Boundary Element analysis of cogging force in linear motor

By: Amandeep Bal, Testing and Benchmarking Engineer, Integrated Engineering Software

A **linear motor** is an electric motor that has had its stator and rotor "unrolled" so that instead of producing a torque (rotation) it produces a linear force along its length. Iron core linear motors have traditionally suffered from a phenomenon known as cogging. This is seen as a periodically varying resistive force and it is caused because the motor coil has preferred positions in relation to the magnet track and resists attempts to move it off these preferred positions. Cogging limits the smoothness of motion systems because the force generated by the motor must change with position in order to maintain a constant velocity. The cogging of the motor must be minimized for high precision applications because it is an undesirable component for the operation of motor. It is especially prominent at lower speeds, with the symptom of jerkiness; however, at high speed the motor moment of inertia filters out its effect. This article investigates the analysis of cogging force of a linear motor using boundary element analysis and built in parametric feature of the two dimensional magnetic solver. The solver used to analyze this problem is an automatic solver that also has option of switching to either Finite Element Method (FEM) or Boundary Element method (BEM) manually. BEM solver has been selected to solve this problem. As its name suggests, the boundary-element method only requires that elements be on the boundary of the model being simulated (figure 2). The question is how are these elements are used to calculate the magnetic field or other derived quantities such as force and torque? The answer lies in the integral form of Maxwell's equations. A known current source lets us calculate the magnetic field at any point arising from this current by integrating the source along with the appropriate so-called Green's function. Without getting into a lot of unnecessary mathematical detail, it is thus possible to calculate the magnetic field from current sources by doing some basic integration with the sources.

Under the hood, the boundary-element method replaces the magnetic materials with an equivalent surface current. Once this value is known, it can be treated the same as any real surface current. Thus, the goal of the boundary-element approach is to replace all magnetic materials with equivalent currents and then use basic integration to calculate the fields at any point.

In contrast, the finite-element method requires a finite-element mesh in the model as well as in the surrounding space. Theoretically, the mesh should extend off to infinity for an exact solution. Of course this is impossible, so it is necessary to arbitrarily decide how far the mesh should extend away from the cylinder to get an acceptable solution. This can be a major problem while dealing with open region problems.

Assuming a proper mesh has been generated, the goal is to ultimately determine the magnetic field. To do this with finite elements typically involves first solving for a scalar or a vector quantity calculated at each of the nodes of the finite-element mesh. For magnetics problems, users typically

calculate magnetic-vector potential. This is an artificial quantity. To get the magnetic field, it is necessary to differentiate or take the *curl* of the magnetic-vector potential. This operation is in contrast to the boundary-element method where a user would integrate the unknowns to calculate the magnetic field.

Figure 1 shows the two dimensional model of a linear motor which consists of magnets and windings. The magnets are bond to an iron plate and the coils are wound in the slots. The current applied to coils controls speed, force and direction of the motor. The magnets shown in the model have opposite polarities.
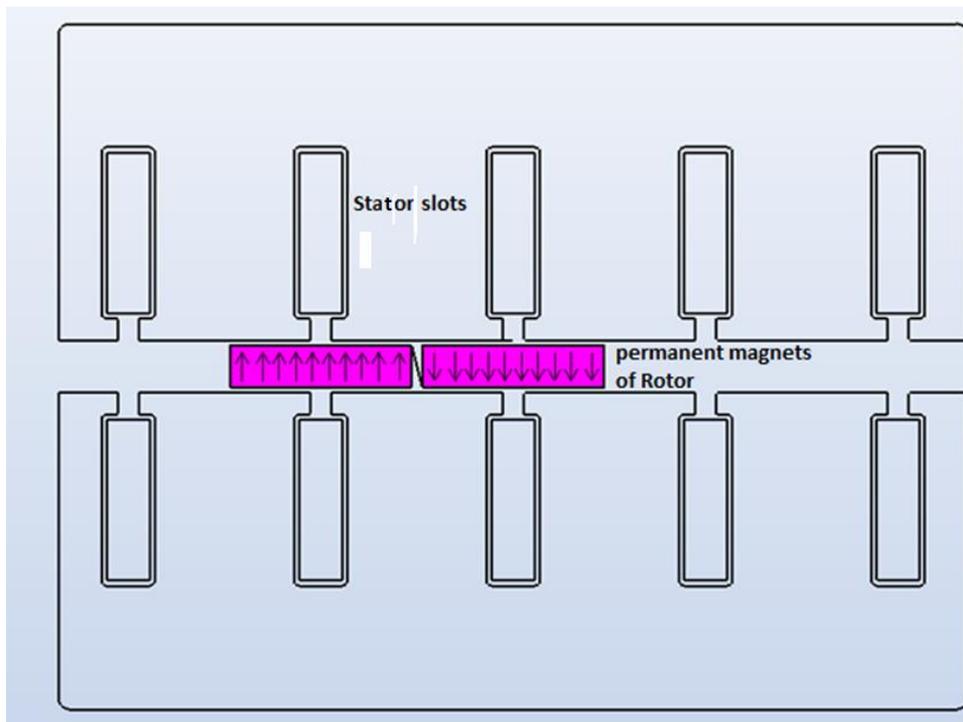

Fig1: Two-dimensional model of linear motor

The stator and rotor are made of steel and Neodymium 10 MGOe Bonded, respectively. Since all the materials are linear, the BEM solver needs to solve for unknowns only at the boundaries. This model contains about 796 1D elements. Without the symmetric conditions, this model would require more elements and a RAM. It can also increase the computational time significantly. Therefore, symmetry about any principal plane should be made use for a faster simulation.

Figure 2 shows the physics settings in the solver. The solver type is set to 'Fields'. In the solver setup, BEM is the method of solution. The matrix solver type can be set to 'Direct', 'Iterative' or 'Auto'. In auto mode, a 2D Magnetic field solver will automatically determine the best solver without requiring any user interaction. The direct solver is robust but requires more time than the iterative solver. The meshing is self-adaptive.
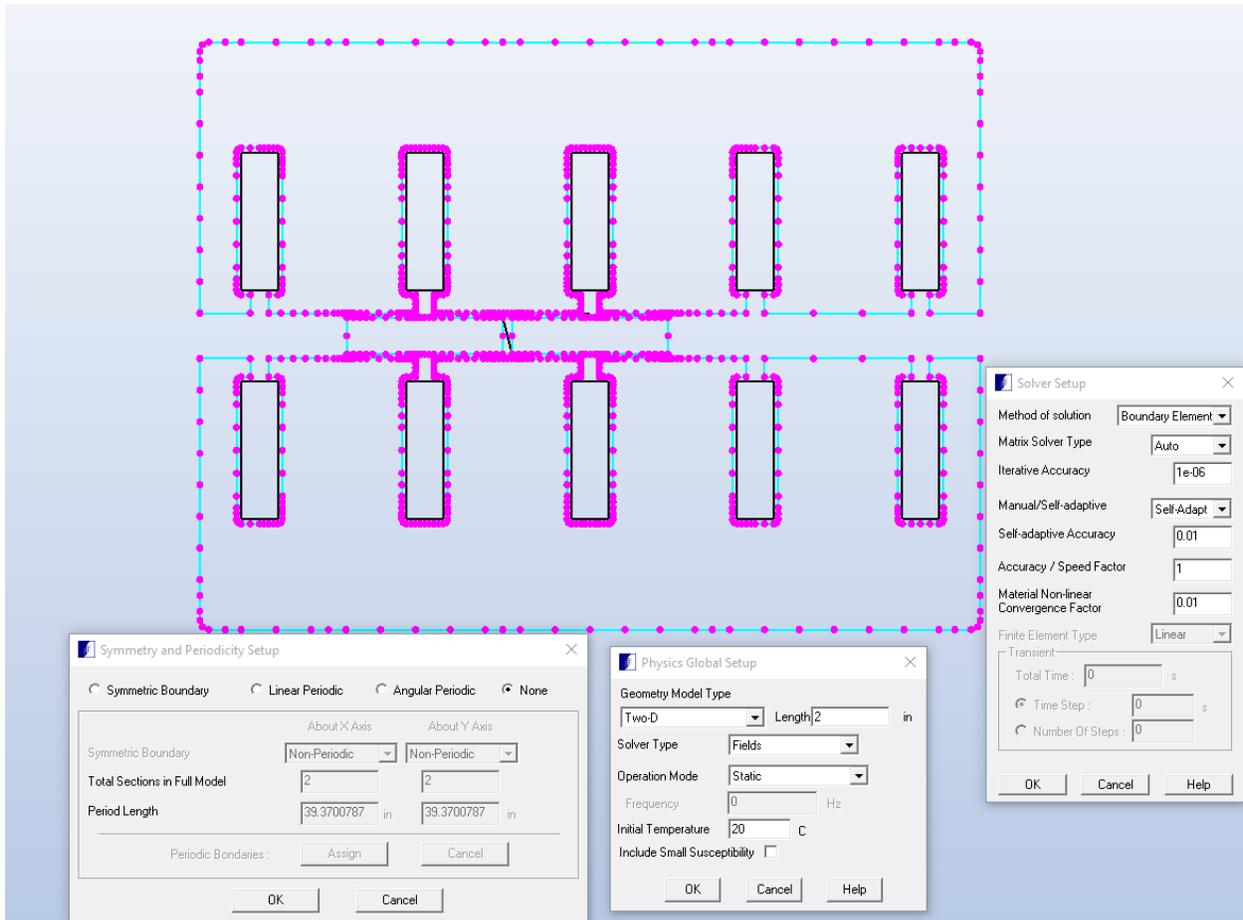
Fig 2: Distribution of elements and physics settings in model
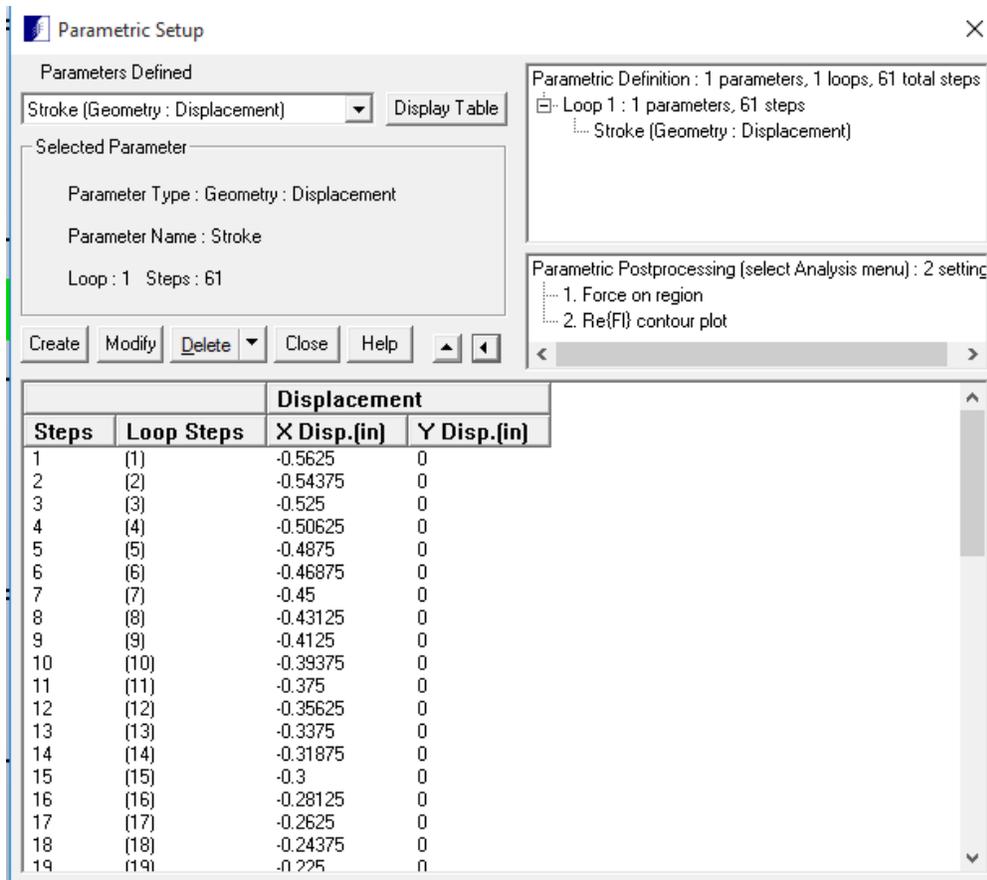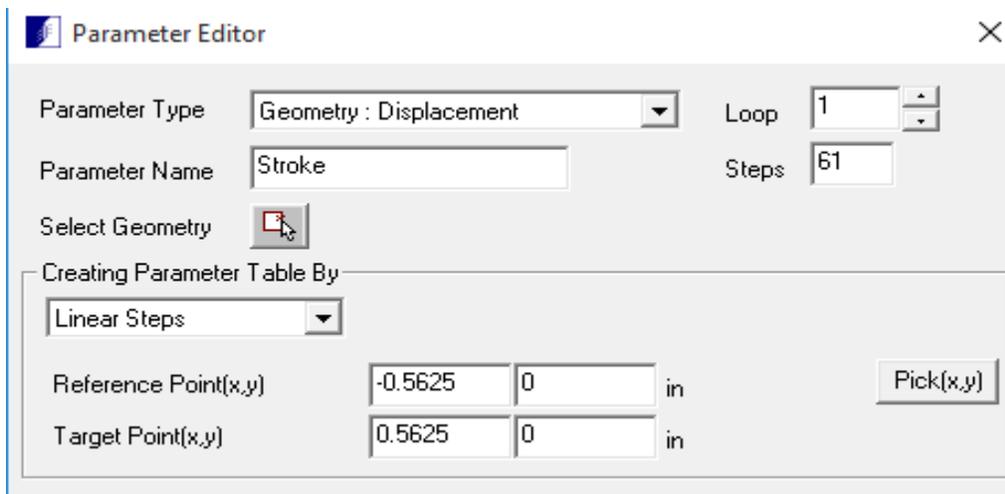
Fig 3: Parametric setup to analyze cogging force

Fig 4: Parameter editor to set up parametric

Solver's built-in parametric features allow the user to change parameters, such as dimensions and materials, and determine how they will affect the ultimate performance of the model. Easily, the user can modify the design by stretching, transforming or rotating parts of the geometry, among other functions. This allow designers to set up calculations and graphical analysis for any parameters not available as standard output. Parametric set up was used to set up parameters shown in figure 3. The parameter type in this problem was set to "Geometry: Displacement" and parameter name was set to "Stroke" as shown in figure 4. Geometry was selected by clicking "Select Geometry" button and then selecting permanent magnet region of rotor in the model. Then the reference point and target points on the model were selected by clicking "Pick (x.y)". One loop with 61 steps were fixed for parametric analyses. Amperian force on selected regions was analyzed. After running the parametrics, the solver iterated through requested parametric variations and final parametric table will appear as shown in figure 5. Plots can be made from this data as shown in figure 6.

Final Parametric Table

Steps	Loop Steps	Stroke (1) Displacement X Disp.(in)	Y Disp.(in)	0. Fx(N)	0. Fy(N)	0. Fm(N)	0. Fa(deg)	0. Area(m^2)
1	(1)	-0.5625	0	0.000743479926	-1.10452447e-13	0.000743479926	-8.51194341e-09	0.00034274125
2	(2)	-0.54375	0	-0.0758706938	-2.12963869e-14	0.0758706938	-180	0.00034274125
3	(3)	-0.525	0	-0.159415249	7.8327389e-14	0.159415249	180	0.00034274125
4	(4)	-0.50625	0	-0.254969858	3.3568881e-14	0.254969858	180	0.00034274125
5	(5)	-0.4875	0	-0.319886276	6.85815849e-15	0.319886276	180	0.00034274125
6	(6)	-0.46875	0	-0.406192911	2.88764568e-14	0.406192911	180	0.00034274125
7	(7)	-0.45	0	-0.482991212	-2.24514451e-13	0.482991212	-180	0.00034274125
8	(8)	-0.43125	0	-0.694447123	1.50879487e-13	0.694447123	180	0.00034274125
9	(9)	-0.4125	0	-0.660035434	-1.21281118e-13	0.660035434	-180	0.00034274125
10	(10)	-0.39375	0	-0.73638786	-2.62775757e-13	0.73638786	-180	0.00034274125
11	(11)	-0.375	0	-0.818015264	-1.03594289e-13	0.818015264	-180	0.00034274125
12	(12)	-0.35625	0	-0.818707697	-1.71814918e-13	0.818707697	-180	0.00034274125
13	(13)	-0.3375	0	-1.01704928	-3.1042191e-13	1.01704928	-180	0.00034274125
14	(14)	-0.31875	0	-1.0572204	-3.41464101e-13	1.0572204	-180	0.00034274125
15	(15)	-0.3	0	-1.12363492	-1.9094557e-13	1.12363492	-180	0.00034274125
16	(16)	-0.28125	0	-1.1985357	-1.95637995e-13	1.1985357	-180	0.00034274125
17	(17)	-0.2625	0	-1.17555397	-2.60970978e-13	1.17555397	-180	0.00034274125
18	(18)	-0.24375	0	-1.27038526	-1.05399067e-13	1.27038526	-180	0.00034274125
19	(19)	-0.225	0	-1.23700972	1.76868298e-14	1.23700972	180	0.00034274125
20	(20)	-0.20625	0	-1.2682402	4.11489509e-13	1.2682402	180	0.00034274125
21	(21)	-0.1875	0	-1.03007538	4.94148367e-13	1.03007538	180	0.00034274125
22	(22)	-0.16875	0	-0.733964386	6.59105126e-13	0.733964386	180	0.00034274125
23	(23)	-0.15	0	-0.144223059	1.27886608e-12	0.144223059	180	0.00034274125
24	(24)	-0.13125	0	0.904670042	2.14552074e-12	0.904670042	1.35883004e-10	0.00034274125
25	(25)	-0.1125	0	2.45772004	3.54711176e-12	2.45772004	8.26923041e-11	0.00034274125
26	(26)	-0.09375	0	5.30860382	5.45151408e-12	5.30860382	5.88382105e-11	0.00034274125
27	(27)	-0.075	0	8.32793516	6.56939392e-12	8.32793516	4.51971033e-11	0.00034274125
28	(28)	-0.05625	0	10.0825161	6.88595208e-12	10.0825161	3.91307077e-11	0.00034274125
29	(29)	-0.0375	0	0	0	0	0	0
30	(30)	-0.01875	0	0	0	0	0	0
31	(31)	0	0	0	0	0	0	0
32	(32)	0.01875	0	0	0	0	0	0
33	(33)	0.0375	0	0	0	0	0	0
34	(34)	0.05625	0	0	0	0	0	0
35	(35)	0.075	0	0	0	0	0	0
36	(36)	0.09375	0	0	0	0	0	0
37	(37)	0.1125	0	0	0	0	0	0
38	(38)	0.13125	0	0	0	0	0	0
39	(39)	0.15	0	0	0	0	0	0
40	(40)	0.16875	0	0	0	0	0	0
41	(41)	0.1875	0	0	0	0	0	0
42	(42)	0.20625	0	0	0	0	0	0
43	(43)	0.225	0	0	0	0	0	0
44	(44)	0.24375	0	0	0	0	0	0
45	(45)	0.2625	0	0	0	0	0	0
46	(46)	0.28125	0	0	0	0	0	0
47	(47)	0.3	0	0	0	0	0	0
48	(48)	0.31875	0	0	0	0	0	0
49	(49)	0.3375	0	0	0	0	0	0
50	(50)	0.35625	0	0	0	0	0	0
51	(51)	0.375	0	0	0	0	0	0
52	(52)	0.39375	0	0	0	0	0	0
53	(53)	0.4125	0	0	0	0	0	0
54	(54)	0.43125	0	0	0	0	0	0
55	(55)	0.45	0	0	0	0	0	0
56	(56)	0.46875	0	0	0	0	0	0
57	(57)	0.4875	0	0	0	0	0	0
58	(58)	0.50625	0	0	0	0	0	0
59	(59)	0.525	0	0	0	0	0	0
60	(60)	0.54375	0	0	0	0	0	0
61	(61)	0.5625	0	0	0	0	0	0

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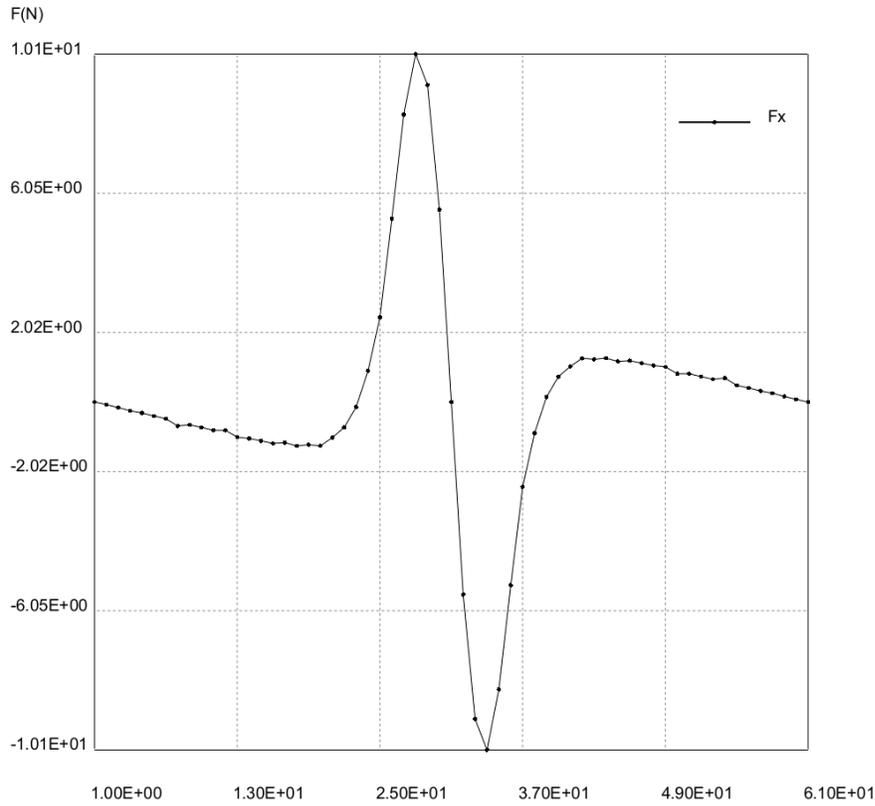
Figure 5: Parametric results

Fig 6: Analysis of cogging force

Hence, parametric analysis feature in the software program allow the user to change parameters, such as dimensions and materials, and determine how they will affect the ultimate performance of the model. Easily, the user can modify the design by stretching, transforming or rotating parts of the geometry, among other functions. Our postprocessor tools allow designers to set up calculations and graphical analysis for any parameters not available as standard output