Sage Model Notes

ActuatorTransverseCoil.scfn

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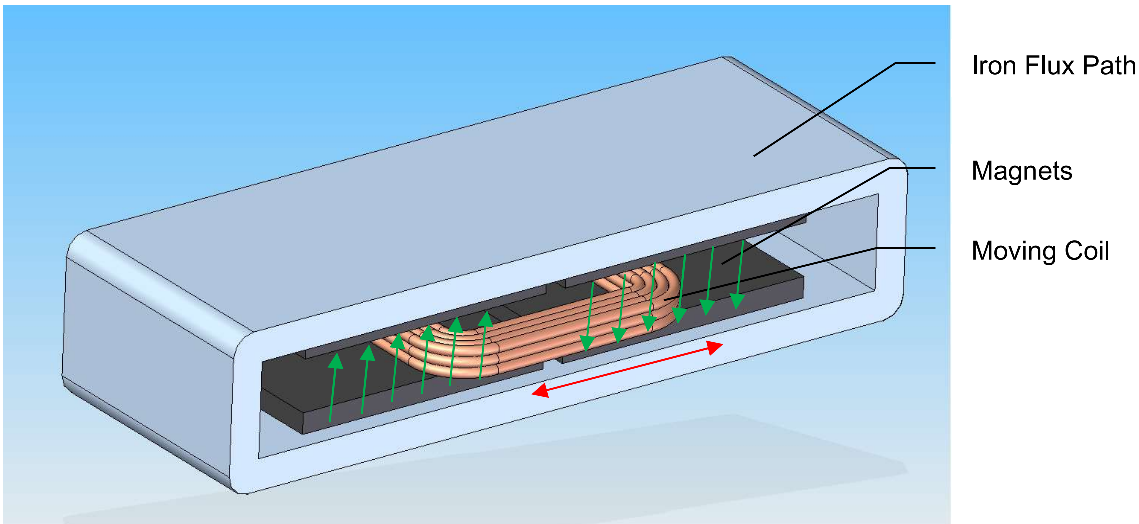
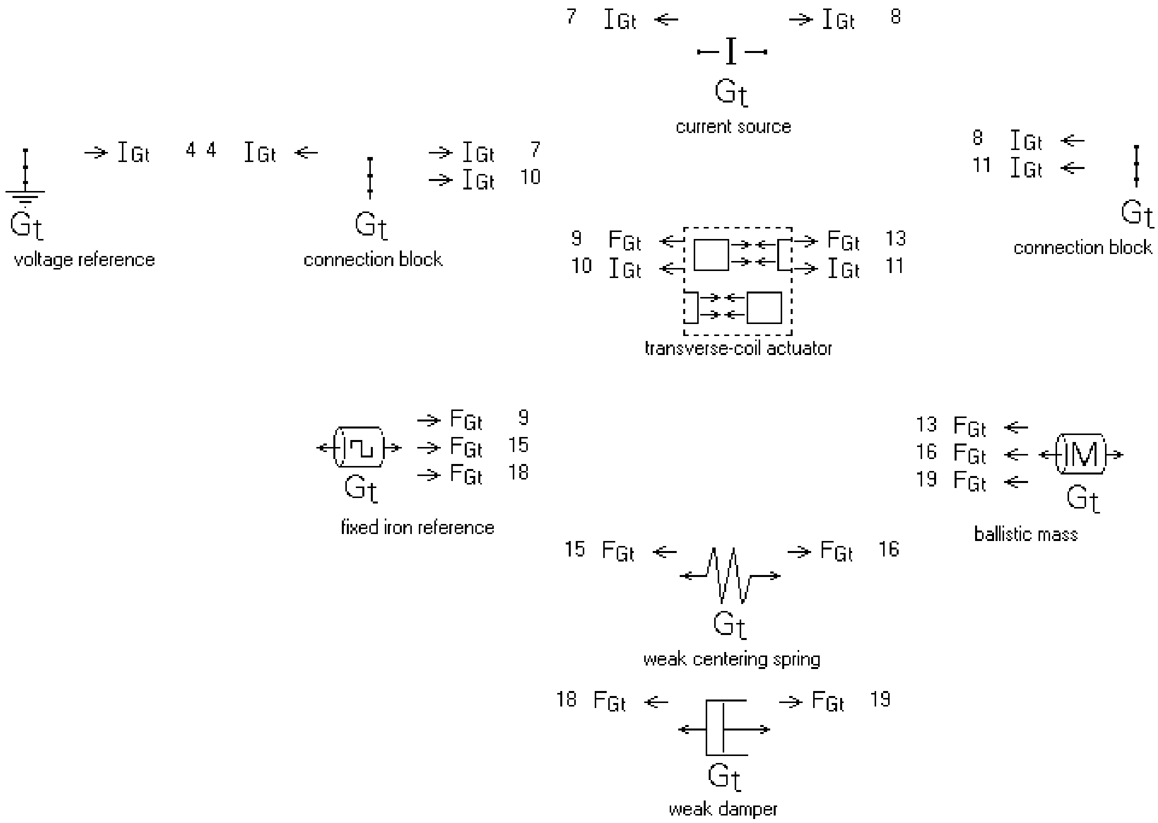
A model of a linear actuator of the type commonly used for hard drive head positioners. A rectangular coil with the winding axis normal to the magnetic field moves in the air gap between permanent magnets. The coil moves parallel to the magnet faces in the direction shown by the red arrow:



The structure that actually moves and aligns the coil is not shown. In hard-drive practice the coil moves along an arc rather than a straight line and the magnets and iron structure are curved accordingly.

There are two pairs of magnets shown above, attached to opposite sides of the air gap for a total of 4 magnets. The magnets are polarized to produce magnetic flux across the air gap. Only the legs of the winding across the magnets (current direction normal to motion direction) contribute to the net actuator force. If the magnets were uniformly polarized there would be no net force because the currents in the two cross legs of the coil are equal and opposite and the forces would cancel. So by design the direction of magnetic polarization is opposite for each pair of magnets, producing magnetic flux in different directions across the air gap, as indicated by the green arrows. That way each of the cross legs moves through a magnetic flux of different direction and the electromagnetic forces are additive. The magnets are shown with a small gap in the middle where the flux changes direction. In practice there may be no physical gap. A single magnet may just be polarized differently in each half.

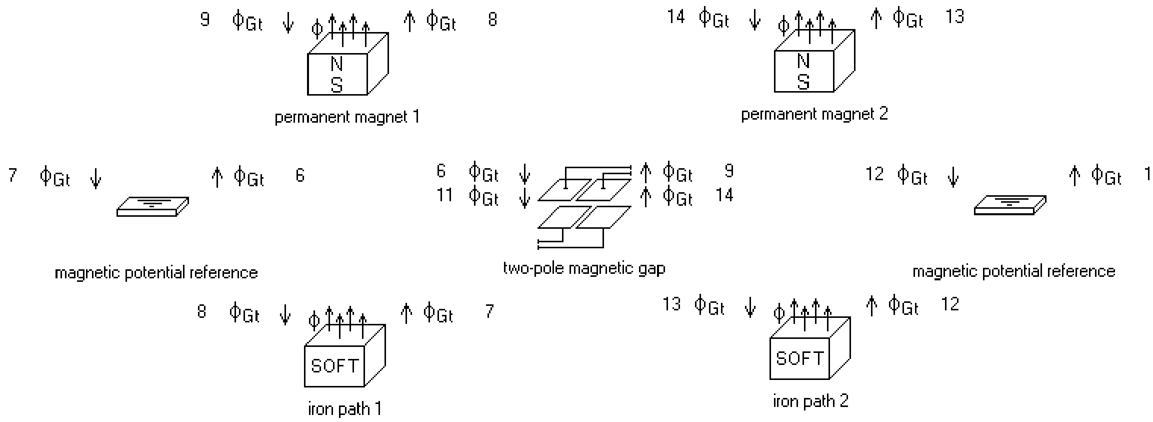
The Sage root model looks like this:



A *current source* (top row) drives electrical current through the coil within the *transverse-coil actuator* submodel. A constrained piston *fixed iron reference* anchors the actuator iron and magnet assembly and the moving coil drives a free-piston *ballistic mass* which is also supported by a *weak centering spring* so that the coil mean position is centered in the gap. There is also a *weak damper* in the model which is not strictly necessary but anyway represents some amount of frictional dissipation.

If one were designing an actual head positioning actuator one might be interested in the transient response. But Sage can only model time periodic behavior so all the model can do is reveal things like displacement and force amplitudes resulting from input electrical current amplitudes at the input operating frequency.

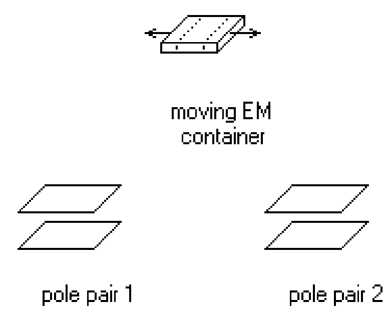
Within the *transverse-coil actuator* submodel are these components:



There are two magnetic flow paths laid out similarly to the way they are laid out in the physical actuator, one on the left and one on the right. But the magnets on opposite pole faces (across the gap) are combined together into single magnets. *Permanent magnet 1* representing the left half of the air gap in the above drawing is polarized one way. Permanent magnet 2 is polarized the other way by setting the polarization multiplier input Jmult to -1 in the component *permanent magnet object 2*.

The lower poles of pole pairs 1 and 2 are anchored to magnetic potential references with the same zero potential as are the upper poles of the two iron paths. The upper poles are connected to the lower poles of the two permanent magnets, which have equal but opposite magnetic potentials. So the Sage model captures the magnetic potential drops across the two halves of the air gap correctly but puts the equi-potential surface at the lower pole faces rather than the air gap mid-point. The Sage model is not quite physically correct but should produce a reasonable approximation of the magnetic flux in the two halves of the air gap.

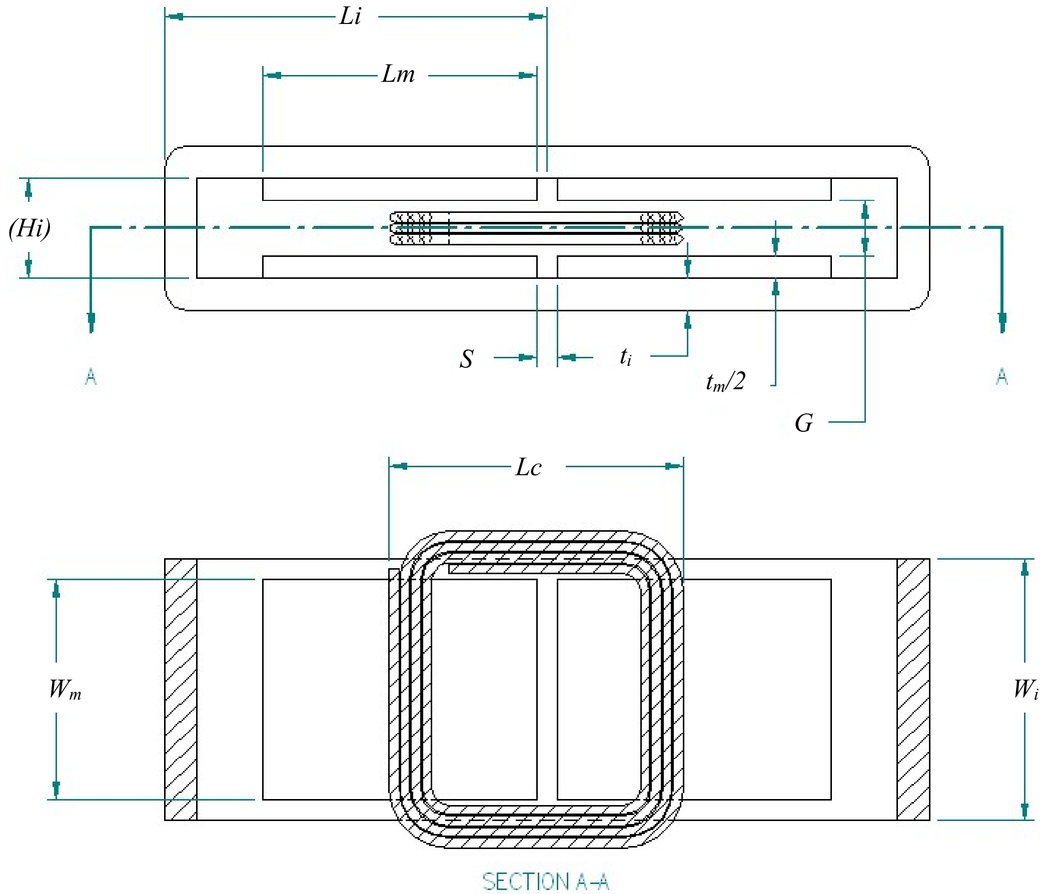
Inside the *two-pole magnetic gap* you can see the *moving EM container* in which the moving magnet resides:



The idea is that whatever is inside the *moving EM container* passes between pole pairs 1 and 2 and sees opposite magnetic flux.

There are user-defined inputs defined in the *transverse-coil actuator* submodel based on the symbols in the dimensioned picture below. All are independent variables except for H_i on the top left which is a dependent variable correspond to a user-defined variable in the Sage model, defined as.

$$H_i = G + 2t_m$$



In the model L_m, S, G and W_m set the dimensions of the *two-pole magnetic gap* via input recasts. The length of the moving container inside the gap is recast to coil length L_c. The offset of the container at the center position is recast to

$$Offset = Lm - \tfrac{1}{2}(L_c - S)$$

The lengths of the two iron flux paths are recast to

$$Lpath = L_i + H_i$$

Which corresponds to an average path length from the magnet midpoint on one pole face around to the magnet midpoint on the other face. Their cross section areas are recast to

$$Apath = t_i W_i$$

The lengths of the two permanent magnets (combined stack) are recast to

$$Lpath = t_m$$

And their cross section areas to

$$Apath = L_m W_m$$

Coil Geometry

Within the moving EM container are the *transverse coil* and *coil object* components. Together with the outer dimensions of the coil established by inputs by L_c and G, the coil geometry is further specified by these *transverse coil* inputs:

XnegRel	parent-relative neg bnd [0, 1] (NonDim)	0.000E+00
XposRel	parent-relative pos bnd [0, 1] (NonDim)	1.000E+00
ZthkRel	thickness fraction of parent Zgap [0, 1]	8.000E-01

And by these *coil object* inputs:

Dwire	wire diameter (m)	2.500E-04
Nturns	number turns in coil (NonDim)	2.000E+02
Alpha	coil packing factor (NonDim)	9.000E-01

An important output is the coil fill factor

FillFac fraction filled by cross legs (NonDim) 2.727E-01

The value roughly corresponds to the above drawing where the combined cross legs occupy about ¼ the total coil length. Sage pops up a warning message is the value exceeds one, which means that the cross legs of the coil are interfering with each other.

Physics

The model operating frequency is 100 Hz which is well above the natural frequency of the *ballistic mass* natural frequency. Its mass set to

Mass reciprocating mass (kg) 5.000E-03

Which is roughly comparible to the mass of the coil itself, available from *coil object* output

Mwire wire mass (kg) 5.069E-03

The weak centering spring is required to keep the coil in its center position (ballistic mass mean displacement FX.mean = 0). Its stiffness is

K stiffness (N/m) 1.000E+00

Without this centering spring the mean position of the coil is undetermined. If it is set too low then solution convergence may be erratic.

The combination of mass and spring gives resonant frequency 2.3 Hz according to the formula

$$2\pi f = \omega = \sqrt{K/M}$$

From Equations in the Sage manual the force acting on the coil cross legs in opposite directed fields with average linear flux densities ± φ_x is

$$F = NI2\varphi_x$$

For the Sage model the number of turns in the coil is N = 200, the current amplitude is I = 5 A. The linear flux density through the coil cross legs varies with time and position but on the average it is φ_x = 3.67E-3 T/m (from the solution grid dump). So the theoretical force amplitude is 7.34 N, which agrees reasonably well with the *moving EM container* output

```
  Fpos          pos boundary force (N, deg)         -2.679E-06...
    ( 7.330,  0.012,  0.095)E+00 Amp
    ( 90.54,  94.01, -42.55)E+00 Arg
```

The theoretical ballistic mass amplitude solved from $F_{amp} = M A = -M \omega^2 X_{amp}$ is X_{amp} = 3.71E-3 M which agrees well with *ballistic mass* output

```
  FX            displacement (m, deg)             2.679E-06...
    ( 3.715,  0.001,  0.005)E-03 Amp
    ( 90.72,  94.10, -42.49)E+00 Arg
```

Energy Balance

It is helpful to consider the energy balance in the stationary parts separate from the moving coil. The following table accounts for the moving coil energy balance within the air gap.

	Power W
Input power from current source (Fwe)	-5.132E+01
Coil I^2R loss (Wdissip)	5.056E+01
Mechanical power output to damper (W)	2.725E-02
Net power leaving air gap	**-7.31E-01**

This same power is also the sum of the mean values for the FWm (magnetic power inflow) outputs for components pole pair 1 and pole pair 2, which is **7.31E-01**.

The next table accounts for the energy dissipation of that power in the stationary magnetic components.

	Power W
Combined Iron path eddy-current loss (Weddy)	6.42E-01
Combined Iron path hysteresis loss (Whyst)	8.6E-02
Combined magnet eddy-current loss (Weddy)	3.5E-3
Total losses	**7.32E-01**

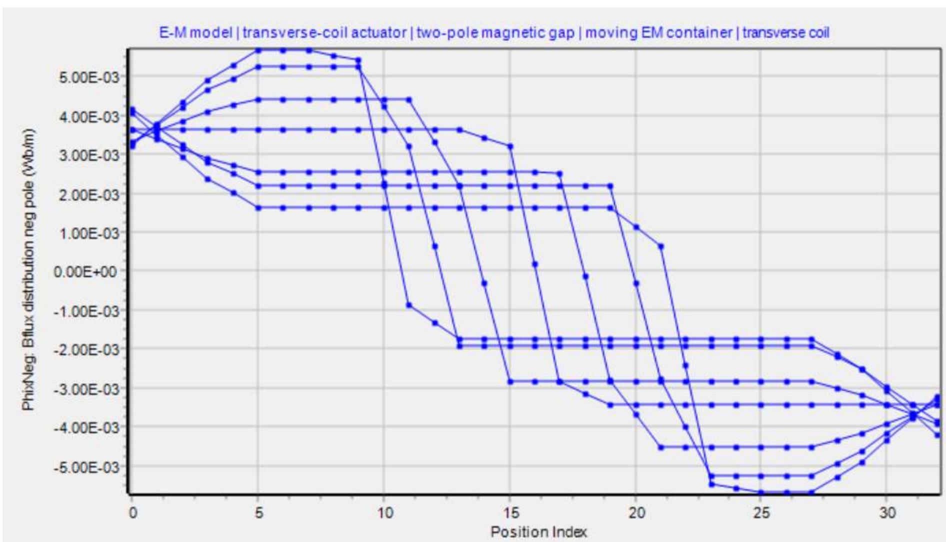
The energy-conservation discrepancy is around 0.001 W, consistent with moving EM container output EfluxErr = -1.563E-03 W. See MotorMovMag.pdf for more discussion on this discrepancy.

The eddy current losses depend on the lamination thicknesses for the iron and magnet components. For moving coil actuators the time variation of magnetic flux in the iron and magnets is relatively low so there are no laminations per say. So the lamination thickness inputs for the iron components are recast to t_i and the magnet components to W_m (in the above drawing) which are the minimum dimensions of the components when looking at a typical cross section normal to the magnetic flux direction. The thkLam inputs are defined in the *object* components inside the *iron path* and *permanent magnet* components.

Solution Grid

You can understand more about the model by plotting the solution grids within the two-pole magnetic gap component, comprising the moving EM container, the transverse coil, the coil object and the two pole pairs.

For example, the plot below from the transverse coil shows the linear magnetic flux distribution in the coil-relative reference frame at various times as it moves through the magnetic gap.



The cross-legs (across the gap) of the coil winding occupy the left and right ends of the plot where the curves are sloped. The magnetic field produced by the current in the coil changes the baseline magnetic flux produced by the permanent magnets alone. That baseline mangnetic flux can be seen in the middle curve which corresponds to the time of zero electrical current. Baseline magnetic flux goes from a positive to a negative value across the gap separating the oppositely polarized magnets.

The reason the other curves are sloped upward or downward near the ends is that the number of windings linked into to the inner coil volume progressively increases from the outer to the inner windings.

The reason the location of the discontinuity from positive to negative magnetic flux moves back and forth is because the plot is in the coil reference frame from which the outer magnetic structure appears to be moving back and forth.