Design Considerations for Force Controllable Series Elastic Actuators

Thesis Committee Meeting

Dec. 7, 1999

David W. Robinson

Agenda

- What is my goal?
- Thesis Outline
- Past Material
  - EM Series Elastic Actuator (FrAP)
- Hydro-elastic Actuator (HyEAP)
- Non-Linear Springs
- Scaling
- Go Downstairs

What is my Goal?

- Several Discussions with people who ask:
  - "How much is bandwidth reduced?"
  - "What spring do I use for my application?"
- Goals
  - Practical Implementation
    - Prototype Actuators
    - Scaling
  - Understand and explain spring choice
    - Stability
    - Large Force Bandwidth
    - Impedance
    - Scaling
    - Non-linear

Written Thesis Outline

- Introduction
- Related Work
- Linear Series Elastic Actuators
- Non-Linear Series Elastic Actuators
- Compliant Element
- Actuator Scaling
- Application
- Conclusion

EM Series Elastic Actuator

- Mass-Spring-Damper Model
- PD Control
- Investigated
  - Large Force Bandwidth & Motor Saturation
  - Non-Linear Friction Reduction
  - Output Impedance
- Guides for Component and Spring Selection

Spring Selection

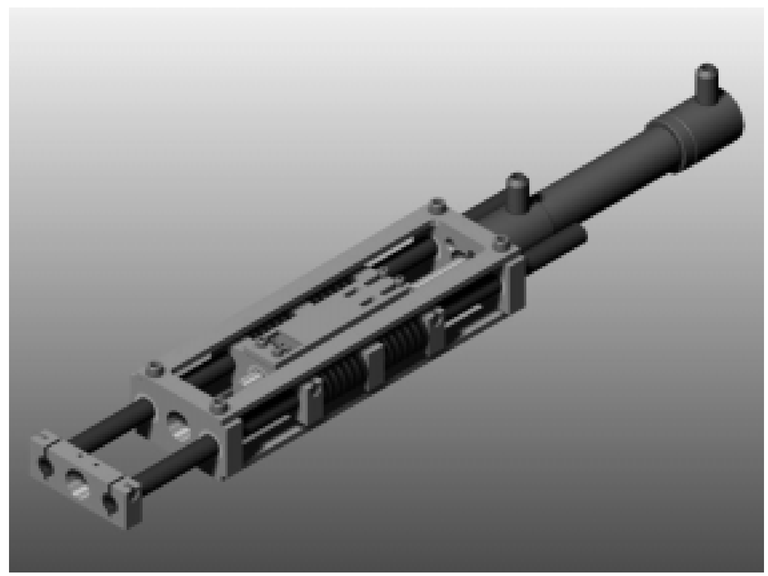
- Competing desires.
  - Large force bandwidth requires large spring.
  - Non-linear friction and impedance requires small spring.
- Choose minimum operational bandwidth (5-10 Hz).
  - Defined by natural mass spring resonance $\omega_{n.}$
  - Upper bound for $k_{s.}$
- Choose minimum friction and impedance levels.
  - Lower bound for $k_{s.}$

Hydroelastic Actuator

- Force controllable hydraulic actuator
- High power density
- Typically very stiff
- Related Work
  - Kliedon & Hogan (1983) Variable pressure pneumatic cylinder at the end of hydraulic cylinder for “tunable impedance”.
  - Wells & Jacobsen (1990) passive accumulators in piston.
  - Alleyne (1997) Lyapunov controller for force control.

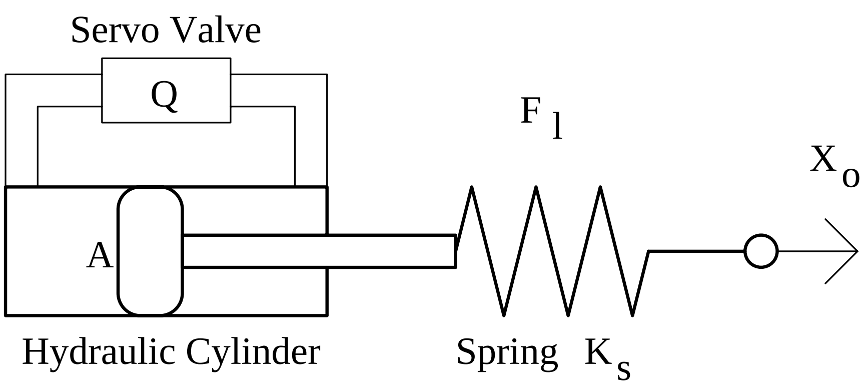
Hydroelastic Goals

- Simple controller achieves moderate bandwidth.
- Stability with Shock Tolerance.
- Actively Back-drivable.
- Low impedance



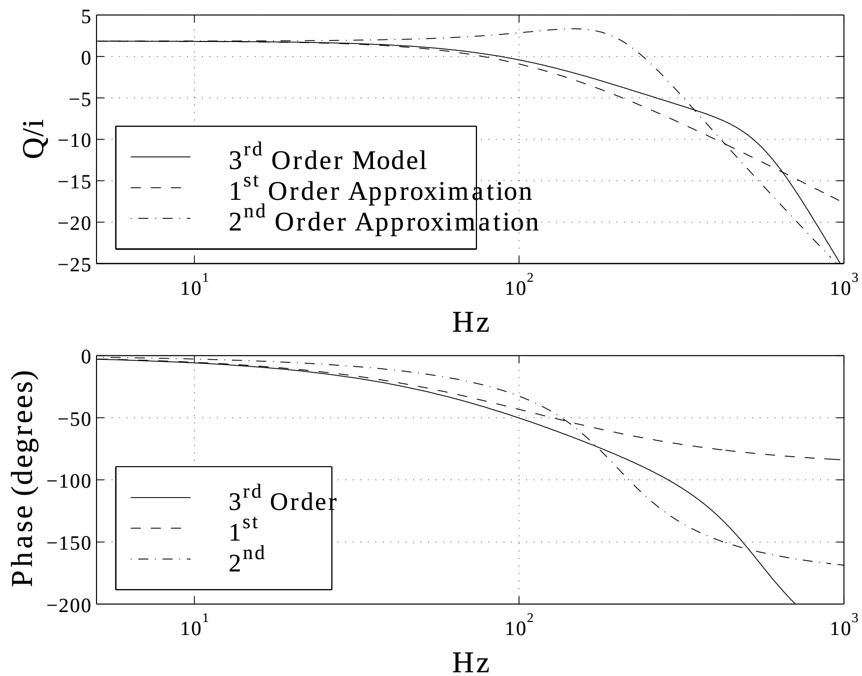
Actuator Model

- Inputs
  - Fluid Flow
  - Position input
- Assumptions
  - Equal Area
  - Current equals flow rate
  - 1^{st} order servo valve
  - No saturation (for now)
  - Incompressible



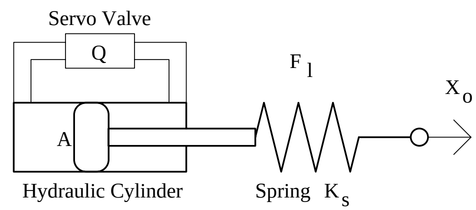
Servo Valve

- Typically 3rd Order Model
- Used 1st order for hand calculations
- Linear Model
- Non-linearity
  - Null bias
  - Threshold



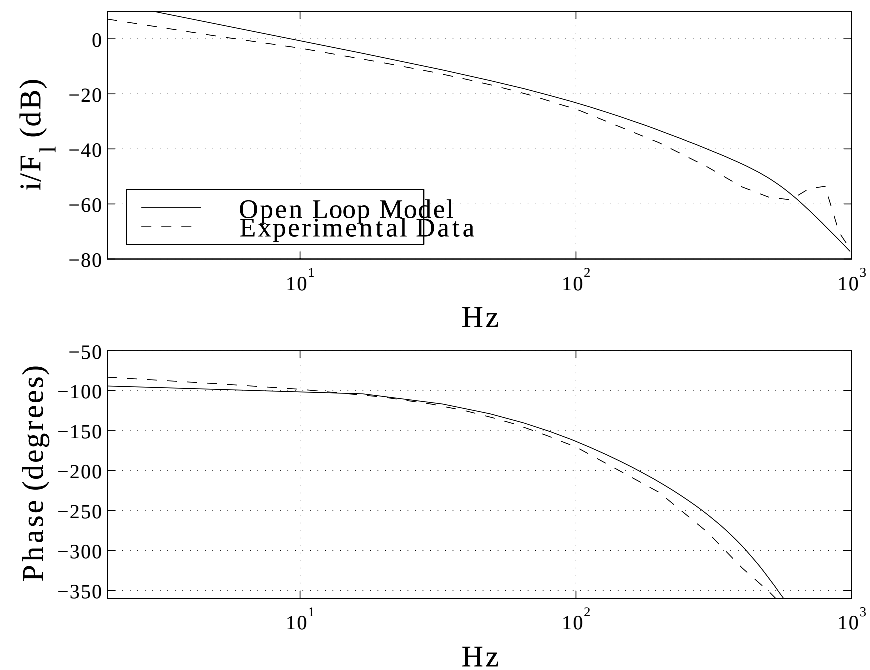
Servo-Spring OL model

- Flow is hard to measure.
- Spring deflection is easy.
- Fixed Endpoint



$$F_L = k_s\left(\frac{\dot{Q}(i)}{As} - x_0\right)$$

$$Q(i) = \frac{K_v}{\tau s + 1} i$$



P Closed Loop Equations

$$F_l = \frac{F_d - \dfrac{A(\tau s + 1)}{k_s K K_v} s k_s x_o}{\dfrac{A\tau}{k_s K K_v} s^2 + \dfrac{A}{k_s K K_v} s + 1}$$

Closed Loop Equations

$$S = \tau s$$

$$\Omega_p = \sqrt{\frac{k_s K K_v \tau}{A}}$$

Dimensional Groups

$$\frac{F_l}{F_d} = \frac{1}{\dfrac{S^2}{\Omega_p^2} + \dfrac{S}{\Omega_p} + 1}$$

Case 1: Fixed End Condition

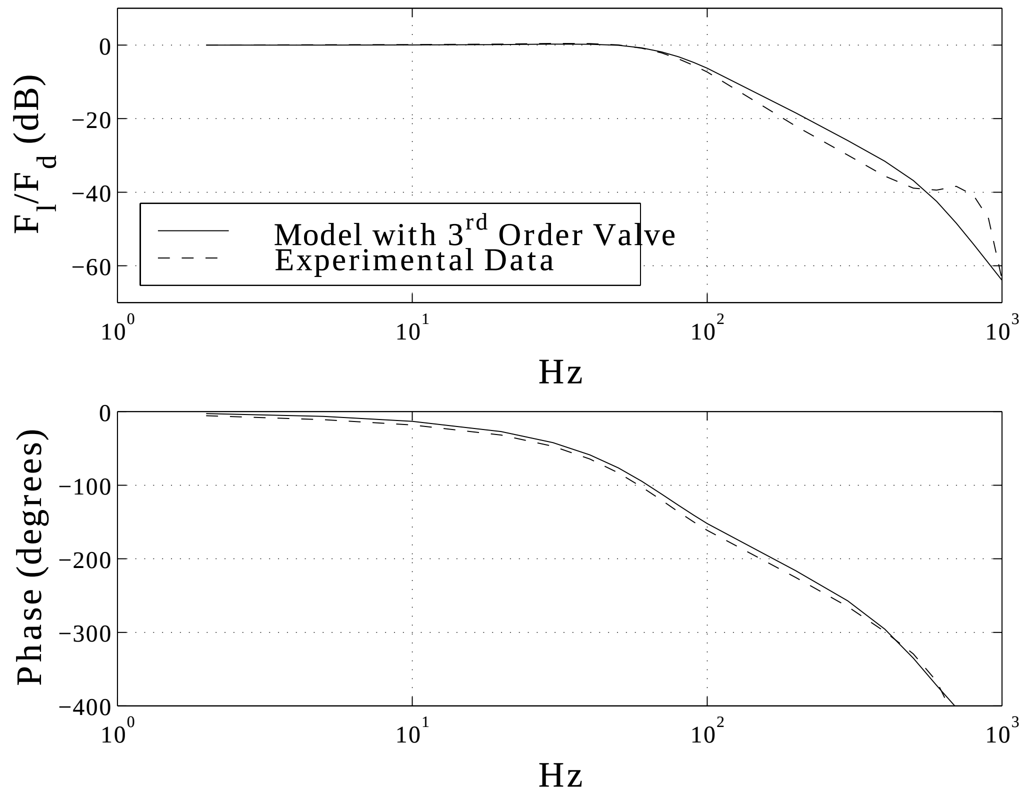
$$\frac{F_l}{k_s x_o} = \frac{\dfrac{(S+1)}{\Omega_p^2} S}{\dfrac{S^2}{\Omega_p^2} + \dfrac{S}{\Omega_p} + 1}$$

Case 2: Free End Condition

P Controller

- Proportional (P)
  - Null bias offset
  - Steady state error despite free integrator in the servo-valve.
  - Unpredictable and moves during operation
- Great Bandwidth
  - Bandwidth and damping are coupled
  - Pick one but not the other

P Bode Plot



0
−20
−40
−60
F_l/F_d (dB)
Model with 3rd Order Valve
Experimental Data
10^0
10^1
10^2
10^3
Hz
0
−100
−200
−300
−400
Phase (degrees)
10^0
10^1
10^2
10^3
Hz

PI Controller

- Proportional Integral (PI)
  - Zero steady state error
  - Lighter touch
- Problems
  - Servovalve Threshold problems
  - Valve Stiction and controller windup
- Solved with dither
  - Adds light vibration during free motion

PI Closed Loop Equations

$$F_l = \frac{\left(\frac{K_p}{K_i}s+1\right)F_d - \frac{A(\tau s+1)}{k_s K K_i K_v}s^2 k_s x_o}{\frac{A(\tau s+1)}{k_s K K_i K_v}s^2 + \frac{K_p}{K_i}s+1}$$

Closed Loop Equations

$$Z = \tau \frac{K_p}{K_i}$$

$$\Omega_{pi} = \tau \sqrt{\frac{k_s K K_i K_v}{A}}$$

Dimensional Groups

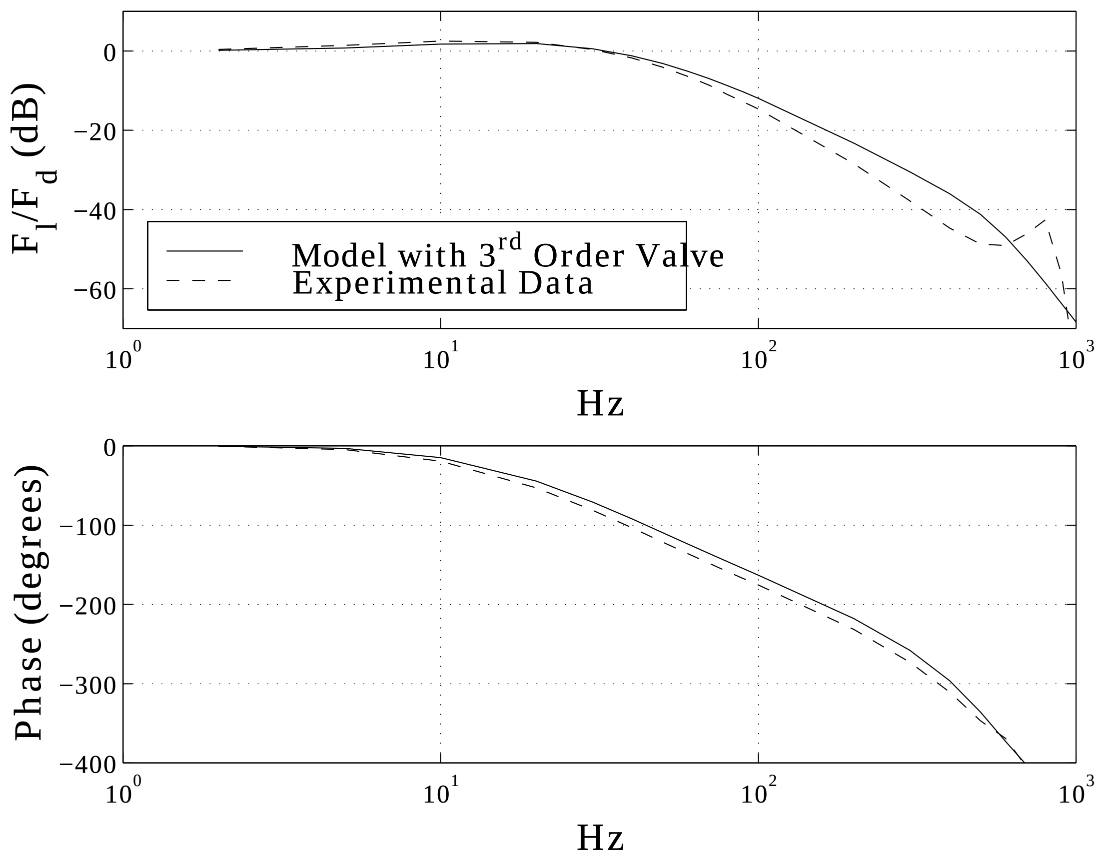
$$\frac{F_l}{F_d} = \frac{\left(\frac{1}{Z}S+1\right)}{\frac{(S+1)S^2}{\Omega_{pi}^2} + \frac{S}{Z} + 1}$$

Case 1: Fixed End Condition

$$\frac{F_l}{k_s x_o} = \frac{-\frac{(S+1)}{\Omega_{pi}^2}S^2}{\frac{(S+1)S^2}{\Omega_{pi}^2} + \frac{S}{Z} + 1}$$

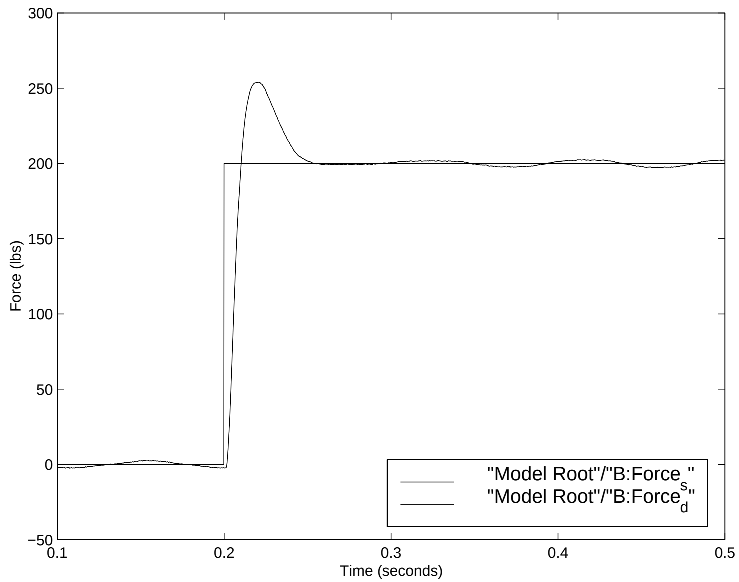
Case 2: Free End Condition

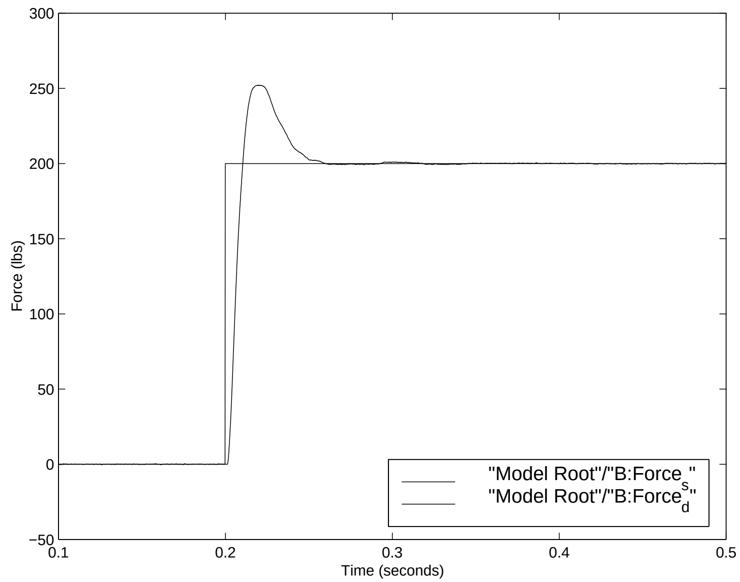
PI Bode Plot



F_l/F_d (dB)
0
−20
−40
−60
Model with 3rd Order Valve
Experimental Data
10^0
10^1
10^2
10^3
Hz
Phase (degrees)
0
−100
−200
−300
−400
10^0
10^1
10^2
10^3
Hz

Threshold and Dither



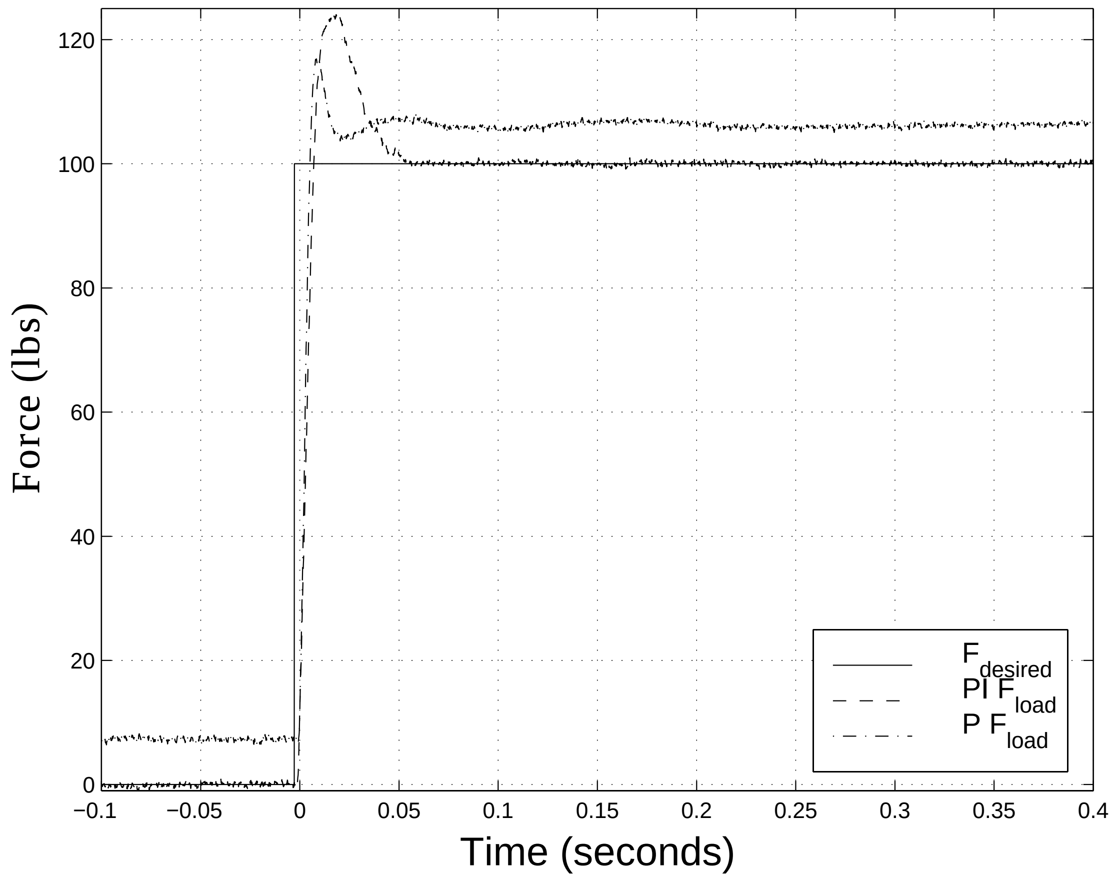


Controller Compromise

- Integral roll-off

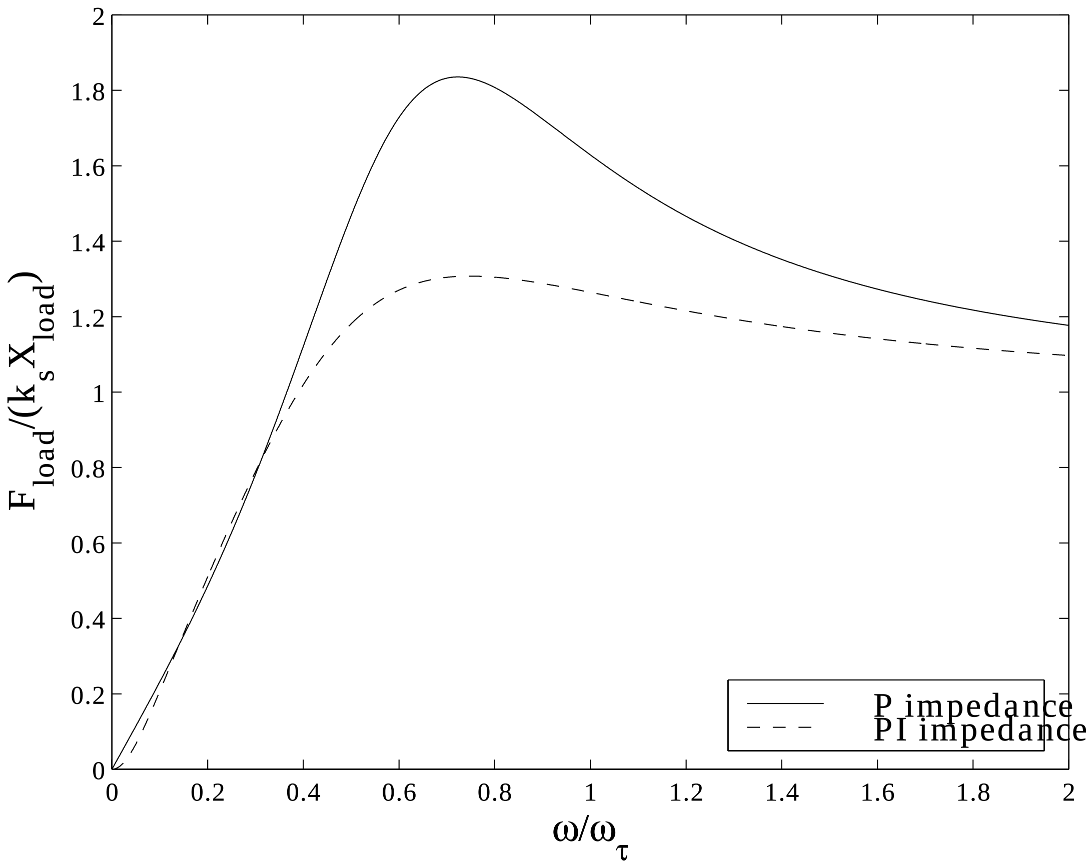
$$\dot{Q} = K\left(K_p + \frac{K_i}{\tau_i s + 1}\right)$$

P and PI Step



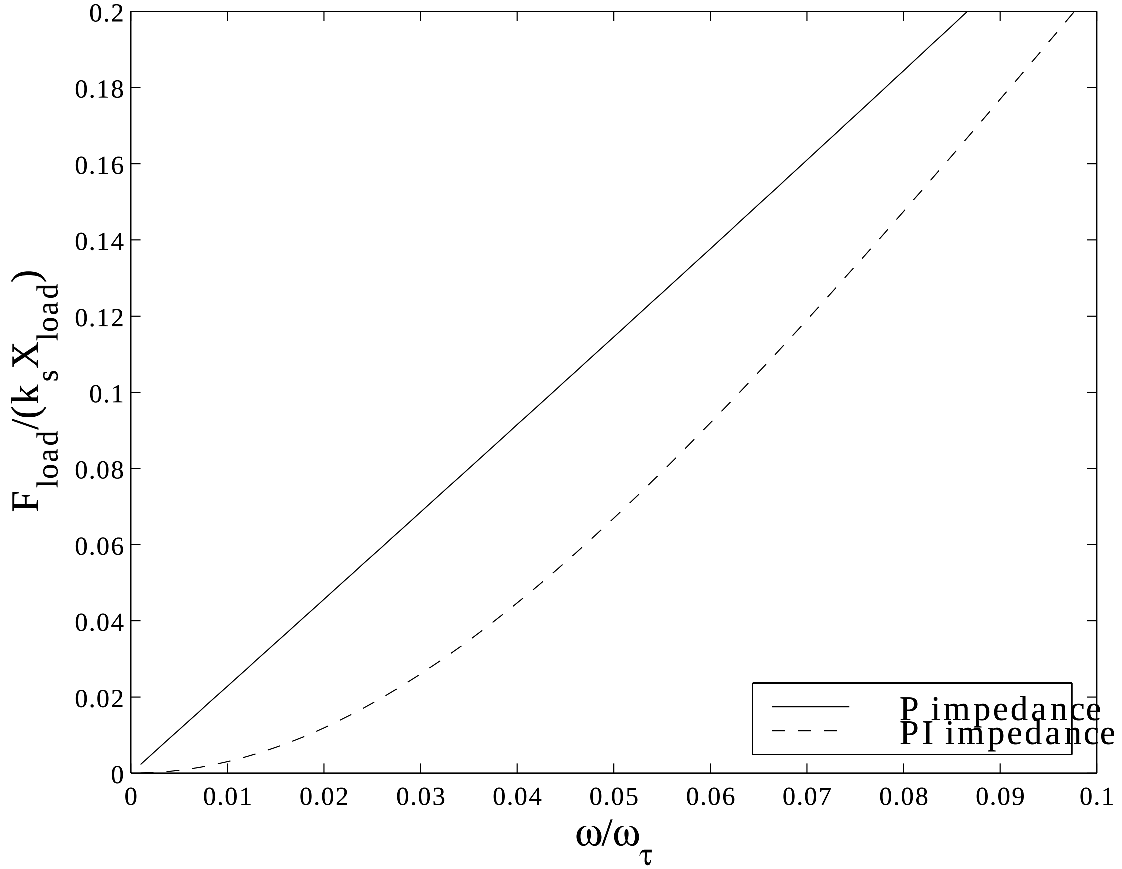
120
100
80
60
40
20
0
−0.1
−0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
Force (lbs)
Time (seconds)
$F_{desired}$
PI F_{load}
P F_{load}

Impedance



2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
F_load/(k_s X_load)
ω/ω_τ
P impedance
PI impedance

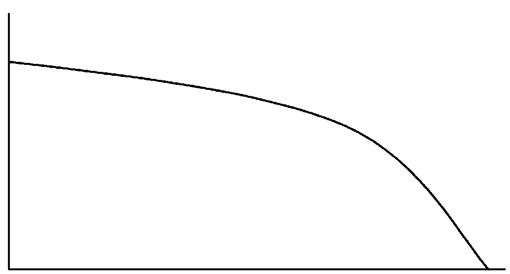
Impedance Close-up

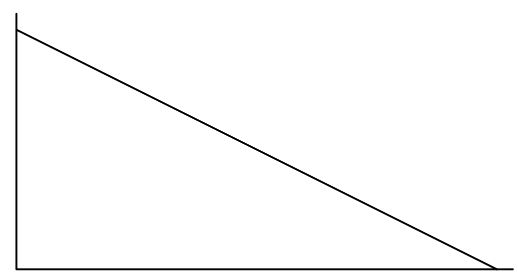


Saturation

- Assume linear saturation model
  - Linear is worse than square root

$$\dot{Q} = C\sqrt{P_s - \frac{F_l}{A}} \qquad \dot{Q} = C\left(P_s - \frac{F_l}{A}\right)$$





Saturation

- Assume Case 1: Zero Load Motion

$$F_l = k_s \frac{C\left(P_s - \frac{F_l}{A}\right)}{As}$$

- Saturation Bandwidth

$$\frac{F_{l\_sat}}{P_s A} = \frac{1}{\frac{A^2}{k_s C}s + 1} \qquad \omega_{sat} = \frac{k_s C}{A^2}$$

Robot Motion

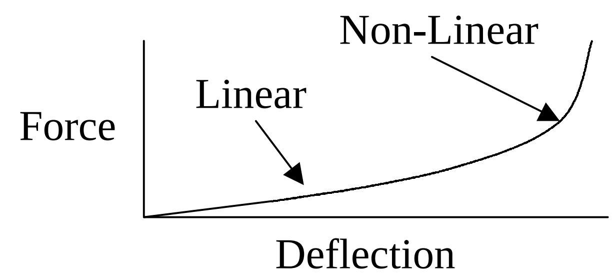
- Stability – minimum load mass
- Saturation
- Energy Storage
- Energy Efficiency

Non-linear springs

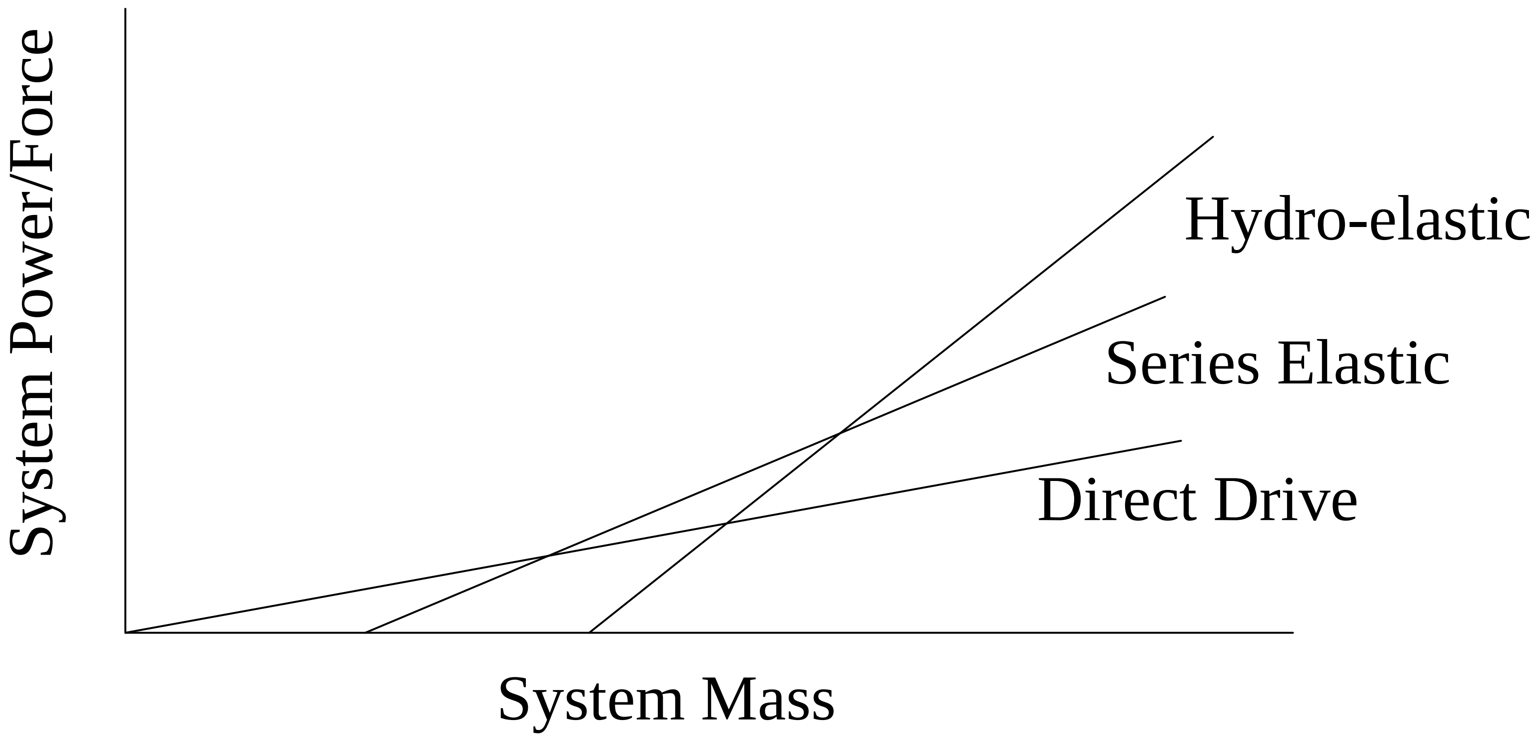
- Stiffening Springs
  - Low impedance at low ks.
  - Increase Saturation bandwidth with high ks.
  - Requires state dependent gain control to maintain stability.
  - Follows biology
    - Humans sense a constant percentage change of load force
- Exponential springs
  - Don’t exist but we can come close.

Non-linear Springs

- Bottoming out springs
  - Volute
  - Tapered coil
  - Good Mathematical Model
- Air Springs
  - Hysteresis due to heat transfer.
- Rubber Springs
  - Low bandwidth
  - Hysteresis due to internal friction



Force Controllable Actuator Scaling



Let’s Go Downstairs

- Rm006