Analyzing Magnetic and Mechanical Hysteresis in a Proportional Solenoid

A CASE STUDY FROM SOLENOID SYSTEMS

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BACKGROUND

A Proportional Solenoid is used to produce precise and variable position control proportional to an input signal. The input signal is electrical voltage or current, which produces a mechanical force output from the Solenoid. This force is used to positions a device, such as a metering component in a hydraulic valve or a mechanism against a known spring force.

An ideal Proportional Solenoid would produce a perfect linear relationship between the input signal and the desired output but due to non linear material properties, Magnetic and Mechanical Hysteresis this is typically not the case. Weather a system uses an open or closed loop control method the Total Hysteresis (Magnetic plus Mechanical) of the Solenoid is an important factor in the performance of the control system.

MAGNETIC HYSTERESIS

When a Solenoid coil is energized a magnetic field (H) is generated and the ferromagnetic components will have a corresponding flux density (B) based on the specific material's B vs H relationship. A typical BH curve for a soft magnetic material is shown in Figure 1 . Initially, the B vs H relationship follows the Initial Magnetization curve from zero. As the coil is de-energized (decreasing H) the B vs H relationship follows the Normal Hysteresis Loop and a Remnant (Residual) Flux Density (Br) remains in the material. Since the Magnetic Force produced by the Solenoid is a function of the Flux Density, the Magnetic Force will have a proportionate hysteresis loop as the Flux Density, B. Figure 2 shows the Force Hysteresis of a Solenoid at a fixed position of 1.2mm as the current is ramped from zero to 1.2 Amp and then back down to zero.

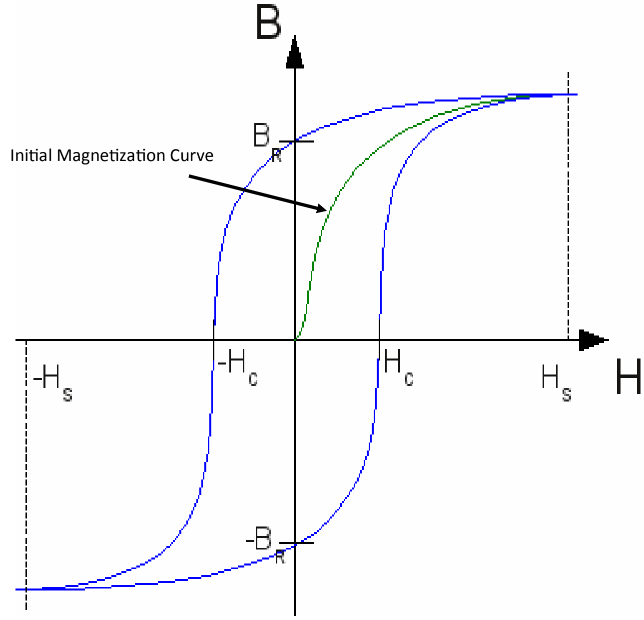


Figure 1. B-H Curve for typical soft magnetic material

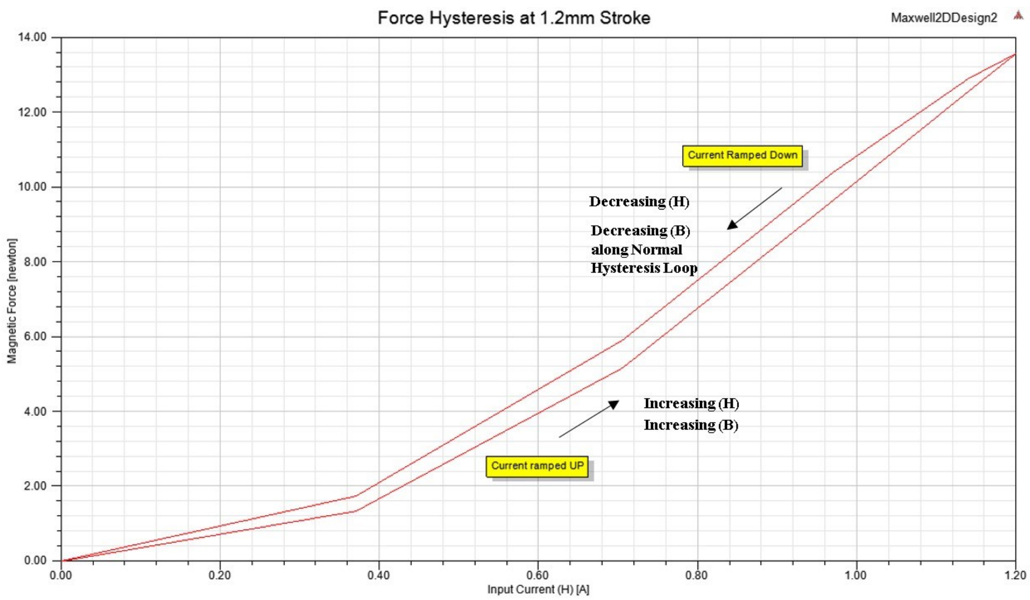


Figure 2. Force Hysteresis

MECHANICAL HYSTERESIS

Mechanical hysteresis in a Solenoid is caused by Magnet Side Loading of the armature against it's bearing surface producing frictional forces.

The amount of Magnetic Side Loading is dependent on the radial clearance (gs) between the armature and the surrounding magnetic component and the eccentricity (e) of the armature.

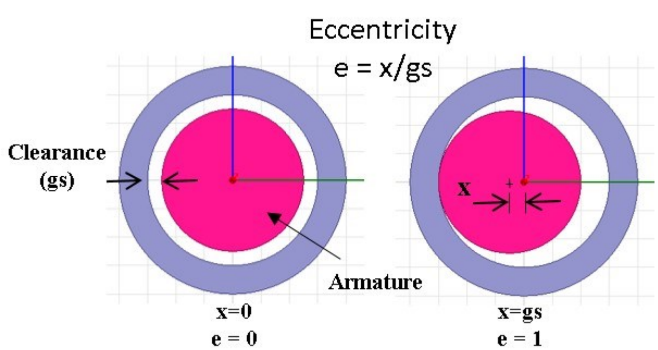


Figure 3. Armature Eccentricity

As eccentricity increases, the magnetic force on the side of decreasing clearance exponentially increases as the magnetic force on the opposite side exponentially decreases, causing a net magnetic side load. If the armature could be perfectly suspended and centered in the clearance gap there would be no magnetic side loading.

Typically, eccentricity is < 1 as a non magnetic bearing material, such as a stainless steel sleeve or a low friction bearing paper, is used within the clearance.

The Magnetic Side Load is the normal force between the armature and bearing surface that produces the frictional force as a function of the static and dynamic coefficients of friction.

The coefficient of friction is a function of lubrication , the surface finish and hardness of the armature and bearing surface as well as the relative speed between the two.

The frictional coefficient relationship to speed is modeled by the simple stick-slip curve as shown in Figure 4. and will be used in this analysis.

The coefficient of friction model can be created empirically or from published data.

For devices requiring very low hysteresis control the analysis of the friction coefficient is as important as the analysis of the Magnetic Side Loading.

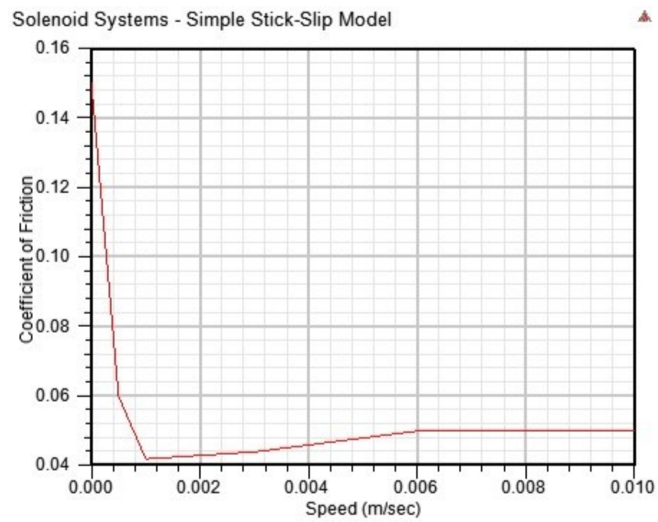
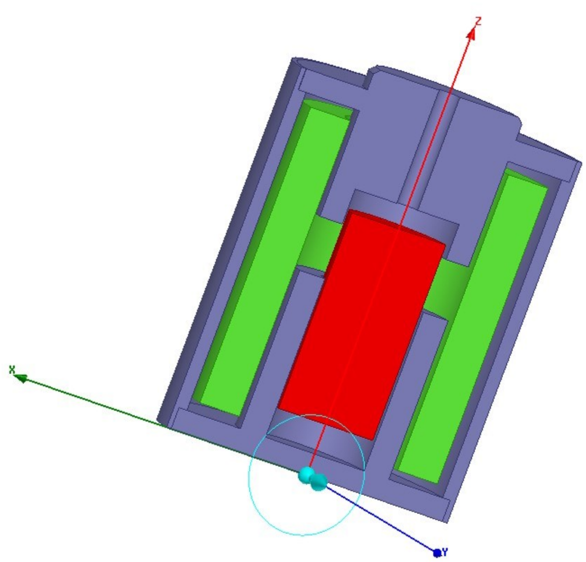


Figure 4. Coefficient of Friction

EVALUATED DESIGN

The Proportional Solenoid to be evaluated is one for a hydraulic application. The Solenoid is required to position a hydraulic spool against a spring load. The specifications are as follows:

- Working Stroke: 1.2 mm
- Max Allowable Stroke: 1.6 mm
- Max Control Current: 1.2 Amp
- Pre-Load: .5 N
- Spring Rate: 8.66 N/mm



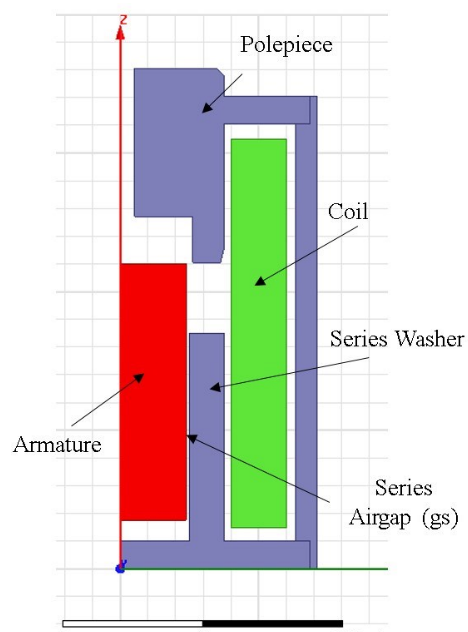


Figure 5. Cross Section of Solenoid

MAGNETIC HYSTERESIS ANALYSIS

To analyze the magnetic hysteresis the Solenoid will be energized at a constant current and moved from zero to full stroke and then back to zero. The material used for the solenoid components in this analysis is a typical low carbon, soft magnetic material with the normal BH hysteresis loop shown in Figure 6.

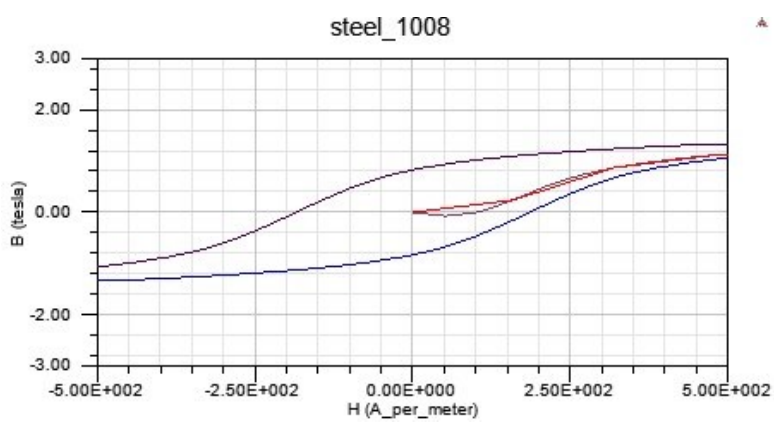


Figure 6. Low Carbon Steel B-H Curve

The results of the Magnetic Hysteresis analysis are shown below in Figure 7. As expected, the hysteresis increases with increasing current as the flux density in the material increases along the normal BH hysteresis loop.

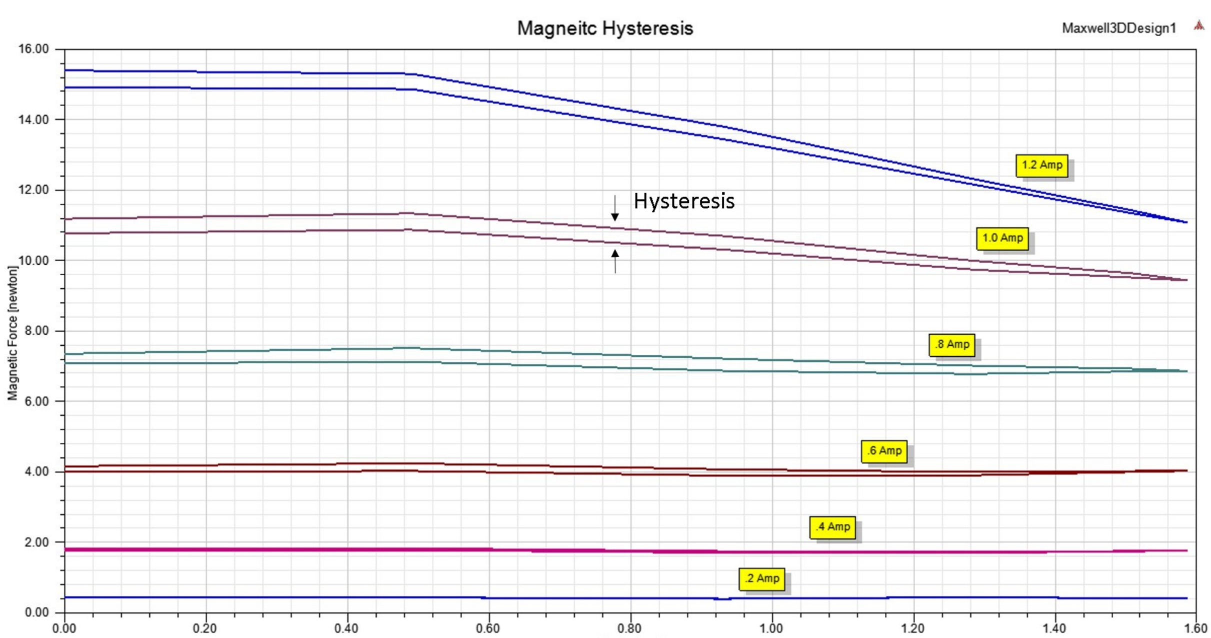


Figure 7. Magnetic Hysteresis

MAGNETIC SIDE LOADING

The Solenoid will be analyzed assuming a non magnetic bearing resides within the series air gap, (gs). The nominal thickness of the bearing is .15 mm and the nominal series gap is .25mm. Therefore, (x) the offset of the armature, is .1 mm and the eccentricity is .1/.25 = .4. The magnetic side loading will be evaluated similar to the magnetic hysteresis, energized at a constant current and moved from zero to full stroke and back to zero at a rate of .5mm/sec which is similar to actual testing in the lab on a force tester. The results of the armature side loading analysis is shown below in Figure 8. and the surface force density on the armature in Figure 9. The surface force density on the armature can be used in more advanced analysis to investigate surface wear and durability.

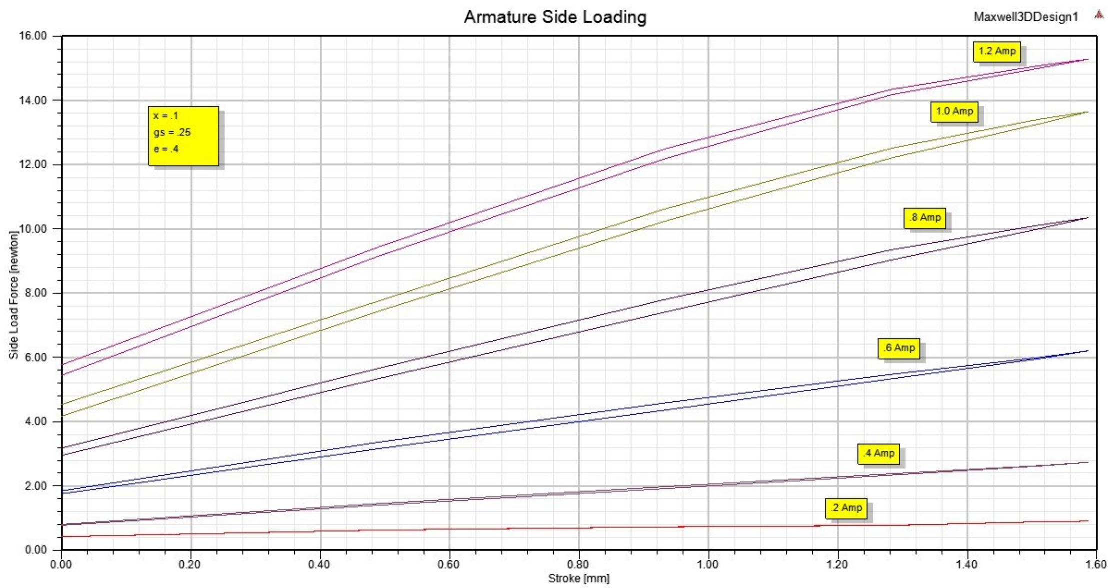


Figure 8. Magnetic Side Loading

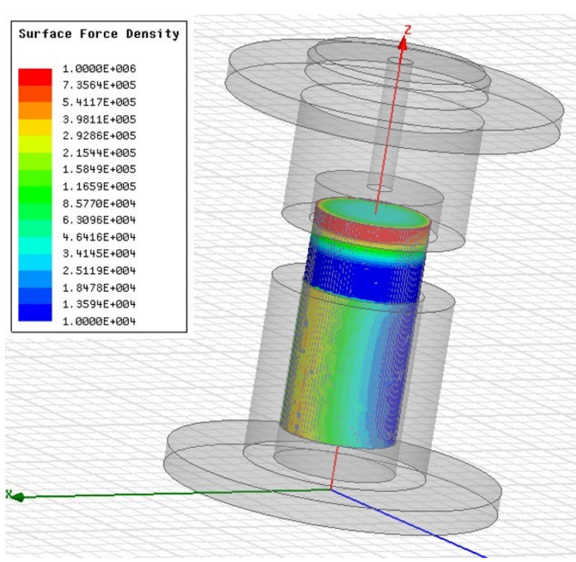


Figure 9. Armature Surface Force Density

With an eccentricity of .4 the Armature Side Loading force in Figure 8. at 1.2 Amp and 1.2mm stroke is greater than the Magnetic Force output of the Solenoid in Figure 7. Since the Armature Side Loading force is the force responsible for the frictional forces it is important to minimize these as much as the design will allow. As mentioned earlier, an eccentricity of zero would produce zero side loading but is not practical as there are tolerances on the components that must be accounted for. Below in Figure 10 is a table of the component dimensions and tolerances. The nominal eccentricity is .4 which has already been analyzed. To see the effects of the tolerances on the Armature Side Loading the min and max eccentricity of .125 and .583 will also be evaluated.

	Nominal	+/-	min	max
Armature OD	10	0.025	9.975	10.025
Series Washer ID	10.5	0.025	10.475	10.525
Series Gap (gs)	0.25	0.05	0.2	0.3
Bearing Thickness	0.15	0.025	0.125	0.175
X	0.1	0.075	0.025	0.175
e	0.4		0.125	0.583

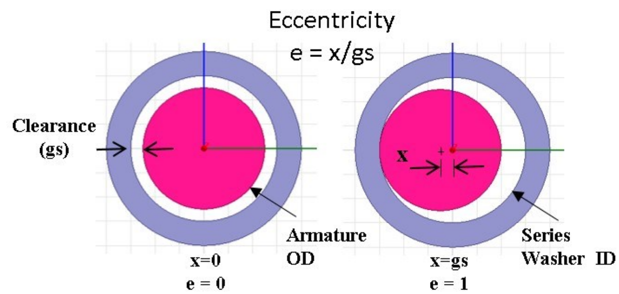


Figure 10. Tolerance Effects on Eccentricity

The Armature Side Loading at 1.2 Amp as a function of eccentricity was analyzed and the results are below in Figure 11.

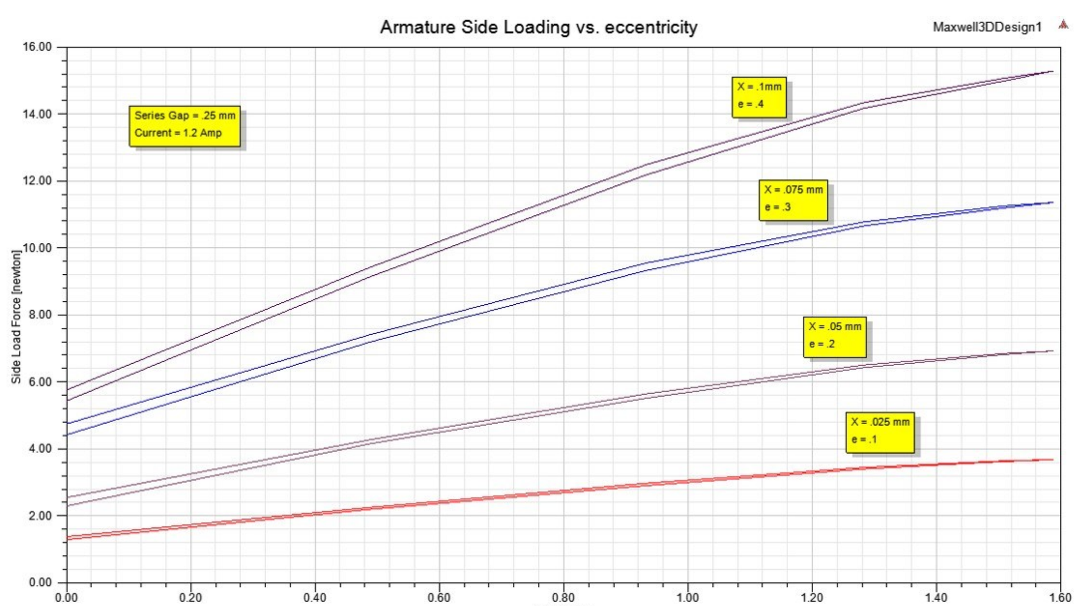


Figure 11. Armature Side Loading vs Eccentricity

MECHANICAL HYSTERESIS

Applying the coefficient of friction from the simple stick-slip model in Figure 4 to the Magnetic Side Loading in Figure 8 the frictional forces along the stroke of the solenoid for the various coil currents are below in Figure 12.

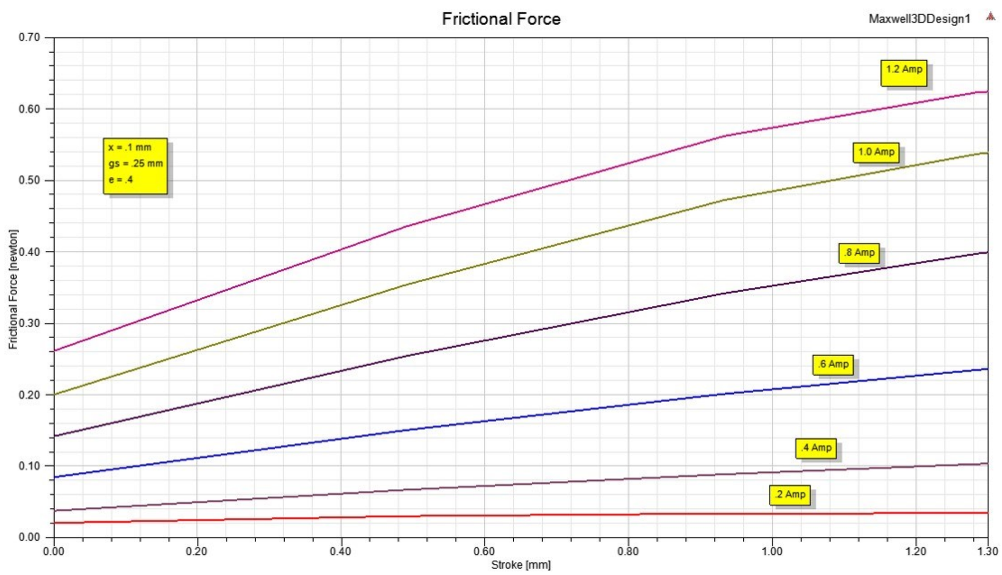


Figure 12. Friction Forces

TOTAL HYSTERESIS

The Magnetic and Mechanical Hysteresis combine to produce an overall Total Hysteresis in the Magnetic Force output of the Solenoid available for positioning the hydraulic component against the load. The Total Hysteresis is shown in Figure 13. The Mechanical Hysteresis is a larger contributor as compared with the Magnetic Hysteresis in Figure 7. This can be reduced by reducing the eccentricity or lowering the coefficients of friction with different bearing materials or lubrication.

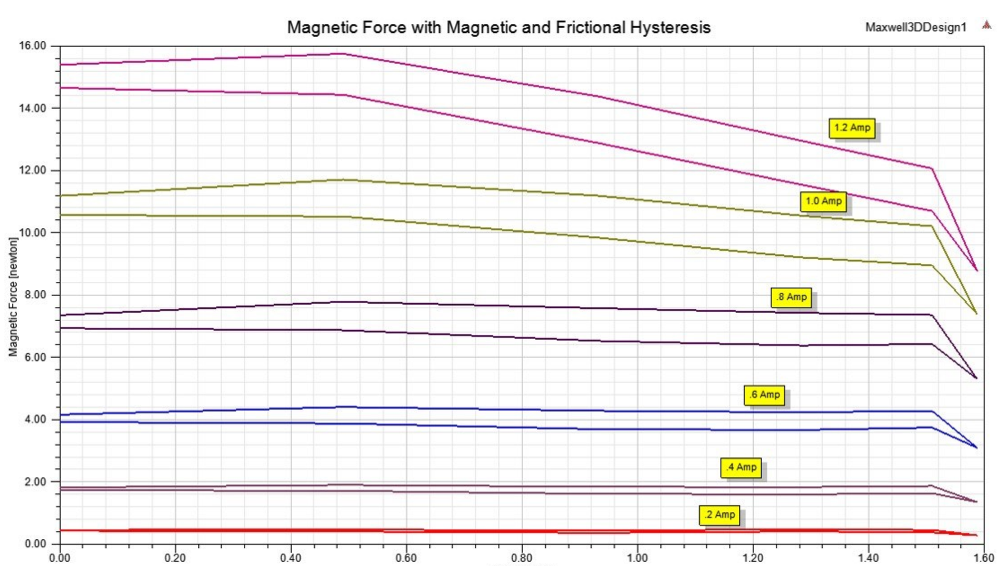


Figure 13. Total Hysteresis

POSITION HYSTERESIS

Since the objective of this Solenoid is to position a hydraulic component against a load, it is important to analyze the effects of the Total Hysteresis as seen in Figure 11 on the positioning hysteresis of the device. To do this a 3D Magnetic Analysis is performed taking into account both the Magnetic and Mechanical Hysteresis forces and the load (.5 N preload with a rate of 8.66 N/mm). The Solenoid is energized from zero to 1.2 Amp and back down to zero and the position vs input current is recorded in Figure 14.

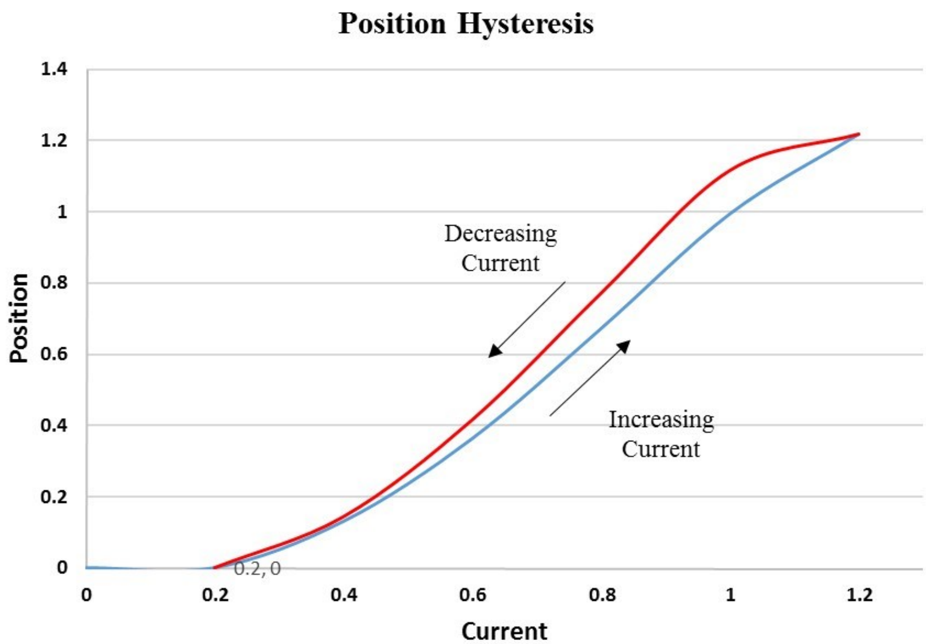


Figure 14. Position Hysteresis

SUMMARY

Both Magnetic and Mechanical Hysteresis contribute to the Total Hysteresis of the Solenoid. In this case, the Magnetic Hysteresis is far less than the hysteresis caused by friction and Magnetic Side Loading. The Mechanical Hysteresis can be reduced by reducing the eccentricity or lowering the coefficients of friction with different bearing materials or lubrication. The eccentricity can be reduced with tighter tolerance components or a larger Series Gap. A larger Series Gap will reduce eccentricity but will also reduces the Magnetic Force output of the Solenoid.

In both cases the Total Hysteresis increases as the current to the Solenoid increases. As the current is increased the material operates on a much larger hysteresis loop which increases the Magnetic Hysteresis. Higher currents also produce higher Magnetic Side Loading forces which also contribute to higher frictional forces.

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