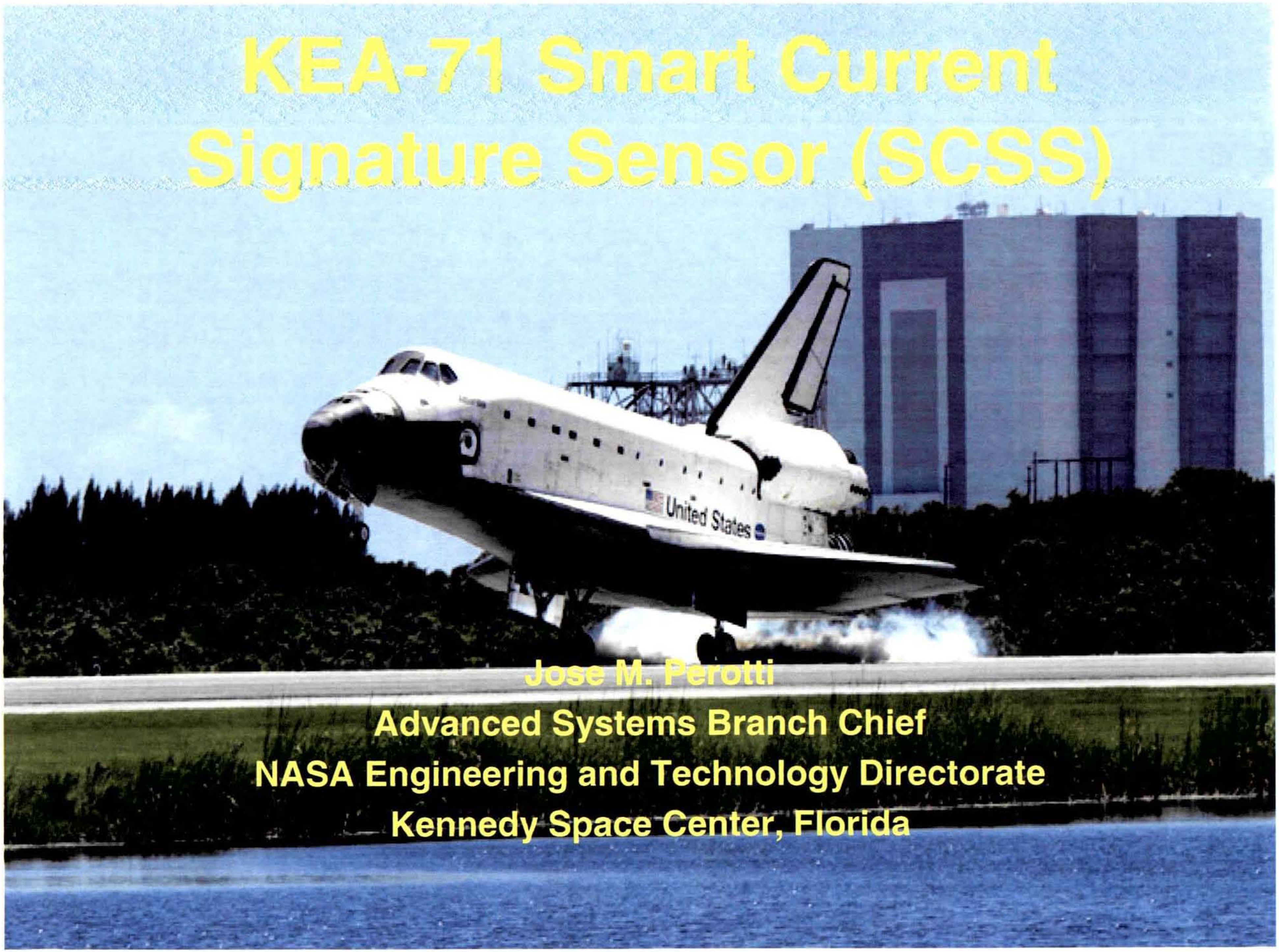
KEA-71 Smart Current Signature Sensor (SCSS)



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SCSS Presentation Outline

- What and Why
- For Whom
- Design Approach
- Algorithm Development
- Solenoid Valve Modeling
- Implementation
- Testing
- Present status
- Future Steps & Intelligent Devices
- Summary and Conclusion
- Innovators, Contributors and Acknowledgements

Also Known as VALVE HEALTH MONITOR

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What and Why?

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What is SCSS?

"The SCSS is a non-invasive sensor that contains embedded knowledge (smarts) about the valve being monitored, and is capable of detecting and ultimately predicting potential faults before they happen (failure trending and prediction). This sensor was one of the first generations of Intelligent Devices (sensors and actuators) developed at KSC..."

- This work is also known by the name of Valve Health Monitor (VHM) System
- SCSS provides a way to not only monitor real-time the valve's operation in a non invasive manner, but also to monitor its health (Fault Detection and Isolation) and identify potential faults and/or degradation in the near future (Prediction/Prognosis)
- This technology approach is not only applicable for solenoid valves, and it could be extrapolated to other electrical components with repeatable electrical current signatures such as motors

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Why SCSS?

- To detect valve faults in the system (Fault Detection)
  - Relatively easy to identify, normally done using internal valve's measurements or associated system's measurements (flow, temperature, pressure, etc.)
  - Problem is identified ***after*** the fault occurs
  - Could generate high cost to program – i.e. launch scrub
  - ***SCSS provides real-time monitoring and fault detection to the valve, it does not rely on looking at associated measurements***

- To diagnose the problem in the valve (Fault Isolation)
  - Performed offline of the system [at vendor/logistics facility]
  - Performed after valve is remove/replaced. Process might be lengthy in time.
  - ***SCSS provides identification of fault mode and identify most probable faulty components using current signature of the valve***

- To predict valve's faults (Prognostics)
  - Data is collected during system checking/validation (when performed, not always)
  - Requires added temporary instrumentation to acquire the signature of the valve
  - Assessment of data is performed post test by engineer/operator
  - ***SCSS performs signature analysis in real-time and performs degradation assessment and impending failure identification that allows for valve replacement before failure occurs***

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Project Goals

Main Requirement

- Detect/Predict problems/faults in solenoid valves

Secondary Requirements (no less important…)

- Reduce system's processing/operational costs
- Increase system's Availability (higher reliability and lower maintainability costs)
- Provide continuous system's health status, detecting and ultimately predicting system's faults before they happen
- No increase in system's probability of failure - Operate independently and autonomously from monitored system
- Minimize human intervention, support autonomous operations concept

Project Objectives

Develop a sensor with following characteristics:

- Non-invasive (do not add to system probability of failure)
- Embed smart algorithms for monitoring and health management in design
- Provide real-time independent and autonomous monitoring and health checks

To determine valve's health and readiness support the mission,
isolate faults to a specific component(s) in the valve, and
predict impending faults in the future

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For Whom?

For Whom: NASA

NASA Integrated Vehicle Health Management (IVHM) HEDS

- SCSS was developed to support IVHM HTD-2 flight experiment
- SCSS was to monitor Orbiter FCV valves for operation/problems/faults
- Since it was attached to a critical system in the Orbiter, it was decided to postpone its implementation until more experienced was gained

Non Destructive Engineering (NDE) program at Langley Research Center

- Program funded KSC to develop a sensor with following characteristics:
- Non-invasive (does not add to system probability of failure)
- Intelligent (embed health assessment tools in design)
- Perform non-destructive assessments

NNWG NA
NASA NDE Working Group

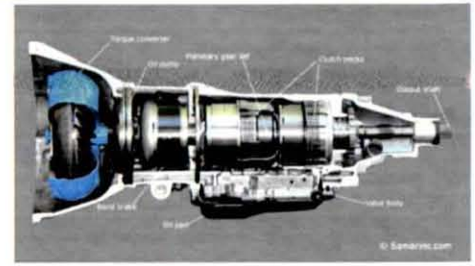
NASA KSC Shuttle Ground Support Equipment (GSE) transducers line

- Subsequently from IVHM, this technology was migrated to Ground Operations at KSC to detect faults/problems in the fuel/oxidizer storage and distribution system
- Murata solenoid valves were selected since they are commonly used across KSC
- Unfortunately, the Launch Processing System (LPS) was not capable to receive the type and amount of digital information provided by the SCSS
- Integration was not possible with present LPS architecture

HEDS: Human Exploration and Development of Space
HTD: HEDS Technology Demonstration
FCV: Flow Control Valve

For Whom: Industry

Schaffer LLC



- Automotive Industry Small Business company
- Dedicate to diagnose and repair automatic transmissions
- Presently, no way to isolate which failed solenoid valve is the source of problems
- Average of $800 in solenoid valves in a transmission
- SCSS provided such capability
- Partial licensing of technology was granted to the company

Graftel INC

- Nuclear Industry Small Business company
- Dedicate to monitor, diagnose and repair valves in nuclear reactors applications
- Important to assess the health and predict potential failures before they happen
- Developing a portable system to perform its assessment function
- Licensing of technology was granted to the company

GRAFTEL INC.

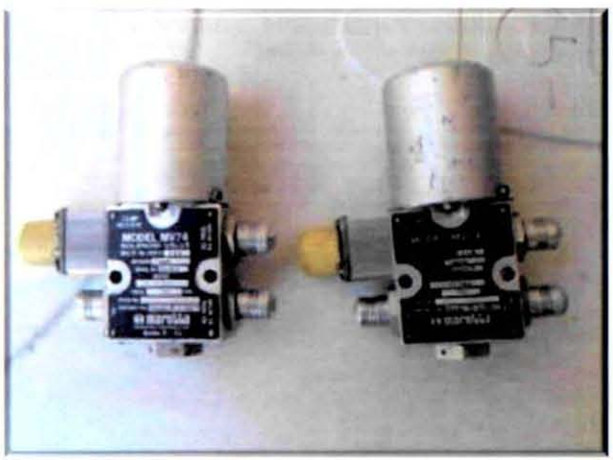
http://www.graftel.com/index.html

Design Approach

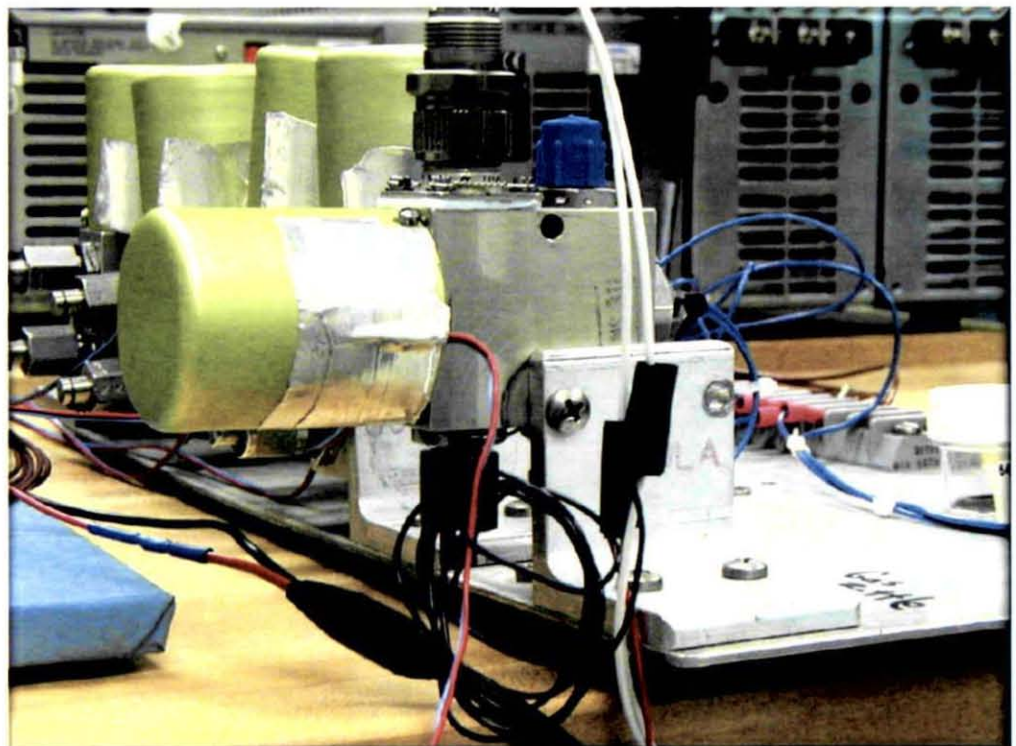
Design Approach

Targeted Valve for Ground Operations

- Selected valve for this project was MV74, manufactured by MAROTTA®
- Currently it is widely used at both Launch Pads at KSC
- Valve's solenoid operates at 24 VDC and consumes 1 Ampere approximately
- Turn-on time for valve is typically 30 milliseconds (20-40 milliseconds range)
- Turn-off time for valve is typically 5 milliseconds (2-10 milliseconds range)



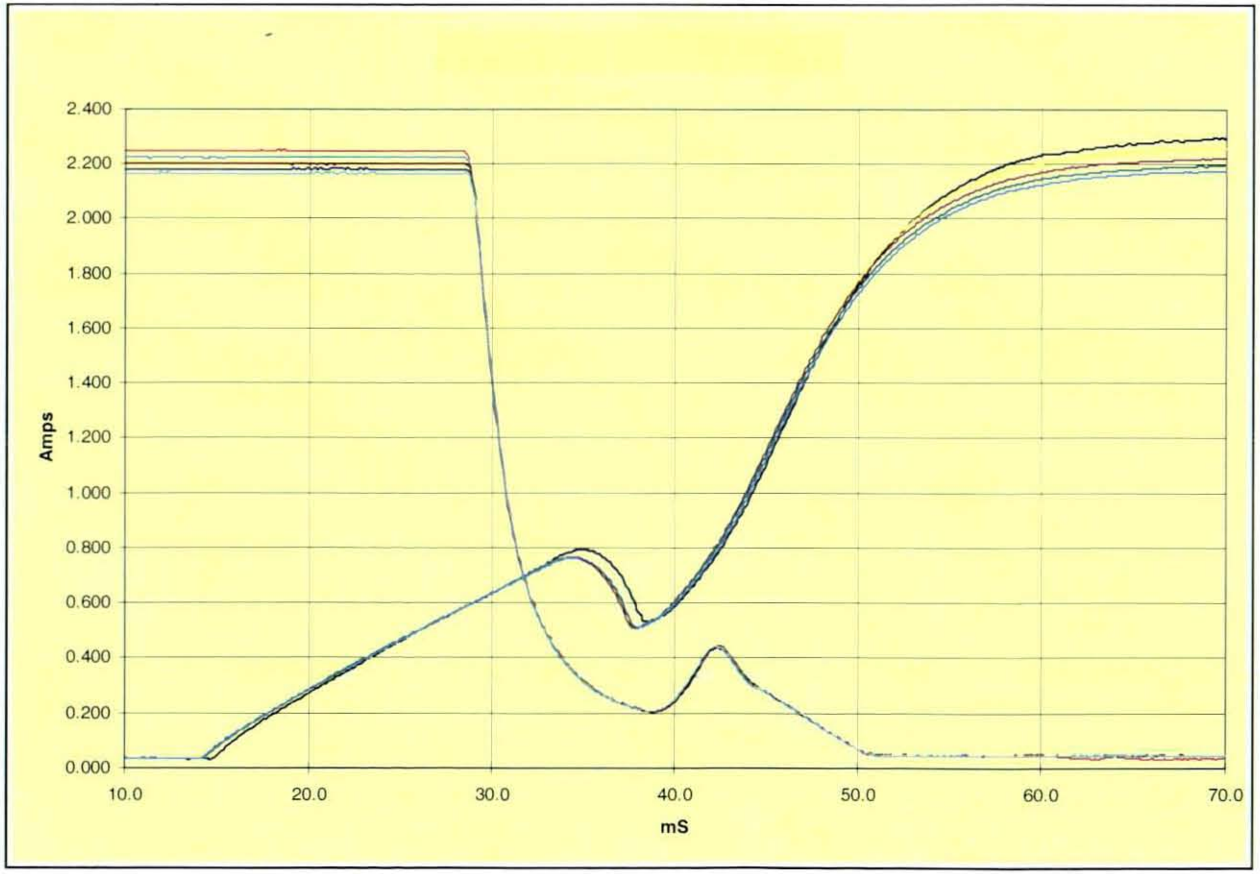
MV74 MAROTTA® Valve



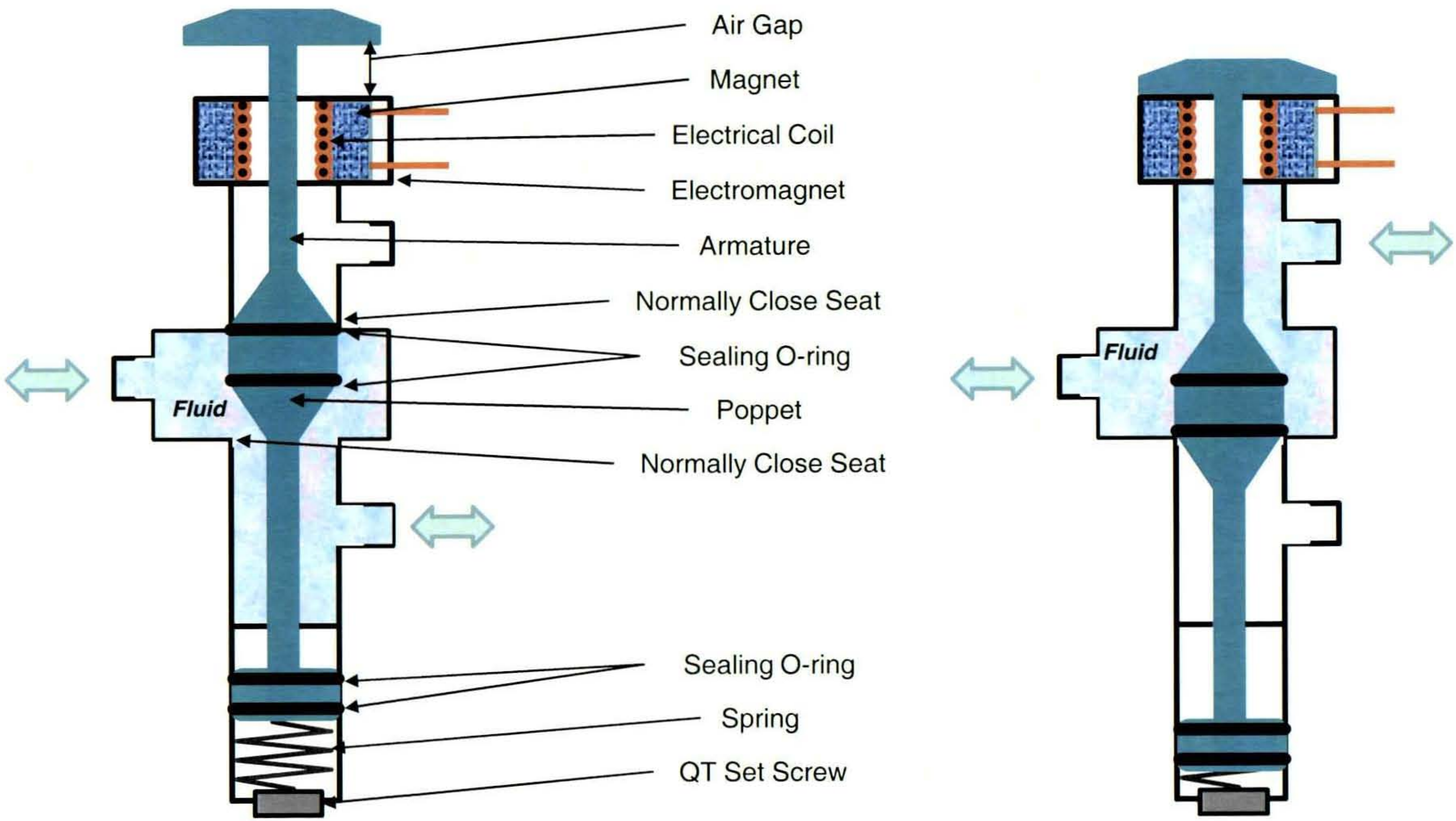
Design Approach

Why Current Signature?

- The electrical current signature is very repeatable
  - From cycle to cycle of the same solenoid valve
  - Within a family of solenoid valves



Design Approach - Components



Valve in **De-*energized*** mode

Valve in ***Energized*** mode

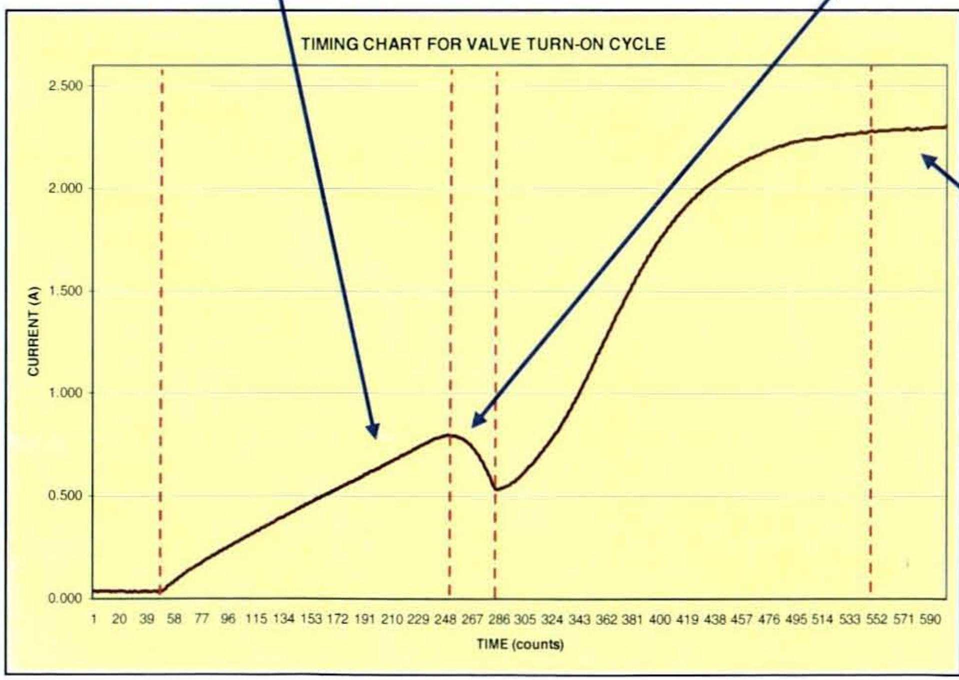
Design Approach

Why Current Signature?

- The electrical current signature of the valve directly represents:
  - The behavior of the valve's mechanical components (spring, poppet, etc)
  - The behavior of the valve's electrical components (electrical coil, etc)
  - It reflects any degradation or anomalous behavior of the valve

Magnetic Field Build-up Phase
information related to internal parameters (coil resistance, inductance) and external parameters (supply voltage, temperature effects, etc.)

Poppet Movement Phase
information related to mechanical movement (poppet travel, spring tension, friction, maximum travel, pre-set force) and proper seating and sealing (debris in seals, gas path, etc.)



Steady State Phase
information derived at this stage is related to internal electrical parameters like coil degradation, magnetic field degradation, etc.

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Design Approach

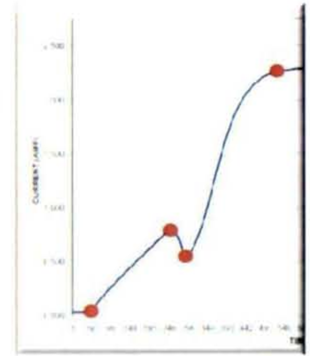
Where to look for valve health information in signature?

- Solenoid Valve in "*De-Energized Steady State*" mode
  - Valve is de-energized, no electrical current flow, *low interest* from health information aspect
  - Signature is affected by: system's electrical noise
- Solenoid Valve in "*Turn-On transition*" mode
  - Valve is energizing, short duration signal (≤ 40 milliseconds), fast rising electrical current flow, *very rich* in health information
  - Signature affected by: valve's electrical components, valve's mechanical components, external variables (supply voltage, temperature effects, etc.)
- Solenoid Valve in "*Energized Steady State*" mode
  - Valve is energized, steady-state electrical current flow, slow signal changes, *some interest* from health information aspect
  - Signature affected by: variables like coil degradation, magnetic field degradation, and external variables such as supply voltage, temperature effects, etc
- Solenoid Valve in "*Turn-Off transition*" mode
  - Valve is de-energizing, very short duration signal (≤ 10 milliseconds), fast decreasing electrical current flow, *very rich* in health information
  - Signature affected by: valve's electrical components, valve's mechanical components, external variables (supply voltage, temperature effects, etc.)

Algorithm Development

Algorithm Development

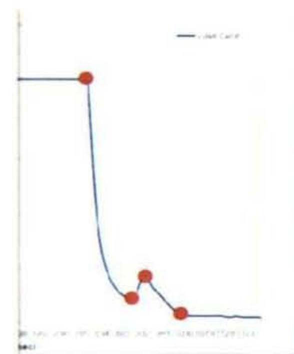
Algorithm – Information extraction



- Global and Local minima, maxima, and inflection points (and their location/duration with respect to time) of the Electrical Current Signature are linked to important health information of the monitored solenoid valve

- The above parameters directly correlate to specific functions, regions and/or components of the valve actuation and they usually signal the transition from a predominantly electrical behavior to a predominant mechanical behavior and vice versa

- These parameters can be identified/located in the time domain by taking successive derivatives of the filtered electrical current signature and by locating the zero crossing points on them (1st and 2nd derivatives)



- Electrical noise in the signal makes it difficult to locate these features accurately. Noise filtering algorithms and proper sensor's shielding is important to achieve desired results

- During the transition phases of the current signature, the peaks and valleys indicate starting/stopping of poppet movement

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Algorithm Development

Algorithm – Information extraction

- **Acquire Current Signature**
- **Filter Electrical Signal**
- **Differentiate Signal**
- **Identify/Measure parameters** ; minima and maxima
- **Differentiate Signal**
- **Identify/Measure parameters** ; inflection points
- **Calculate Health parameters** ; apply tolerances

- Local Max/Min points primarily indicate mechanical movements in the valve
- The inflection points indicate a change in curvature in the current signature. They happen at the maximum rates of change in the current signature

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Algorithm Development

Algorithm – Information extraction

- There are many things affect the exact shape of the current signature. Some of the variables to consider are:
  - Valve's Electrical Variables
    - coil inductance (L)
    - coil resistance (R)
    - electro-magnet material (permeability μ)
    - coil temperature (T_{coil})
  - Valve's Mechanical Variables
    - physical geometry (shape/size, air gap g)
    - poppet's pre-set force (F_o),
    - spring mechanical strength (elasticity k)
    - friction in the poppet's path (damping b)
    - poppet's mass (m)
  - External Variables to the Valve
    - supply voltage and current (V, I)
    - clamping diodes in the solenoid's driving circuit
    - pressure inside the solenoid valve (P)
    - debris in the fluid path
    - environment temperature (T_{amb})
  - etc

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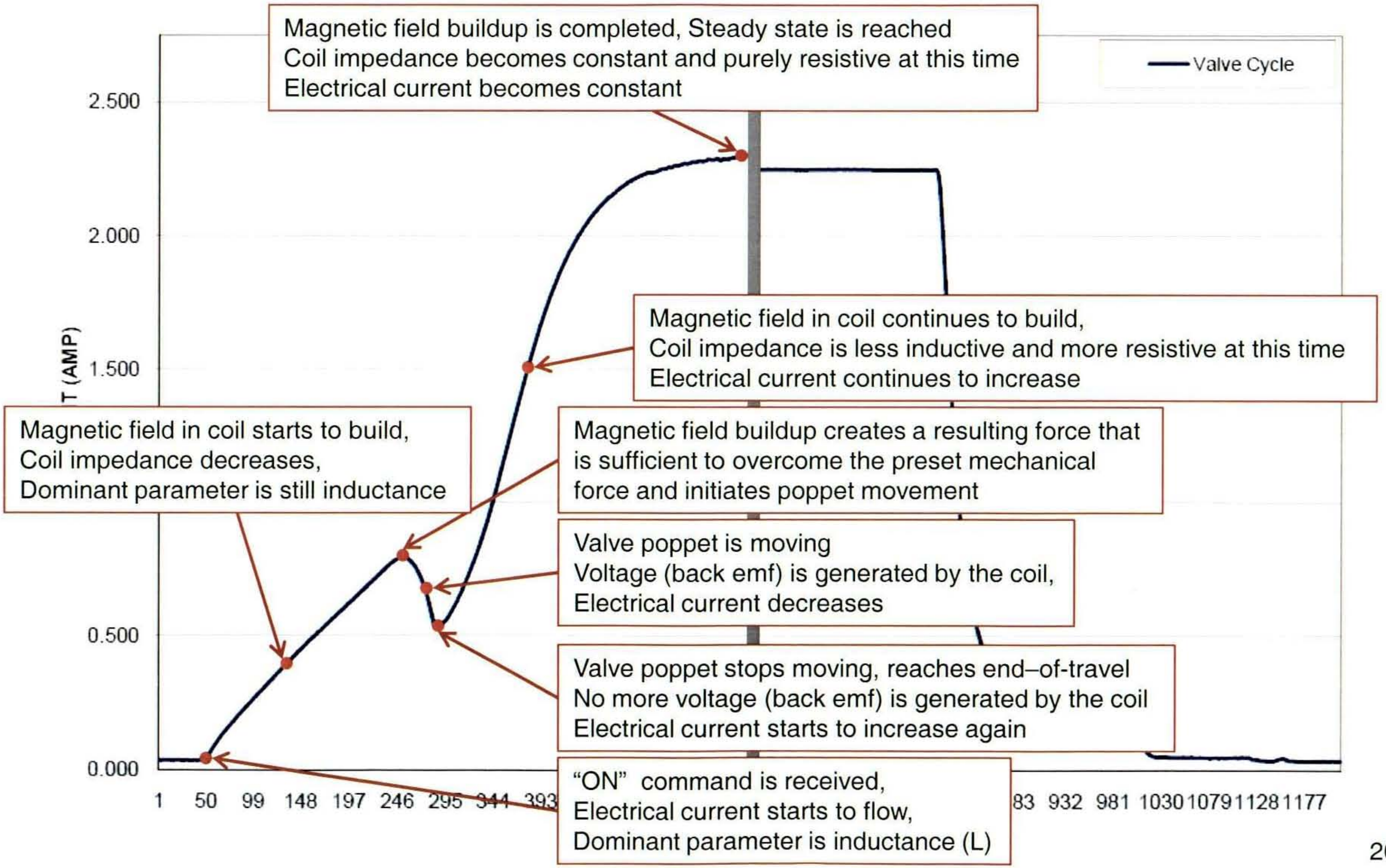
Algorithm Development

What does this signature tell us?



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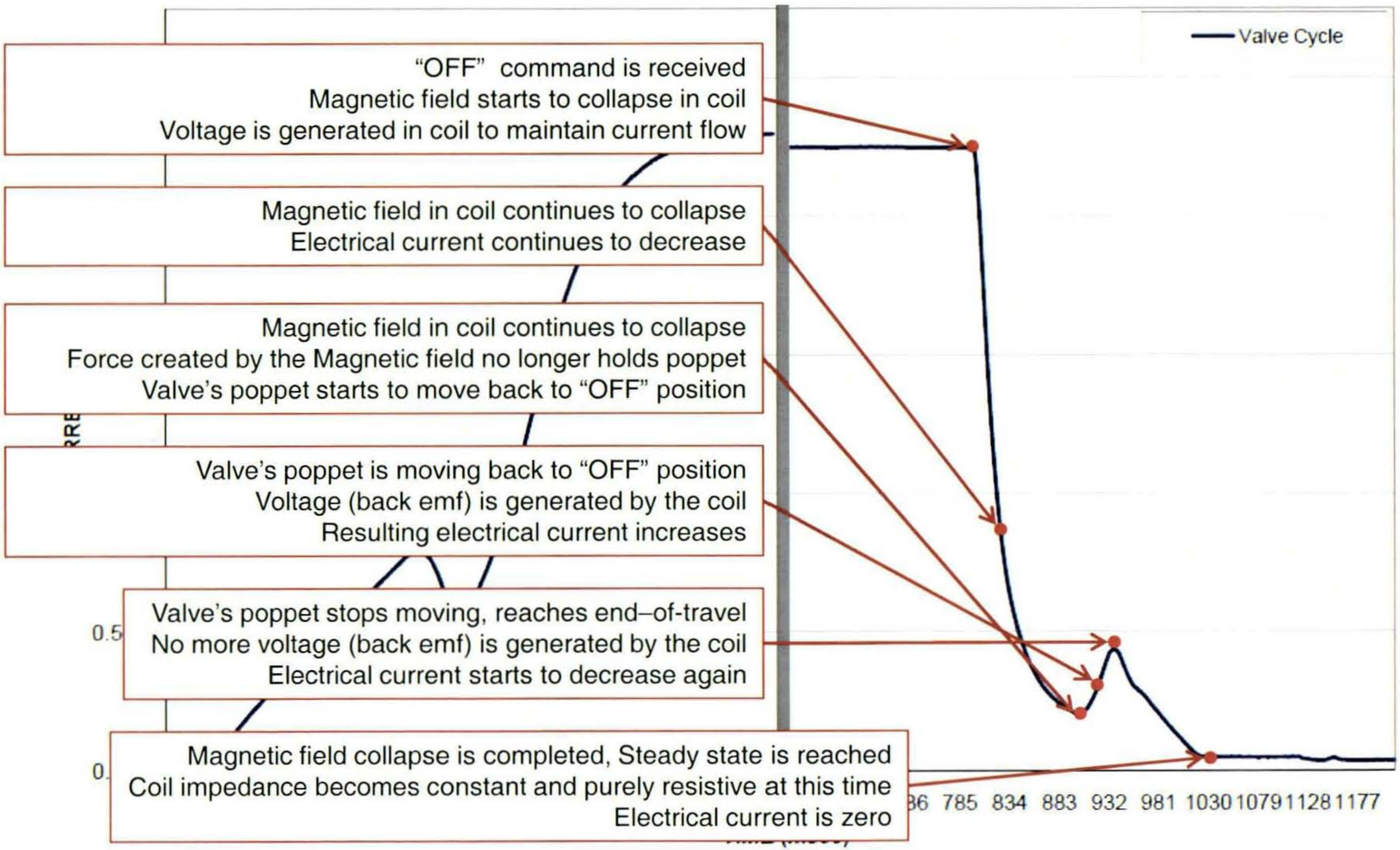
Algorithm Development

What does this signature tell us?



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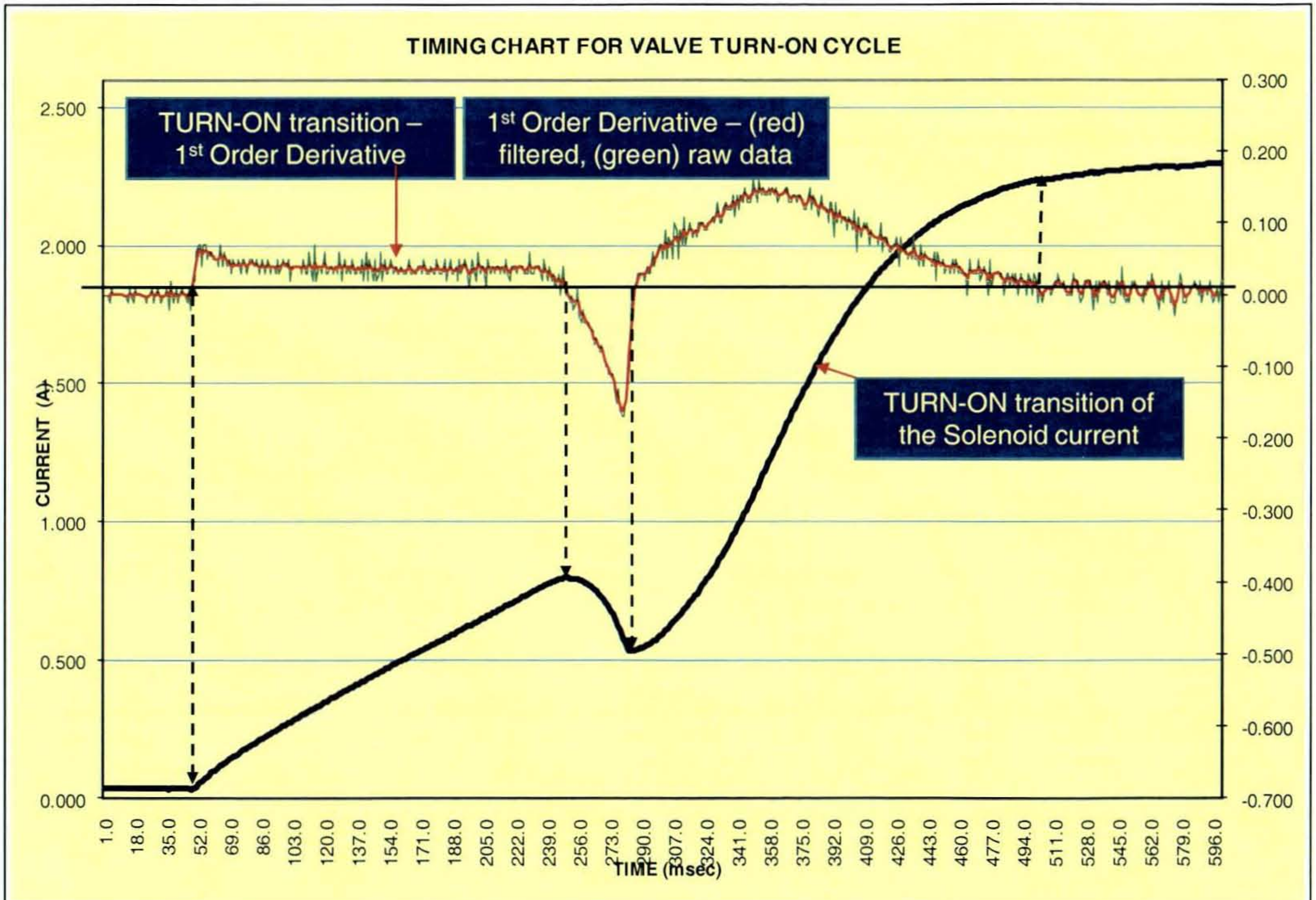
Algorithm Development

"Turn-ON" Transition - Regions to look for information



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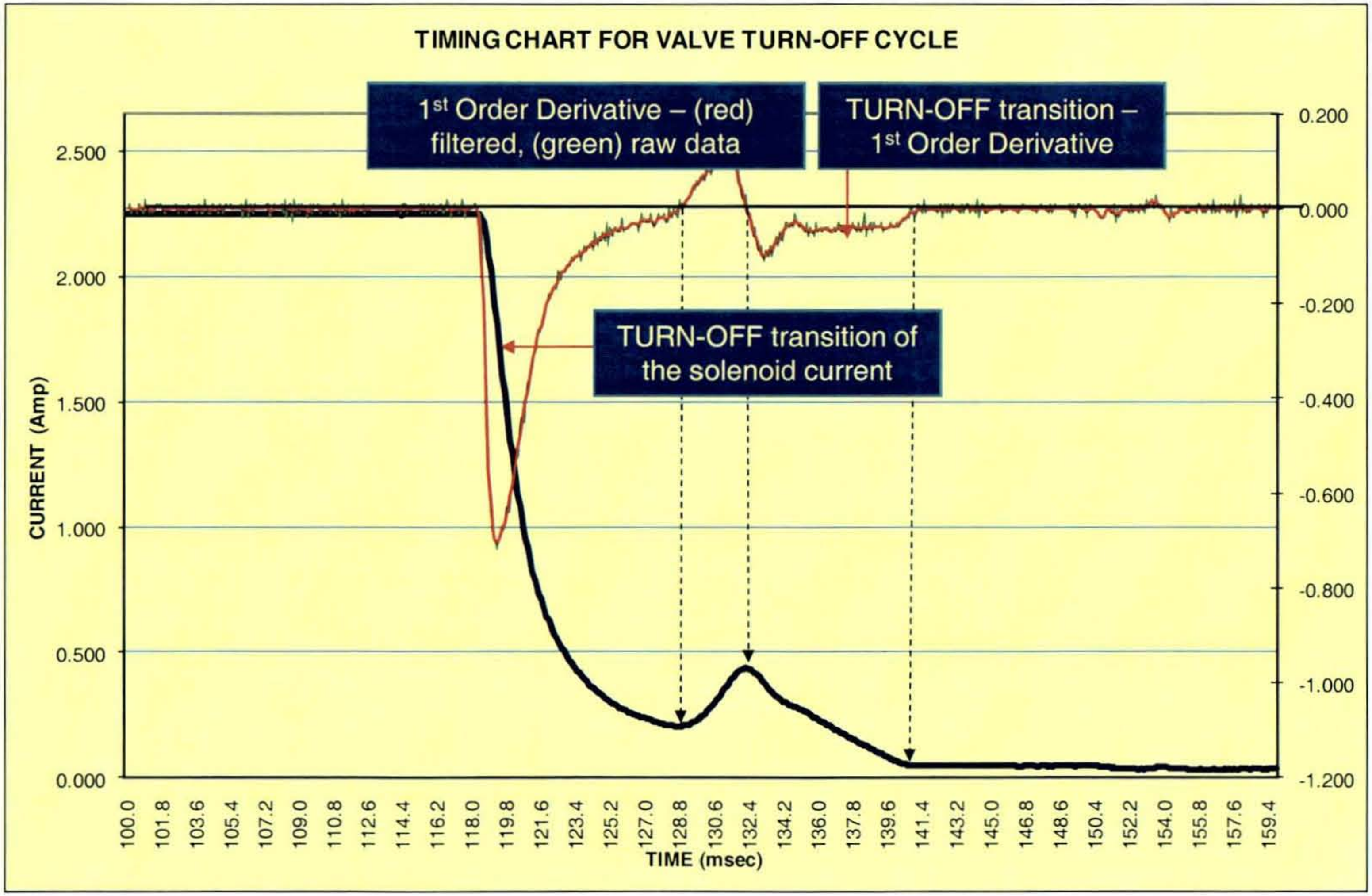
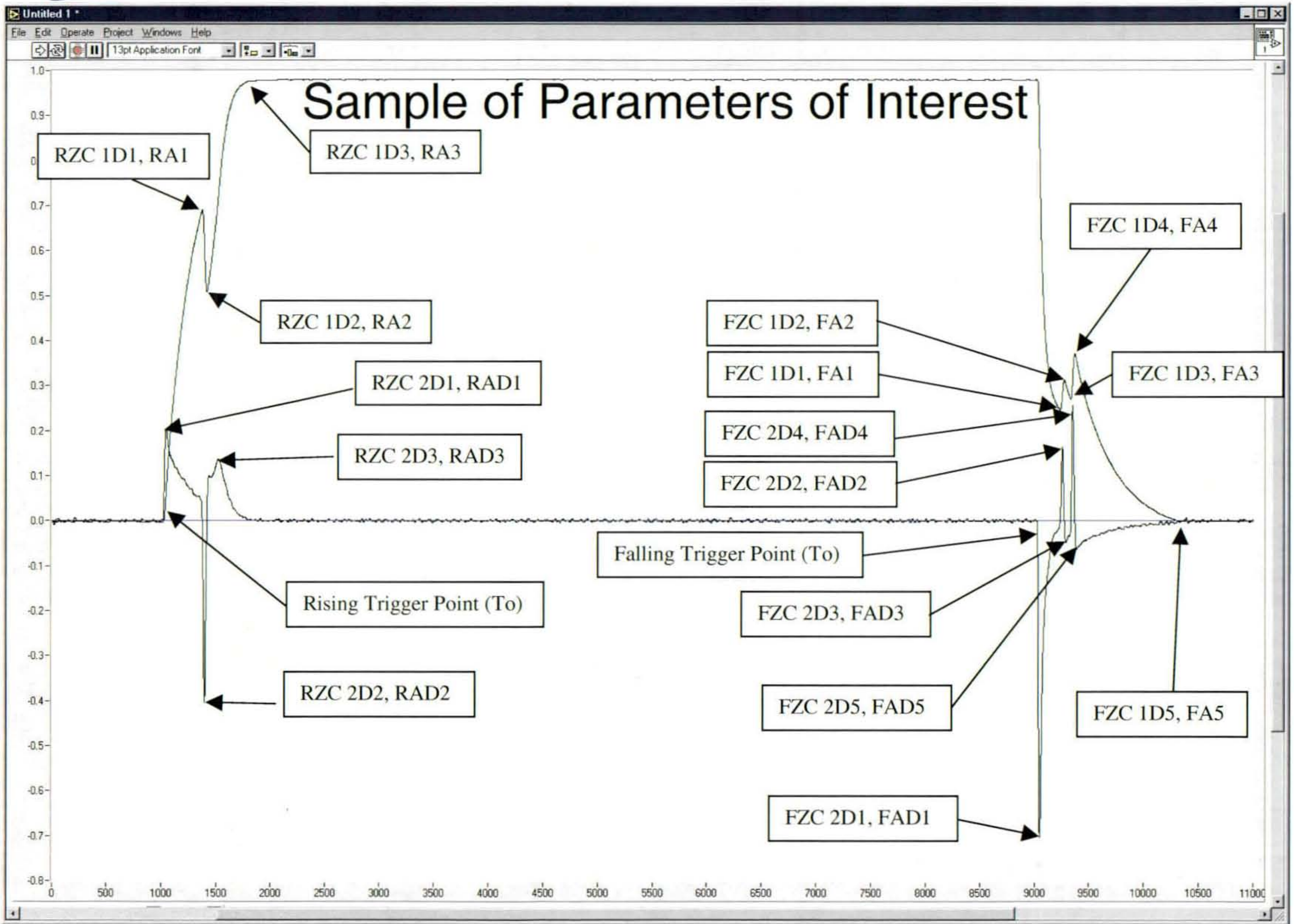
Algorithm Development

"Turn-OFF" Transition - Regions to look for information



Algorithm Development



Algorithm Development

Sample of selected parameters being monitored

Rising Edge (energizing solenoid valve)

RZC 2D1	Rising Zero Crossing 2nd Derivative #1 (*First inflection point of original signal*)
RAD1	Amplitude of 1st derivative @ 1st inflection point (*rate of change* of the current)
RZC 1D1	First peak (Rising Zero Crossing 1st Derivative #1) (*Poppet movement begins)*
RA1	Amplitude of the first peak
RS1	Average slope from the trigger point to the first peak. The average slope is computed by adding up all of the points on the difference waveform and dividing by the number of points
RZC 2D2	Second inflection point (*between when the poppet starts and stops*).
RAD2	Amplitude of the 1st derivative at the second inflection point.
RZC 1D2	First valley (Rising Zero Crossing 1st Derivative #2) (*Poppet movement completes*)
RA2	Amplitude of the first valley.
RS2	Average slope between the first peak and the first valley.
RZC 2D3	Third inflection point (after the poppet stops).
RAD3	Amplitude of the 1st derivative at the third inflection point.
RZC 1D3	Second peak, (*this is most likely the beginning of the "ON" steady state condition)*
RA3	Amplitude of the second peak.
RS3	Average slope between the first valley and the second peak.
RZC 2D4	Forth inflection point, a high steady state point.
RAD4	Amplitude of the 1st derivative at the forth inflection point.
RZC 2D4	Second valley, a high steady state point.
RA4	Amplitude of the second valley.
RS4	Average slope between the second peak and the second valley.

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Solenoid Valve Modeling

Solenoid Valve Modeling

GOAL:

- To develop a simple math model (physics-based model), which describes and explains the basic behavior of the MV74 Solenoid Valve

BASIC MODEL:

- Lumped Parameter, Electro-mechanical Model
- 2nd Order equation to describe the Mechanical portion of the valve (*Spring, Mass,* and *Damper)*

$$A \cdot \partial^2 f(t)/\partial t^2 + B \cdot \partial f(t)/\partial t + C \cdot f(t) + D = 0$$

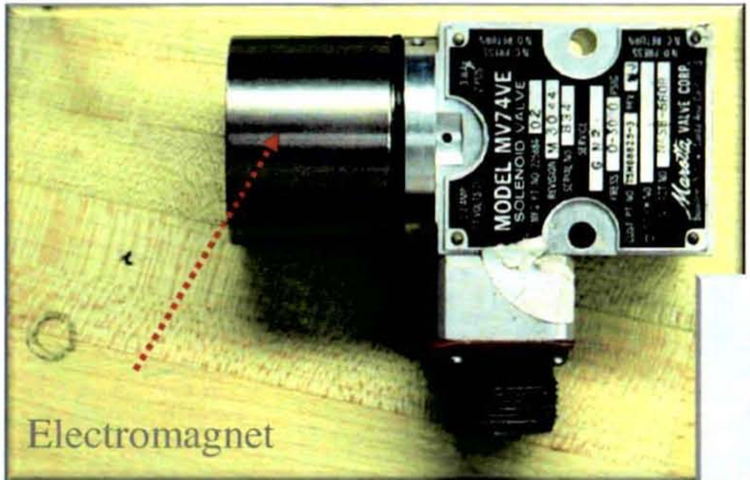
- 1st Order equation to describe the Electrical portion of the valve (*Resistance* and *Inductance*)

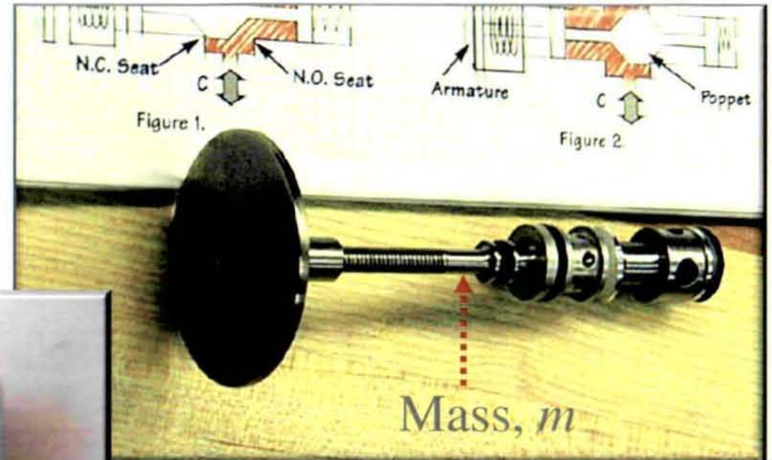
$$A \cdot \partial f(t)/\partial t + B \cdot f(t) + C = 0$$

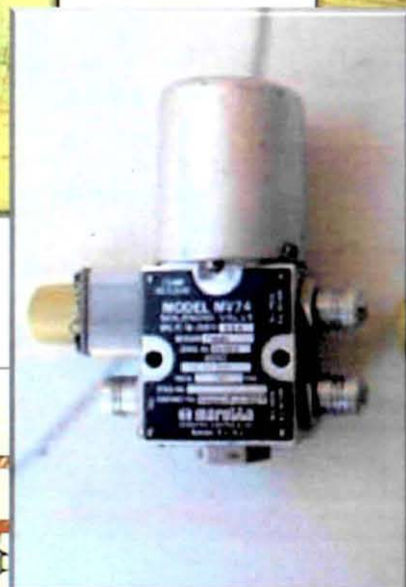
- Inductance is a function of poppet displacement with time $L(x[t]) = f\,[x(t)]$
- Valve's driving force is proportional to the *Gradient* of Inductance and the square of the electrical current

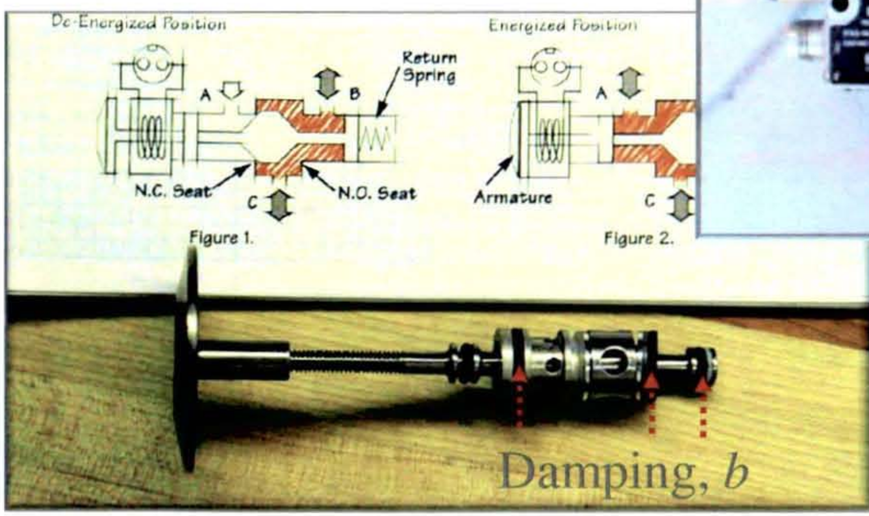
$$\mathcal{F}(x[t]) = \frac{I^2(t)}{2} \, \frac{\partial L(x[t])}{\partial x}$$

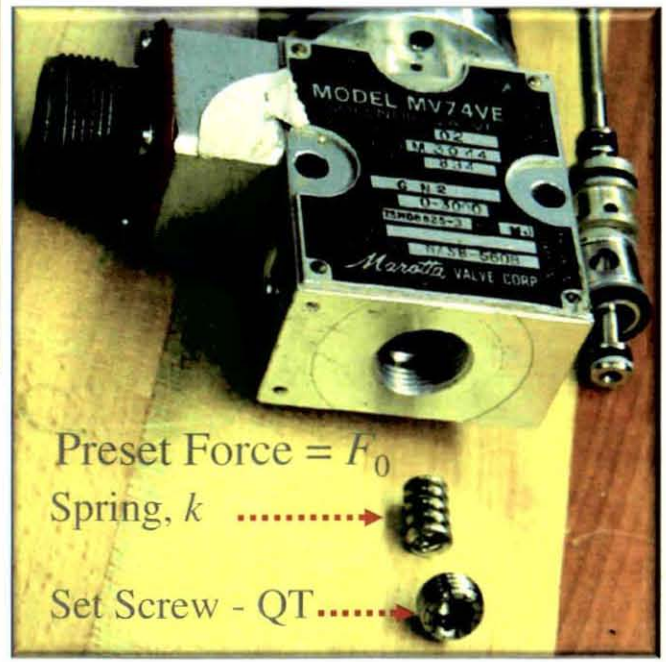
Solenoid Valve Model Components



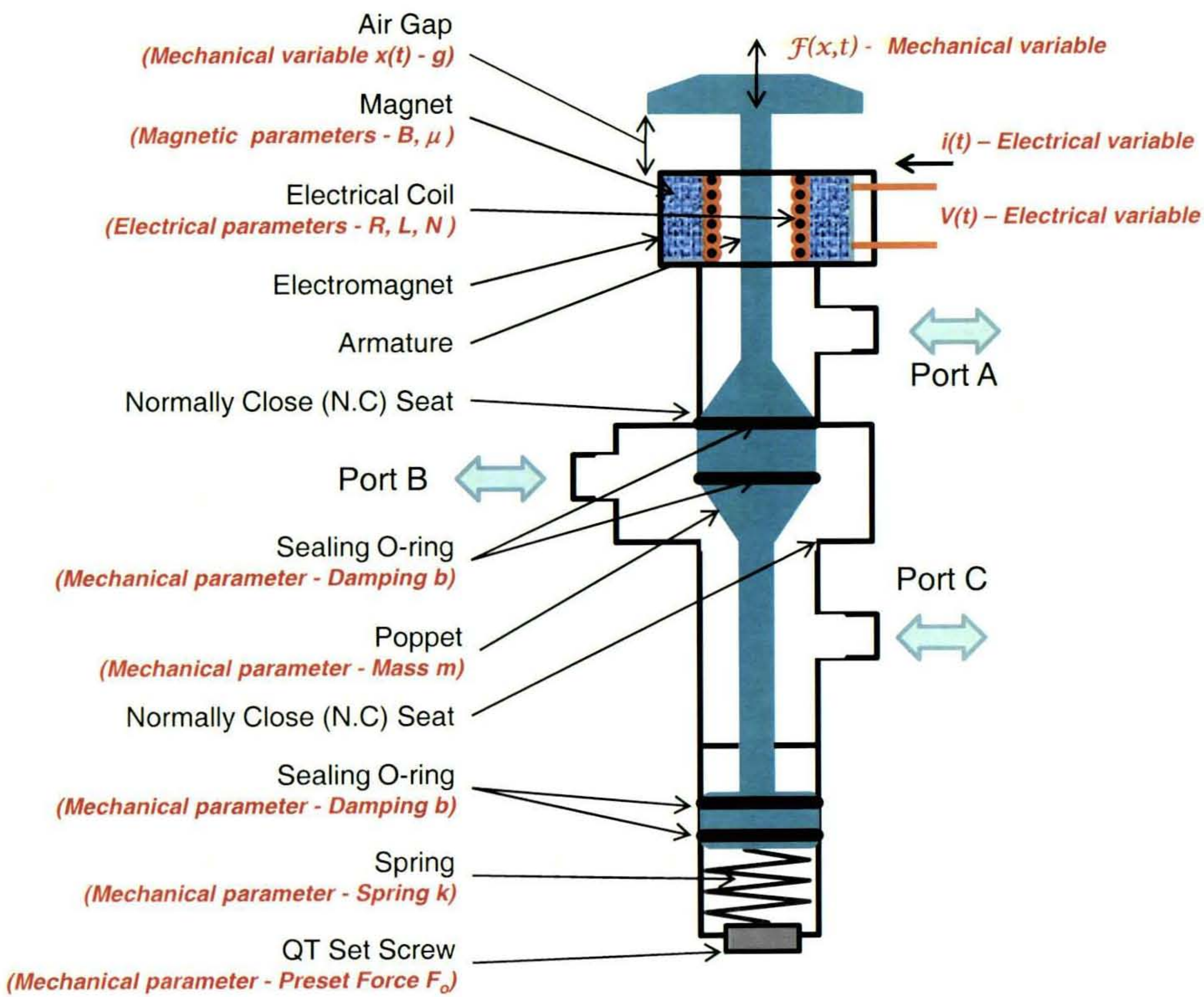




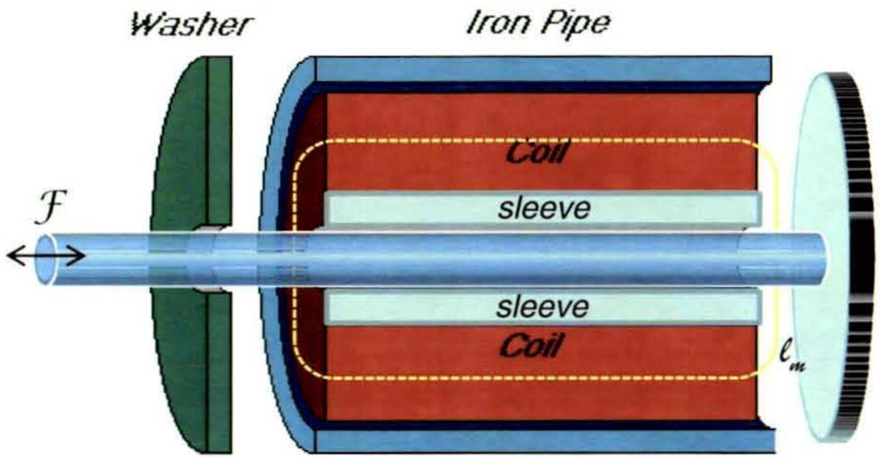




Solenoid Valve Model Components

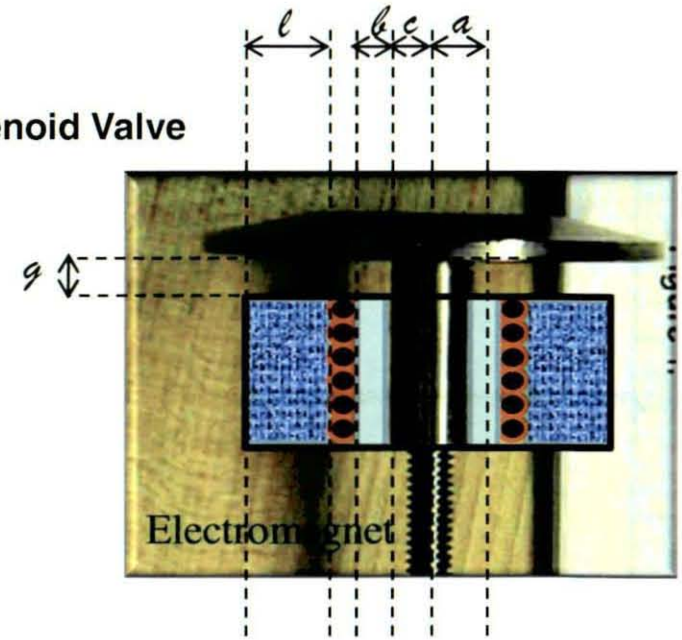


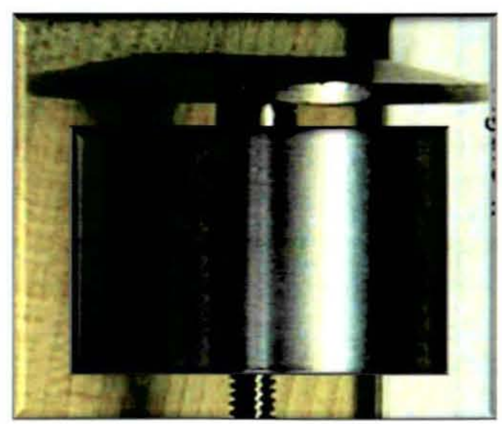
Solenoid Valve Model – Components



- a = mean radius of sleeve
- b = non-magnetic sleeve thickness
- c = radius of cylindrical plunger
- g = air gap
- ℓ = magnetic core thickness
- ℓ_m = magnetic core average length
- N = number of turns in coil
- μ = core permeability
- μ_{sleeve} = permeability of sleeve
- μ_{air} = permeability of air
- μ_{Core} = permeability of magnetic core

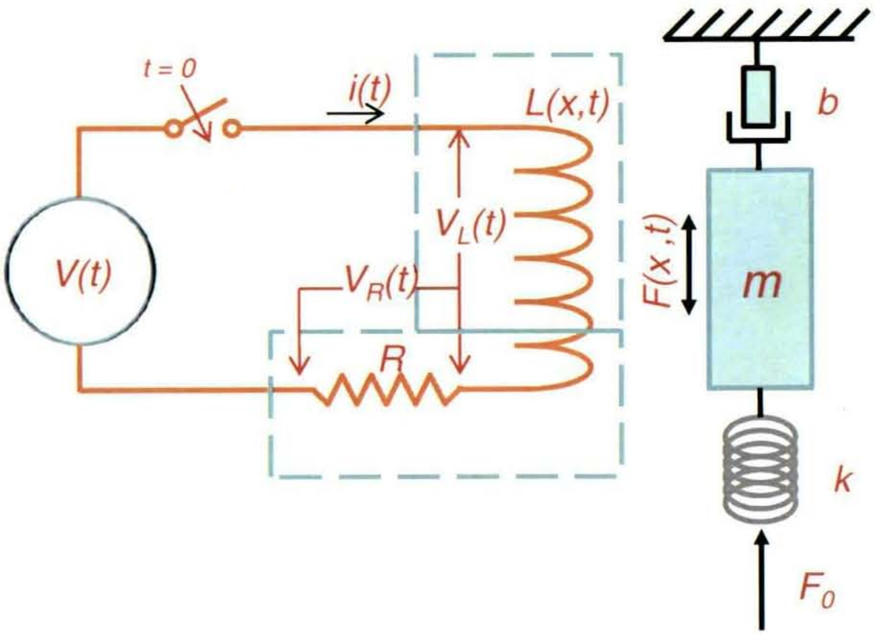
MV74 Solenoid Valve



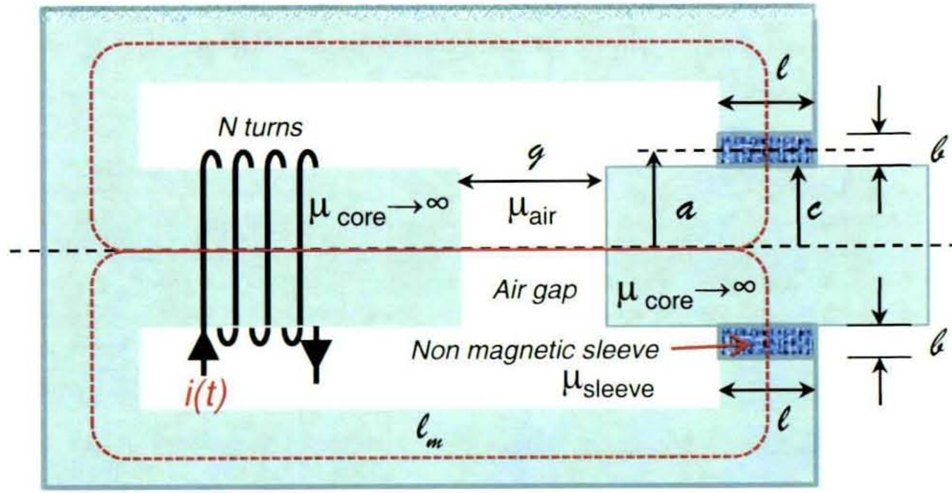


Solenoid Valve Model – Equivalent Circuit

Electro-mechanical Equivalent Circuit



Basic Solenoid Model



a = mean radius of sleeve

b = non-magnetic sleeve thickness

c = radius of cylindrical plunger

g = air gap

ℓ = magnetic core thickness

ℓ_m = magnetic core average length

N = coil number of turns

μ_{sleeve} = permeability of sleeve

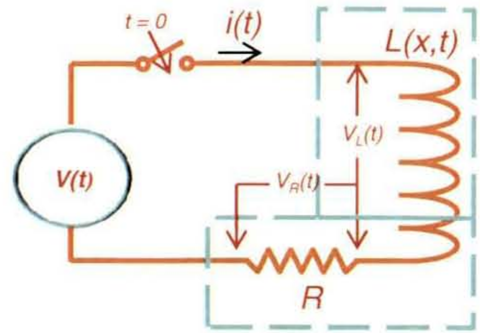
μ_{air} = permeability of air

μ_{Core} = permeability of magnetic core

Solenoid Valve Model – Electrical Equations

Electrical equations: $A \cdot \partial f(t)/\partial t + B \cdot f(t) + C = 0$

- $V_o = V_{L(x,t)} + V_R = \frac{\partial}{\partial t}[L(x[t]) * i(t)] + R * i(t)$ for $t \geq$ "ON" command
- $0 = V_{L(x,t)} + V_R = \frac{\partial}{\partial t}[L(x[t]) * i(t)] + R * i(t)$ for $t \geq$ "OFF" command



- **Magnetic Inductance** $L(x[t]) = (N^2 / \mathcal{R})$
- **Magnetic Reluctance** $(\mathcal{R}) = \mathcal{R}_{gap} + [\mathcal{R}_{sleeve}]/2 = \frac{x(t)}{\mu_o \pi c^2} + \frac{b}{2\mu_s \pi a \ell}$ where $c = a - b/2$
- **Magnetic Inductance** $L(x[t]) = (N^2 / \mathcal{R}) = \frac{2\pi \mu_o \mu_s a \ell c^2 N^2}{2\mu_s a \ell x(t) + \mu_o b c^2} = \frac{k_1}{k_2 x(t) + k_3}$

where $k_1 = 2\pi \mu_o \mu_s a \ell c^2 N^2$; $k_2 = 2\mu_s a \ell$; $k_3 = \mu_o b c^2$

- **Electrical Resistance** $R = R_0[\alpha(T - T_0) + 1]$; where T is its temperature, T_0 is a reference temperature (usually 25°C), R_0 is the resistance at T_0, and α is the % change in resistivity per unit temperature.
- Also **Resistance** $R = \rho * L/A$; where L is the conductor's length (m), A is the conductor's cross-sectional area (m^2), ρ is the electrical resistivity (also called *specific electrical resistance*) of the material (Ω m)

Solenoid Valve Model – Electrical Equations

- $V_{L(x,t)} = \frac{\partial}{\partial t}[\, L(x[t]) * i(t) \,]$

$$\frac{\partial}{\partial t}[L(x[t]) * i(t)] = L(x[t]) \frac{d}{dt}[\, i(t) \,] + i(t) \frac{d}{dt}[L(x[t])] = L(x[t]) \frac{d}{dt}[\, i(t) \,] + i(t) \frac{d}{dt}\left[\frac{k_1}{k_2\, x(t) + k_3}\right]$$

$$\frac{d}{dt}\left[\frac{k_1}{k_2\, x(t) + k_3}\right] = \frac{(k_2\, x(t) + k_3) \overset{=0}{\cancel{\frac{d}{dt}}} k_1 - k_1 \frac{d}{dt}[\, k_2\, x(t) + k_3 \,]}{[k_2\, x(t) + k_3]^2} = \frac{-\, k_1 k_2 \frac{d}{dt}[\, x(t) \,]}{(k_2\, x(t) + k_3)^2}$$

so:

$$\frac{\partial}{\partial t}[\, L(x[t])\, i(t) \,] = L(x[t]) \frac{d}{dt}[\, i(t) \,] - i(t) \frac{k_1 k_2 \frac{d}{dt}[\, x(t) \,]}{(k_2\, x(t) + k_3)^2} \qquad \text{and}$$

therefore:

$$V_0 = \frac{k_1}{k_2\, x(t) + k_3} \frac{d}{dt}[\, i(t) \,] - i(t) \frac{k_1 k_2 \frac{d}{dt}[\, x(t) \,]}{(k_2\, x(t) + k_3)^2} + R\, i(t)\,; \quad \text{for } t >= \text{“ON” command}$$

$$0 = \frac{k_1}{k_2\, x(t) + k_3} \frac{d}{dt}[\, i(t) \,] - i(t) \frac{k_1 k_2 \frac{d}{dt}[\, x(t) \,]}{(k_2\, x(t) + k_3)^2} + R\, i(t)\,; \quad \text{for } t >= \text{“OFF” command}$$

Solenoid Valve Model – Electrical Equations

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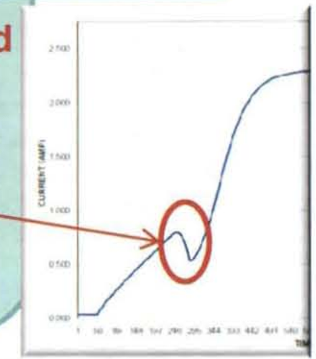
$A * \partial f(t)/\partial t + B * f(t) + C = 0$

$$\frac{d}{dt}[\,i(t)\,] + \left[\frac{R[\,k_2\, x(t) + k_3\,]}{k_1} - \boxed{\frac{k_2 \frac{d}{dt}[\,x(t)\,]}{(k_2\, x(t) + k_3)}}\,\right] * i(t) - V_0 = 0$$ **for t >= "ON" command**

$$\frac{d}{dt}[\,i(t)\,] + \left[\frac{R[\,k_2\, x(t) + k_3\,]}{k_1} - \frac{k_2 \frac{d}{dt}[\,x(t)\,]}{(k_2\, x(t) + k_3)}\right] * i(t) = 0$$ for t >= "OFF" command



Case	Condition	Air Gap x(t)	Inductance L(x (t))	Electrical Equation	Boundary conditions
(a)	**Steady State "OFF"**, valve de-energized, poppet not moving	constant (g)	$L = \frac{k_1}{k_2\, g + k_3} = L_1$	V(t) = 0; i(t)= 0	$V_i = V_f = 0$; $I_i = I_f = 0$; $x_i = x_f = g$; t = continuous OFF steady state
(b)	**Command set "ON"**, valve energized, poppet not moving	constant (g)	$L = \frac{k_1}{k_2\, g + k_3} = L_1$	$V(t) = R\, i(t) + L_1 \frac{d}{dt} i(t) = V_o$	$V_i = V_f = V_o$; $I_i = 0$; $I_f = V_o/R$; $x_i = x_f = g$; $t \in [\,t_{on}, t_1\,]$
(c)	**Command set "ON"**, valve energized, poppet is moving	varies with time	$L = \frac{k_1}{k_2\, x(t) + k_3} = L_2$	$V_o = R\, i(t) + L_2 \frac{d}{dt} i(t) - i(t)(L_2)^2 \frac{k_2}{k_1} \frac{d}{dt} x(t)$	$V_i = V_f = V_o$; $I_i = I_{t1}$; $I_f = I_{t2}$; $x_i = g$; $x_f = 0$; $t \in [\,t_1, t_2\,]$
(e)	**Command set "ON"**, valve energized, poppet is resting in "ON" position	constant (0)	$L = \frac{k_1}{k_3} = L_3$	$V(t) = R\, i(t) + L_3 \frac{d}{dt} i(t) = V_o$	$V_i = V_f = V_o$; $I_i = I_{t2}$; $I_f = V_o/R$; $x_i = x_f = 0$; $t \in [\,t_2, t_{on\text{-}ss}\,]$
(f)	**Command set "ON"**, valve energized, **Steady State** "ON"	constant (0)	$L = \frac{k_1}{k_3} = L_3$	$V(t) = R\, i(t) = R * I_{ss} = V_o$	$V_i = V_f = V_o$; $I_i = I_f = V_o/R$; $x_i = x_f = 0$; t = continuous ON steady state

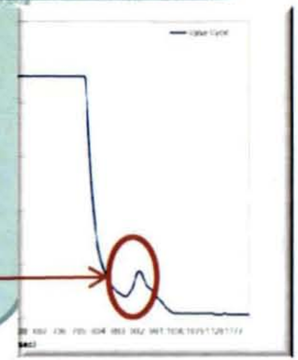
KSC ENGINEERING

Solenoid Valve Model – Electrical Equations

$A \cdot \partial f(t)/\partial t + B \cdot f(t) + C = 0$

$$\frac{d}{dt}[\,i(t)\,] + \left[\frac{R[\,k_2\,x(t) + k_3\,]}{k_1} - \frac{k_2 \frac{d}{dt}[\,x(t)\,]}{(k_2\,x(t) + k_3)}\right] * i(t) - V_0 = 0 \quad \text{for } t >= \text{“ON” command}$$

$$\frac{d}{dt}[\,i(t)\,] + \left[\frac{R[\,k_2\,x(t) + k_3\,]}{k_1} - \boxed{\frac{k_2 \frac{d}{dt}[\,x(t)\,]}{(k_2\,x(t) + k_3)}}\right] * i(t) = 0 \quad \text{for } t >= \text{“OFF” command}$$



Case	Condition	Air Gap x(t)	Inductance $L(x(t))$	Electrical Equation	Boundary conditions
(g)	**Steady State “ON”**, valve energized, poppet not moving	constant (0)	$L = \frac{k_1}{k_3} = L_3$	$V(t) = R\,i(t) = R * I_{ss} = V_o$	$V_i = V_f = V_o$; $I_i = I_f = V_o/R$; $x_i = x_f = 0$; t = continuous ON steady state
(h)	**Command set “OFF”**, valve de-energizing, poppet not moving	constant (0)	$L = \frac{k_1}{k_3} = L_3$	$V(t) = R\,i(t) + L_3 \frac{d}{dt} i(t) = 0$	$V_i = V_f = 0$; $I_i = V_o/R$; $I_f = I_{t3}$; $x_i = x_f = 0$; $t \in [\,t_{off}, t_3\,]$
(i)	**Command set “OFF”**, valve de-energizing, poppet is moving	varies with time	$L = \frac{k_1}{k_2\,x(t) + k_3} = L_2$	$0 = R\,i(t) + L_2 \frac{d}{dt} i(t) - i(t)(L_2)^2 \frac{k_2}{k_1} \frac{d}{dt} x(t)$	$V_i = V_f = 0$; $I_i = I_{t3}$; $I_f = I_{t4}$; $x_i = 0$; $x_f = g$; $t \in [\,t_3, t_4\,]$
(j)	**Command set “OFF”**, valve de-energizing, poppet is resting in “OFF” position	constant (g)	$L = \frac{k_1}{k_2\,g + k_3} = L_1$	$V(t) = R\,i(t) + L_1 \frac{d}{dt} i(t) = 0$	$V_i = V_f = 0$; $I_i = I_{t4}$; $I_f = 0$; $x_i = x_f = g$; $t \in [\,t_4, t_{off\text{-}ss}\,]$
(k)	**Command set “OFF”**, valve de-energized, **Steady State** “OFF”	constant (g)	$L = \frac{k_1}{k_2\,g + k_3} = L_1$	$V(t) = 0$; $i(t) = 0$	$V_i = V_f = 0$; $I_i = I_f = 0$; $x_i = x_f = g$; t = continuous OFF steady state

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Solenoid Valve Model – Mechanical Equations

Mechanical equations:

$$m \cdot \partial^2 x(t)/\partial t^2 + b \cdot \partial x(t)/\partial t + k \cdot x(t) = \mathcal{F}$$

$$A \cdot \partial^2 f(t)/\partial t^2 + B \cdot \partial f(t)/\partial t + C \cdot f(t) + D = 0$$

where	m	is the mass of the system
	b	is the friction (damping) coefficient of the system
	k	is the spring constant
	$x(t)$	is the displacement of the system
	$\mathcal{F}$	is the required force to produce the displacement

---

- **Energy** stored in an Inductance L, carrying a current i is:

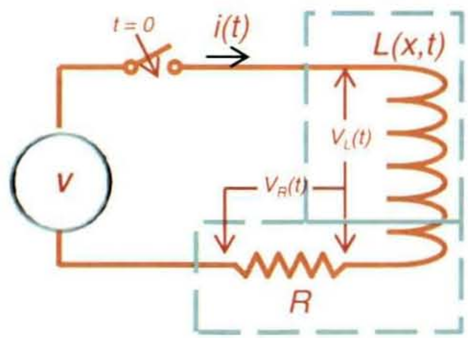
$$\mathcal{W}_m = \tfrac{1}{2} L\, i^2 = \tfrac{1}{2} L\,(x[t])\, i^2(t)$$

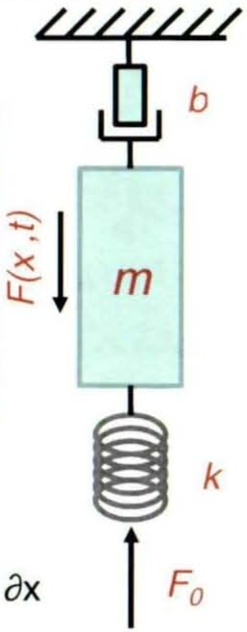
- **Force** created by current excitation of an inductance is:

$$\mathcal{F}_e = \partial \mathcal{W}_m(i, x) / \partial x$$

- As defined before, the solenoid **Inductance** is:

$$L\,(x[t]) = (N^2 / \mathcal{R}) = \frac{2\,\pi\,\mu_o\,\mu_s\, a\,\ell\, c^2\, N^2}{2\,\mu_s\, a\,\ell\, x(t) + \mu_o\, b\, c^2} = \frac{k_1}{k_2\, x(t) + k_3}$$





- So the **Force** created by current excitation of the inductance is:

$$\mathcal{F}_e = \partial \mathcal{W}_m(i, x) / \partial x = \partial\,(\tfrac{1}{2} L\, i^2)\, / \partial x = \tfrac{1}{2}\, i^2(t) * \partial L / \partial x = \tfrac{1}{2}\, i^2(t) * \partial \left(\frac{k_1}{k_2\, x(t) + k_3}\right) / \partial x$$

$$\boxed{\mathcal{F}_e = \tfrac{1}{2}\, i^2(t)\, \frac{-\,k_1\, k_2}{(k_2\, x(t) + k_3)^2}}$$

where the minus sign indicates that the force tends to decrease the air gap

Solenoid Valve Model – Mechanical Equations

<u>Mechanical equations:</u>

$$m \cdot \partial^2 x(t)/\partial t^2 + b \cdot \partial x(t)/\partial t + k \cdot x(t) = - [\, \mathcal{F}_e + \mathcal{F}_o \,]$$

where $\mathcal{F}_o$ is the solenoid valve's preset force; it is a constant value
$\mathcal{F}_e = \mathcal{F}\,(i, x)$ is the resultant magneto motive force (mmf) generated by the magnetic field

$$m \cdot \partial^2 x(t)/\partial t^2 + b \cdot \partial x(t)/\partial t + k \cdot x(t) = - \left[\, \tfrac{1}{2}\, i^2(t) \frac{-k_1 k_2}{(k_2\, x(t) + k_3)^2} + \mathcal{F}_o \,\right]$$

and

$$\mathcal{F}_e = \left[\, \tfrac{1}{2}\, i^2(t) \frac{-k_1 k_2}{(k_2\, x(t) + k_3)^2} \,\right]$$

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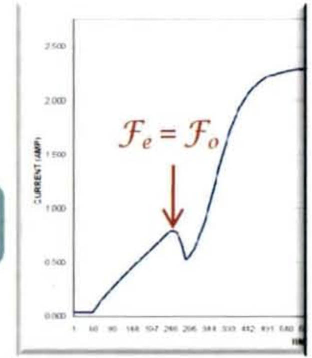
Solenoid Valve Model – Mechanical Equations

$$m \cdot \partial^2 x(t)/\partial t^2 + b \cdot \partial x(t)/\partial t + k \cdot x(t) = - \left[\tfrac{1}{2}\, i^2(t) \frac{-k_1 k_2}{(k_2\, x(t) + k_3)^2} + \mathcal{F}_o \right]$$

$$\mathcal{F}_e = \left[\tfrac{1}{2}\, i^2(t) \frac{-k_1 k_2}{(k_2\, x(t) + k_3)^2} \right]$$

$$A \cdot \partial^2 f(t)/\partial t^2 + B \cdot \partial f(t)/\partial t + C \cdot f(t) + D = 0$$



for t >= "ON" command

Case	Condition	Air Gap x(t)	Inductance L(x)	Mechanical Equation	Boundary conditions
(a)	**Steady State "OFF"**, valve de-energized, poppet not moving	constant (g)	$L = \frac{k_1}{k_2\, g + k_3} = L_1$	$\mathcal{F}_e = 0$; $i(t) = 0$; $x(t) = g$	$V_i = V_f = 0$; $I_i = I_f = 0$; $x_i = x_f = g$; t = continuous OFF steady state
(b)	**Command set "ON"**, valve energized, poppet not moving	constant (g)	$L = \frac{k_1}{k_2\, g + k_3} = L_1$	$\mathcal{F}_e(t) = \frac{-k_1 k_2}{2(k_2\, g + k_3)^2} i^2(t)$; $kg = -[\mathcal{F}_e(t) + \mathcal{F}_o]$	$V_i = V_f = V_o$; $I_i = 0$; $I_f = V_o/R$; $x_i = x_f = g$; $t \in [t_{on}, t_1]$
(c)	**Command set "ON"**, valve energized, poppet is moving	varies with time	$L = \frac{k_1}{k_2\, x(t) + k_3} = L_2$	$\mathcal{F}_e(t) = \frac{-k_1 k_2}{2(k_2\, x(t) + k_3)^2} i^2(t)$; $m\, \partial^2 x(t)/\partial t^2 + b\, \partial x(t)/\partial t + k\, x(t) = -[\mathcal{F}_e(t) + \mathcal{F}_o]$	$V_i = V_f = V_o$; $I_i = I_{t1}$; $I_f = I_{t2}$; $x_i = g$; $x_f = 0$; $t \in [t_1, t_2]$
(e)	**Command set "ON"**, valve energized, poppet is resting in "ON" position	constant (0)	$L = \frac{k_1}{k_3} = L_3$	$\mathcal{F}_e(t) = \frac{-k_1 k_2}{2(k_3)^2} i^2(t)$; $0 = -[\mathcal{F}_e(t) + \mathcal{F}_o]$	$V_i = V_f = V_o$; $I_i = I_{t2}$; $I_f = V_o/R$; $x_i = x_f = 0$; $t \in [t_2, t_{on\text{-}ss}]$
(f)	**Command set "ON"**, valve energized, **Steady State** "ON"	constant (0)	$L = \frac{k_1}{k_3} = L_3$	$\mathcal{F}_e(t) = \frac{-k_1 k_2}{2(k_3)^2} (V_o/R)^2 = \mathcal{F}_{e\text{-}max}$	$V_i = V_f = V_o$; $I_i = I_f = V_o/R$; $x_i = x_f = 0$; t = continuous ON steady state

Solenoid Valve Model – Mechanical Equations

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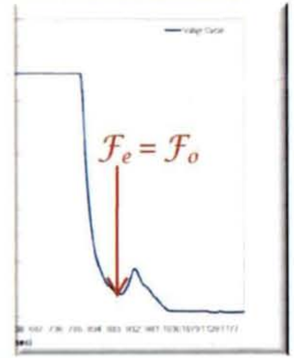
$$m \cdot \partial^2 x(t)/\partial t^2 + b \cdot \partial x(t)/\partial t + k \cdot x(t) = -\left[\tfrac{1}{2}\, i^2(t) \frac{-k_1 k_2}{(k_2\, x(t) + k_3)^2} + \mathcal{F}_o \right]$$

$$\mathcal{F}_e = \left[\tfrac{1}{2}\, i^2(t) \frac{-k_1 k_2}{(k_2\, x(t) + k_3)^2} \right]$$

$$A \cdot \partial^2 f(t)/\partial t^2 + B \cdot \partial f(t)/\partial t + C \cdot f(t) + D = 0$$



for t >= "OFF" command

Case	Condition	Air Gap $x(t)$	Inductance $L(x)$	Mechanical Equation	Boundary conditions
(g)	**Steady State "ON"**, valve energized, poppet not moving	constant (0)	$L = \dfrac{k_1}{k_3} = L_3$	$\mathcal{F}_e(t) = \dfrac{-k_1 k_2}{2(k_3)^2} (V_o/R)^2 = \mathcal{F}_{e\text{-}max}$	$V_i = V_f = V_o$; $I_i = I_f = V_o/R$; $x_i = x_f = 0$; t = continuous ON steady state
(h)	**Command set "OFF"**, valve de-energizing, poppet not moving	constant (0)	$L = \dfrac{k_1}{k_3} = L_3$	$\mathcal{F}_e(t) = \dfrac{-k_1 k_2}{2(k_3)^2}\, i^2(t)$; $0 = -[\mathcal{F}_e(t) + \mathcal{F}_o]$	$V_i = V_f = 0$; $I_i = V_o/R$; $I_f = I_{t3}$; $x_i = x_f = 0$; $t \in [t_{off}, t_3]$
(i)	**Command set "OFF"**, valve de-energizing, poppet is moving	varies with time	$L = \dfrac{k_1}{k_2\, x(t) + k_3} = L_2$	$\mathcal{F}_e(t) = \dfrac{-k_1 k_2}{2(k_2\, x(t) + k_3)^2}\, i^2(t)$; $m\, \partial^2 x(t)/\partial t^2 + b\, \partial x(t)/\partial t + k\, x(t) = -[\mathcal{F}_e(t) + \mathcal{F}_o]$	$V_i = V_f = 0$; $I_i = I_{t3}$; $I_f = I_{t4}$; $x_i = 0$; $x_f = g$; $t \in [t_3, t_4]$
(j)	**Command set "OFF"**, valve de-energizing, poppet is resting in "OFF" position	constant (g)	$L = \dfrac{k_1}{k_2\, g + k_3} = L_1$	$\mathcal{F}_e(t) = \dfrac{-k_1 k_2}{2(k_2\, g + k_3)^2}\, i^2(t)$; $kg = -[\mathcal{F}_e(t) + \mathcal{F}_o]$	$V_i = V_f = 0$; $I_i = I_{t4}$; $I_f = 0$; $x_i = x_f = g$; $t \in [t_4, t_{off\text{-}ss}]$
(k)	**Command set "OFF"**, valve de-energized, **Steady State** "OFF"	constant (g)	$L = \dfrac{k_1}{k_2\, g + k_3} = L_1$	$\mathcal{F}_e = 0$; $i(t) = 0$; $x(t) = g$	$V_i = V_f = 0$; $I_i = I_f = 0$; $x_i = x_f = g$; t = continuous OFF steady state

Backup Information

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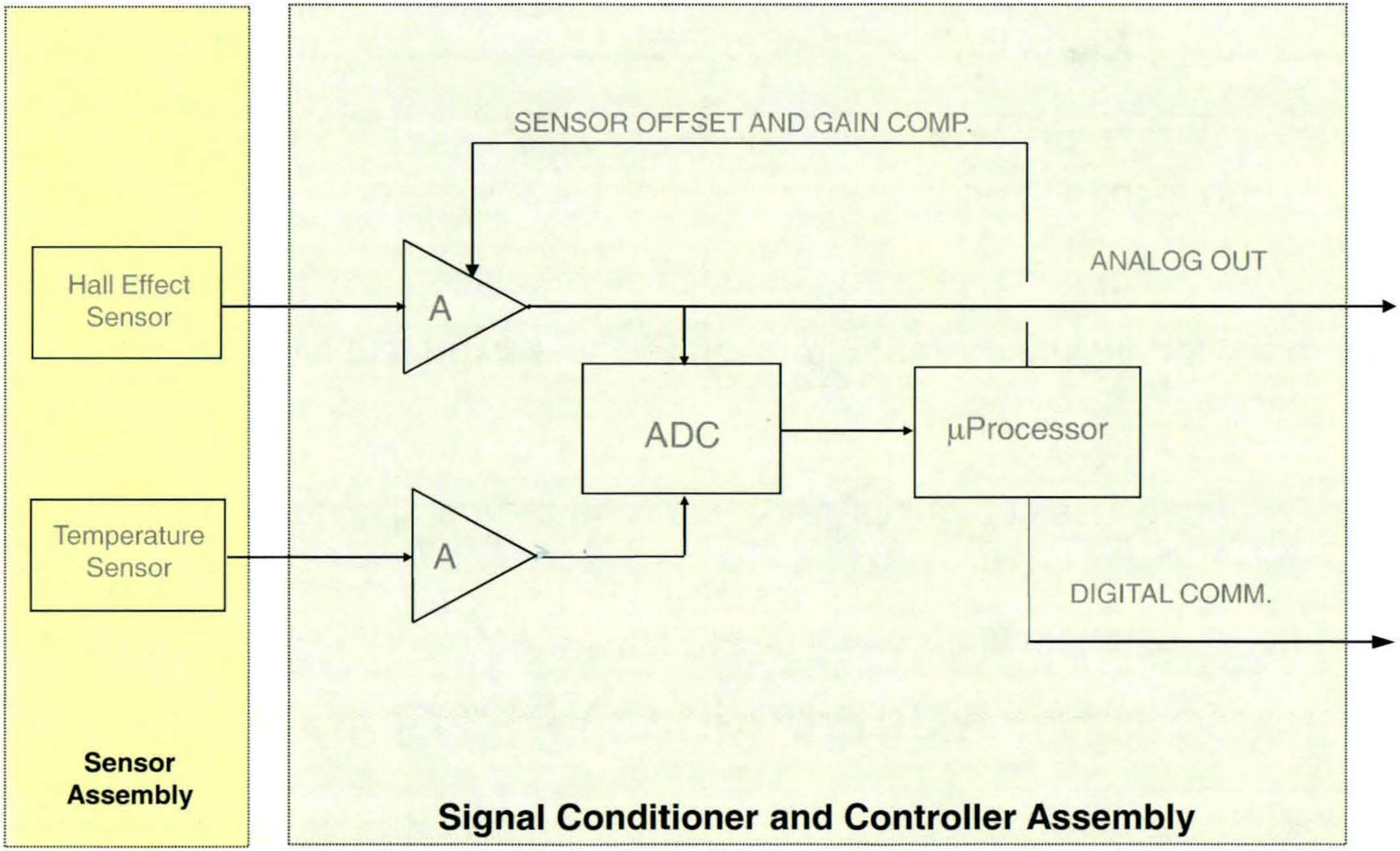
SCSS Implementation

SCSS Components

- A non-invasive current sensor (Hall Effect sensor) to monitor the electrical current signature of the solenoid valve
- An Analog Module that provides signal conditioning and sensor compensation
- A Digital Module that processes the data from the sensors and provides the resulting information/health assessment to the users/operators
- An embedded set of software algorithms that interpret the data from the sensor and assess the health of the valve in real-time and indicates how the valve parameters are behaving prior and during operation of the valve
- A communication circuit to transmit the information to the user
- A Graphical User Interface (GUI) to display information to users/operators

SCSS Implementation

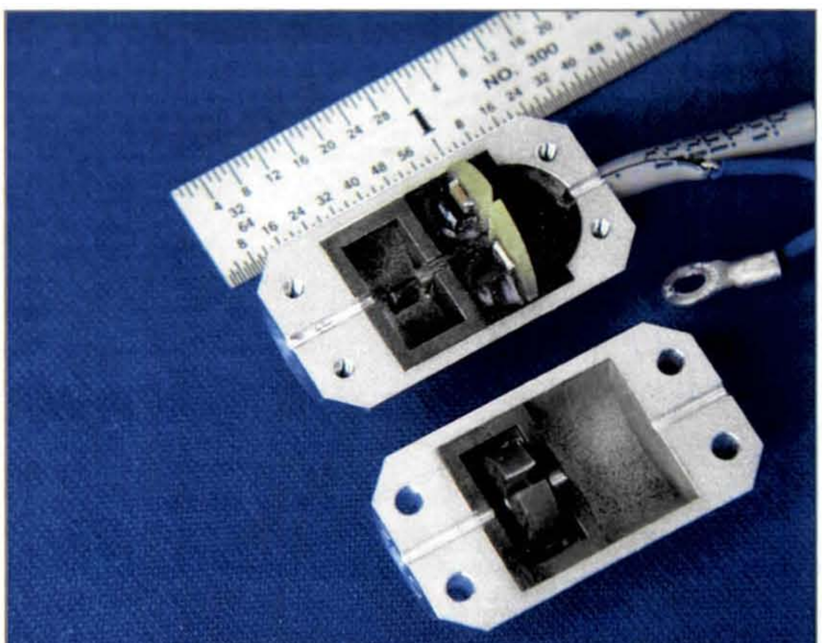
Block Diagram

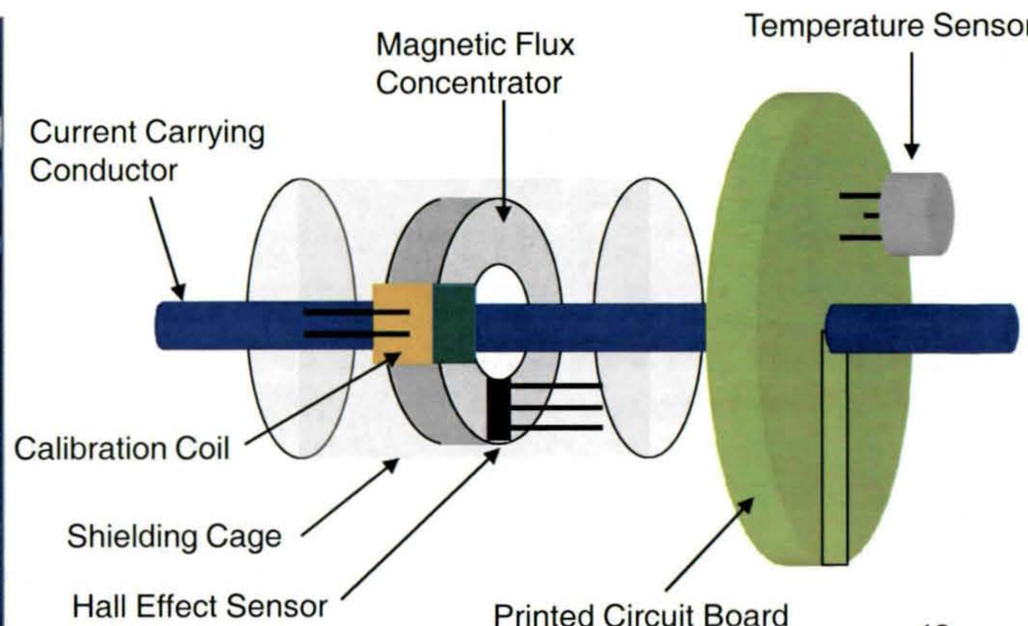


SCSS Implementation - Hardware

Sensor Assembly

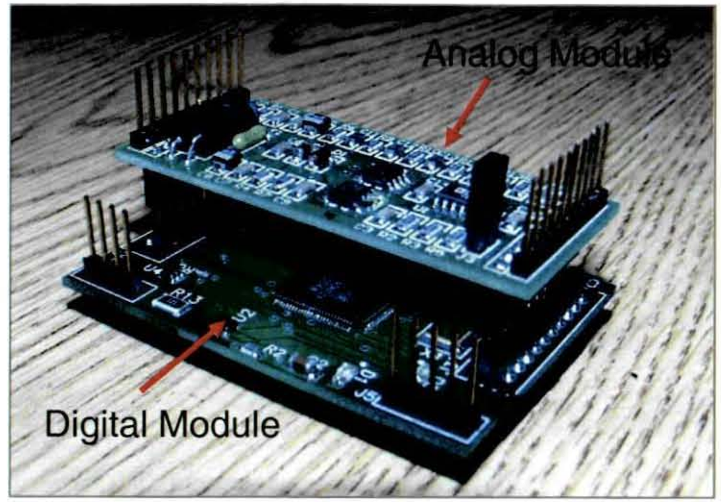
- The Sensor Assembly acquires the electrical current signature from the valve's electrical conductors
  - A Hall effect sensor picks up the associated magnetic field from the electrical current and translate it in an equivalent voltage signal
  - A temperature sensor monitors the Sensor Assembly's temperature information to provide temperature compensation to the SCSS
  - Shielding and magnetic flux concentration is provided by the housing





SCSS Implementation - Hardware

Signal Conditioner and Controller Assembly



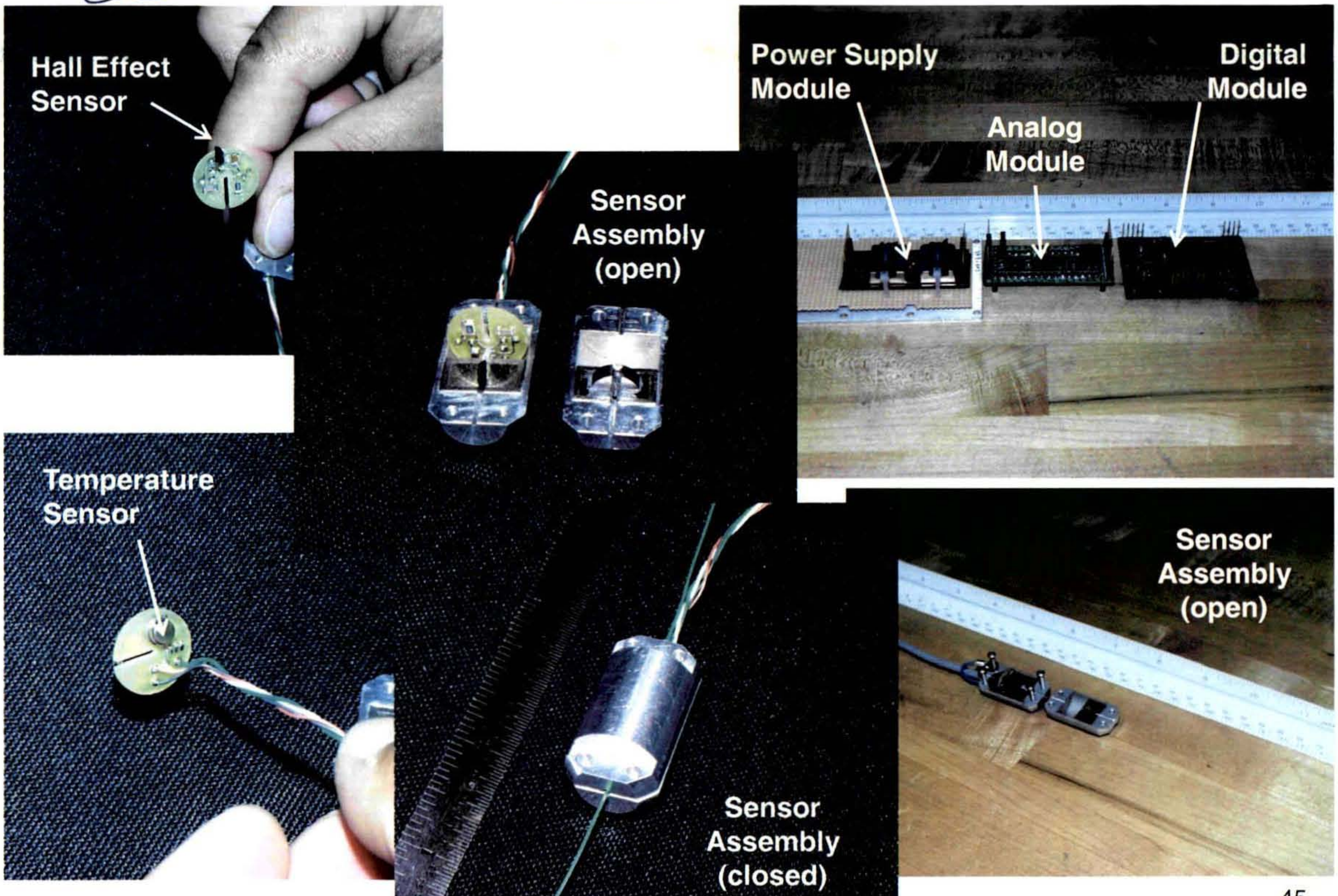
ANALOG MODULE

- Provides signal conditioning to Sensor Assembly
- Extend Hall Effect sensor's acquisition range over temperature to meet required accuracy
    - Provides real-time autonomous compensation
    - Provides real-time calibration adjustments

DIGITAL MODULE

- Processes the data from the sensors in the Sensor Assembly (Hall, temperature)
- Executes the SCSS embedded software algorithms in real-time
    - Filters the current signal from the valve
    - Obtains the first and second derivatives of signal
    - Extract the valve's parameters of interest
    - Identify the parameters that are out of tolerance
    - Stores information related to the valve on board the SCSS
    - Communicates information/health status to the users/operators
- Contains a Digital Signal Processor (DSP) for complex calculations

SCSS Implementation - Prototype



Embedded Software Modes of Operation

SCSS Learning Mode

a. Exercise good valve N cycles to acquire the valve's nominal profile
b. Calculate the identified parameters for each of the signature regions
c. Calculate and baseline the representative values for each parameter
d. Calculate and baseline their associated tolerances

SCSS Operational Mode

1) *Monitoring Mode (in SCSS)*

a. Keep count of the total number of times the valve is cycled
b. Calculate all the identified parameters for each region
c. Verify that the obtained values fall within the nominal (baseline) values plus or minus the specified tolerances for each of the parameters
d. Keep count and record the number of times any "out of tolerance" is detected for any of the parameters in the valve
e. If any "out of tolerance" is detected, report the cycle as "an anomalous" cycle as well as report all the "anomalous" parameters
f. Keep count the total number of "anomalous" cycles in the valve

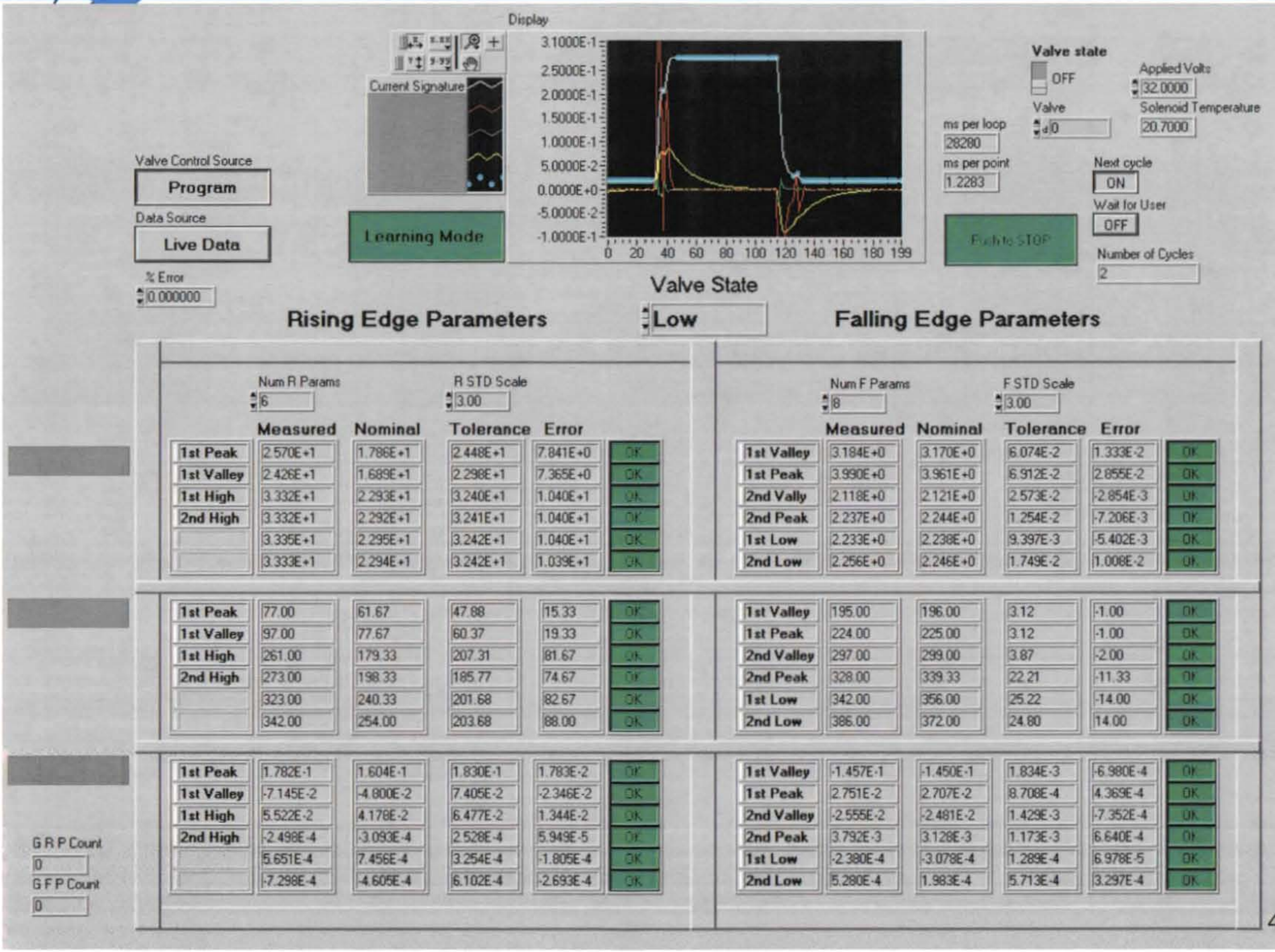
SCSS Implementation - Software

Embedded Smart Software Algorithm

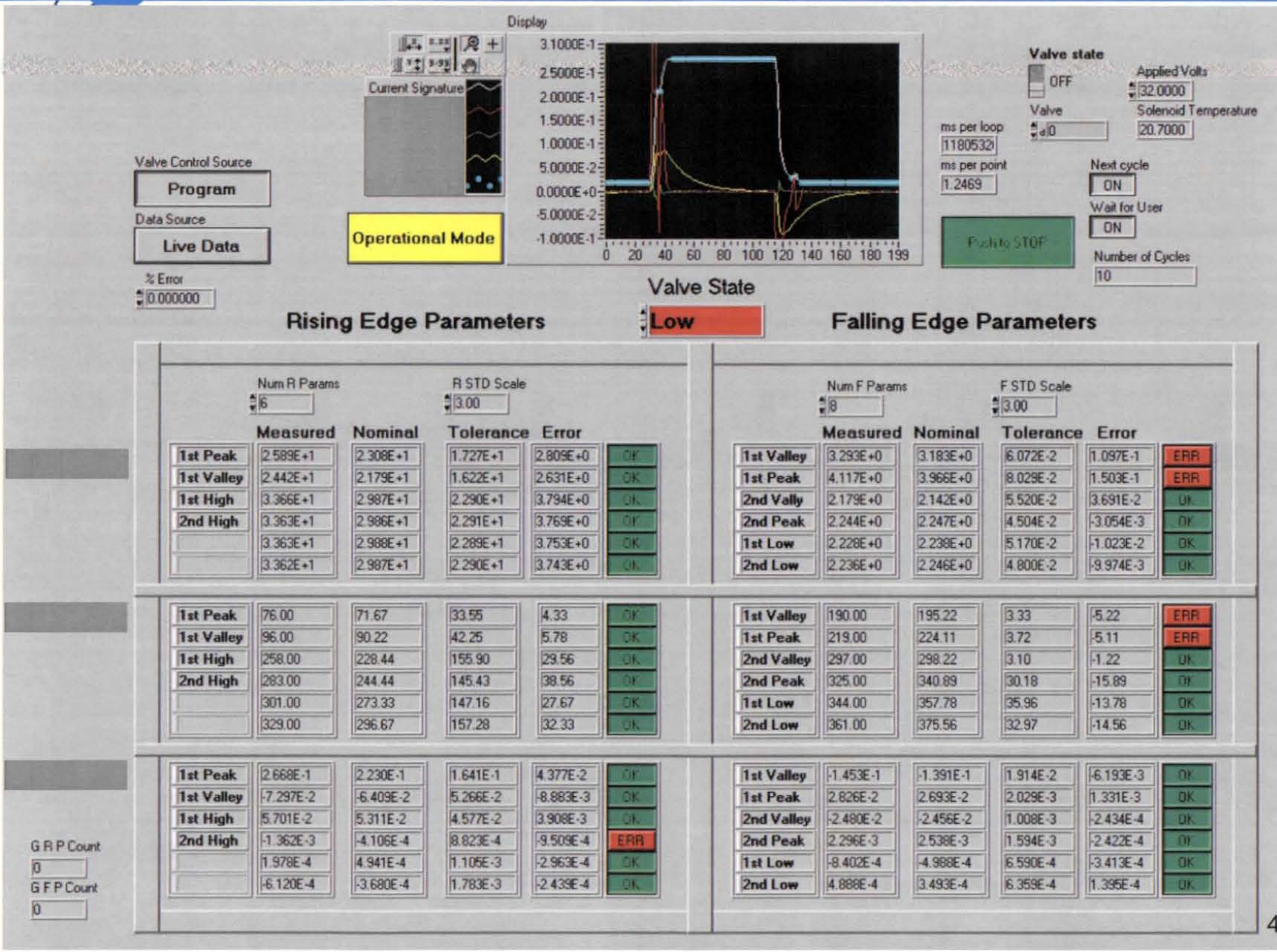
2) *Reporting Mode (in SCSS)*
   a. Remain in *Monitoring Mode* until user/customer requests data
      - Switch to transfer data to user/customer
      - Output the Total Number of cycles
      - Output the Total Number of anomalous cycles
      - Report parameters that were out of tolerance

3) *Analyze, Store, Display Mode (User Interface, external to SCSS)*
   a. External program which reads the data from the Digital Module
   b. Stores information in user's hard-drive, and displays on SCSS GUI
   c. Analyzes which reported anomalous parameters correspond to physical failures, changes or degradation in the valve. Start with known failures to build up the knowledge base of how the valves behave under anomalous / failure conditions.

SCSS Implementation - Graphical User Interface



SCSS Implementation - Graphical User Interface



Rising Edge Parameters

	Measured	Nominal	Tolerance	Error	
1st Peak	2.589E+1	2.308E+1	1.727E+1	2.809E+0	OK
1st Valley	2.442E+1	2.179E+1	1.622E+1	2.631E+0	OK
1st High	3.366E+1	2.987E+1	2.290E+1	3.794E+0	OK
2nd High	3.363E+1	2.986E+1	2.291E+1	3.769E+0	OK
	3.363E+1	2.988E+1	2.289E+1	3.753E+0	OK
	3.362E+1	2.987E+1	2.290E+1	3.743E+0	OK

1st Peak	76.00	71.67	33.55	4.33	OK
1st Valley	96.00	90.22	42.25	5.78	OK
1st High	258.00	228.44	155.90	29.56	OK
2nd High	283.00	244.44	145.43	38.56	OK
	301.00	273.33	147.16	27.67	OK
	329.00	296.67	157.28	32.33	OK

1st Peak	2.668E-1	2.230E-1	1.641E-1	4.377E-2	OK
1st Valley	-7.297E-2	-6.409E-2	5.266E-2	-8.883E-3	OK
1st High	5.701E-2	5.311E-2	4.577E-2	3.908E-3	OK
2nd High	-1.362E-3	-4.106E-4	8.823E-4	-9.509E-4	ERR
	1.978E-4	4.941E-4	1.105E-3	-2.963E-4	OK
	-6.120E-4	-3.680E-4	1.783E-3	-2.439E-4	OK

Falling Edge Parameters

	Measured	Nominal	Tolerance	Error	
1st Valley	3.293E+0	3.183E+0	6.072E-2	1.097E-1	ERR
1st Peak	4.117E+0	3.966E+0	8.029E-2	1.503E-1	ERR
2nd Vally	2.179E+0	2.142E+0	5.520E-2	3.691E-2	OK
2nd Peak	2.244E+0	2.247E+0	4.504E-2	-3.054E-3	OK
1st Low	2.228E+0	2.238E+0	5.170E-2	-1.023E-2	OK
2nd Low	2.236E+0	2.246E+0	4.800E-2	-9.974E-3	OK

1st Valley	190.00	195.22	3.33	-5.22	ERR
1st Peak	219.00	224.11	3.72	-5.11	ERR
2nd Valley	297.00	298.22	3.10	-1.22	OK
2nd Peak	325.00	340.89	30.18	-15.89	OK
1st Low	344.00	357.78	35.96	-13.78	OK
2nd Low	361.00	375.56	32.97	-14.56	OK

1st Valley	-1.453E-1	-1.391E-1	1.914E-2	-6.193E-3	OK
1st Peak	2.826E-2	2.693E-2	2.029E-3	1.331E-3	OK
2nd Valley	-2.480E-2	-2.456E-2	1.008E-3	-2.434E-4	OK
2nd Peak	2.296E-3	2.538E-3	1.594E-3	-2.422E-4	OK
1st Low	-8.402E-4	-4.988E-4	6.590E-4	-3.413E-4	OK
2nd Low	4.888E-4	3.493E-4	6.359E-4	1.395E-4	OK

SCSS Testing

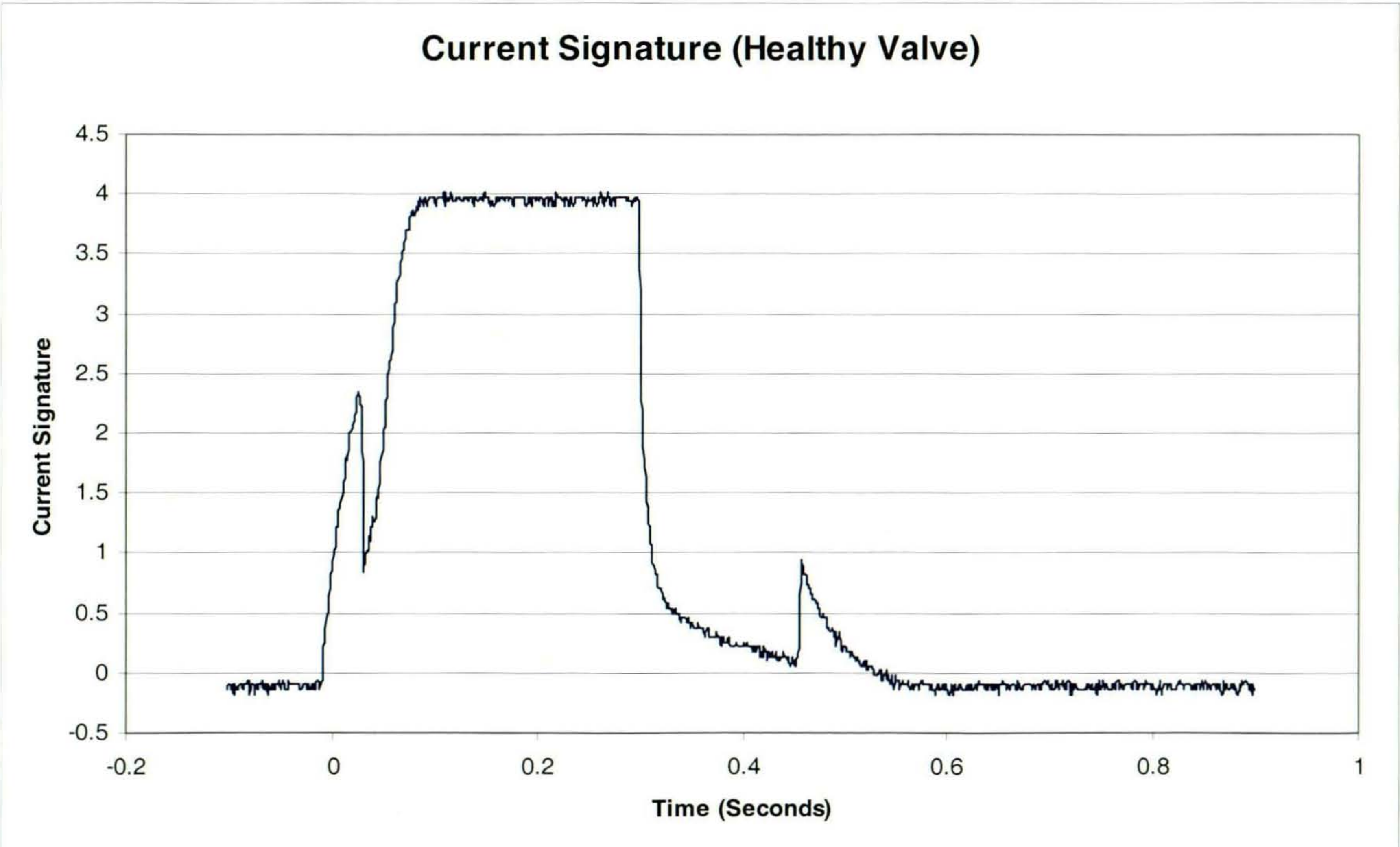
SCSS Testing

- Testing of the SCSS was very comprehensive and included several valves of same family and many cycles for each of the valve

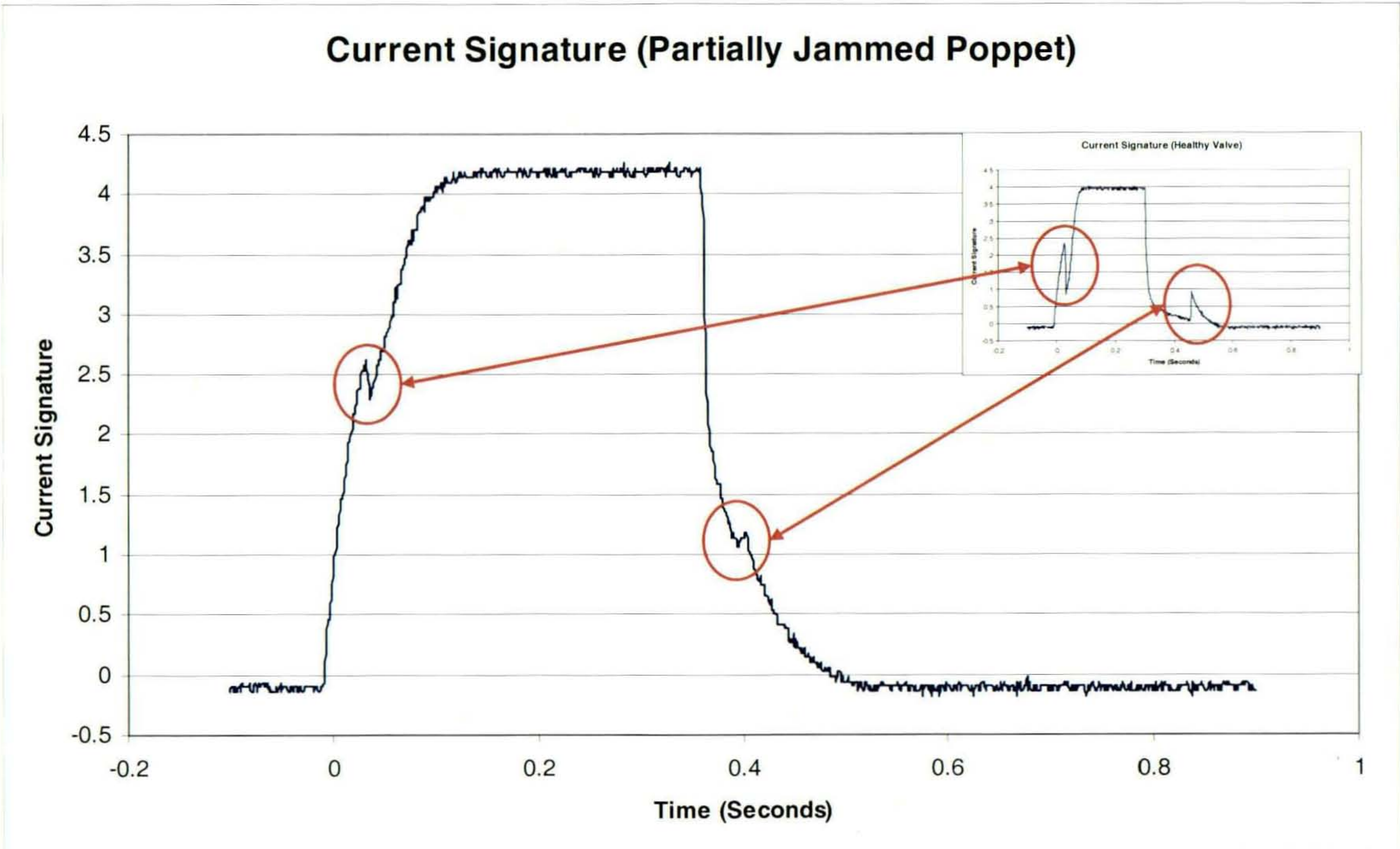
- Testing was conducted a room temperature and at extreme temperature ranges (controlled temperature in an environmental chamber)

- These valve parameters, among others, were controlled and/or physically modified during testing to test/demonstrate the SCSS algorithm:
  - Temperature of the solenoid valve and the Sensor Assembly (T_{amb})
  - Valve's Spring mechanical strength (*k*)
    - To simulate degradation of spring
  - Valve's poppet travel (*x*)
    - To simulate degradation and/or debris in the poppet seat
  - Friction in the poppet's path (*b*)
    - To simulate degradation and/or debris in the valve
  - External power supply voltage (V)
  - Pressure inside the valve (P)

SCSS Testing examples

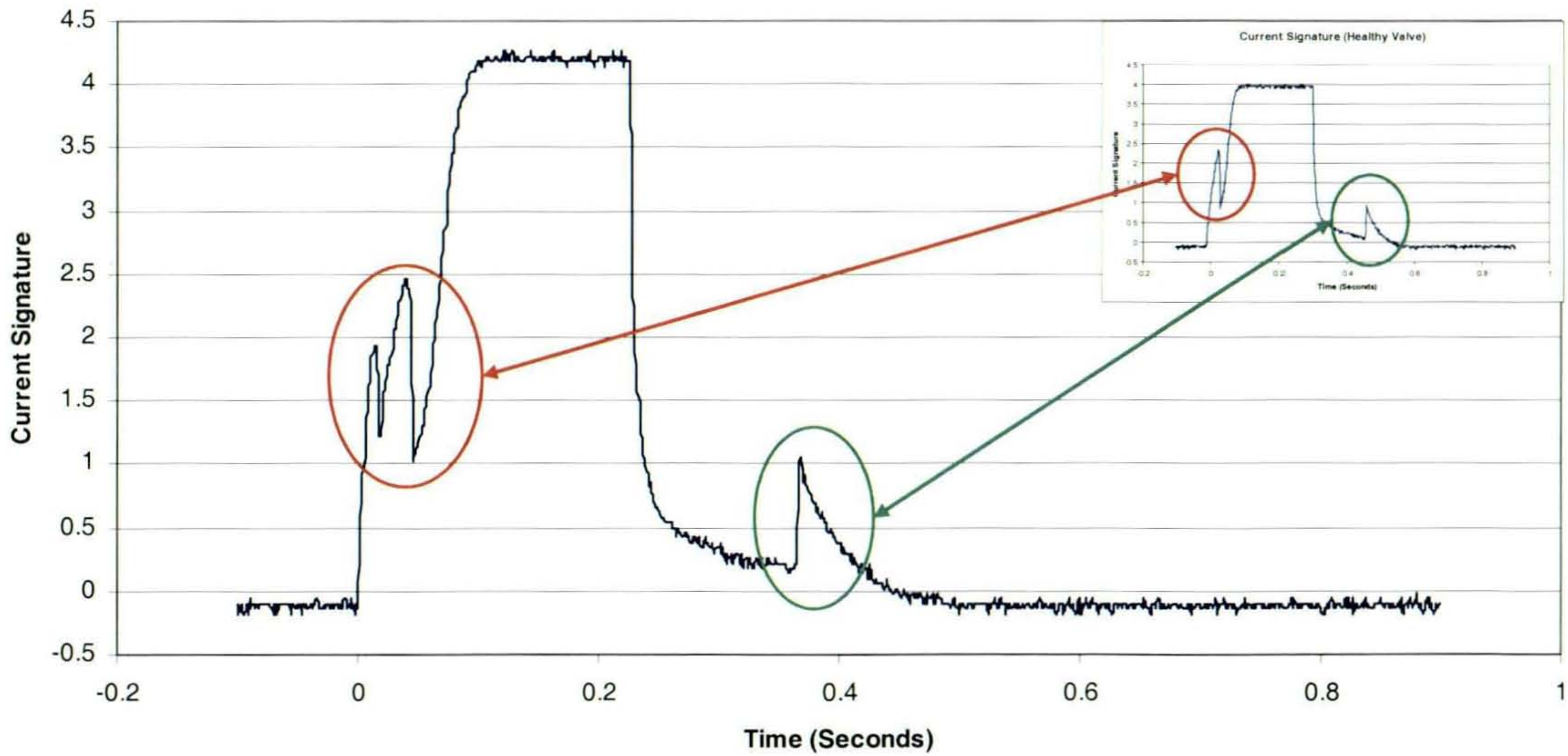


SCSS Testing examples



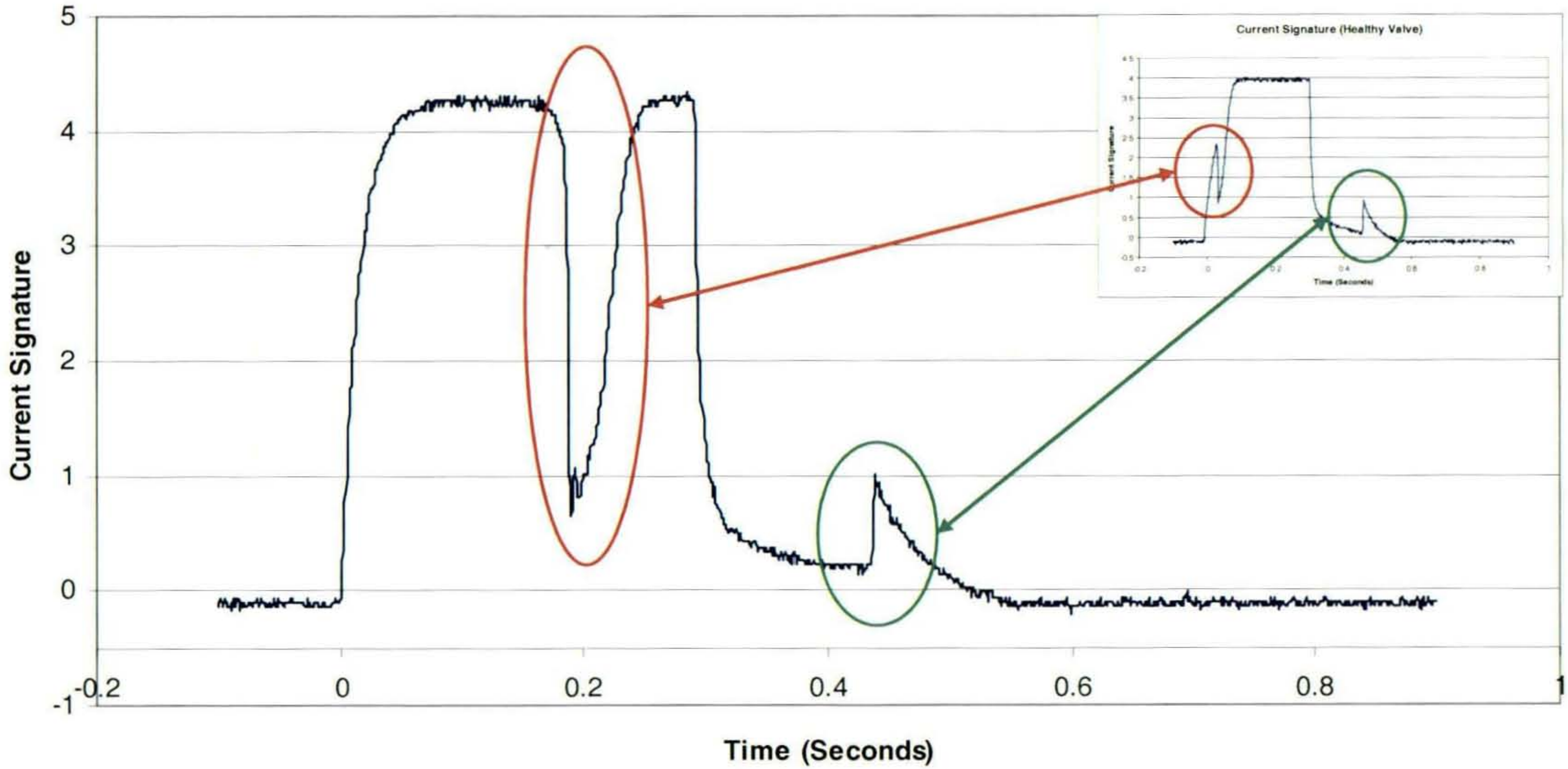
SCSS Testing examples

Current Signature (Poppet Pulled Slightly Out of the Solenoid Before Energizing, The De-Energizing Phase is Normal)

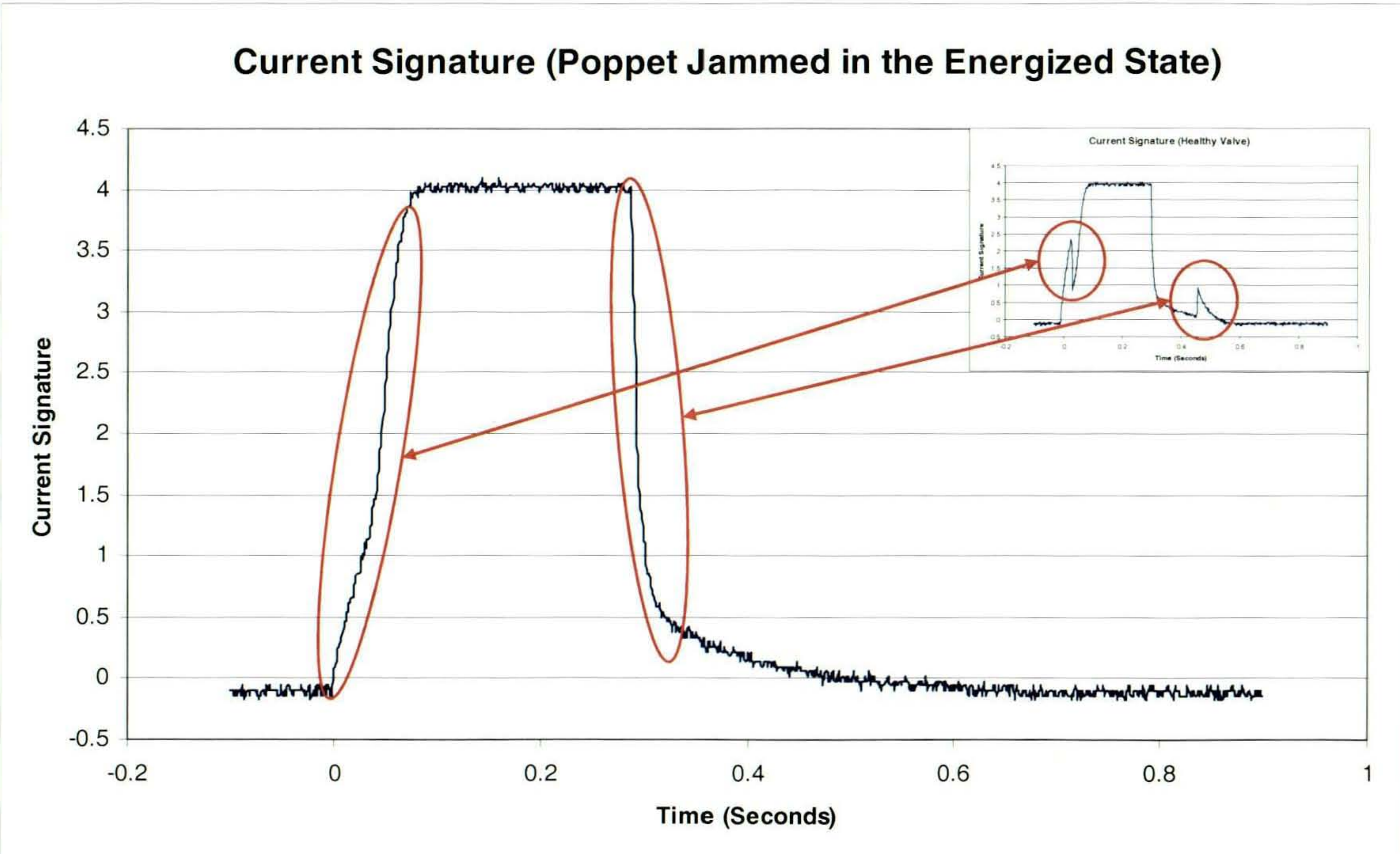


SCSS Testing examples

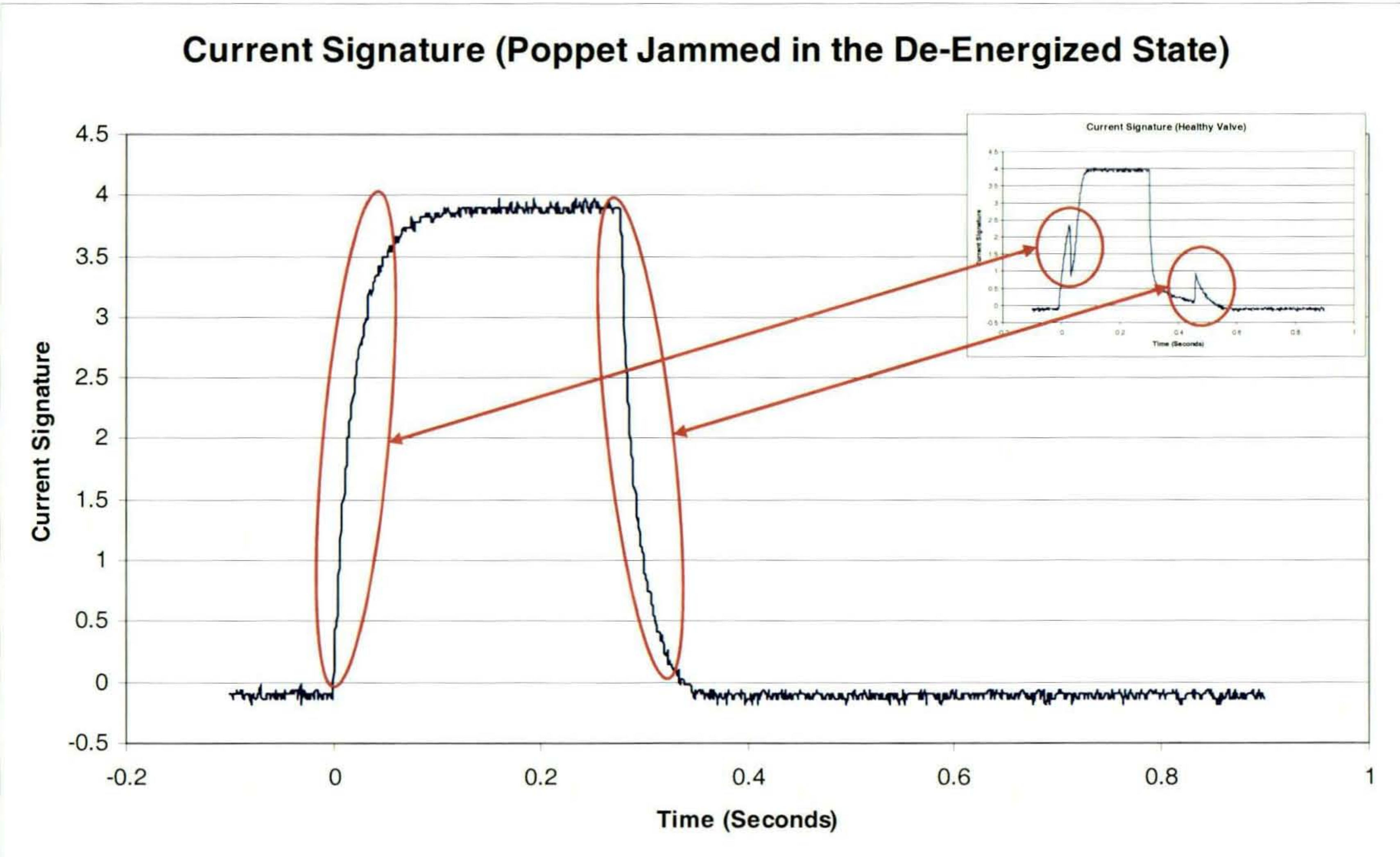
Current Signature (Poppet Pulled Significantly Out of the Solenoid Before Energizing, The De-Energizing Phase is Normal)



SCSS Testing examples



SCSS Testing examples



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SCSS Present Status

Present status

- Technology Present Status
  - Software Algorithms and prototype were developed and tested in the laboratory under extreme temperature environment
  - A few prototypes were built to demonstrate the technology
  - Associated User interface software was generated, tested and implemented in a laptop environment
  - Simulation software was created to run algorithms against recorded data
  - No additional funding was received for the project

- Commercial Spin-Off
  - Limited licensing agreement with Schaffer LLC for commercialization (2006)
  - Limited licensing agreement with Graftel LLC for commercialization (2009)

- Technology Patents and Awards
  - US Patent was awarded to KSC for this design (U.S. # 6,917,203 - 2005)
  - Honorable Mention by the Federal Laboratories Consortium FLC Southeast region for Excellence in Technology Transfer (2010)

Future Steps & Intelligent Devices

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Future Steps for SCSS

- Future Steps for SCSS
  - Hardware
    - Implementation needs to be redesign due to components' obsolescence (DSP, memory)
    - Auto-calibration circuit needs to be implemented in hardware
    - New implementation should be redesigned to conform to latest Intelligent Devices architecture/standards
  - Software
    - DSP embedded code needs to be updated/upgraded to the new available DSP
  - Algorithms
    - Additional algorithms should be developed to include embedded prognosis capabilities
  - Health algorithms could be implemented in many different hardware platforms

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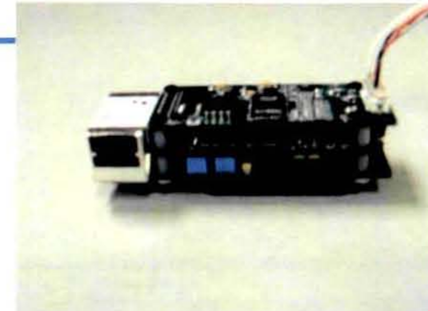
Intelligent Devices

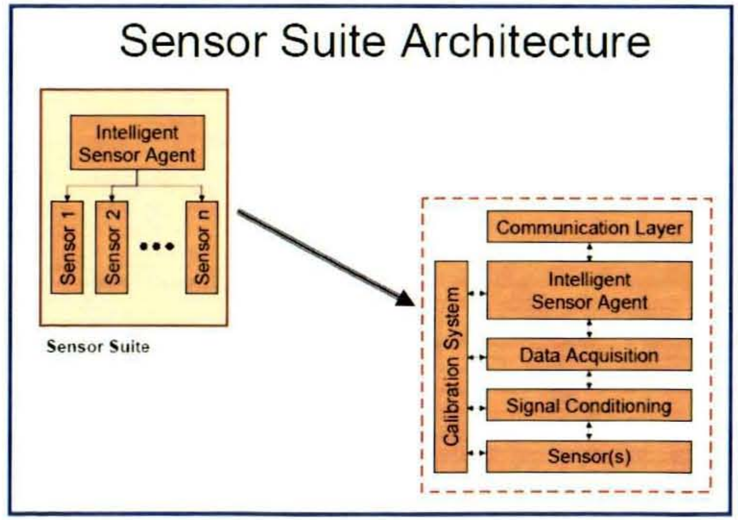


INTELLIGENT DEVICES GOALS

- Provide valid information (assess and qualify the validity of the data)
- Provide information versus raw data (data conversion and compensation)
- Provide sensor/actuator health status (degradation and failure detection)
- Provide embedded self-healing capabilities (self-calibration and self-reconfiguration)
- Provide networking capability (wired and/or wireless)
- Provide higher reliability and longer calibration cycles
- Provide automation and ultimately autonomy, reducing human intervention (reduced maintainability costs)
- Provide measurement standardization (IEEE 1451, Power over Ethernet, etc)

INTELLIGENT DEVICES CHARACTERISTICS

- Self-identification (Configuration Control)
- Embedded intelligence
  - Data digitization and conversion,
  - Time stamping and data synchronization
  - Complex signal processing (trending, averaging, etc)
  - Data storage
  - Self-health assessment (Data Validity and Availability)
  - Auto-calibration capability
  - Self-reconfiguration capability
  - Health Management capability
- Proposed Health Electronic Data Sheets (HEDS) approach



PROJECT STATUS

- Sensor Architecture has been defined and baselined
- Hardware prototypes have been developed and tested for temperature and pressure
- Implementation of IEEE 1451 standards have been demonstrated
- Implementation of IEEE 1588 Precision Time Protocol (PTP) standard has been demonstrated
- Implementation of IEEE 802.3af Power over Ethernet (PoE) standard has been demonstrated
- Communication over Ethernet and ControlNet protocols have been demonstrated

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Summary/Conclusion

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- Algorithm has been designed and demonstrated
- An implementation of the design has been built and demonstrated
- Commercialization of the design has been done
- Intellectual property has been secured through patent
- Design needs to be incorporated in the new Ground Operations architecture

Innovators, Contributors and Acknowledgements

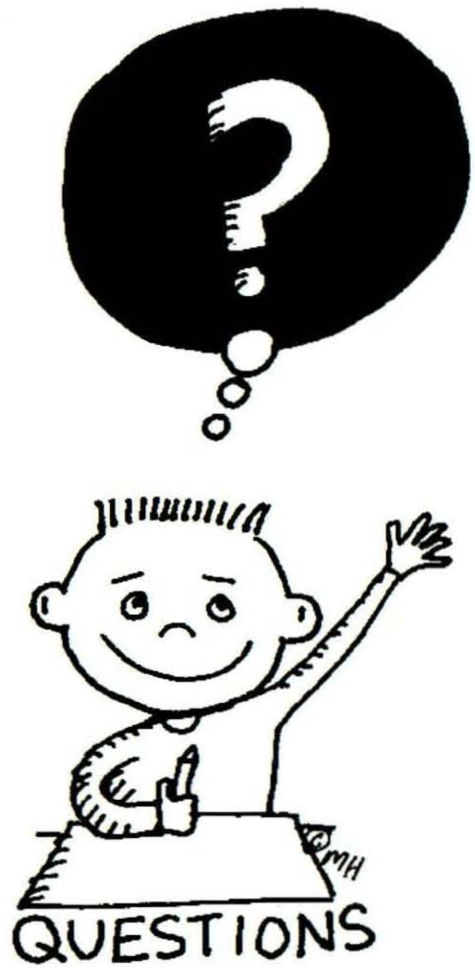
SCSS Development Team

Development Team

- Mr. Angel Lucena, NASA, Embedded Systems Developer
- Mr. Mario Bassagnani, NASA, Mechanical Designer
- Mr. Curtis Ihlefeld, NASA, Electrical/Electronics Designer
- Mr. Bradley Burns, ASRC, Electrical Electronics Designer
- Dr. John Lane, ASRC, Valve Modeling

Contributors

- Dr. Carl Latino, Oklahoma State University, Neural Networks algorithms
- Dr. Ibrahim Tansel, Florida International University, Wavelet algorithms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QUESTIONS