Equivalent Resistor for Nonlinear Magnetic Diffusion in Electromechanical and Electrohydraulic Systems Models

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Outline

- 1) Introduction – Why study?
- 2) Simplorer model for slow speed electromechanical operation without nonlinear eddy currents
- 3) Magnetic diffusion time predictions using Maxwell's nonlinear transient capability
- 4) Equivalent resistor for nonlinear diffusion
- 5) Electromechanical Simplorer models for high speed operation without and with diffusion resistor
- 6) Electrohydraulic Simplorer models for high speed operation without and with diffusion resistor
- 7) Conclusions

INTRODUCTION

- 1) **Magnetic actuators** must produce **rapid motion** for applications including: *solenoids*, *other electromechanical systems*, *fuel injectors*, *brakes*, *and other electrohydraulic systems*.
- 2) Maxwell magnetostatic finite element analysis is often used to model magnetic actuators in Simplorer, and an example Bessho actuator is accurately modeled here.
- 3) Many actuators are axisymmetric and made of solid steel. Turning on a DC voltage causes *eddy currents* which can slow the actuator response due to *magnetic diffusion*.

INTRODUCTION continued

- 4) This paper shows that Maxwell accurately computes *nonlinear magnetic diffusion times* for various nonlinear B-H curves of steel.
- 5) It then shows how the diffusion times obtain an equivalent resistor, and uses it in Simplorer models of high-speed performance of electromechanical and electrohydraulic systems.

Slow Speed Performance of Bessho DC Plunger Actuator

- Solid steel geometry is used by Bessho, Yamada, and Kanamura in their 1978 paper from Japan:

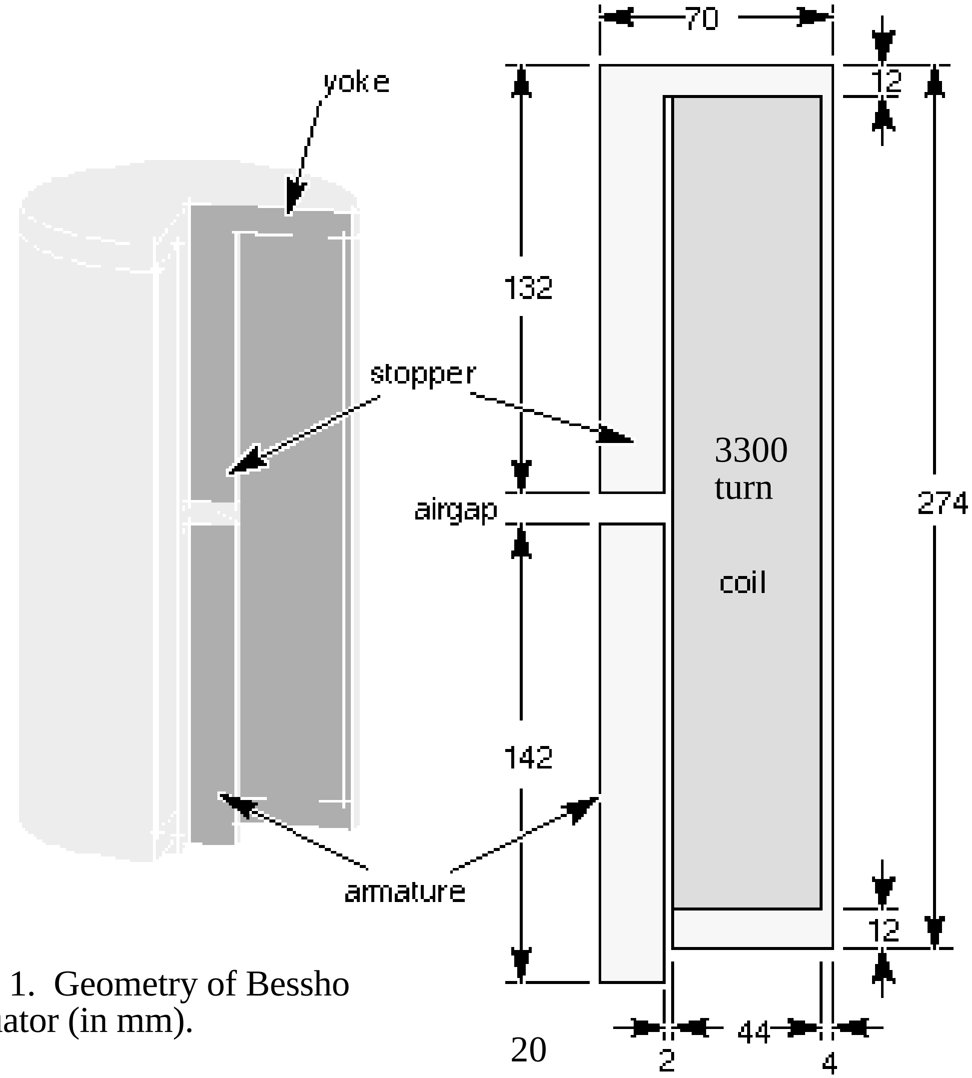
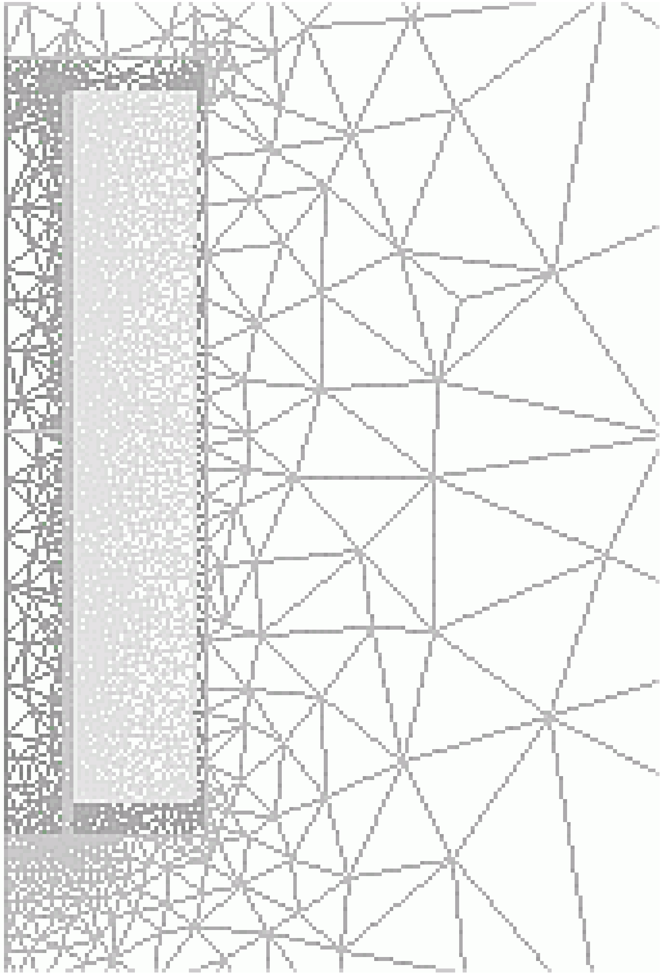


Fig. 1. Geometry of Bessho actuator (in mm).

Finite Element Actuator Model

for typical armature position (closed) of Bessho actuator

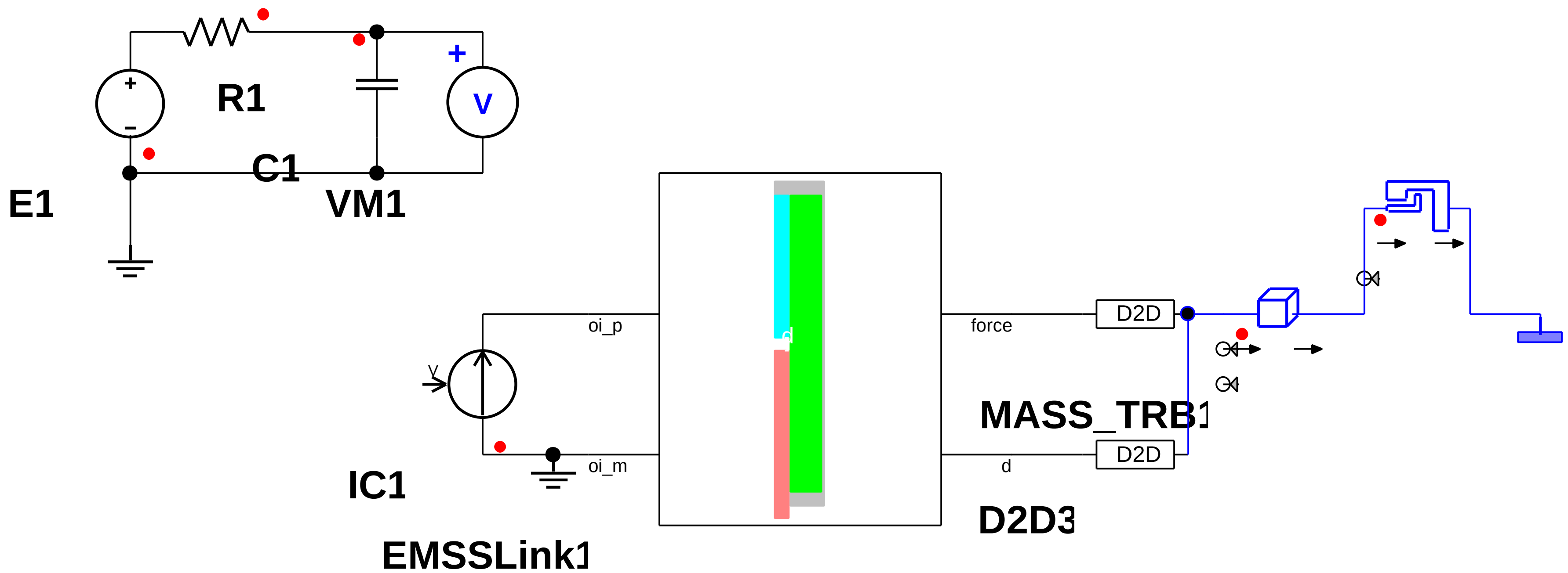


Model and results obtained using Maxwell® magnetostatic solution at air gaps ranging from 0 to 10 mm and currents ranging from 0 to 0.5 amps, the maximum input.

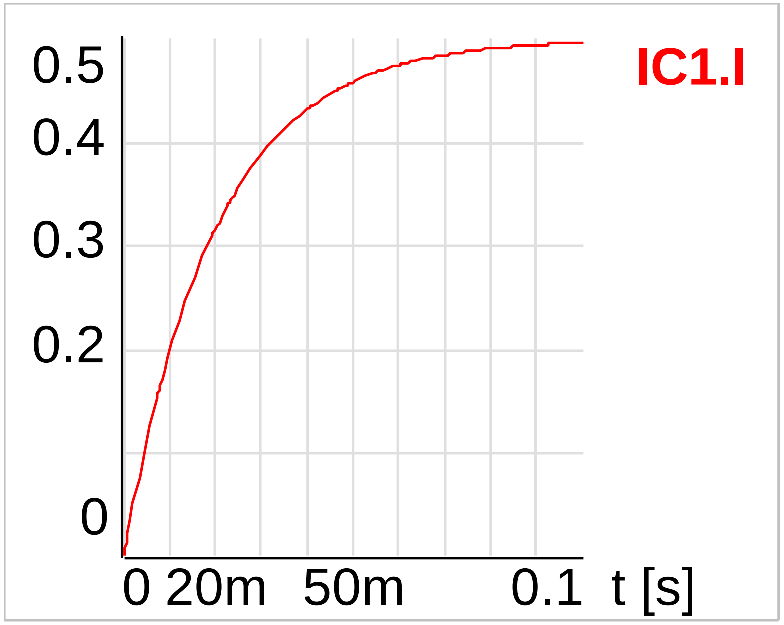
Performance of Bessho DC Plunger Actuator at Slow Speed

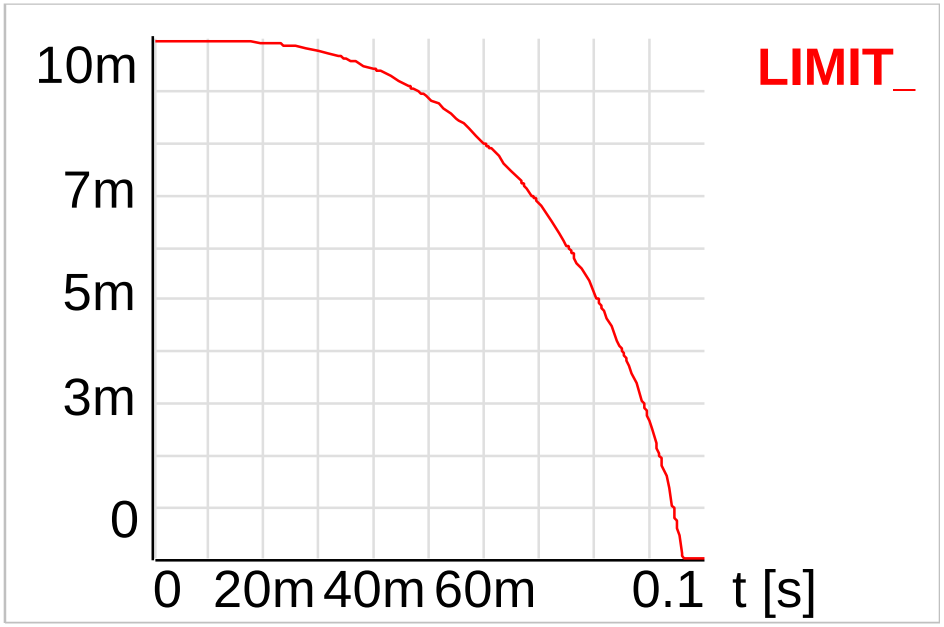
- Maxwell magnetostatic model is transferred to Simplorer using its ECE link.
- Simplorer model has total moving mass = 6 kilograms, following Bessho measurements.
- Input current waveform is assumed to follow Bessho measurements of time constant = 20 ms and peak I = 0.5 amps.
- Due to heavy mass and slow current rise, the actuator operates *slowly*, with measured closing time (for 10 mm movement) of approximately 100 ms.
- The computed closing (operation) time of the Simplorer model is 97 ms, agreeing closely with measurements.

Simplorer Model of Bessho DC Plunger Actuator at Slow Speed with No Diffusion Resistor



Input and Output of Bessho DC Plunger Actuator at Slow Speed with No Diffusion Resistor





97 ms computed compares with approx. 100 ms measured

Magnetic Diffusion Time for linear B-H

- Magnetic diffusion time t_m is the time it takes for B in the center of a conducting material to reach approximately 63% of its final value.
- Diffusion time for actuators can be estimated using the formula *for cylindrical materials with constant permeability* μ *(linear B-H)* [Brauer & Chen, 2000]:
- $$\mathbf{t_m = \mu s \; R^2 / (2.4048)^2} \qquad (1)$$

  where s is electrical conductivity, R is the cylinder radius, and the value 2.4048 is the root of 1st order Bessel function. If **s** = 0 there are no eddy currents and $\mathbf{t_m}$ **=** 0.

Magnetic Diffusion Time for linear B-H Cont.

- For the Bessho actuator, the conductivity of all steels is specified as 1.7E6 S/m. There are two different B-H curves; one for the armature and stopper, and the other for the yoke. The armature B-H curve begins with a constant permeability of 630 times that of air. The resulting magnetic diffusion time $\mathbf{t_m = 93\ ms}$.
- However, nonlinear transient finite element computations [Brauer & Ruehl, 1994] have obtained closing times with the above steel as low as **51 ms**.

Magnetic Diffusion Time for linear B-H Cont.

- In my experience, a manufacturer of fuel injectors has stated (paraphrasing): "Application of the linear diffusion time formula to our injectors shows that they would never work nearly as fast as they actually do!"
- Unfortunately, due to proprietary agreements, I cannot discuss these actuators nor any others I have studied for various manufacturers.

Magnetic Diffusion Time Including Nonlinear B-H cont.

- *Nonlinear* magnetic diffusion time t_m is here investigated using the nonlinear transient capability of Maxwell.
- While the entire actuator could be modeled, here a thin (10 mm) slice is modeled to observe general behavior. It includes plunger, coil, and yoke, modeled with 1000 to 3000 elements.
- First, with constant relative permeability = 630, the computed diffusion time agreed with 93 ms of (1).
- Next the actual B-H curves were used at various current levels, assumed to jump from 0 in 0 time.

Magnetic Diffusion Time Including Nonlinear B-H cont.

- Flux lines for I=0.5 amp jump at t=5, 20, 40 ms:

5

20

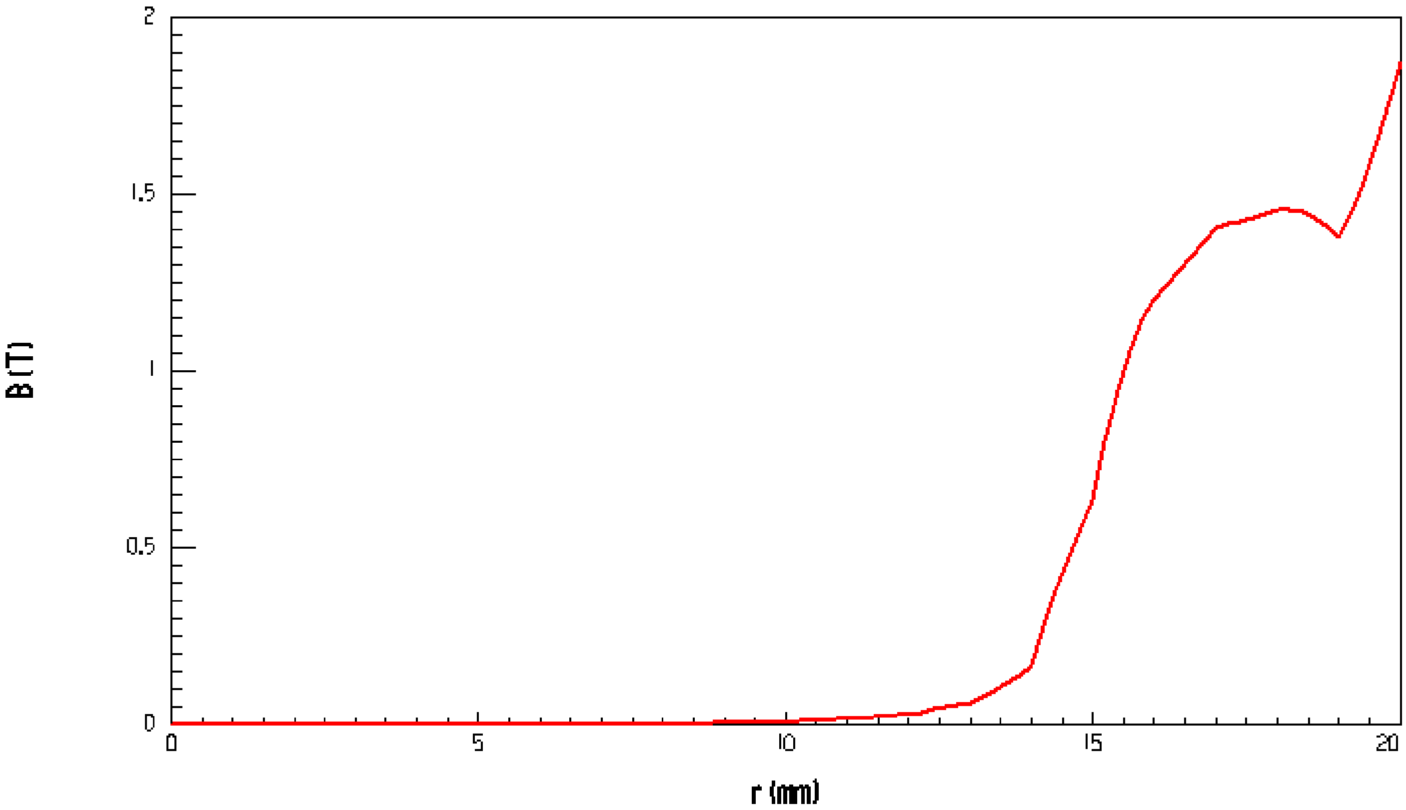
40

Approx = t_m

NL Magnetic Diffusion cont.

- B vs r for I=0.5 amp jump at t=5, 20, 40 ms:

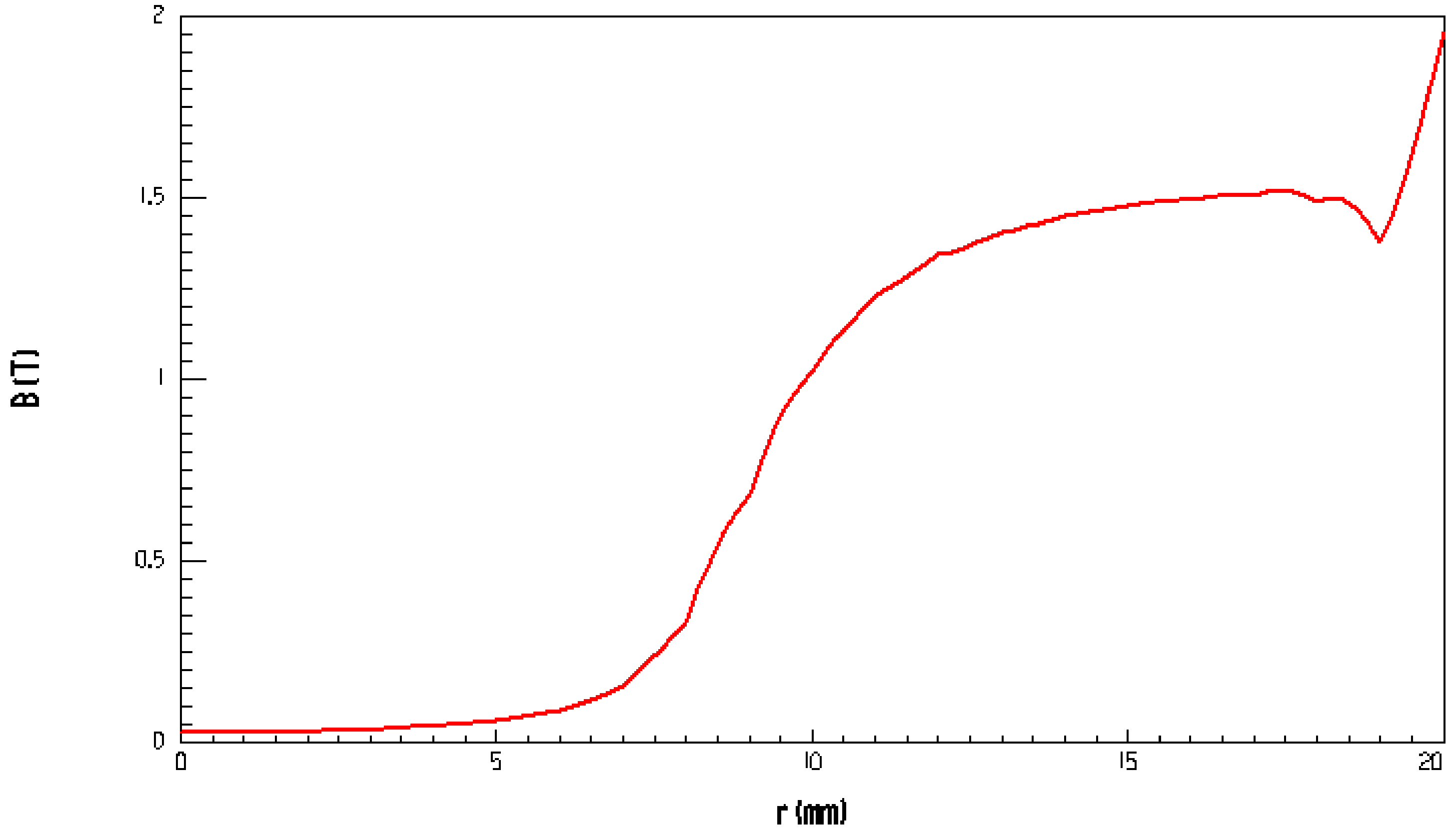
5 ms



NL Magnetic Diffusion cont.

- B vs r for I=0.5 amp jump at t=5, 20, 40 ms:

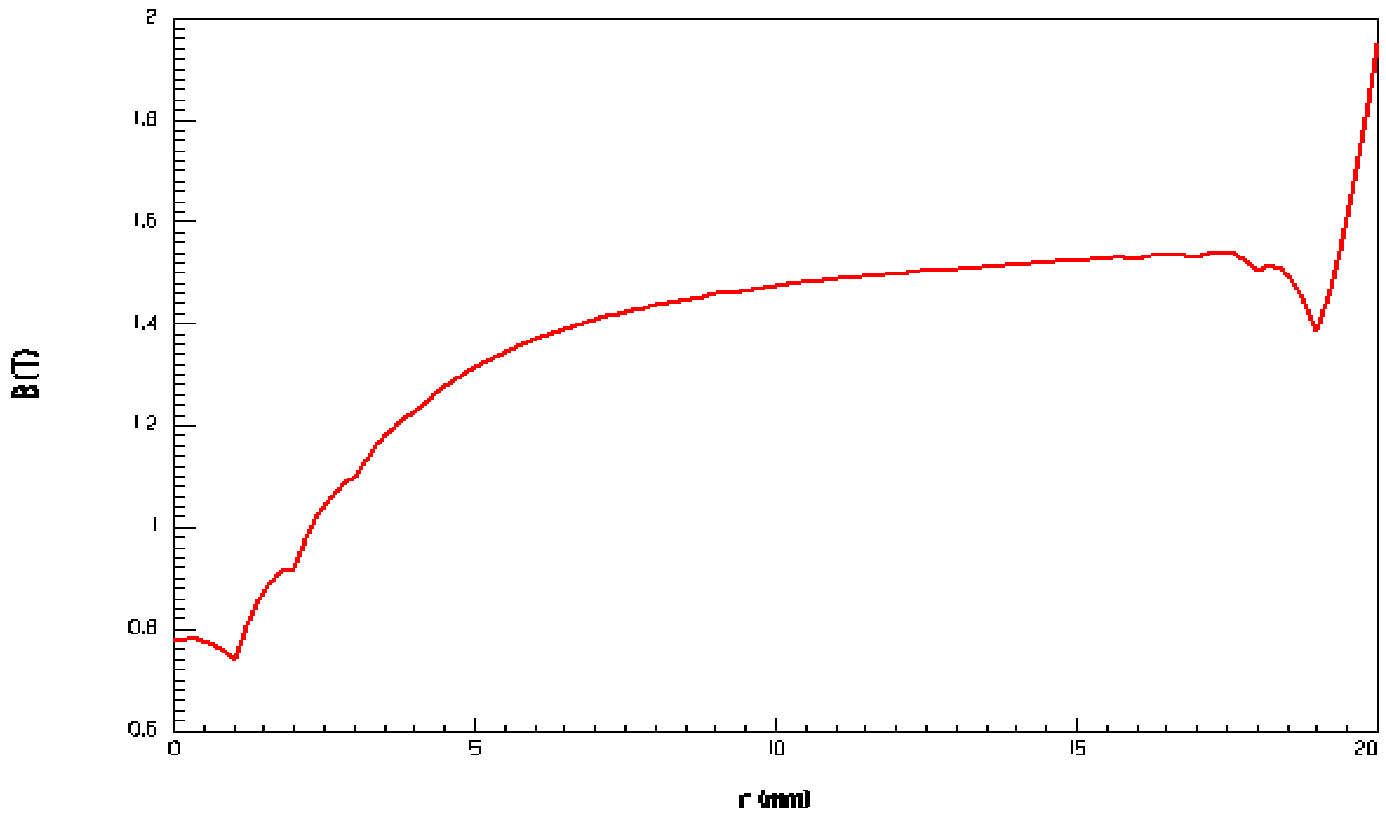
20 ms



NL Magnetic Diffusion cont.

- B vs r for I=0.5 amp jump at t=5, 20, 40 ms:

40 ms

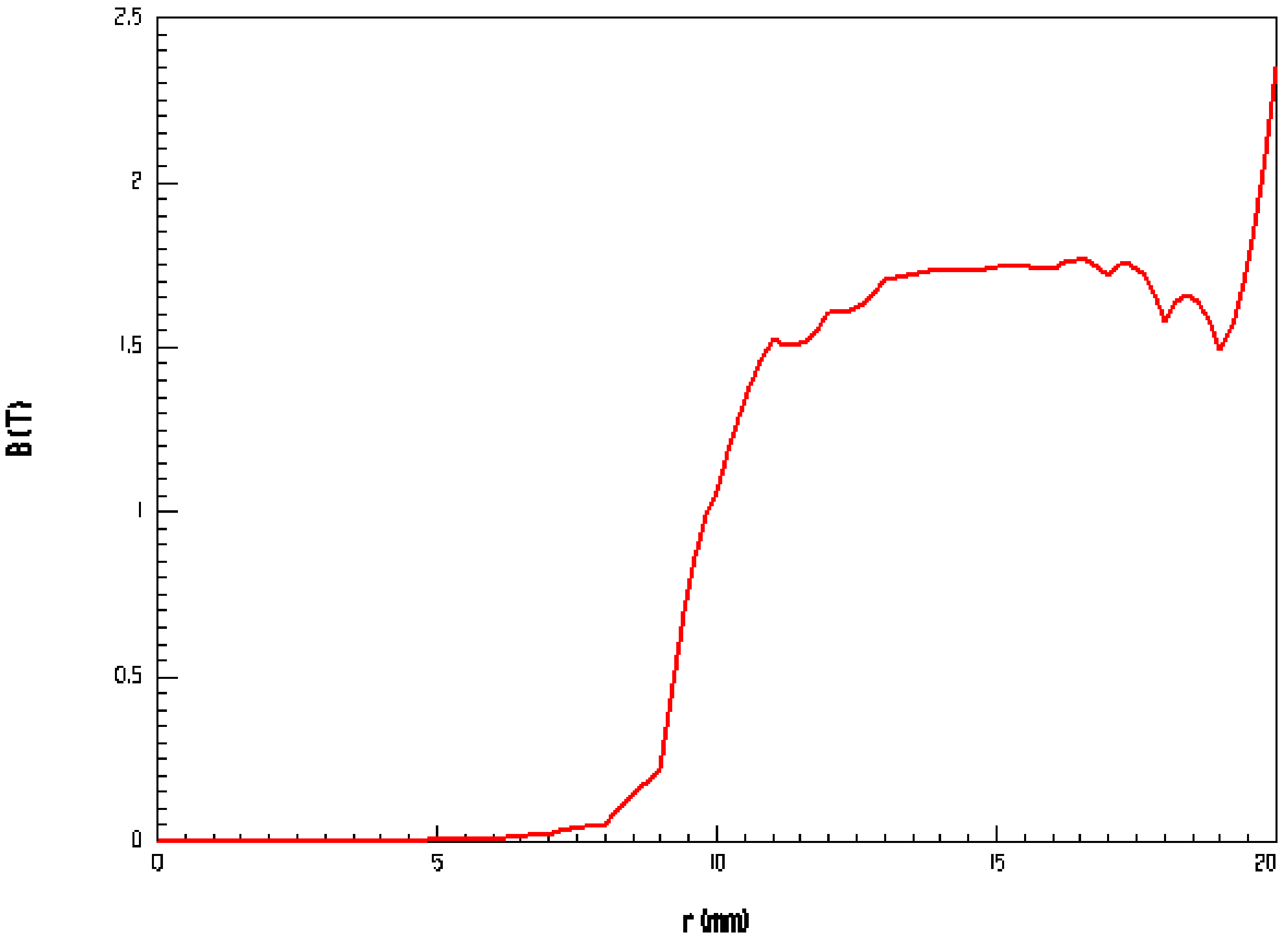


Approx = t_m

NL Magnetic Diffusion cont.

- B vs r for I=**2** amp jump at t=5, 10, 11 ms:

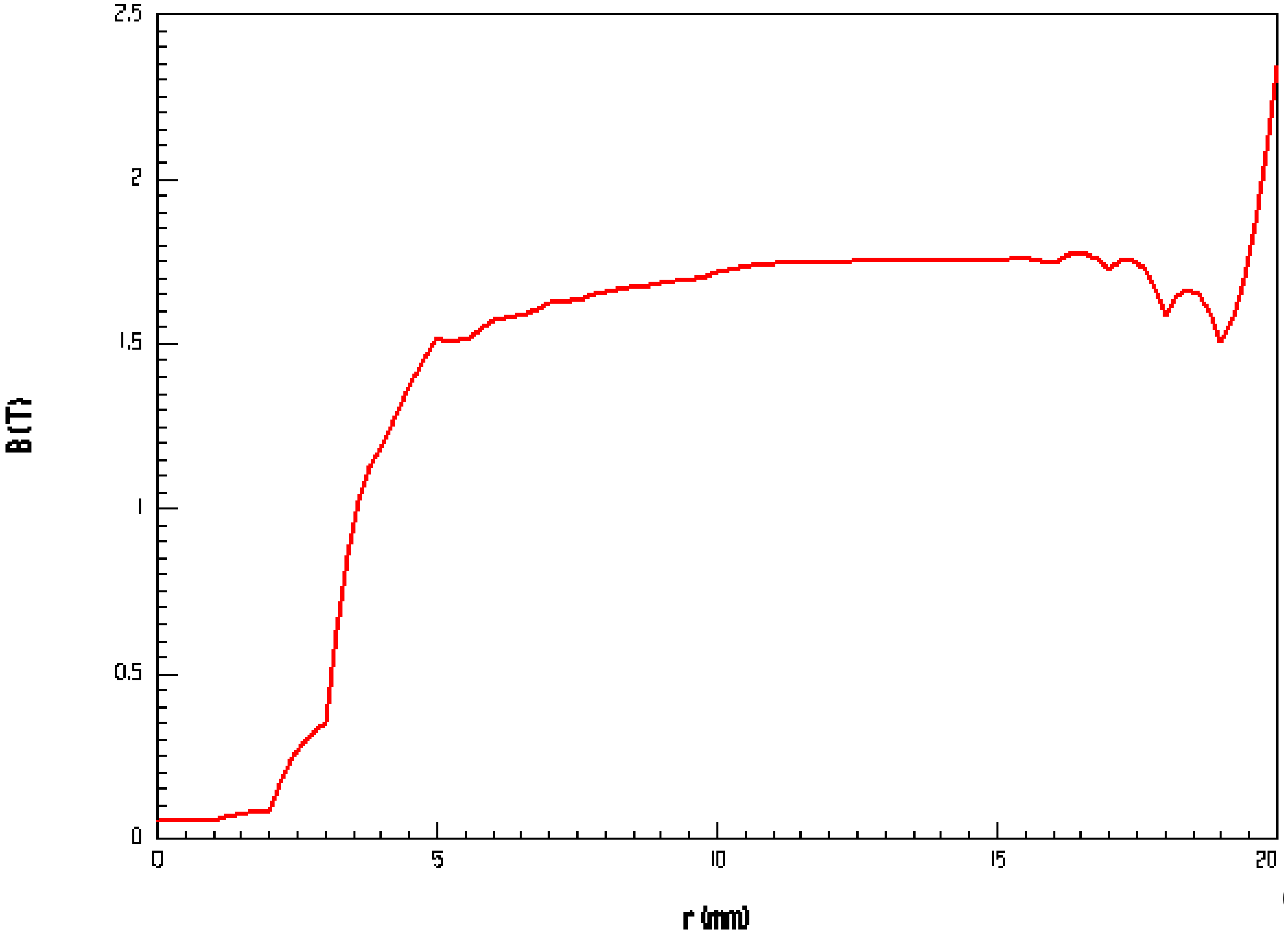
5 ms



NL Magnetic Diffusion cont.

- B vs r for I=**2** amp jump at t=5, 10, 11 ms:

10 ms



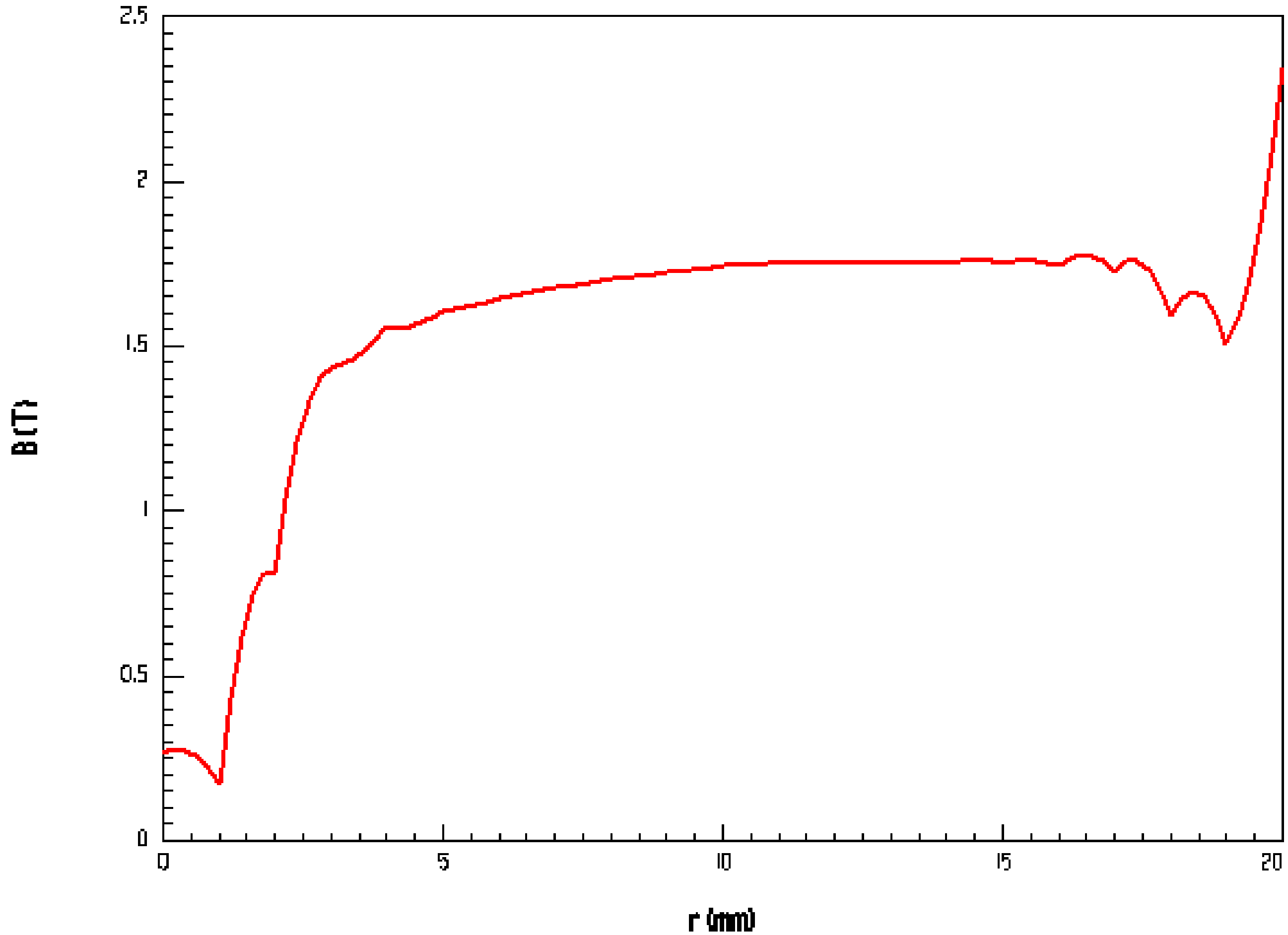
NL Magnetic Diffusion cont.

- B vs r for I=**2** amp jump at t=5, 10, 11 ms:

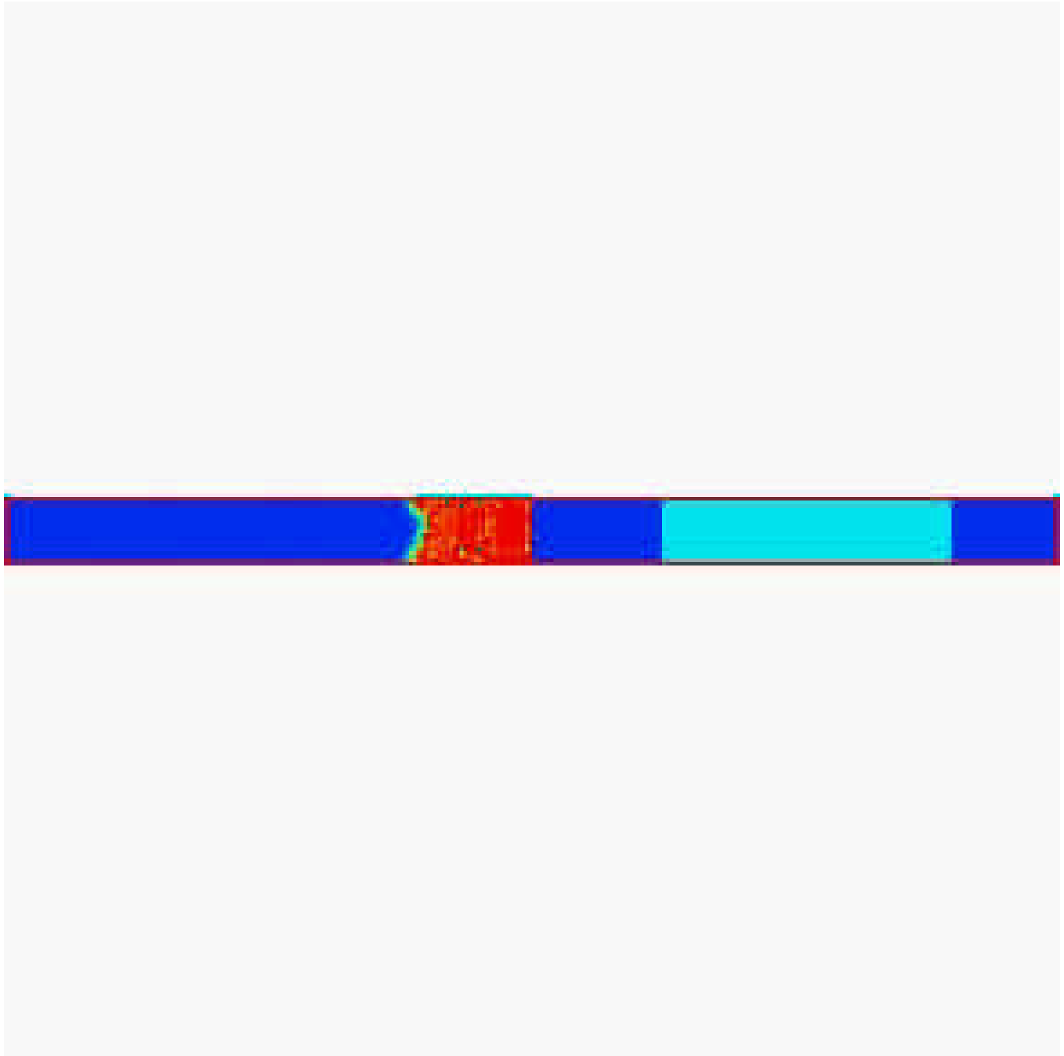
11 ms

Approx = t_m

Faster with more saturation! (qualitative agreement with Mayergoyz 1998 book)



Typical Movie of B vs time



Computed Nonlinear Diffusion Times

TABLE 1.
BESSHO ACTUATOR NONLINEAR MAGNETIC DIFFUSION TIMES (ms)

Current (amps)	Analytical	FEA (step B-H)	FEA (real B-H)
0.5	51.5	53.0	42.0
2.0	12.9	13.4	11.5

Where analytical results are obtained using formula by Brauer and Mayergoyz (2003 July Compumag Conference):

$t_m = [s R^2 B_m] / [4H_o]$ (2)

Where R=cylinder radius, H_o is applied field, and step B-H curve has infinite permeability (slope) for B less than B_m =2.0 teslas, and has a slope of zero at B = 2.0 teslas.

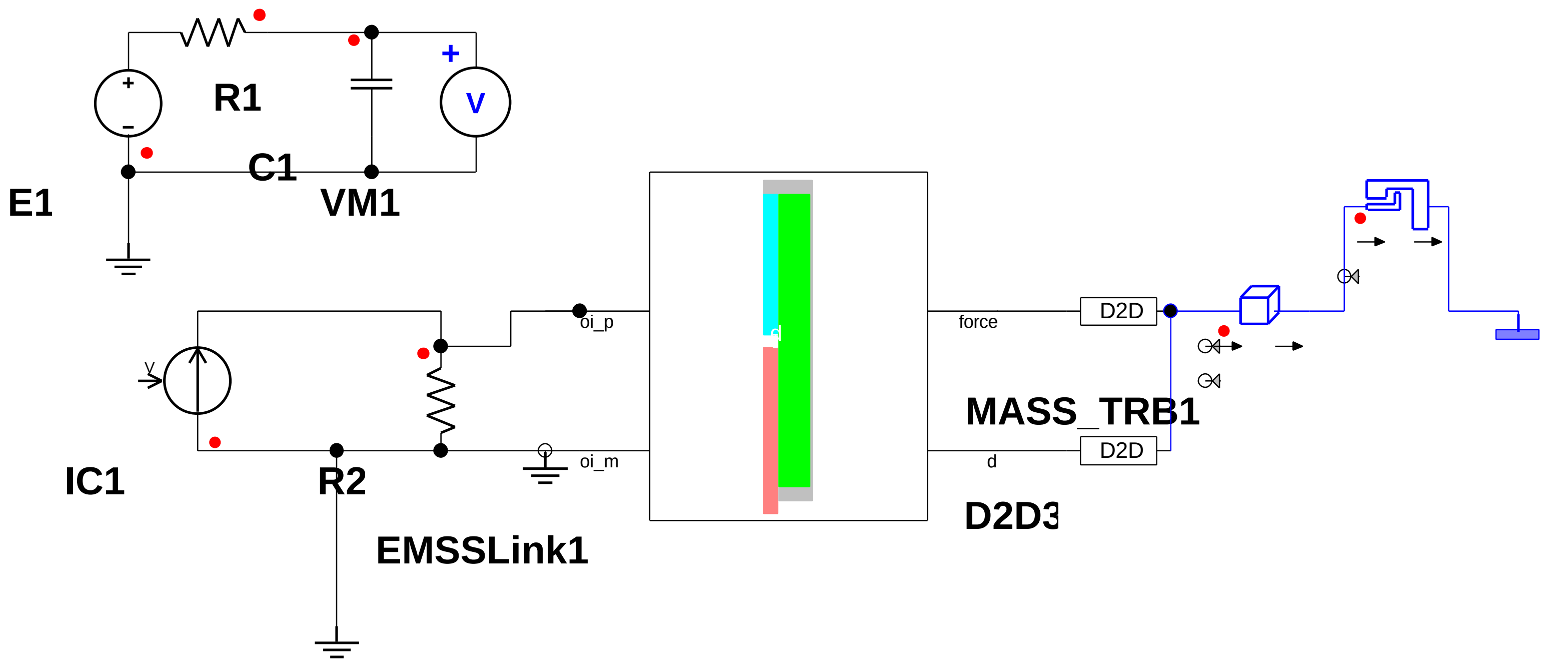
Computed Nonlinear Diffusion Times cont.

- The diffusion times computed by Maxwell nonlinear transient FEA for the step B-H curve agree closely with the times obtained by the analytical formula.
- Maxwell does not allow a perfect step B-H curve. Instead a curve was input with a constant permeability of 10,000 for B below 1.93 T, above which the slope was gradually reduced to the permeability of free space above 2.07 T.
- The computed diffusion times for the real B-H curves differ considerably from those of the step B-H curve.
- The computed nonlinear diffusion times are all considerably faster than the linear diffusion time of 93 ms.

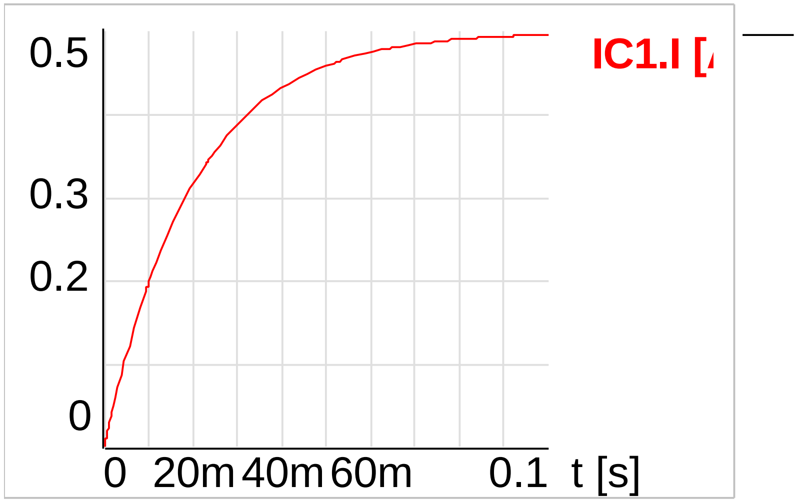
Equivalent Nonlinear Resistor

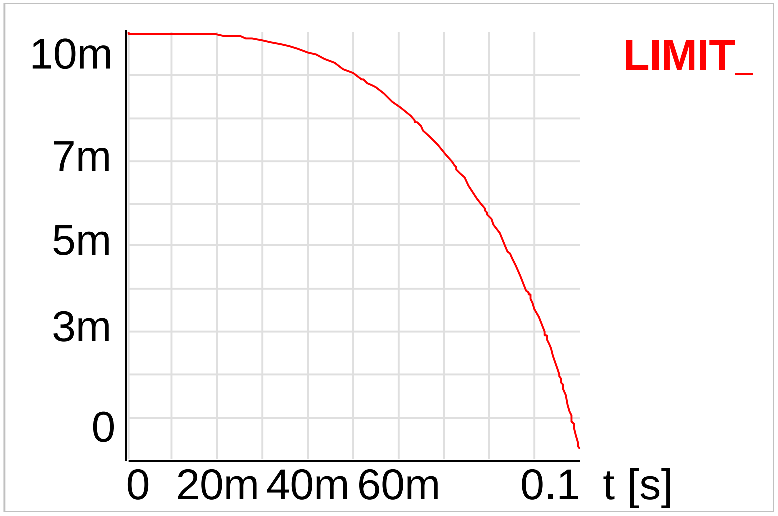
- Parallel resistors are commonly used to account for eddy current losses in transformers, motors, etc.
- Eddy R is inserted parallel to actuator model.
- Eddy R is computed using linear formula [Brauer and Chen, *IEEE Trans. Magnetics*, 2000] for axisymmetric actuator with linear B-H and height h:
- R_{EL} = 4p (N/½)^2 /[2s h] (3)
- The resulting L-R circuit simulates the linear diffusion time.
- To include nonlinear B-H effects, the L/R time constant must be adjusted by the ratio of linear to nonlinear diffusion times, giving a nonlinear eddy resistor:
- R_{EN} = (t_{ml} / t_{mn}) 16p N^2 /[2s h] (4)
- From above computations at 0.5 amps, (t_{ml}/t_{mn})=(93/42). Also N=3300 and h=0.27 m, giving R_{EN} = 1320 ohms.

Simplorer Model of Bessho DC Plunger Actuator at Slow Speed with Diffusion Resistor



Input and Output of Bessho DC Plunger Actuator at Slow Speed with Diffusion Resistor



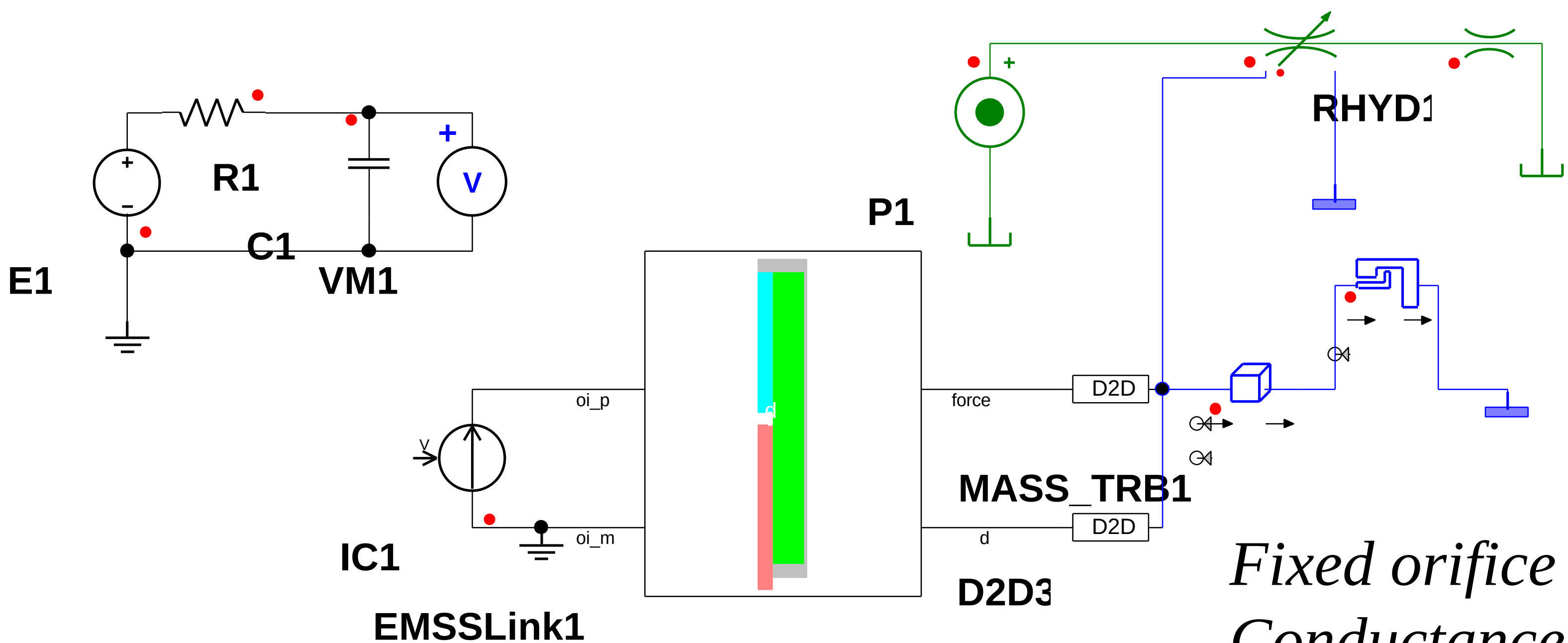


Closes now in 101 ms (4% increase), agreeing a bit more closely with measured approx. 100 ms.

Transient Behavior of Fast System

- At time zero, a current of 0.5 amps with 1 microsecond rise time is applied to coil.
- For even faster speed, the moving mass is reduced from 6 kg to that of the armature only, which is 1.4 kg.
- Diffusion (eddy) R is removed or inserted.

Simplorer High Speed ElectroHydraulic Variable Orifice Model without Diffusion Resistor



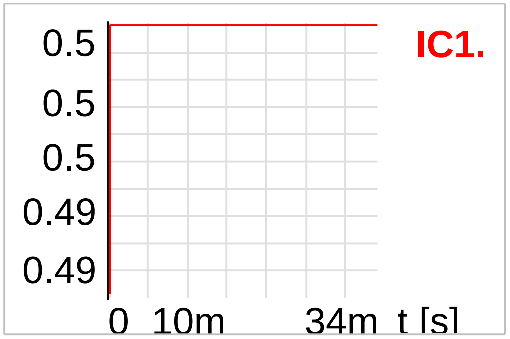
*Fixed orifice has Conductance = 1n[m^3/(s*Pa)]*

Hydraulic Library Variable Orifice Parameters

all values except maximum displacement are Version 6 defaults

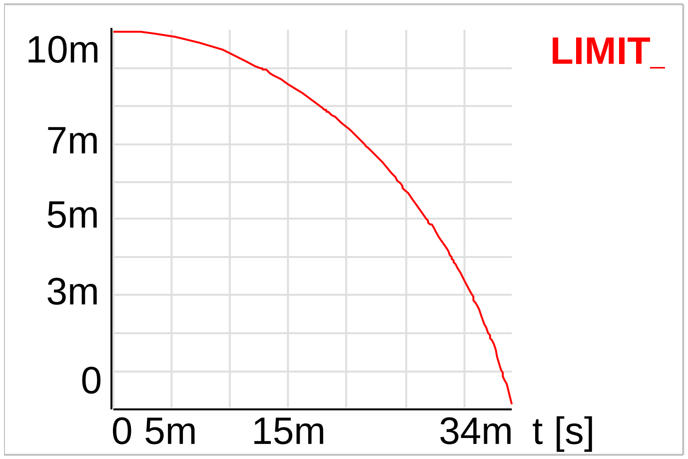
- Discharge Coefficient 0.6
- Linear Gain
- Flow Force Factor 0 *(will change later to 10)*
- Reynolds Number (Transition) 10
- Fluid Density [kg/m^3] 1k
- Absolute Viscosity [Pa*s] 10m
- Minimum Displacement [m] 0
- Maximum Displacement [m] 10m
- Minimum Flow Area [m^2] 1.e-9
- Maximum Flow Area [m^2] 1.e-6

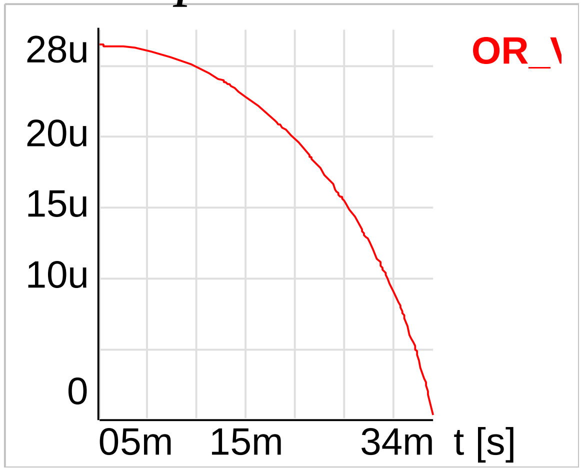
Simplorer High Speed ElectroHydraulic Results without Diffusion Resistor



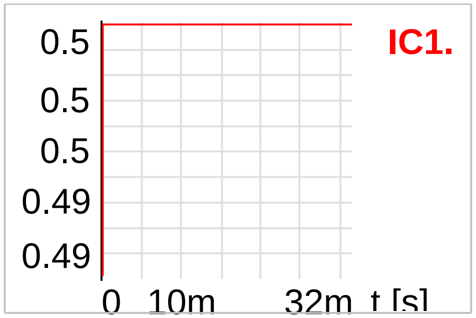
Closes in 34 ms.

Pressure source of 1 MPa (10 bar) produces flow in cubic meters per second:

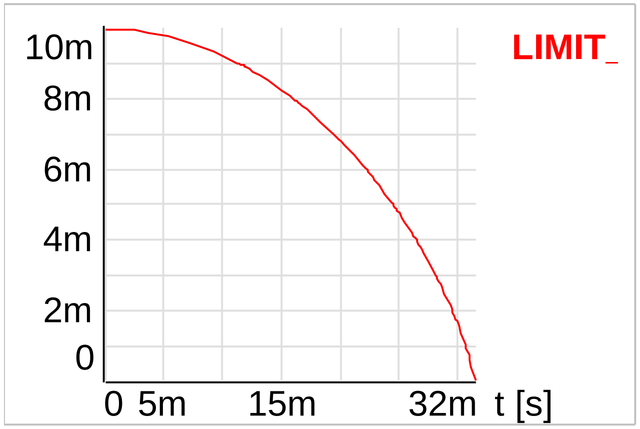


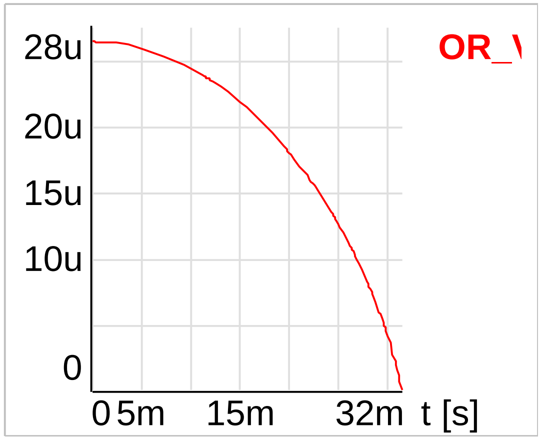


Simplorer High Speed ElectroHydraulic Results without Diffusion Resistor, with Flow Force

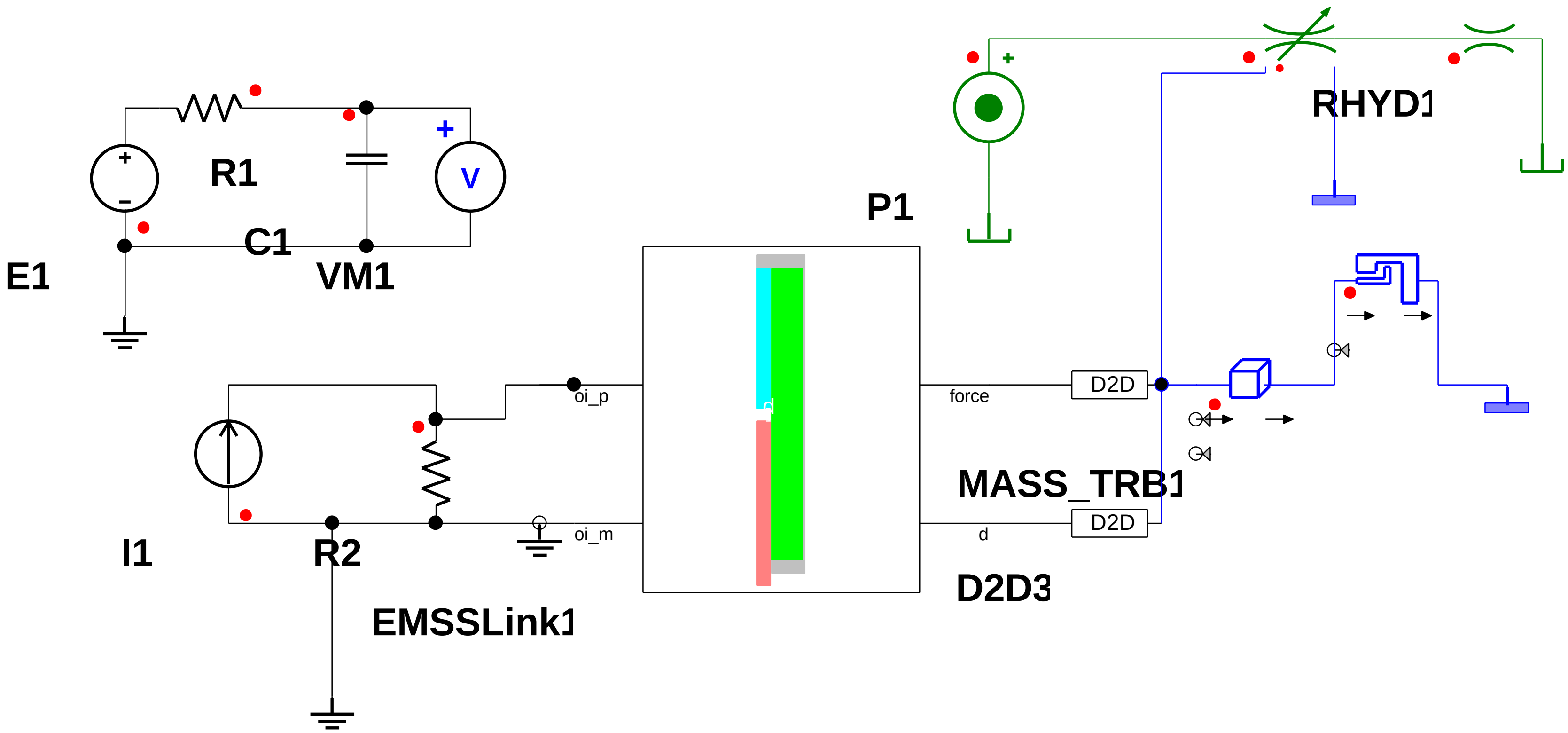


Orifice flow force factor = 10 gives helping force which speeds operation to 31.5 ms.

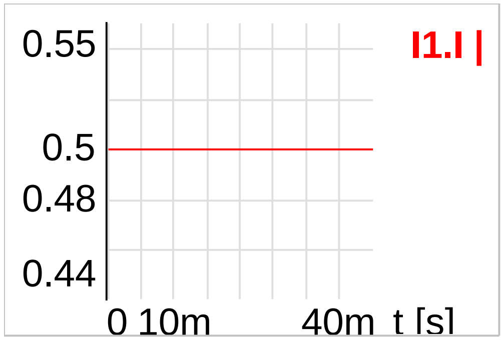




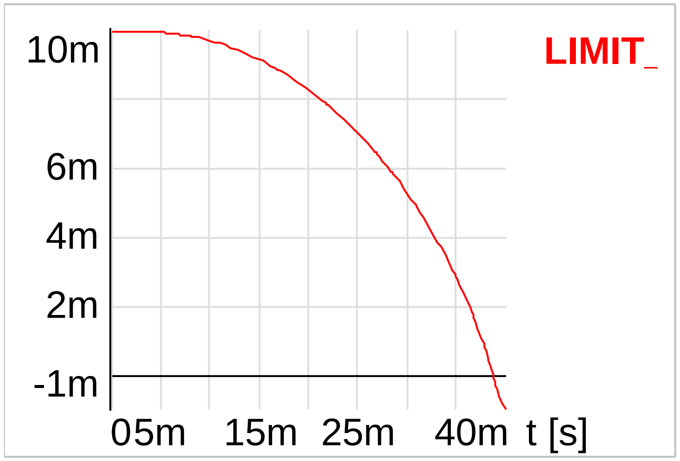
Simplorer High Speed ElectroHydraulic Model with Diffusion Resistor

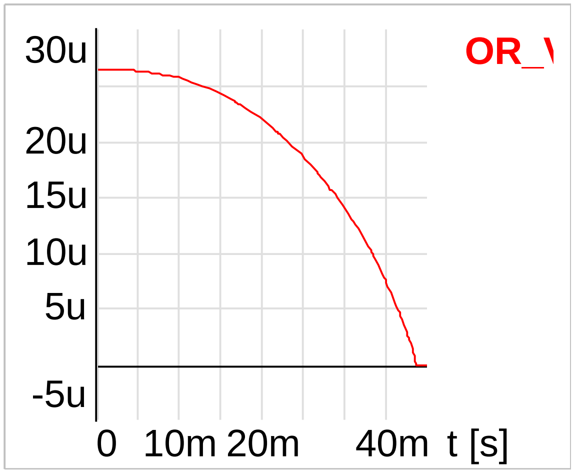


Simplorer High Speed ElectroHydraulic Results with Diffusion Resistor

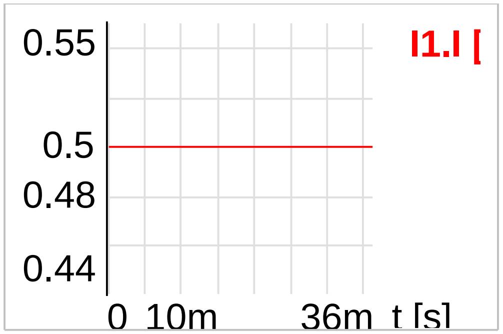


Diffusion does indeed slow the operation, which now requires 40 ms (18% increase)

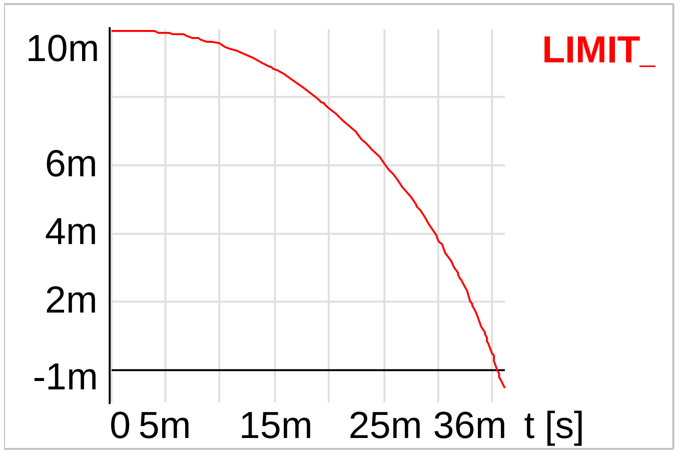


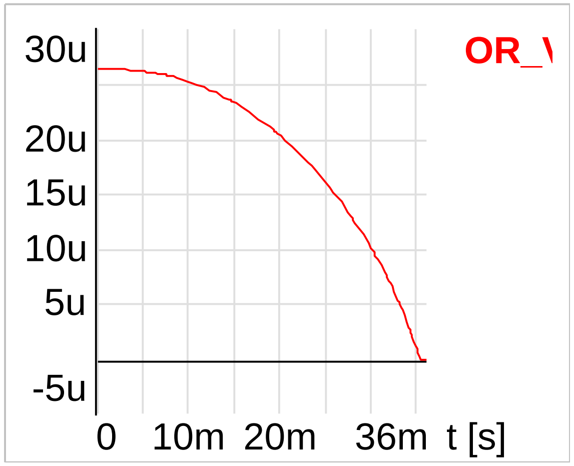


Simplorer High Speed ElectroHydraulic Results with Diffusion Resistor, with Flow Force



Due to helping force of flow, operation speed is now 36 ms, 14% increase due to diffusion.





Conclusions

- In the Bessho dc actuator the nonlinear magnetic diffusion time delay is approximately 42 ms at the rated current of 0.5 amp, considerably less than the 93 ms predicted by a classical formula for constant permeability. When higher current is used, the even heavier saturation produces further decreases in magnetic diffusion time.
- The nonlinear magnetic diffusion times predicted by Maxwell agree closely with a formula for step B-H.
- Under slow speed operation, the closing time predicted by Simplorer agrees closely with measured 100 ms, which diffusion increases by 4%.

Conclusions ended

- Under high speed operation, diffusion significantly slows the operation time. Without flow forces, diffusion increases time from 34 to 40 ms, or 18%.
- Flow forces also influence the actuator response, as shown when the Bessho actuator is used in a typical electrohydraulic system, where the Simplorer model may include the equivalent diffusion resistor.
- For more details, consult the referenced papers and/or attend the seminar “Analysis of Magnetic Actuators and Sensors for Electromechanical Applications” that I will teach on November 17th and 18th at Milwaukee School of Engineering.
- I thank Yihong Zhong, Mark Jenich & Scott Stanton.