Georgia Tech
Intelligent Machine Dynamics Lab

Actuator Design for a Passive Haptic Display

Lawrence Tognetti

Georgia Institute of Technology

July, 1999

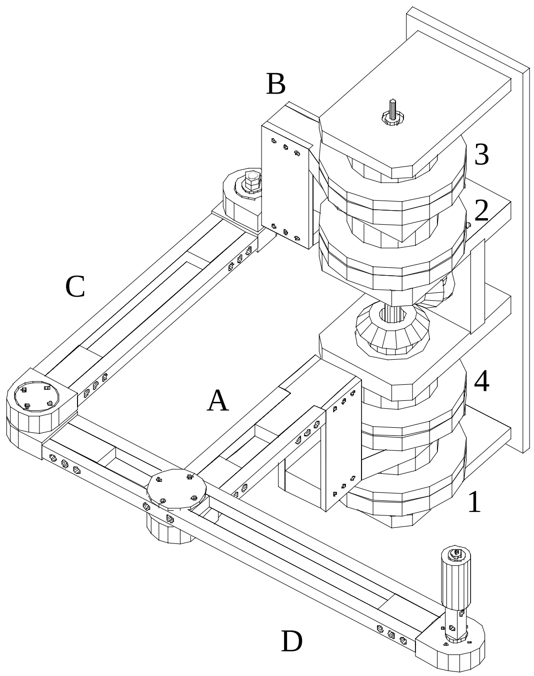
Research Supported by National Science Foundation Grant IIS-9700528

Georgia Tech
Intelligent Machine Dynamics Lab

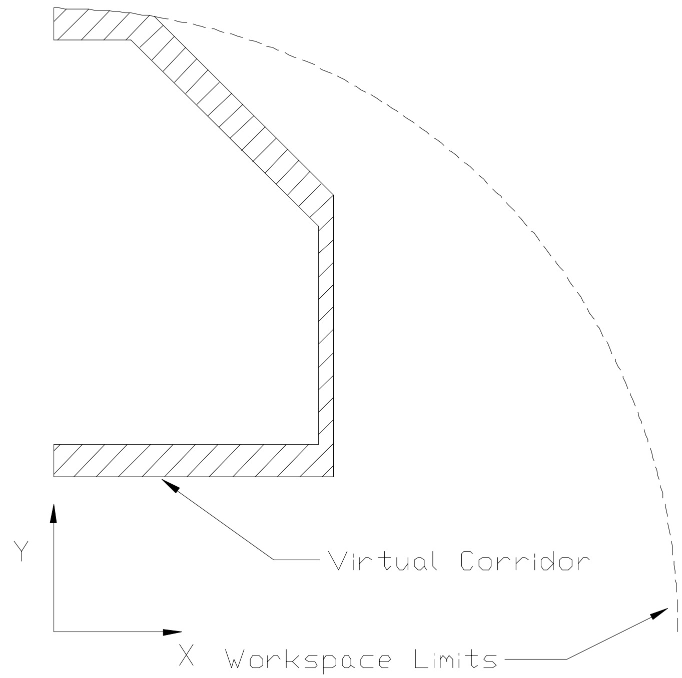
Overview

- Background
- Description of existing actuators and their deficiencies
- Alternative clutches / brakes
- Redesign of PTER's existing Dynacorp brakes / clutches
- Calibration of the new torque sensor
- Digital feedback control, experimental & simulation
- Conclusion
- Future work
- Questions

Background



Passive Trajectory Enhancing Robot (PTER)

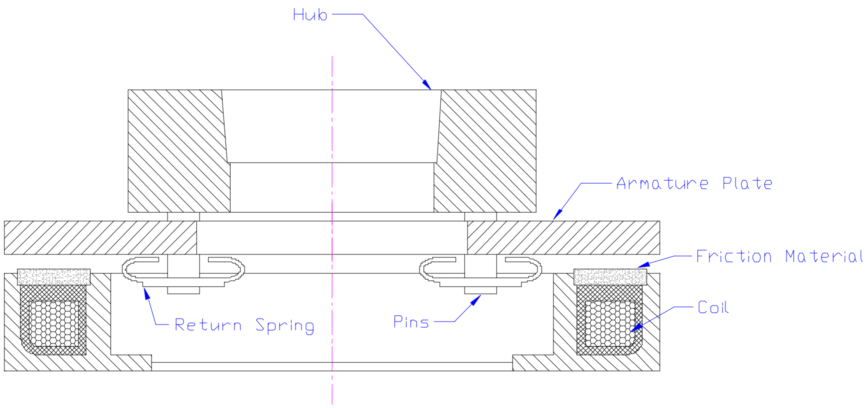


Virtual Corridor simulated on PTER

- PTER uses friction brakes to constrict motion for simulation of haptic features.
- Over actuated

PTER's Existing Brakes / Clutches

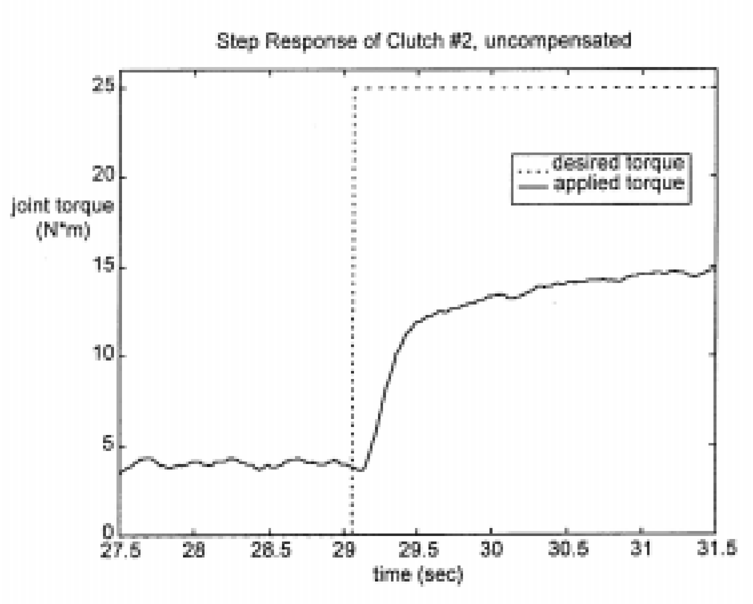
- Industrial electromagnetic friction units from Dynacorp
  - Model 310
  - Original max torque
    300 ft-lbf (407 N-M)
  - Rated time constant
    0.105 sec (coil build up)
- Modified to eliminate metal to metal contact
  - Reduced available torque
- No provisions of measuring actual applied torque for feedback control



Intelligent Machine Dynamics Lab

Dynamic Response of PTER's Actuators

- Open Loop Control
- Undesirable Dynamics
  - Non-linear electromagnet
  - Sliding on pins (binding)
  - First order response
    - R-L circuit
  - Pure time delay
    - Coil build up to attract armature plate
  - Steady state error
    - Each clutch's output torque different
    - Max torque ranged from 15 to 125 Ft-Lbf, depending on unit



(Borrowed from Gomes, 1997)

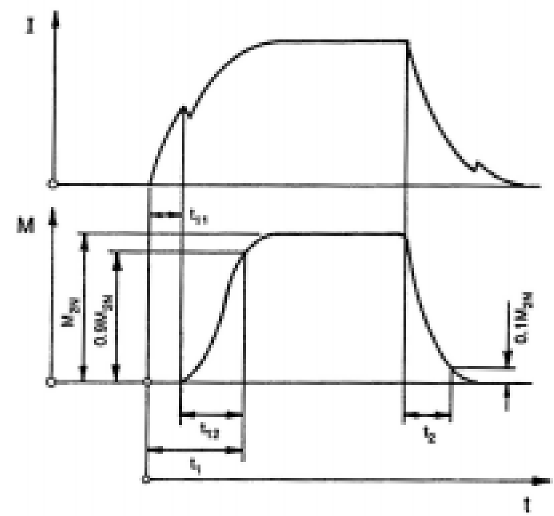
Georgia Tech
Intelligent Machine Dynamics Lab

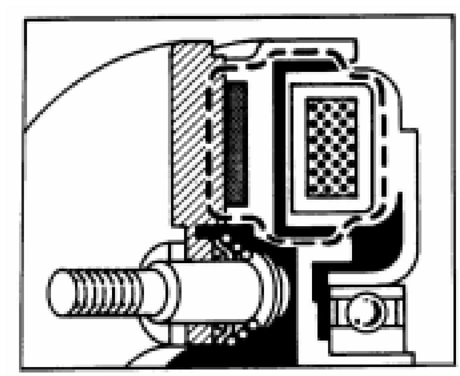
Alternative Brakes / Clutches

- Hysteresis
  - Low torque rattings (2.5 oz-in (0.013 lbf-ft) -- 3200 oz-in (16.67 lbf-ft))
  - Cogging
  - Hysteresis in actuation curve
- Eddy Current
  - Torque dependent on both slip velocity and applied current
  - Large scale applications
- Magnetic Particle
  - Required to turn a full revolution for redistribution of magnetic particles (for consistent operation)
- Electro-Rheological
  - Not much information available

Electromagnetic Friction

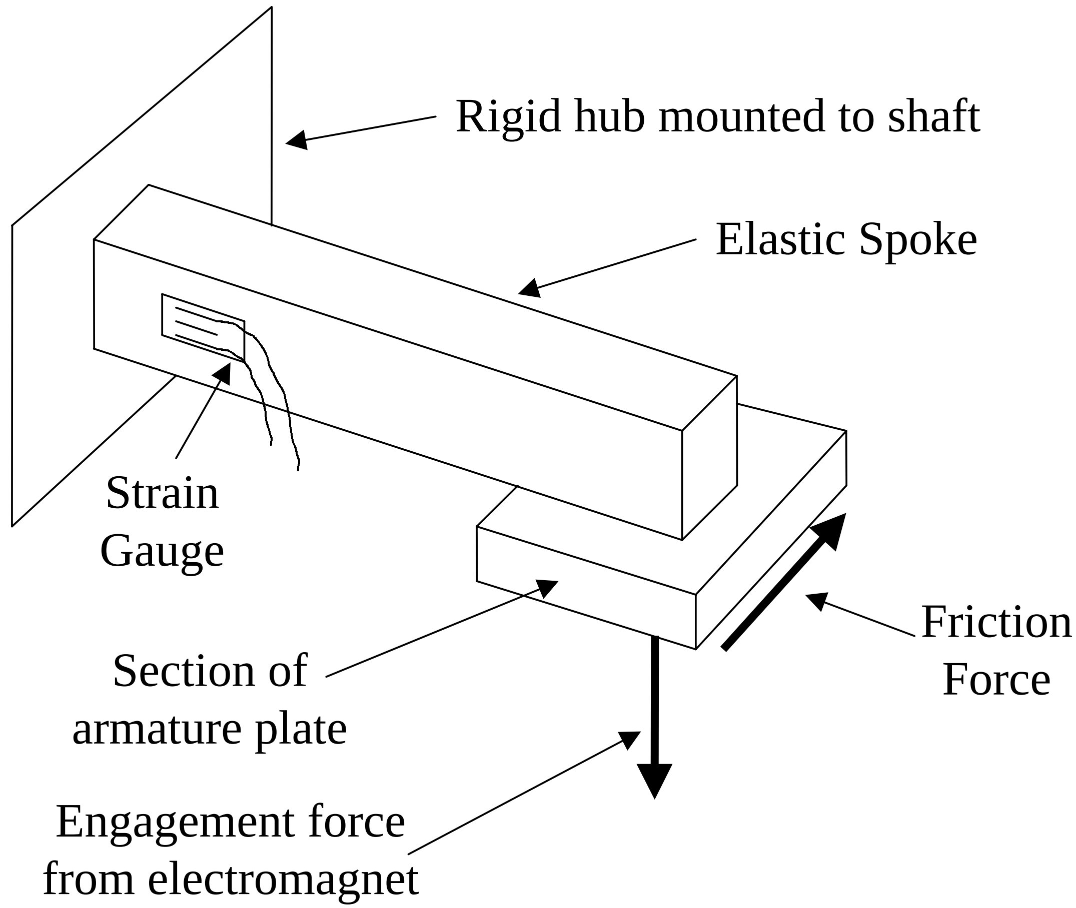
- Metal to metal contact for completing the magnetic circuit
- Friction material is only used for stabilizing torque
- Max torque
  - 5 oz-in (0.026 lbf-ft) to 465 lbf-ft
- Response consists of both mechanical and electrical (applied voltage)
- Dynamic times depend on size of the unit (Kebco)
  - Pure time delay: t_{11} = 0.004 - 0.055 sec.
  - Rise time: t_{12} = 0.006 - 0.240 sec.
  - Engagement time: t_1 = 0.01 - 0.295 sec.



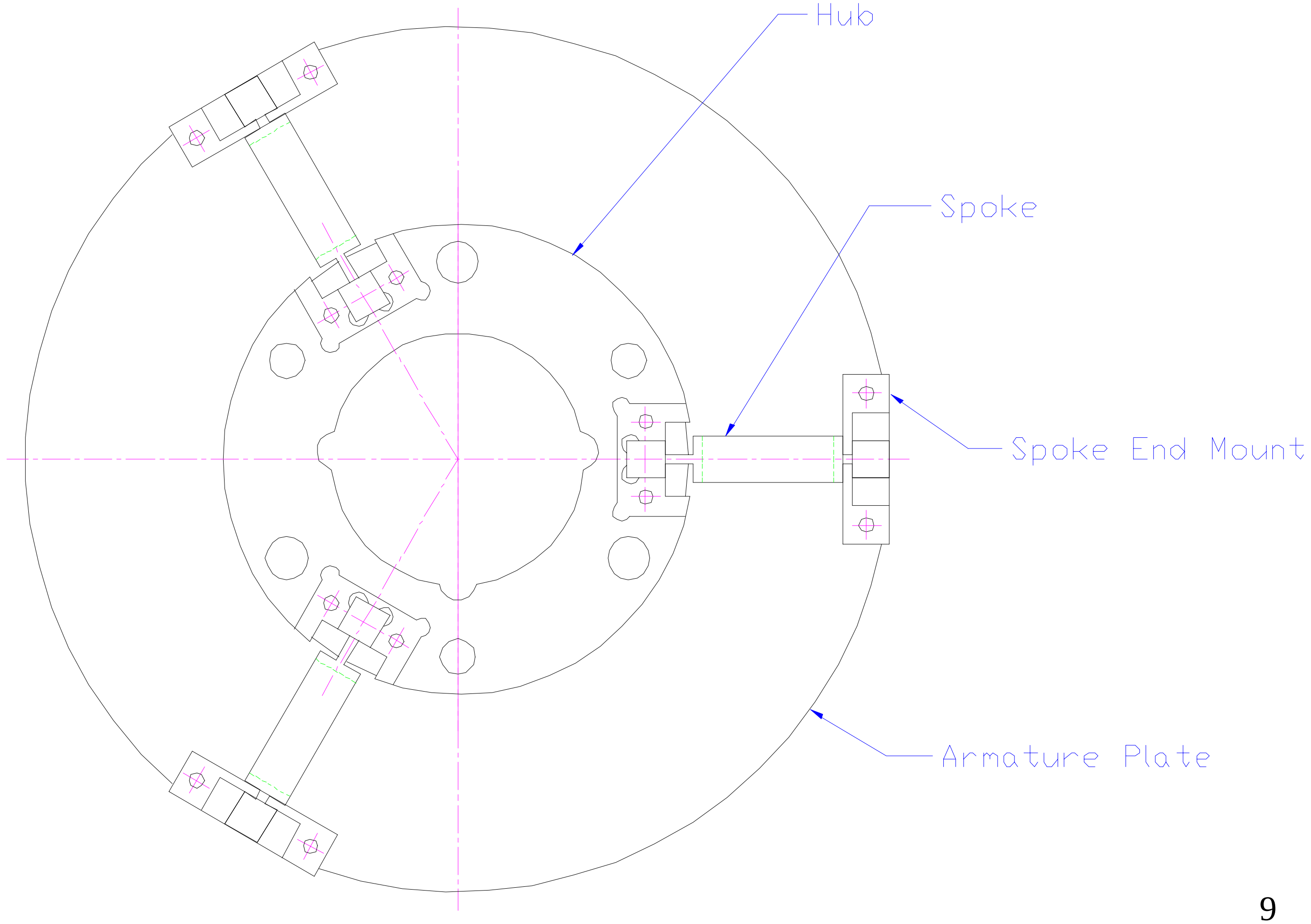


New Design Concept With Torque Sensor

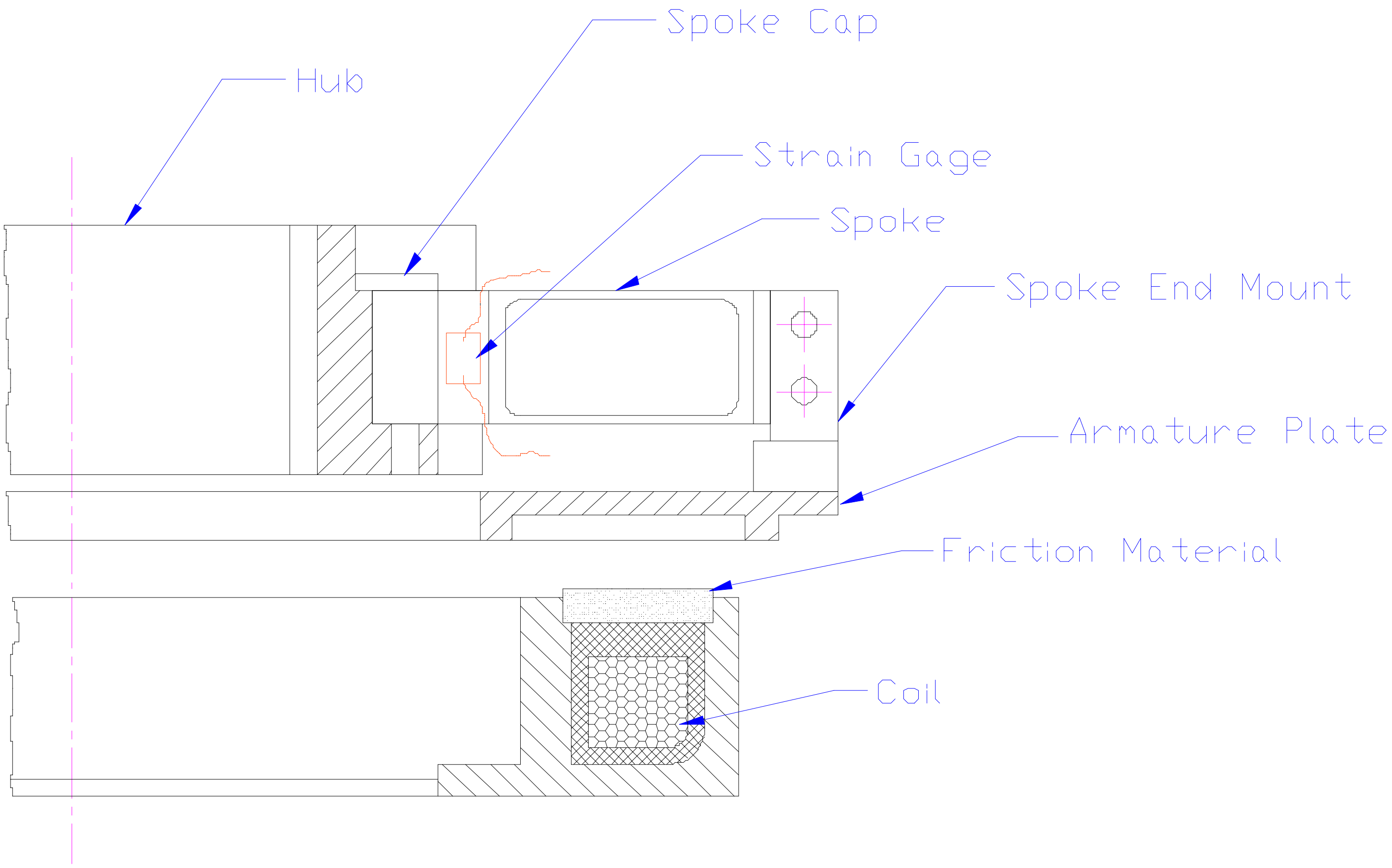
- Spoke transmits torque from friction
- Spoke locates and supports armature plate
- Spoke deflects under vertical engagement and torque transmission
- Strain gauge measurement proportional to transmitted torque



Modified Clutch Layout (Top View)

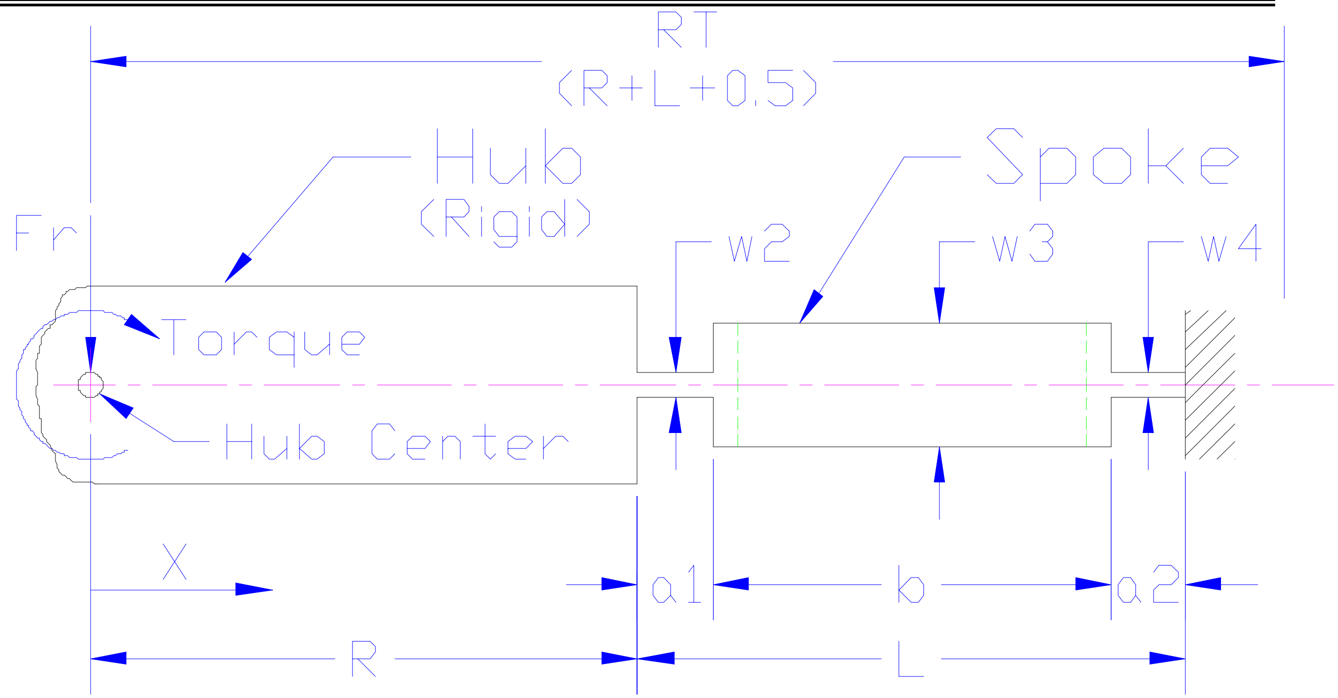


Modified Clutch (Section View)

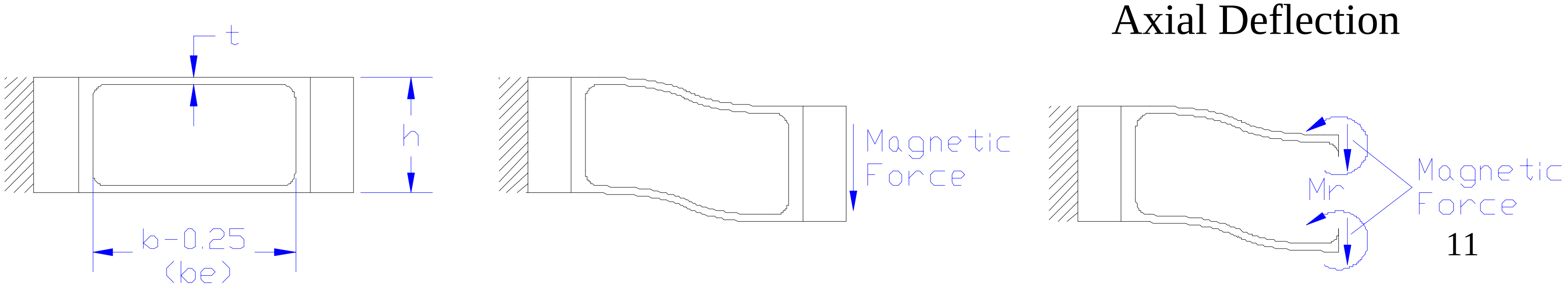


Spoke Def - Bod Model

Torque
Bending



Axial Deflection

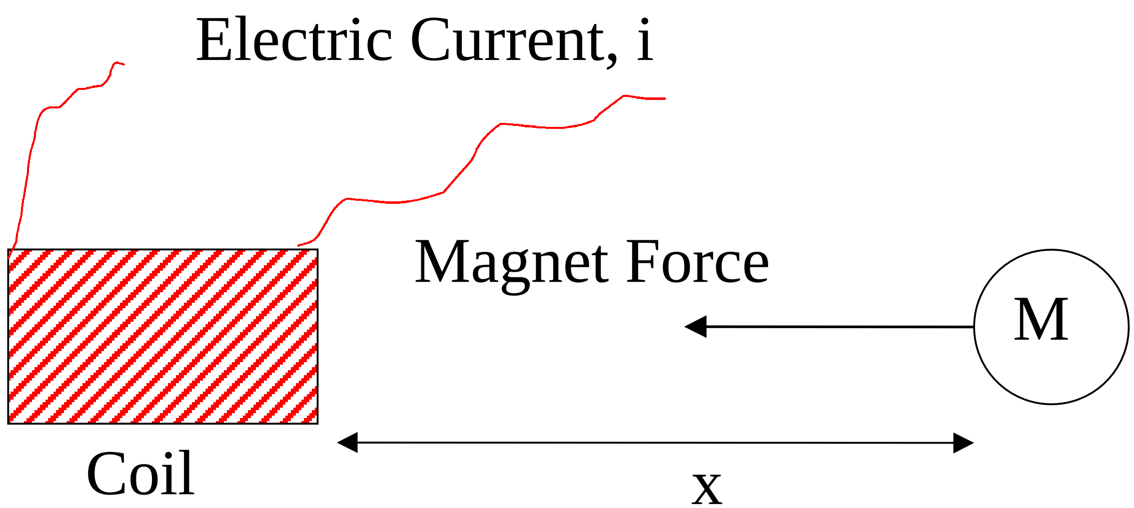


Integration Constants (Torque Bending)

$$
\begin{bmatrix}
0 & R & -1 & 0 & 0 & 0 & 0 \\
\frac{-1}{2}\cdot\frac{\left(2\cdot a1\cdot R + a1^{2}\right)}{(E2\cdot I2)} & \frac{1}{(E2\cdot I2)} & 0 & \frac{-1}{(E3\cdot I3)} & 0 & 0 & 0 \\
\frac{-1}{6}\cdot\frac{\left(3\cdot a1^{2}\cdot R + a1^{3}\right)}{(E2\cdot I2)} & \frac{a1}{(E2\cdot I2)} & \frac{1}{(E2\cdot I2)} & 0 & \frac{-1}{(E3\cdot I3)} & 0 & 0 \\
\frac{-1}{2}\cdot\frac{\left(2\cdot b\cdot R + 2\cdot b\cdot a1 + b^{2}\right)}{(E3\cdot I3)} & 0 & 0 & \frac{1}{(E3\cdot I3)} & 0 & \frac{-1}{(E4\cdot I4)} & 0 \\
\frac{-1}{6}\cdot\frac{\left(3\cdot b^{2}\cdot a1 + b^{3} + 3\cdot b^{2}\cdot R\right)}{(E3\cdot I3)} & 0 & 0 & \frac{b}{(E3\cdot I3)} & \frac{1}{(E3\cdot I3)} & 0 & \frac{-1}{(E4\cdot I4)} \\
\frac{-1}{2}\cdot\frac{\left(2\cdot a2\cdot L + 2\cdot a2\cdot R - a2^{2}\right)}{(E4\cdot I4)} & 0 & 0 & 0 & 0 & \frac{1}{(E4\cdot I4)} & 0 \\
\frac{-1}{6}\cdot\frac{\left(3\cdot a2^{2}\cdot R - 2\cdot a2^{3} + 3\cdot a2^{2}\cdot L\right)}{(E4\cdot I4)} & 0 & 0 & 0 & 0 & \frac{a2}{(E4\cdot I4)} & \frac{1}{(E4\cdot I4)}
\end{bmatrix}
\times
\begin{bmatrix} F \\ C2 \\ D2 \\ C3 \\ D3 \\ C4 \\ D4 \end{bmatrix}
=
\begin{bmatrix}
0 \\
\frac{-a1\cdot T}{E2\cdot I2} \\
\frac{-1}{2}\cdot\frac{a1^{2}\cdot T}{(E2\cdot I2)} \\
\frac{-b\cdot T}{E3\cdot I3} \\
\frac{-1}{2}\cdot\frac{b^{2}\cdot T}{(E3\cdot I3)} \\
\frac{-a2\cdot T}{E4\cdot I4} \\
\frac{-1}{2}\cdot\frac{a2^{2}\cdot T}{(E4\cdot I4)}
\end{bmatrix}
$$

Georgia Tech
Intelligent Machine Dynamics Lab

Electromagnet Model



$$Power = v * i$$

$$L = L_1 + \frac{L_0}{1 + x/a}$$

$$Energy = \frac{1}{2} L i^2$$

$$Force * \delta X = \delta Energy$$

$$Force = \frac{d(E)}{dx} = -\frac{1}{2} \frac{L_0}{a} \frac{1}{(1 + x/a)^2} i^2$$

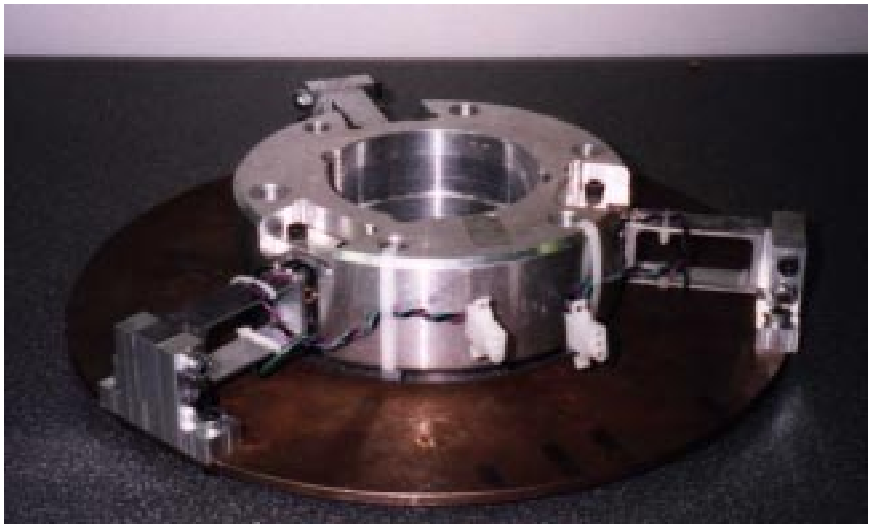
Using Principle of Virtual Work

$a \approx 0.0113$, $L_0 \approx 11.298$

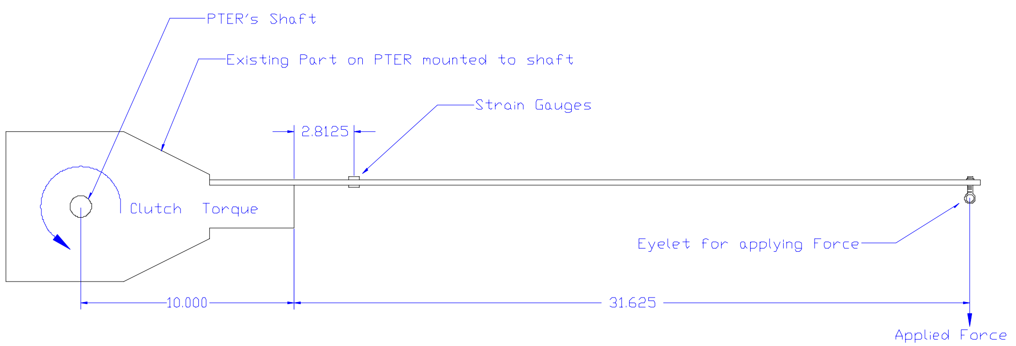
Intelligent Machine Dynamics Lab

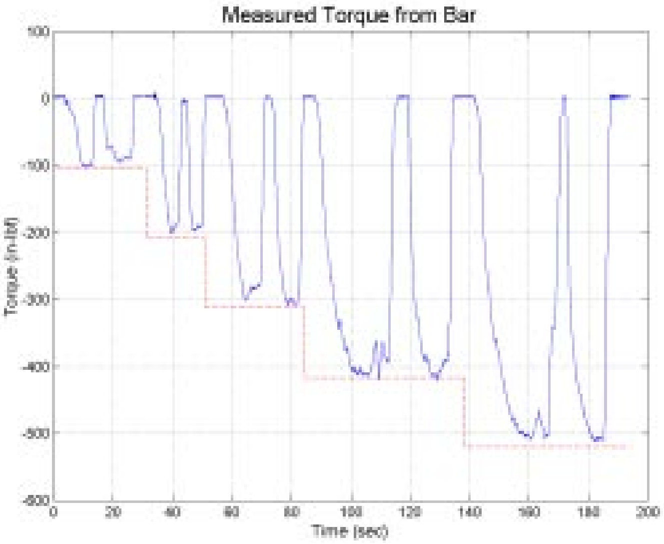
Design Considerations

- Available magnetic force
- Cyclic fatigue
- Physical size constraints
- Sensor sensitivity
- Material selection
  - Spokes
    - Delrin 100P
    - Steel ASTM-A514
    - Aluminum 7075-T651
  - Armature Plate
    - Low carbon steel (under 1010)
- Alternative friction material



Torque Bar Calibration

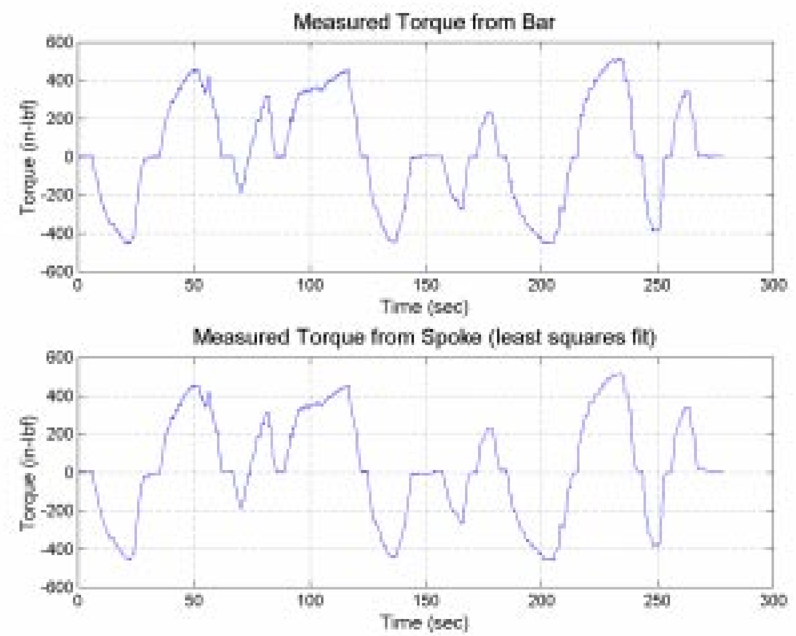




- Strain measured with strain gauges in a half bridge
- Simple beam theory used to relate applied torque
- Spring scale used to apply approximate known torque
- Measurements compared, found to be sufficiently close

Clutch's Sensor Calibration

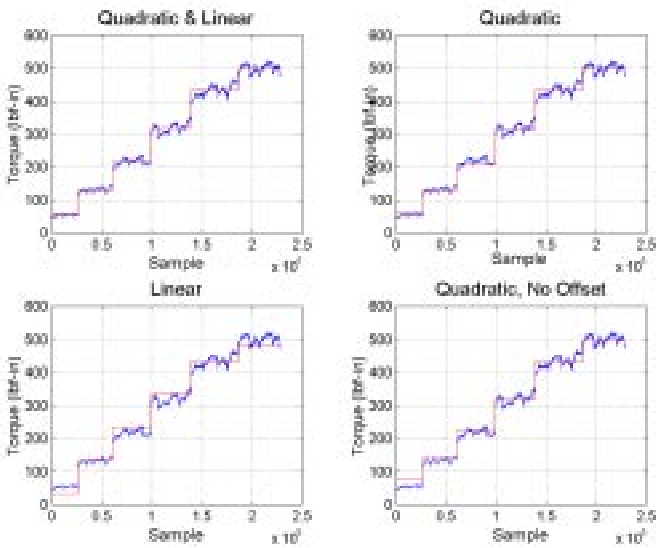
- Strain in spokes measured by strain gauges in a full bridge
- First order equation fitting strain to measured torque from torque bar
- Model predicted a scaling factor of $3.361x10^5$
  - 9.94% discrepancy from actual
- Model's predicted spring constants
  - Axial -- $1.77x10^3$ lbf/in
  - Radial -- 2,217 lbf-in/deg

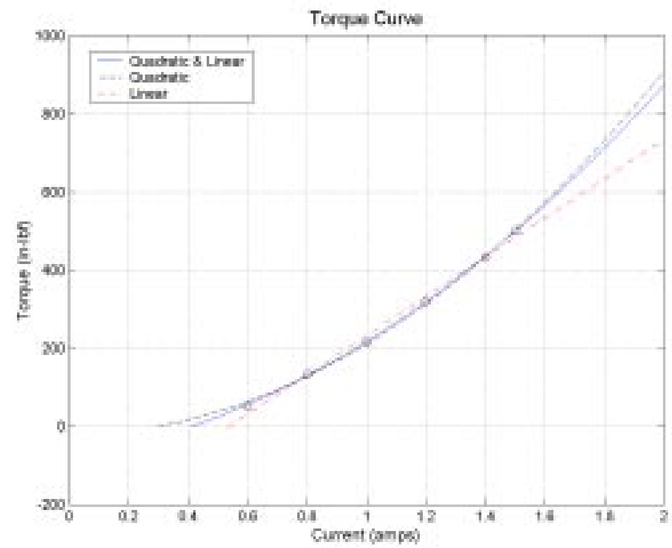


$$\tau = 3.057x10^5 \varepsilon_{spoke} + 4.818 \text{ (in-lbf)}$$

Georgia Tech
Intelligent Machine Dynamics Lab

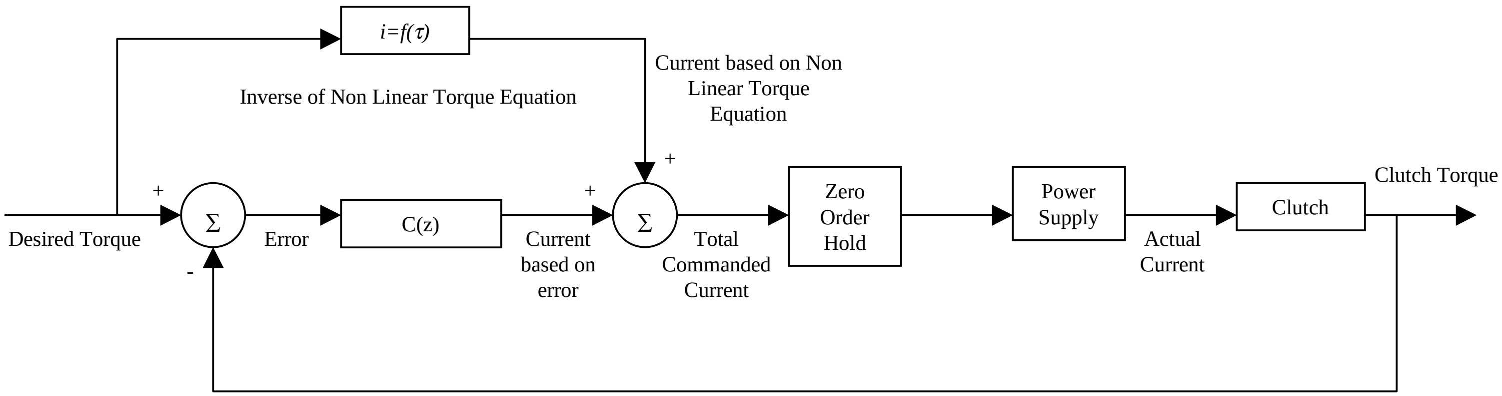
Torque vs. Current Calibration





(Quadratic & Linear)	$\tau = 181i^2 + 111i - 76$	MSE = 148 (4.1)
(Quadratic)	$\tau = 232i^2 - 20$	MSE = 164 (23.4)
(Linear)	$\tau = 502i - 269$	MSE = 340 (207.6)
(Quadratic, No Offset)	$\tau = 221i^2$	MSE = 238 (126.5)

Digital Control

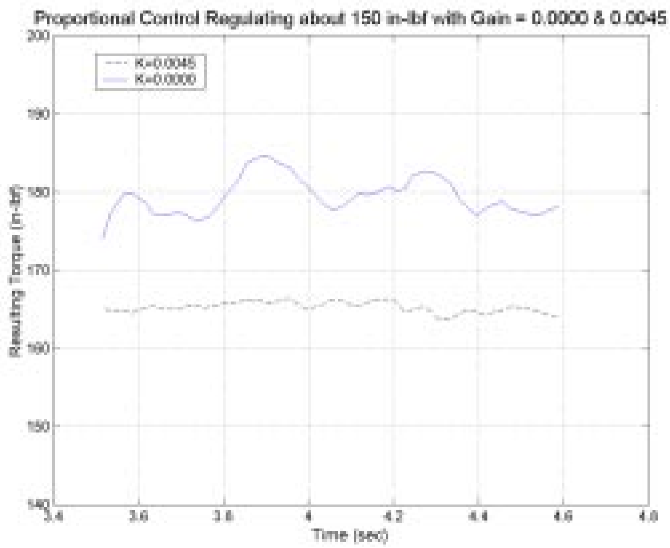


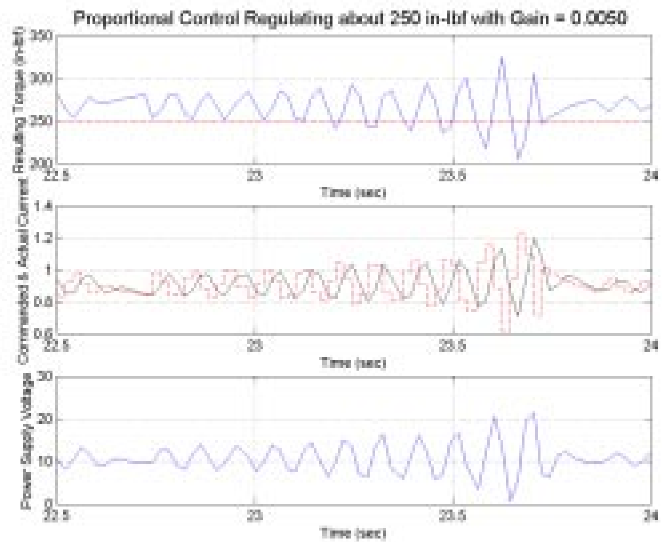
$$\tau = ai^2 + bi + c \Rightarrow k_{clutch} = \frac{d\tau}{di} = 2ai + b \qquad \tau = \tau_{eq} + \frac{k_p k_{clutch}}{1 + k_p k_{clutch}}(\tau_d - \tau_{eq}) + \frac{1}{1 + k_p k_{clutch}}\tau_{dist}$$

- Nonlinear feed-forward based on quadratic torque mapping
- Absolute value of torque fed back (direction insensitive)
- Proportional control based on error
- Larger gain equates to larger disturbance and error rejection

Georgia Tech
Intelligent Machine Dynamics Lab

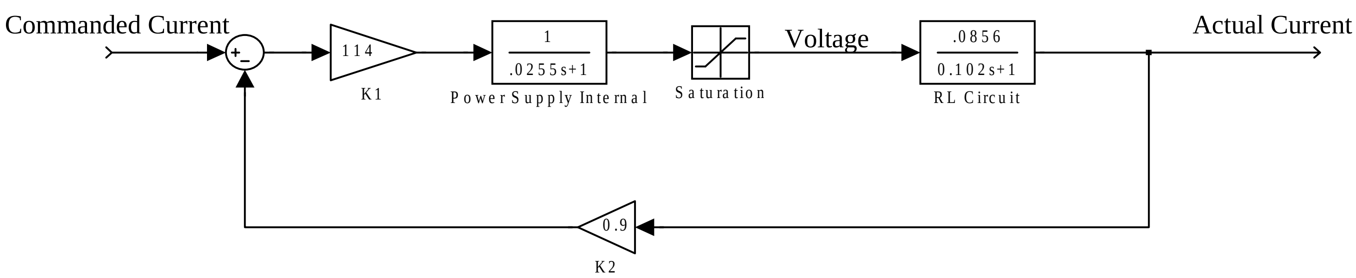
Experimental Results





- Labview processing controller at a non-deterministic 50 Hz ($t_s \approx 0.02$ sec)
- Small gains stabilized torque
- Large gains caused system to go unstable

Power Supply Model



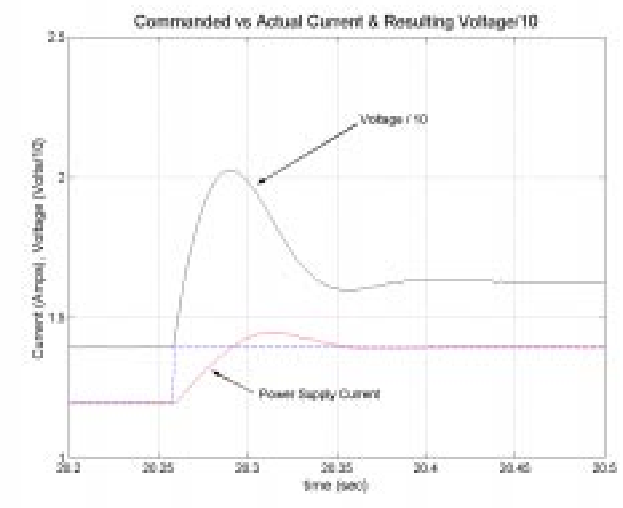
- Second order response
  - $t_r \approx 0.056$ sec
  - %OS ≈ 25%
  - $\omega_n = 61.25$ rad/sec
  - $\xi = 0.40$

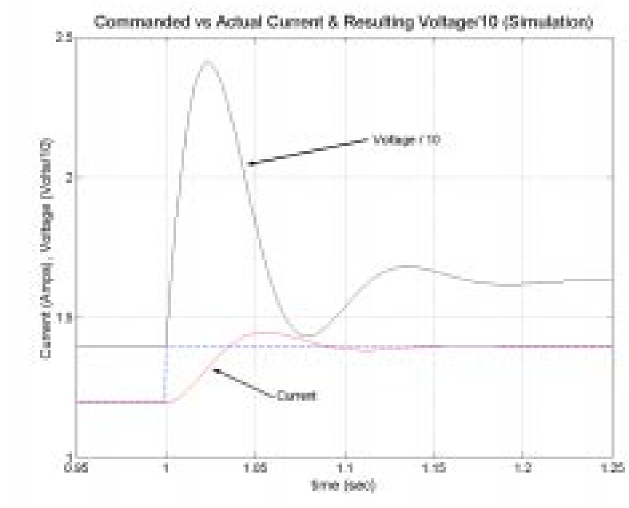
$$PS(s) = \frac{I(s)}{I_c(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{3751}{s^2 + 49s + 3751}$$

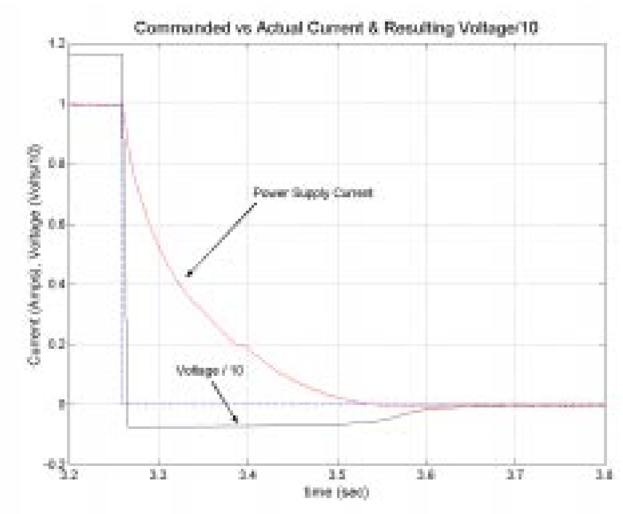
- Voltage applied to a first order system (RL Circuit)
  - $R \approx 11.68\Omega$
  - $L \approx 1.19$H
- Voltage saturation: 0 - 36 volts

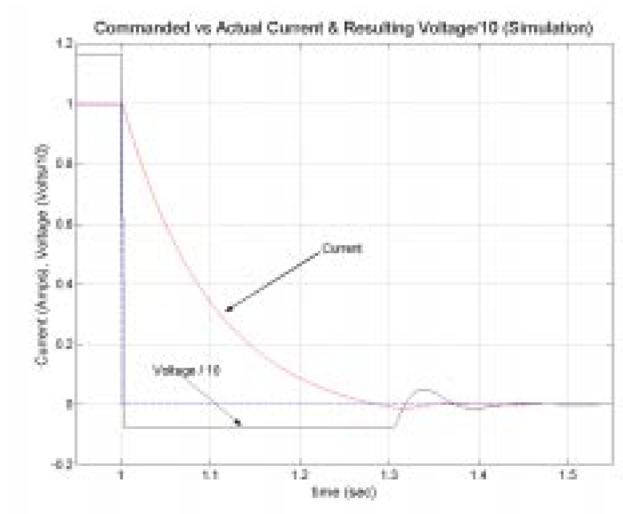
Intelligent Machine Dynamics Lab

Power Supply Data vs. Simulation









Intelligent Machine Dynamics Lab

Digital Stability -- Gain Margin

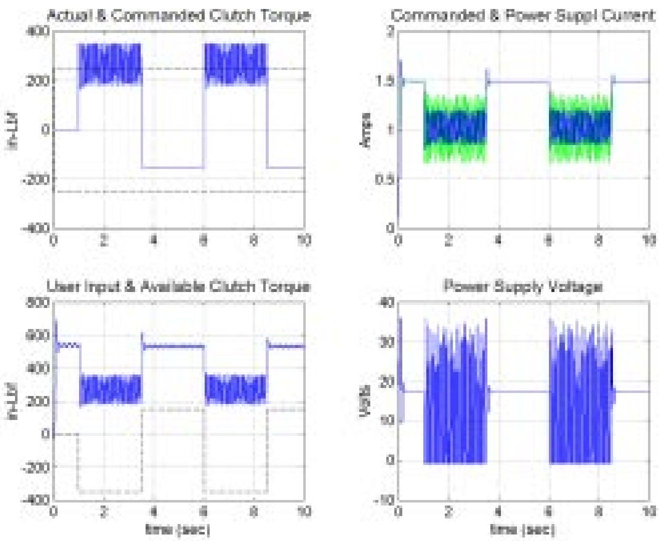
- $i \approx 0.9$ amps for unstable experiment
  - k_{clutch} = 435 in-lbf / amp

- ts = 0.02 (50 Hz) $\Longrightarrow$ $$Ps(z) = \frac{0.4936z + 0.3508}{z^2 - 0.5309z + 0.3753}$$
  - Gain margin = 5.011 db
  - Max system gain: $k_p k_{clutch} = 1.78$
  - Max controller gain: $k_p = 0.0041$ amps / in-lbf
  - Error & disturbance rejection to 36%

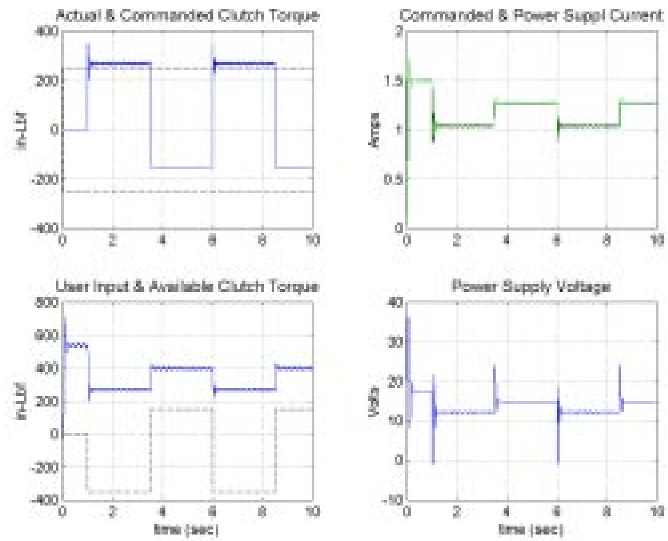
- ts = 0.002 (500Hz) $\Longrightarrow$ $$Ps(z) = \frac{0.007254z + 0.007021}{z^2 - 1.892z + 0.9066}$$
  - Gain margin = 22.475 db
  - Max system gain: $k_p k_{clutch} = 13.30$
  - Max controller gain: $k_p = 0.0306$ amps / in-lbf
  - Error & disturbance rejection to 7%

Georgia Tech
Intelligent Machine Dynamics Lab

Simulations for Regulating @ 250 in-lbf



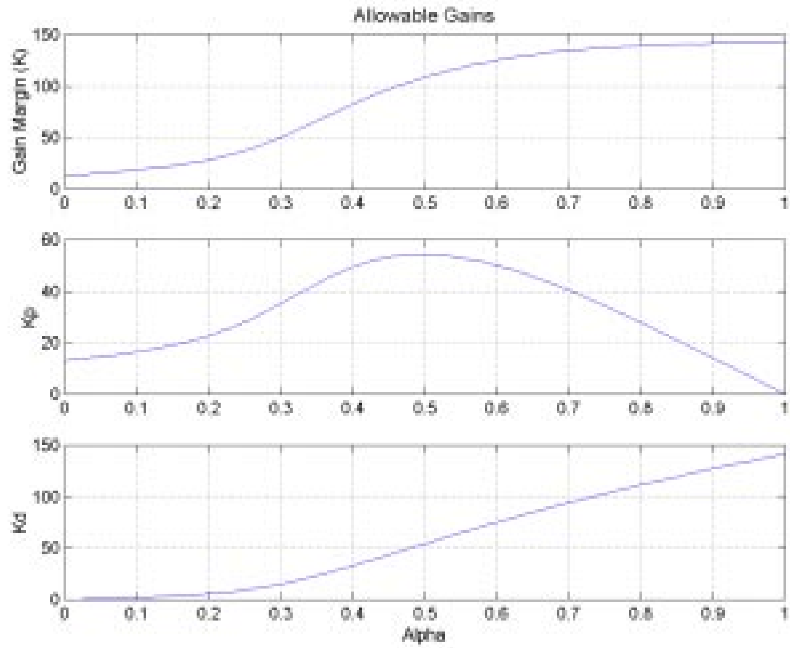
(t_s = 0.02 (50 Hz), k_p = 0.0041)



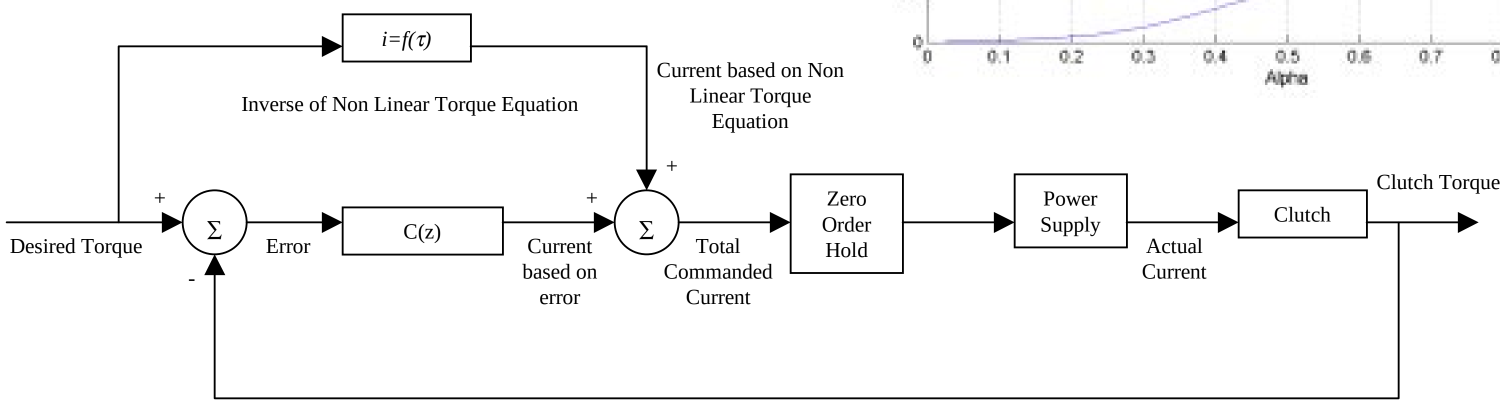
(t_s = 0.002 (500 Hz), k_p = 0.02)

- Increased sampling rate allows increased proportional gain and increased error rejection
- Strong evidence that instability is caused by relatively slow controller and quick second order underdamped power supply dynamics

Digital PD Control



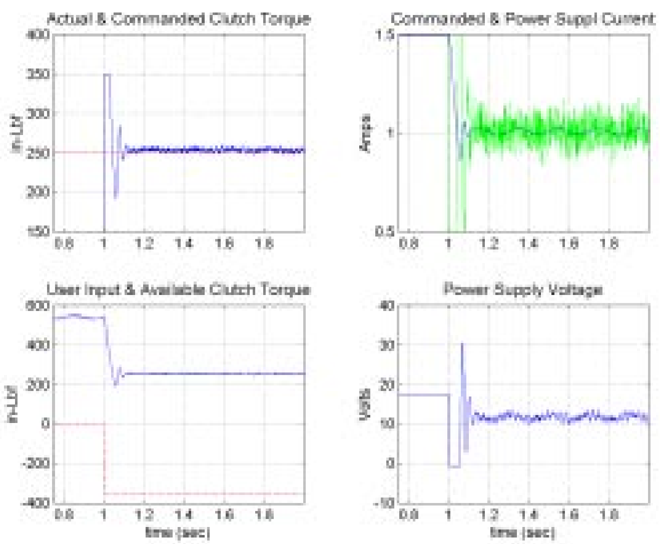
$$C(z) = k_p + k_d \frac{z-1}{z} = (k_p + k_d)\frac{z-\alpha}{z} = K\frac{z-\alpha}{z}$$



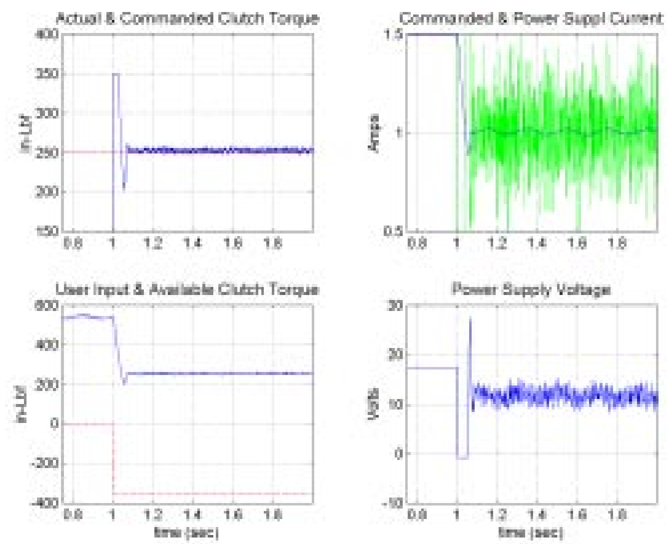
Intelligent Machine Dynamics Lab

Digital PD Regulating @ 250 in-lbf

α	K	k_p	k_d	Adjusted k_p	Adjusted k_d
0.5	16.25	8.125	8.125	0.0163	0.0163
0.7	38.75	12	28	0.024	0.056



(α = 0.5)

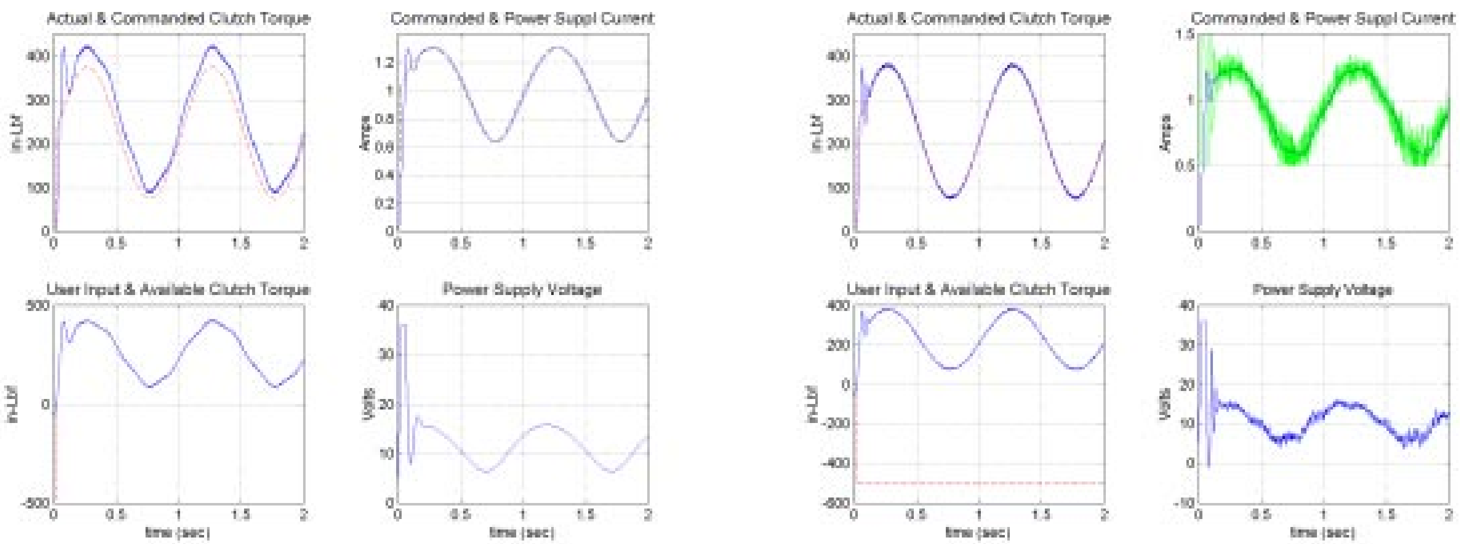


(α = 0.7)

(Simulations)

Georgia Tech
Intelligent Machine Dynamics Lab

Reference Tracking (Digital PD)



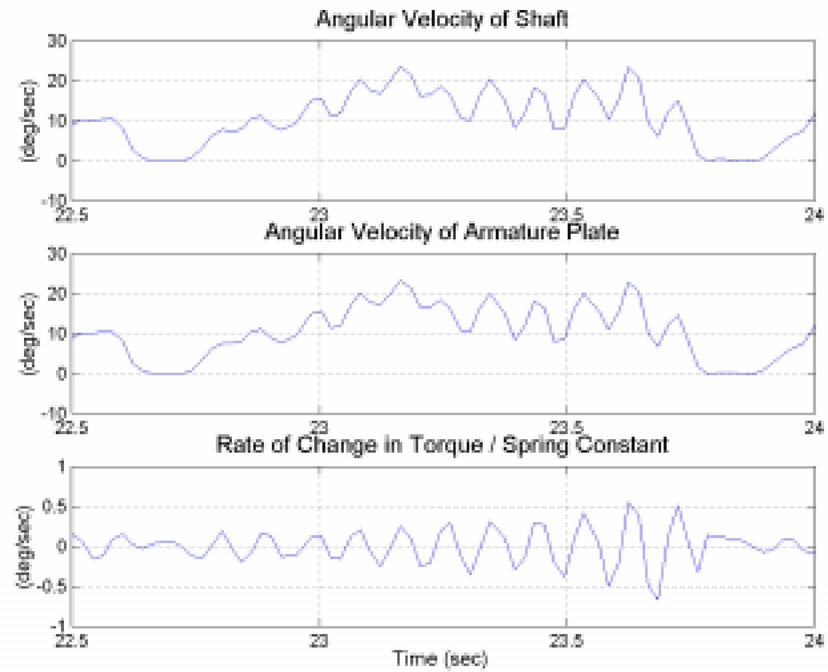
- $\alpha = 0.5$
  - $k_p k_{clutch} = 8.125$
  - $k_d k_{clutch} = 8.125$
- Online gain normalization based on estimated clutch gain from feed-forward actuation.

(Simulations)

Georgia Tech
Intelligent Machine Dynamics Lab

Stick / Slip of the Armature Plate

- Determine if the armature plate comes to rest, sticking then slipping, causing the instability or limit cycle
- Compare angular velocity of the Shaft hub with the angular velocity of the armature plate
- Numerically differentiate and filter data
- Armature plate appears to not come to rest while hub is moving



$$\tau = k(\theta_1 - \theta_2) \Rightarrow \dot{\tau} = k(\dot{\theta}_1 - \dot{\theta}_2)$$

(Data from unstable experiment displayed in slide 19)

Georgia Tech
Intelligent Machine Dynamics Lab

Closing Remarks -- Conclusion

- Industrial available clutches / brakes were not found appropriate for our application.
- Redesigned electromagnetic clutch incorporating a torque sensor for feedback control was developed and one prototype was built.
- More thorough modeling & testing of the new clutch and power supply combination.
- Feasibility and benefits of closed loop control were demonstrated.
- Power Supply dynamics became a dominant factor.
- Faster digital sampling required for effective disturbance rejection

Closing Remarks -- Future Work -- I

- Faster Digital Controller
  - dSPACE & Real Time workshop
  - Hyperkernal
- Online Parameter Identification
- Analog Control
- Alternative Friction Materials
  - Delrin: $\mu_s = 0.20$, $\mu_d = 0.35$
- Power Supply Upgrade
  - Bipolar
  - Larger current and voltage ratings
- Design Modifications

Closing Remarks -- Future Work -- II

- Manufacture three more units
- Upgrade other components of PTER
  - Replace position potentiometers (Encoders, Resolvers)
  - Tachometers
  - Remount strain gauges in force sensors
  - Computer and Software
- Programming of old and new haptic algortihms
- Bilateral control of Hurbirt
- Possible improvements to the design of PTER

Questions

- What do you mean?
- How can you justify that?
- I don’t agree!
- Why didn’t you……..?
- Did you try………….?
- Etc?

Digital Control of a fast Power Supply

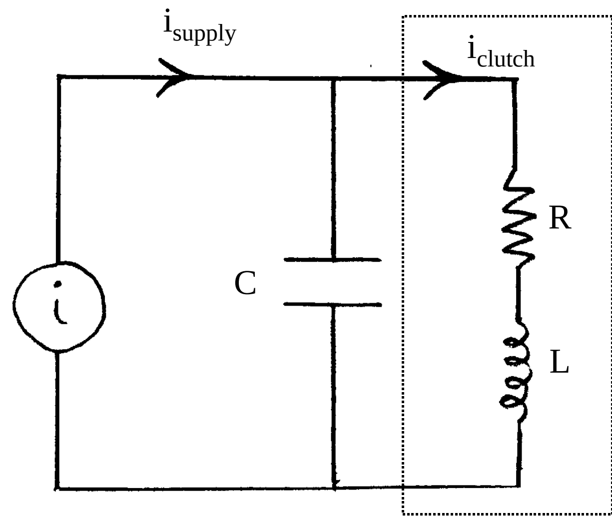
$$PS(z) = Z[Zoh * PS(s)] = Z\left[\frac{1-e^{-Ts}}{s} * \frac{1}{s/a + 1}\right] = (1-z^{-1}) * Z\left[\frac{1}{s(s/a + 1)}\right] = \frac{1-e^{-aT}}{z-e^{-aT}}$$

$$\lim_{a\to\infty}\left[\frac{1-e^{-aT}}{z-e^{-aT}}\right] = \frac{1}{z} = z^{-1}$$ $\Longrightarrow$ Max open loop gain is 1

- With an open loop gain of "1", disturbance rejection is limited to only 50%
- Systems dynamics become much quicker then the digital controller

Tuning of the RL circuit

- Pro
  - Addition of resistors and capacitors can tune the circuit for desirable second order dynamics
- Con
  - Limited by achievable output
- Increasing "R" increases damping and required voltage
- Large "L" causes low damping and low natural frequency
- Small "C" increases natural frequency.



Electronic Magnet

$$\frac{I_{clutch}(s)}{I_{supply}(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{1/CL}{s^2 + \frac{R}{L}s + \frac{1}{CL}}$$

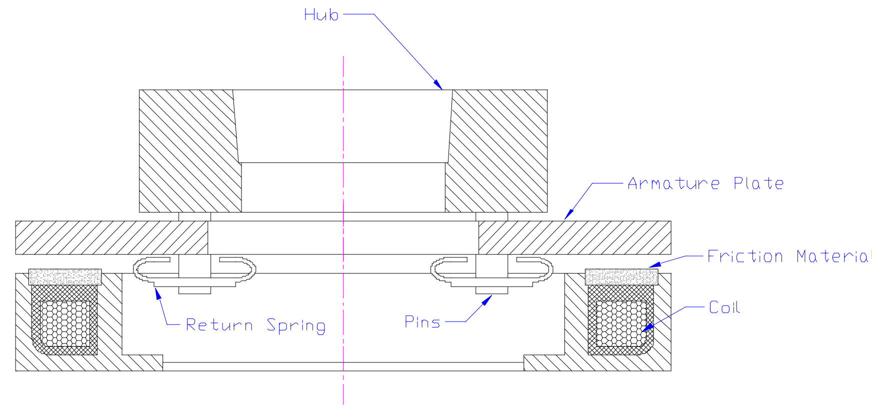
Stick / Slip Dynamic Model

$$\begin{bmatrix} I_{shaft+Hub} & 0 \\ 0 & I_{Armature} \end{bmatrix}\begin{bmatrix} \ddot{\theta}_{shaft+Hub} \\ \ddot{\theta}_{Armature} \end{bmatrix} + \begin{bmatrix} B_1 + B_2 & -B_2 \\ -B_2 & B_2 \end{bmatrix}\begin{bmatrix} \dot{\theta}_{shaft+Hub} \\ \dot{\theta}_{Armature} \end{bmatrix} + \begin{bmatrix} k & -k \\ -k & k \end{bmatrix}\begin{bmatrix} \theta_{shaft+Hub} \\ \theta_{Armature} \end{bmatrix} = \begin{bmatrix} \tau_{in} \\ \tau_{friction} \end{bmatrix}$$

- Account for braking force through the armature plate, compliant spoke, and to the hub.
- Karnopp model utilized for friction force.
- Damping added to account for viscous friction in the bearings & material damping in the spoke
- Stiff spoke and small armature plate results in a stiff system that Simulink can not successfully integrate.
- Fixed step simulations gave erroneous information

Intelligent Machine Dynamics Lab

PTER's original clutch/brake.



Section view of clutch/brake.

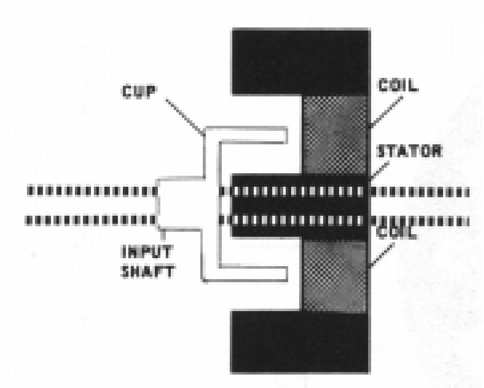
Industrial electromagnetic friction clutch / brakes (Dynacorp Model 310).

- Time constant for coil build up: τ = 0.105sec (given applied voltage)
- Original max rated torque = 300 Ft-Lbf (407 N-M)
- Max voltage: V = 24 volts
- Max current: I = 2.376 amps
- Non asbestos friction material with coefficient of friction: μ = 0.45
- Modified to eliminate metal to metal contact (reduce max torque capabilities)

Hysteresis & Eddy Current

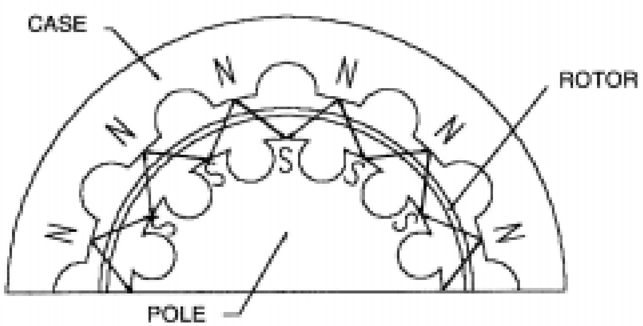
Hysteresis

- Max torque ratings
  - 2.5 oz-in (0.013 lbf-ft) -- 3200 oz-in (16.67 lbf-ft)
- No rubbing parts
- Hysteresis in the torque vs current mapping
- Cogging



Eddy Current

- Torque dependent on both slip velocity and applied current
- Large scale applications



STATOR TOOTH STRUCTURE

Magnetic Particle

- Max torque
  - 5 oz-in (0.026 lbf-ft) to 738 lbf-ft
- Torque generated by shear and tensile stress between attracted magnetic particles
- Dynamic time constants ranging from 0.009 to 1.31 sec., depending on the size of the unit.
- Clean sealed operation
- Required to turn a full revolution to redistribute magnetic particles (for consistent operation)