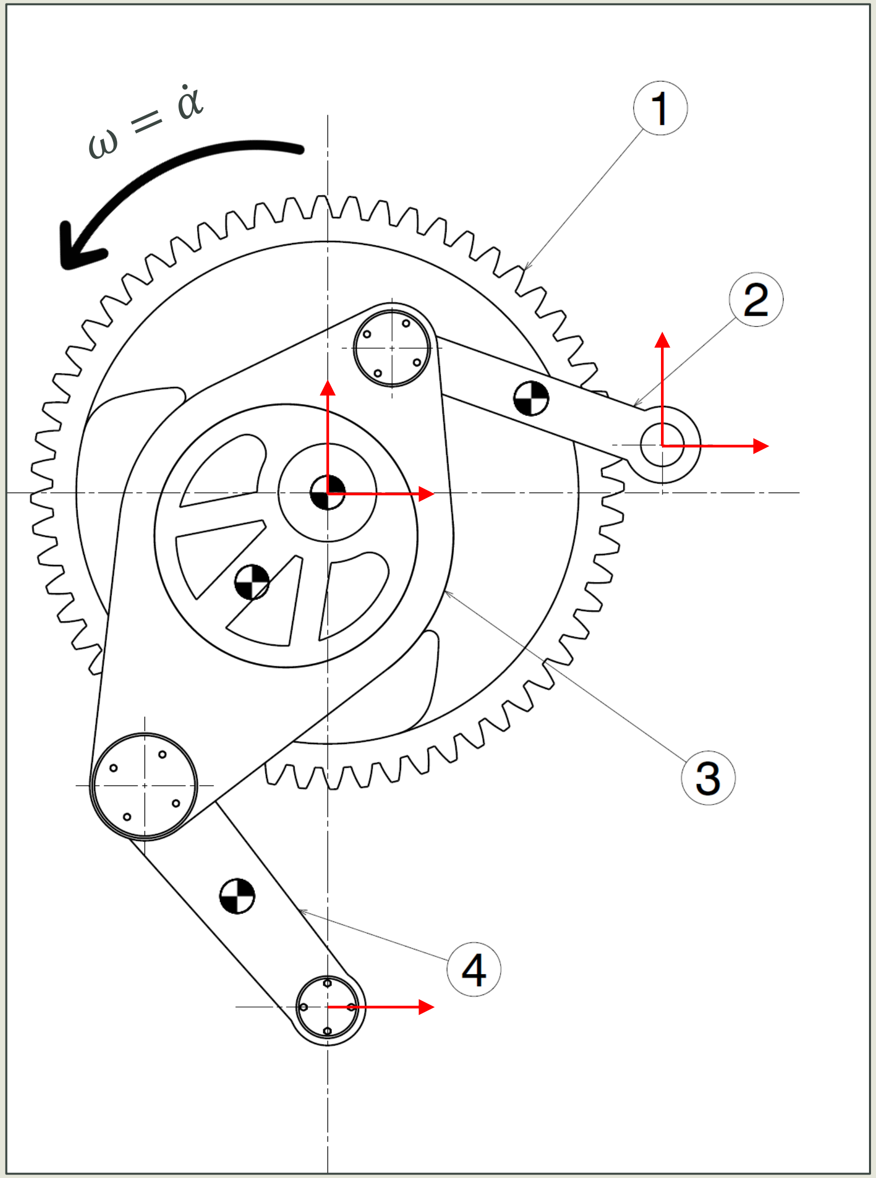
!! FOR EACH δq_k !! --> n eq.

↓

- Lagrange's equation

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_k}\right) - \frac{\partial E_k}{\partial q_k} + \frac{\partial D}{\partial \dot{q}_k} + \frac{\partial V}{\partial q_k} = \frac{\partial W_{nc}}{\partial q_k} \qquad \forall\ k = 1, \dots, n$$





But this is a 1 degree of freedom system ($\omega = \dot{\alpha}$)…

Work–Energy principle (Differential version) ---> **Balance of Power**

$$\sum P_{in} + \sum P_{out} + \sum P_w = \frac{d}{dt}\left(\sum_{i=1}^{n_b} E_{k,i}\right)$$

- P_{in} is given by engine ---> $T_{eng}(\dot{\alpha_{eng}})\dot{\alpha_{eng}}$
- P_{out} is needed:
  - for the manufacturing process ---> $T_{mp}(\alpha)\dot{\alpha}$
  - to move the parts of the press ---> $\sum_{i=1}^{n_b} m_i \boldsymbol{g} * \boldsymbol{v_{G,i}} = \sum_{i=1}^{n_b} m_i g v_{Gy,i}$
- P_w is wasted in the transmission (η_τ) and in the brakes (Coulomb model) ---> $(1-\eta_\tau)P_{in} + T_{brake}\dot{\alpha_{brake}}$
- $\sum_{i=1}^{n_b} E_{k,i} = \sum_{i=1}^{n_b}\left(\frac{1}{2} m_i \left\|\boldsymbol{v_{G,i}}\right\|^2 + \frac{1}{2} J_{zz,i}\omega_i^2\right)$

$$\eta_\tau T_{eng}(\dot{\alpha_{eng}})\dot{\alpha_{eng}} + T_{mp}(\alpha)\dot{\alpha} + \sum_{i=1}^{n_b} m_i g v_{Gy,i} + T_{brake}\dot{\alpha_{brake}} = \frac{d}{dt}\left(\sum_{i=1}^{n_b}\left(\frac{1}{2} m_i \left\|\boldsymbol{v_{G,i}}\right\|^2 + \frac{1}{2} J_{zz,i}\omega_i^2\right)\right)$$

$$\eta_\tau T_{eng}(\dot{\alpha}_{eng})\dot{\alpha}_{eng} + T_{mp}(\alpha)\dot{\alpha} + \sum_{i=1}^{n_b} m_i g v_{Gy,i} + T_{brake}\dot{\alpha}_{brake} = \frac{d}{dt}\left(\sum_{i=1}^{n_b}\left(\frac{1}{2}m_i\left\|\boldsymbol{v}_{\boldsymbol{G},\boldsymbol{i}}\right\|^2 + \frac{1}{2}J_{zz,i}\omega_i^2\right)\right)$$

- $\dot{\alpha}_{eng} = \prod_{k=1}^{n_\tau} \tau_k\,\dot{\alpha}$ (...and for $\dot{\alpha}_{brake}$)
- $\boldsymbol{v}_{\boldsymbol{G},\boldsymbol{i}}(\alpha,\dot{\alpha}) = \frac{d}{dt}\left(\boldsymbol{x}_{\boldsymbol{G},\boldsymbol{i}}(\alpha(t))\right) = \frac{\partial \boldsymbol{x}_{\boldsymbol{G},\boldsymbol{i}}}{\partial\alpha}\frac{d\alpha}{dt} = \Lambda_\alpha\,\dot{\alpha}$ (...and for ω_i)
  - $m_i g v_{Gy,i} = m_i g\,\Lambda_\alpha\,\dot{\alpha} = \widetilde{m_i}(\alpha)g\dot{\alpha}$

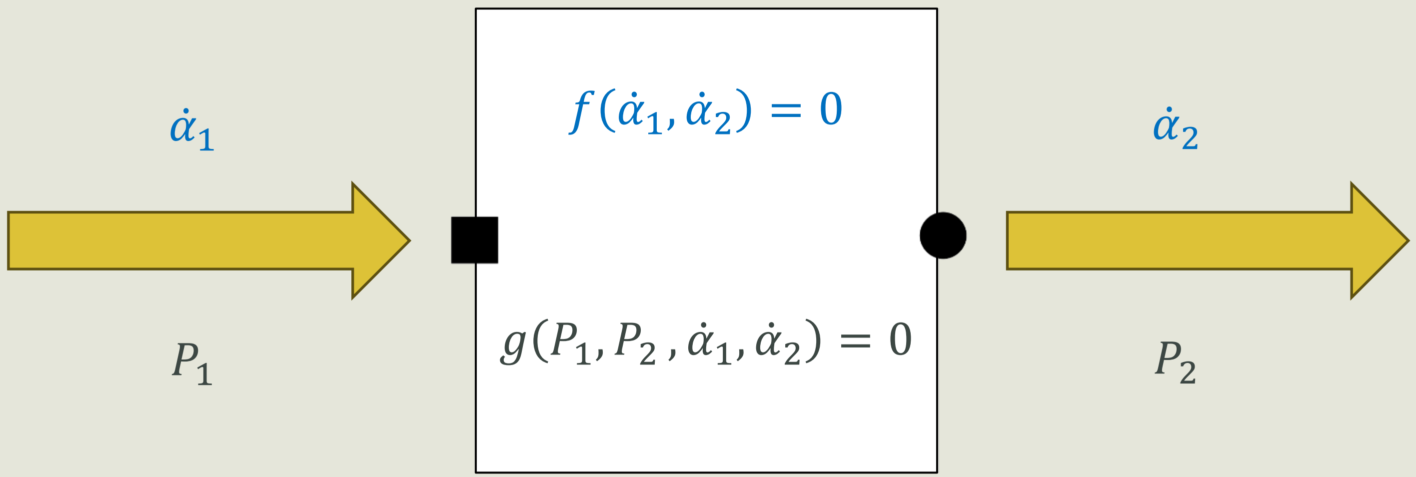
$$\eta_\tau T_{eng}(\dot{\alpha})\prod_{k=1}^{n_\tau}\tau_k\,\dot{\alpha} + T_{mp}(\alpha)\dot{\alpha} + \sum_{i=1}^{n_b}\widetilde{m_i}(\alpha)g\dot{\alpha} + T_{brake}\prod_{k=1}^{n_\tau}\tau_k\,\dot{\alpha} = \frac{d}{dt}\left(\frac{1}{2}\left[\sum_{i=1}^{n_b}\widetilde{M_i(\alpha)} + \widetilde{J_i(\alpha)}\right]\dot{\alpha}^2\right)$$

DAE problem in $\alpha, \dot{\alpha}, \ddot{\alpha}$

Open Modelica

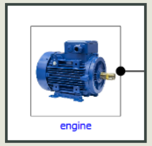
- Connectors
- Models of components
- Scenarios of simulation

Connectors

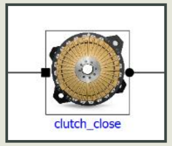


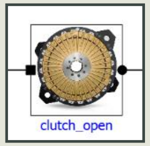
- Effort variable: $\dot{\alpha}$ ---> Because it's the degree of freedom used for power transfer calculation
- Flow variable: P ---> Because the model is structured as power flow through engine - transmission - load chain

Models of components

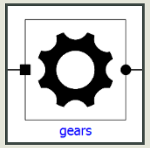


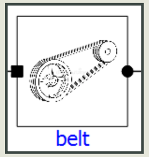
Three-phase asynchronous electric Engine



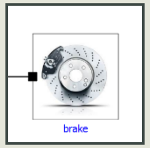


Clutch

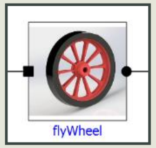


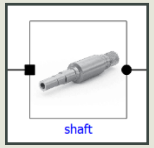


Transmission systems (τ)

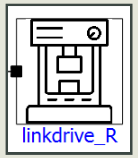


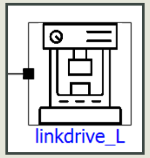
Coulomb friction (Brake)





Rotational inertia (J_{zz})

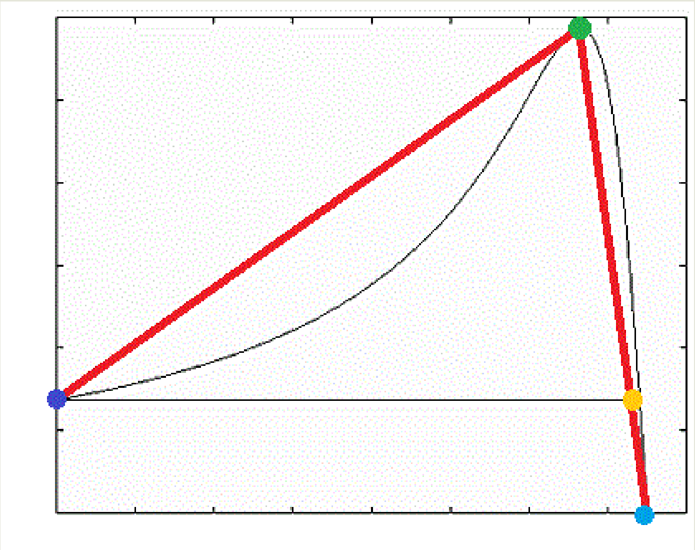




Link drive

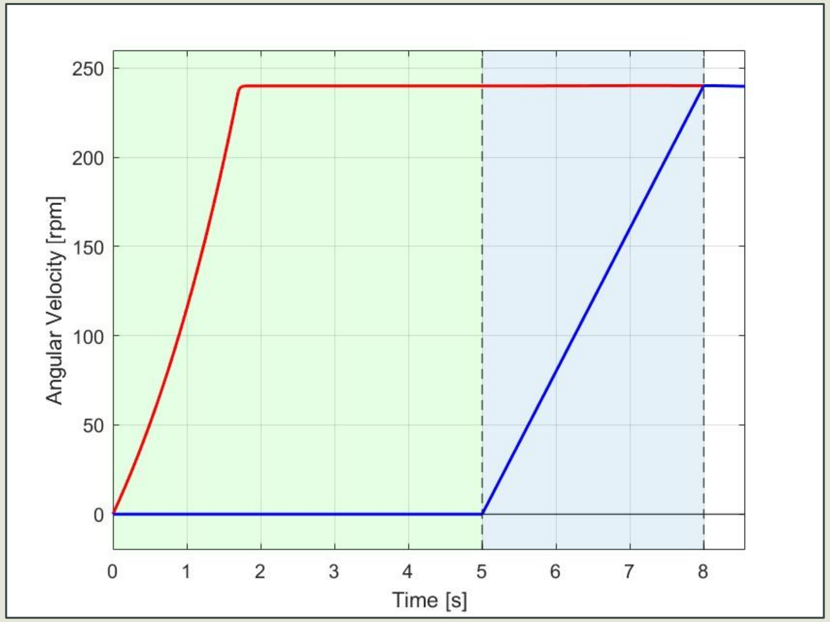
Three-phase asynchronous electric Engine

Torque

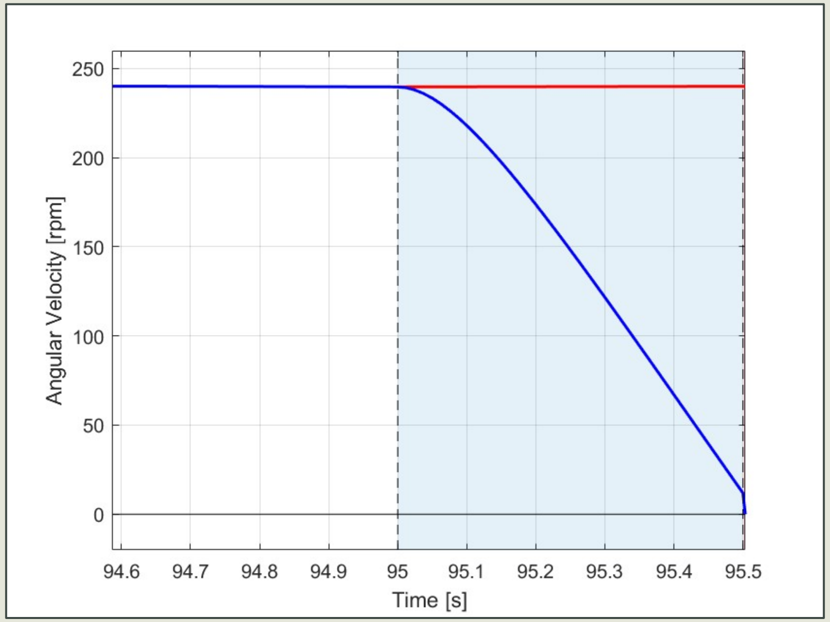


Angular velocity

Clutch engagement



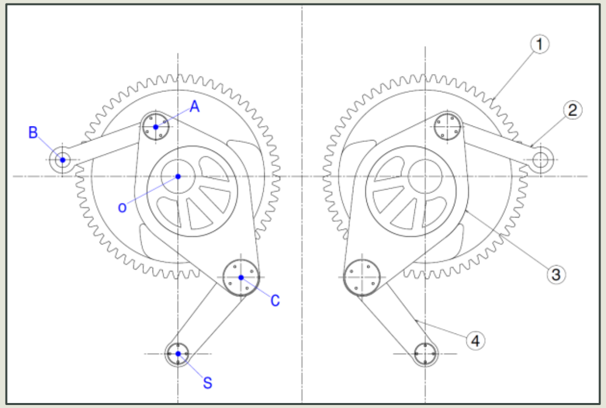
Clutch opening

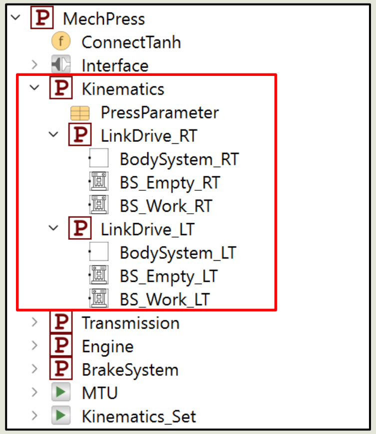


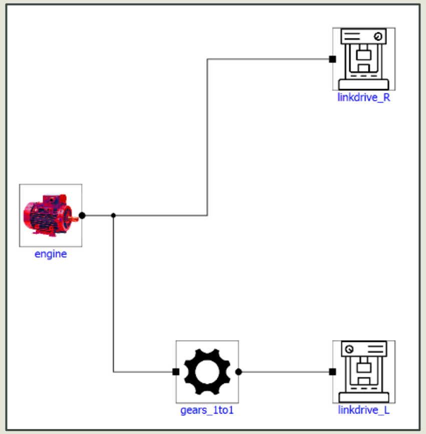
1st Scenario of simulation --> Link drive

The Link drive model contains:

- Physical parameters (partial model)
- Dynamics equations (partial model)
- Force for manufacturing process (model)

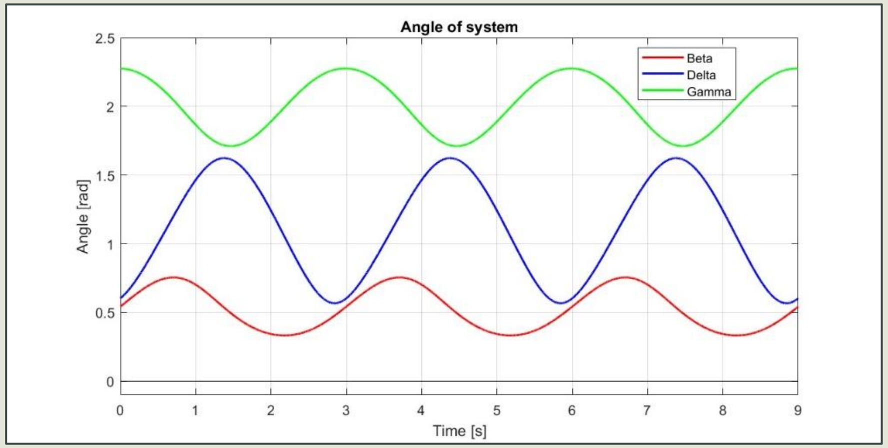


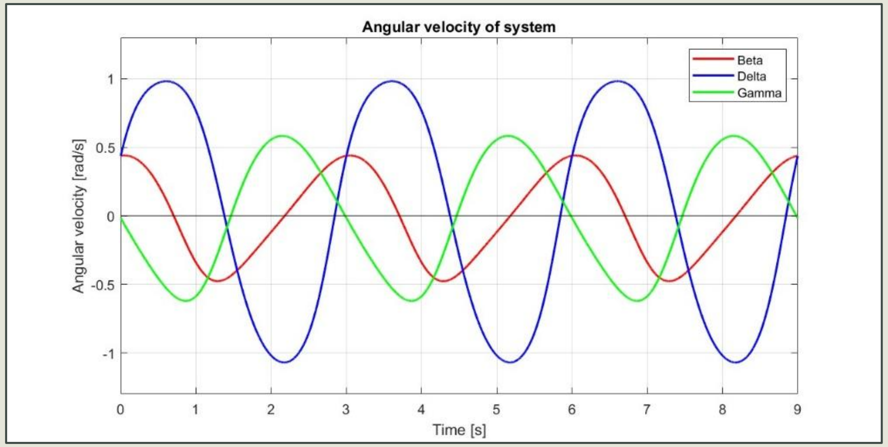


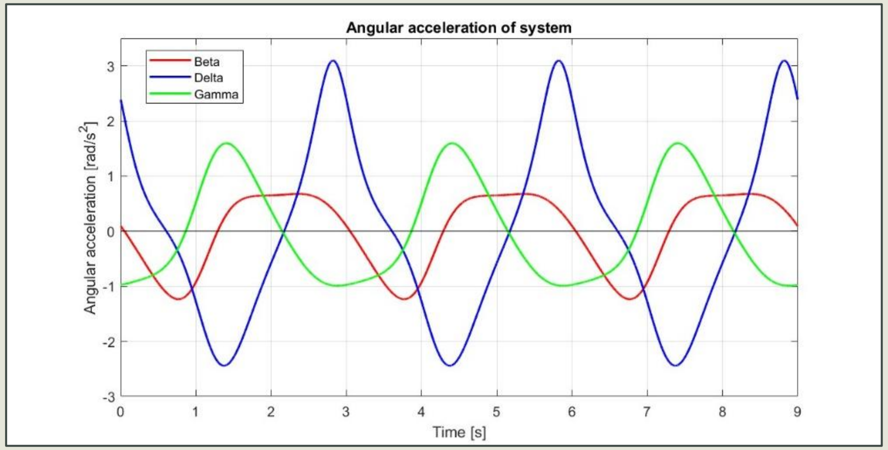


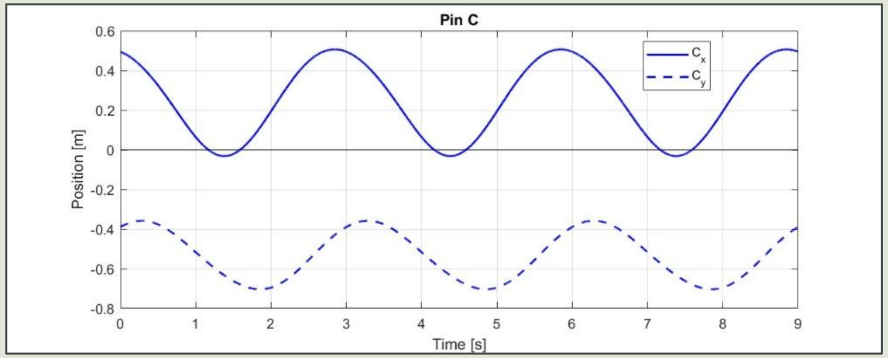
Simulation with imposed kinematics: $\dot{\alpha} = 20rpm$

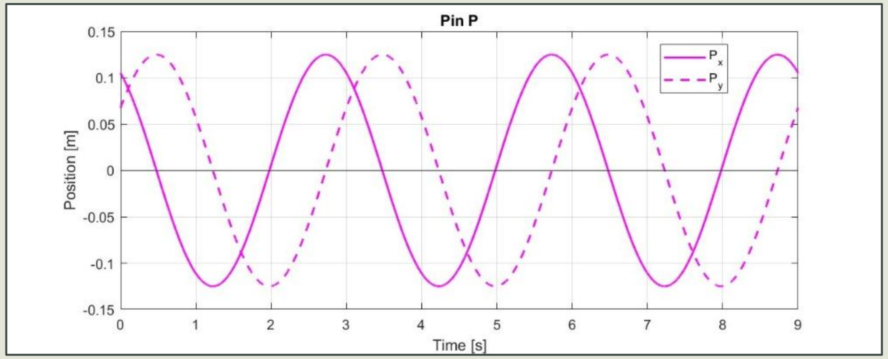
Focus on the kinematic chain

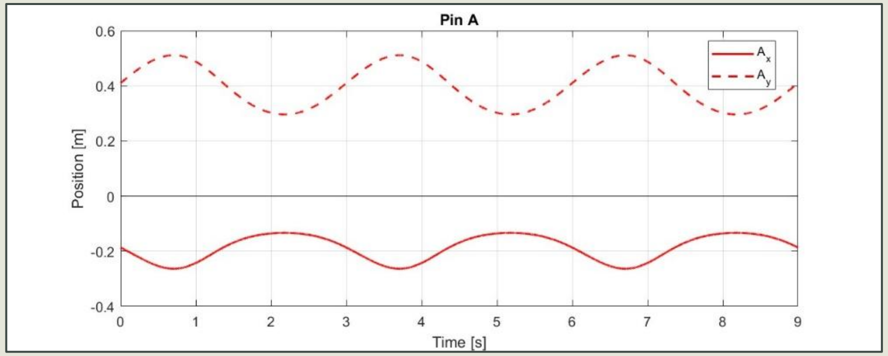

Angle of system
Beta
Delta
Gamma
Angle [rad]
Time [s]

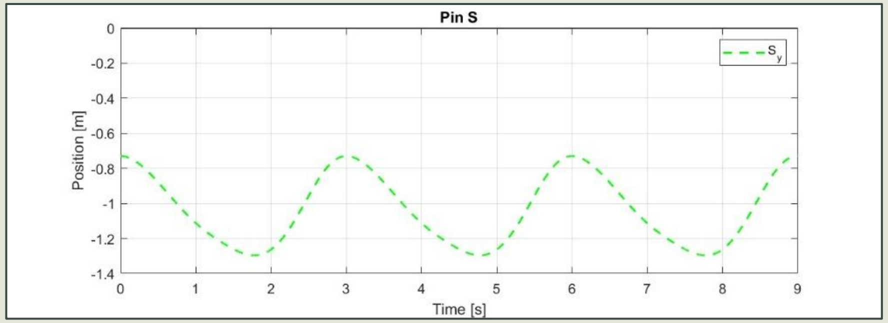

Angular velocity of system
Beta
Delta
Gamma
Angular velocity [rad/s]
Time [s]

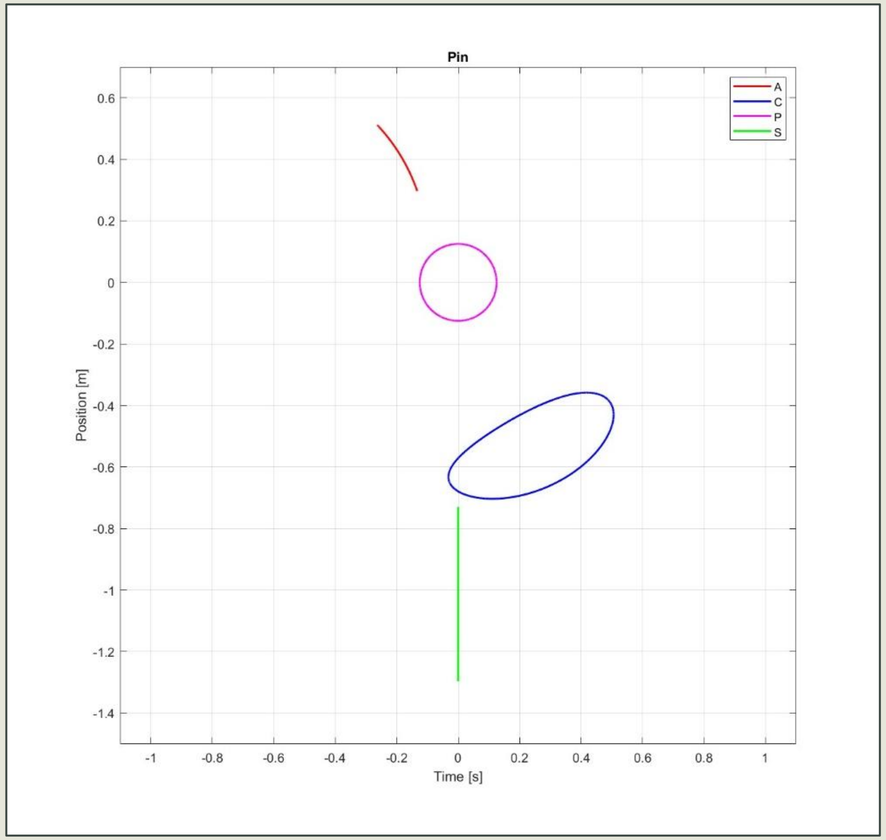

Angular acceleration of system
Beta
Delta
Gamma
Angular acceleration [rad/s2]
Time [s]


Pin C
Cx
Cy
Position [m]
Time [s]

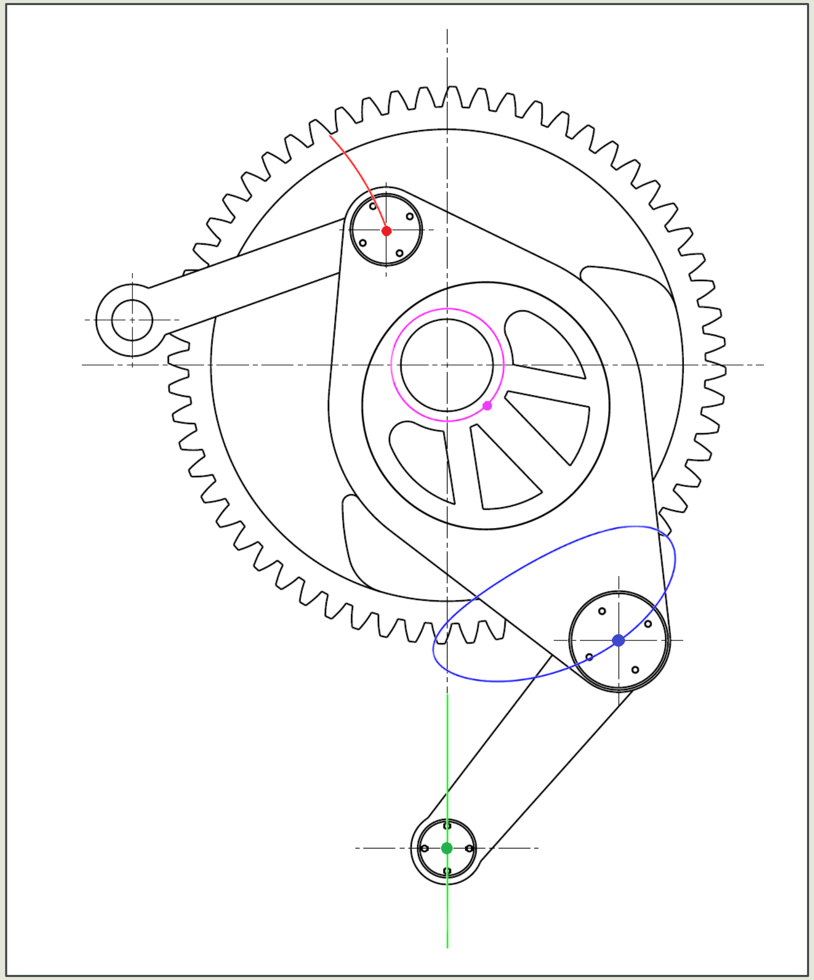

Pin P
Px
Py
Position [m]
Time [s]

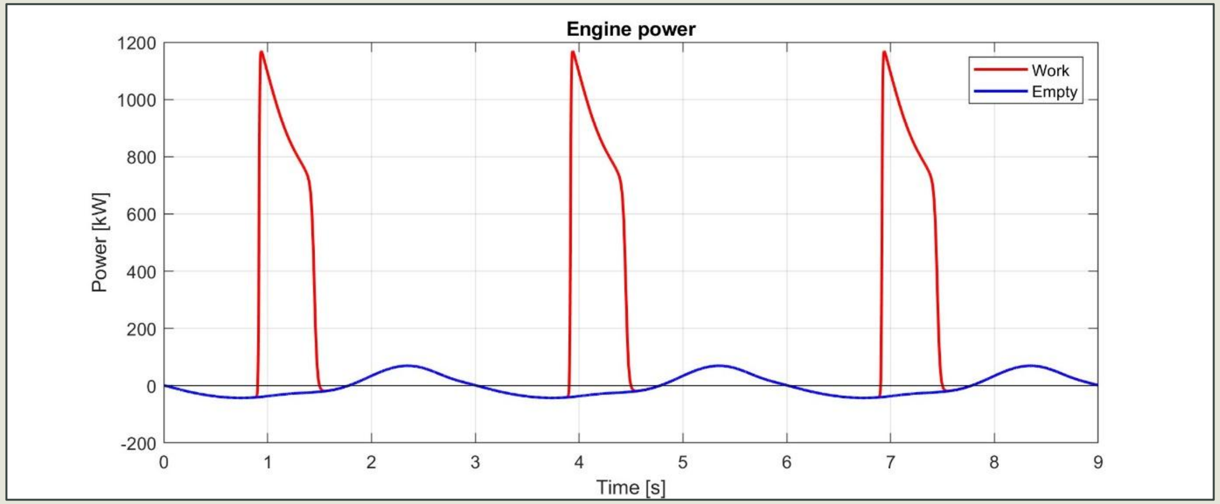

Pin A
Ax
Ay
Position [m]
Time [s]


Pin S
Sy
Position [m]
Time [s]

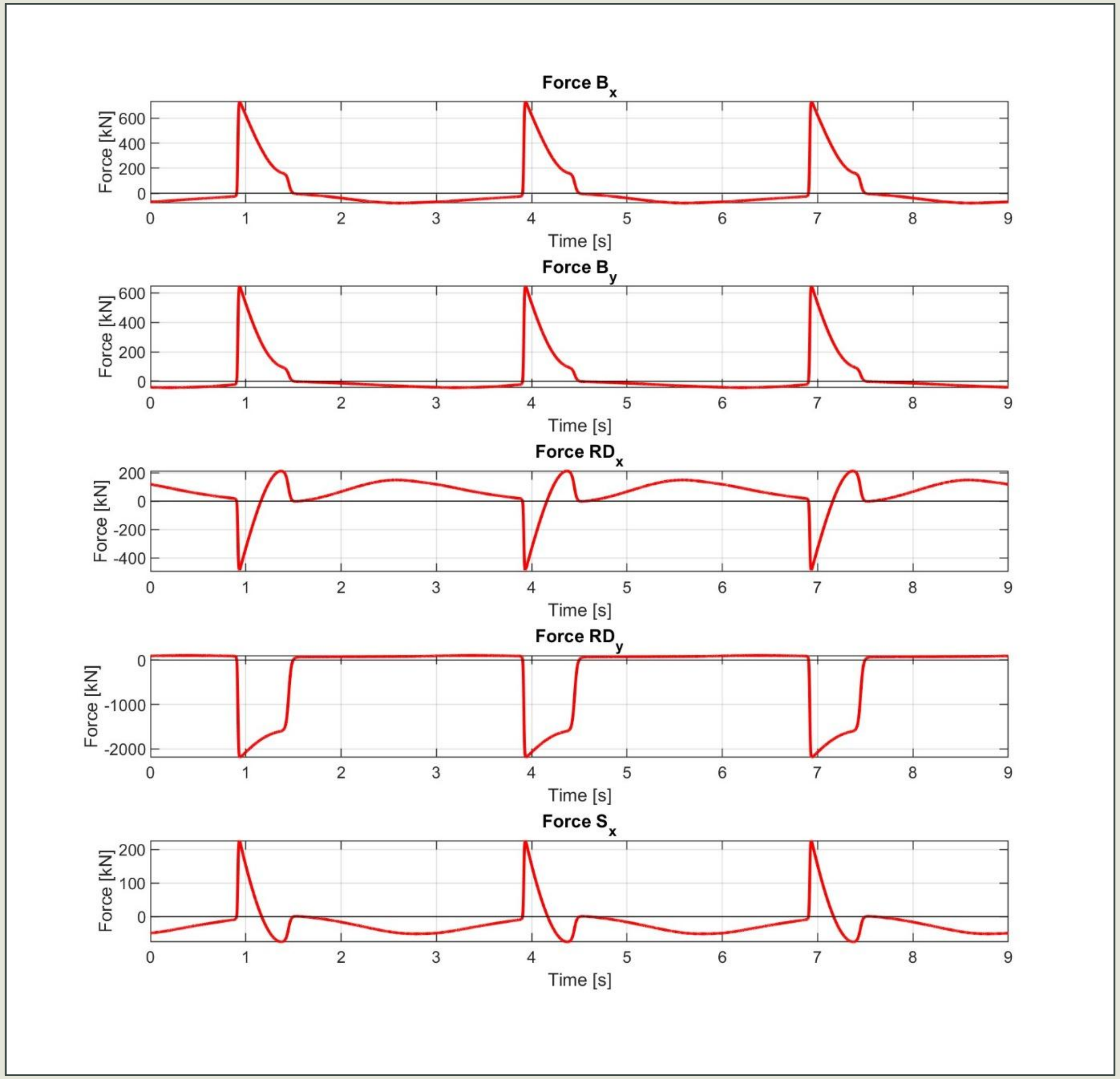


Pin
A
C
P
S
Position [m]
Time [s]
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1



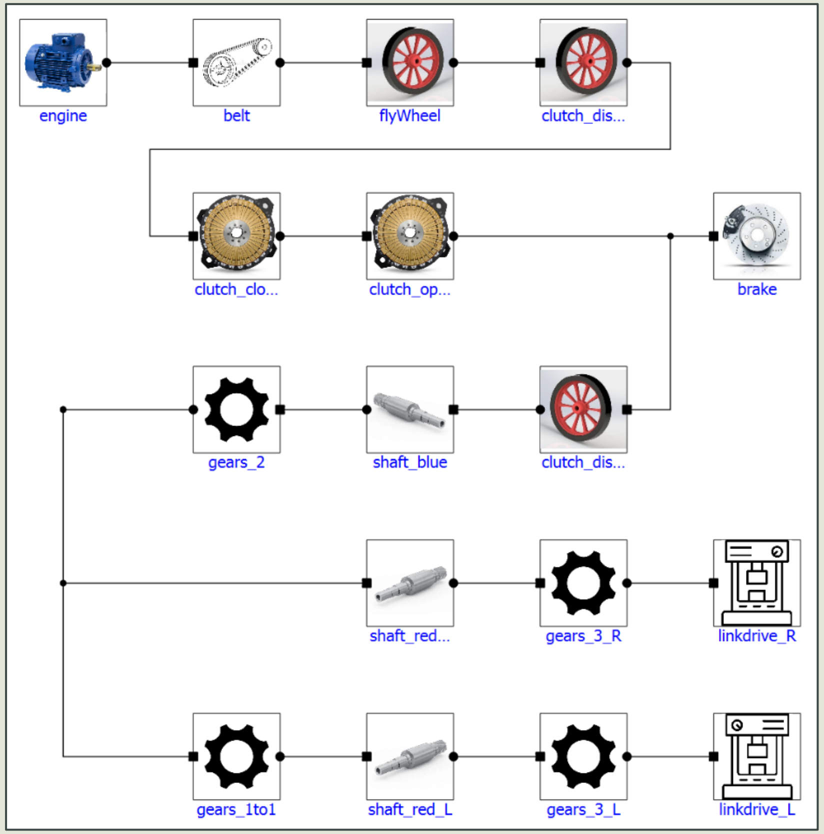


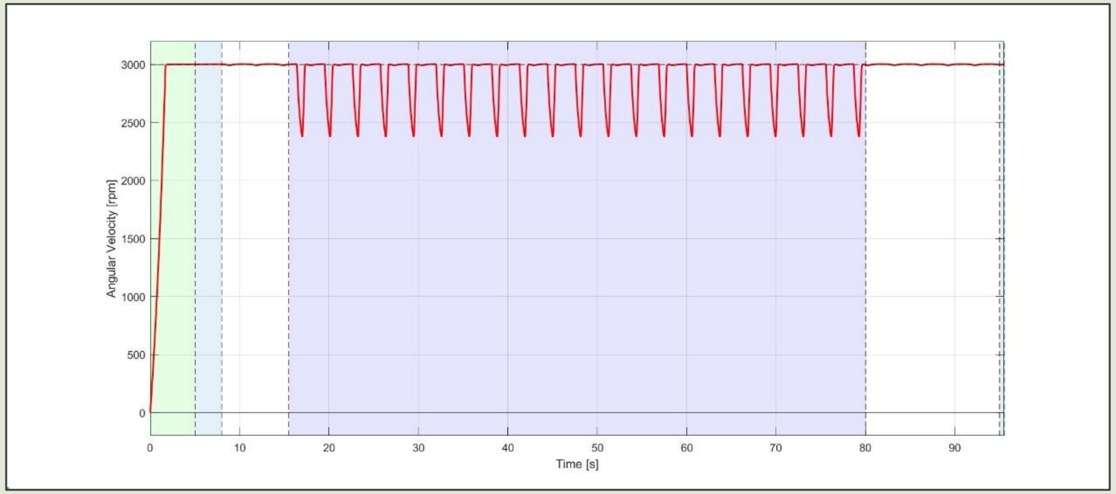
Engine power
Work
Empty
Power [kW]
Time [s]

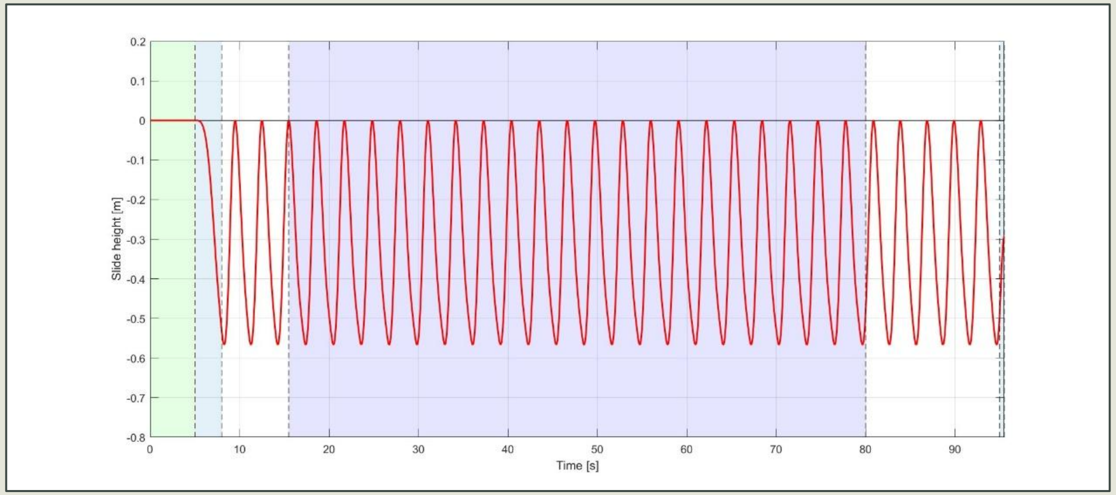


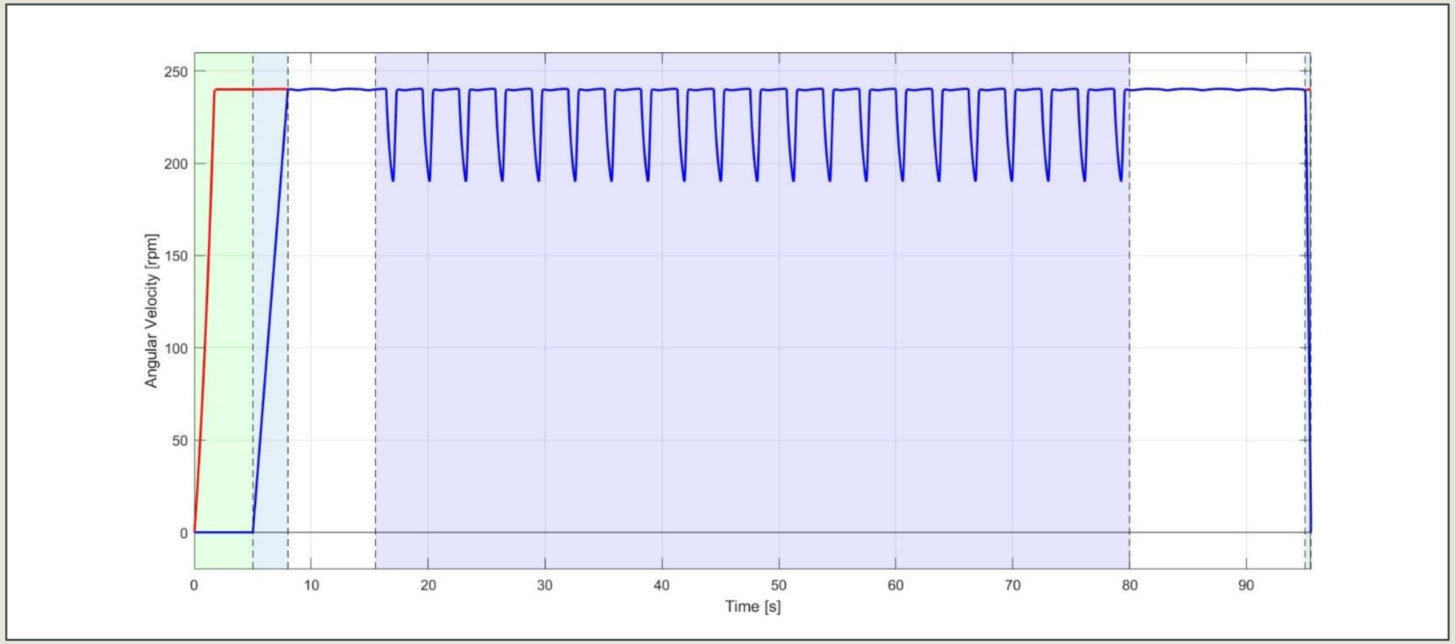
Force B_x
Force [kN]
Time [s]
Force B_y
Force [kN]
Time [s]
Force RD_x
Force [kN]
Time [s]
Force RD_y
Force [kN]
Time [s]
Force S_x
Force [kN]
Time [s]

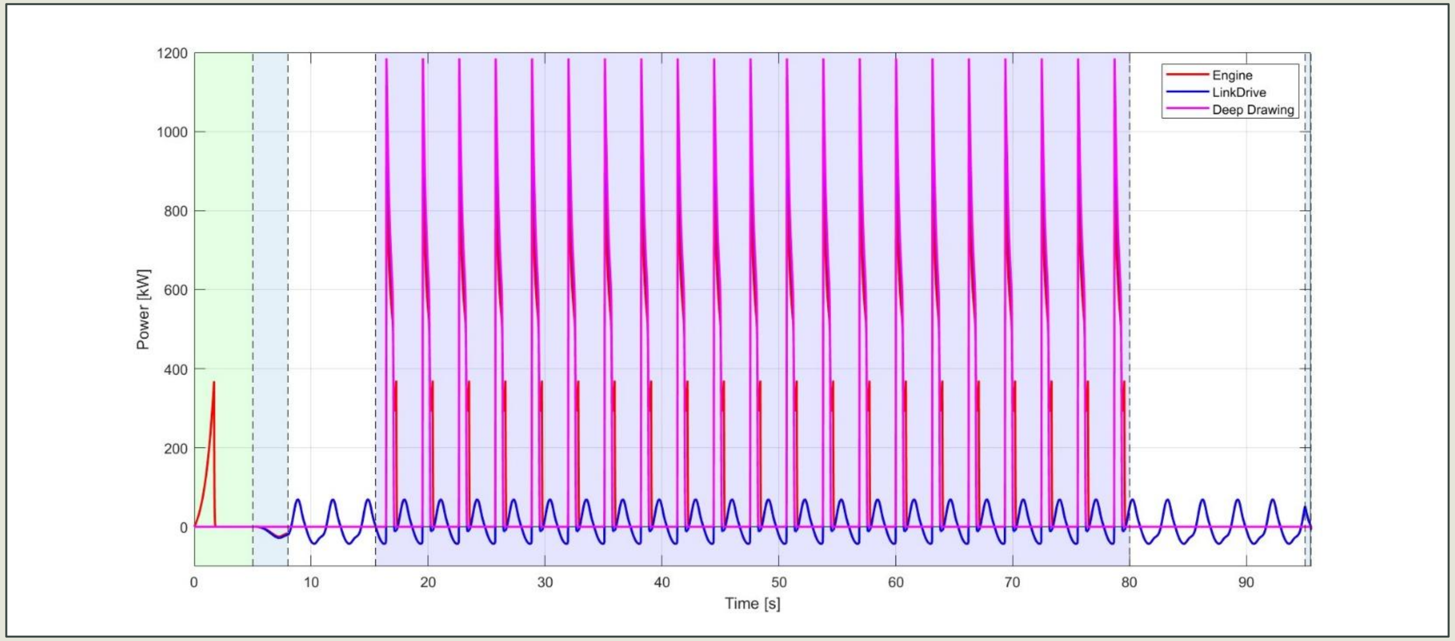
2nd Scenario of simulation --> All mechanical press

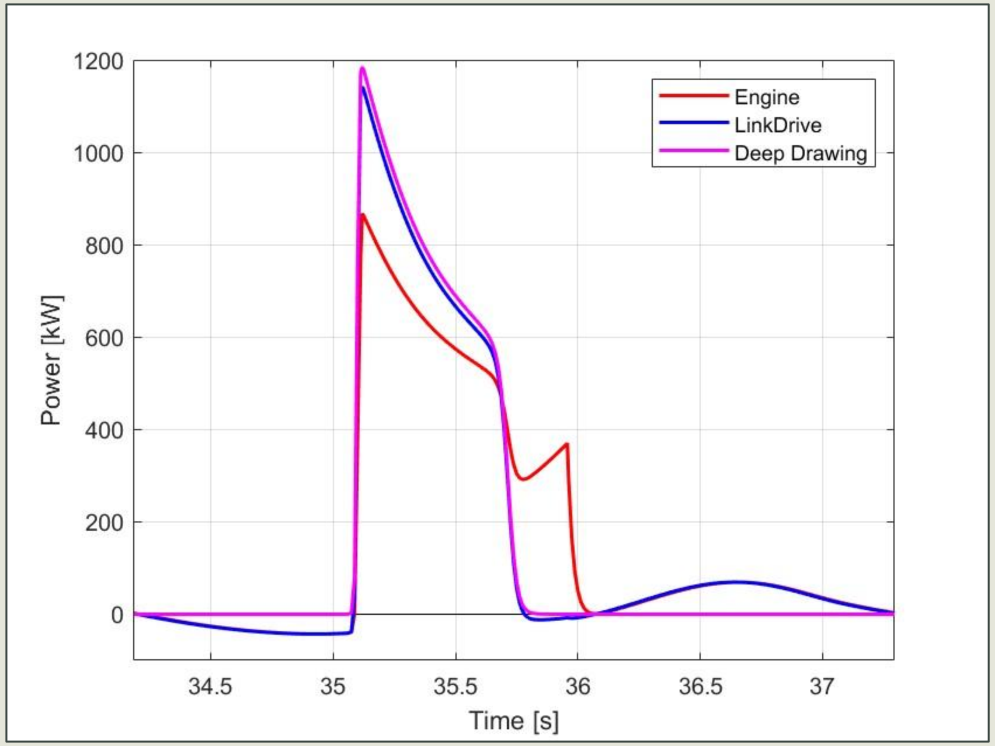




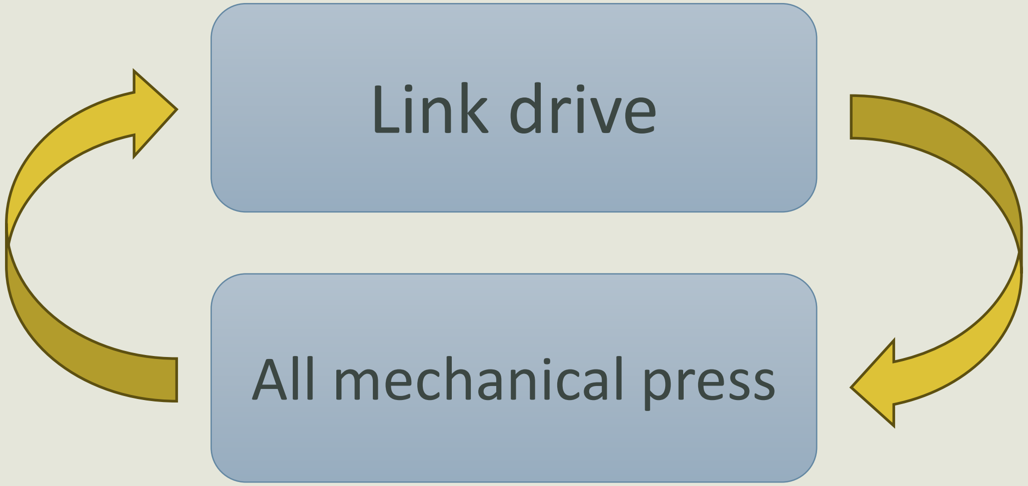


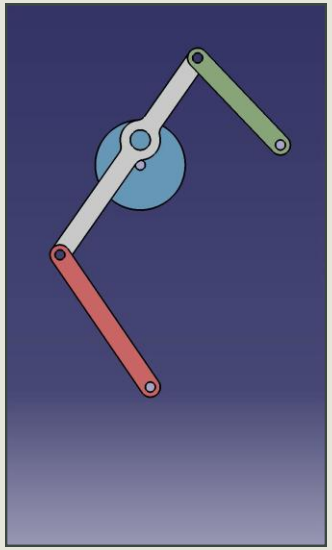

Angular Velocity [rpm]
Time [s]

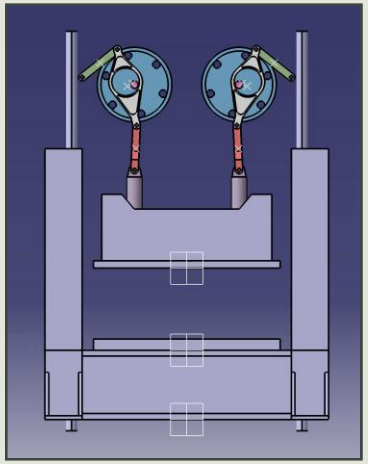

Power [kW]
Time [s]
Engine
LinkDrive
Deep Drawing

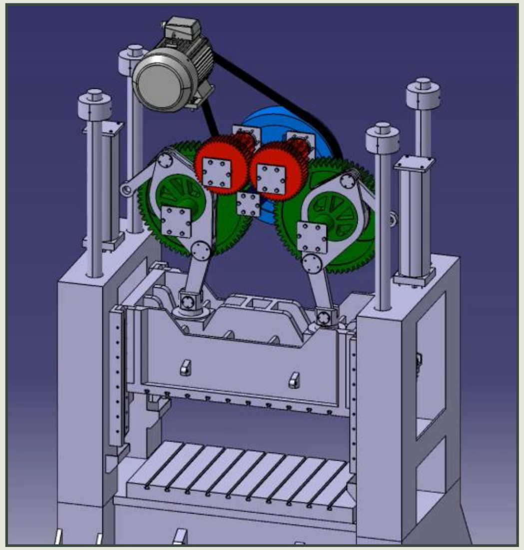

Power [kW]
Time [s]
Engine
LinkDrive
Deep Drawing

How did we use these scenarios?









“Se l'uomo non sapesse di matematica non si eleverebbe di un sol palmo da terra.”

Galileo Galilei, 1600 A.D.

“If human didn't know mathematics, he wouldn't rise a single inch from the ground.”

Thanks for your attention!

[1] Design of a mechanical press: https://www.researchgate.net/publication/387156798_Design_of_a_mechanical_press