Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17)
Prague, Czech Republic, August 17 –22, 2003
Paper # O03-7

Electromagnetic Analysis of the Magnetic Jack Type Control Element Drive Mechanism

Hyun Min Kim, In Yong Kim, Il Kon Kim

Korea Power Engineering Company, Inc., Daejon, Korea

ABSTRACT

The magnetic Jack Type Control Element Drive Mechanism (CEDM) had been developed and verified through electromechanical testing including the testing of the magnetic force required to lift the control element assembly. It would become inefficient in view of cost and time for parametric studies to be performed by test to improve the CEDM system. So it becomes necessary to develop a computational model to simulate the electromagnetic characteristics of the CEDM in order to improve the CEDM design efficiently. In this paper it is presented that electromagnetic analysis using a 2D axisymmetric model has been carried out to simulate magnetic force of the lift magnet of the CEDM and to provide effective evaluation between the leakage flux and lift force. The analysis results are compared to test results, which show good agreement. This developed model will be applied to generate a current trace curve for each electromagnetic coil of the CEDM to simulate the CEDM operation.

KEY WORDS: control element drive mechanism, CEDM, motor housing, coil, electromagnetic analysis, finite element method, simulation, B-H curve, magnetic field, leakage flux, lift force.

INTRODUCTION

The magnetic Jack Type Control Element Drive Mechanism (CEDM) for the Korean Standard Nuclear Power Plant (KSNP) is an electromechanical device which provides a controlled linear motion for the control element assembly (CEA) and the extension shaft assembly (ESA) in response to operational signals received from the Control Element Drive Mechanism Control System (CEDMCS). The CEDM is operated by magnetic force, which is generated by applying localized magnetic flux fields to the latch magnets and the lift magnets, which are in the primary pressure boundary.

The electromagnetic equipment is usually developed through tests using physical components. During testing its components are checked, redesigned, replaced and finally verified. The CEDM has also been developed through this procedure. In order to improve the performance of the CEDM, it is necessary to find the relations between the magnetic force and the configuration of the main components such as the motor assembly, motor housing and coil stack assembly. If these relations can not be found from a test performed previously, the cost and the time will be too much and inefficient.

Recently studied was the use of the finite element method to simulate the electromagnetic characteristics [1]. The Linear Pulse Motor for CEDM of the SMART (System-Integrated Modular Advanced Reactor) has been designed by getting the maximum thrust force under the structural constraints using a 2D finite element method [2,3]. For the CEDM in the APR 1400, the mechanical force to hold a CEA has been calculated using a numerical model with the electromagnetic principle [5].

In this paper it is presented that the finite element method can be adopted to simulate the electromagnetic operation and that a 2D axisymmetric model of the CEDM for KSNP has been developed in order to simulate the CEDM operation. The lift forces calculated using this model are compared to test results to check applicability and usefulness.

THE OVERVIEW OF CEDM FUNCTION

The CEDM, which is installed on the reactor vessel closure head nozzle, consists of a upper and lower pressure housing, motor housing, motor assembly, coil stack assembly, an ESA, a shroud and two reed switch assemblies as shown in Fig. 1. The withdrawal or the insertion of a CEA is performed by sequential step motions using magnetic forces. The main components of a CEDM, which are related with magnetic flux and magnetic force, are as follows.

The motor assembly is an integral unit which consists of a latch guide tube, upper latches and lower latches, and fits into the motor housing to provide the linear motion to the CEA. In the first step a latch coil in the coil assembly is energized and a latch magnet slides upward to move a latch inward to engage the ESA. In the next step a lift coil is energized and a lift magnet slides upward to lift the CEA. These sequential and alternate movements of the lower magnet and latch and the upper magnet and latch move the CEA in a double step per cycle.

The coil stack assembly for the CEDM consists of four large DC magnetic coils mounted on the outside of the motor housing assembly. The coils supply magnetic force to actuate the mechanical latches for engaging and driving the CEA and extension shaft assembly. Electric power for the magnetic coils is supplied from the CEDMCS. The CEDMCS actuates the stepping cycle and obtains the correct CEA position by a forward or reverse stepping sequence. The coil housing, which is made of carbon steel of ferromagnetic material, around each coil serves as flux return paths and also supports the coils. The CEA scrams into the core if all coils are deenergized.

The pressure housing consists of a motor housing and a upper pressure housing. The motor housing, inside which the ESA moves up and down, is attached on the RV head nozzle by threading and seal-welding. The magnetic flux from the coil assembly passes this motor housing, which has a flute beside the coil to induce the concentrated flux from the coil.

ELECTROMAGNETIC FORCE OF CEDM

The CEDM is an electromechanical system actuated by the electromagnets, which can be represented by the equations relating to the electrical, mechanical and magnetic properties of the system.

The magnetomotive force (mmf) can be defined as Equation (1) from the Ampere's principle, and the magnetic flux density (B) is calculated by the multiplication of the permeability (μ) of the CEDM material and the magnetic field intensity (H) as Equation (2) [4,6].

$$mmf = \oint H \cdot dl = A \times T \tag{1}$$

$$B = \mu H \tag{2}$$

where A is current and T is number of coil turns. If B of the CEDM coil is proportional to H as in Equation (2), the energy in the unit volume of the magnetic field (W_m) becomes as follows.

$$W_m = \frac{1}{2}\int_{vol} B \cdot H dv \tag{3}$$

Inserting Equation (2) into Equation (3),

$$W_m = \frac{1}{2}\int_{vol} \mu H^2 dv \,. \tag{4}$$

The magnetic energy in the coil expressed by the coil inductance (L) and the current (I) induces mechanical force in the magnet of the motor assembly through the coil housing and the motor housing. Such a magnetic system can be analyzed by Equation (1) and the law of energy conservation [4] expressed by Equation (5) (Fig. 3).

$$dW_{coil} = dW_{coil\ housing+motor\ housing\ +air\ gaps} = dW_{lift\ magnet} \quad (5)$$

Until the coil energy generates the mechanical force, the magnetic flux crossing the coil should be constant. Then the change of the magnetic energy due to the change of volume of the coil housing, the air gap-1, the motor housing and the air gap-2 can be expressed as follows using Equations (3), (4) and (5).

$$\begin{aligned} dW_{coil\ housing\ +\ motor\ housing +\ air\ gaps} &= (w_c + 2w_{a1} + w_m + w_{a2})dv \\ &= \frac{B_c^{\ 2}}{2\mu_c} S_c dx + 2\frac{B_{a1}^{\ 2}}{2\mu_0} S_{a1} dx + \frac{B_m^{\ 2}}{2\mu_m} S_m dx + \frac{B_{a2}^{\ 2}}{2\mu_0} S_{a2} dx \end{aligned} \quad (6)$$

where w and S are magnetic energy density and effective sectional area, respectively. And the subscripts of c, a1, m, a2 are the coil housing, the air gap-1, the motor housing and the air gap-2, respectively. Using Equations (5) and (6), one obtains

$$dW_{lift\ magnet} = - F\ dx = (w_c + 2\omega_{a1} + w_m + w_{a2})dv \quad (7)$$

where the negative sign means that the energy increases as the displacement *dx* reduces. Using Equations (6) and (7), the mechanical force *F* can be obtained as follows, which will be applied to the CEDM design

$$-F = \frac{B_c^{\ 2}}{2\mu_c} S_c + \frac{2B_{a1}^{\ 2} S_{a1} + B_{a2}^{\ 2} S_{a2}}{2\mu_0} + \frac{B_m^{\ 2}}{2\mu_m} S_m \quad (8)$$

This means that the magnetic force is due to the magnetic energy generated by the current density of the coil and the B-H curve (magnetization curve) of the magnetic material.

When one applies the finite element method to get the magnetic force in the CEDM, the force in Equation (8) is expressed with a vector form [4] and the B is expressed as a function of a magnetic vector potential using a magnetic element as follows.

$$\{B\} = \nabla \times [N_A]^T \{A_e\} \quad (9)$$

where $[N_A]^T$ is a shape function of the magnetic element and $\{A_e\}$ is a magnetic vector potential of the node. This can be applied to analyse the lifting force of the CEDM.

ELECTROMAGNETIC ANAYSIS OF CEDM

Analysis Model

The finite element modeling and the electromagnetic analysis of the CEDM are performed using two independent computational codes of ANSYS [7] and FEMM [8] to verify the adequacy of the model. Fig. 2 shows a sectional configuration of the driving parts of the CEDM, which is modeled with PLANE 53(2D 8 node magnetic solid) element of ANSYS and triangular element of FEMM using a cylindrical coordinate system as shown in Fig. 4. The permeability values of the magnetic material for the coil housing, the motor housing and the motor assembly are calculated using the B-H curves of Fig. 5 and Fig. 6, whose nonlinear properties should be considered during analysis [4,6]. The permeability of the reactor coolant in the motor housing is assumed to be 1.0 as well as the air. As the direction of the magnetic flux is perpendicular to the boundary surface, the Dirichlet boundary condition is applied. A constant current is used as an input to calculate the CEDM lift force.

Analysis Results

Two kinds of lifting cases are calculated using the aforementioned model: To energize the upper lift coil and to energize the lower lift coil. For input currents of 22A, 24A, 28A and 30A in the upper lift coil, the lift forces are calculated using ANSYS and FEMM, whose differences compared to the test results are 1 ~ 17 % and 3 ~ 7 %, respectively (Fig. 7 and Fig. 10). For the same input current in the lower lift coil, the lift forces are also calculated using ANSYS and FEMM, whose differences compared to the test results are 2 ~ 18 % and 1 ~ 9 %, respectively (Fig. 8 and Fig. 11). As these results show a good agreement between the ANSYS and FEMM and between the analysis and the tests, the analysis model developed using the finite element method is applicable for the electromagnetic simulation of the CEDM.

As a parametric study, the lift forces are checked for various thickness of coil housing, which affects the magnetic flux and the leakage flux. Various cases of 15.75mm thickness to 20.83mm in thickness are used and the input current of 30A is applied for each case. The leakage flux outside the coil housing of 20.83mm shown in Fig. 9 is much less than the one for 15.75mm shown in Fig. 7. In Fig. 12 it is found that the lift force is increased by 11% for 5.1mm increment of thickness of the coil housing, which shows that the analysis model developed is useful also for the improvement of the CEDM.

CONCLUSION

The finite element model of the CEDM for the KSNP is developed to perform the electromagnetic analysis using two different finite element analysis codes. The lift forces calculated with this model agree well with the test results. As the thickness of the coil housing is increased, the lift force calculated with this model also increased. This shows that the analysis model developed is stable and applicable to the electromagnetic analysis and useful for the improvement of the CEDM. In the future, the transient analysis will be performed with this model to generate a current trace curve for the coil to simulate the electromechanical operation of the CEDM and to check the heat quantity generated from the coil.

REFERENCES

1. Dal Ho Lim, *FEM of the Electromagnetic Field*, Dong Myung Sa, 1987.
2. Hyung Huh, Jiho Kim and Jongin Kim, "Design of Linear Pulse Motor Type Control Element Drive Design Mechanism for SMART", *Proc. of the Korean Nuclear Society '98 Autumn Conference*, Korean Nuclear Society, 1998.
3. K. C. Chang, D. H. Kang, J. H. Kim, J. I. Kim, J. P. Hong, "A Design of the Cylindrical VR type Linear Pulse Motor for the CEDM of Reactor", *Proc. of the ICEE '99*, Volume 2, August 1999.
4. Richard E. Dubroff, S. V. Marshall and G. G. Skitek, *Electromagnetic Concepts and Allocations*, Prentice Hall, 1996.
5. Suhn Choi, Seop Hur, Yong Suk Suh, Gwi Sook Jang, Jong Kyun Park and E. G. Sirica, "Simulation of a Single Motor of Latch Type CEDM for Korean Next Generation Reactor", *Proc. of the 16th SMiRT*, 2000.
6. Seong Kun Oh, *Theory of the Electric*ity, Seong Ahn Dang, 1998.
7. *ANSYS Revision 5.5 User's Manual*, ANSYS Inc., 1999.
8. *FEMM Version 3.2 User's Manual*, 2002.

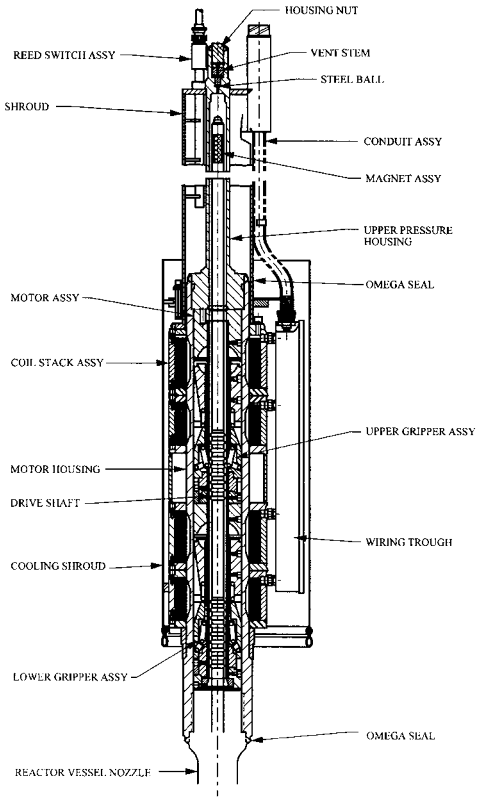


Fig. 1 Magnetic jack type CEDM for KSNP

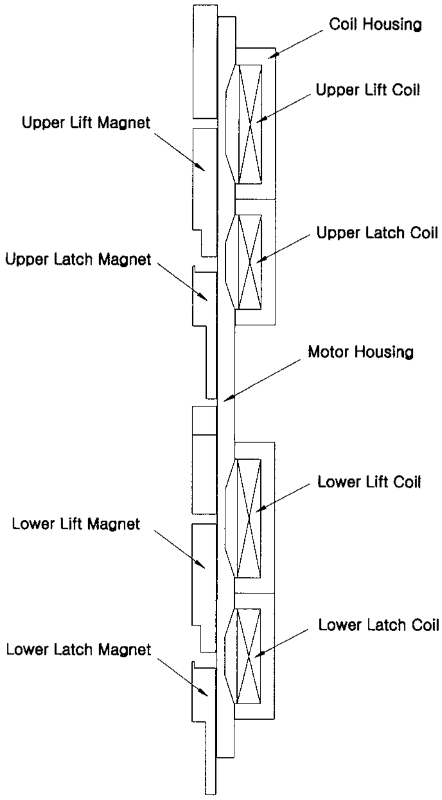


Fig. 2 Driving parts of the CEDM

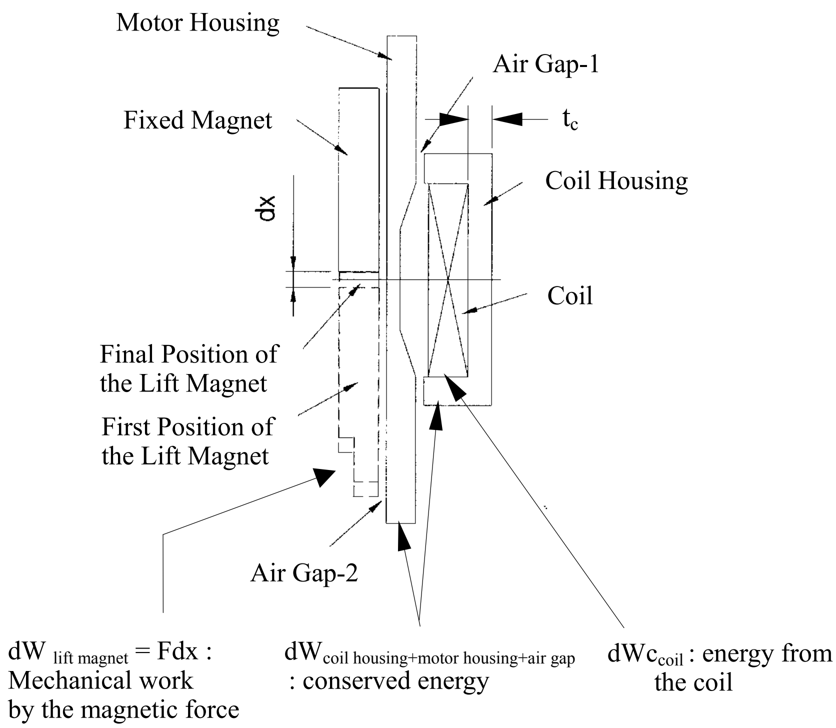


Fig. 3 Energy related to the CEDM operation

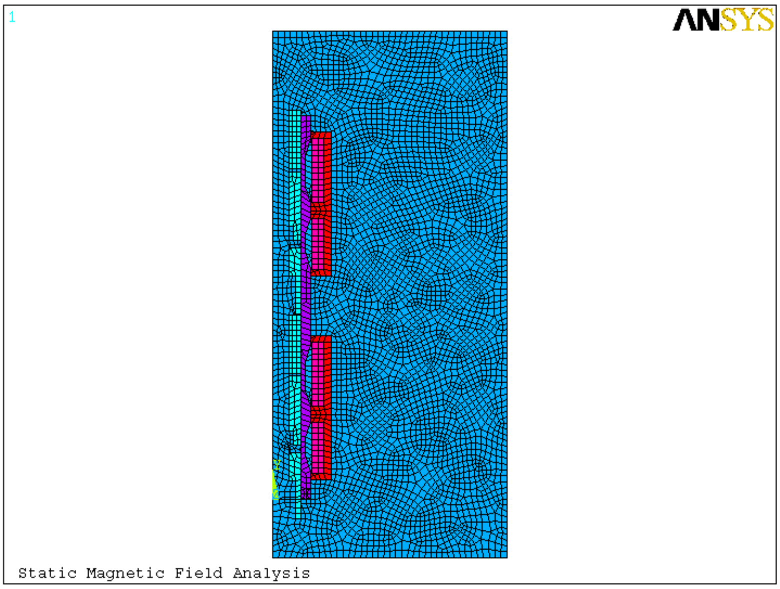
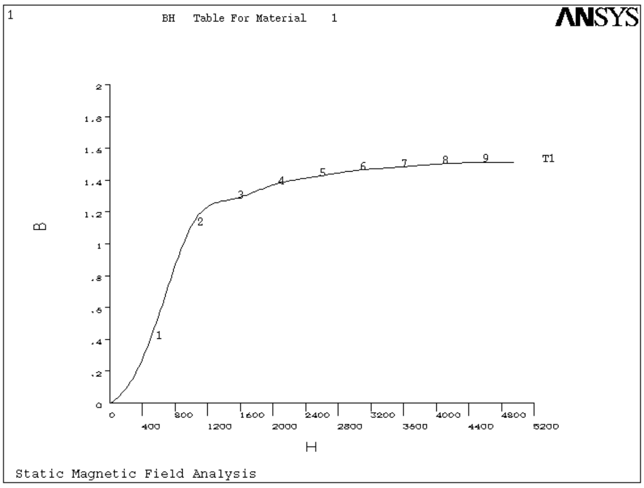


Fig. 4 2D axisymmetric model of the CEDM



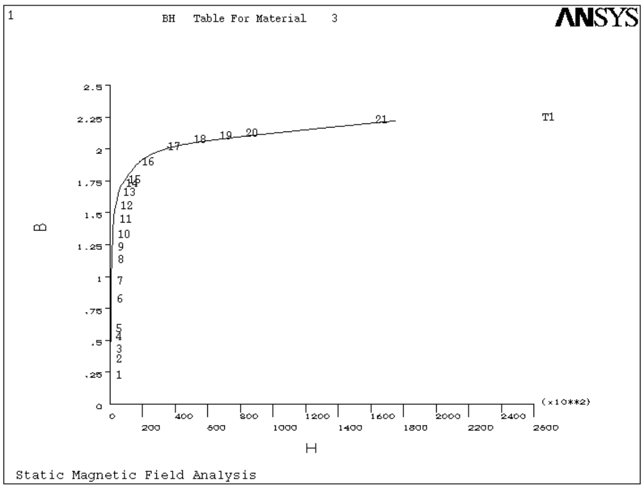


Fig. 5 B-H curve of the lift magnet(410 SS)

Fig. 6 B-H curve of the coil housing (1010 CS)

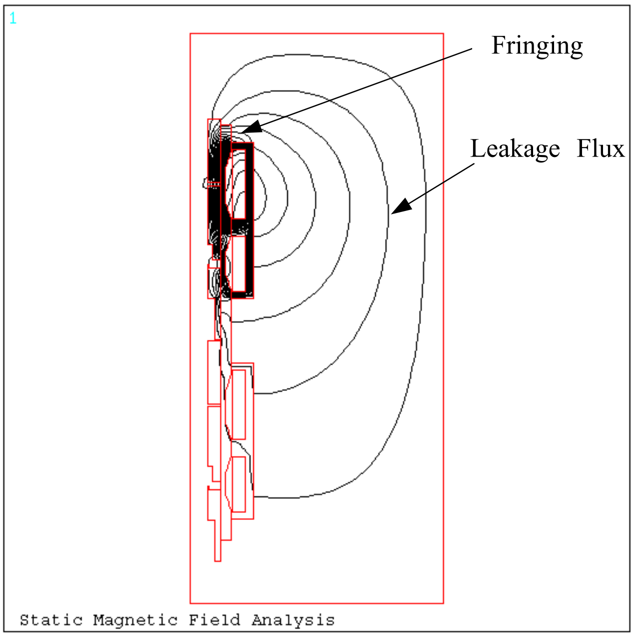


Fig. 7 Magnetic flux line due to the upper lift coil energized (Thickness of the coil housing, tc = 15.75 mm)

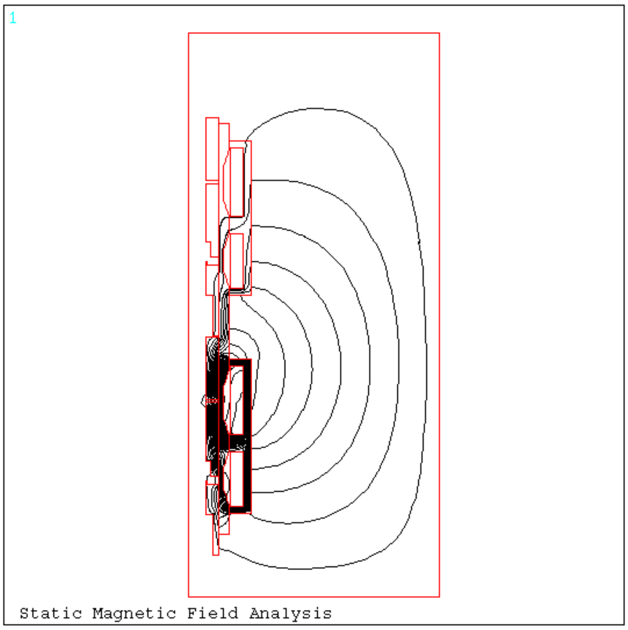


Fig. 8 Magnetic flux line due to the lower lift coil energized (Thickness of the Coil Housing, tc = 15.75 mm)

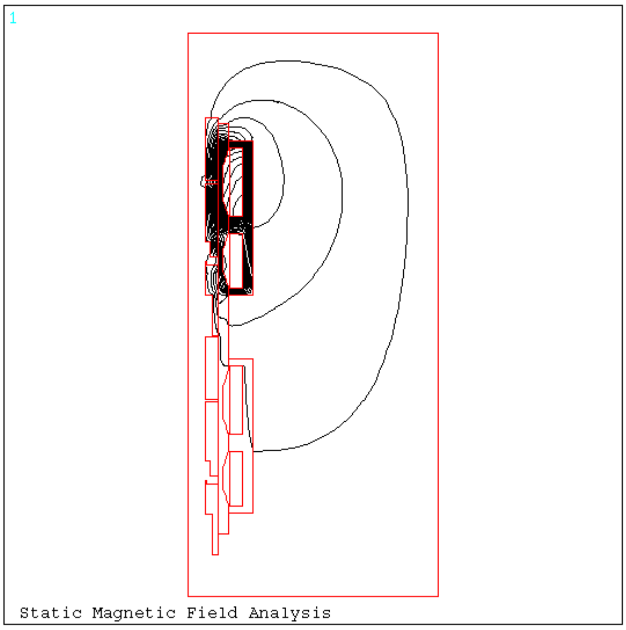


Fig. 9 Improved magnetic flux line due to the upper lift coil energized (Thickness of the coil housing, tc = 20.83 mm)

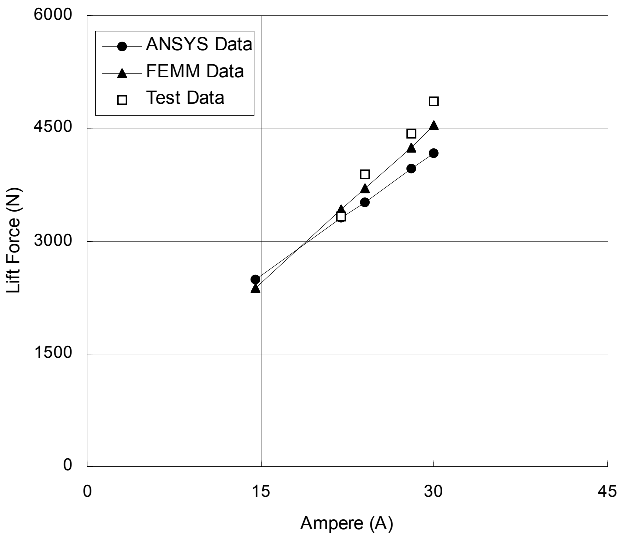


Fig. 10 Comparison of the upper lift force between analysis and test

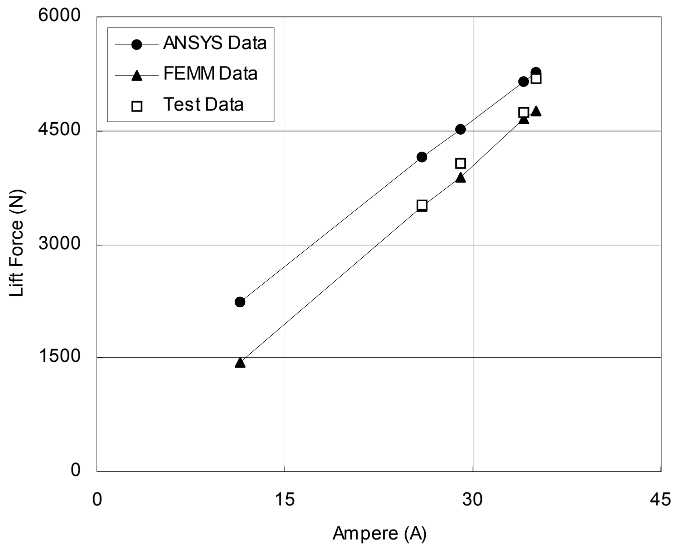


Fig. 11 Comparison of the lower lift force between analysis and test

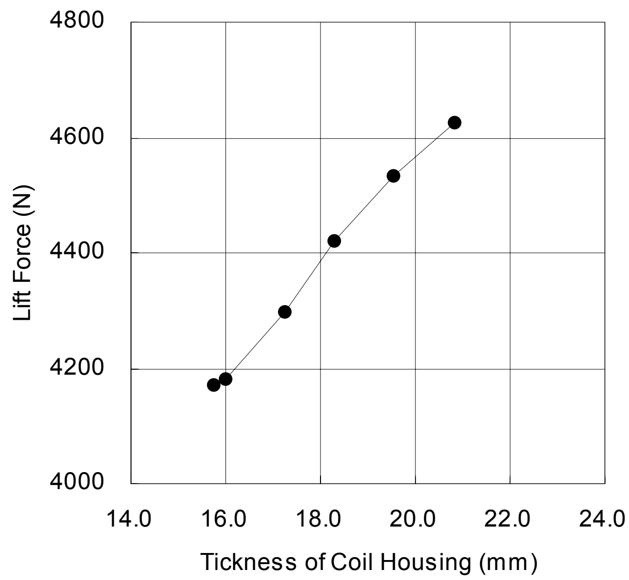


Fig. 12 The lift force to the thickness of the coil housing