



Bond-Graph Modeling and System Identification of Flight Actuation Systems: EHS, EHA, and MEA

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Presentation Outline



- Objective and Motivations;
- Overview of Flight Actuation Systems: EHS, EHA, EMA;
- Bond-Graph Methodology for Modeling and Parametric System Identification;
- Case studies: BG Simulation and Validation
- Conclusions.



Objective and Motivations

Objective :

Energy based multiport modeling and parametric system identification for fly-by-wire and power-by-wire flight actuators and experimental model validation with flight-test and/or laboratory data (aircraft iron bird).

Motivations :

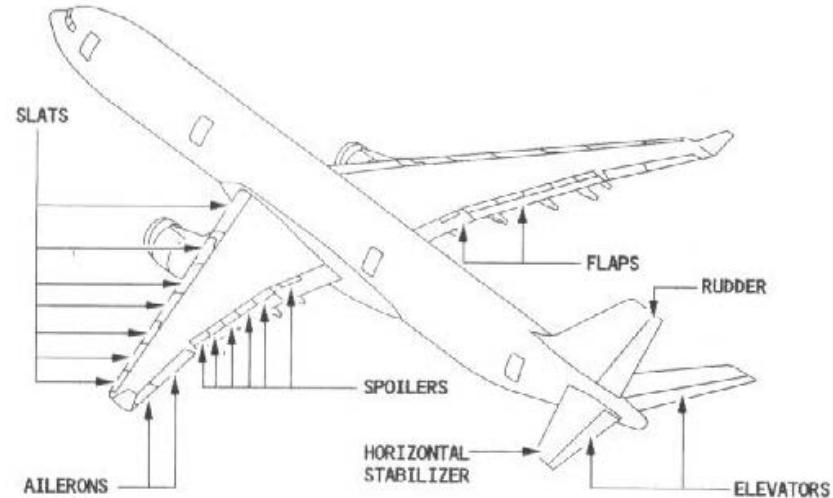
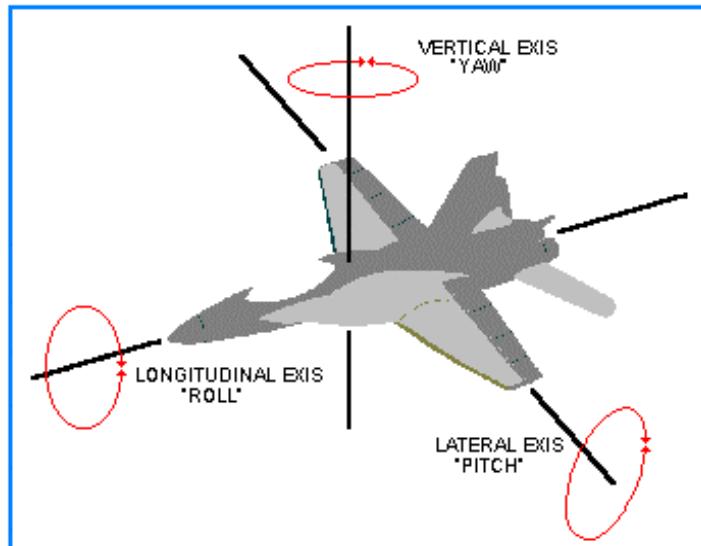
- Quick analysis of dynamic behavior of a FBW/PBW control system using Bond-Graph modeling and system identification techniques;
- Contribution to ITA/Embraer PEE graduation work of FBW PBW hardware electrohydromechanical technologies.

Overview – FBW Control Systems



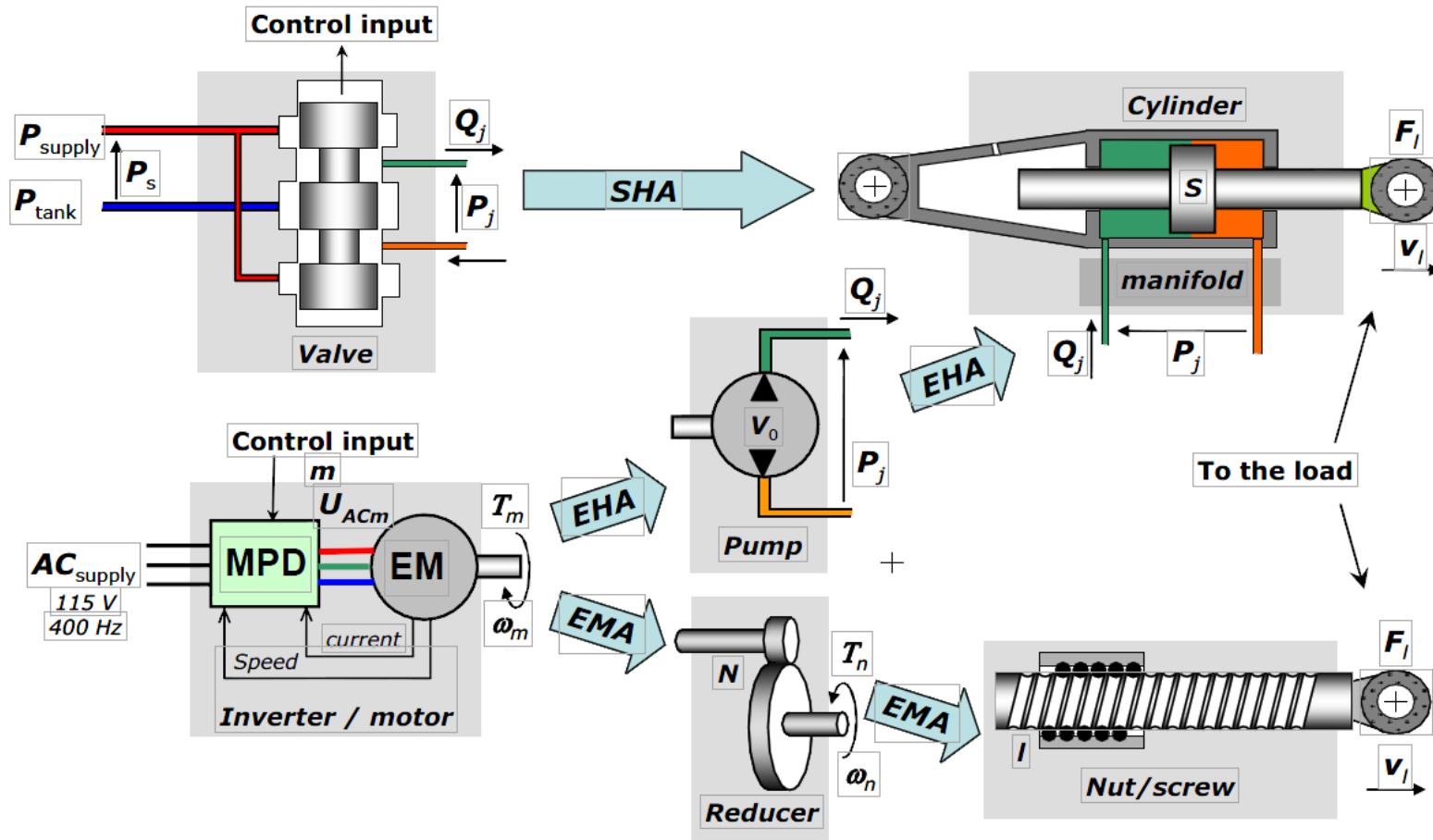
Flight Control Systems

- Missions : - Primary : control Roll, Yaw, Pitch axis
- Secondary : help to control lift (flap/slat)
drag (speedbrake) and landing (gnd spoilers)



“This work focus on Primary Flight Controls (Rudder, Elevator, Aileron/spoilers)”

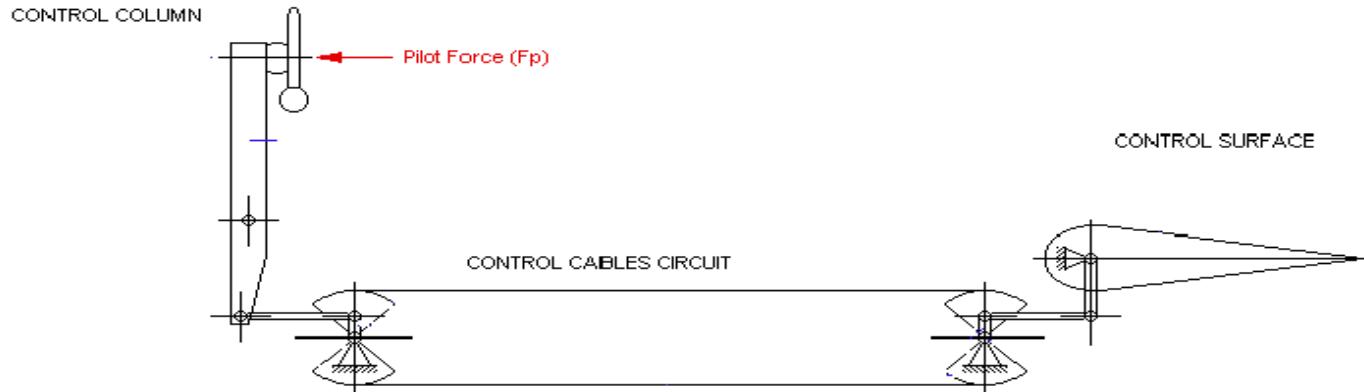
Overview of Flight Actuation Systems



From J-C Maré, SICFP 09

Mechanical Control Systems

Types of Flight Control Systems : 1 – Cable :



Neiva EMB200 "Ipanema"

- Aileron Control System
- Elevator Control System
- Rudder Control System



Embraer ALX314 "Super Tucano"

- Aileron Control System
- Elevator Control System
- Rudder Control System



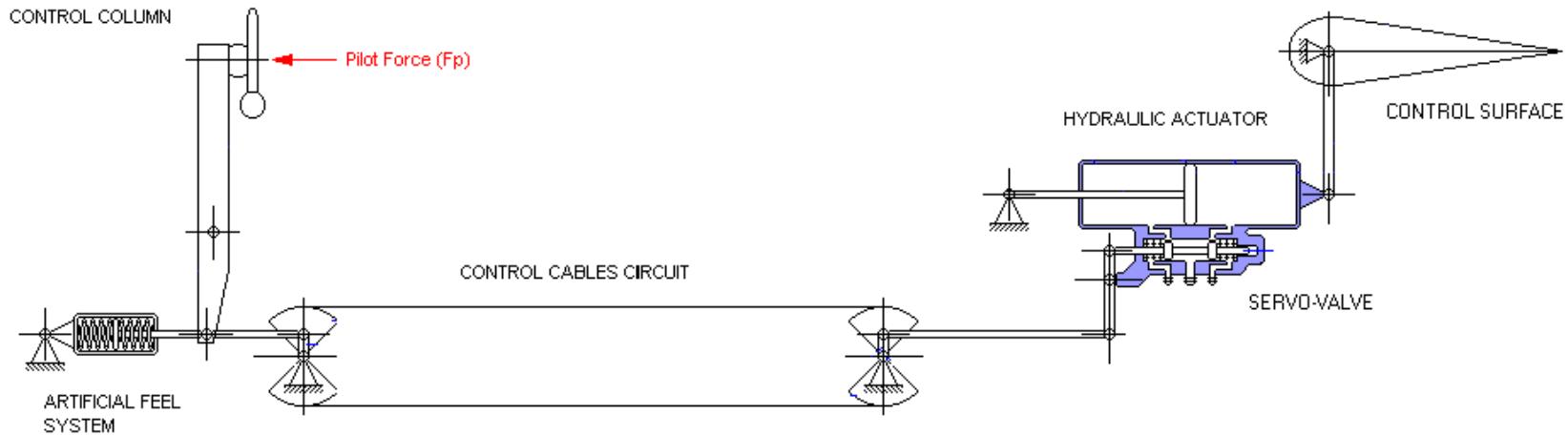
Embraer EMB120 "Brasilia"

- Aileron Control System
- Elevator Control System

Hydromechanical Control Systems



Types of Flight Control Systems : – Hydromechanic



Boeing 737-700

- Aileron Control System
- Elevator Control System
- Rudder Control System
- Spoiler Control System



Embraer ERJ-145

- Aileron Control System
- Rudder Control System
- Spoiler Control System



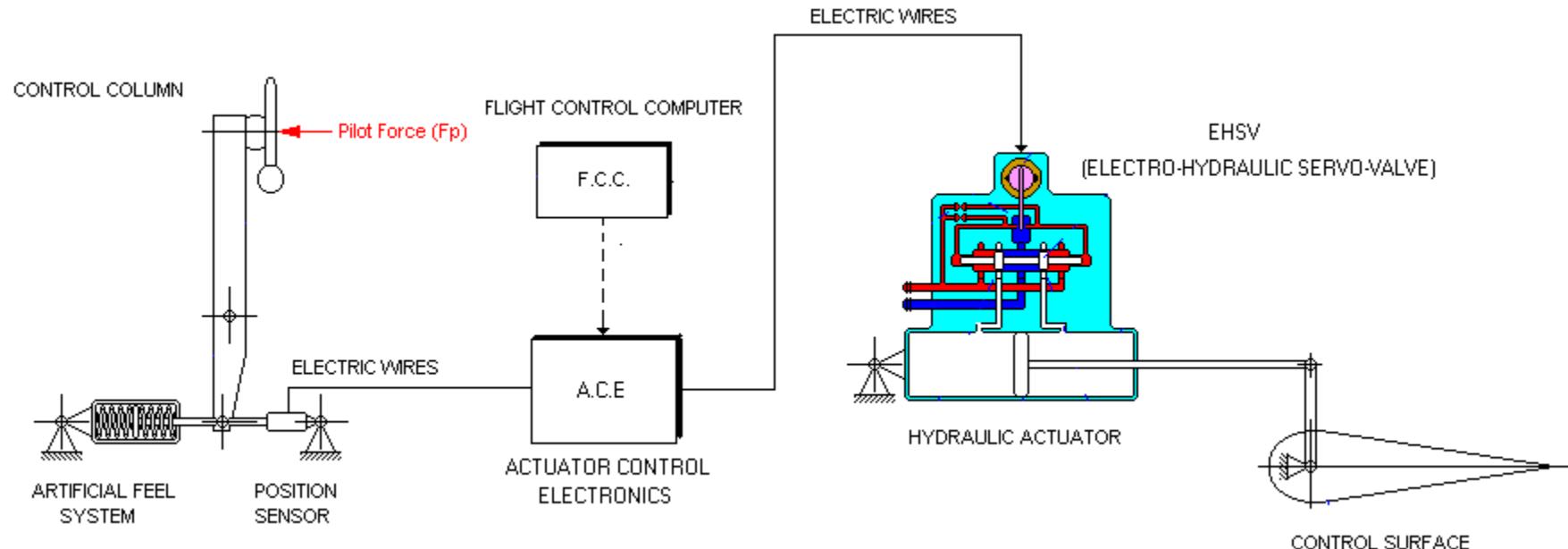
Embraer AMX-T

- Aileron Control System
- Elevator Control System

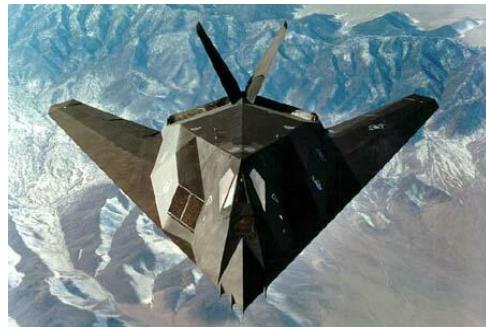


FBW Control Systems

Types of Flight Control Systems : EHS-FBW



Airbus A340



Lockheed F-117



BAC Concorde



Bond-Graph Conjugate Variables

Domínio	Esforço, e	Fluxo, f	Momento, p	Deslocamento, q
Mecânico de translação	Força [N]	Velocidade [m/s]	Impulso [N.s]	Posição [m]
Mecânico de rotação	Momento [N.m]	Vel. Angular [rad/s]	Momentoangular [N.m.s]	Ângulo [rad]
Elétrico	Tensão [V]	Corrente [A]	Fluxoenlaçado [V.s]	Carga [C]
Hidráulico	Pressão [Pa]	Vazão volumétrica [m³/s]	Momentode pressão [Pa.s]	Volume [m³]
Termodinâmico	Temperatura [K]	Fluxode entropia [W /K]	—	Entropia [J/K]
Magnético	Força magnetomotriz [A]	Taxade fluxo [Wb/s]	—	Fluxo [Wb]
Difusão	Potencial Químico [J/mole]	Fluxo molar [mole/s]	—	Quantidade[mole]
Reação química	Afinidade [J/mole]	Veloc. da reação [mole/s]	—	Progresso da reação [mole]
PseudografoS-Sistemas Termofluidos	Temperatura [K]	Fluxode energia [W]	—	Energia [J]
	Pressão [Pa]	Vazão mássica [kg/s]	—	Massa [kg]

Bond-Graph Elements

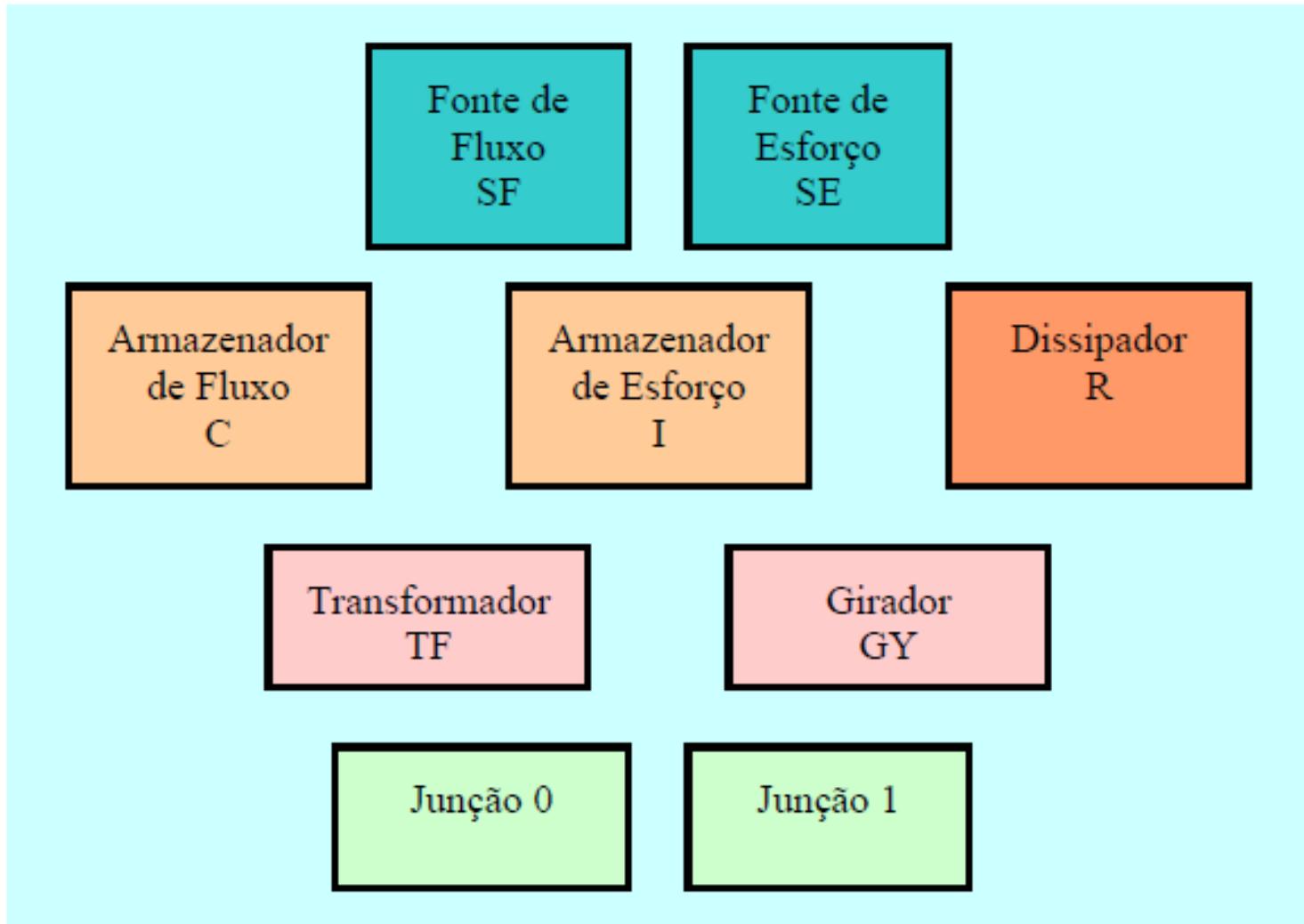




Table of BG Basic BG Elements

Tabela Resumo dos Elementos Básicos e Representações					
elemento	grafo	símbolo	elemento BG	equações	diagrama de blocos
Tipo-C		$\leftrightarrow \leftarrow \rightarrow$	$C: C \leftarrow \frac{e}{f}$	causalidade integral $e = \frac{1}{C} f$ $g = \int f dt + g(0)$	
Tipo-I		$\leftarrow \rightarrow \leftarrow \rightarrow$	$H: H \leftarrow \frac{e}{f}$	causalidade integral $f = \frac{1}{H} e$ $p = \int e dt + p(0)$	
Tipo-R		$\leftarrow \sim \sim \rightarrow$	$R: R \leftarrow \frac{e}{f}$	$e = R f$ $f = \frac{1}{R} e$	

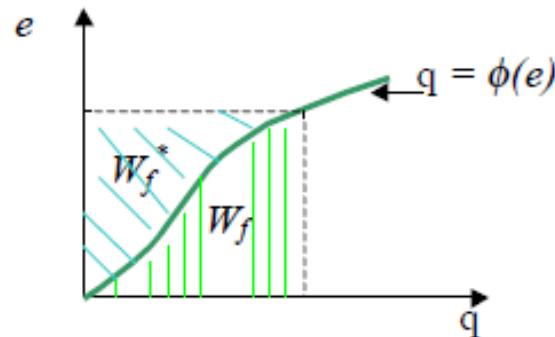
Tabela 5 – Resumo dos Elementos Básicos e Representações 2

Tabela Resumo dos Elementos Básicos e Representações (cont.)					
elemento	grafo	símbolo	elemento BG	equações	diagramas de blocos
Transformador			$\frac{e_1}{f_1} \xrightarrow{T_F} \frac{e_2}{f_2}$	$f_2 = n^{-1} f_1$ $e_1 = n^{-1} e_2$	
			$\frac{e_1}{f_1} \xleftarrow{T_F} \frac{e_2}{f_2}$	$e_2 = n e_1$ $f_1 = n f_2$	
Girador			$\frac{e_1}{f_1} \xrightarrow{GT} \frac{e_2}{f_2}$	$e_1 = r f_1$ $f_1 = r e_1$	
			$\frac{e_1}{f_1} \xleftarrow{GT} \frac{e_2}{f_2}$	$f_2 = r^{-1} e_1$ $f_1 = r^{-1} e_2$	

Constitutive Relations for BG Elements



Armazenadores de Fluxo (Tipo-C)



$$\text{Linear : } q = C e$$

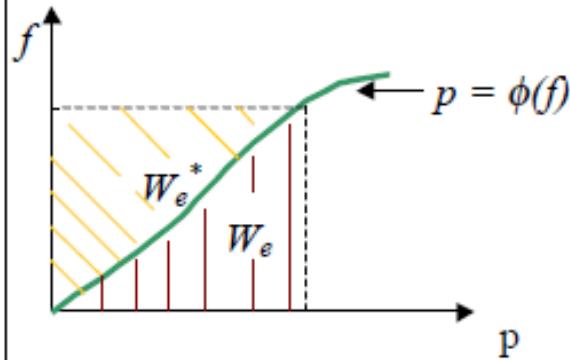
$$W_f^* = \frac{1}{2} C e^2$$

$$W_f = \frac{1}{2C} q^2$$

$$\frac{\partial W_f^*}{\partial e} = q$$

$$\frac{\partial W_f}{\partial h} = e$$

Armazenadores de Esforço (Tipo-I)



$$\text{Linear : } p = L f$$

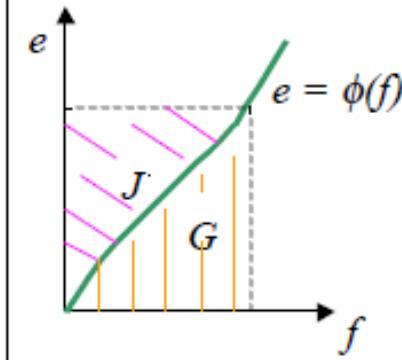
$$W_e^* = \frac{1}{2} L f^2$$

$$W_e = \frac{1}{2L} p^2$$

$$\frac{\partial W_e^*}{\partial e} = p$$

$$\frac{\partial W_e}{\partial x} = f$$

Dissipadores (Tipo-R)



$$\text{Linear : } e = R f$$

$$G = \frac{1}{2} R f^2$$

$$J = \frac{1}{2R} e^2$$

$$\frac{\partial J}{\partial e} = f$$

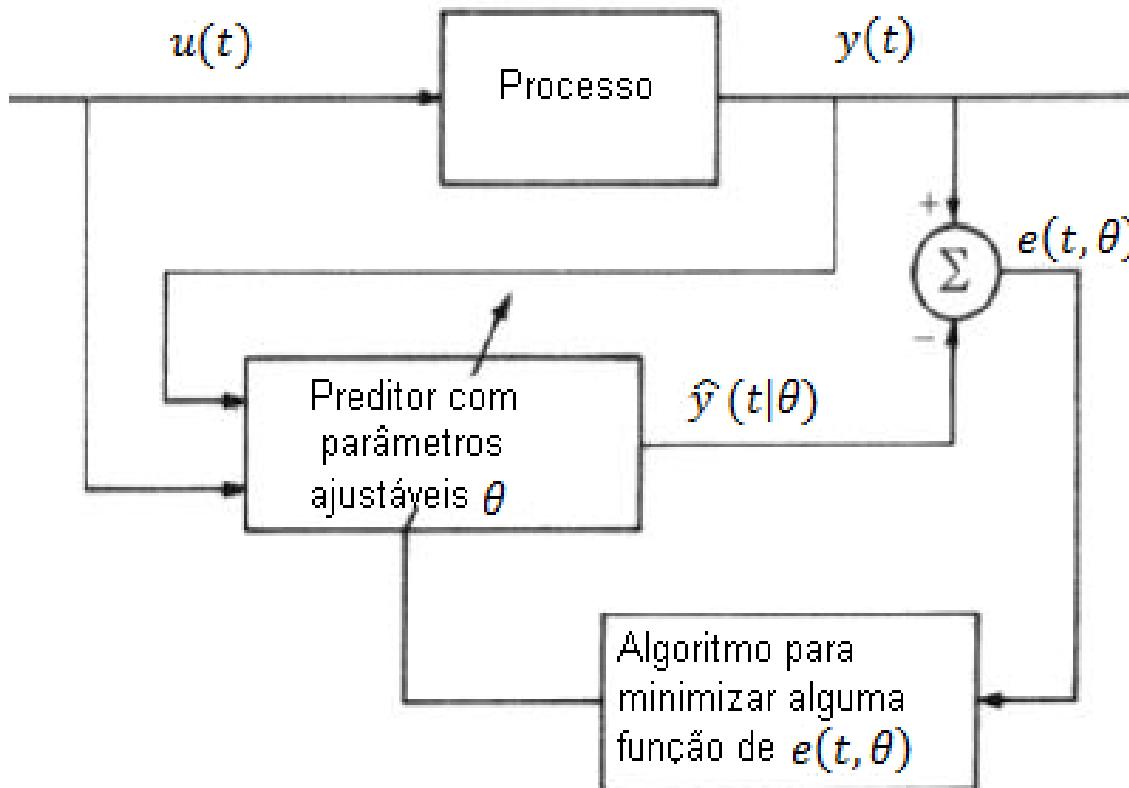
$$\frac{\partial G}{\partial f} = e$$



BG Causality Effects

$\dot{x} = f(x, t)$	explicita causalidade integral
$\dot{x} = f(x, \dot{x}, t)$	implicita causalidade derivativa na designação da causalidade
$\dot{x} = f(x, y, t)$ $y = g(x, y, t)$	laço algébrico causalidade arbitrária na designação da causalidade
$\dot{x} = f(x, \dot{x}, y, t)$ $y = g(x, \dot{x}, y, t)$	implicita com laço algébrico causalidade derivativa e causalidade arbitrária na designação da causalidade
Restrições incompatíveis (não há equações possíveis)	conflito causal (como fontes)

BG Parametric Identification





- Erro de Predição:

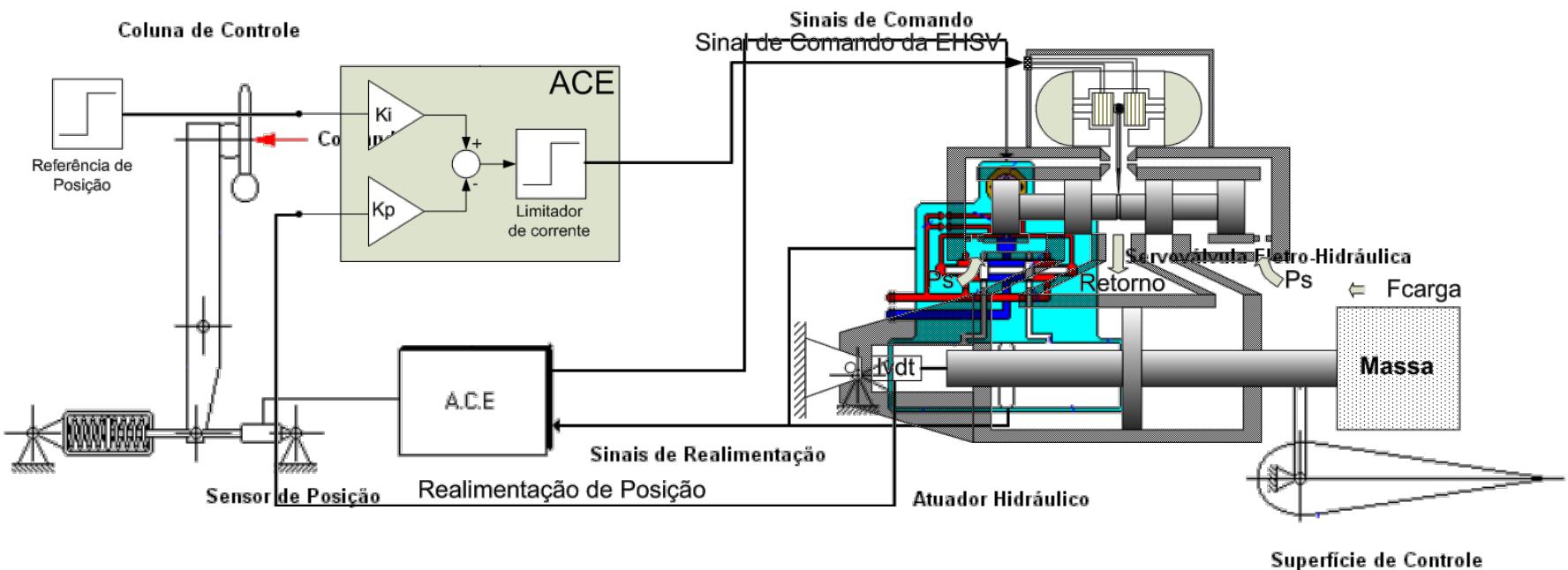
$$e(t, \theta) = y(t) - \hat{y}(t|\theta)$$

- Minimização da Função Custo:

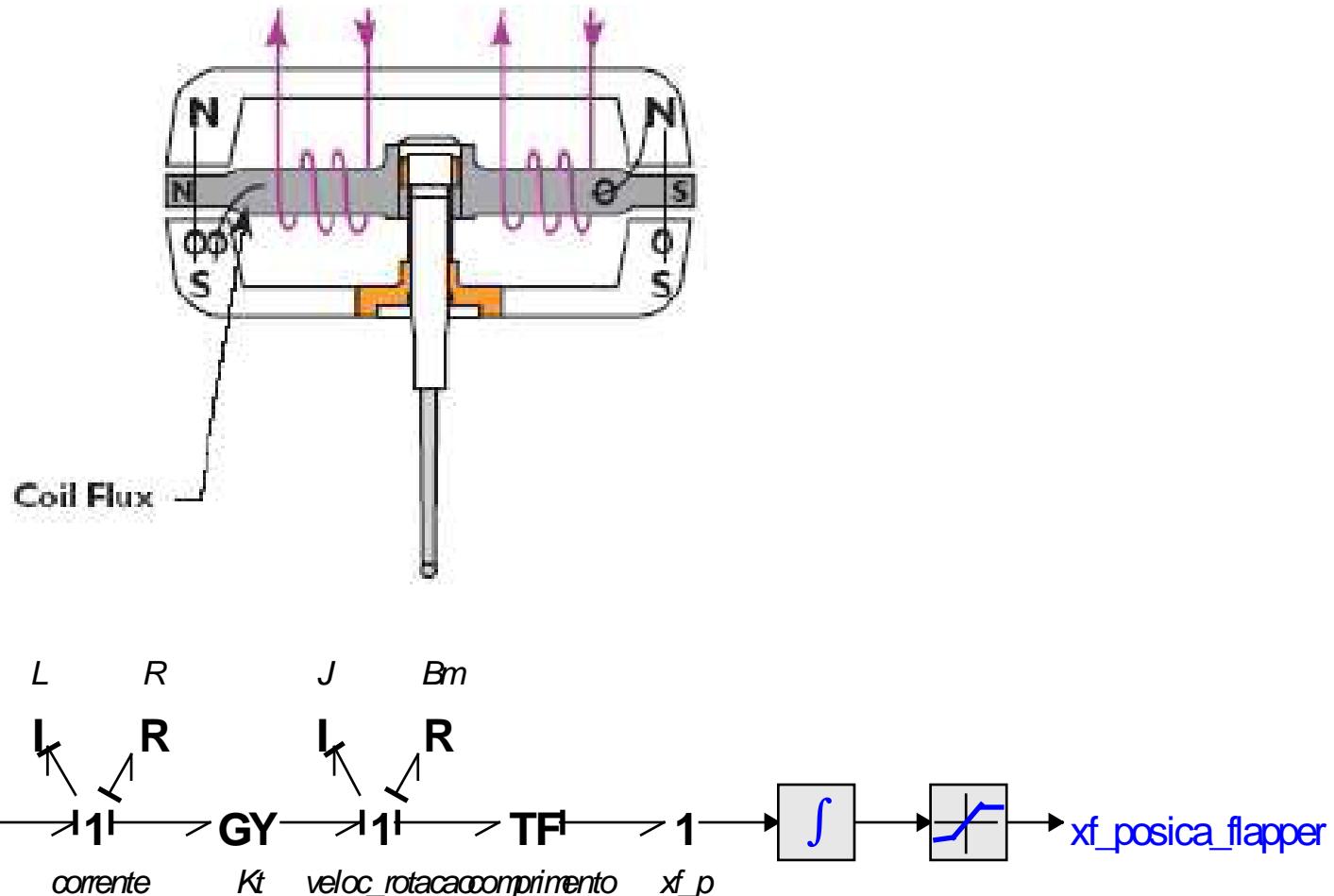
$$\hat{\theta}_N = \arg \min V_N(\theta, Z^N)$$

$$\hat{\theta}_N = \arg \min \det \left(\frac{1}{N} \sum_{t=1}^N e(t, \theta) \cdot e^T(t, \theta) \right)$$

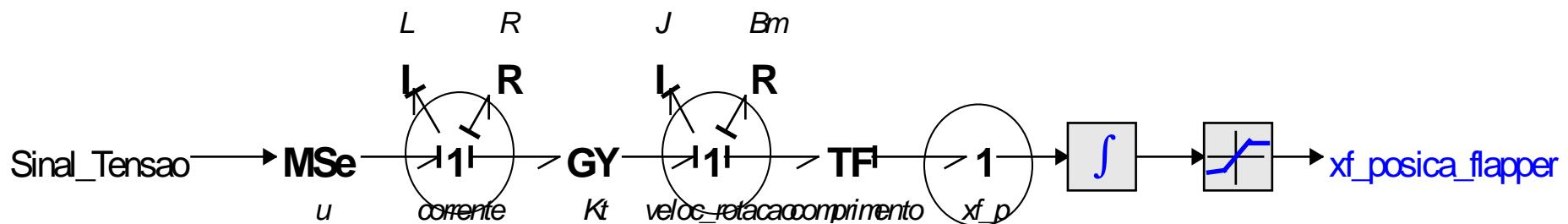
Estudo do Sistema de Atuação



BG Model Torque Motor F-N Valve



State Space Equation for the Servo Valve 1st Stage



$$x_1 = Li$$

$$x_2 = Jw$$

$$x_3 = \frac{raio}{J} \int x_2$$

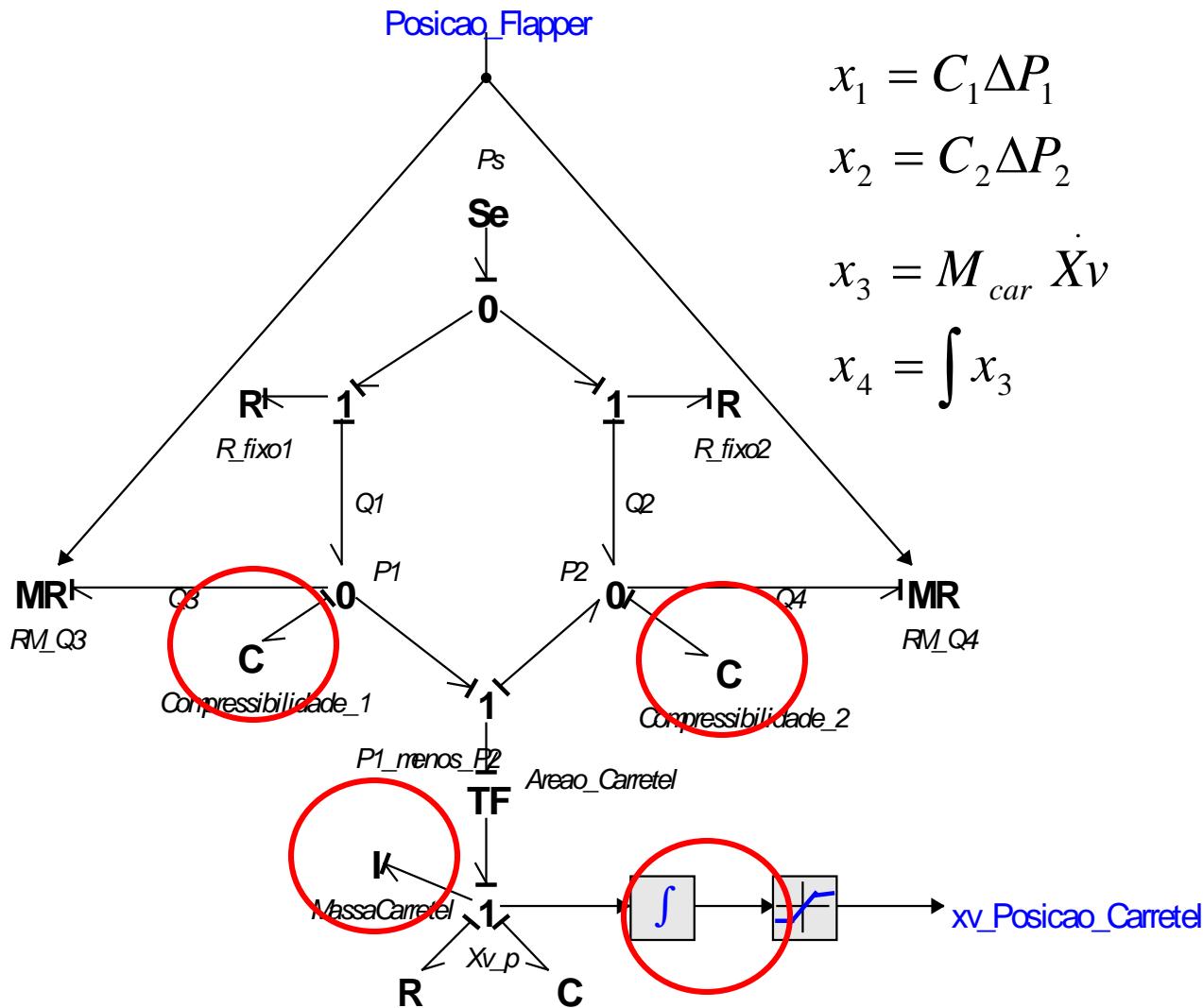
$$e_1 = \dot{x}_1 = u - e_3 - e_5 = u - \frac{R}{L} x_1 - \frac{Kt}{J} x_2$$

$$e_2 = \dot{x}_2 = e_6 - e_4 = \frac{Kt}{L} x_1 - \frac{b}{J} x_2$$

$$\dot{x}_3 = \frac{raio}{J} x_2$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{Kt}{J} & 0 \\ \frac{Kt}{L} & -\frac{b}{J} & 0 \\ 0 & \frac{raio}{J} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u$$

BG Model F-N Valve



$$x_1 = C_1 \Delta P_1$$

$$x_2 = C_2 \Delta P_2$$

$$x_3 = M_{car} \dot{X}_v$$

$$x_4 = \int x_3$$

$$\dot{f}_1 = C_1 \Delta P_1 = \dot{X}_1$$

$$\dot{f}_2 = C_2 \Delta P_2 = \dot{X}_2$$

$$\ddot{e}_3 = M_{car} \ddot{X}_v = \dot{X}_3$$

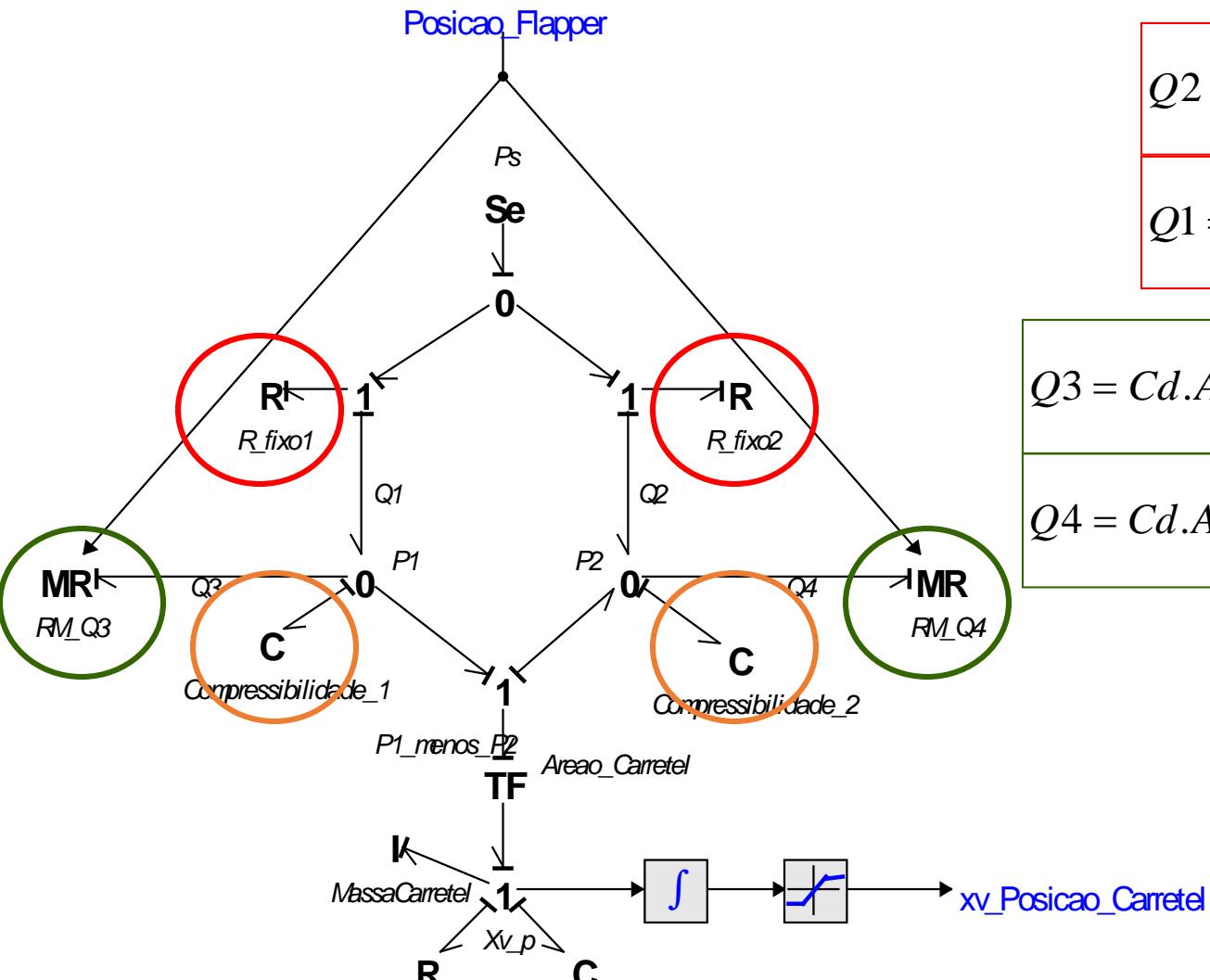
$$\dot{X}_1 = Q_1 - Q_3 - Q_L$$

$$\dot{X}_2 = Q_2 - Q_4 + Q_L$$

$$\dot{X}_3 = e_L - e_{atrito} - e_{mola}$$

$$\dot{X}_4 = X_3$$

BG Model F-N Valve



$$Q2 = Cd \cdot A_o \cdot \sqrt{\frac{2}{\rho} (P_s - P_2)}$$

$$Q1 = Cd \cdot A_o \cdot \sqrt{\frac{2}{\rho} (P_s - P_1)}$$

$$Q3 = Cd \cdot A_3(x) \cdot \sqrt{\frac{2}{\rho} (P_1)}$$

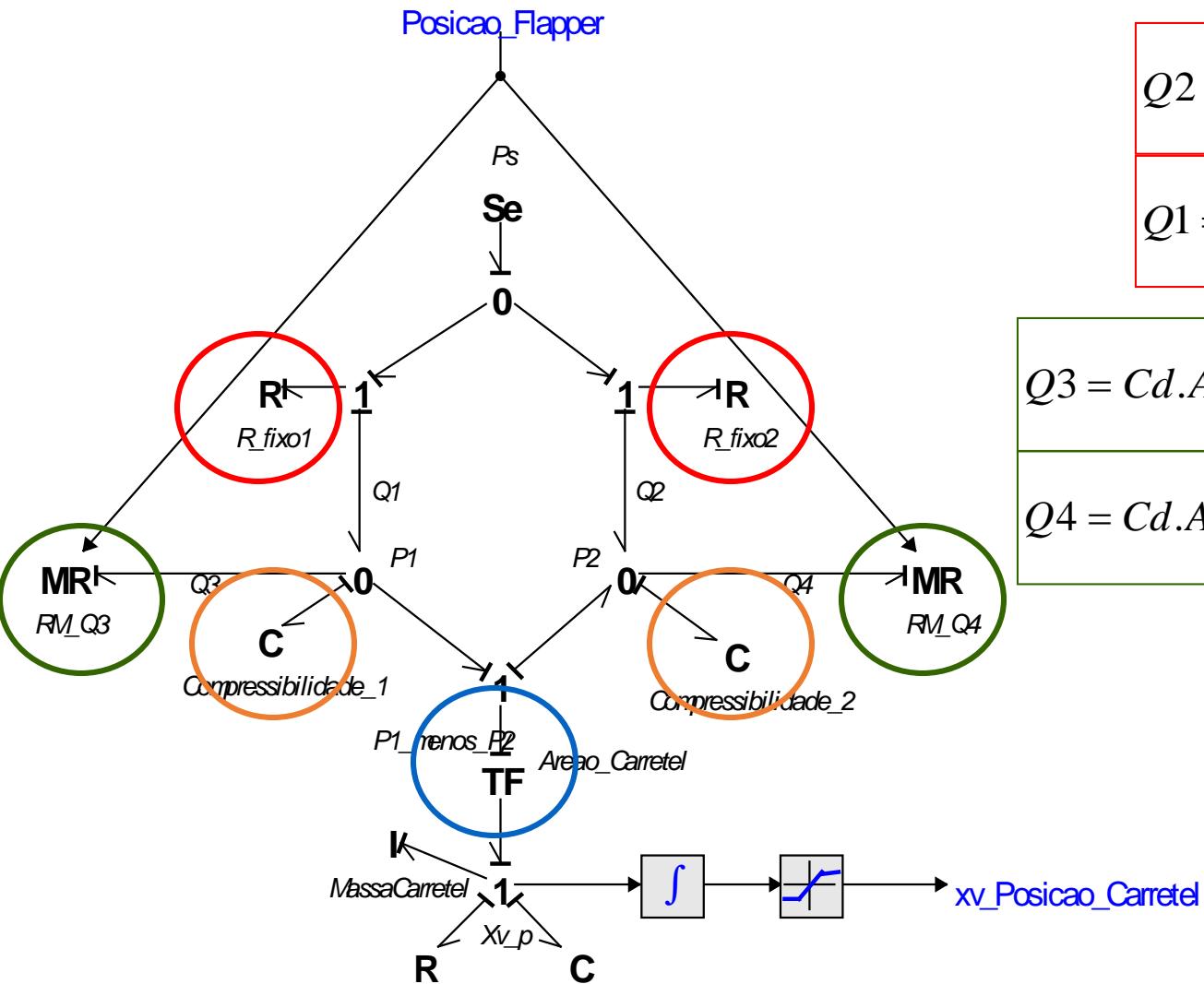
$$Q4 = Cd \cdot A_4(x) \cdot \sqrt{\frac{2}{\rho} (P_2)}$$

$$A3(x) = \pi \cdot d_n \cdot (L + x)$$

$$A4(x) = \pi \cdot d_n \cdot (L - x)$$

$$C = \frac{V}{\beta}$$

BG Model F-N Valve



$$Q2 = Cd \cdot Ao \cdot \sqrt{\frac{2}{\rho} (Ps - P2)}$$

$$Q1 = Cd \cdot Ao \cdot \sqrt{\frac{2}{\rho}} (Ps - P1)$$

$$Q3 = Cd \cdot A3(x) \cdot \sqrt{\frac{2}{\rho}}(P1)$$

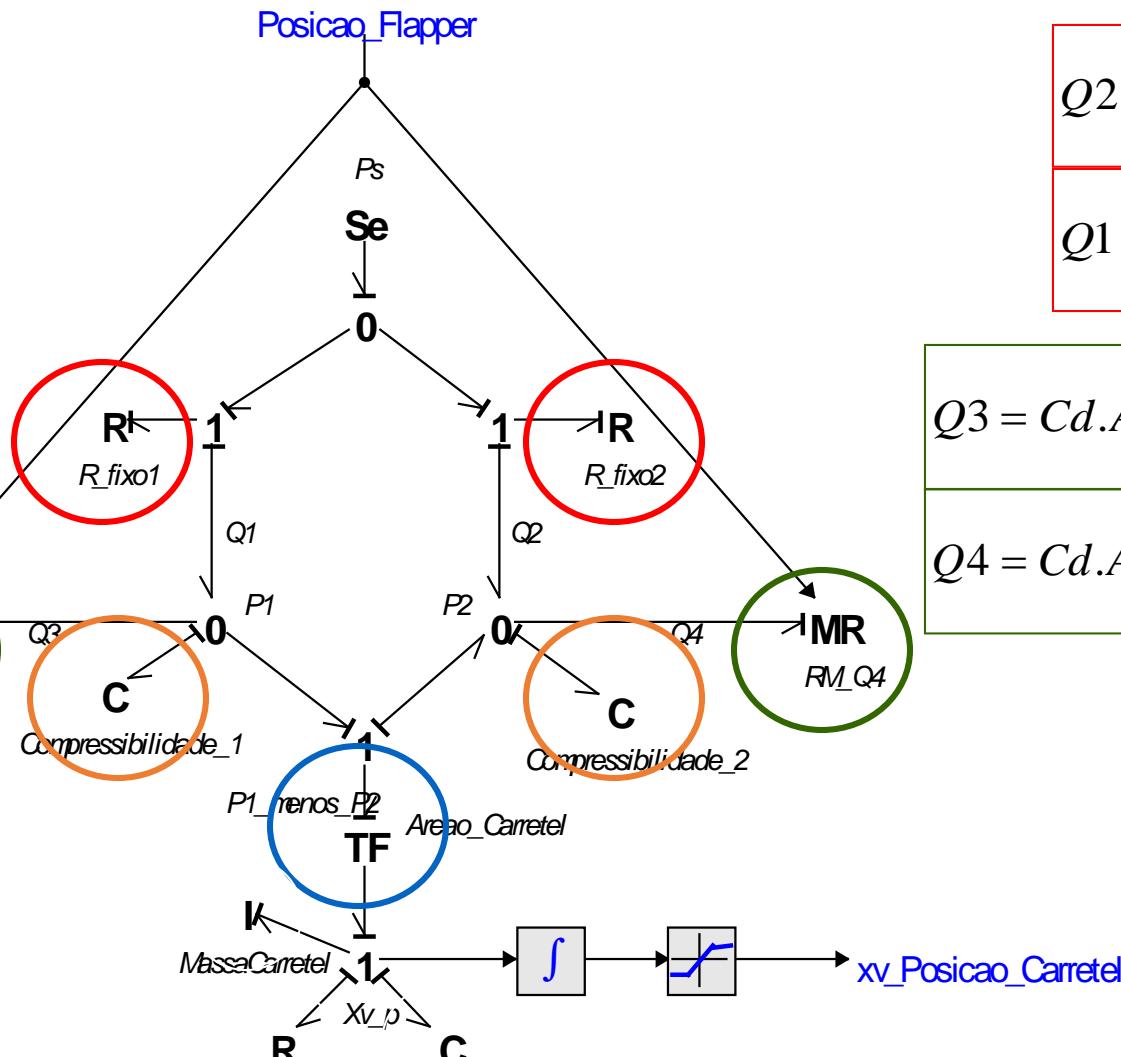
$$Q4 = Cd.A4(x).\sqrt{\frac{2}{\rho}}(P2)$$

$$A3(x) = \pi.dn.(L + x)$$

$$C = \frac{V}{\beta}$$

$$F = A.(P1 - P2)$$

BG Model F-N Valve



$$Q_2 = Cd \cdot A_o \cdot \sqrt{\frac{2}{\rho} (P_s - P_2)}$$

$$Q_1 = Cd \cdot A_o \cdot \sqrt{\frac{2}{\rho} (P_s - P_1)}$$

$$Q_3 = Cd \cdot A_3(x) \cdot \sqrt{\frac{2}{\rho} (P_1)}$$

$$Q_4 = Cd \cdot A_4(x) \cdot \sqrt{\frac{2}{\rho} (P_2)}$$

$$A_3(x) = \pi \cdot d_n \cdot (L + x)$$

$$A_4(x) = \pi \cdot d_n \cdot (L - x)$$

$$C = \frac{V}{\beta}$$

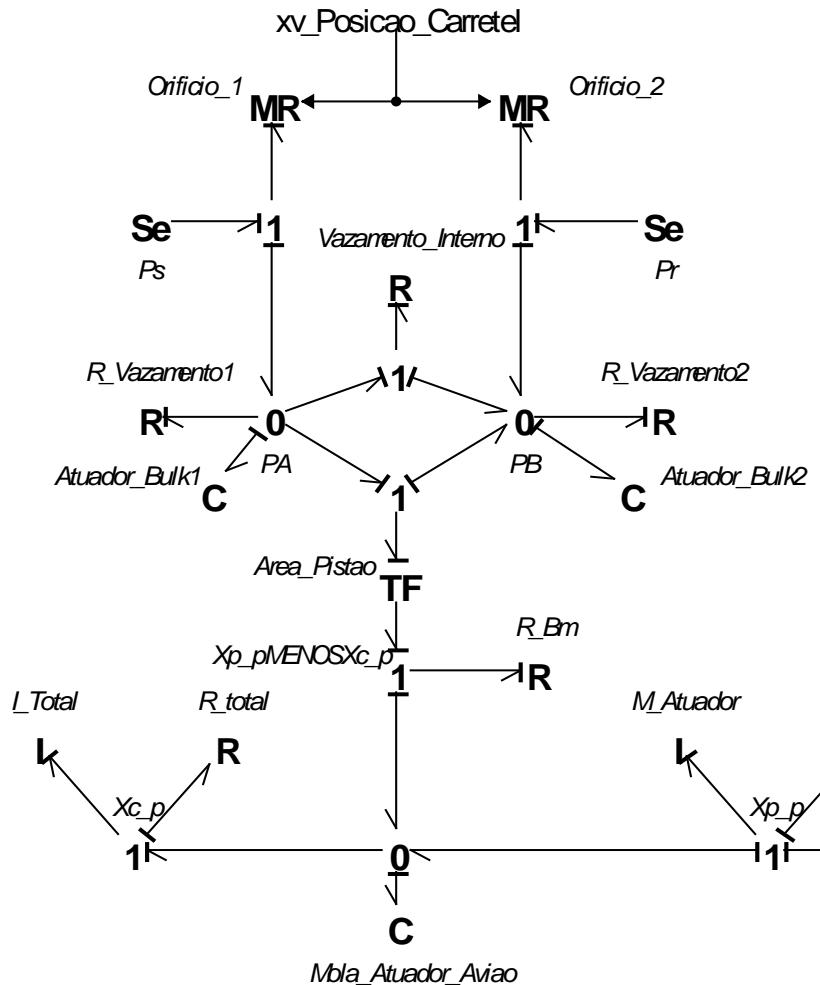
$$F = A \cdot (P_1 - P_2)$$

$$I = M$$

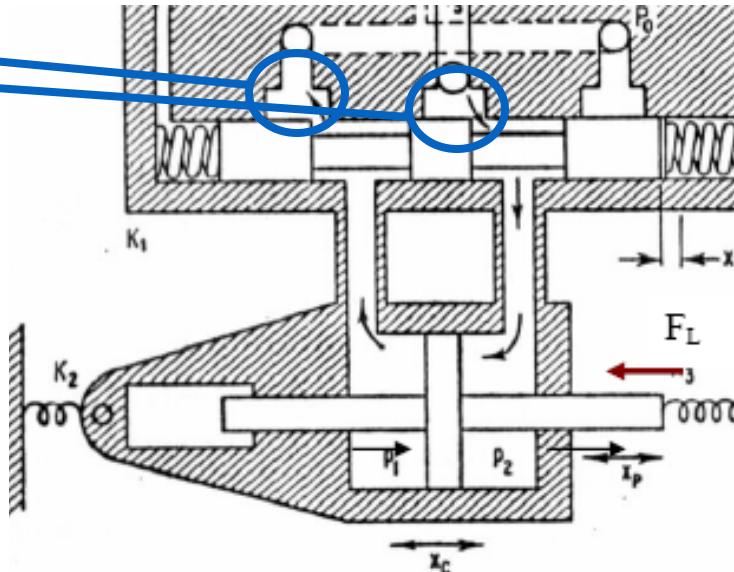
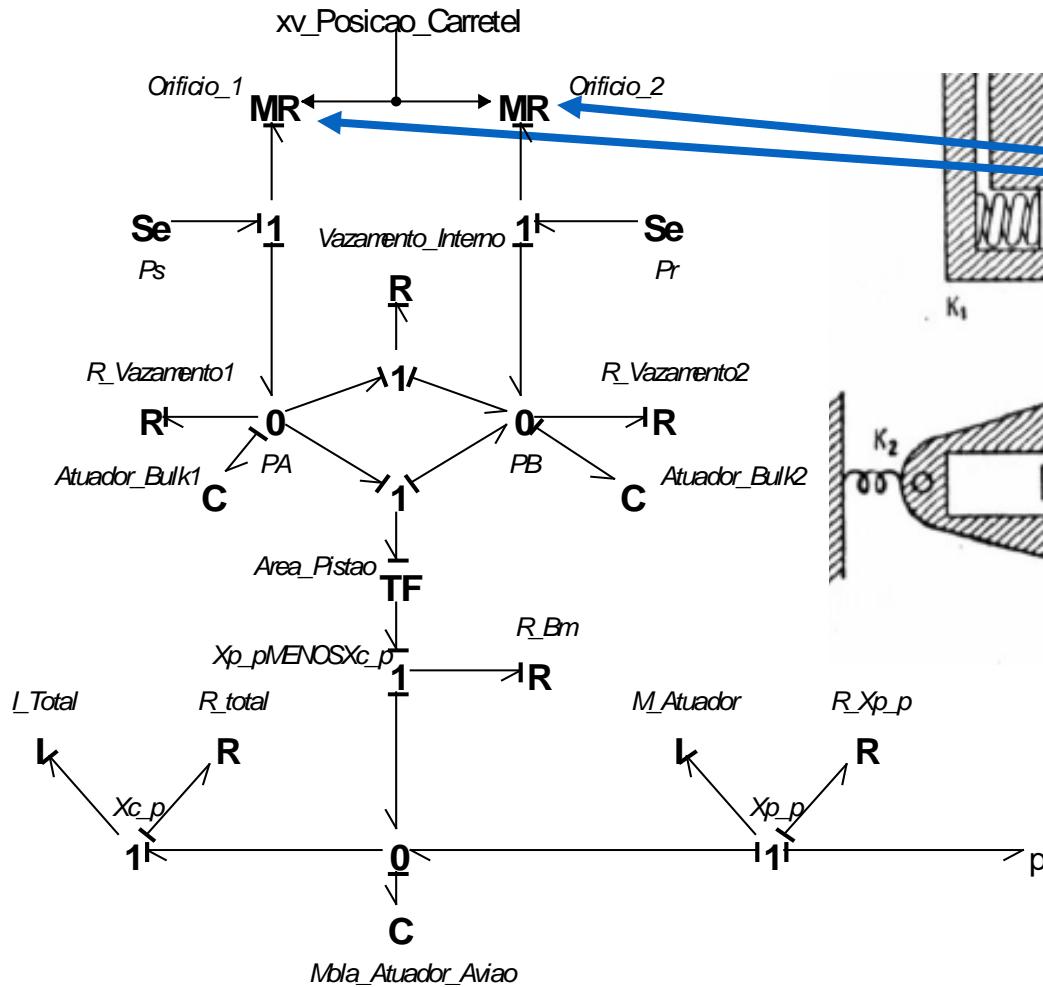
$$R = B_m$$

$$C = \frac{1}{K}$$

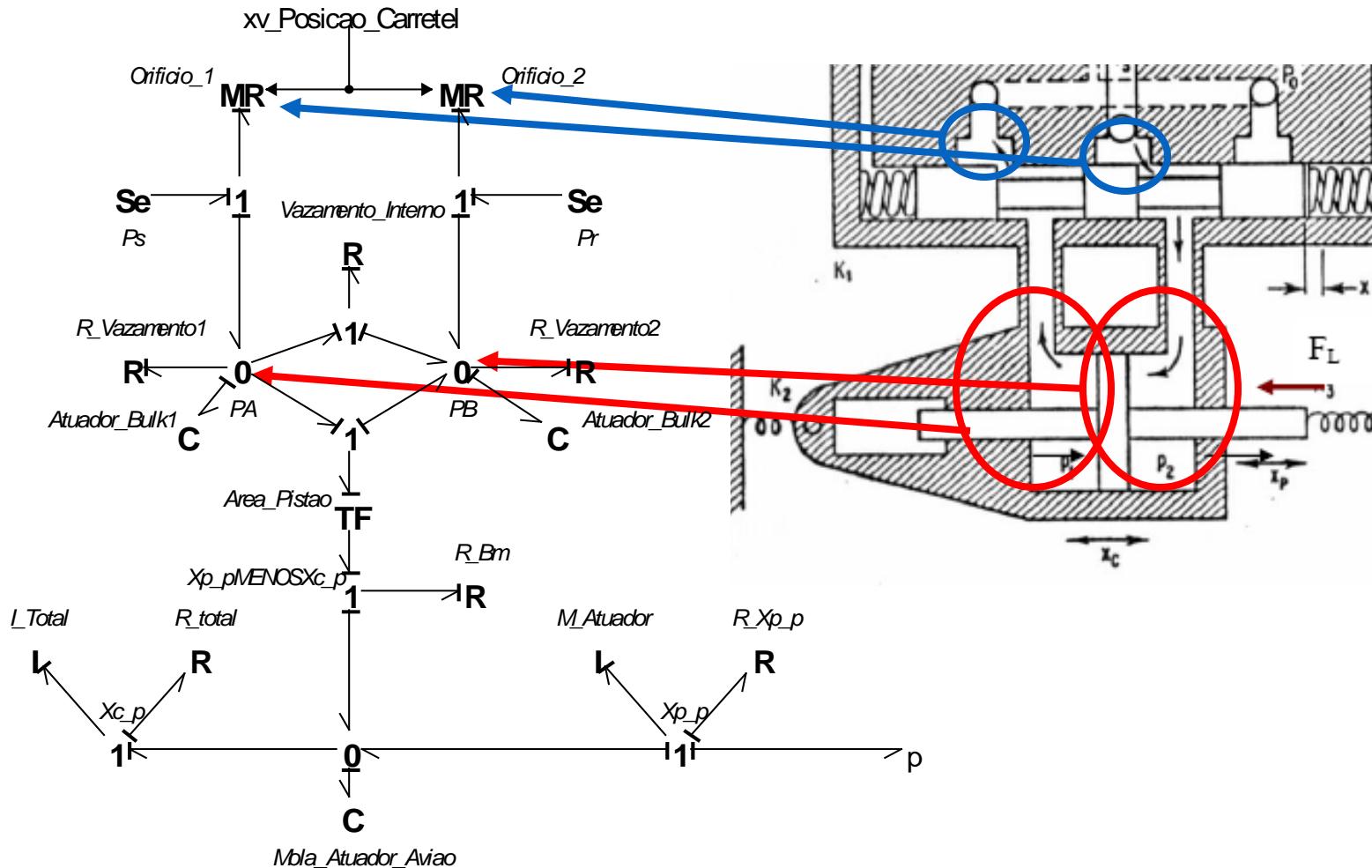
BG Model Spool Valve and Piston



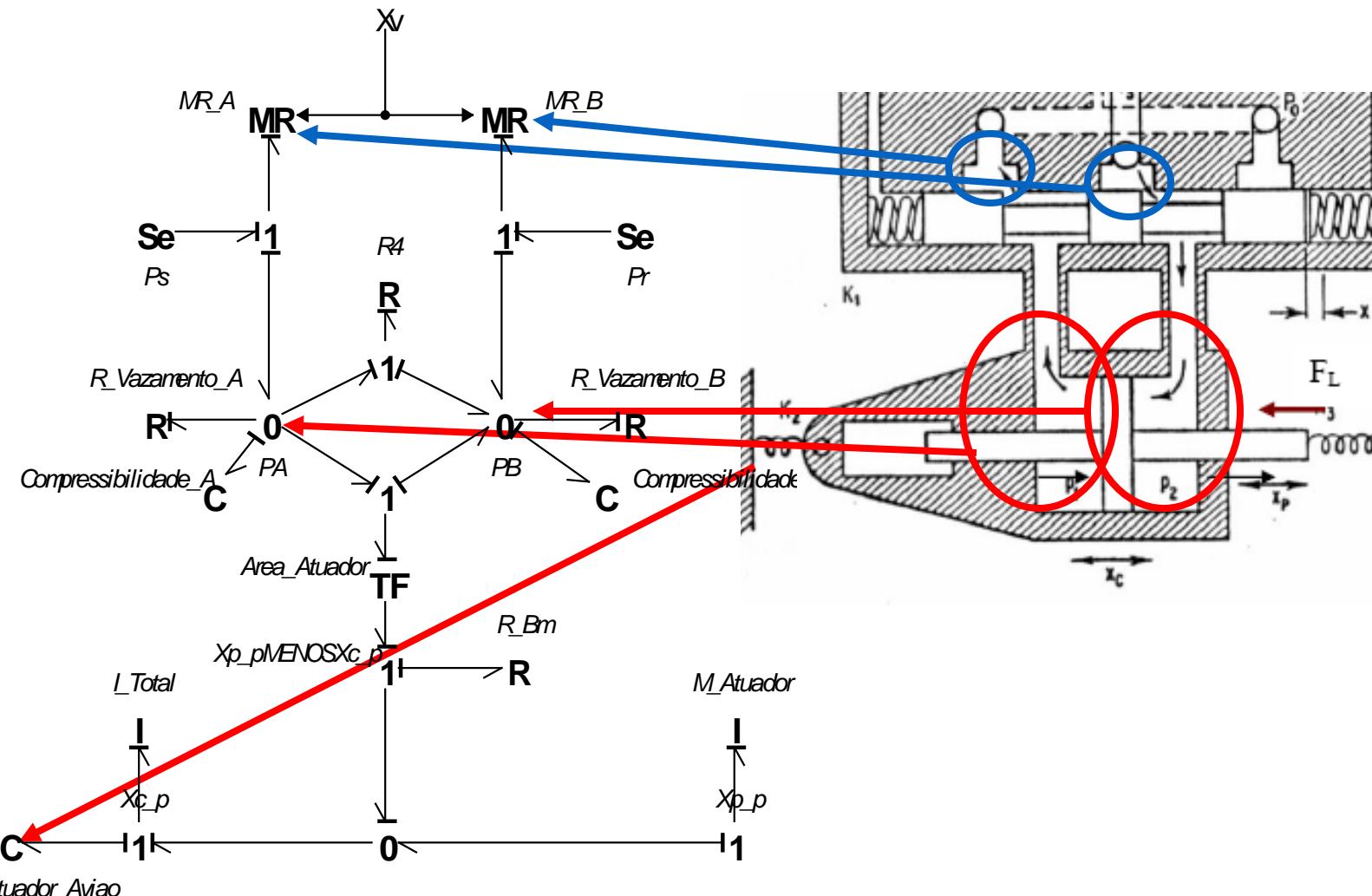
BG Model Spool Valve and Piston



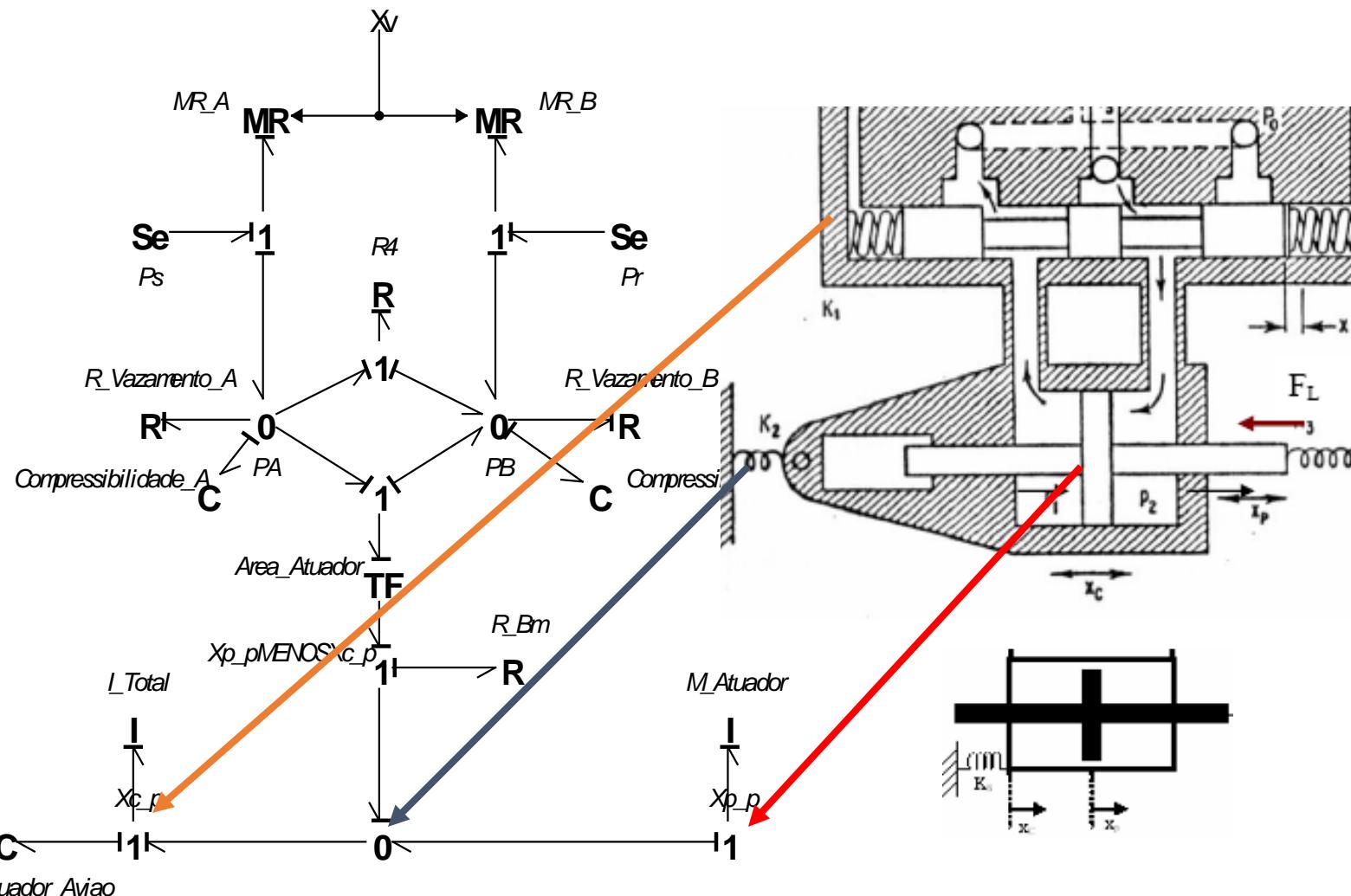
BG Model Spool Valve and Piston



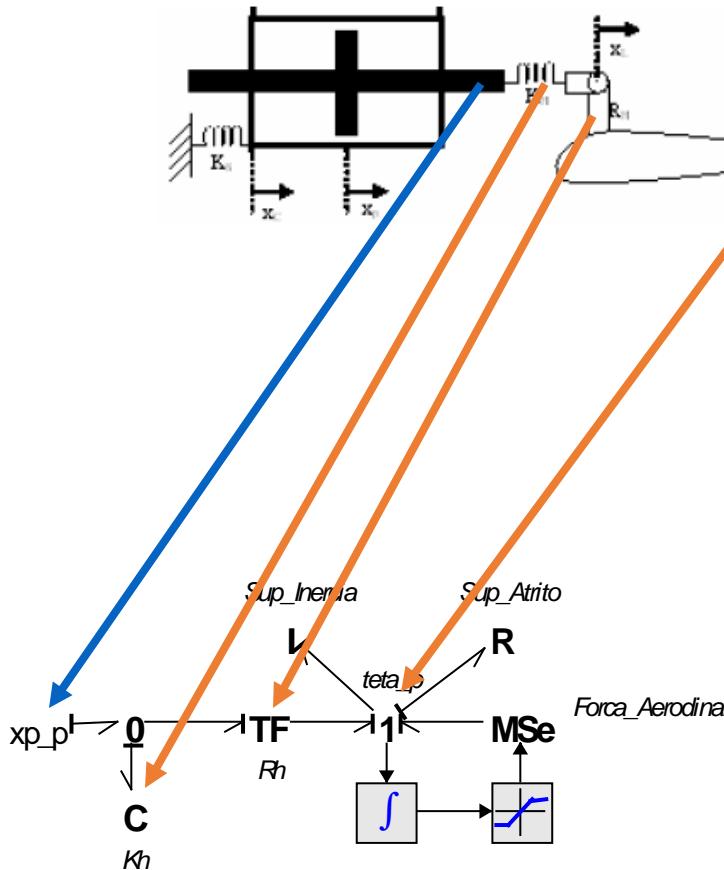
BG Model Spool Valve and Piston



BG Model Spool Valve and Piston



BG Model Piston and Load Coupling

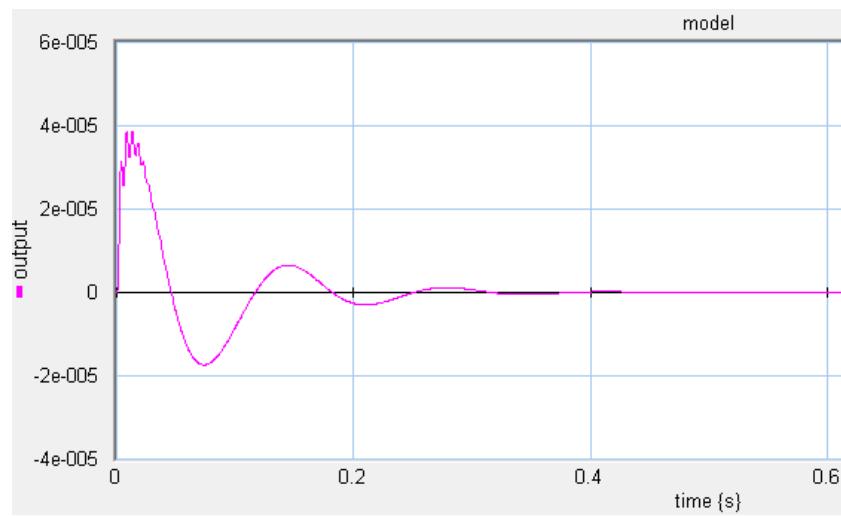


$$\dot{\theta} p = \frac{\dot{x} l}{R h}$$

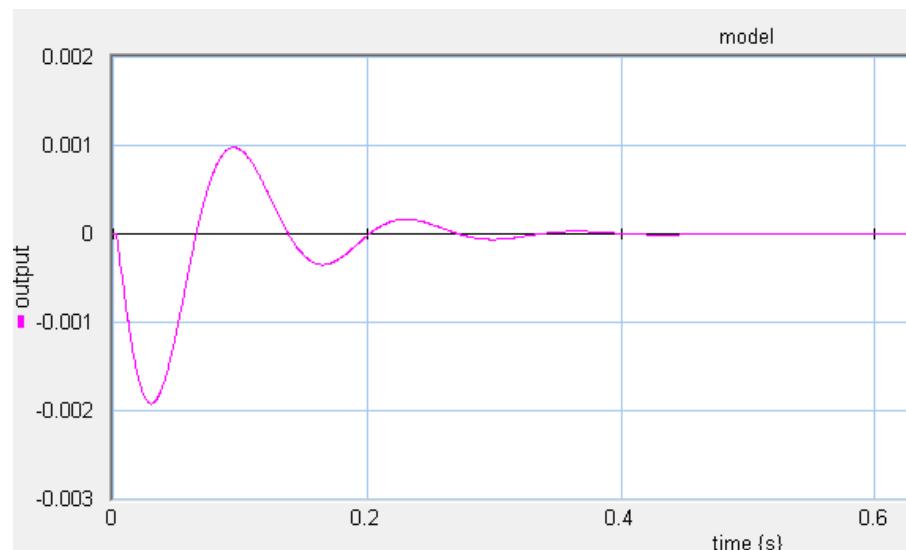
$$F_{aero} = \left(\frac{C_m \delta p \cdot q \cdot S \cdot c}{R h} \right) \cdot \theta p$$

EHS BG Simulation

Flapper Nozzle Valve Response



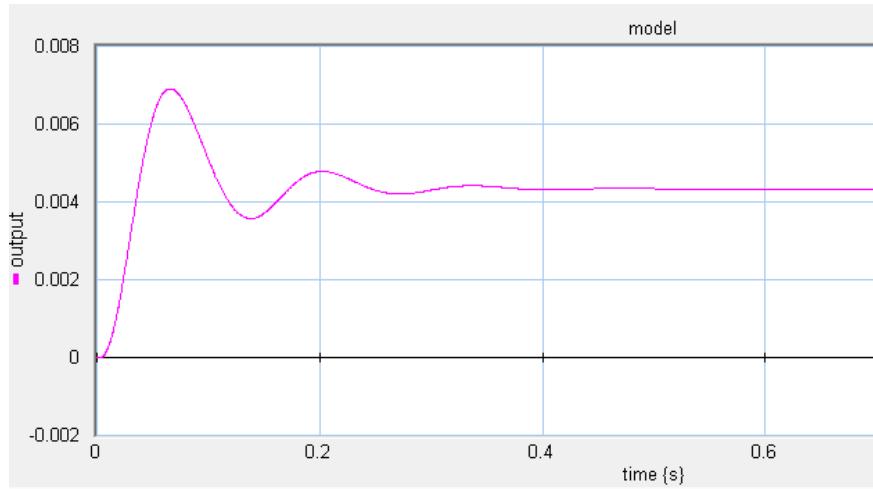
Spool dynamics



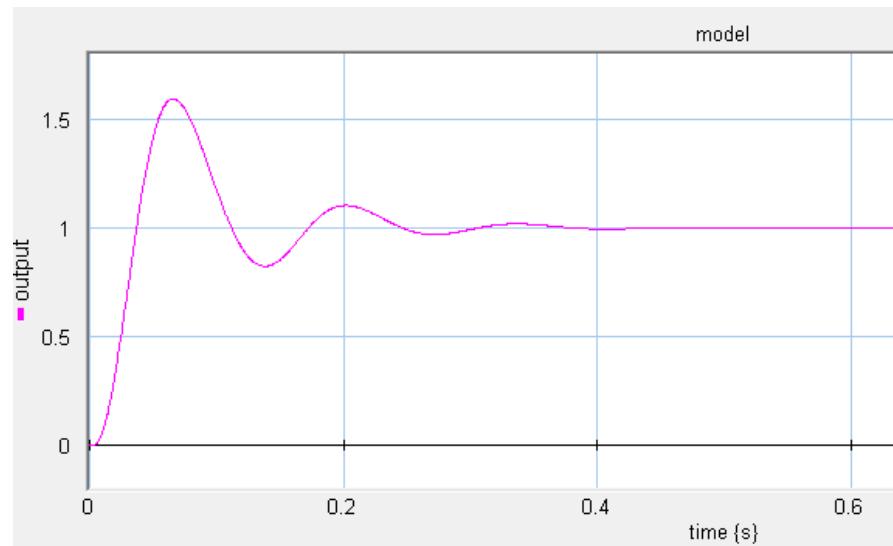
BG Simulation EHS Flight Actuator



Actuator



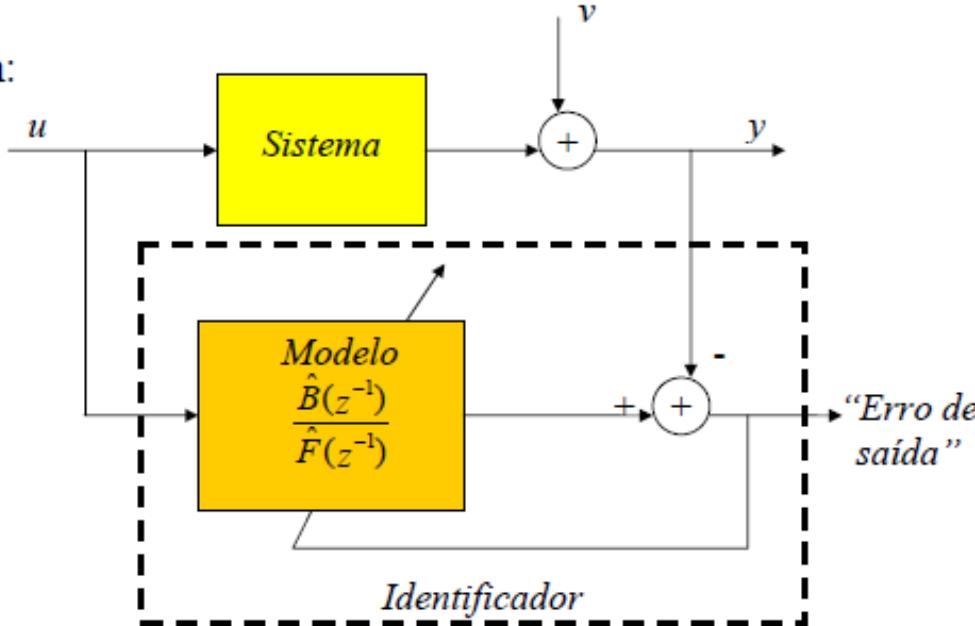
Control Surface Displacement





IDENTIFICAÇÃO PARAMÉTRICA

Uma abordagem:



Modelo do Sistema: $y_k = \frac{B(z^{-1})}{F(z^{-1})} u_k + v_k$

Método do “erro de saída”: $\min_{B,F} \sum_{k=0}^{N-1} \left| y_k - \frac{\hat{B}(z^{-1})}{\hat{F}(z^{-1})} u_k \right|^2$

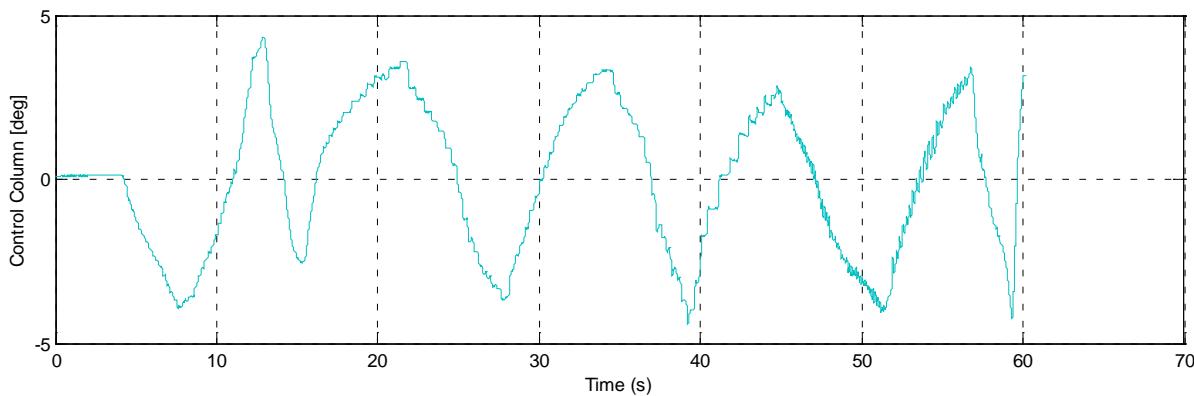
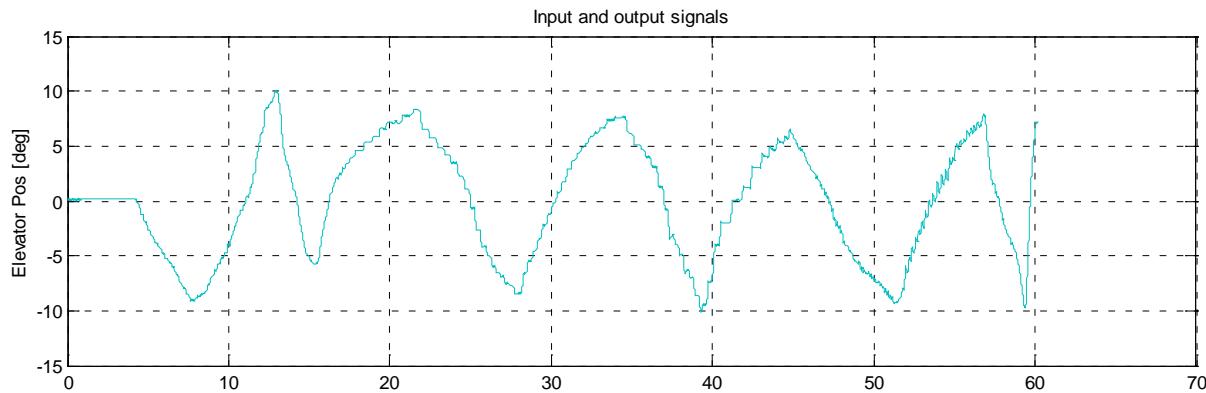
Development – Iron bird tests

Collecting of working data

Input = control column position (deg)

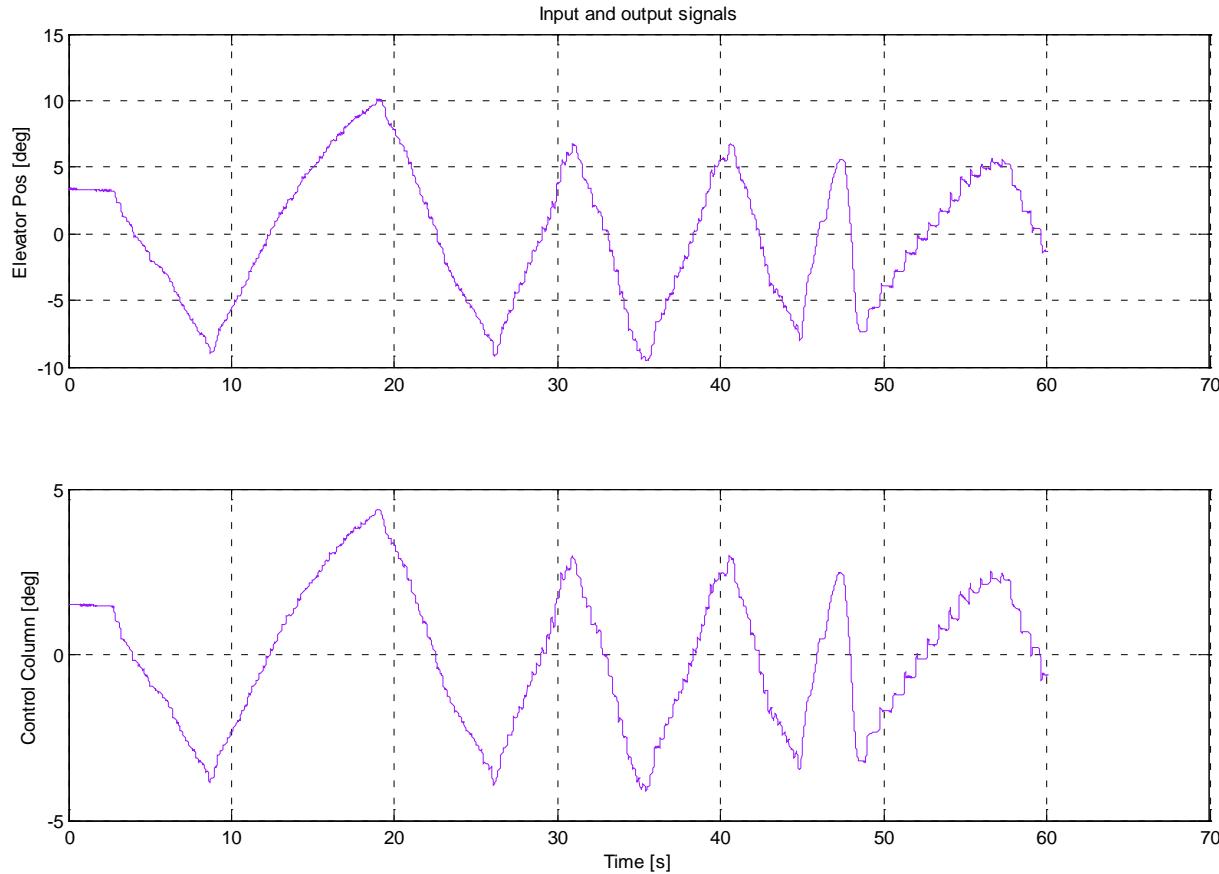
Output = elevator surface position (deg)

Actuator max oper. Freq = 20 Hz ($F_{aq}=200\text{Hz}$)



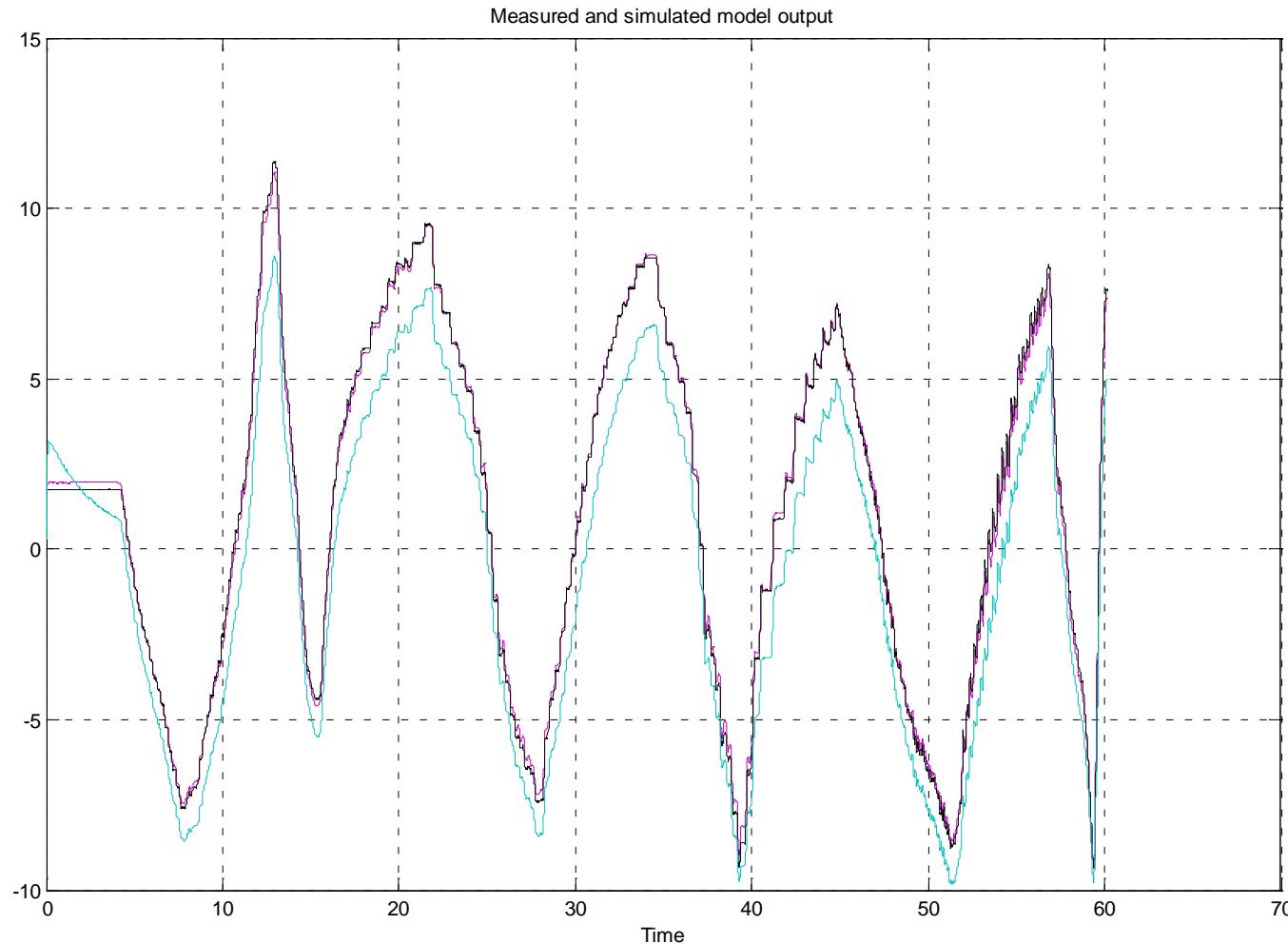
Development – Iron bird tests

Collecting of validation data



Preliminary Results – System Identification

Model Structures Identified – Best fits



Preliminary Results – System Identification

Best fit : State-space model: $x(t+Ts) = A x(t) + B u(t) + K e(t)$
 $y(t) = C x(t) + D u(t) + e(t)$

A =

$$\begin{matrix} & x_1 & x_2 & x_3 \\ x_1 & 0.99835 & -0.01529 & -0.0042415 \\ x_2 & -0.010468 & 0.89974 & -0.07363 \\ x_3 & 0.019338 & 0.1637 & 0.84 \end{matrix}$$

B =

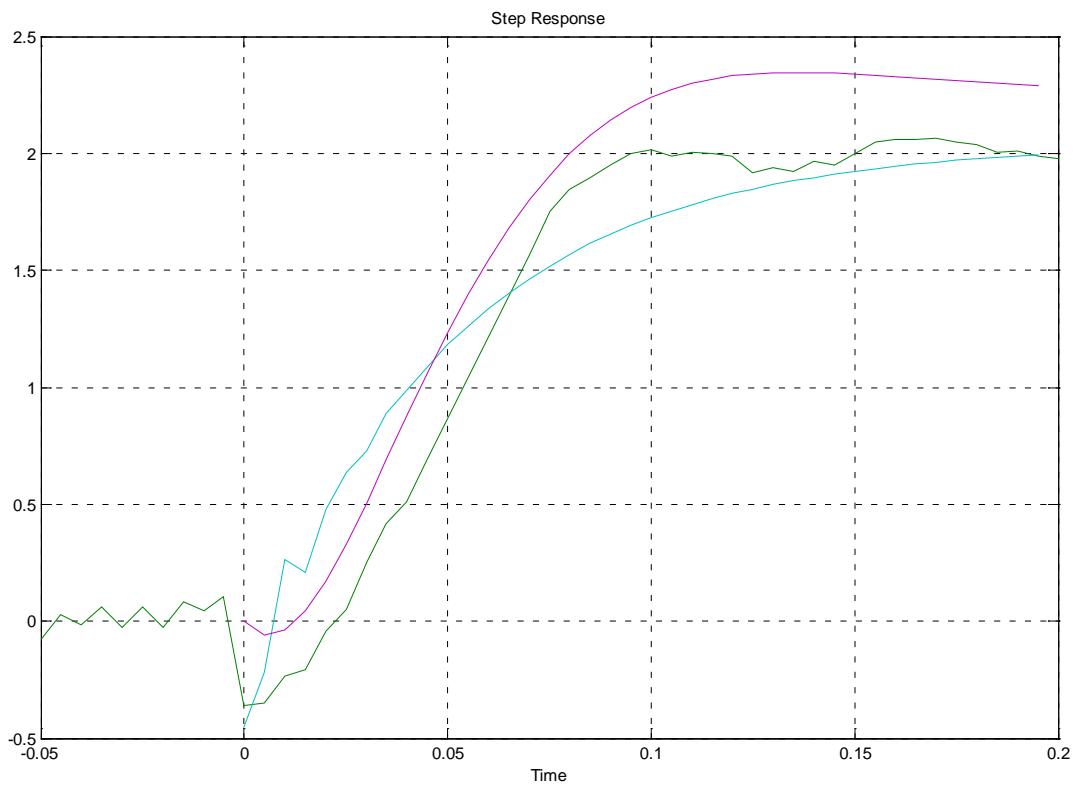
$$\begin{matrix} & u_1 \\ x_1 & -0.00011992 \\ x_2 & -0.011715 \\ x_3 & -0.047686 \end{matrix}$$

C =

$$\begin{matrix} & x_1 & x_2 & x_3 \\ y_1 & 183.96 & 1.6012 & 0.3627 \end{matrix}$$

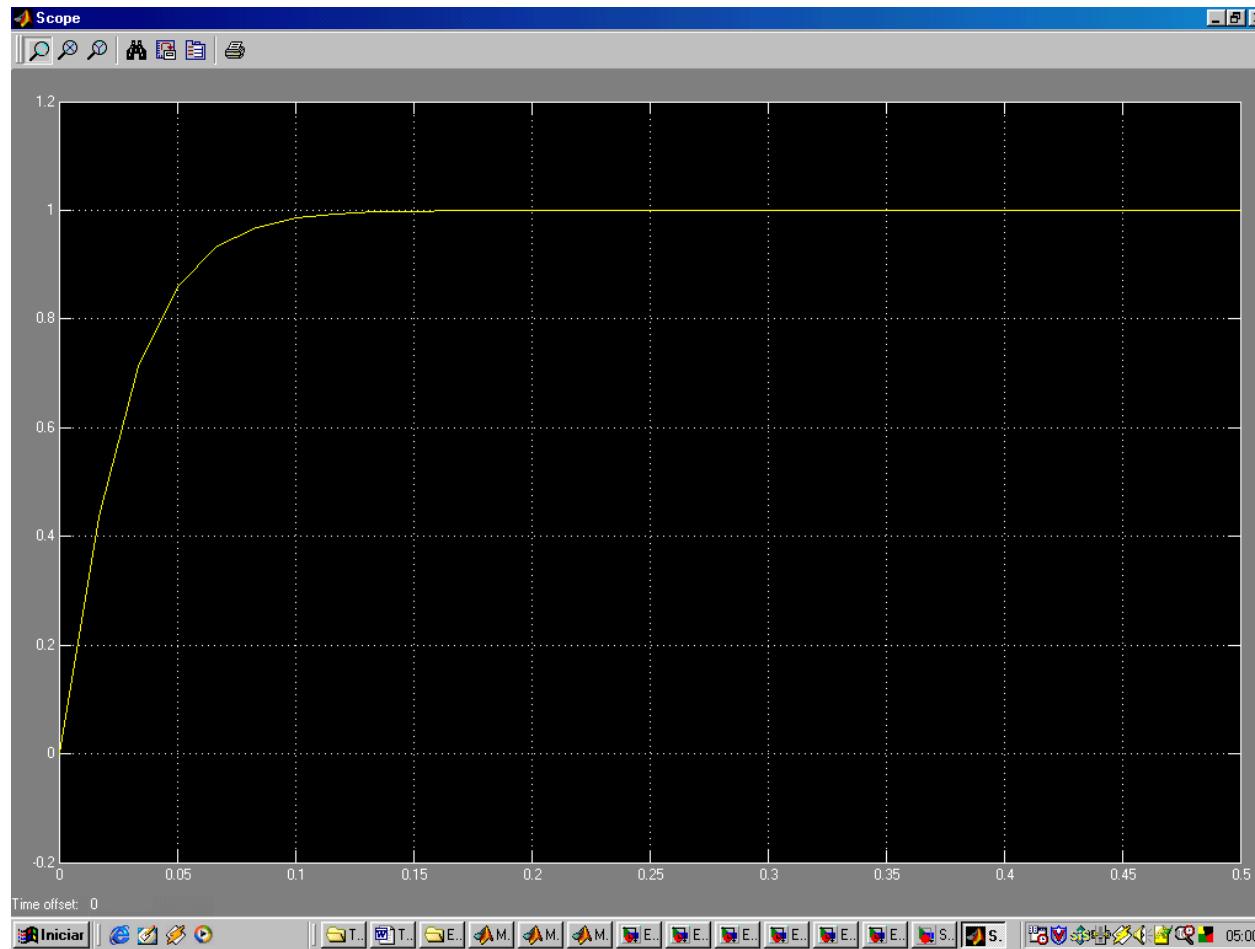
D =

$$\begin{matrix} & u_1 \\ y_1 & 0 \end{matrix}$$

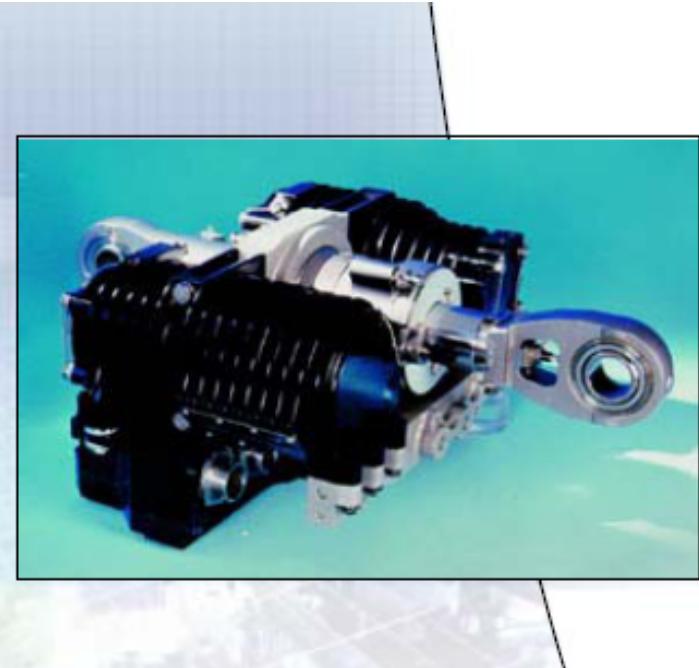
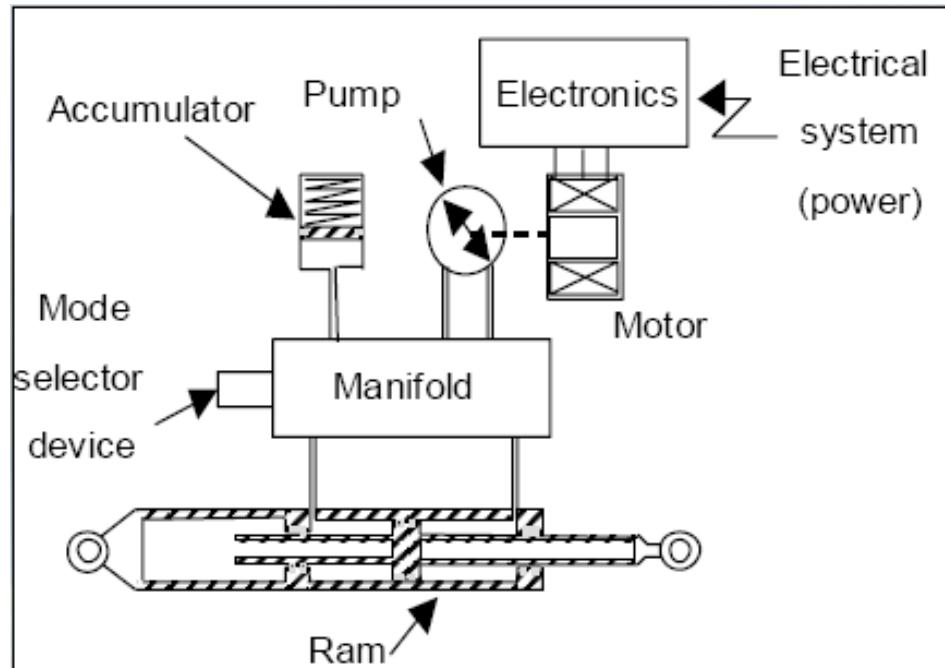


Preliminary Results – Non-linear Analysis

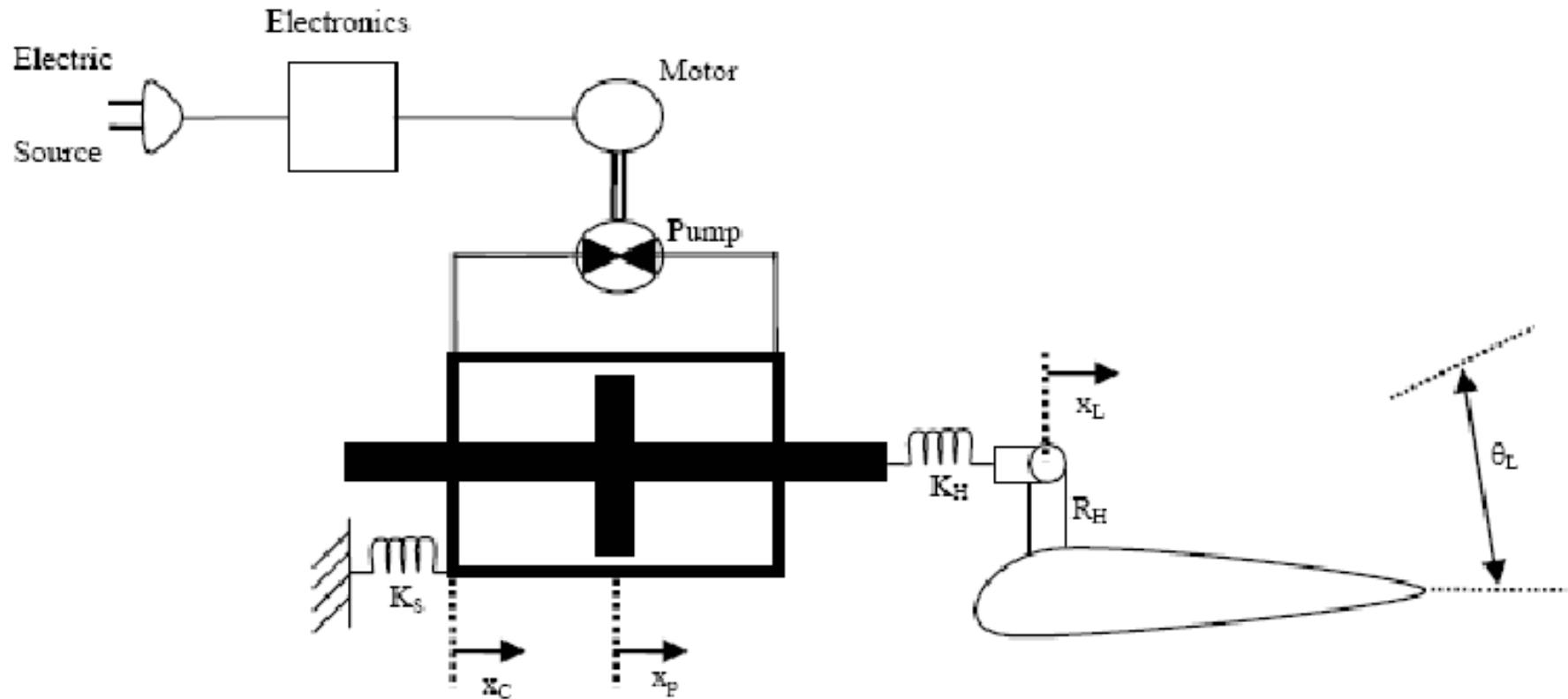
Step response for 1 deg command → almost linear



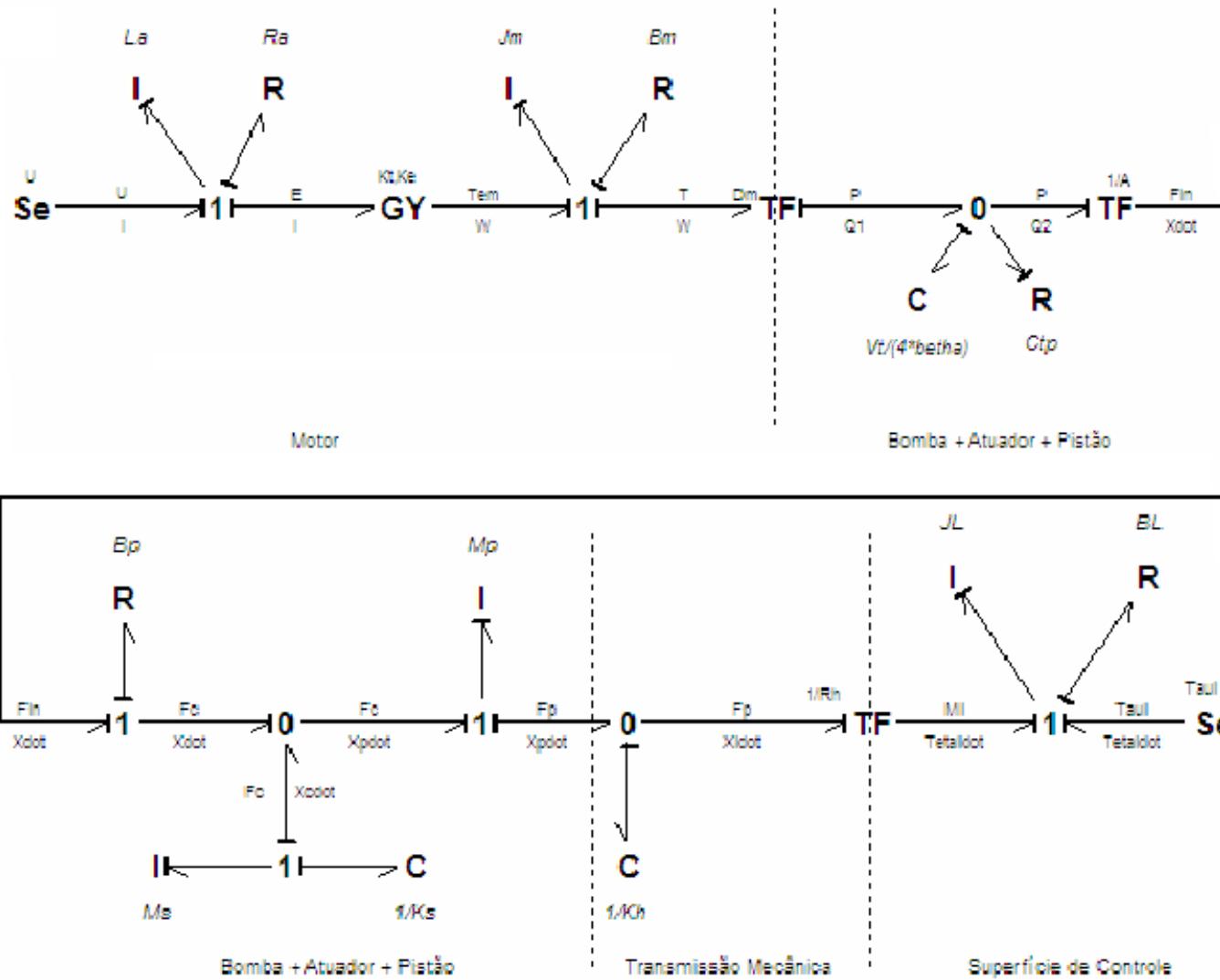
EHA-FDHP Flight Actuator



EHA-FDHP Model

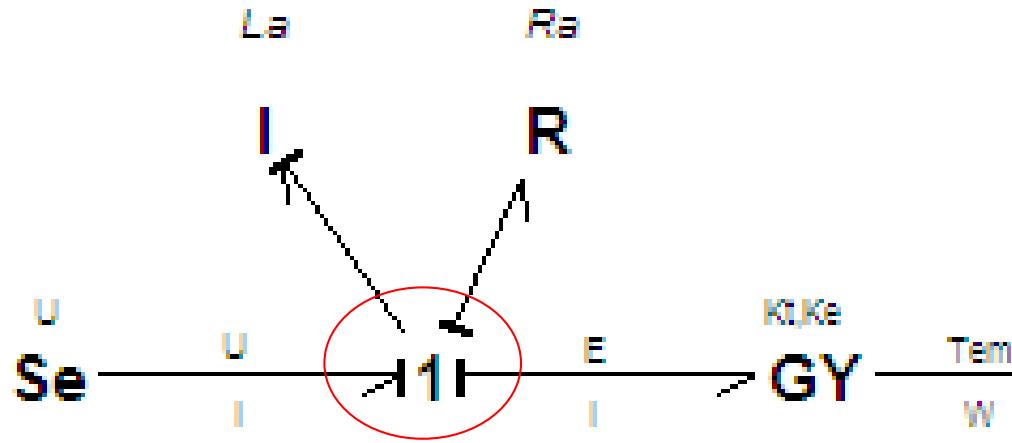


EHA-FDHP Bond-Graph Model





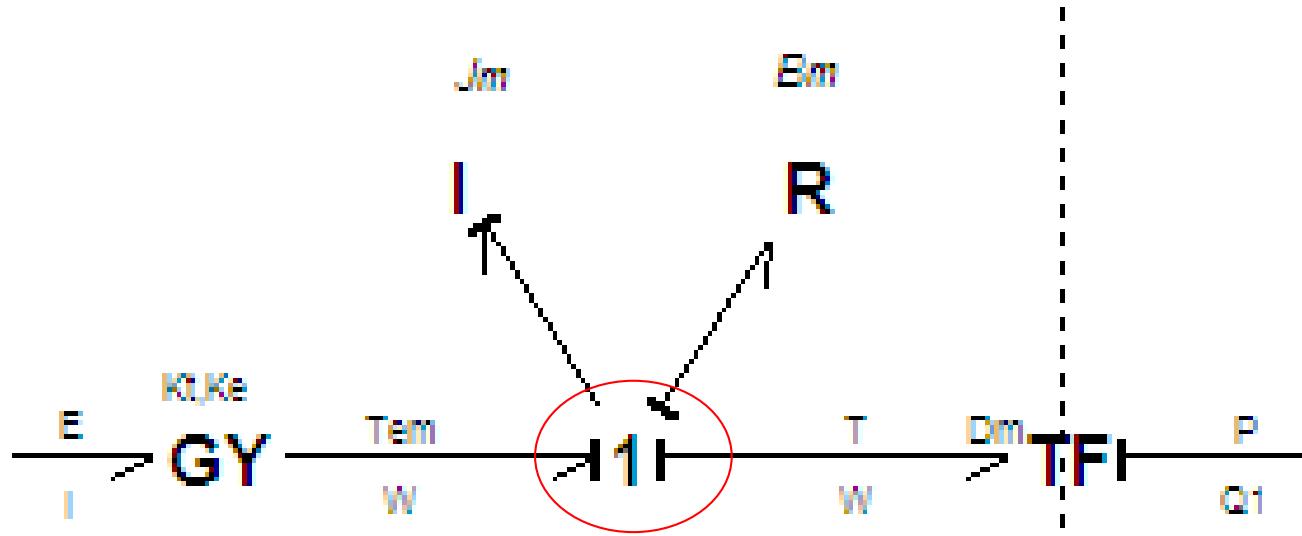
EMA BG Model



$$\sum u = 0 \quad \Rightarrow \quad u - L_A \dot{i} - R_A i - K_E \omega = 0$$

$$\dot{i} = \frac{1}{L_A} u - \frac{R_A}{L_A} i - \frac{K_E}{L_A} \omega$$

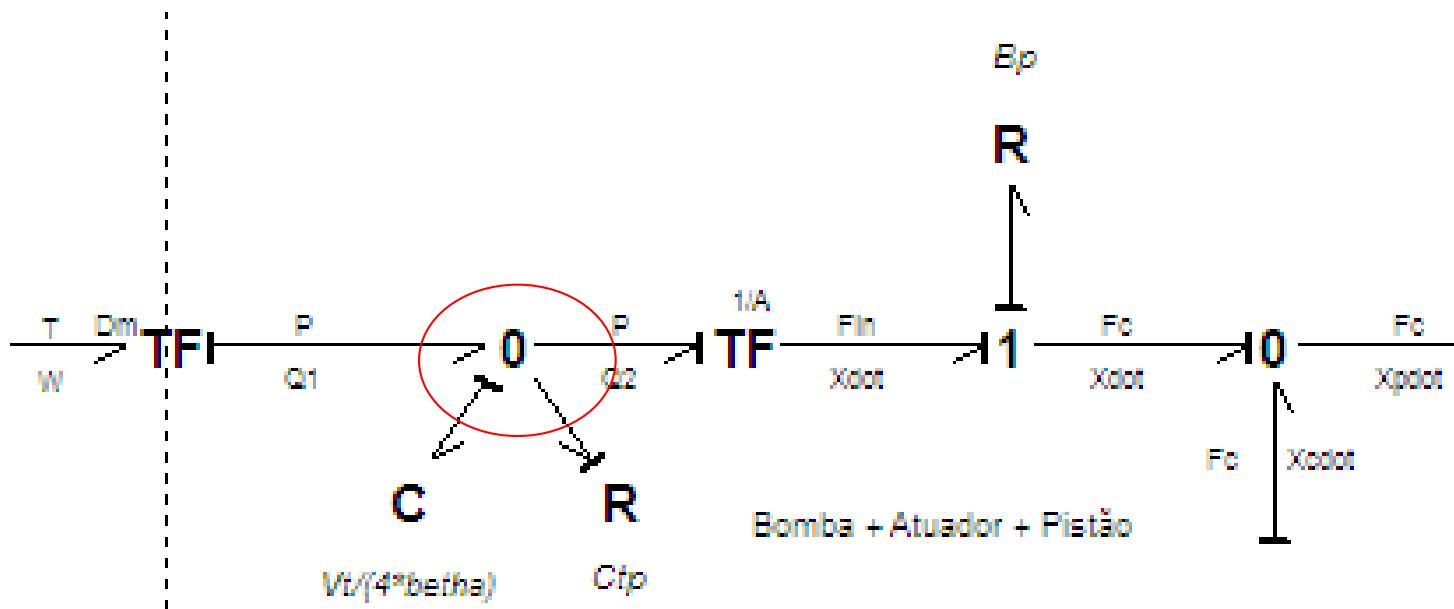
BG Model for EMA-Pump Coupling



$$\sum T = 0 \Rightarrow K_T i - B_M \omega - J_M \dot{\omega} - D_M P = 0$$

$$\dot{\omega} = \frac{K_T}{J_M} i - \frac{B_M}{J_M} \omega - \frac{D_M}{J_M} P$$

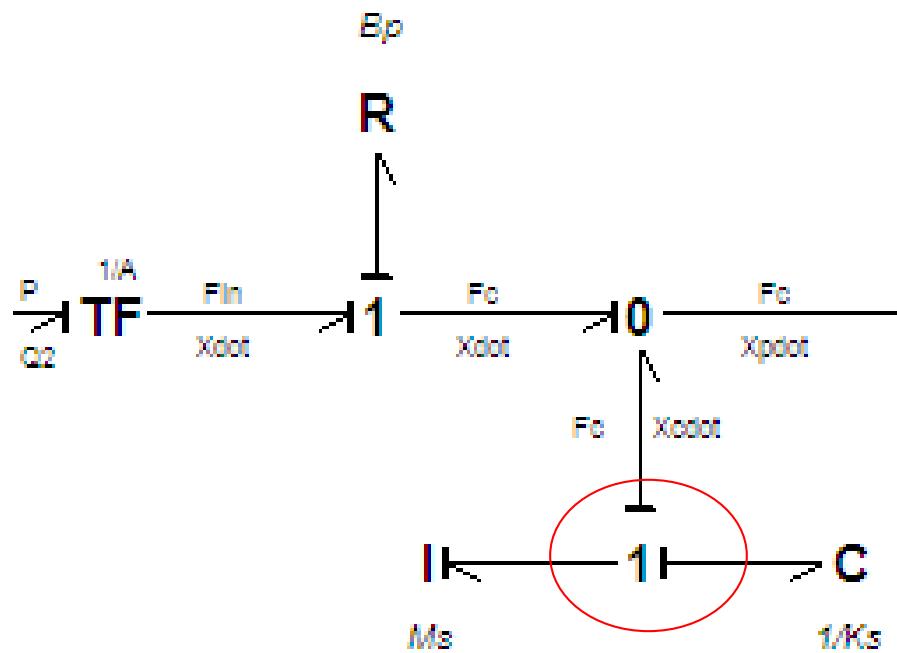
Variável de Estado: Pressão Linha



$$\sum Q = 0 \Rightarrow D_M \omega - A \dot{x} - C_{tp} P - \frac{V_t}{4\beta} \dot{P} = 0$$

$$\dot{P} = \frac{4\beta D_M}{V_t} \omega - \frac{4\beta A}{V_t} \dot{x}_P + \frac{4\beta A}{V_t} \dot{x}_C - \frac{4\beta C_{tp}}{V_t} P$$

BG Model for Actuator Body Force Balance



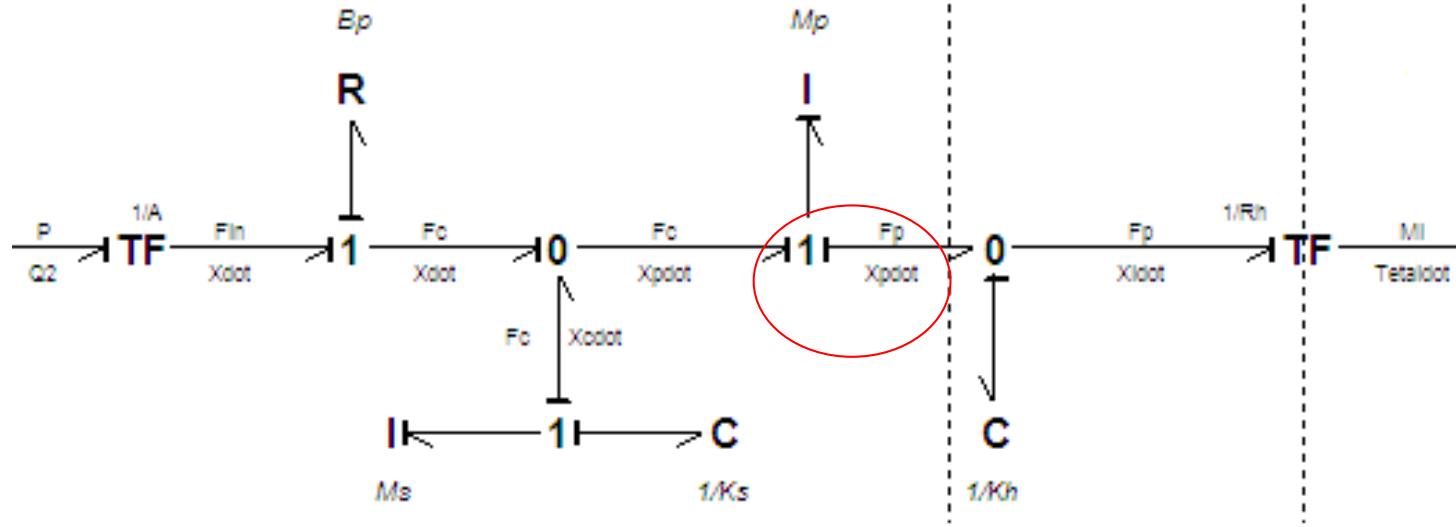
Bomba + Atuador + Pistão

$$\sum F = 0 \quad \Rightarrow \quad -F_C - M_S \ddot{x}_C - K_S x_C = 0 \quad F_C = AP - B_P \dot{x}$$

$$\ddot{x}_C = -\frac{A}{M_S}P + \frac{B_P}{M_S}\dot{x}_P - \frac{B_P}{M_S}\dot{x}_C - \frac{K_S}{M_S}x_C$$



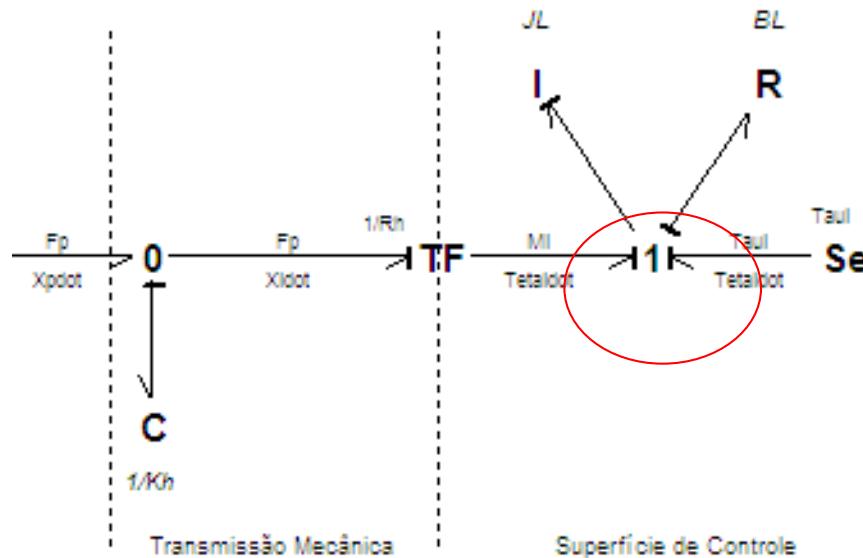
Actuator Force Balance



$$\sum F = 0 \Rightarrow AP - B_P \dot{x} - M_P \ddot{x}_P - K_H (x_P - R_H \theta_L) = 0$$

$$\ddot{x}_P = \frac{A}{M_S} P - \frac{B_P}{M_S} \dot{x}_P + \frac{B_P}{M_S} \dot{x}_C - \frac{K_H}{M_S} x_P + \frac{K_H R_H}{M_S} \theta_L$$

Hinge moment load balance equation



$$\sum T = 0 \Rightarrow K_H(x_P - R_H \theta_L)R_H - J_L \ddot{\theta}_L - B_L \dot{\theta} + \tau_L = 0$$

$$\tau_L = \bar{q} S_T R_H \left(Ch_\alpha \frac{\alpha(s)}{\theta_L(s)} + Ch_\delta \right) \theta_L = \bar{q} S_T R_H Ch \theta_L$$

$$\ddot{\theta}_L = \frac{K_H R_H}{J_L} x_P - \frac{\bar{q} S_T R_H Ch + K_H R_H^2}{J_L} \theta_L - B_L \dot{\theta} = 0$$



Matrizes do Espaço de Estados

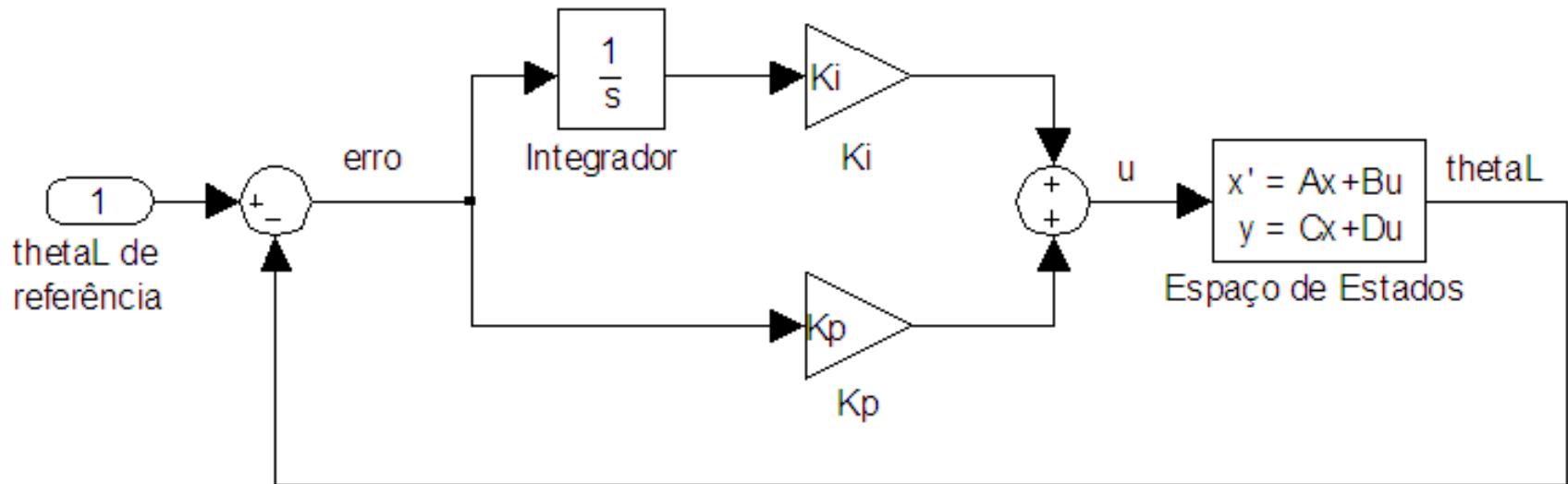
$$A = \begin{bmatrix} i & \omega & x_p & \dot{x}_p & x_c & \dot{x}_c & \theta_L & \dot{\theta}_L & P \\ -\frac{R_A}{L_A} & -\frac{K_E}{L_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{K_T}{J_M} & -\frac{B_M}{J_M} & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{D_M}{J_M} \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{K_H}{M_P} & -\frac{B_P}{M_P} & 0 & \frac{B_P}{M_P} & \frac{K_H R_H}{M_P} & 0 & \frac{A}{M_P} \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{B_P}{M_S} & -\frac{K_S}{M_S} & -\frac{B_P}{M_S} & 0 & 0 & -\frac{A}{M_S} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{K_H R_H}{J_L} & 0 & 0 & 0 & -\left(\frac{\bar{q} S_T R_H C h + K_H R_H^2}{J_L}\right) & -\frac{B_L}{J_L} & 0 \\ 0 & \frac{4D_M \beta}{V_t} & 0 & -\frac{4A\beta}{V_t} & 0 & \frac{4A\beta}{V_t} & 0 & 0 & -\frac{4C_{tp}\beta}{V_t} \end{bmatrix}$$

$$B = \begin{bmatrix} 1 \\ -\frac{1}{L_A} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T$$

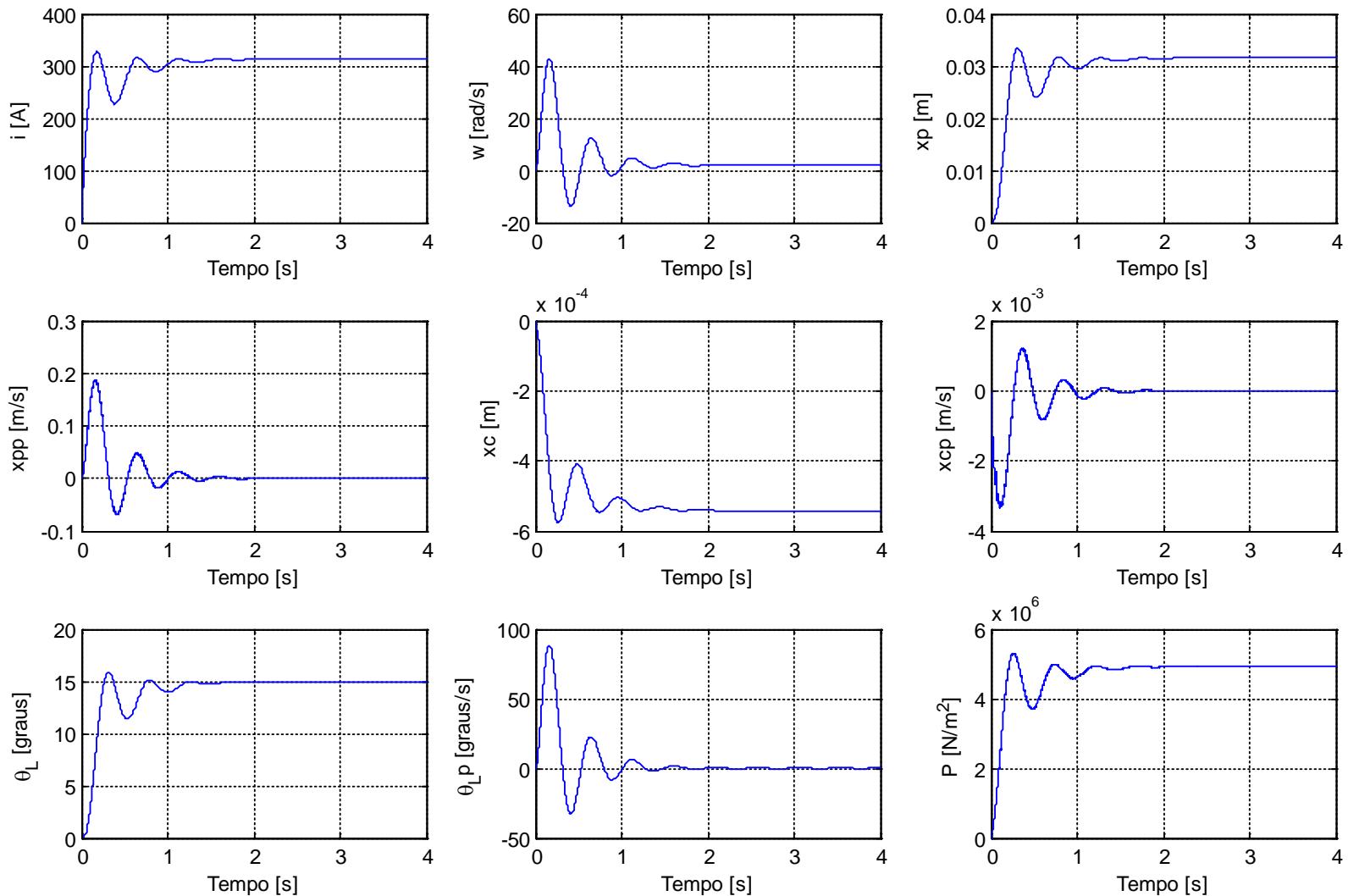
EHA Closed Loop Control



- PI Control: $K_I = 2613$; $K_P = 718.7$
- Tuning method: minimization ITAE criterium



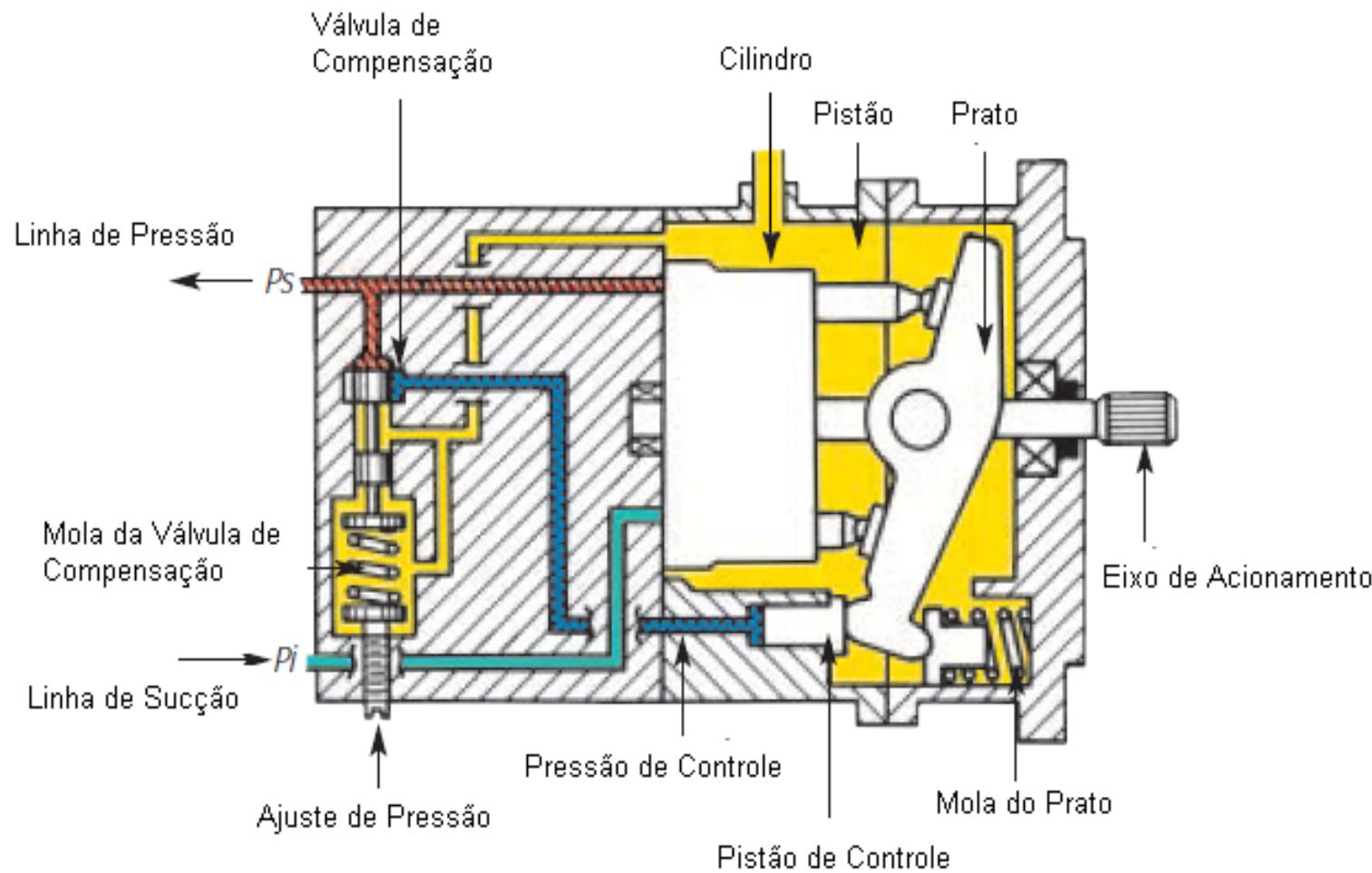
Resultados da Simulação





- The variable displacement hydraulic pump is an importante component of flight actuation systems;
- The servopump maintains the outlet pressure constant independente of variations of load flow in the actuator manifold;
- The objective of this case study is to develop a BG model of the servopump with pressure comensation and adjust the pump paramters to mathch the simulated and the experimental data.

VDHP-Variable Displacement Hydraulic Pump



Servo pump with pressure compensation.

VDHP Representation

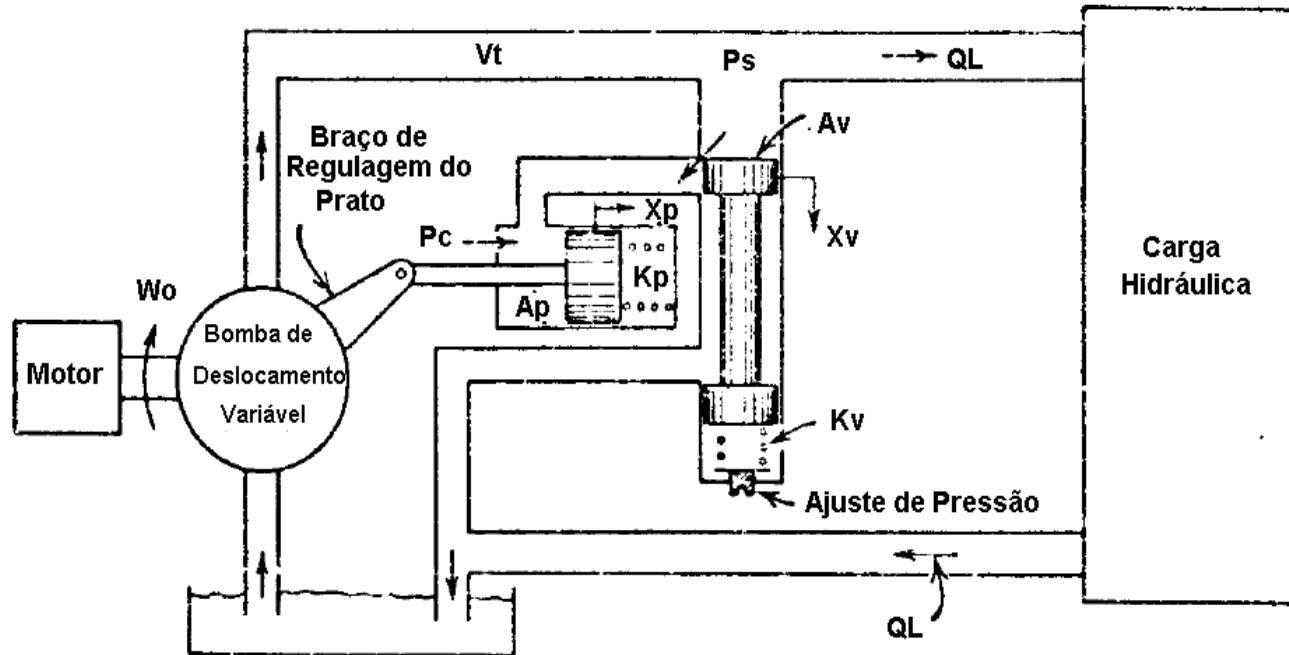
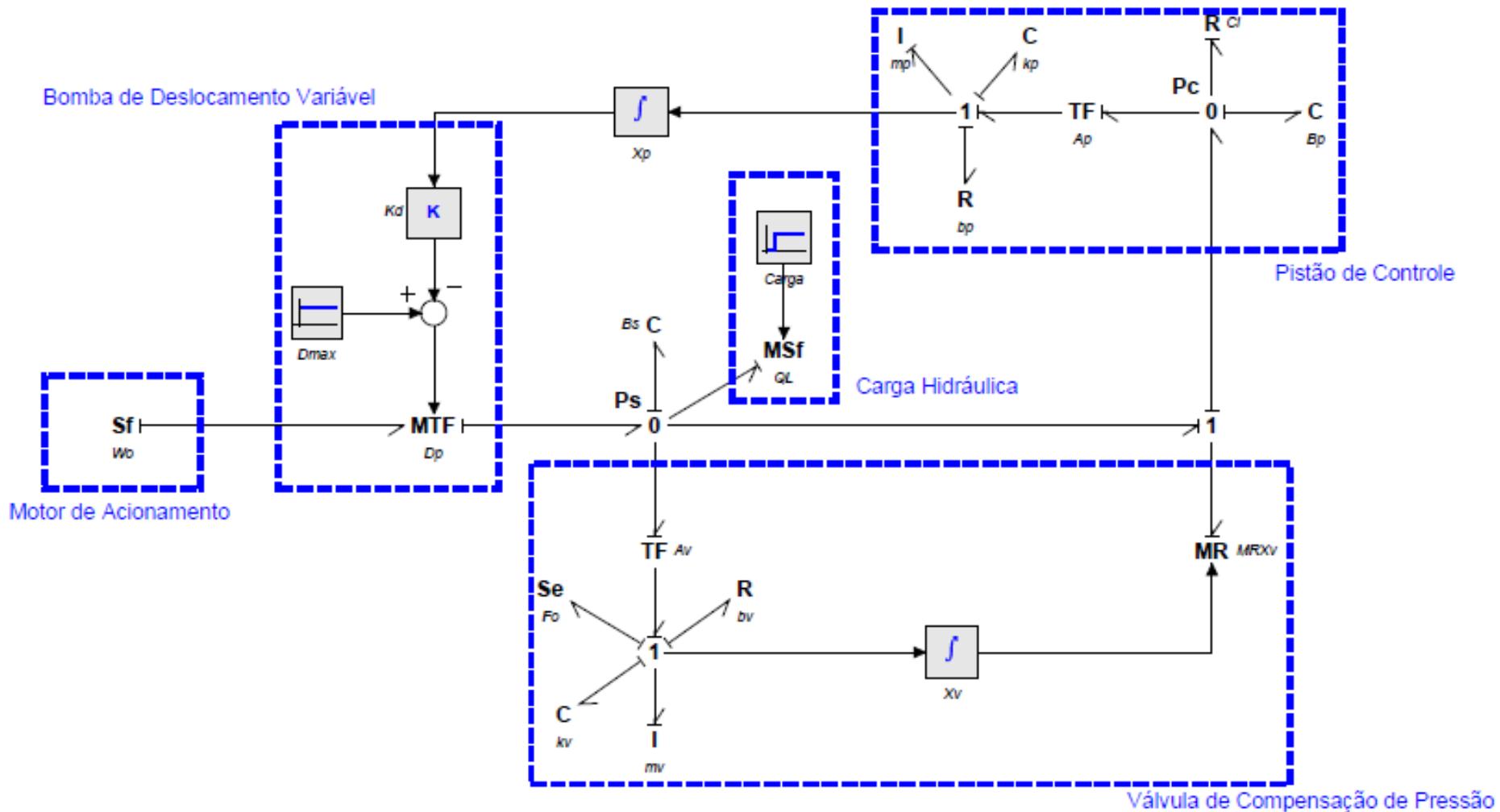


Figura 3 - Representação esquemática de uma bomba de deslocamento variável com compensação de pressão. Adaptado de: (MERRIT, 1967)

Bond-Graph Model VDHP





Mathematical Model of the VDHP

- State-space Equations:

$$\begin{cases} \dot{x}(t) = A \cdot x(t) + B \cdot u(t) \\ y(t) = C \cdot x(t) + D \cdot u(t) \end{cases}$$

$$x(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_3(t) \\ x_4(t) \\ x_5(t) \\ x_6(t) \end{bmatrix} = \begin{bmatrix} P_c(t) \\ P_s(t) \\ x_p(t) \\ x_v(t) \\ \dot{x}_p(t) \\ \dot{x}_v(t) \end{bmatrix} \quad u(t) = \begin{bmatrix} u_1(t) \\ u_2(t) \\ u_3(t) \end{bmatrix} = \begin{bmatrix} F_0(t) \\ W_0(t) \\ Q_L(t) \end{bmatrix}$$

Modelo do Sistema

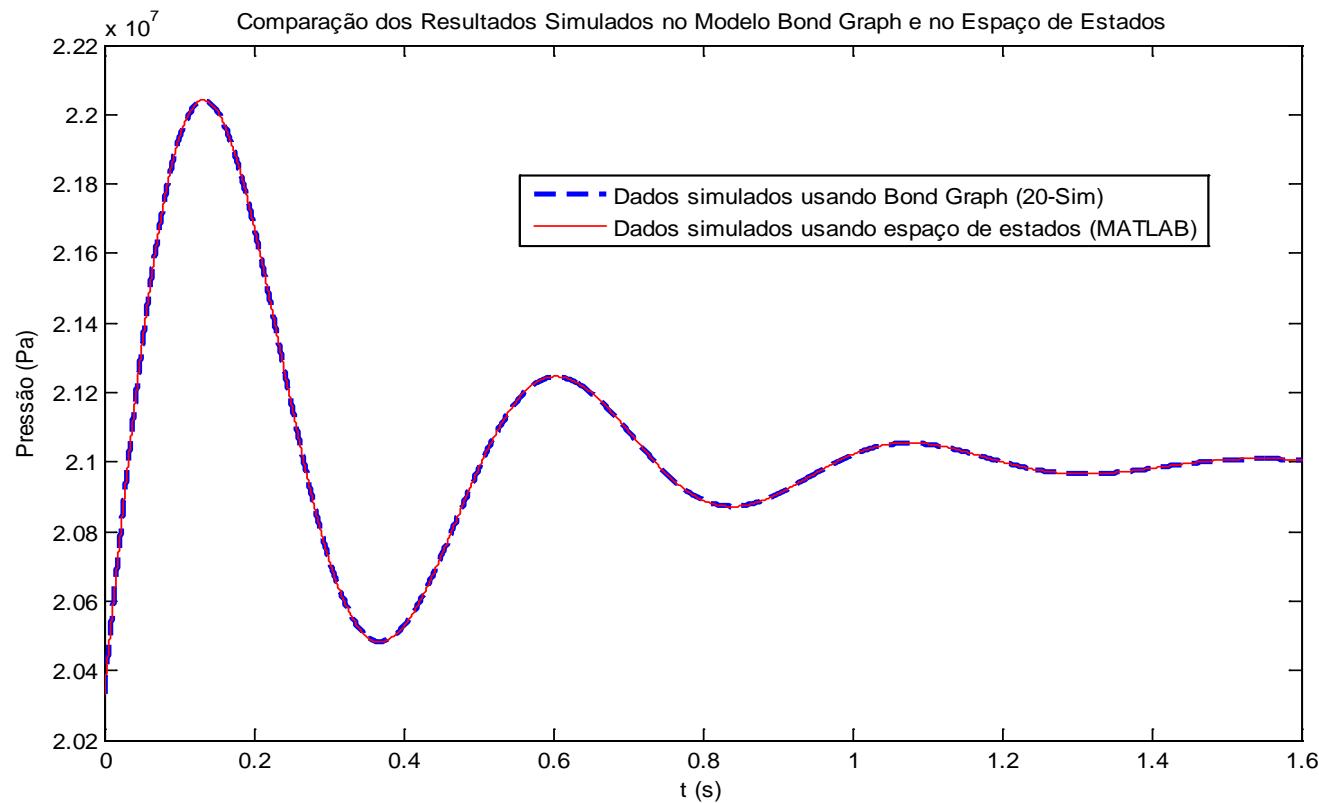
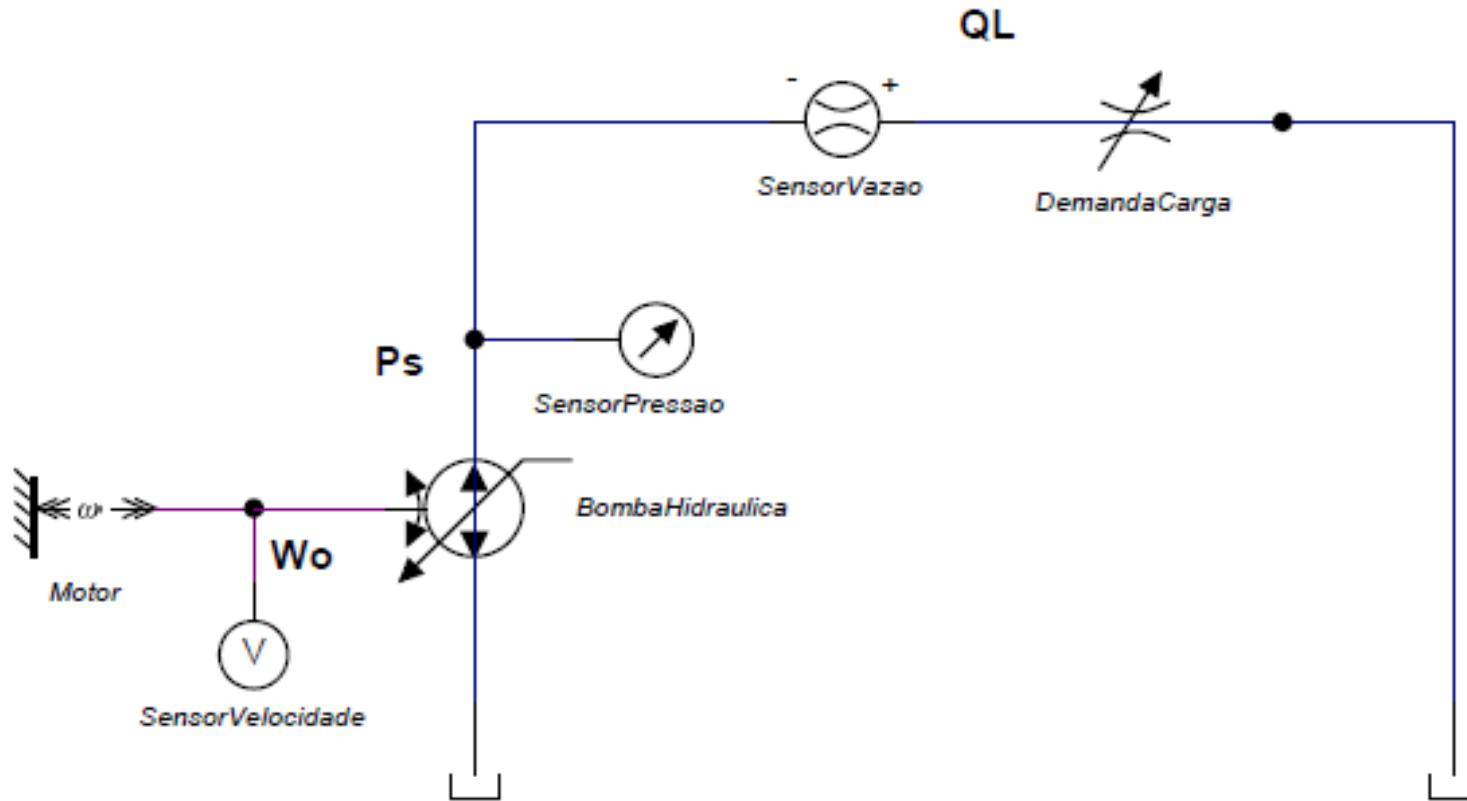


Figura 5 - Comparação entre os resultados simulados utilizando o modelo Bond Graph (20-sim) e o modelo no espaço de estados (Matlab).

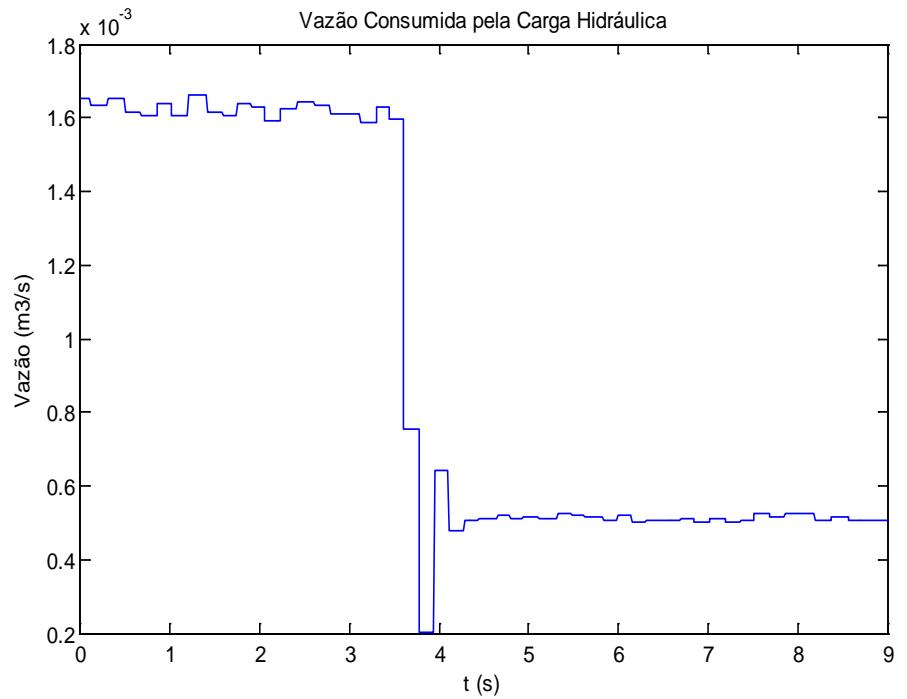
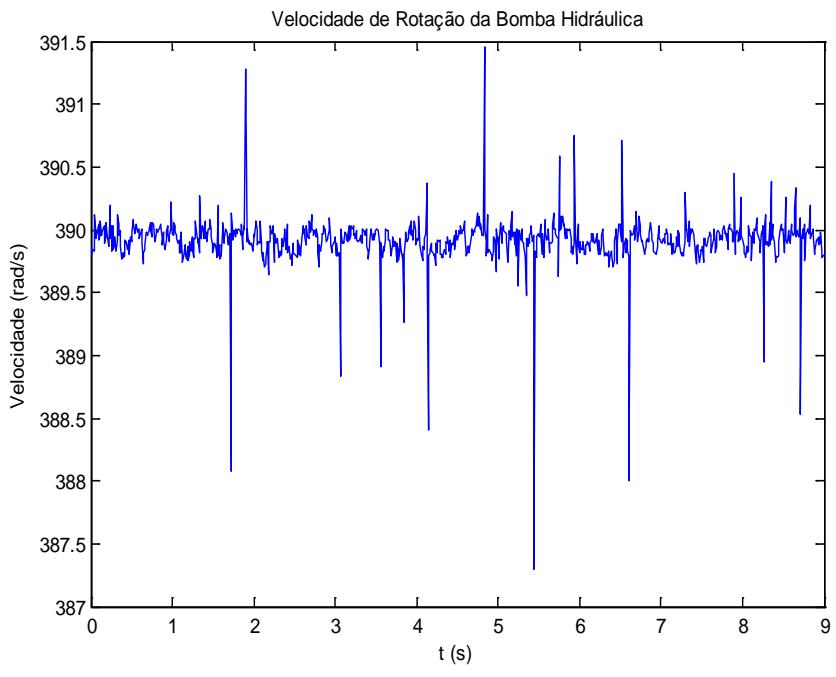


- Aquisição de dados experimentais: pressão de saída e demanda de vazão
- Pré tratamento dos dados
- Aplicação do método de identificação de sistemas: Método do Erro de Predição (PEM)

Experimental Setup for VDHP Testing

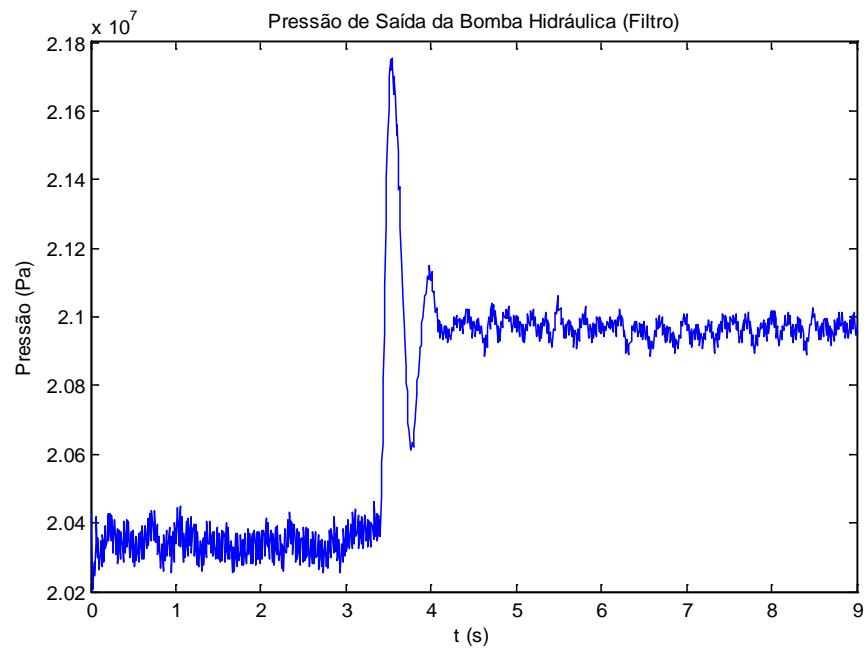
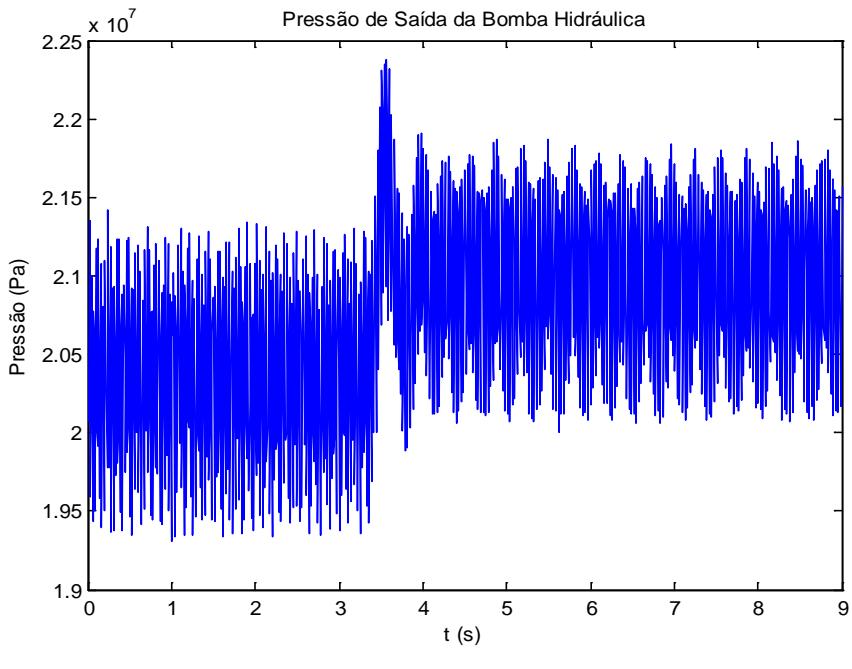


Identificação Paramétrica



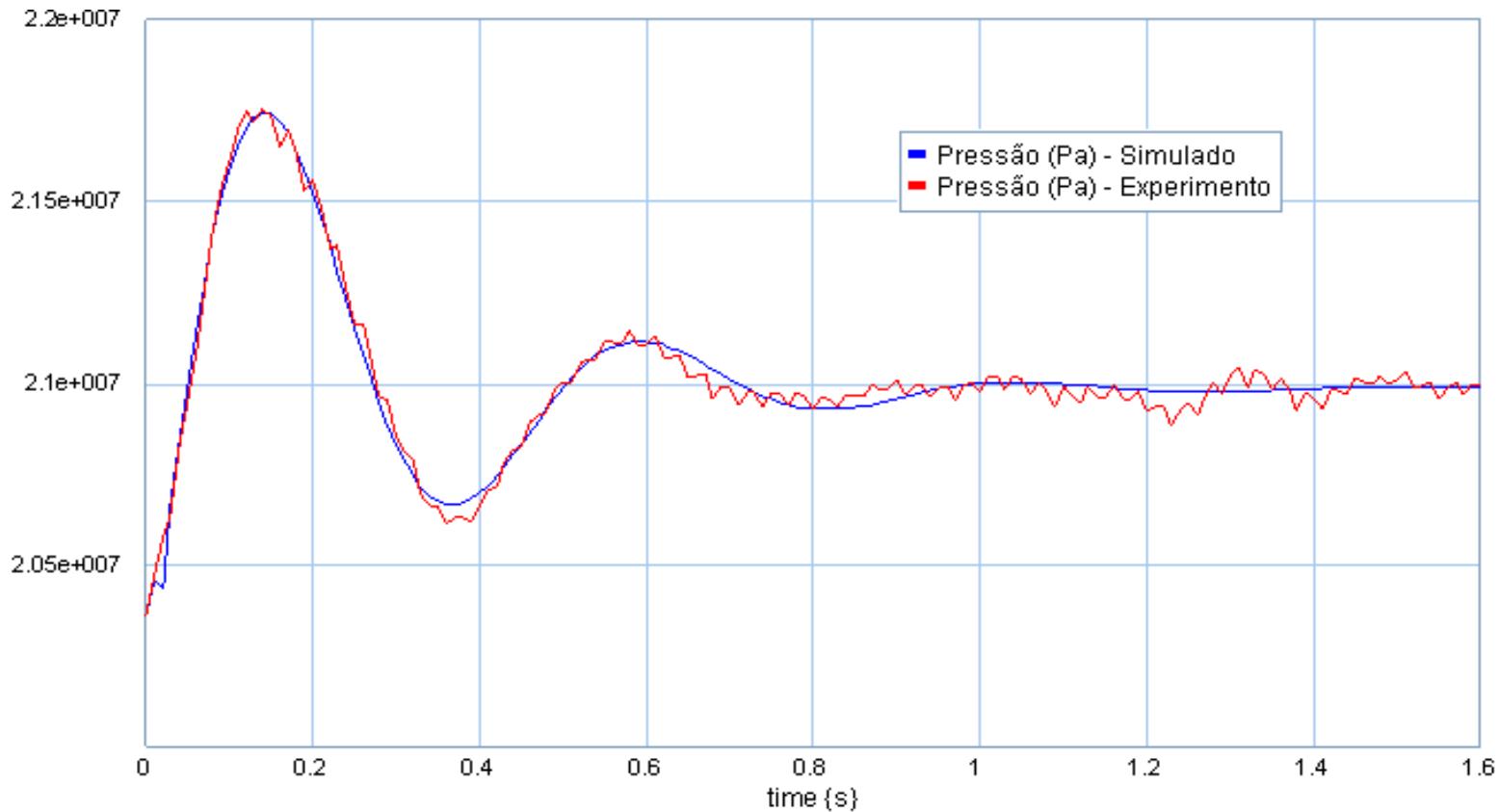
Pump rotational speed and flow consumption variation

Identificação Paramétrica

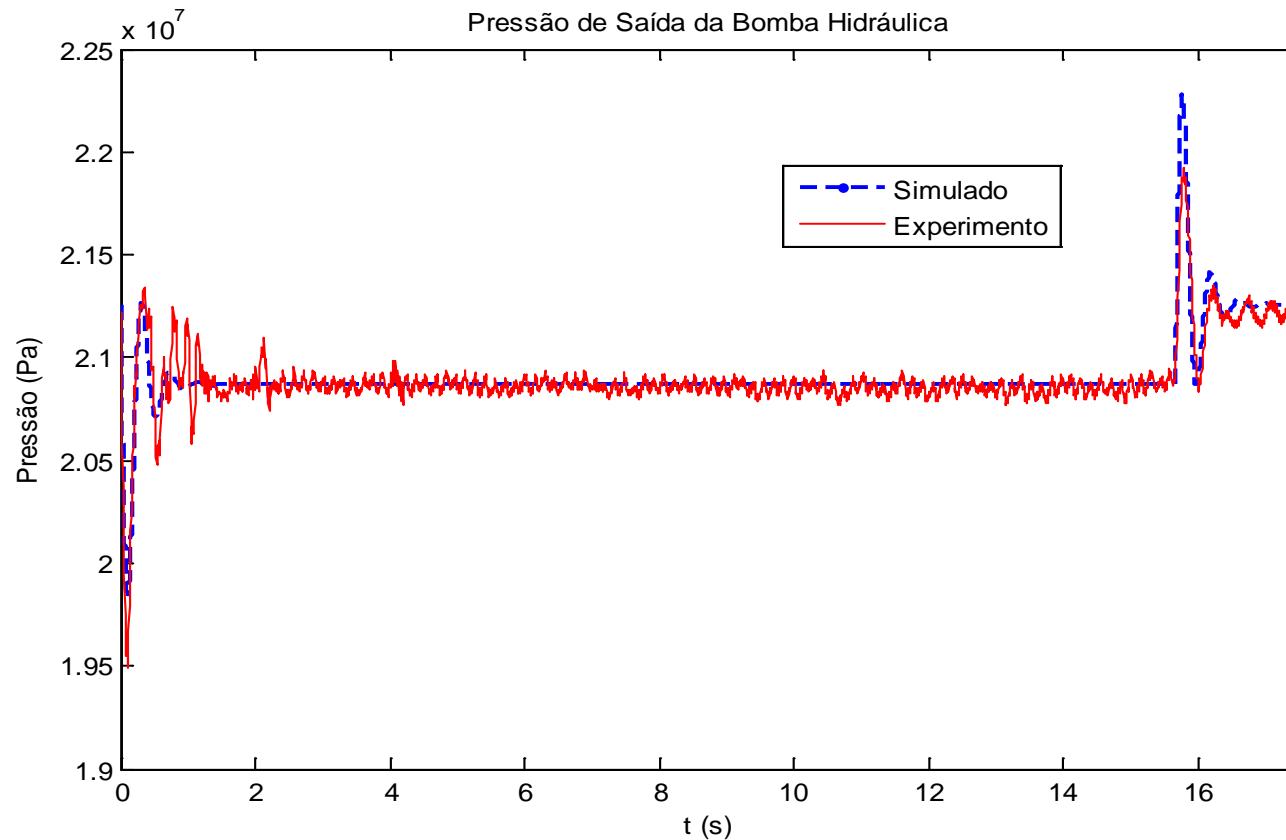


Output pressure variation with and w/o smoothing filter

Simulation and Validation



Simulação e Validação



Regulated pressure regulation with load flow variation

Conclusions



- *Bond-Graph* (BG) models have good representativeness of experimental data of flight actuation systems;
- The application of multi-physics BG models in conjunction with parametric identification methods is an effective methodology for experimental data validation for more accurate flight actuator models;
- *Bond-graph* model is a compact graphical representation of the system dynamics and helps to understand the type of mathematical involved in the systems representation;
- The application of *BG-SysId* allows the determination of physical parameters which are difficult to obtain by other methods.



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Thanks for the Attention.