Interstate Report

Simulations were carried out by varying some selected parameters of the Nacelle and Rail arrangement using 3D magnetic field software **AMPERES.** Boundary Element Method (BEM) is implemented in **AMPERES** for analyzing the magnetic field simulation. This report consists of two parts. First part is the study of the single Nacelle and Rail section and the second being the study of the 3 Nacelle and Rail sections.

Part-I Single Nacelle & Rail section

The orientation and arrangement of single Nacelle & Rail section is shown in Fig. 1. Dimensions of the Nacelle are given below:

Nacelle outer radius = 14.25 inch
Nacelle inner radius = 7.625 inch
Nacelle Arc angle = 315^{o}
Nacelle Thickness = 1 inch
Rail outer radius = 6.625 inch
Rail inner radius = 0.475 inch
Rail Thickness = 1 inch

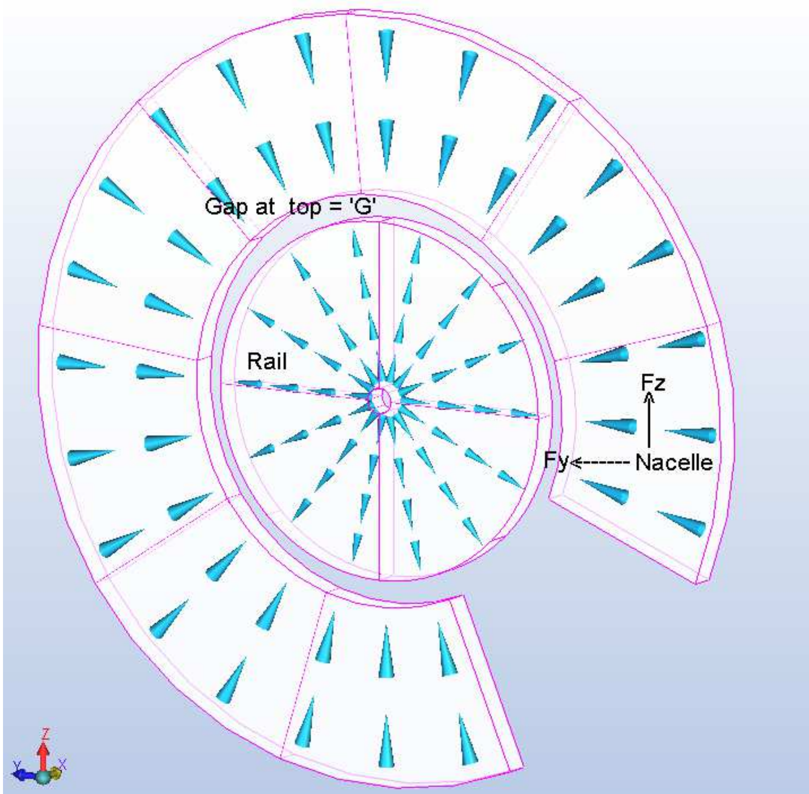

Fig.1 Nacelle and Rail section

Nacelle is modeled as one radial permanent magnet whereas the Rail is modeled as two radial magnets. The magnet orientations of these permanent magnets are seen in Fig. 1.

Magnetic material used in the simulation is Neodymium 45 MGOe Sintered permanent magnet rare earth material. The demagnetization curve (B-H curve) of this material is shown in Fig. 2. Rare earth permanent magnetic materials are used for building very high magnetic fields for the given size of the magnet.

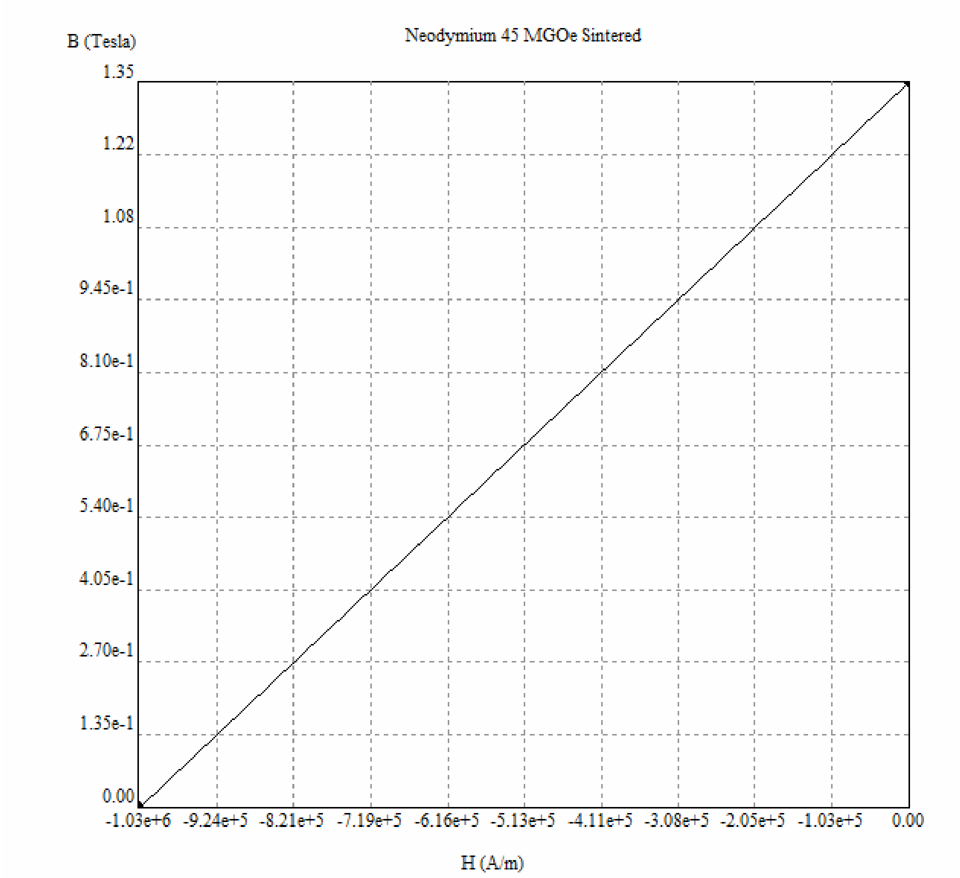

Fig. 2 Demagnetization curve of Neodymium 45 MGOe Sintered material

Referring to the Fig. 1, the gap 'G' between the Nacelle and Rail is varied for studying the variation of the force acting on the Nacelle. When 'G' is 1 inch Nacelle and Rail are concentric and the gap between them is uniform. When the Nacelle is pushed downwards 'G' becomes less than 1 inch and the uniformity of the gap is lost. The force components **Fy** and **Fz** on the Nacelle are calculated as a function of the gap at the top of the Rail. The force component **Fz** is the force acting vertically upwards on the Nacelle whereas, **Fy** is the force component that pulls the Nacelle towards left (the Rail).

The 2D-surface elements used in this simulation are quadrilateral elements. For improved accuracy around 2500 quadrilateral 2D-elements are used in this simulation. Fig. 3 shows the element structure used in the present model. It is important to note that only 2D surface mesh (element structure) is required for modeling permanent magnets in BEM analysis, whereas a 3D mesh is required in Finite Element Method (FEM) of analysis.

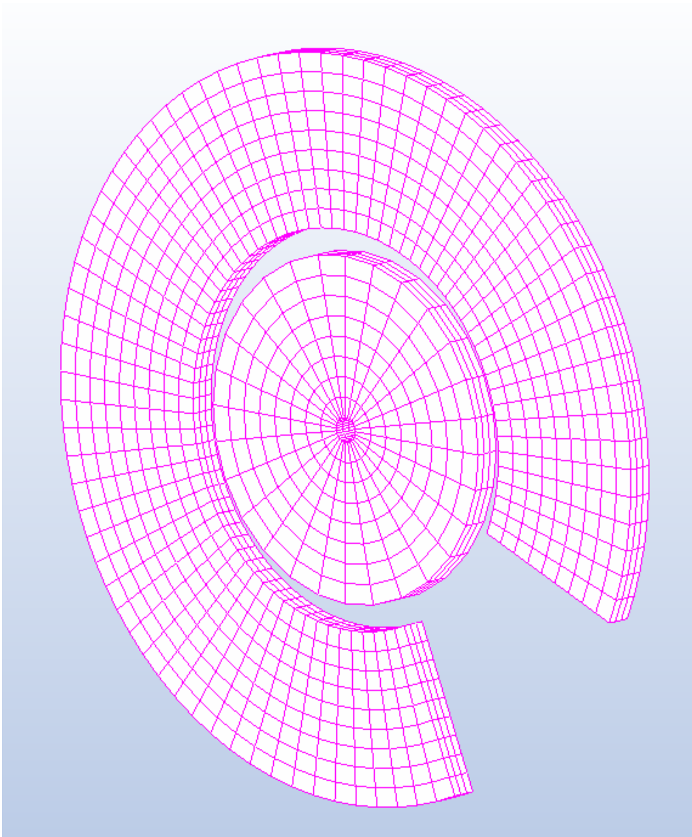

Fig. 3 Quadrilateral boundary element surface mesh.

The variation of the force components **Fy** and **Fz** on the Nacelle as a function of gap at the top of the Rail is shown in Figs. 4 and 5, respectively.

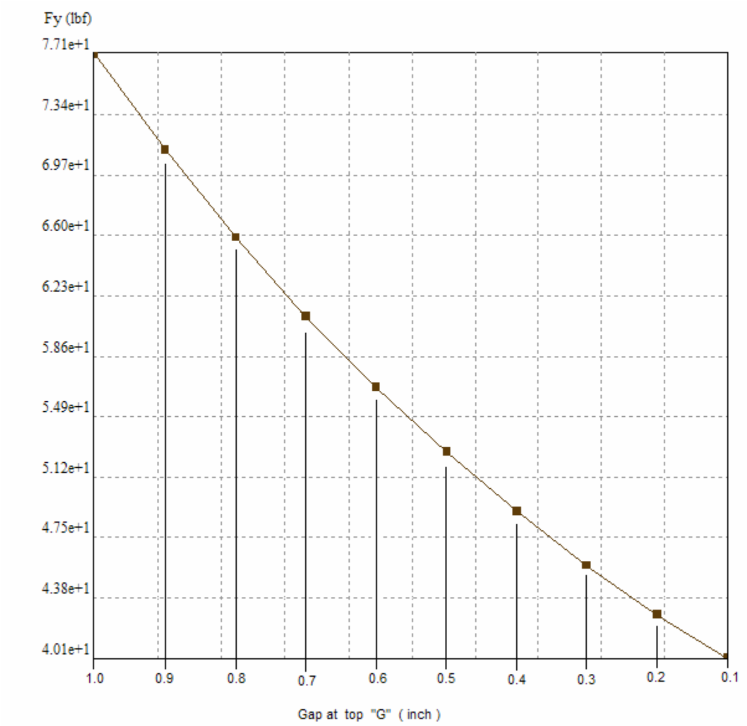

Fig. 4 Force component **Fy** variation with gap at top ‘G’

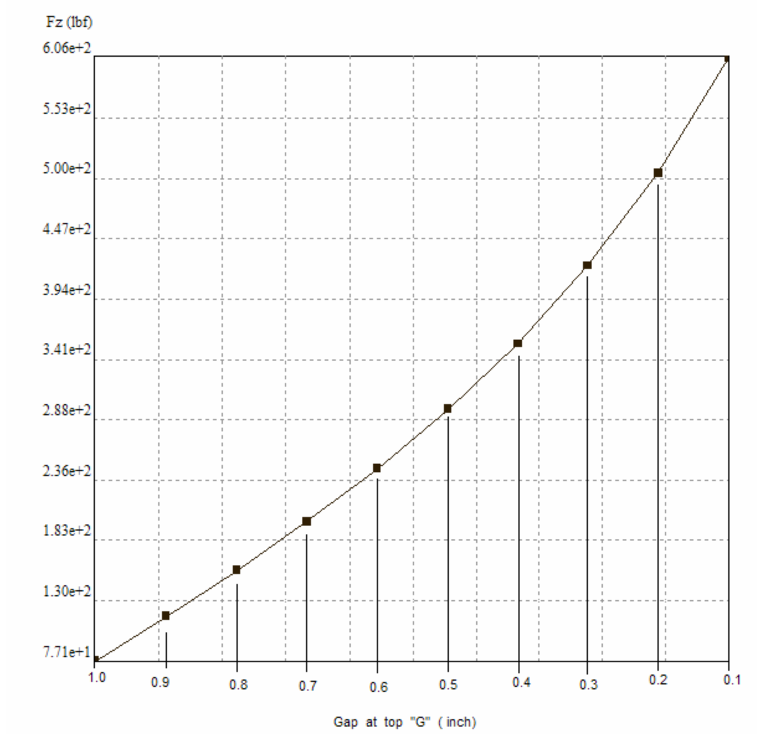

Fig. 5 Force component **Fz** variation with gap at top ‘G’

Next, a parametric study of the force components on the Nacelle with the thickness of the concentric Nacelle and Rail system as a parameter has been performed. Thickness of the system is varied from 1 inch to 24 inches in 1 inch step and the results are shown in Figs. 6 and 7. In this parametric study a uniform gap of 1 inch is maintained between the Nacelle and Rail.

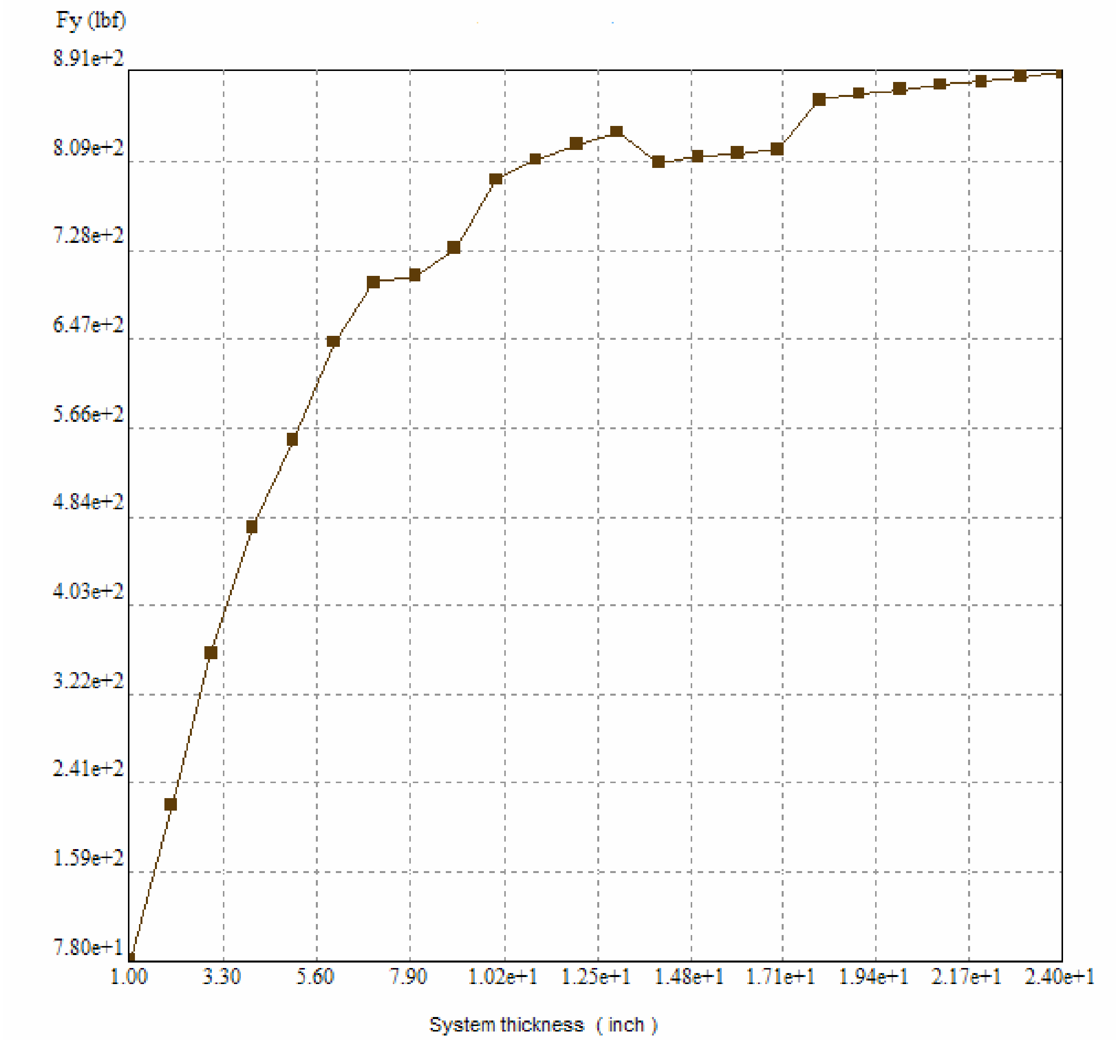

Fig.6 Force component **Fy** variation with thickness

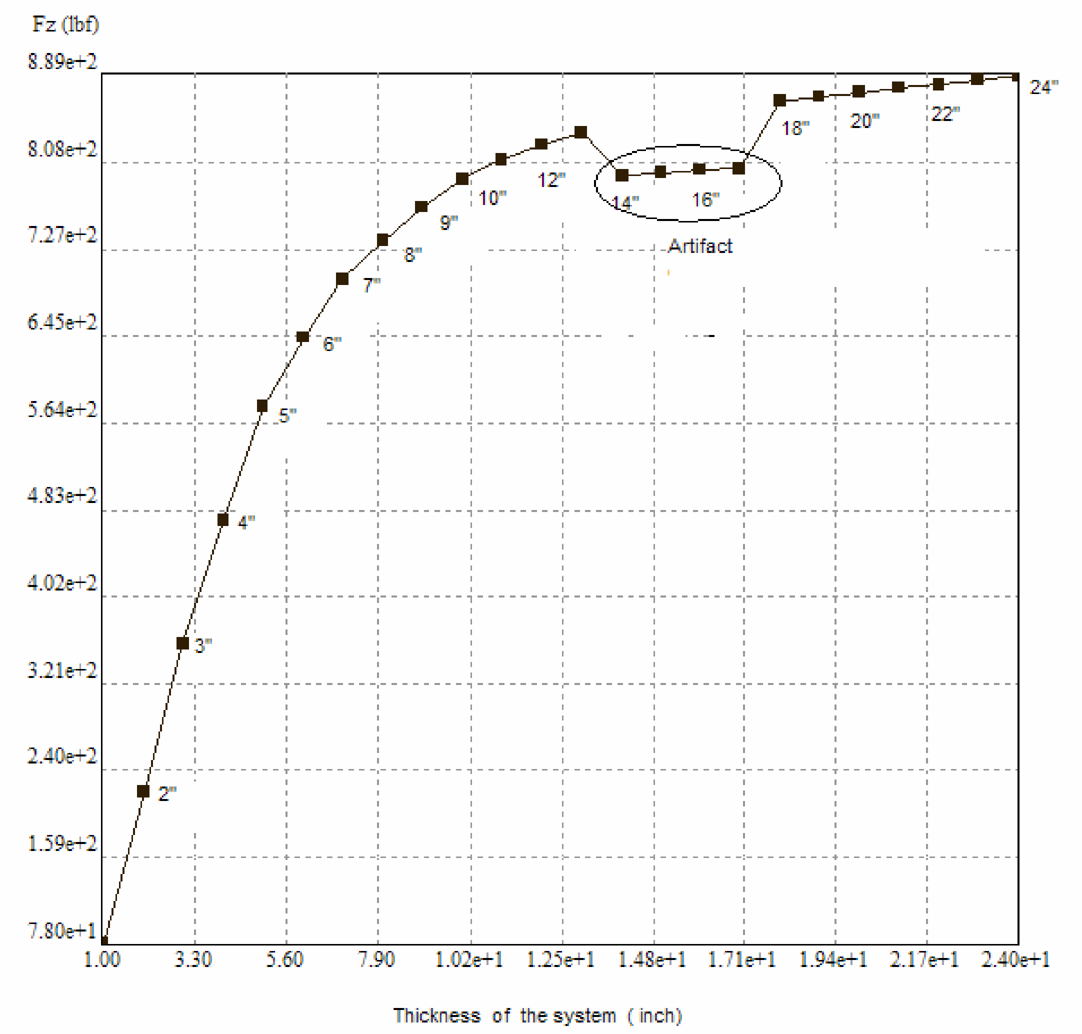

Fig.7 Force component **Fz** variation with thickness

Variations of the force components shown in Figs. 6 and 7 are not smooth in 14-17 inch thickness range. This artifact is due to the software(**AMPERES**) limitations. The surface mesh used in the model with different thicknesses has been kept same in this parametric study. This is the reason for the artifacts in the graphs shown in Fig. 7 and 8. Actual force components can easily be estimated by the interpolation/extrapolation of the smooth parts of the graphs.

From this parametric study, it is clear that the lift and lateral force components on the Nacelle do practically level off once the thickness of the system reaches a value. In the present study, when the thickness of system reaches 10 inch the incremental change in the force components is not significant and hence it is cost effective to limit the system thickness to 10 inch.

To have an idea about the magnetic field density (B) values involved in this system the B-filed arrow plot taken in the bulk of the Nacelle is shown in Fig. 8. Also a B-filed iso-surfaces plot is calculated in a box just fitting the Nacelle and Rail and is shown in Fig. 9.

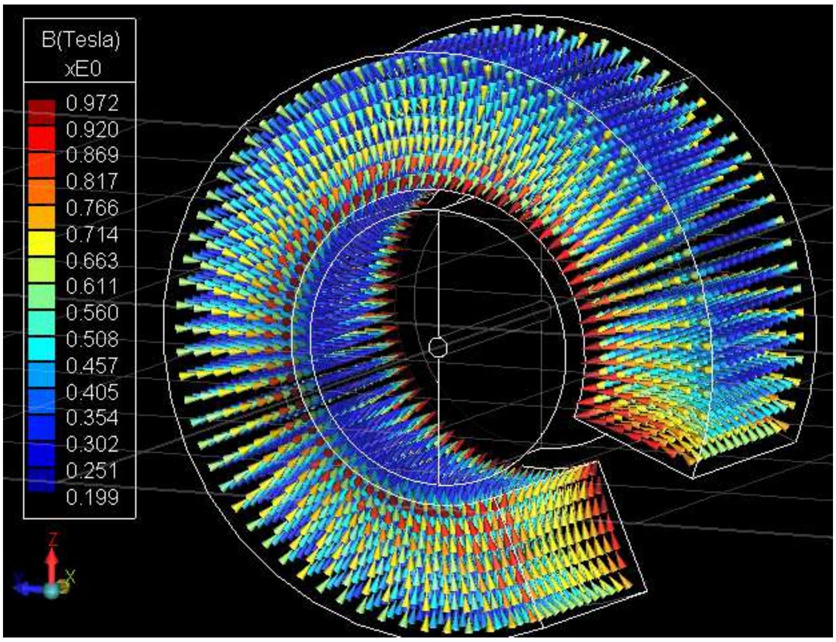

Fig. 8 B-field arrow plot in Nacelle, system thickness = 12 inch

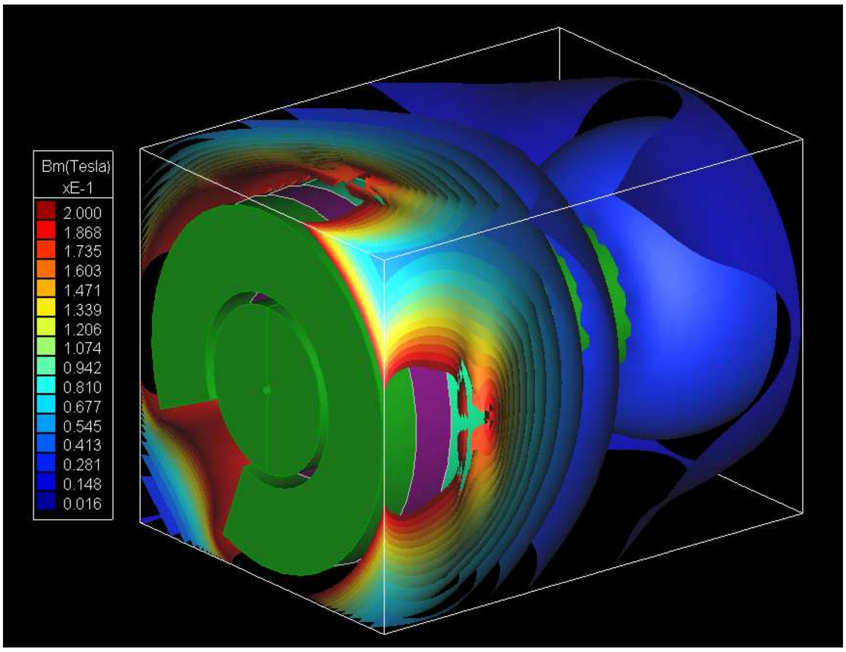

Fig. 9 B-field iso-surfaces plot in a box

It would be of major interest to know about the force components on the Nacelle if the entire Nacelle is not polarized radially in the same direction. To conduct this study the Nacelle is modeled as a composition of 14 radial magnets, each being 22.5^{o} extent as shown in Fig. 10. The polarity of the first two of the 14 radial Nacelle magnets are reversed with an aim to increase the lift force component **Fz** on the Nacelle for a uniform gap of 1 inch. For this arrangement, the computed force components on the Nacelle are **Fx = 0 lbf ; Fy = 78 lbf ; Fz = 299 lbf**.

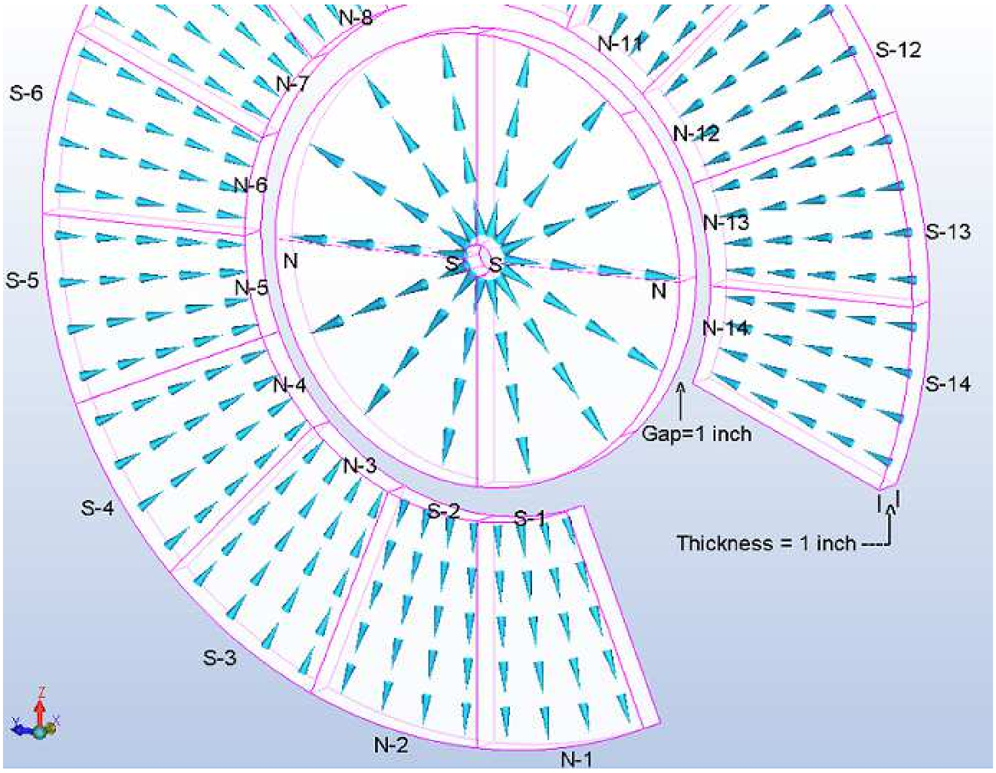

Fig. 10 Nacelle modeled as 14 pieces, polarization of first two pieces reversed

If the polarity of one more magnet piece of the Nacelle is reversed as shown in Fig. 11, the force components computed are **Fx = 0 lbf ; Fy = 15 lbf ; Fz = 394 lbf**. Comparing the force components of these two arrangements, the force components of Fig. 11 are better suited for the present application because the lift force is increased by 33.3% and the lateral force is decreased by a factor 5. Further optimization can be attempted by selectively choosing several magnet pieces of Nacelle. This type of optimization requires many trials on the software.

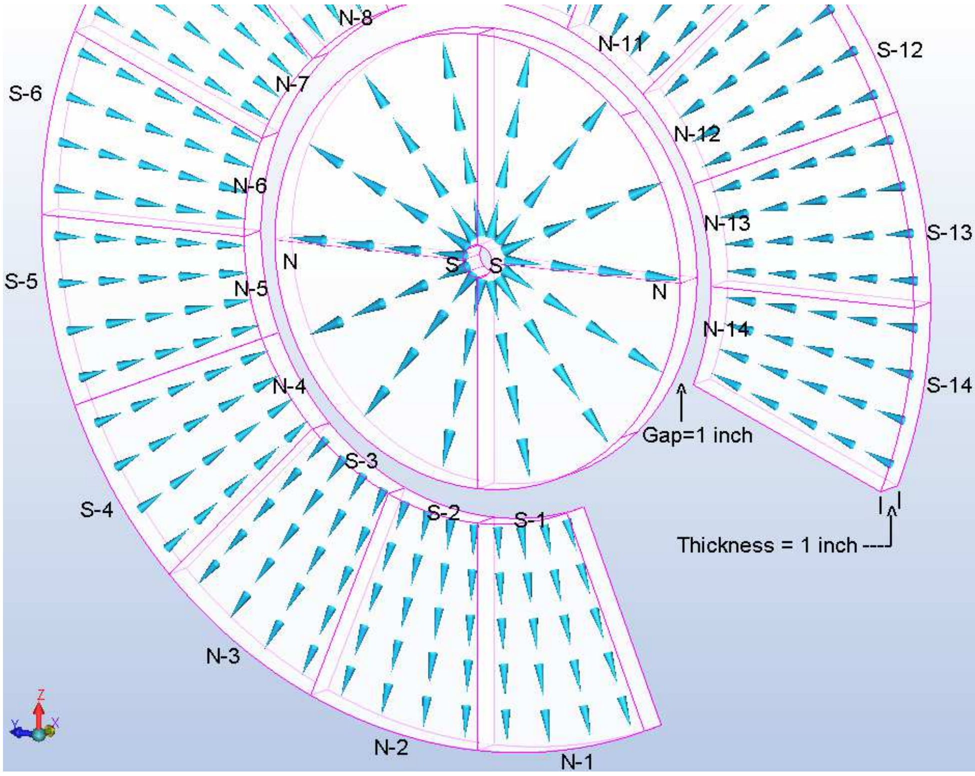

Fig. 11 Nacelle modeled as 14 pieces, polarization of first three pieces reversed

It has been noted that with a single Nacelle and Rail section the force components on the Nacelle are the lift force (**Fz**), lateral force (**Fy**), but no drag force (**Fx**). From Figs. 6 and 7 the force components on the Nacelle for 10 inch system thickness are **Fx = 0** ; **Fy = 784 lbf** ; **Fz = 784 lbf**. To create a drag force in a single section the Nacelle is made out three permanent magnetic materials of various strength as shown in Fig. 12. In this simulation Neodymium 45 MGOe, Neodymium 35 MGOe, and 10 Neodymium MGOe sintered rare earth materials are used. The demagnetization curves of the later two materials are shown in Figs. 13 and 14. The force components on the entire 3 layers of Nacelle are **Fx = 1163 lbf** ; **Fy = 602 lbf** ; **Fz = 602 lbf**. Due to unequal strength magnet composition, the drag force component **Fx** has increased tremendously.

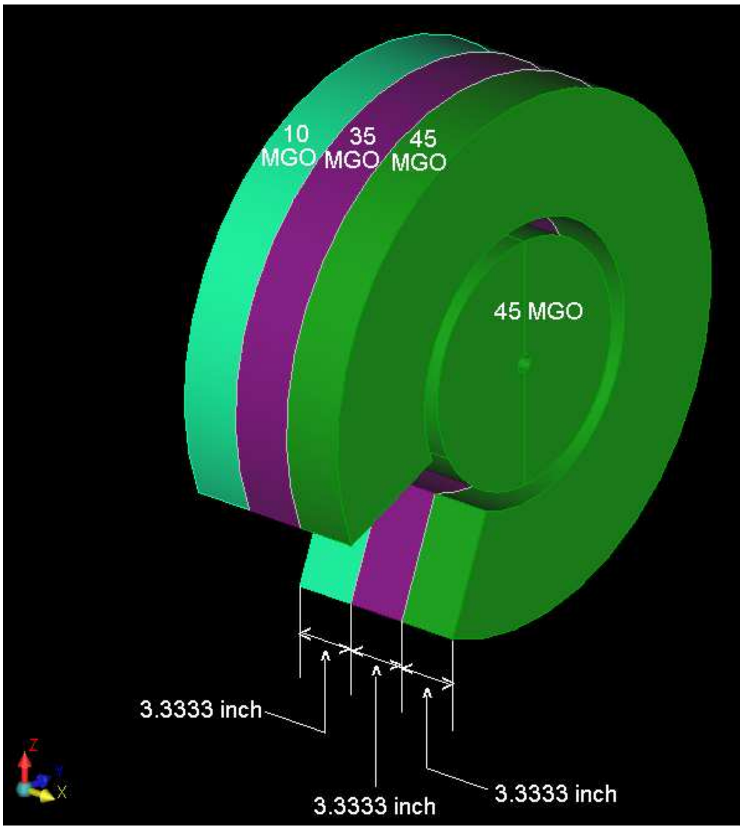

Fig. 12 Nacelle is divided up into three unequal strength magnets

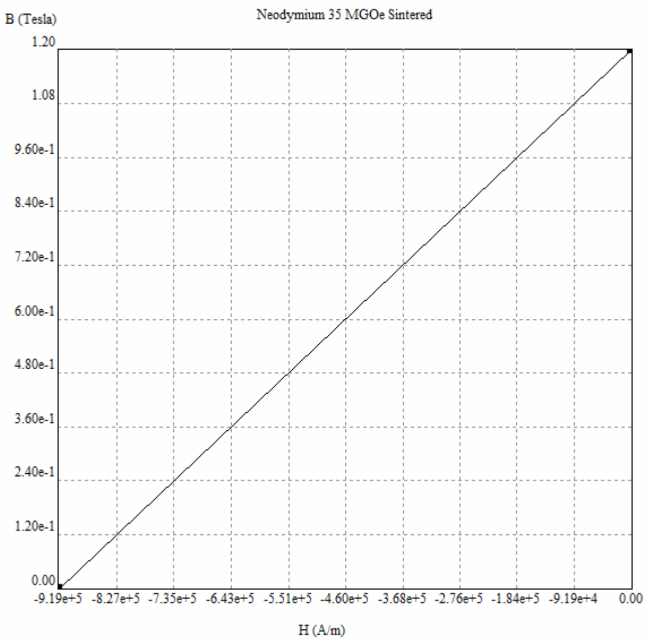

Fig. 13 Demagnetization curve of Neodymium 35 MGOe Sintered material

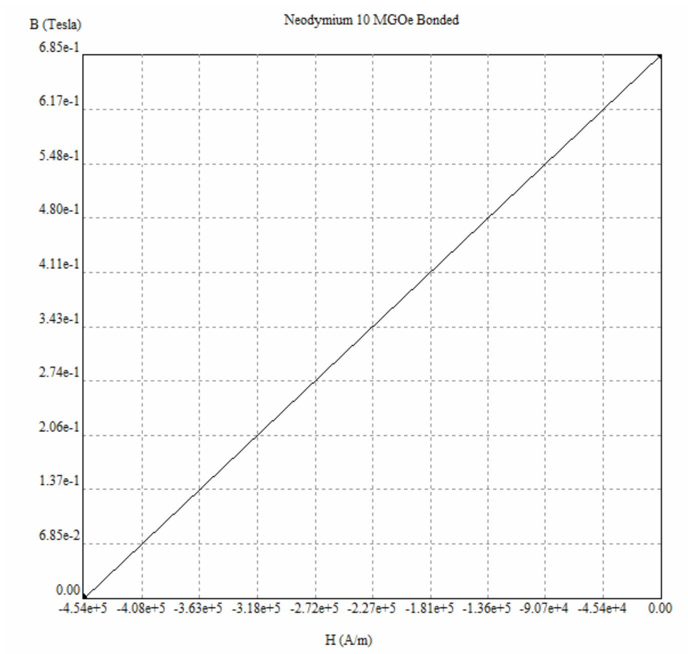

Fig. 14 Demagnetization curve of Neodymium 10 MGOe Sintered material

Part-II Three sections of Nacelle and Rail

In this section the results of the simulations with three Nacelle and Rail sections modeled are presented. In this study, each Nacelle is modeled as a single radial magnet as shown in Fig. 15. Width of the Nacelle and Rail section 'M' and the separation

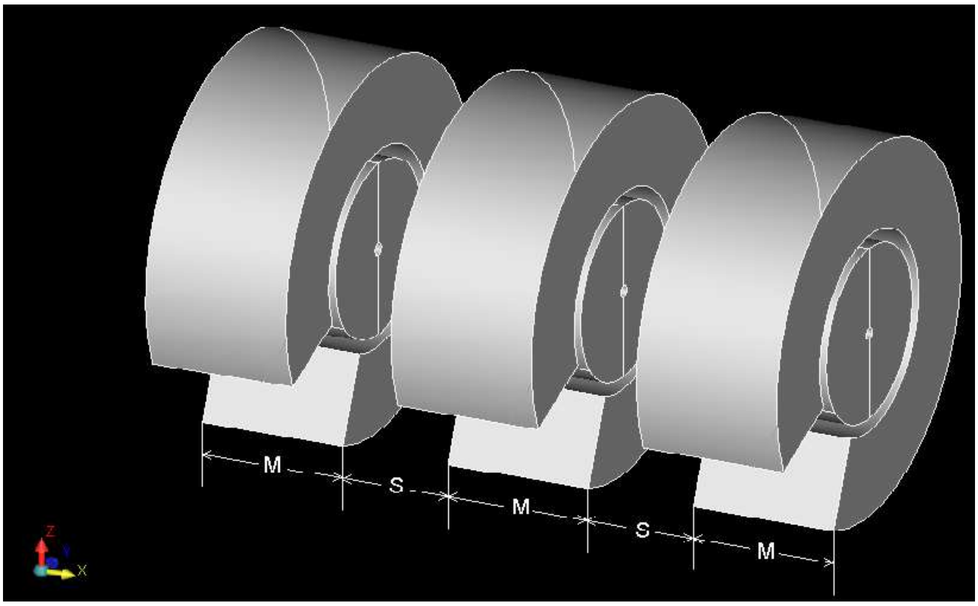

Fig. 15 Three Nacelle and Rail sections

between two consecutive sections 'S' are varied with a view to maximize the total lift force component **Fz** on the three Nacelles. Results of Nacelle and Rail magnets made up of Neodymium 45 MGOe Sintered rare earth material Nacelle and Rail magnets are given below.

Serial Number	Section Width 'M' (inch)	Separation 'S' (inch)	Lift force on 3 Nacelles Fz (lbf)
1	13	3	1588
2	12	4.5	1870
3	10	7.5	2114

Further study has been carried out in this section with M=10 inch and S=7.5 inch. For this case the drag and lateral force components **Fx=0 lbf** and **Fy=2114 lbf**, respectively. To increase the drag force component, Nacelles are modeled with unequal strength magnetic materials Neodymium 45 MGOe, 35 MGOe, and 10 MGOe a shown in Fig. 16.

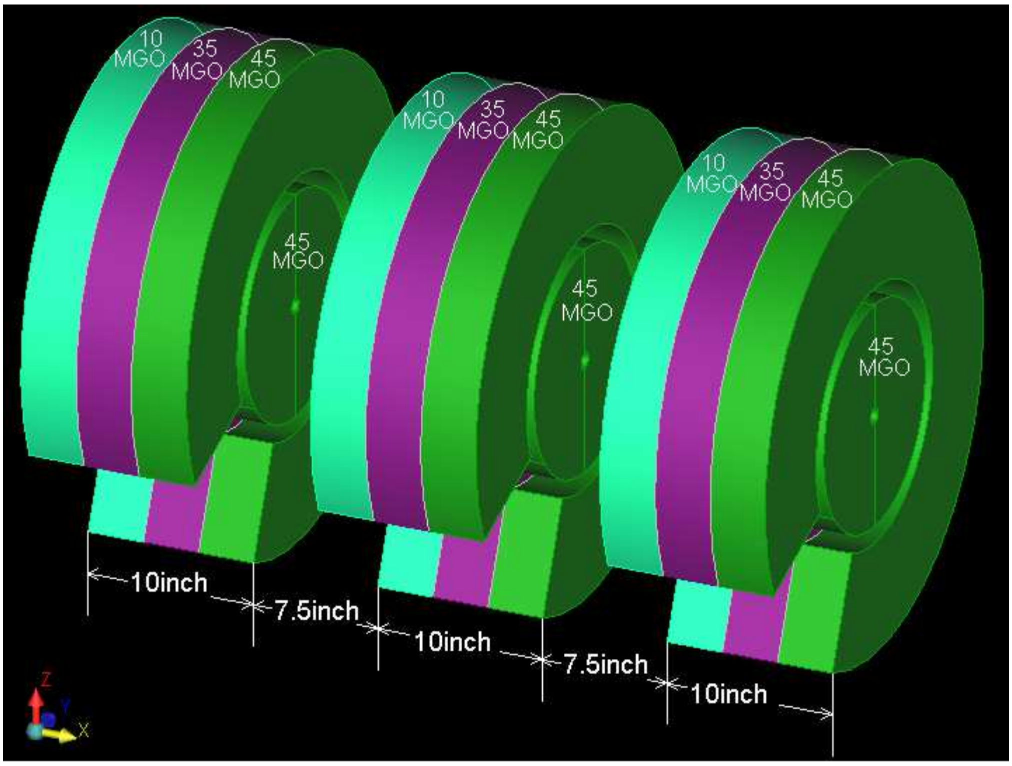

Fig. 16 Three Nacelles of unequal strength magnetic materials

Force components on the 3 Nacelles simulated by unequal magnetic strength materials are:

Drag Force **Fx = 3790 lbf** ; Lateral Force **Fy = 1620 lbf** ; Lift Force **Fz = 1620 lbf**

The force components variation as the three Nacelles move over the Rails as a group are found next. The “start” and “stop” positions for this parametric study are shown in Fig. 17. The distance between the start and stop positions is 17.5 inch. Hence the Nacelle group is placed at a total of 36 positions, each position separated by 0.5 inch. Two extra Rail sections, one section before the three Nacelle and Rail sections and another after were modeled for this parametric study. Fig. 17 shows the first position of the Nacelle group and Fig. 18 shows the 36th position. For each position, the force components on the Nacelle group were calculated. The drag force component **Fx** and the lift force component **Fz** are plotted in Figs. 19 and 20, respectively. Since the value of the lateral force component **Fy** is the same as **Fz**, the plot of the **Fy** variation is not shown separately. The B-field contour plots on a cylindrical surface is shown in Fig. 21.

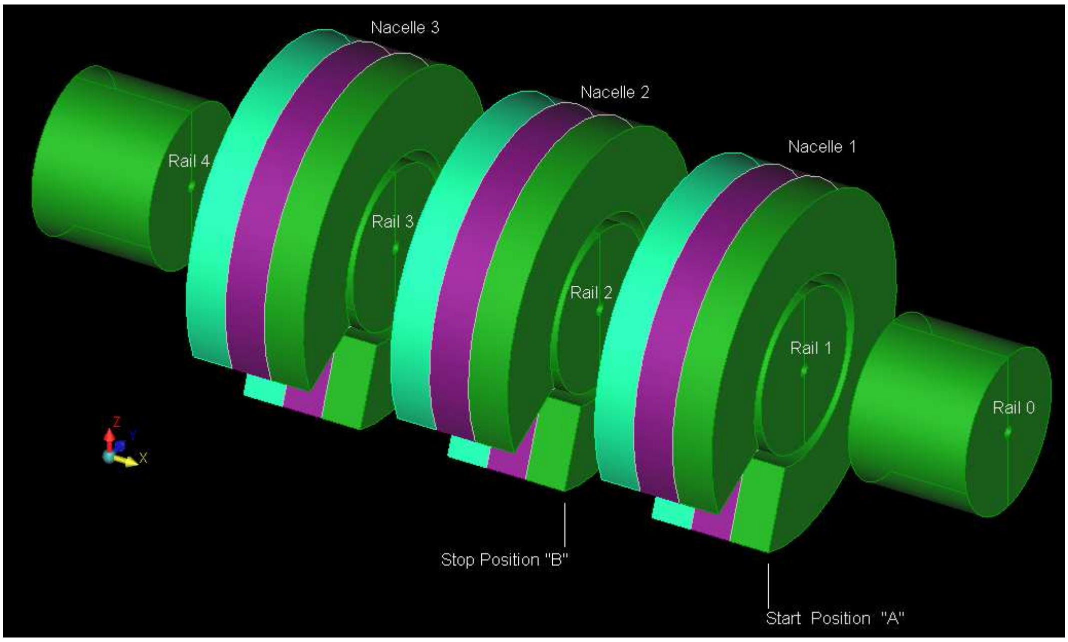

Fig. 17 Reference diagram for the parametric study of the 3 Nacelles movement

In conclusion, this report brings out the usage of simulation software **AMPERES** for determining the forces acting in a magnetic system. Though we have used permanent magnets for the simulation of the Nacelle and Rail, similar analysis can be carried out with electro-magnets driven by current coils.

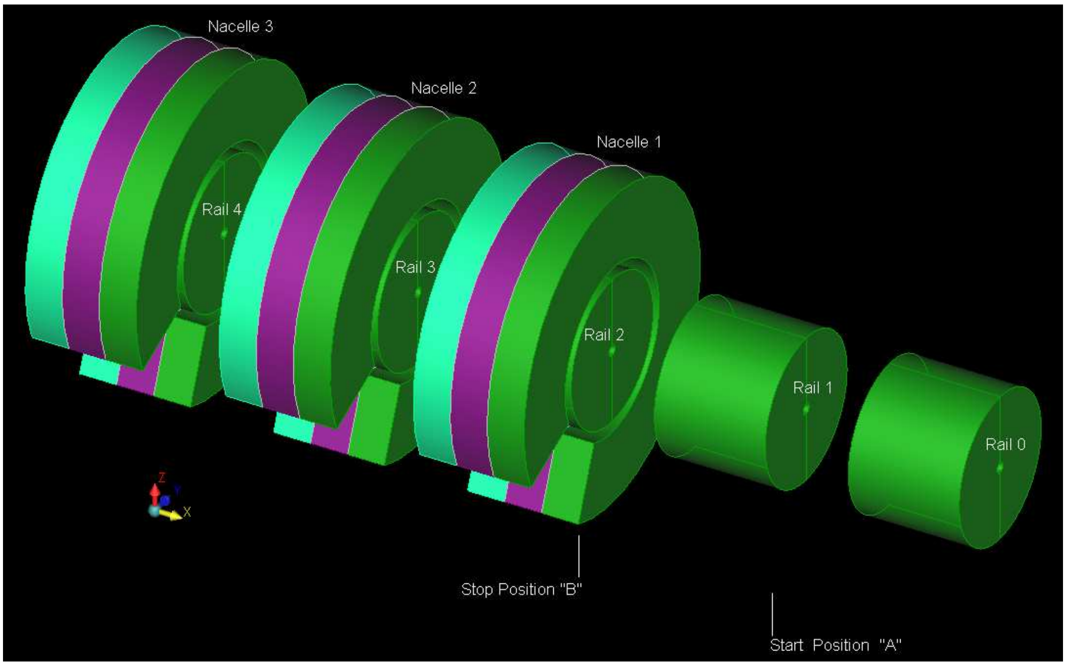

Fig. 18 36th location of the Nacelle group in the parametric study

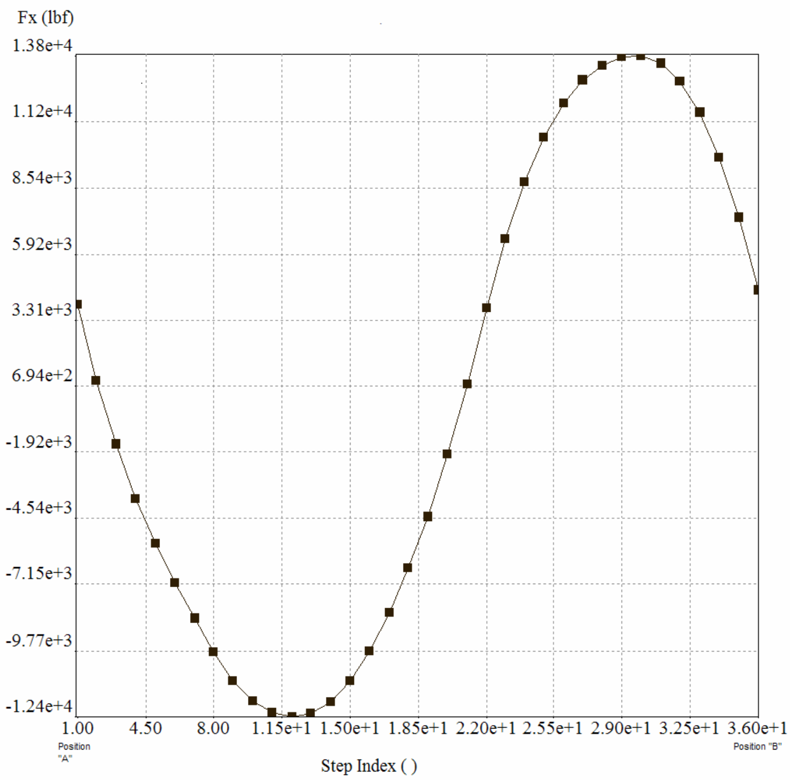

Fig. 19 Drag Force **Fx** variation with Nacelle group location

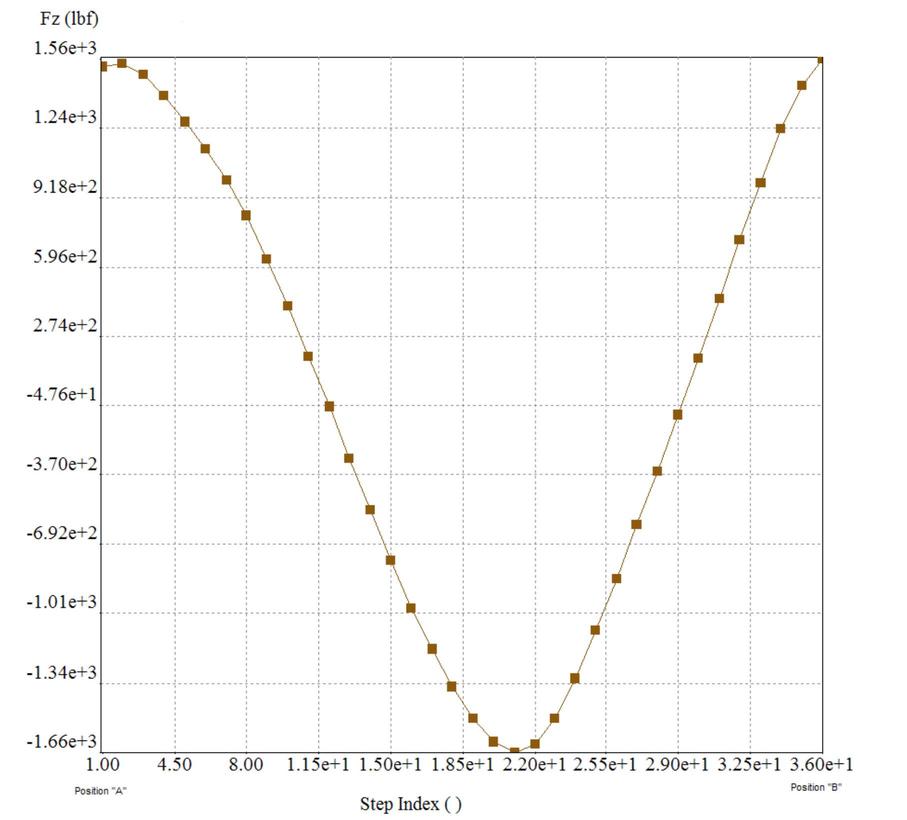

Fig. 20 Lift Force **Fz** variation with Nacelle group location

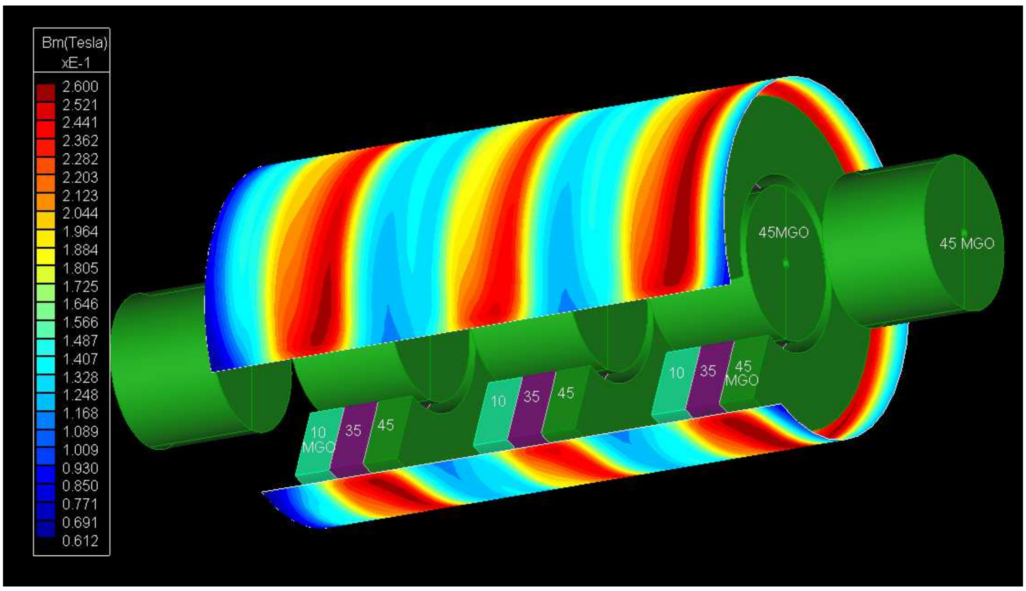

Fig. 21 B-field contour plot on a cylindrical surfaces 1.2 inch away from Nacelles