Design Method for Valve-Controlled Hydraulic Positioning Systems

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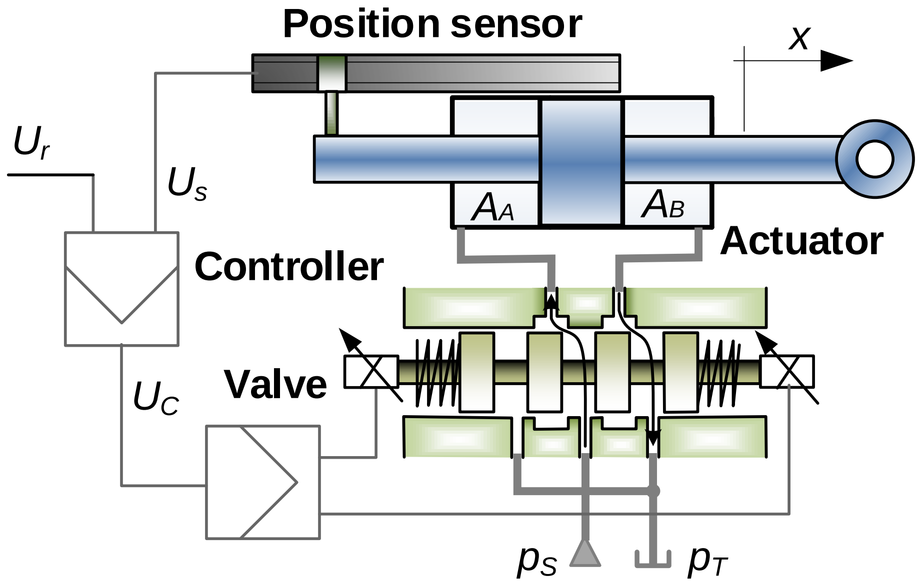
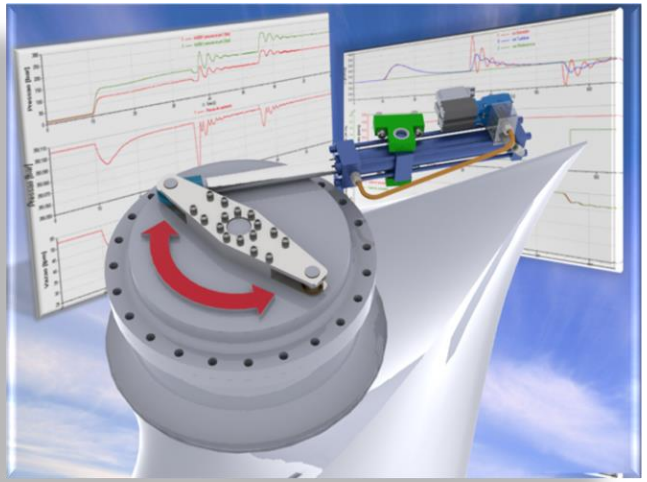
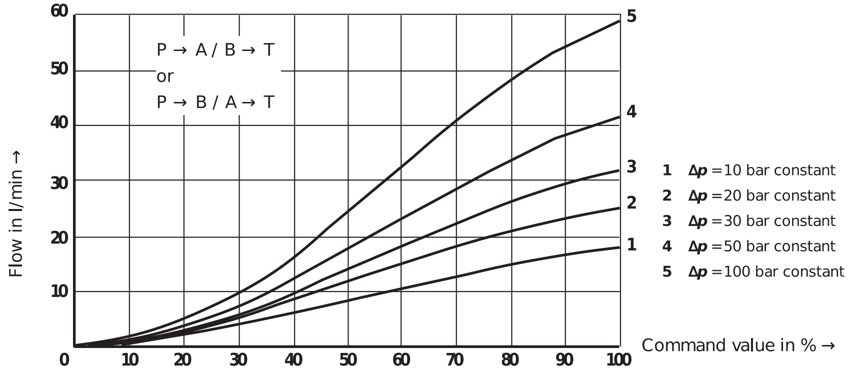
Content

- Electro-hydraulic positioning systems (EHPS):
  - For driving and controlling high loads with reliability, speed, and accuracy
- Main components:
  - Electrically modulated hydraulic control valve
    - Servovalves, Proportional valves
  - Cylinder
  - Controller

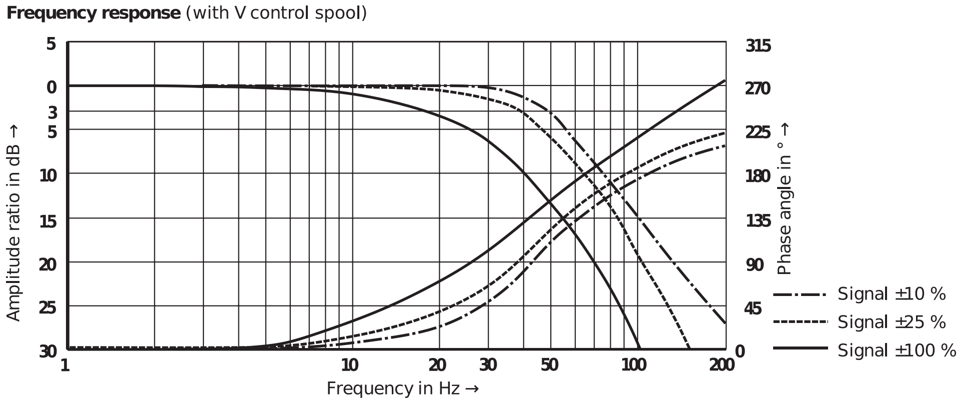




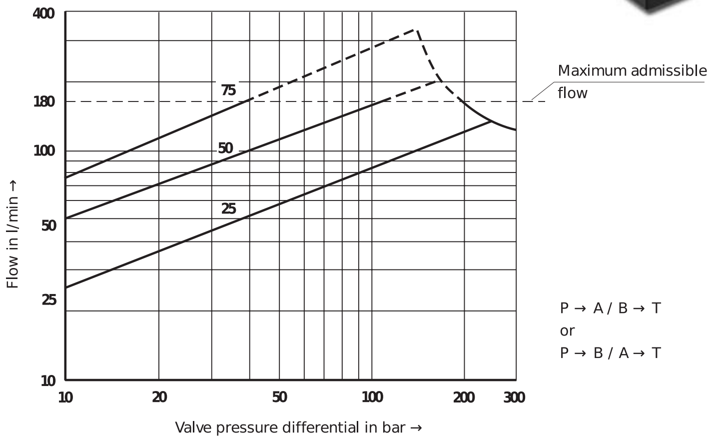
- Control valves:
  - Pressure dependence of the valve flow rate
  - Dead zone



  - Variable dynamic behavior

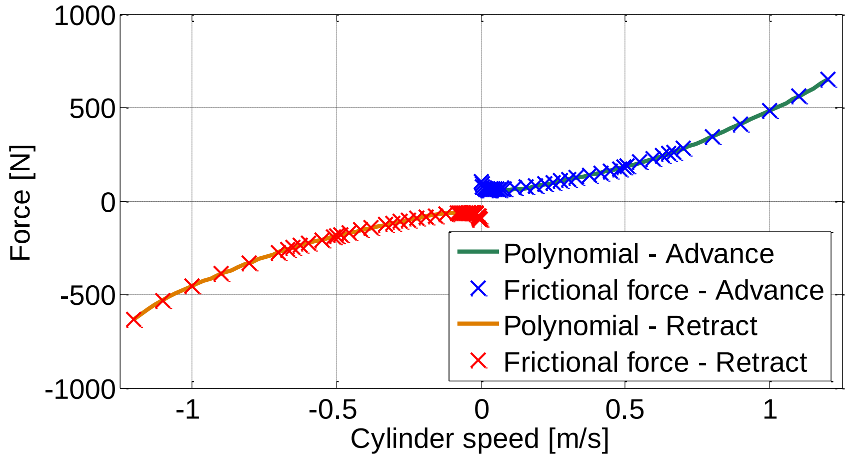


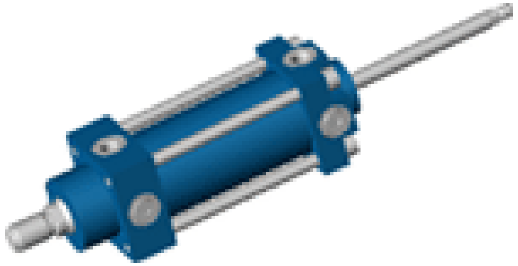
  - Operating limits

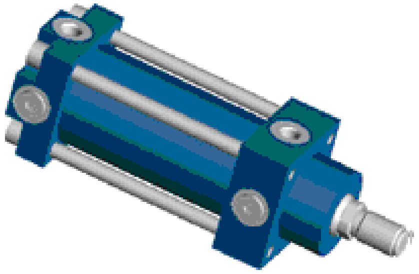


Cylinder + load

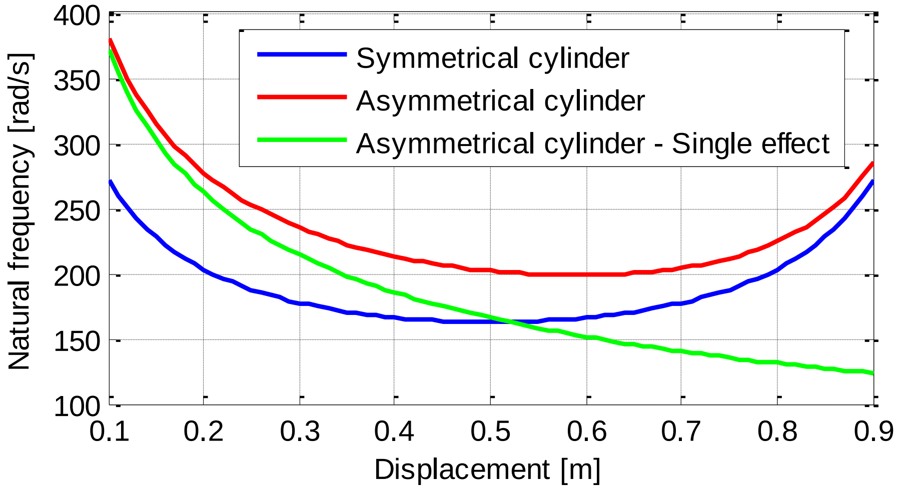
- Non-linear friction





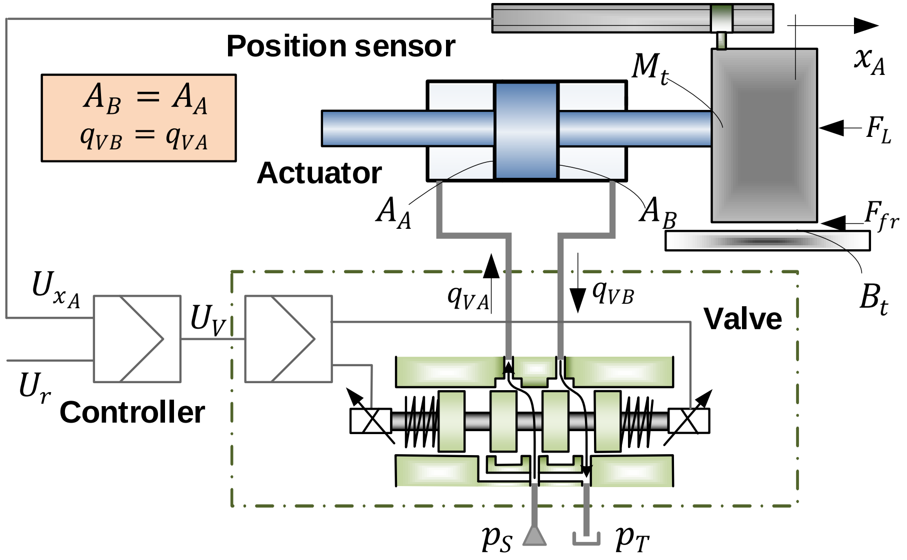


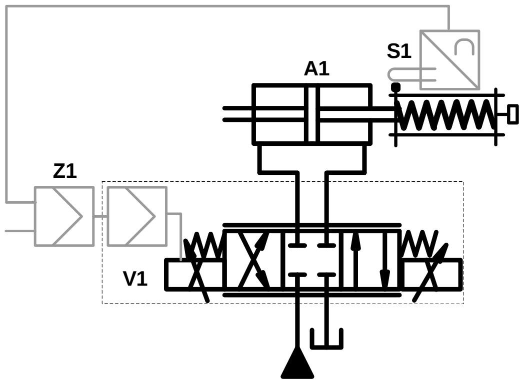
- Dynamic behavior function of the cylinder position



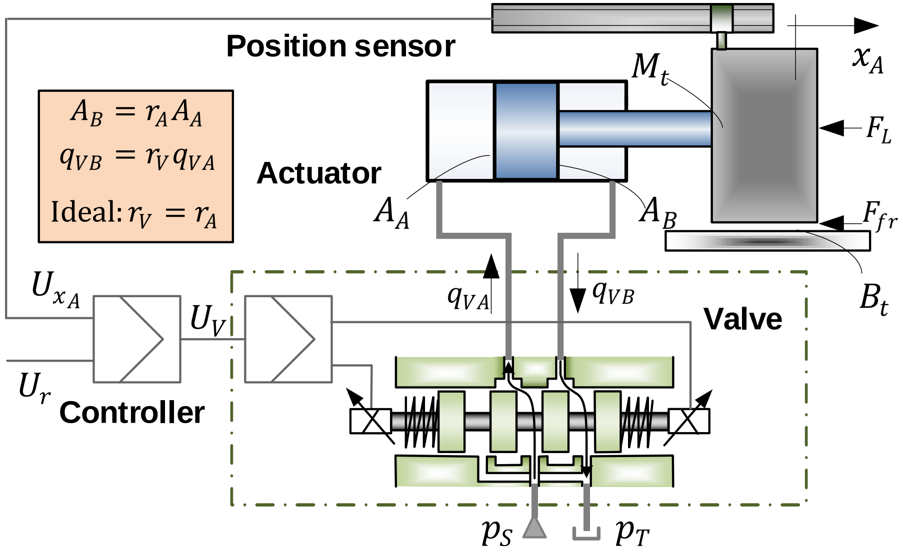
System configurations:

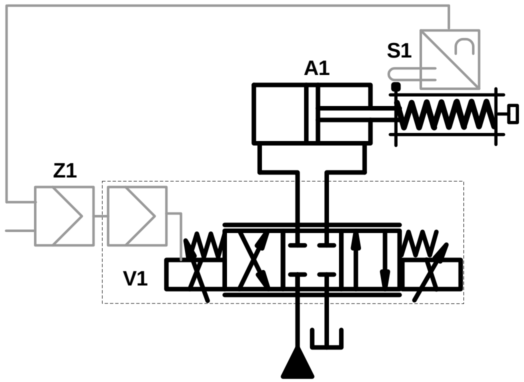
- Symmetrical cylinder + symmetrical valve



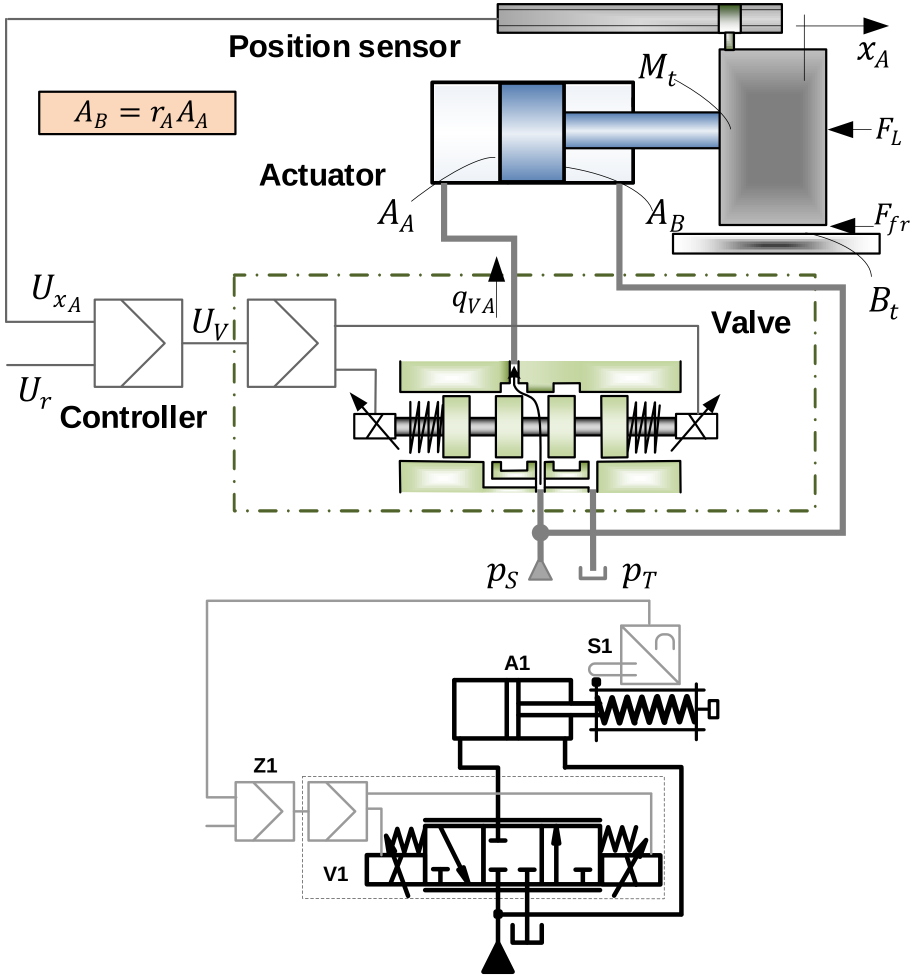


- Asymmetrical cylinder + asymmetrical valve
  - It is also usual: Asymmetrical cylinder + symmetrical valve

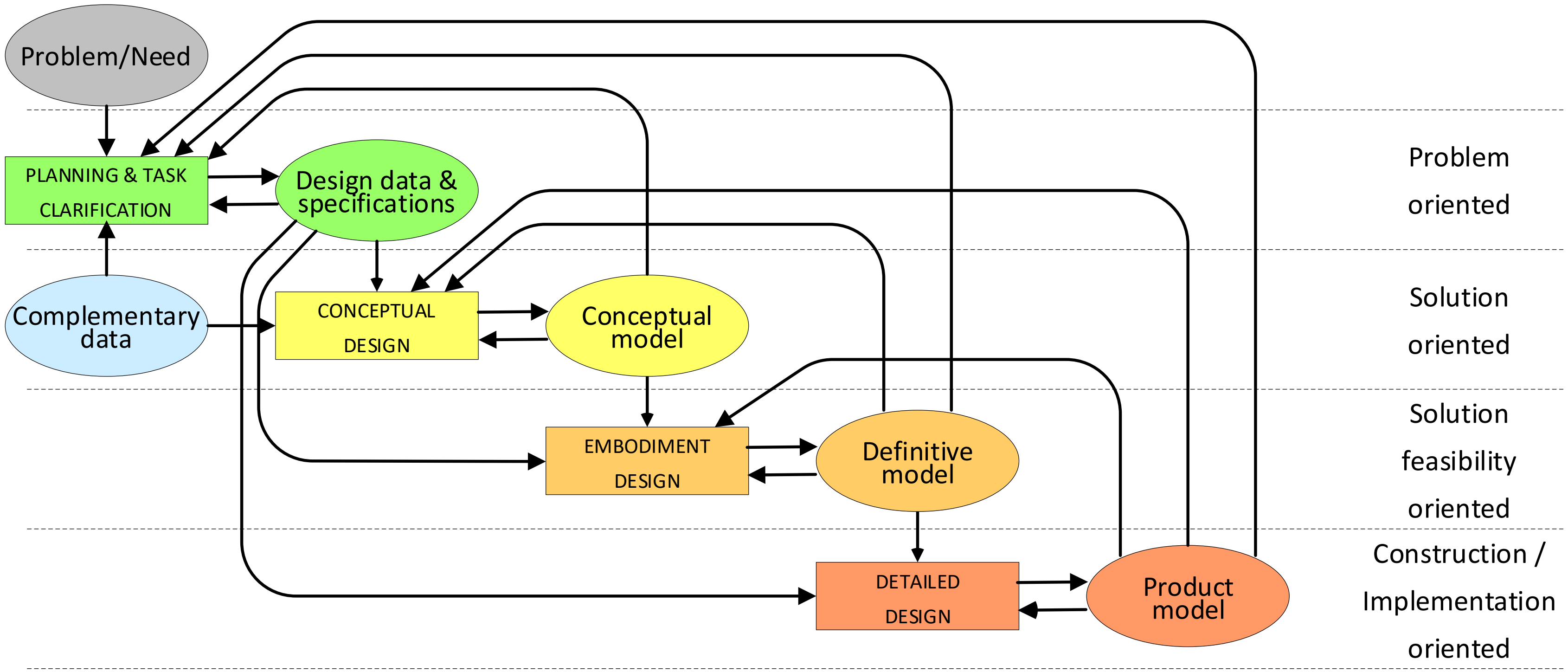




- System configurations:
  - Asymmetrical cylinder (single effect) + 3 port valve.



- Design Methodology for Mechatronic Systems:
  - Four classical phases according to design methology for technical systems as in Pahl *et al*., 2007[1]
  - Tasks, steps, and activities developted for mechatronic systems as in De Negri *et al.*, 2021[2]



[1] Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. *Engineering design: a systematic approach* (3 ed.). London: Springer Science & Business Media, 2007.

[2] De Negri, V. J.; Muñoz Salas, K. ; Vigolo, V. Design methodology for mechatronic systems: An approach using function/means tree and channel/agency net. E-book. Florianopolis: Universidade Federal de Santa Catarina, 2021.

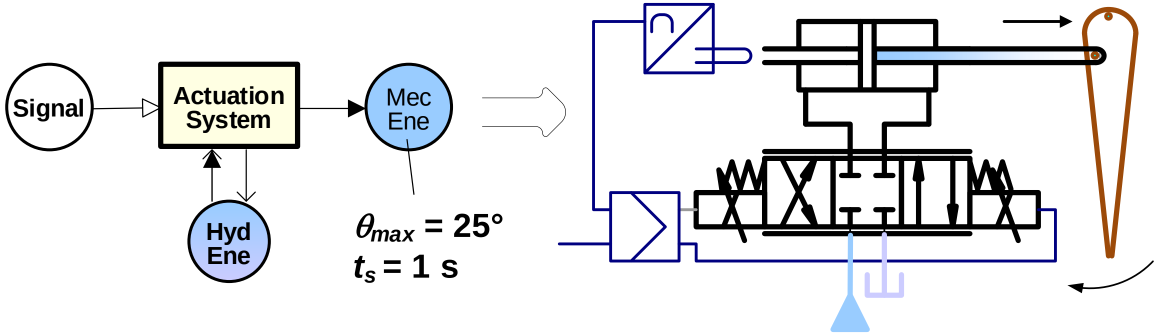
PLANNING & TASK CLARIFICATION

FUNCION = Rudder positioning

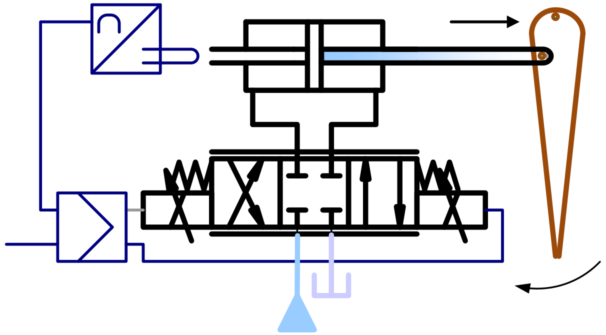
Maximum angle = 25°

Settling time = 1 s

CONCEPTUAL DESIGN



EMBODIMENT DESIGN



Controller gains: $K_P = 2$; $K_I = 0,1$

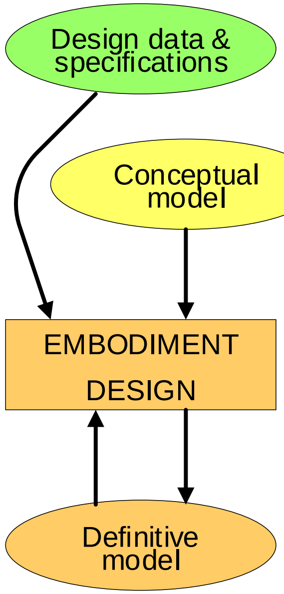
Position sensor: K_s = 300 V/m

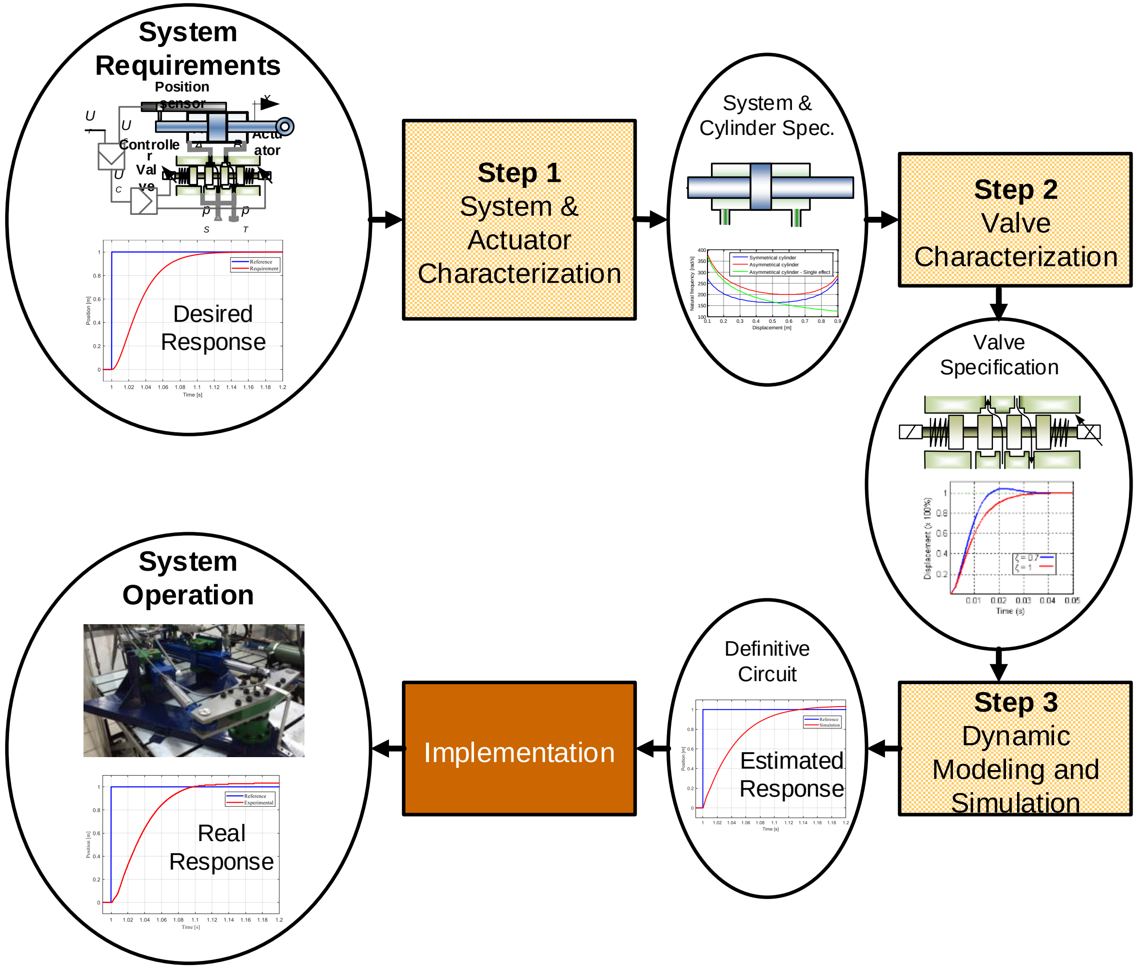
Cylinder: d = 50 mm

Valve: q_{Vn} = 10 L/min (@ Δp = 10 bar)

DETAILED DESIGN

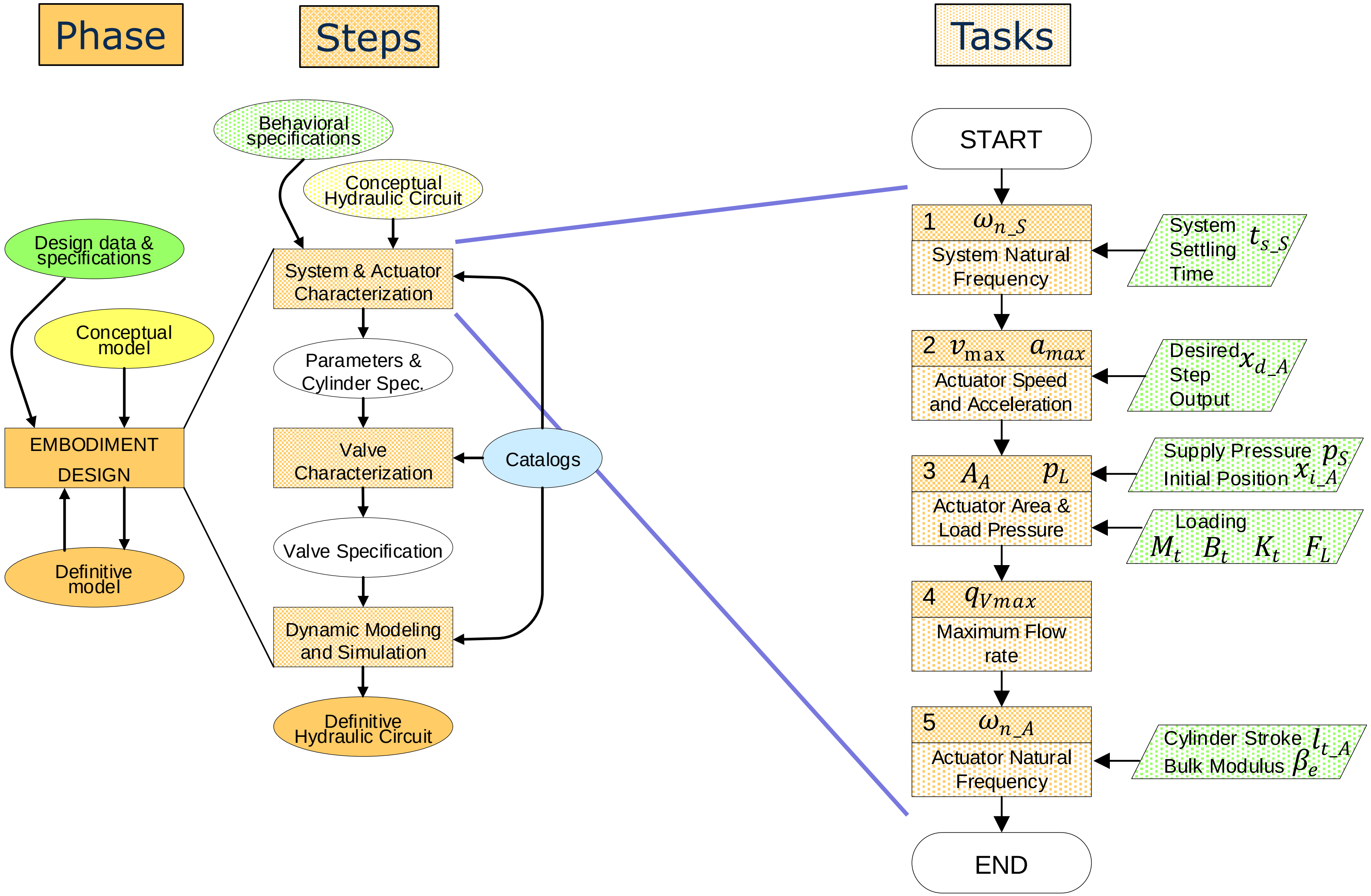
SENSOR = Type HDY0905
CONTROLLER = Type DSP1312
Cylinder = Type DXY09
Valve = Type 4QE600





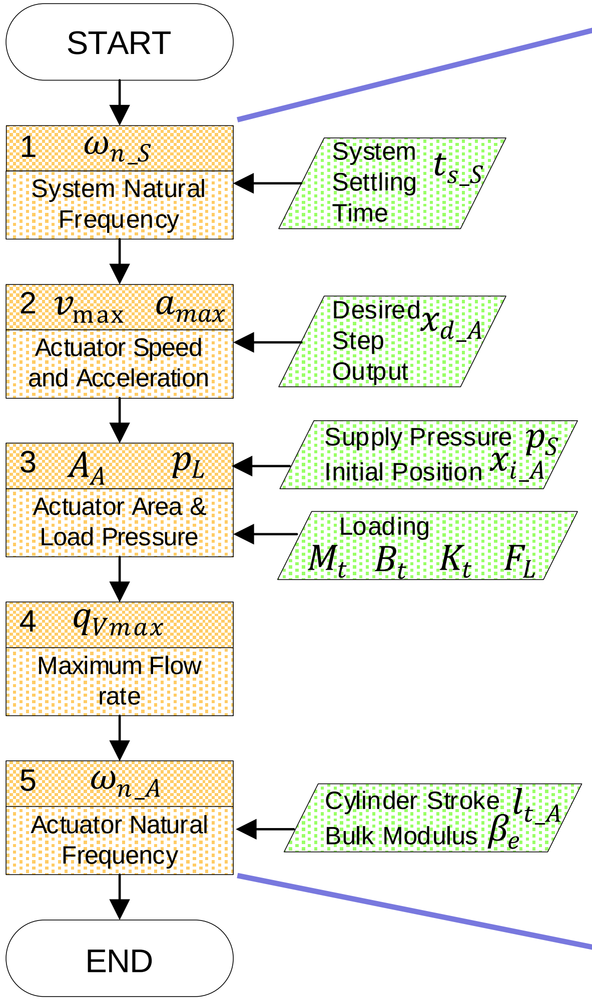
This design method is implemented in the HyPS Tool software available at laship.ufsc.br

Step 1 - System & Actuator Characterization

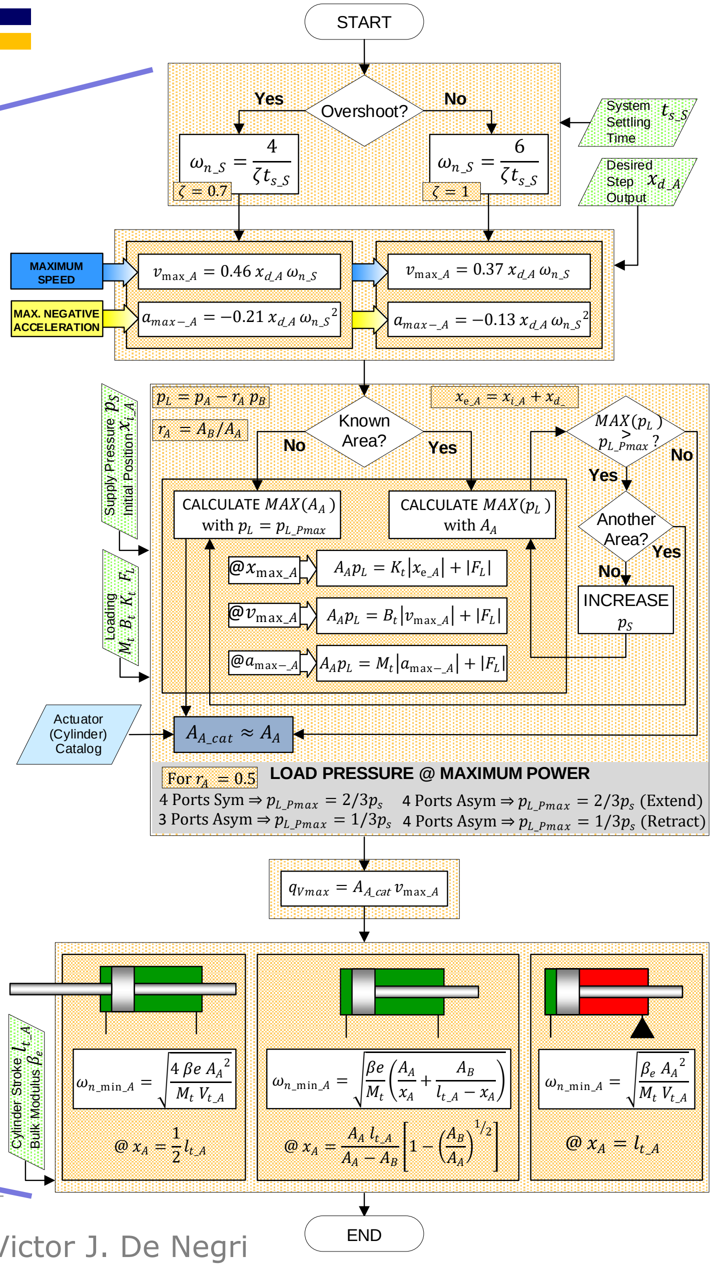


Step 1 - System & Actuator Characterization

Tasks



Activities



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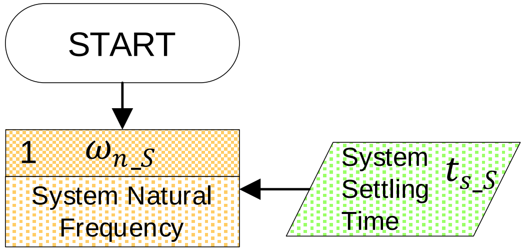
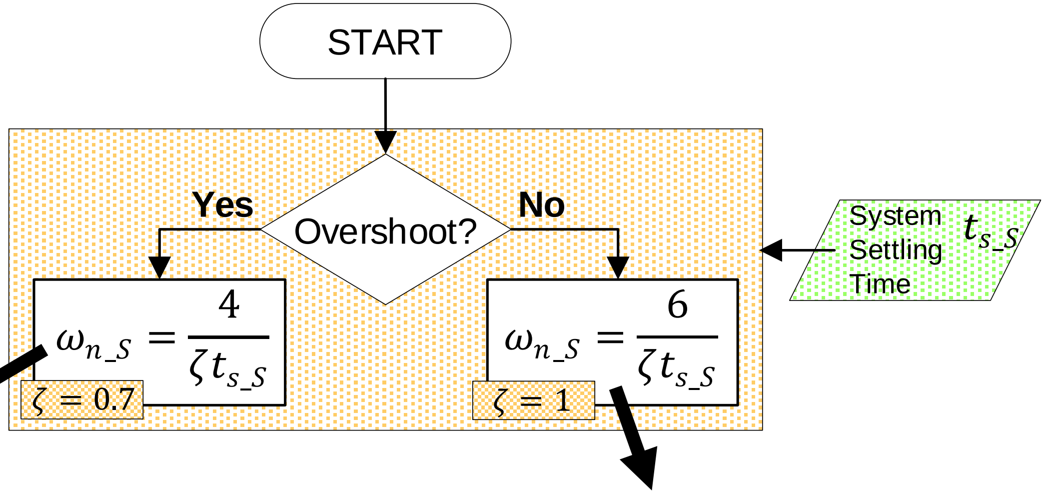
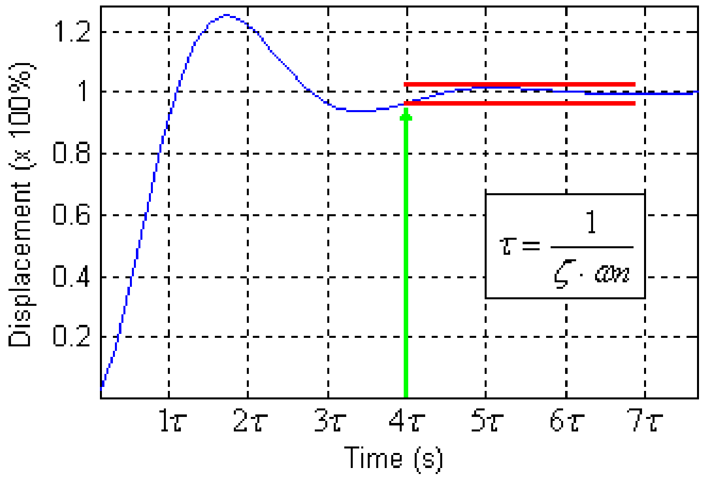
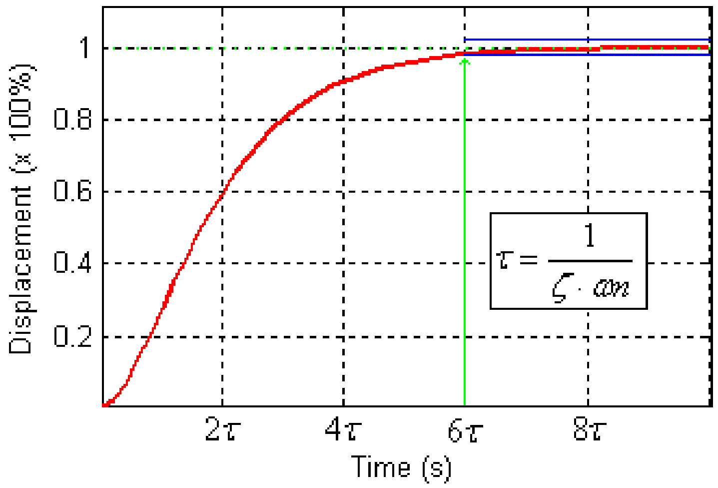




2nd order underdamped system response



2nd order critically damped system response



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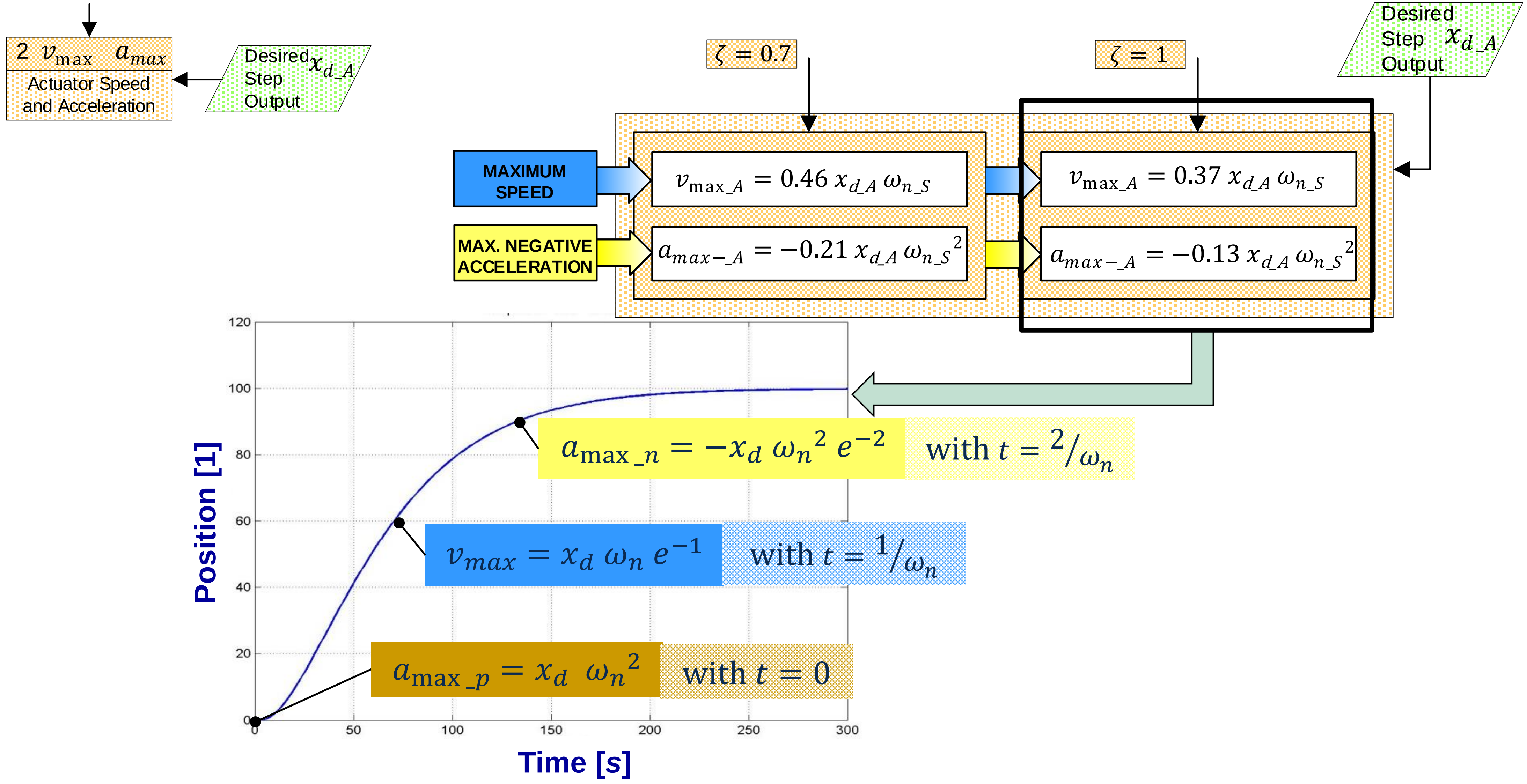

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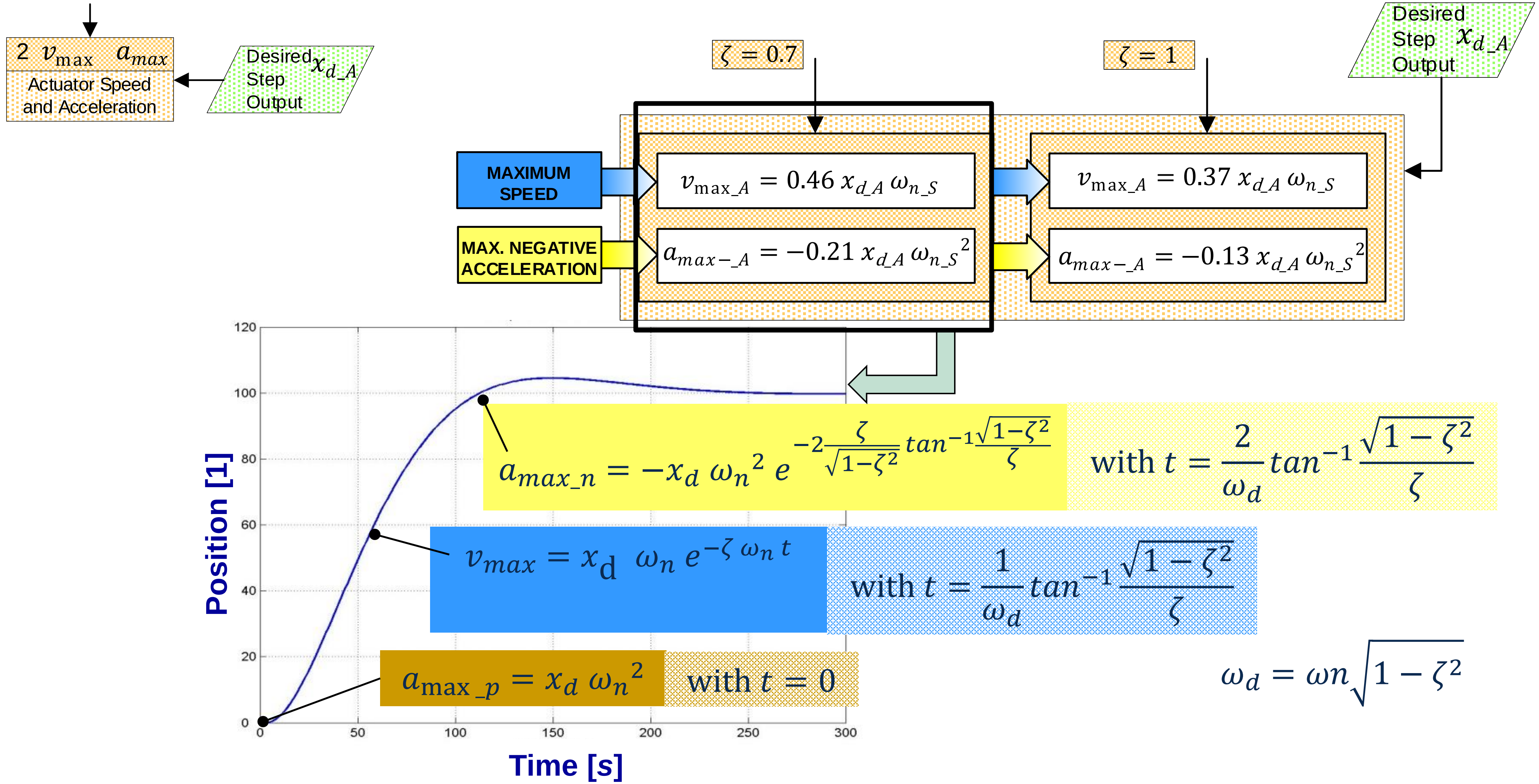

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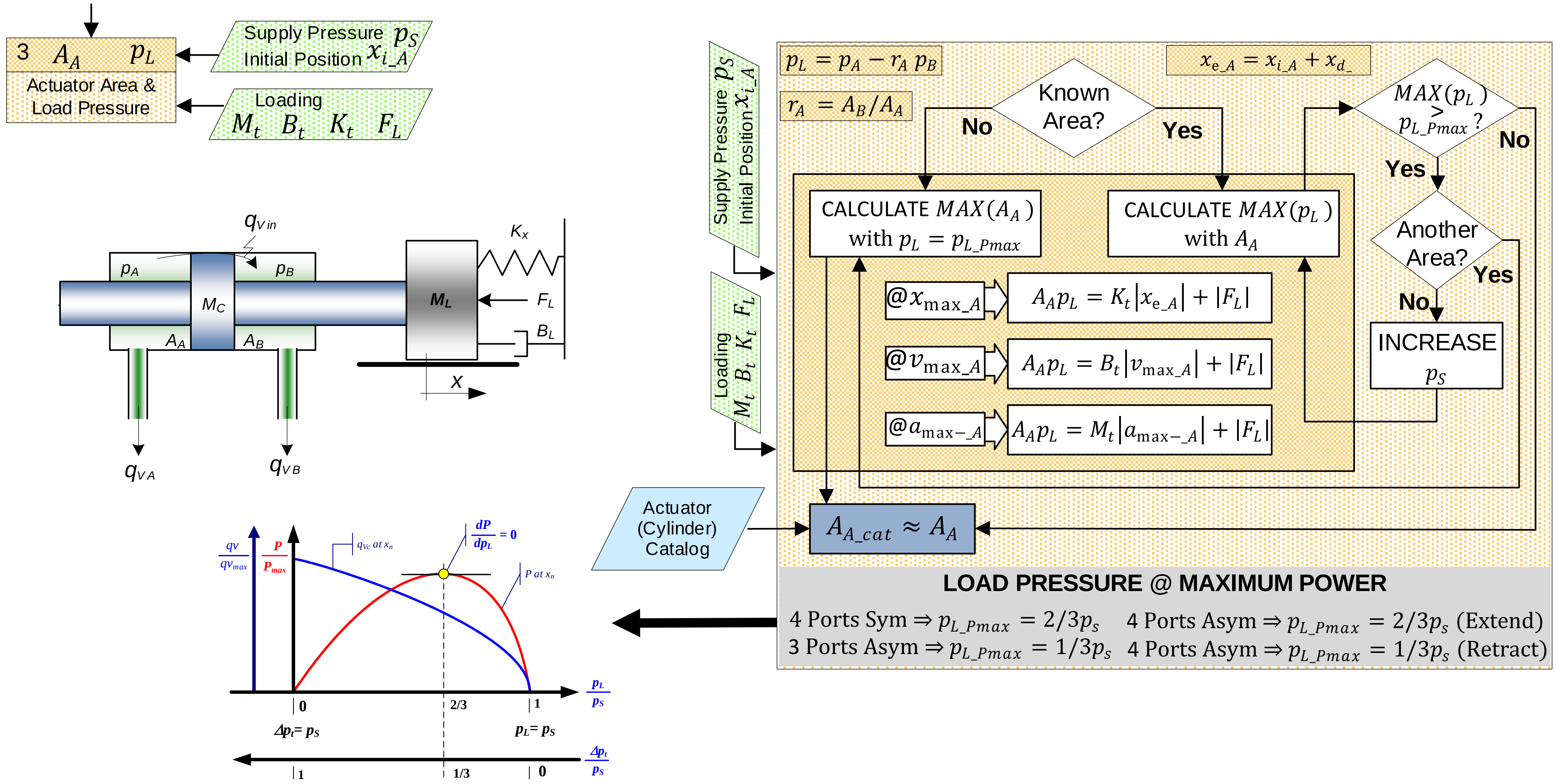
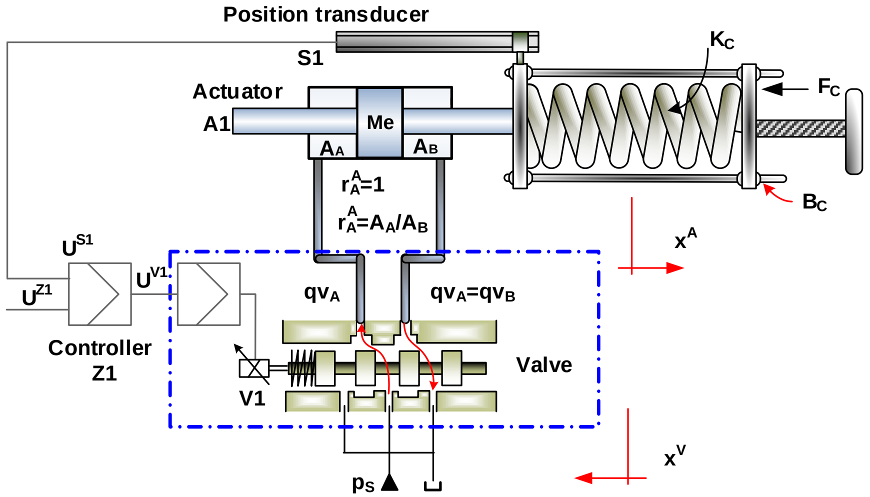


Step 1 - System & Actuator Characterization

LOAD PRESSURE @ MAXIMUM POWER

4 Ports Sym $\Rightarrow p_{L\_Pmax} = 2/3P_s$	4 Ports Asym $\Rightarrow p_{L\_Pmax} = 4/3P_s$ (Extend)
3 Ports Asym $\Rightarrow p_{L\_Pmax} = 1/3P_s$	4 Ports Asym $\Rightarrow p_{L\_Pmax} = 1/3P_s$ (Retract)

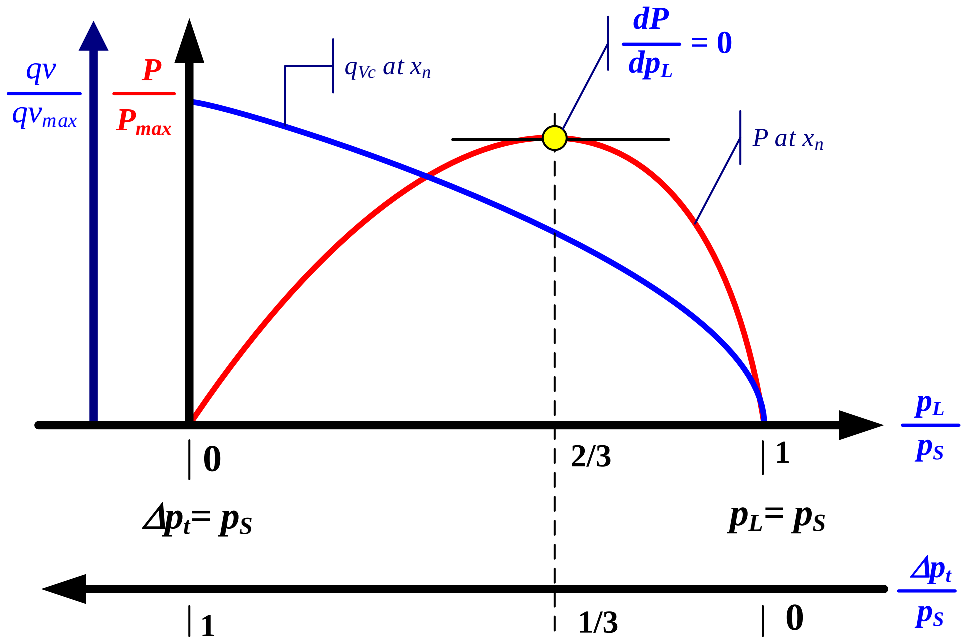


$$p_L = p_A - p_B$$

$$p_{L\_Pmax} = {}^2/_3\, P_s$$

- Symmetrical cylinder + symmetrical valve

For $r_A = 1$



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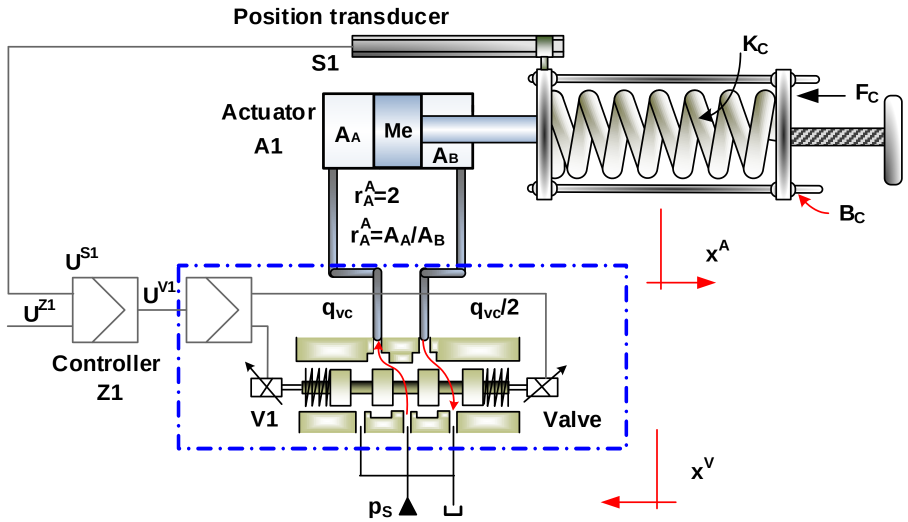


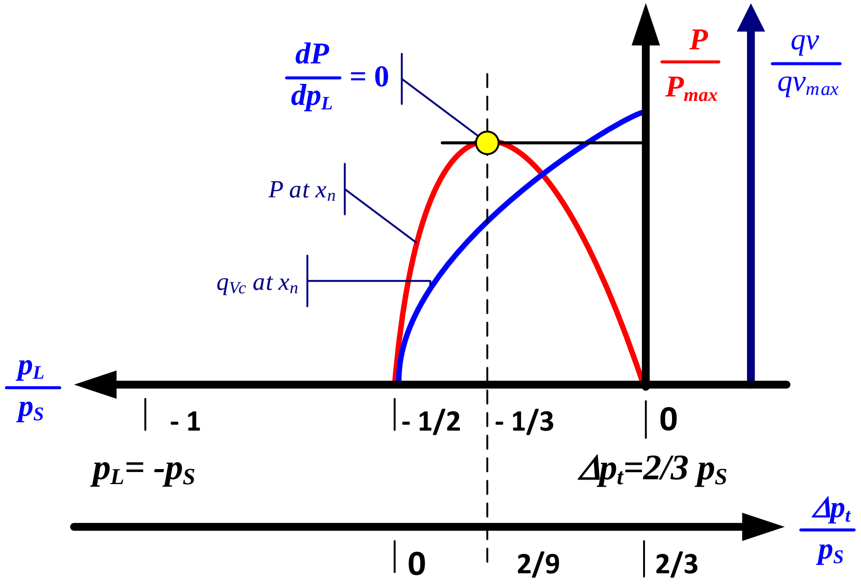
- Asymmetrical cylinder + asymmetrical valve

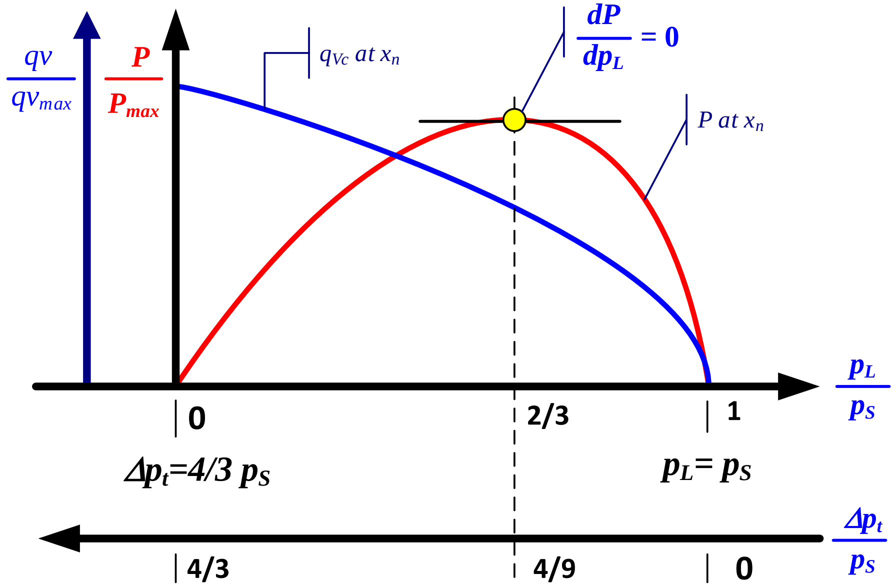
For $r_A = 0.5$

$$p_L = p_A - {}^{1}\!/_{2}\, p_B$$

$$p_{L\_Pmax} = {}^{2}\!/_{3}\, P_s \text{ for cylinder extension}$$

$$p_{L\_Pmax} = {}^{1}\!/_{3}\, P_s \text{ for cylinder retraction}$$





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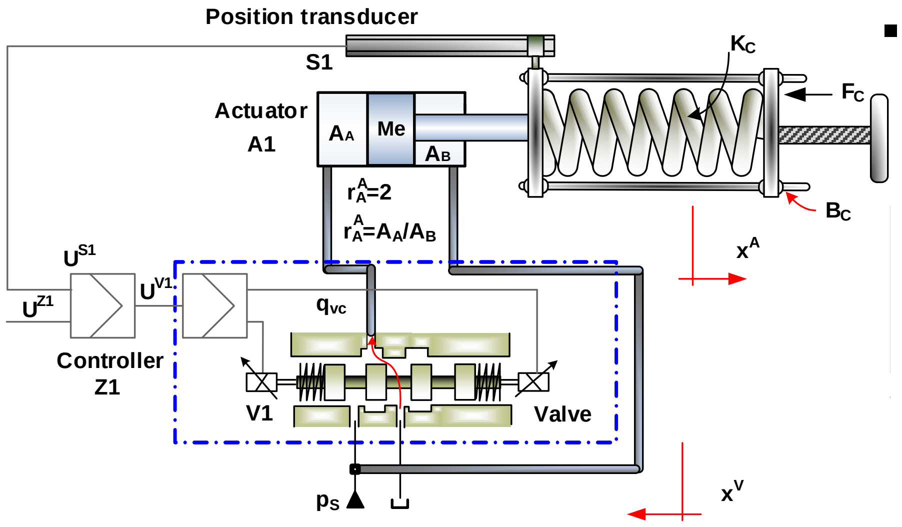
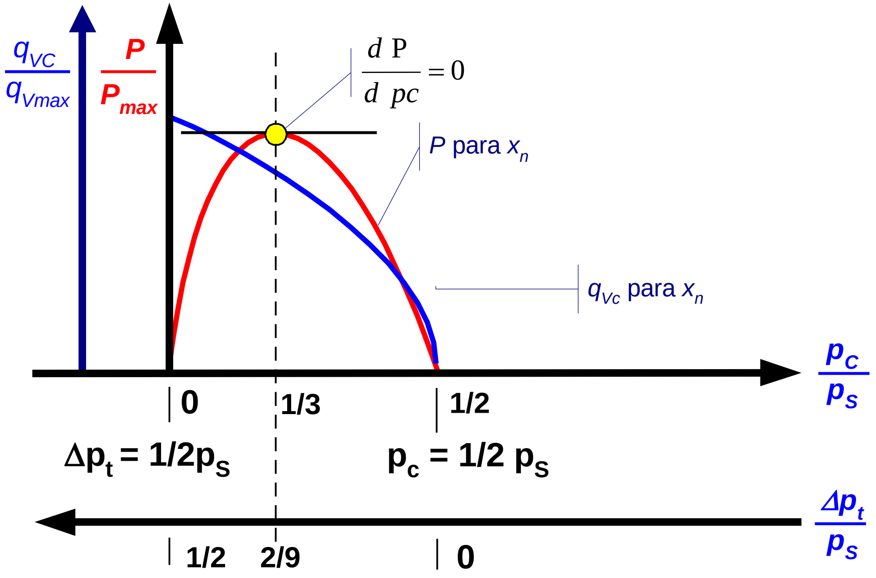


- Single effect asymmetrical cylinder + 3 port valve

For $r_A = 0.5$

$$p_L = p_A - {}^1\!/_2\, p_S$$

$$p_{L\_Pmax} = {}^1\!/_3\, P_s$$

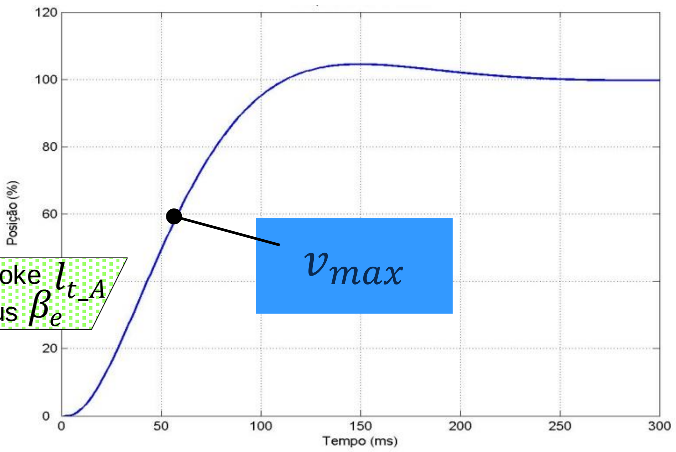


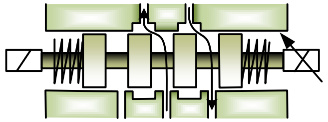
4 q_{Vmax} — Maximum Flow rate

5 ω_{n_A} — Actuator Natural Frequency

Cylinder Stroke l_{t_A}
Bulk Modulus β_e

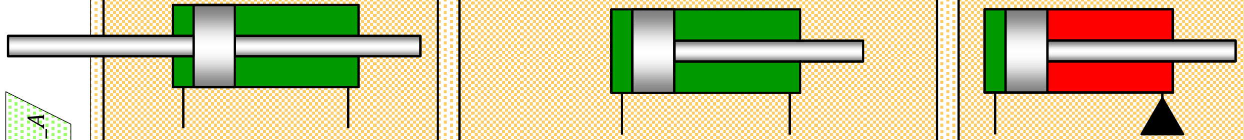
END





$$q_{Vmax} = A_{A\_cat}\, v_{\max\_A}$$

Cylinder Stroke l_{t_A}
Bulk Modulus β_e

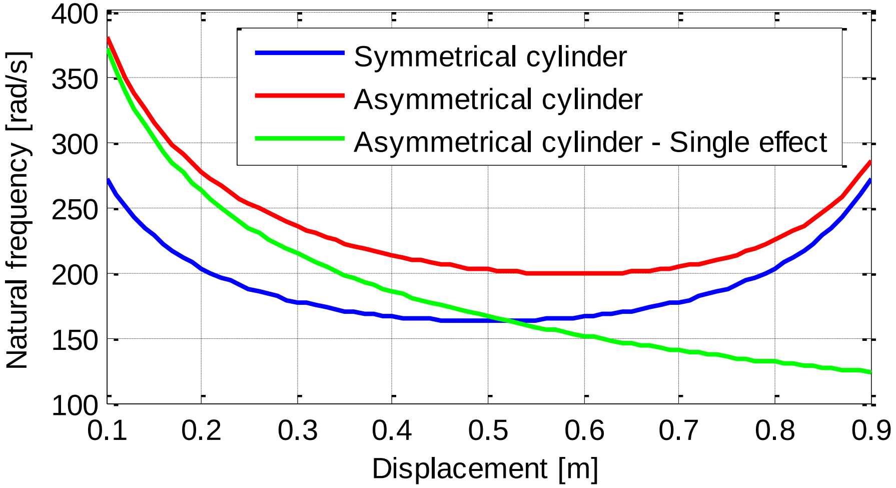


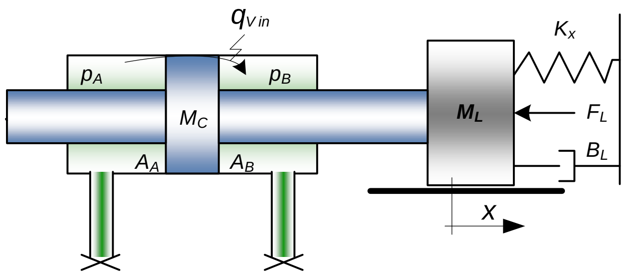
$$\omega_{n\_\min\_A} = \sqrt{\frac{4\,\beta e\, A_A^{\,2}}{M_t\, V_{t\_A}}} \qquad @\; x_A = \frac{1}{2} l_{t\_A}$$

$$\omega_{n\_\min\_A} = \sqrt{\frac{\beta e}{M_t}\left(\frac{A_A}{x_A} + \frac{A_B}{l_{t\_A} - x_A}\right)} \qquad @\; x_A = \frac{A_A\, l_{t\_A}}{A_A - A_B}\left[1 - \left(\frac{A_B}{A_A}\right)^{1/2}\right]$$

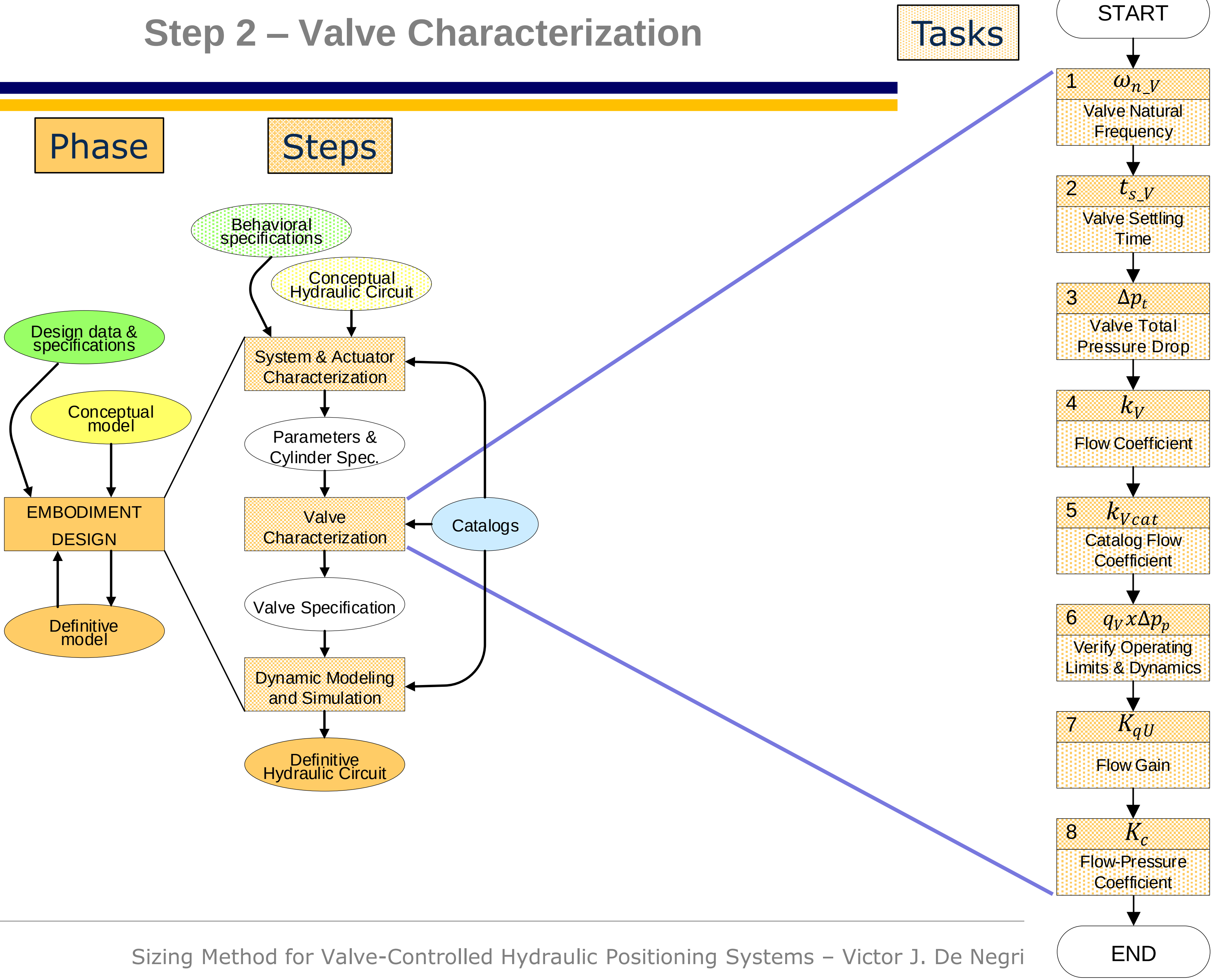
$$\omega_{n\_\min\_A} = \sqrt{\frac{\beta_e\, A_A^{\,2}}{M_t\, V_{t\_A}}} \qquad @\; x_A = l_{t\_A}$$

END





Step 2 – Valve Characterization



Step 2 – Valve Characterization

EMC-UFSC LASHIP HYDRAULICS & PNEUMATICS

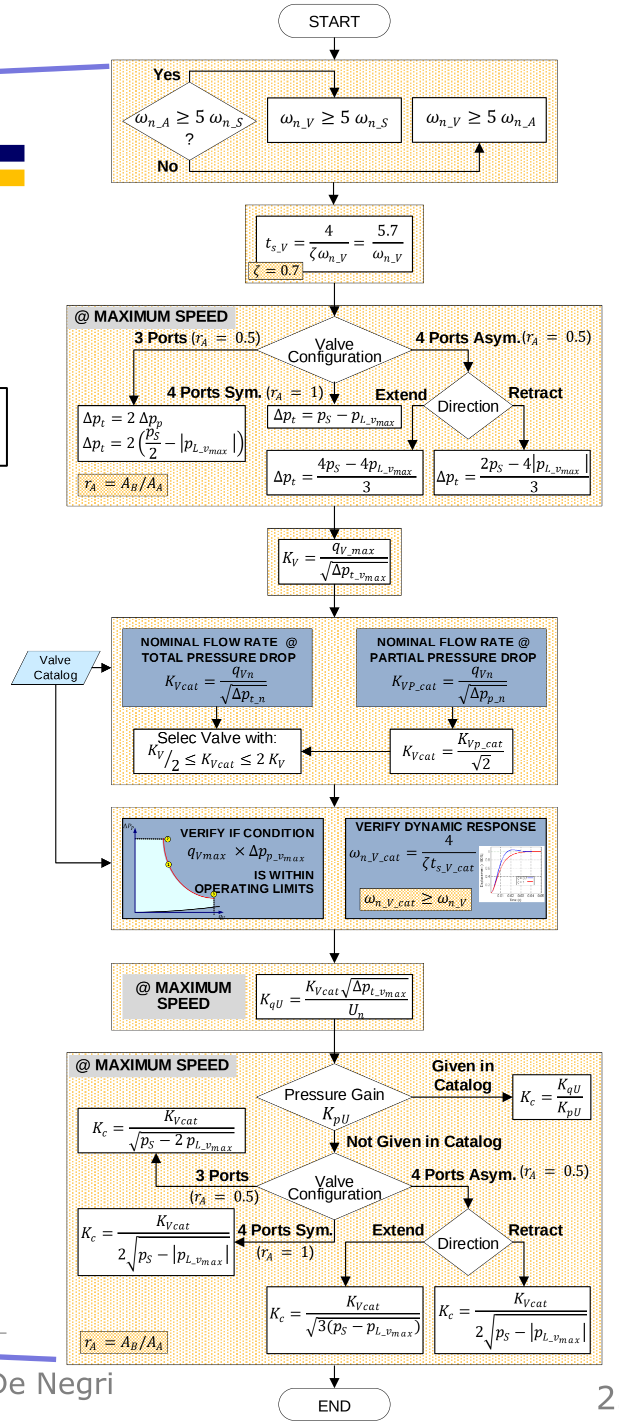
Tasks

START

1. ω_{n_V} – Valve Natural Frequency
2. t_{s_V} – Valve Settling Time
3. Δp_t – Valve Total Pressure Drop
4. k_V – Flow Coefficient
5. k_{Vcat} – Catalog Flow Coefficient
6. $q_V x \Delta p_p$ – Verify Operating Limits & Dynamics
7. K_{qU} – Flow Gain
8. K_c – Flow-Pressure Coefficient

END

Activities



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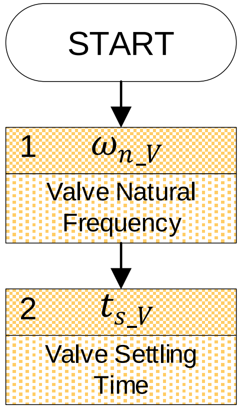
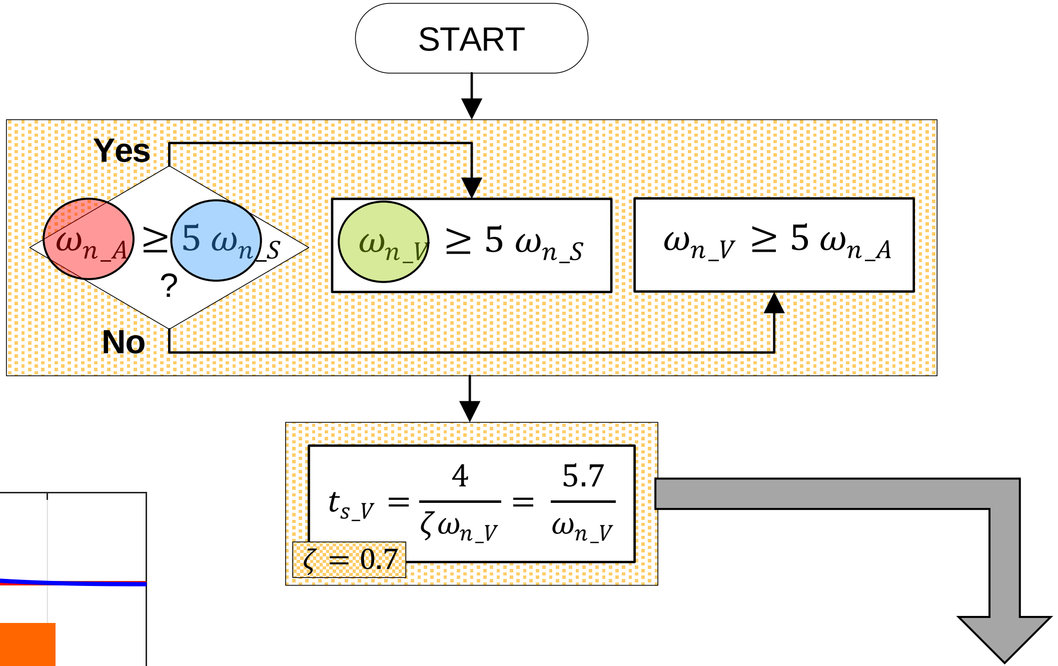
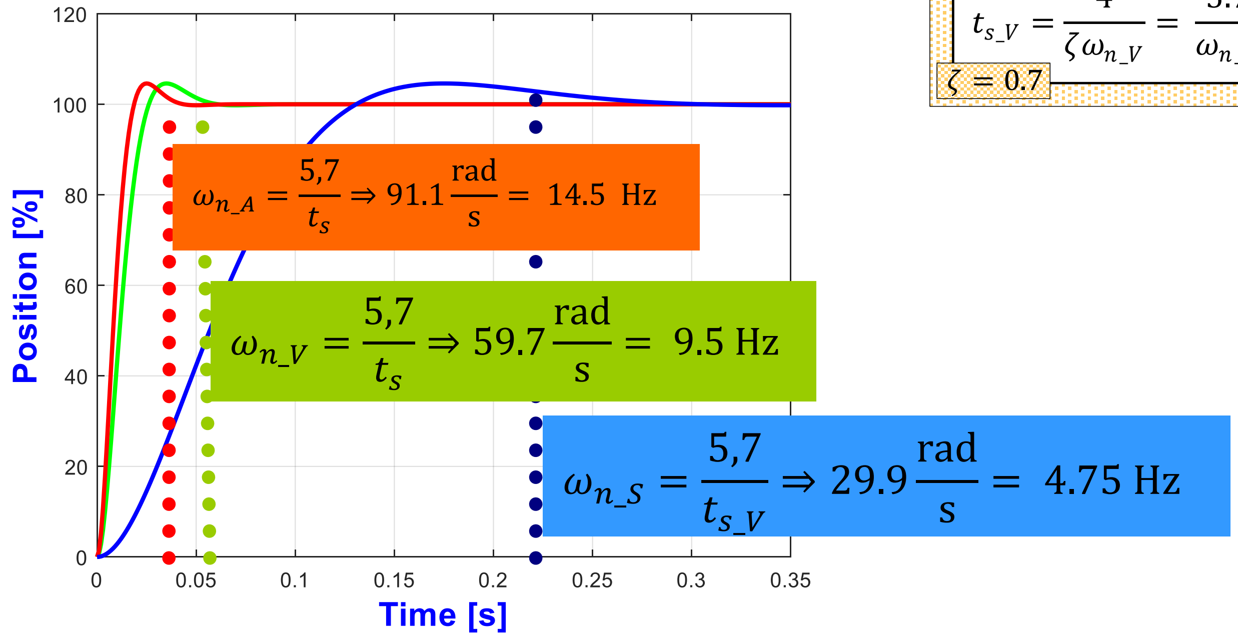
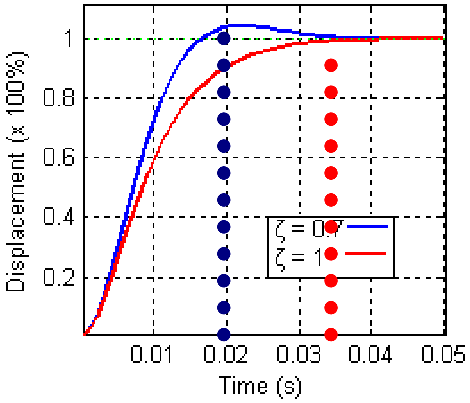




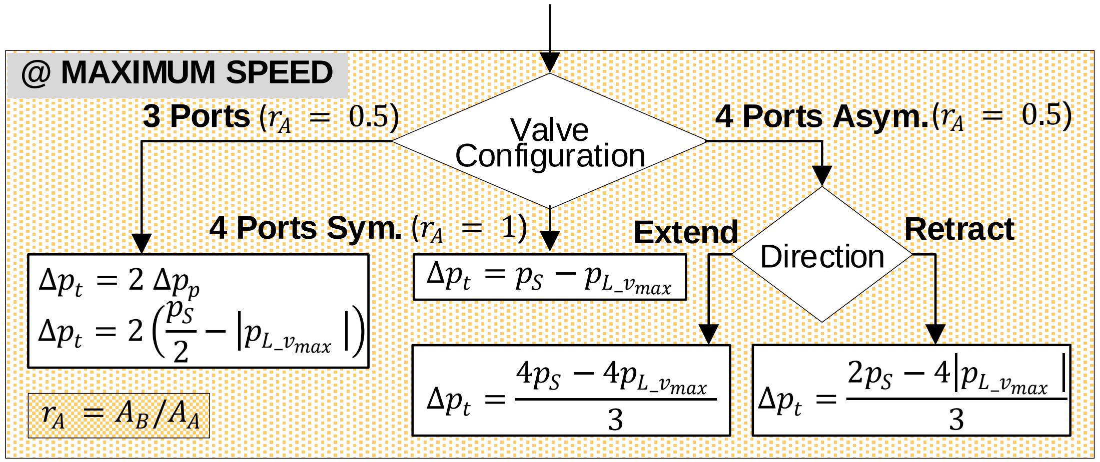


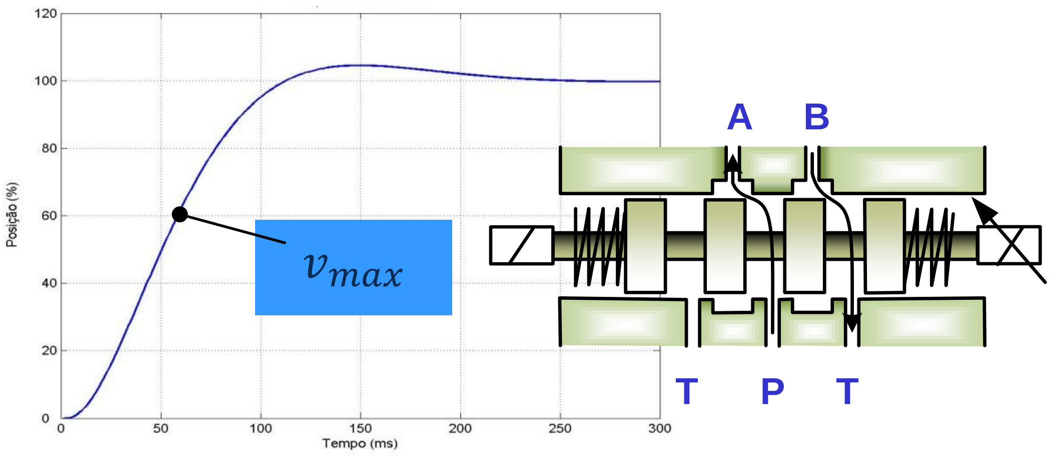


Step 2 – Valve Characterization

3 Δp_t

Valve Total Pressure Drop





$@v_{max}$ ⇒ $A_A p_L = B_t v_{max} + F_L$

TOTAL pressure drop: Δp_t

P => A + B => T or **P => B + A=>T**

PARTIAL pressure drop: Δp_p

P => A or **B => T** **P => B** or **A => T**

Step 2 – Valve Characterization

4 k_V
Flow Coefficient

5 k_{Vcat}
Catalog Flow Coefficient

$$K_V = \frac{q_{V\_max}}{\sqrt{\Delta p_{t\_vmax}}}$$

Valve Catalog

NOMINAL FLOW RATE @ TOTAL PRESSURE DROP

$$K_{Vcat} = \frac{q_{Vn}}{\sqrt{\Delta p_{t\_n}}}$$

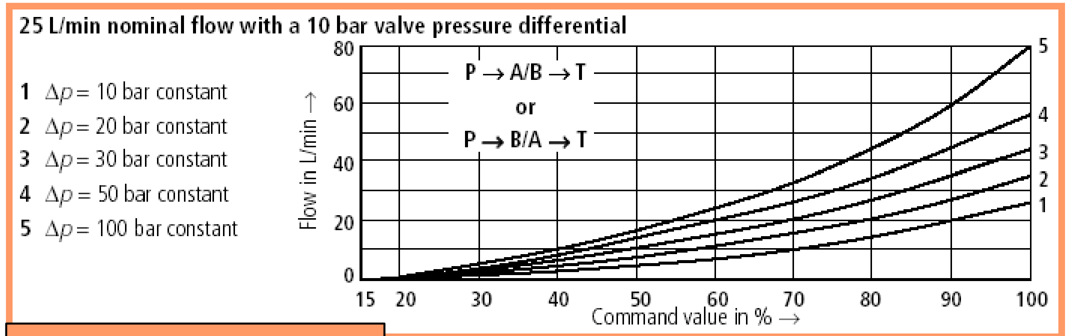
NOMINAL FLOW RATE @ PARTIAL PRESSURE DROP

$$K_{VP\_cat} = \frac{q_{Vn}}{\sqrt{\Delta p_{p\_n}}}$$

$$K_{Vcat} = \frac{K_{Vp\_cat}}{\sqrt{2}}$$

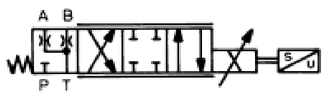
Selec Valve with:

$$K_V/_2 \leq K_{Vcat} \leq 2\,K_V$$



$$K_{V\_cat} = \frac{q_{V\_n}}{\sqrt{\Delta p_{t\_n}}}$$

$$K_{V\_p\_cat} = \frac{q_{V\_n}}{\sqrt{\Delta p_{p\_n}}}$$

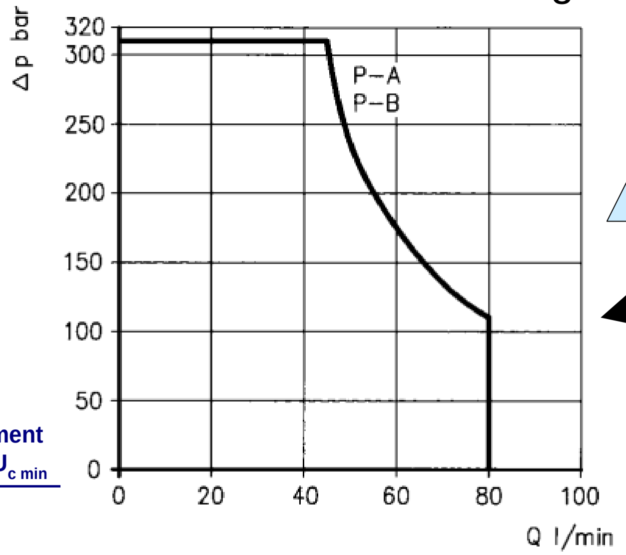
Sinnbild Symbol Symbole	V/VA max	Δp [bar]	$Q_{nom.}$ [l/min]
18 	24 V= 40 VA max U_{D-E} 0 … ±10 V	35	4
			12
			24
			40

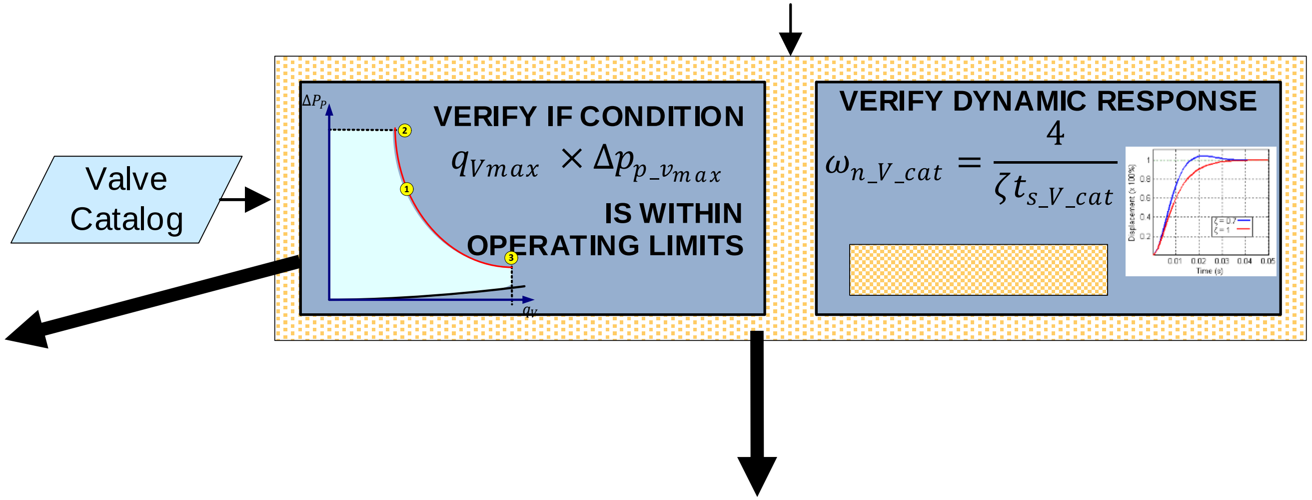
Step 2 – Valve Characterization

6 $q_V x \Delta p_p$

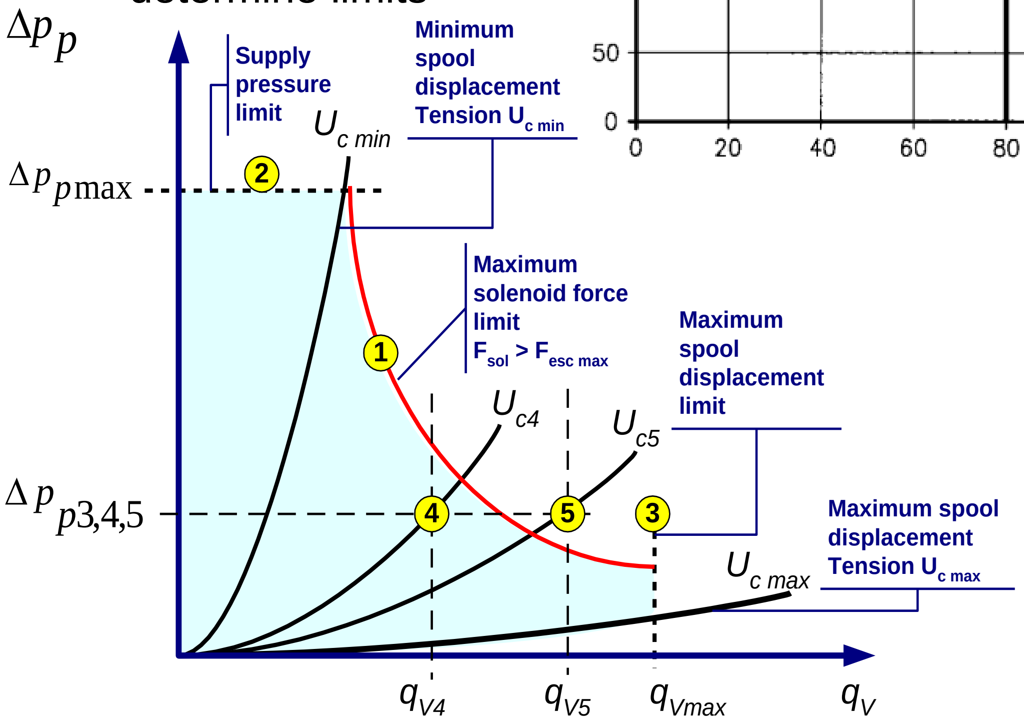
Verify Operating Limits & Dynamics

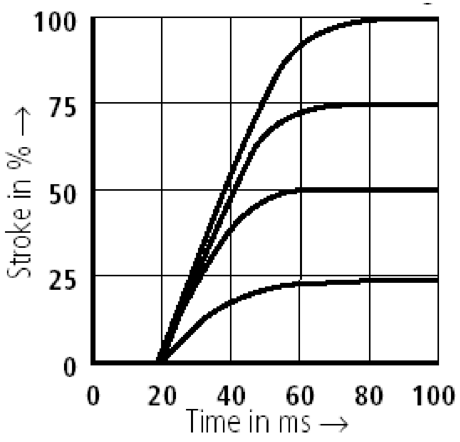
Curve from valve catalog

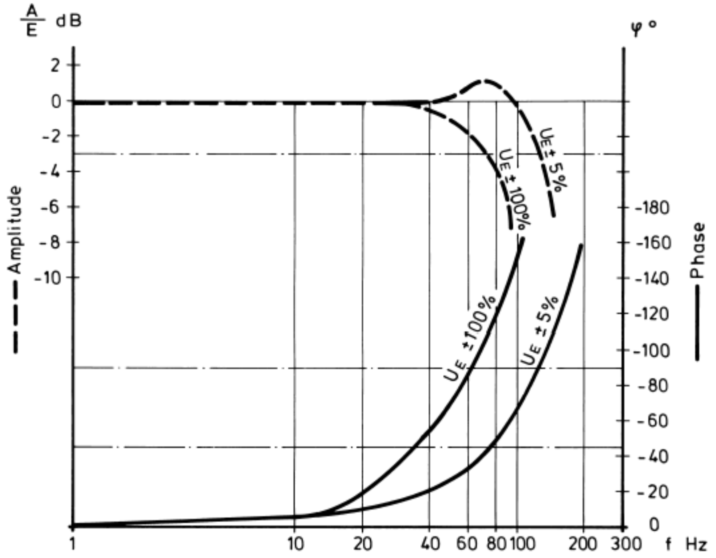




Operating conditions determine limits







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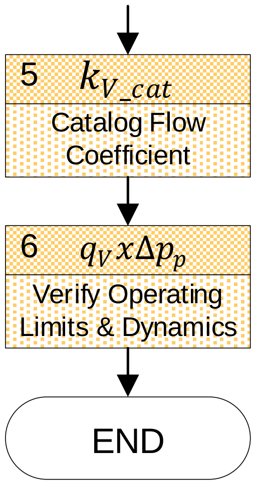
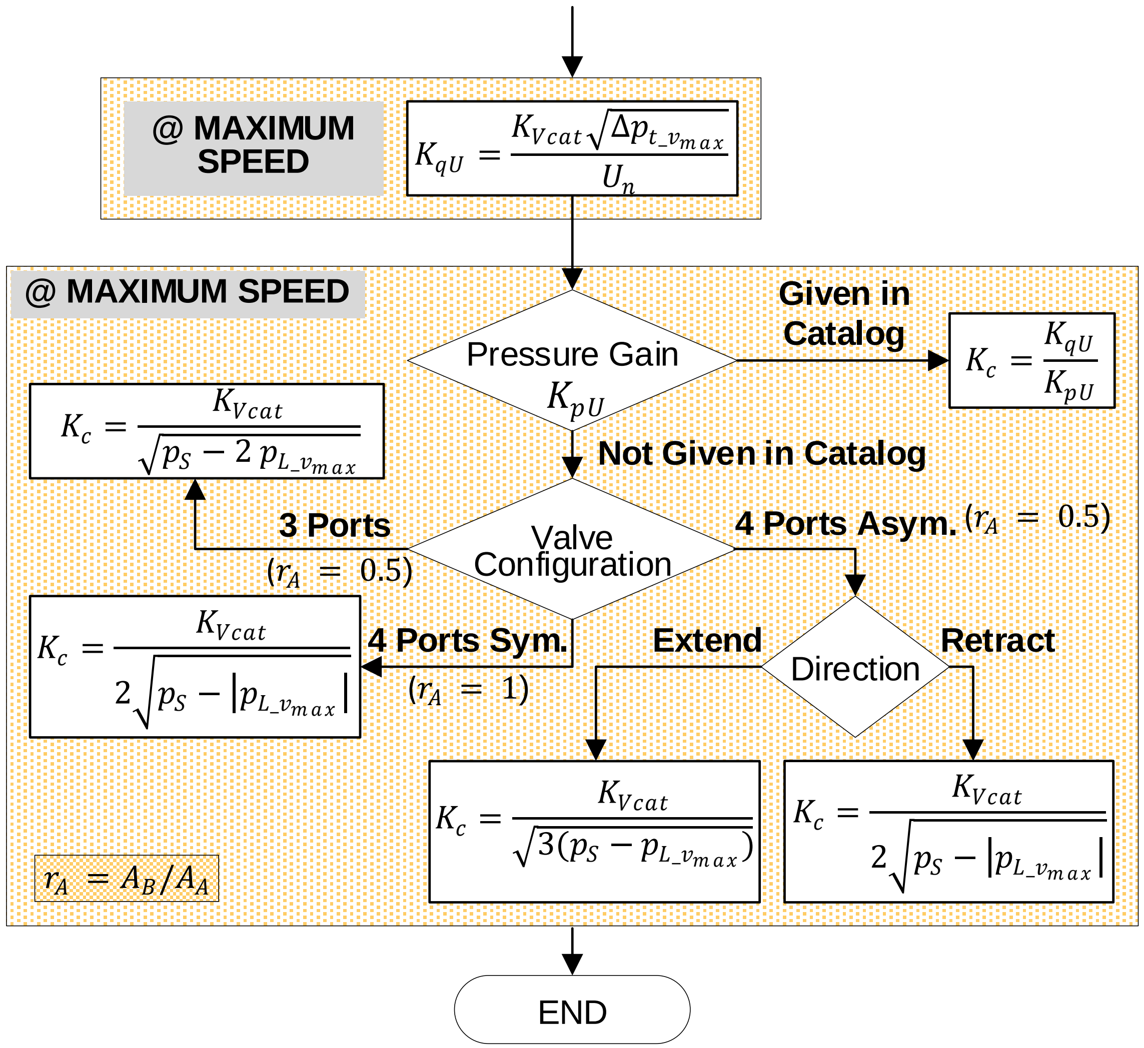
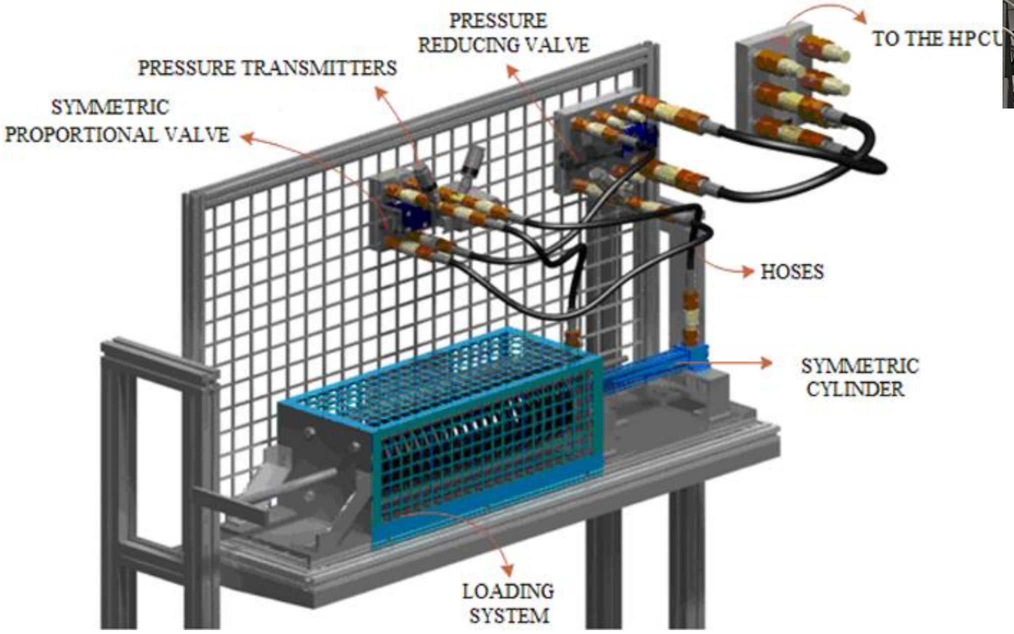




▪ Proportional Hydraulic Platform (PHP)

- Hydraulic power unit
- Two workstations
- Data acquisition and control system

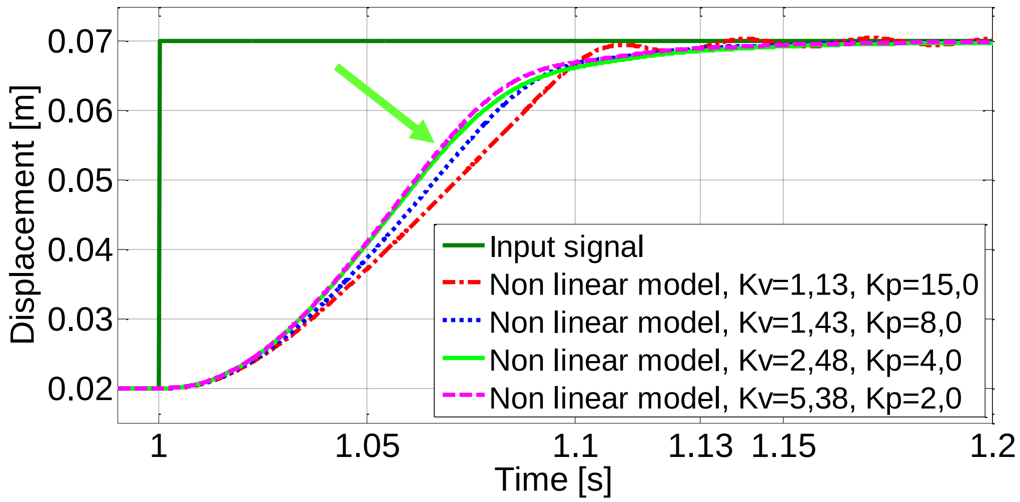


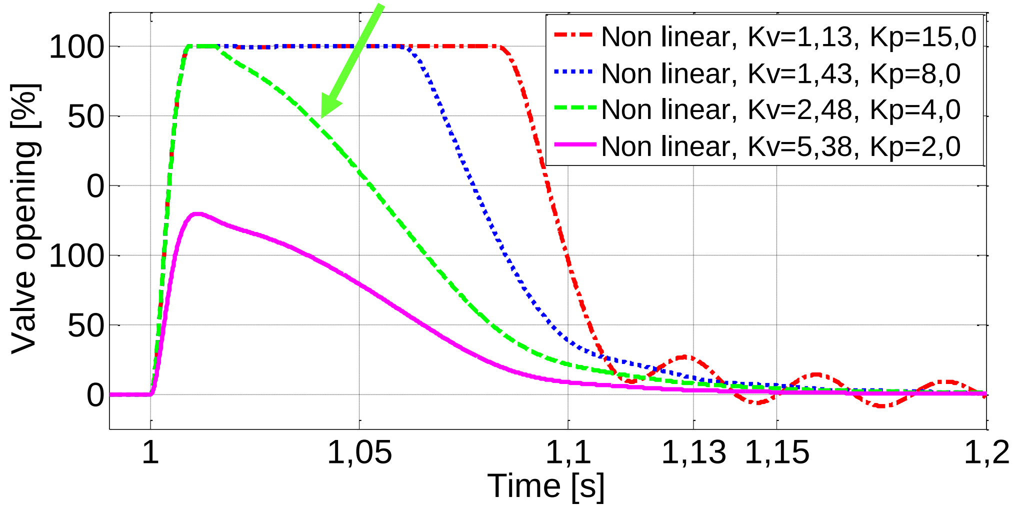
▪ Workstation:

- Loading system
  - Forces up to 3900 N
- Symmetrical and asymmetrical valves
- Differential and non-differential cylinders

Flow Coefficient (Kv)		Relative to selected value
L/min.bar$^{1/2}$	$\times10^{-7}$ m^3/s.Pa$^{1/2}$	%
1.13	0.60	~ 40
1.43	0.76	~ 50
2.48	1.31	Specified value
5.38	2.84	~ 200

- Results (M = 76.5 kg):
  - Kv < 1.24 L/min.bar1/2 (50%)
    - Higher controller gains are required
    - Larger periods of valve saturation
    - Tendency of instability
  - Kv > 4.96 L/min.bar1/2 (200%)
    - Smaller proportional gains
    - No valve saturation
    - Larger valves do not exhibit performance improvement
    - Slower and more expensive valve





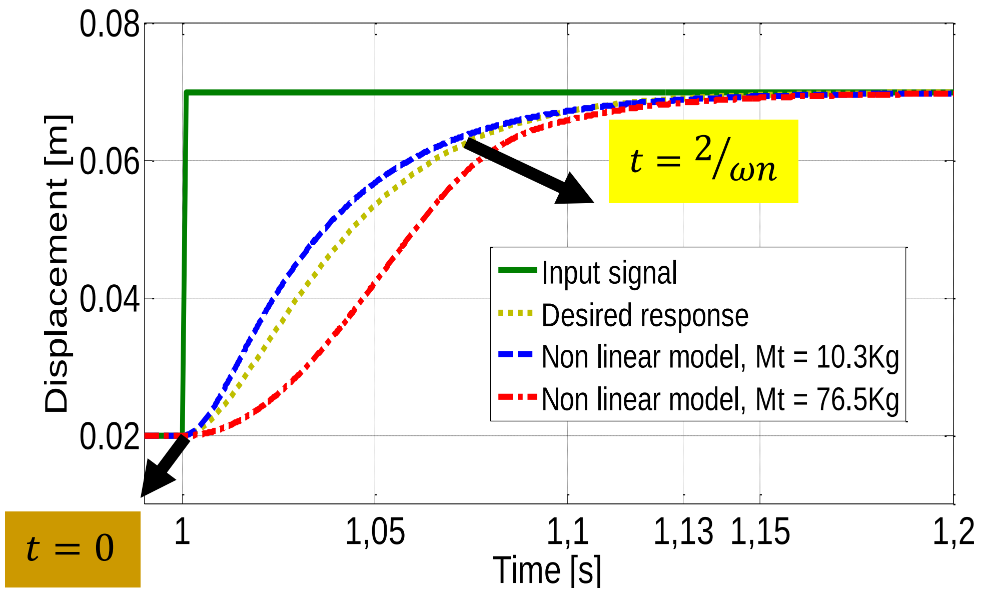
Maximum Acceleration

- Maximum positive acceleration = Maximum acceleration
  - Occurs at t = 0 s

$$a_{\max\_p} = x_d\ \omega_n{}^2$$

- Maximum negative acceleration:
  - Occurs at the end of motion

$$a_{\max\_n} = -x_d\ \omega_n{}^2\ e^{-2}$$



- Using negative acceleration:
  - Smaller cylinder can be used
  - or
  - Higher mass can be moved

Acceleration	Mass
106.5 m/s²	10 kg
-14.4 m/s²	76.5 kg
Hydraulic force = 1100 N $A^C\,.\,p_L = M_t.\,a^C_{\max}$	

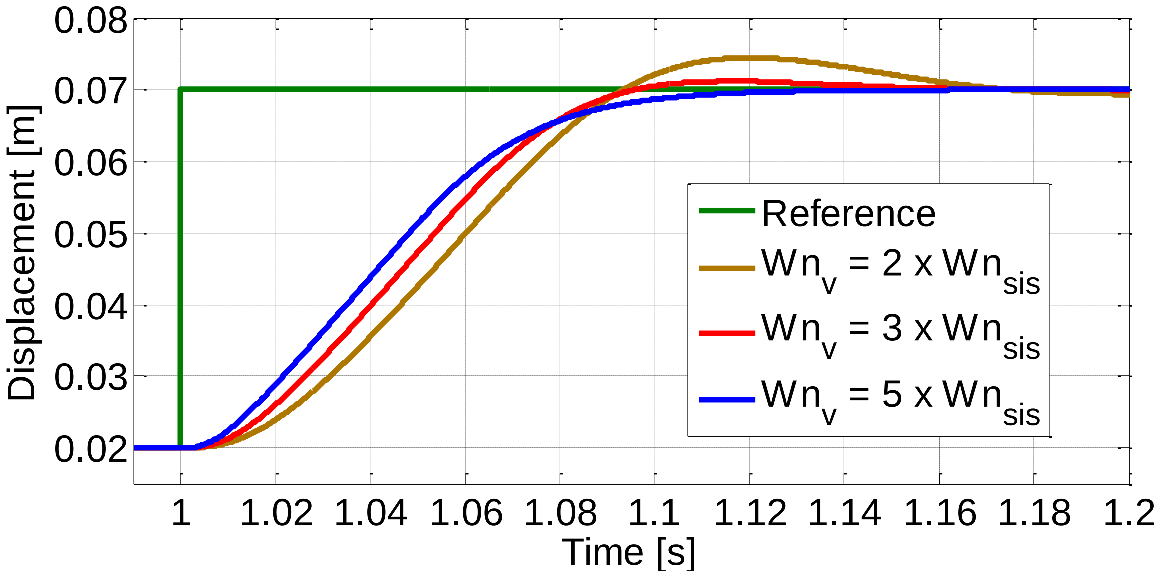
Correlation between Natural Frequencies

- Valve Natural Frequency x Positioning System Natural Frequency:
  - Experimental system:
    - Valve natural frequency = 440 rad/s (70 Hz)
    - System natural frequency = 46.15 rad/s (7.3 Hz)

      $\omega_{n\_V} \approx 9.5\ \omega_{n\_S}$
    - Without load mass and coupled spring:

      Ensure a high cylinder+load natural frequency $\omega_{n\_C} > 5\ \omega_{n\_S}$

- With $\omega_{n\_V} < 3\ \omega_{n\_S}$
  - The dynamic performance cannot be achieved
- With $\omega_{n\_V} \geq 5\ \omega_{n\_S}$
  - The dynamic performance is effectively achieved
    - Desired response without overshoot

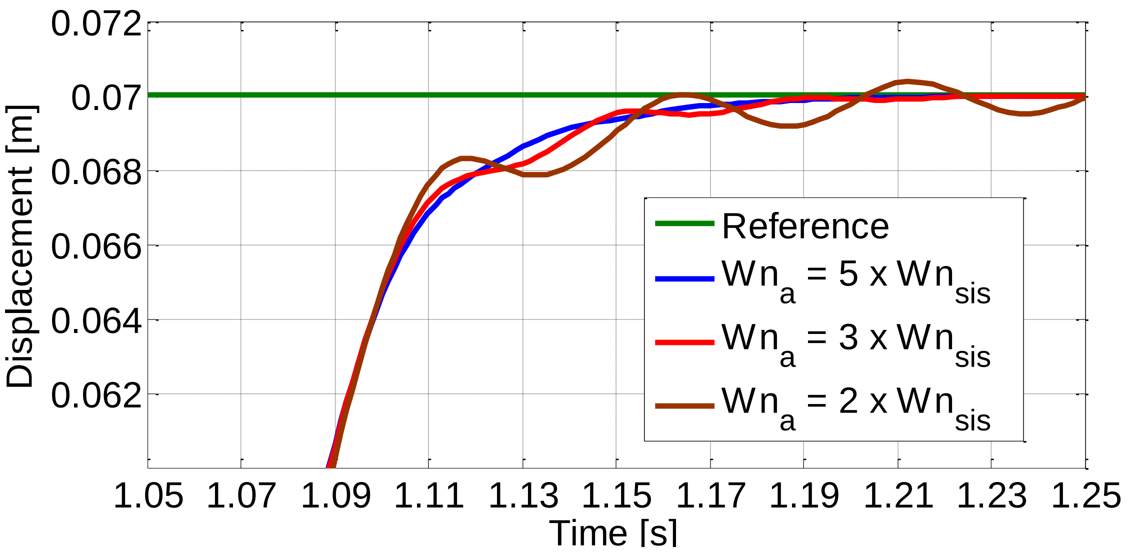


- Cylinder Natural Frequency x Positioning System Natural Frequency:
  - Cylinder natural frequency = 220 rad/s (35 Hz)
  - System natural frequency = 46.15 rad/s (7.3 Hz)

  $\omega_{n\_C} \approx 5\,\omega_{n\_S}$

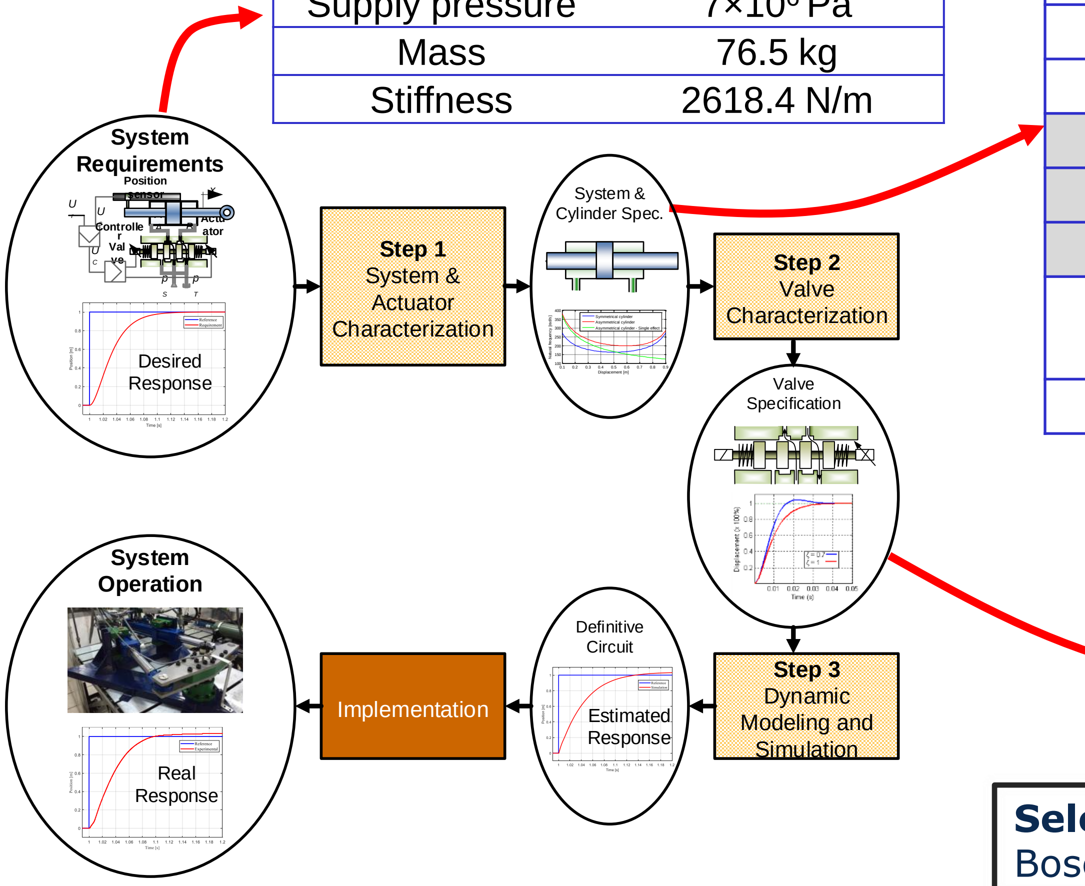
  - Changing fluid volumes: $\omega_{n\_C} = 2\,\omega_{n\_S}$ $\omega_{n\_C} = 3\,\omega_{n\_S}$

- With $\omega_{n\_A} < 3\,\omega_{n\_S}$
  - The dynamic performance cannot be achieved
- With $\omega_{n\_A} \geq 5\,\omega_{n\_S}$
  - The dynamic performance is effectively achieved
    - Desired response without overshoot



Results from the Design Method

Requirement	Value
Settling time	0.13 s
Displacement	0.05 m
Overshoot?	No
Supply pressure	7×10^6 Pa
Mass	76.5 kg
Stiffness	2618.4 N/m



Parameter	Value
System nat. freq.	46.15 rad/s
Max. Cyl. speed	0.849 m/s
Max. Negative Cyl. acceleration	-14.4 m/s^2
Max. Power Load Pressure	4.67×10^6 Pa
Calculated Cyl. area	2.28×10^{-4} m^2
Cylinder rod diameter	18 mm
Cylinder bore diameter	25 mm
Cylinder annulus area	2.364 cm^2
Max. flow rate	2×10^{-4} m^3/s (12 L/min)
Cylinder nat. frequency	220 rad/s

Selected cylinder
Bosch Rexroth CGT3MS2 25/18/200

Parameter	Value
Valve nat. frequency	230.75 rad/s
Valve flow coefficient	1.31×10^{-7} m^3/s.Pa$^{1/2}$ (2.48 L/min.bar$^{1/2}$)
Catalog flow coefficient	1.41×10^{-7} m^3/s.Pa$^{1/2}$ (2.68 L/min.bar$^{1/2}$)

Selected valve:
Bosch Rexroth valve 0 811 404 038 (Kv = 2.68)

Design Method for Valve-Controlled Hydraulic Positioning Systems

This method originated from the thesis by **Fernando L. Furst** (2001) and was updated based on the later contributions of other graduate students: **Alisson D. C. de Souza** (2005), **José R. B. Ramos Filho** (2007), **Rodrigo Szpak** (2008), **Irving Muraro** (2009) and **Mario Destro** (2015).

Theses:

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- FUST, Fernando Luiz Sistematização do projeto preliminar de circuitos hidráulicos de controle de posição. Florianópolis,. 2001. Master’s Thesis. Universidade Federal de Santa Catarina.
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- RAMOS FILHO, José Roberto Branco. Análise Teórico-Experimental de Falhas em Válvulas Direcionais Servoproporcionais. 2009 Master’s Thesis Universidade Federal de Santa Catarina.
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Design Method for Valve-Controlled Hydraulic Positioning Systems

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- DE NEGRI. V., J., R. FILHO. J., R. B., SOUZA. A., D., C. **A Design Method for Hydraulic Positioning Systems.** 51th National Conference on Fluid Power (NCFP), in conjunction with IFPE 2008, p. 669-679, 2008, Las Vegas, USA.

Desing Method for Valve-Controlled Hydraulic Positioning Systems

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