Dynamic Characteristics Analysis of Moving Coil Type Linear Oscillatory Actuator Considering Asymmetric Magnetic Circuit

Duk-Hyun Kim, Ki-Chae Lim, Gyu-Hong Kang, Jung-Pyo Hong and Gyu-Tak Kim

***Abstract*--This paper deals with a dynamic analysis of Moving Coil type Linear Oscillatory Actuator (MC-LOA) having asymmetric magnetic circuit based on moving model node technique in Finite Element Method (FEM). Dirichlet boundary condition is applied to the analysis model and there should be a lot of works to handle the analysis model in order to consider the variation of parameters by moving displacement and load condition. To overcome these demerits, we propose an on-line batch process composed by both voltage and kinetic equation using moving model node technique. The facility and validation of the proposed process are confirmed by comparing with individually analyzed one through manual works**

***Index Terms*--MC-LOA, asymmetric magnetic circuit, moving model node technique**

I. INTRODUCTION

Moving Coil type Linear Oscillatory Actuator (MC-LOA) is a suitable machine for a short stroke reciprocating system. It is also applicable for a large capacity industrial machine in the case of using Permanent Magnet (PM) containing high magnetic energy density [1].

MC-LOA having asymmetric magnetic circuit has a very simple structure and it does not need an extra support. However, there is a different flux distribution on the air-gap depending on the motion direction of mover. That is to say, the interaction of two fluxes between the PM and the armature current causes the unbalanced thrust and interferes with the proper oscillation of MC-LOA [1,3,4].

When analyzing a model of asymmetric structure with Dirichlet boundary condition, it is unsuitable to apply moving mesh technique, which accepts the Finite Element Method (FEM) without re-meshing the total elements in analysis model. Moreover, in a dynamic analysis using FEM, there are a lot of manual works to handle and modify the analysis model in order to consider the variation of parameters in each moving displacement and load condition.

This paper proposes moving model node technique that reduces the ineffective manual works, such as repetition of pre-process, and obtains the more accurate dynamic analysis. Moving model node technique automatically generates the modified model and updated pre-process data according to the variation of each design variable constant. This on-line process is performed through mesh generation after moving the initial modeling data (node, line, region and etc.). Information of moving region, mesh generation and characteristic analysis in each step is used to establish the further modeling.

The proposed dynamic analysis uses the combination of on-line batch process and moving node technique, furthermore, load condition (reciprocating compressor load) is considered. At first, parameters of voltage equation, thrust coefficient and inductance are calculated. And then, the dynamic analysis results considering load condition are compared with the individually analyzed results through manual works.

II. ANALYSIS METHOD BY ON-LINE PROCESS

A. Analysis Model

In the case of symmetric structure, periodic boundary condition is suitable for the analysis model and it can adopt the moving mesh technique in order to solve the continuous boundary problems according to the variations of parameters. However, if the moving displacement is very small, the number of node on the moving line increases and it takes a lot of time to analyze the model [4].

On the other hand, moving mesh technique is unsuitable for asymmetric structure due to the Dirichlet boundary condition. The analysis model is shown in Fig. 1. It has an asymmetric magnetic circuit for moving direction because the left side is magnetically open circuit while the other side is close circuit. In this case, Dirichlet boundary condition must be adopted for

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the all analysis regions. Therefore, it is required to perform pre-process, such as re-modeling, re-mesh and etc. And it takes a lot of manual works according to the variations of moving displacement and load condition. In this paper, therefore, moving model node technique is proposed in order to solve the continuous boundary problems according to the parameters variation of analysis model having the Drichlet boundary condition.

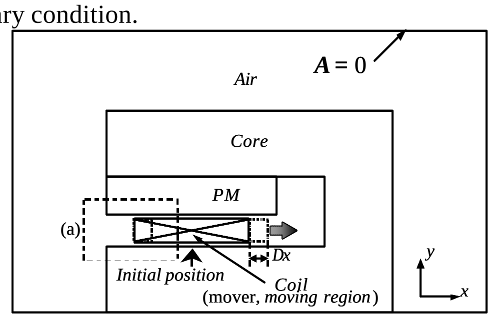

Fig. 1. Analysis model

B. Application of Moving Model Node Technique

Moving model node technique automatically generates modified model and information of pre-process for the variations of moving part. It is performed through the re-mesh after moving the initial modeling object (node, line, region and etc.). At first, analysis model for variable dimensions requires the input of the modeling and material properties. Then, the individual information of moving part (node, moving line and etc.) should be determined and saved as a script file.

When the moving objects are selected and moved, the distance of node, used in mesh generation stage, among the moved nodes on the moving line is calculated based on initial node distance to avoid the variations of the distance among new nodes. After generating the new moving model data through the transformation of the initial modeling data with individual moving information, modified model is automatically generated using the beforehand inputted source and material properties. The characteristics of new model generated by moving model node technique are analyzed after re-mesh and it is possible to product repeatedly the analysis model with new dimension and figure by the transformation of individual moving information. Therefore, it can reduce the efforts of modeling, pre-process and the analysis time by batch process including the input of moving part information, mesh generation and characteristic analysis.

The detail of (a), moving region in Fig. 1, is illustrated in Fig. 2. Line No. $\boldsymbol{L_3}$ and node No. ***10*** and ***11*** of moving regions are initial modeling data. It should be stored as a script format. As the mover is moving to the illustrated direction, the length of $\boldsymbol{L_1}$ and $\boldsymbol{L_2}$ is different from the initial position. However, the distance between a node and the other must be uniformed in order to prevent the variations of element. $D\boldsymbol{x}_1$ and $\boldsymbol{v}_1$ obtained by ① and ② in Fig. 3 give new information for moving region and the moved region is generated by the information. The next $D\boldsymbol{x}_2$, $\boldsymbol{v}_2$, ···, $D\boldsymbol{x}_n$, $\boldsymbol{v}_n$ can be calculated by the same process.

C. Formulation for Analysis

The field equation from Maxwell' s electromagnetic equation of electromagnetic field in quasi-steady state, that is possible to ignore the displacement current, is (1). And equivalent magnetization current density is (2) [3].

$$\frac{1}{m}\frac{\partial^2 A}{\partial x^2}+\frac{1}{m}\frac{\partial^2 A}{\partial y^2}=-(J_0+J_m) \qquad (1)$$

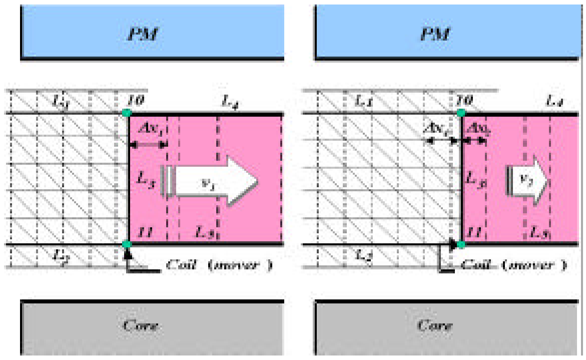

Fig. 2. Detail of moving model node technique, (a) in Fig. 1

$$J_m=\frac{1}{m}\left(\frac{\partial M_x}{\partial x}-\frac{\partial M_y}{\partial y}\right) \qquad (2)$$

Where, A is magnetic vector potential, J_0 is coil excitation current density, J_m is equivalent magnetization current density. A, J_0 and J_m are z-axis component of each $\boldsymbol{A}$, $\boldsymbol{J_0}$ and $\boldsymbol{J_m}$, and M is intensity of magnetization.

D. On-Line Process for Dynamic Analysis of MC-LOA

Combined equation between voltage and kinetic equation performs the dynamic analysis of MC-LOA. Kinetic equation is composed of load, friction and damping coefficient term in the system without the spring. Load force term, F_L due to the mover mass, required force including friction and damping force are as follows [1,2].

$$F = F_L + F_f + D\,v \qquad (3)$$

In this paper, the required maximum thrust is 52(N). Load force, F_L is shown in Fig. 4, which is characteristic modeling of compressor load condition.

Fig. 3 shows the on-line process, which is combination of electric and kinetic equation, moving model node technique, and batch processing of the dynamic analysis.

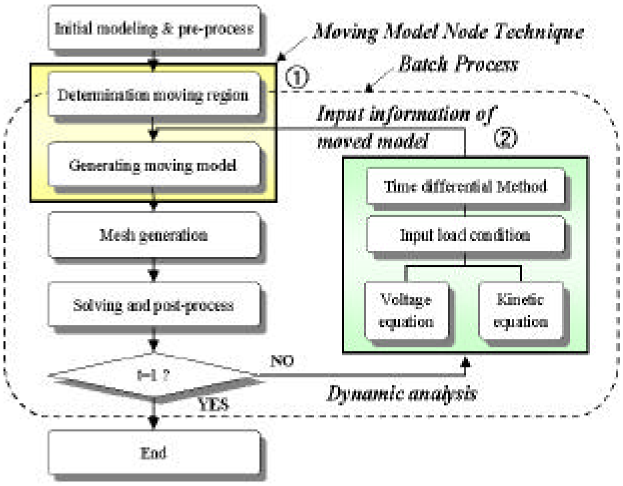

Fig. 3. On-line process for dynamic analysis

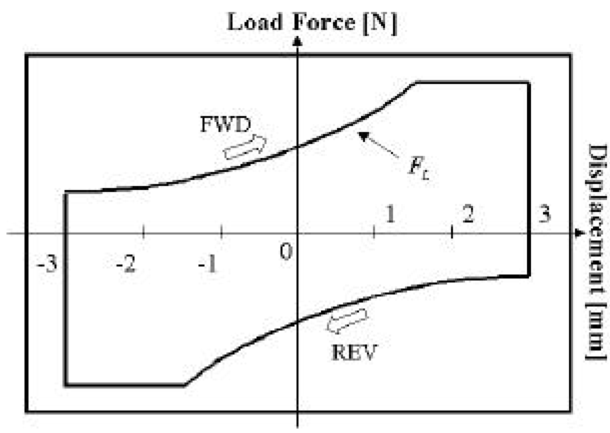

Fig. 4. Load configuration

III. Comparison of Analysis Results

A. Estimation of Parameters for Manual Work

The circuit parameters, inductance and Electro-Motive Force (EMF) coefficient in voltage equation, are used for the dynamic characteristics analysis of MC-LOA. They are obtained by FE analysis because it is variable due to the mover moving displacement. The analysis results of these parameters, which are flux density distribution, thrust coefficient and inductance according to displacement, are shown in Fig. 5-7.

As shown in Fig. 5, the airgap flux density distribution is different depending on the mover's direction due to the asymmetric magnetic circuit and armature reaction field. The difference of flux density generates the unbalanced thrust according to direction of mover as shown in Fig. 6.

In Fig. 7, as the mover goes on to forward direction, inductance has also lager than backward because linkage flux of inner core is larger than the opposite part.

The mover goes on to inner core direction (+*x*), forward direction, thrust coefficient has larger value than the other case that the mover goes to the opposite direction (–*x*), backward direction. It should be noted that this thrust variation cause the eccentricity of the mover.

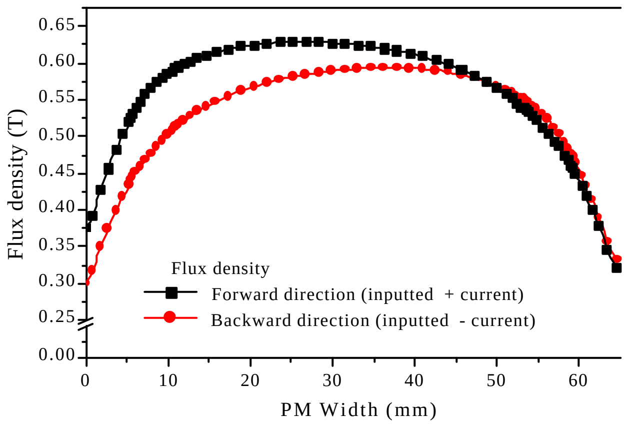

Fig. 5. Airgap flux density distribution in accordance with mover direction

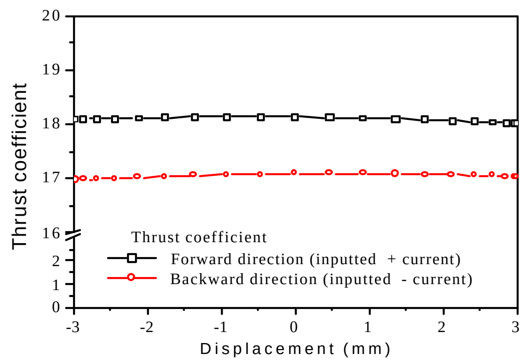

Fig. 6. Thrust coefficient in accordance with mover direction

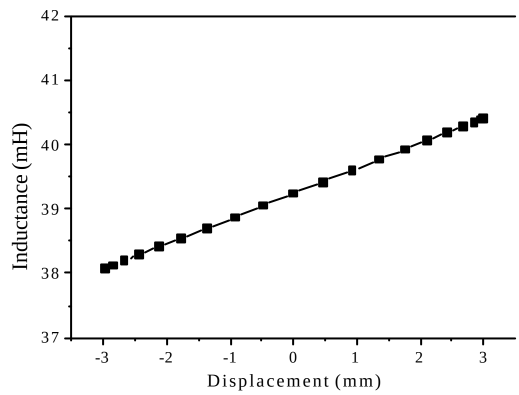

Fig. 7. Inductance in accordance with mover direction

In the case of manual works, after the geometry modeling and pre-process taking into account the moving displacement as the mover velocity per a period, the analysis results are obtained by FE analysis individually. On the other hand, in the case of on-line process, they are not needed because the characteristics analysis is performed by batch process including the modeling and pre-process.

B. Characteristics of load condition

The results of dynamic analysis are shown in Fig. 8-12 through comparing the proposed on-line process with manual work.

Fig. 8 and Fig. 9 respectively show the displacement versus the load force and the time versus displacement for the case of two methods. In Fig. 4, the maximum stroke of mover is designed as ±3 (mm) according to load condition. The case of forward direction, it is accordance with the required specification each other but backward direction doesn't satisfy the conditions as shown in Fig. 8 and Fig. 9. This is caused by unbalanced thrust due to the asymmetric structures of MC-LOA. Especially, the displacement of backward direction is different from each other. On-line process can consider armature reaction field and saturation, while manual work cannot.

Fig. 10 shows the EMF characteristic calculated by on-line process and manual work. The effect of armature reaction field is large. Moreover, in the relation of EMF and displacement characteristic, the case of on-line process is faster and more accurate than manual work.

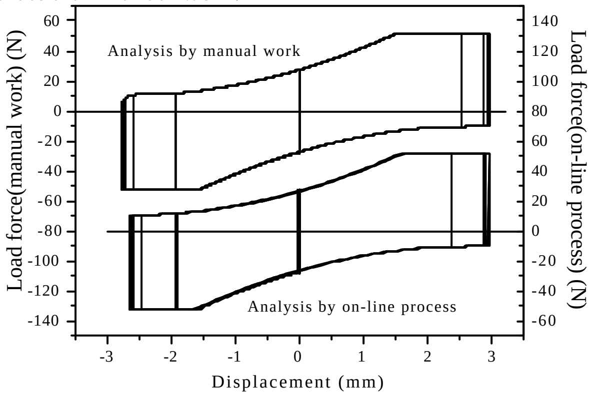

Fig. 8. The load force estimation by dynamic analysis

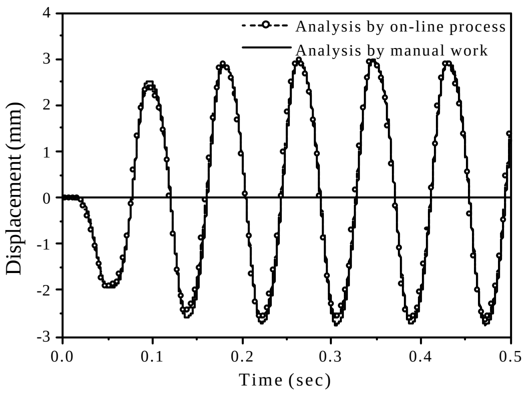

Fig. 9. The characteristic of displacement according to the time

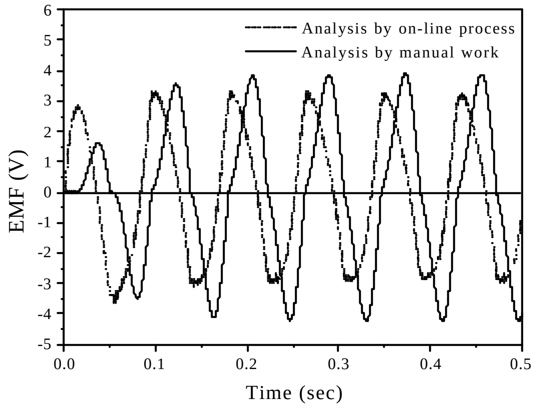

Fig. 10. The EMF characteristic in accordance with the time

Fig. 11 shows the relation of thrust and load force according to the time. The generating thrust of MC-LOA is smaller than the required load force for backward. In Fig. 8, the analyzed displacement by on-line process is smaller than that of manual work. This is due to the difference that the effect of armature reaction field and leakage flux. The current characteristic is shown in Fig. 12. In concluding, the appropriateness and effectiveness of the proposed on-line process in dynamic analysis is verified by comparing the result with manual work.

IV CONCLUSIONS

This paper presents a dynamic analysis of MC-LOA having asymmetric magnetic circuit based on FEM, which is coupling problem composed by numerical method and kinetic equation. This paper, therefore, proposes the moving model node technique, which could be applicable to any boundary condition only from moving region and regenerating the node.

The dynamic analysis of MC-LOA is performed by using the combination of electric, kinetic equation and moving node technique, and on-line process. Furthermore, reciprocating compressor load is considered as load condition. By comparing the analysis result with manual works, the reasonable result of the proposed on-line process has been obtained, and the validation of moving model node technique is confirmed.

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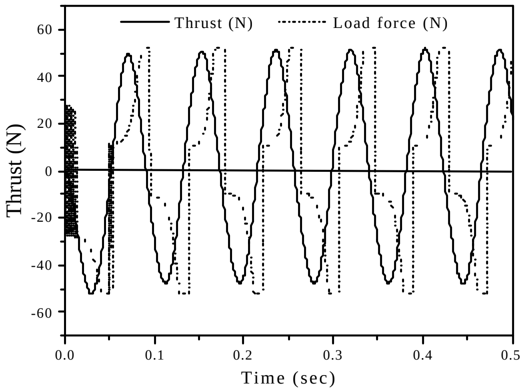

Fig. 11. The characteristic of displacement in accordance with the time

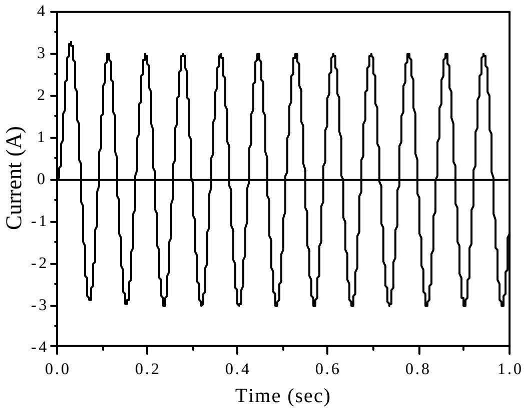

Fig. 12. The current characteristic in accordance with the time