Multi-domain Modeling and Simulation of a Linear Actuation System

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Outline

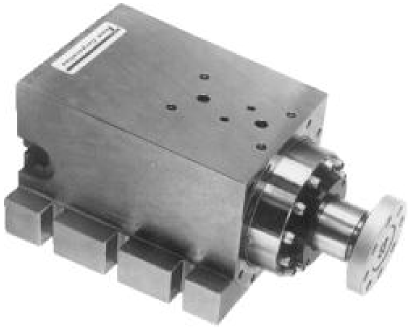
- Introduction
- Multi-domain Modeling of a Linear Actuation System
  - Top-level schematic
  - Modeling systems belonging to different domains
- Modeling Approaches of Solenoid
  - Behavioral VHDL-AMS
  - Table look-up model
  - Comparison of simulation characteristics
- Discussion and Conclusions

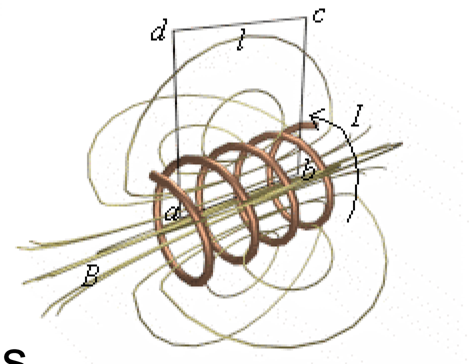
Introduction

- System Design in the Automotive Industry
  - Mixed-signal multi-domain systems
  - Previously proprietary languages used for component and system modeling
  - Dependent on simulation tool vendors
- Standardization of VHDL-AMS
  - Choice of simulation tools
  - Easy model delivery from suppliers to OEMs
  - Large community of model developers

Multi-domain Modeling

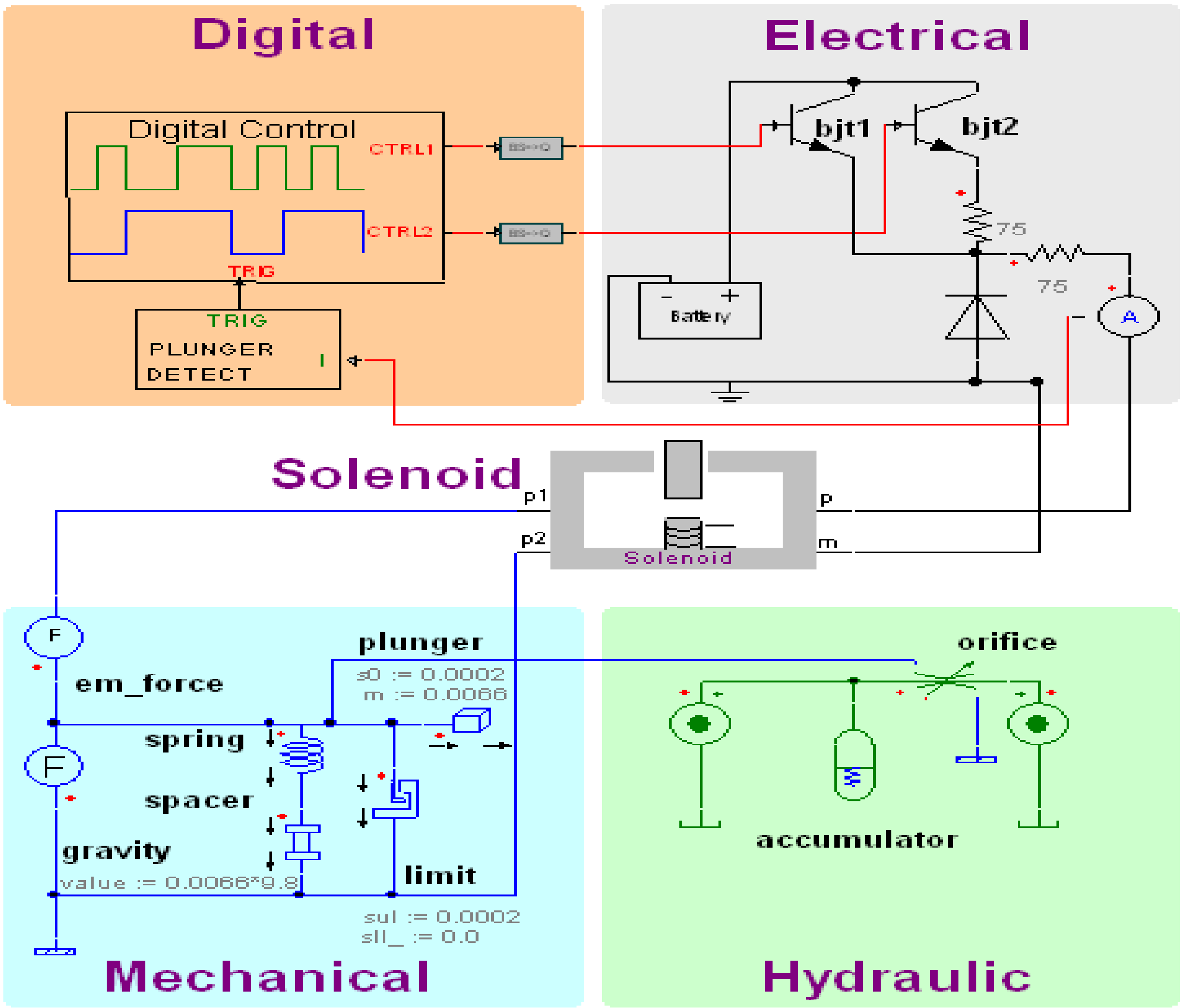
- Linear Actuation System
  - Domains
    - Electrical
    - Mechanical
    - Hydraulic
    - Digital control
- Solenoid
  - Interfaces electrical and mechanical domains
  - Complex electromagnetic principles





Solenoid pictures sources:
http://www.univ-mlv.fr/enseignement/cours/sctechno/s2_chap2/solenoid.gif
http://www.tecalemit.co.uk/solenoids.html
http://www.teamcorporation.com/ team2002/lin_act.html

Linear Actuation System



Modeling Approaches

- Constant Lumped Inductance Value
  - Behavioral VHDL-AMS model
  - Derive inductance parameter
    - Hand calculations
    - Output from finite element analysis tool
  - Low accuracy
- Non-linear Inductance Value
  - State space model
  - Table look-up
    - Multi-dimensional table model implemented as internal component
    - Limited support in VHDL-AMS
  - Better accuracy because inductance changes with coil current and plunger position

Behavioral VHDL-AMS Model

$$L_{\max} = N^2 * L_0$$

$$L(x) = \frac{L_{\max}}{1 + Kx}$$

$$F_k = \frac{K}{2 * L_{\max}}$$

$$\phi = L(x) * i$$

$$v = \frac{\partial \phi}{\partial t}$$

$$F = \phi^2 * F_k$$

N = Number of coil turns
K = Inductance coefficient
x = Plunger position, m

L_0 = Max inductance value/turn at min air gap, H
L(x) = Instantaneous inductance value at *x*, H
L_{max} = Max inductance for all turns, H

F_k = Force at max inductance for given K, N
ϕ = Instantaneous flux through solenoid, Wb
i = Current through solenoid, A
v = Voltage across solenoid, V
F = Force output from solenoid, N

Behavioral VHDL-AMS Model (2)

```
LIBRARY IEEE;
USE IEEE.ELECTRICAL_SYSTEMS.ALL;
USE IEEE.MECHANICAL_SYSTEMS.ALL;

ENTITY solenoid IS
  GENERIC (
    L0 : REAL := 4.05e-7;
    K : REAL := 6328.0;
    N  : REAL := 1500.0);
  PORT (
    TERMINAL p,m : ELECTRICAL;
    TERMINAL pos1, pos2 : TRANSLATIONAL);
END ENTITY solenoid;
```

```
ARCHITECTURE behav OF solenoid IS
  CONSTANT Lmax : REAL := L0 * N * N;
  CONSTANT Fk   : REAL := K / (2.0 * Lmax);
  QUANTITY v ACROSS i THROUGH p TO m;
  QUANTITY position ACROSS force THROUGH pos1 TO pos2;
  QUANTITY L, flux : REAL;
BEGIN
  IF (position > 0.0) USE
    L == Lmax / (1.0 + K * position);
  ELSE
    L == Lmax;
  END USE;
  flux == L * i;
  v == flux'dot;
  force == flux * flux * Fk;
END ARCHITECTURE behav;
```

Hand Calculation

$$L_0 = \frac{\mu N^2 A}{l}$$

$\mu = \mu_0 \mu_r$ = Permeability of medium, H/m

N = Number of turns of solenoid

A = Cross-sectional area of solenoid, m^2

l = Length of solenoid, m

- Uses classical equation for solenoid inductance
- Assumption
  - Permeability of medium is constant
  - Solenoid is very long
    - Does not include fringing effects

$\mu_0 = 4\pi \times 10^{-7}$ H/m

$\mu_r = 800$

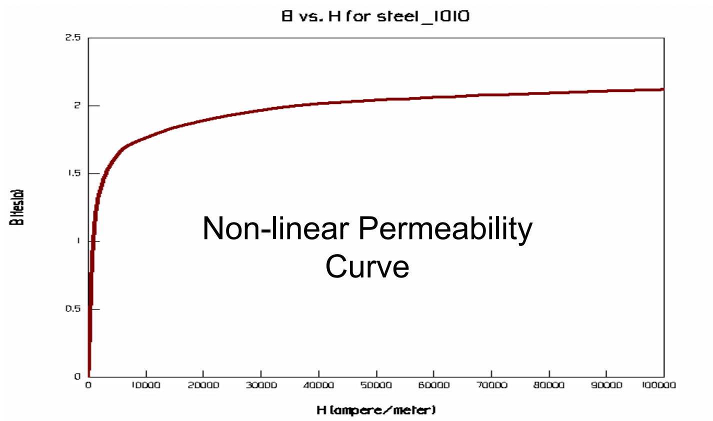
N = 1 turn

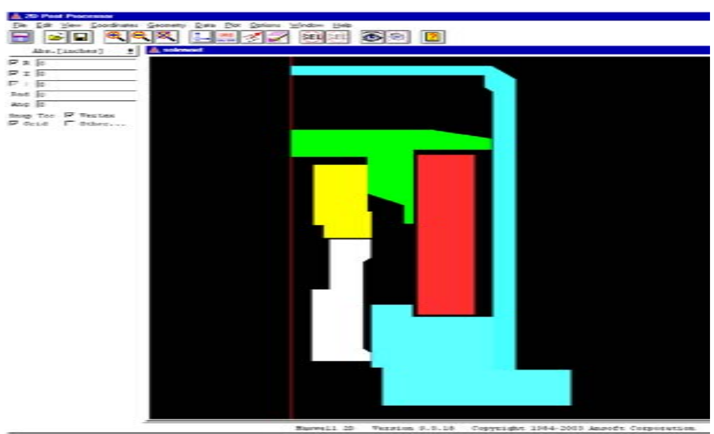
$A = 1.2 \times 10^{-5}$ m^2

$l = 1.5 \times 10^{-2}$ m

$L_0 = 0.8\ \mu H$

FEA Calculation



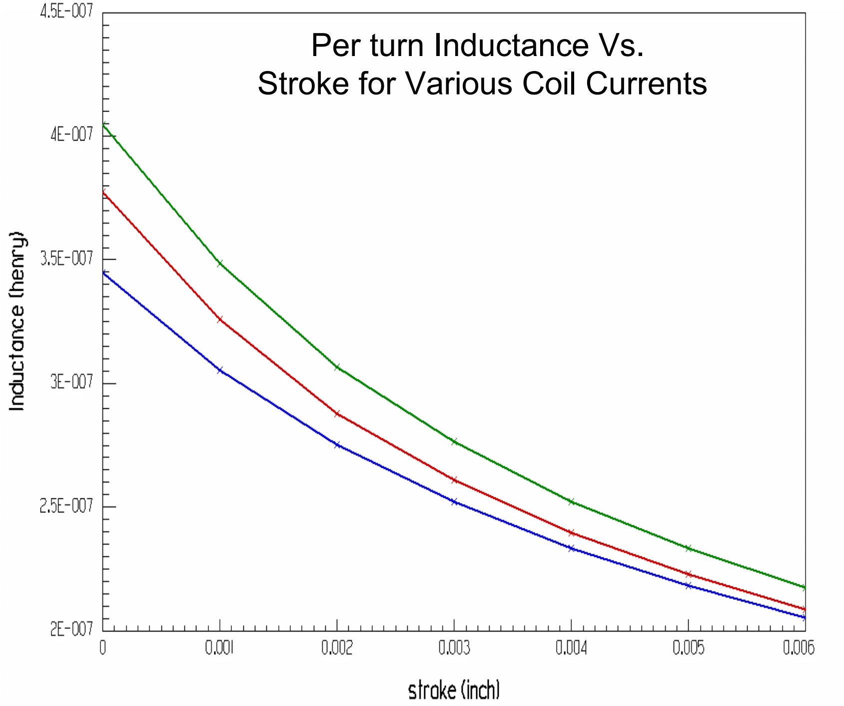


Cross section of the Solenoid

- In reality
  - The L_0 value depends on the permeability μ
- The permeability varies
  - Spatially
  - Temporally
- FEA considers
  - Exact geometry of structure
  - Non-linear material definition
- By solving a static magnetic field problem we arrive at:

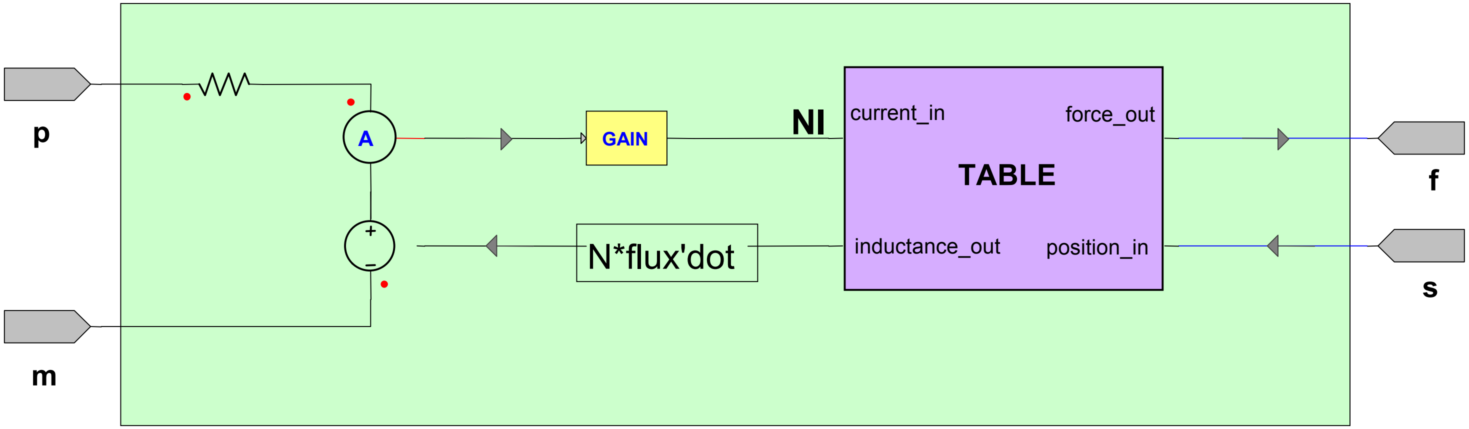
$$L_0 = 0.405\ \mu\text{H}$$

Non-linear Table Look-up Model



- Inductance varies non-linearly with
  - Coil current
  - Stroke (position)
- Parametric FEA analysis
  - Series of magnetostatic solutions
  - Assemble values in a table for look-up

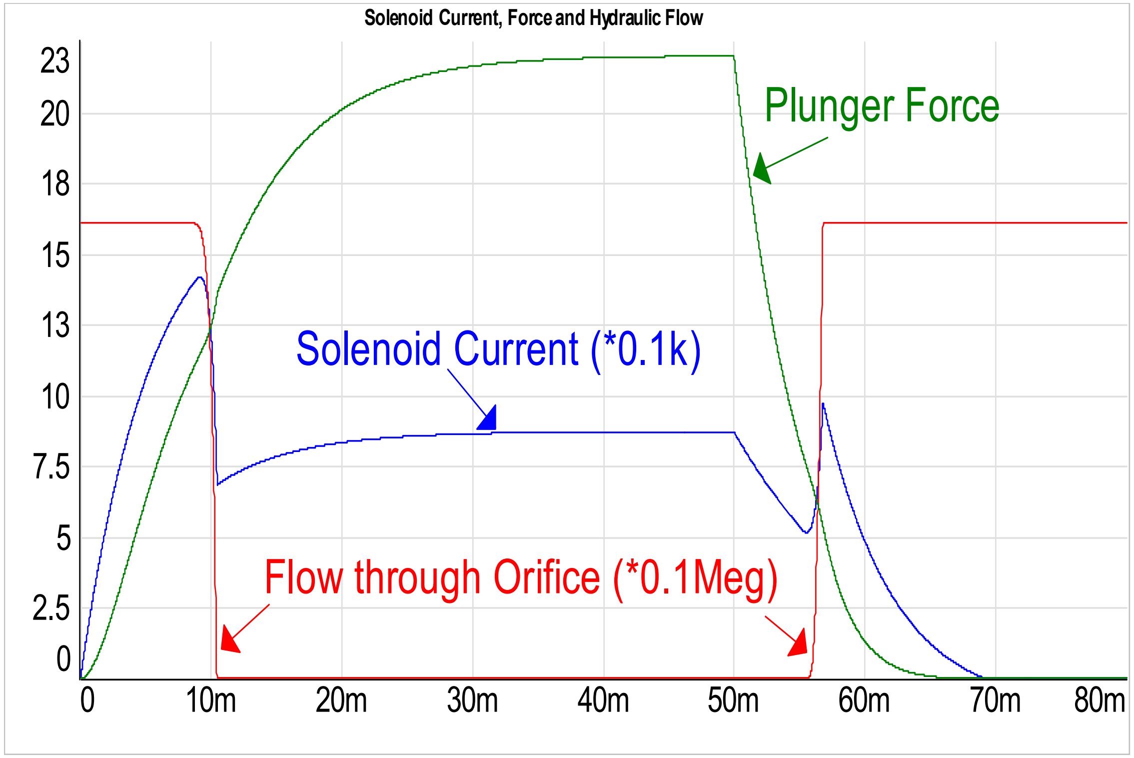
Non-linear Table Look-up Model (2)



- Table look-up Model
  - Inputs
    - Coil current
    - Stroke
  - Outputs
    - Force
    - Inductance

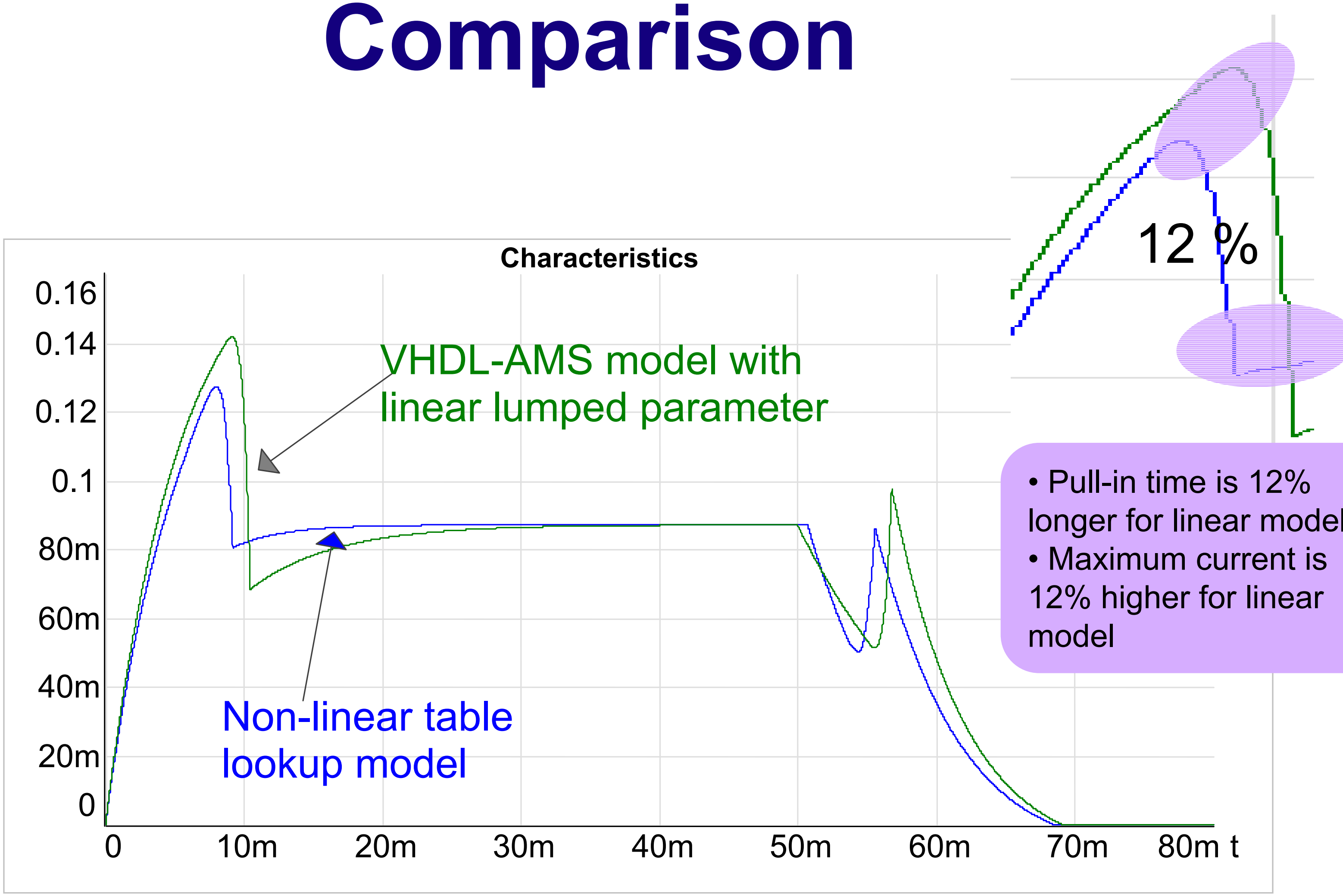
- Implemented in SIMPLORER®
- No direct support in VHDL-AMS
  - Can be implemented indirectly

Simulation Characteristics



Solenoid Current, Force, and Hydraulic Flow

Comparison



- Pull-in time is 12% longer for linear model
- Maximum current is 12% higher for linear model

Comparison of Solenoid Current Characteristics

Language Extension

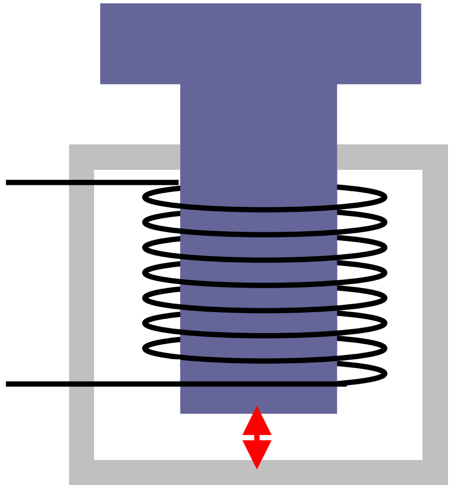
- Currently Possible with Separate Package
  - User defined table datatypes for look-up
  - Interpolation functions for data in the table
- Disadvantages
  - Implementation at the language level
  - Interpolation functions not optimized for individual simulators
  - Large simulation times
- Suggested Approach
  - Standardize table element and functions in VHDL-AMS
  - Individual vendors can include optimized functionality in their tools

Conclusions

- VHDL-AMS is suitable for multi-domain mixed-signal automotive applications
- Multi-domain linear actuation system was examined
- Non-linear solenoid modeling approaches were discussed
- VHDL-AMS language extension suggested
  - Standardized table element and associated functions

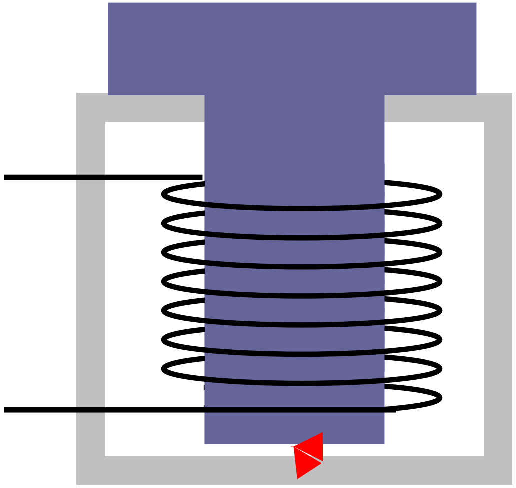
Solenoid Action

Plunger Out



Long Air Gap

Plunger Attracted In



No Air Gap

- Challenging
- Multi-domain component
- Electromagnetic principles