Thrust Force Analysis Based on H Error Evaluation and Adaptive Mesh for Linear Micromotor

Jie Chai, Jiaping Yang, Chao Bi, and Yi Lu

***Abstract*—To predict the thrust force accurately in the design of linear micromotor, the Coulomb virtual work (CVW) method was applied to calculate the electromagnetic thrust force based on the finite-element solution of the electromagnetic field. Since only the magnetic field intensity H in the air layer surrounding the moving part is used to calculate the thrust force in the CVW method, the local errors of H in the sheath air layer severely affect the calculation accuracy. To reduce the considerable local errors of H in finite-element field solution, an estimation method of H error with an adaptive mesh algorithm was proposed. The proposed method can adaptively refine the mesh according to the evaluation of H error and thus increase the accuracy of force calculation effectively while require less computation time.**

***Index Terms*—Adaptive mesh, electromagnetic force, finite-element analysis, local error.**

I. Introduction

DUE TO ITS relatively larger thrust force and distance, a linear micromotor is designed to drive the recording material for microelectromechanical system-based probe storage devices. The design includes the association of classical technologies for the rotor and micromachining technologies for the coil structure. One key issue is accurate prediction of the thrust force developed in the micromotor. In this work, the Coulomb virtual work (CVW) method [1] was applied to calculate the thrust force. The method is based upon the law of conservation of energy and the principle of virtual displacement. The global magnetic force acting on the moving part is calculated as the derivative of the energy/coenergy of the system with respect to the virtual displacement. In general, the CVW method is sensitive to the mesh discretization because the force or torque was computed only using a tiny amount of finite elements and the local error of the magnetic field intensity H in these elements will severely affect the calculation accuracy of the thrust force [2], [3]. To yield sufficient accuracy of the thrust force, the finest discretization is needed to reduce the local error of H. With the finest discretization of all the elements evenly, however, it will require enormous amount of elements, whilst it is unnecessary to refine the elements with small local error of H. In this paper, an adaptive algorithm based on the evaluation of H error is presented. In the proposed method, only the elements with maximum and near the maximum errors are refined with the finest discretization. Other elements are refined adaptively. The method can generate the optimum density of mesh, greatly reduce the number of elements and thus need much less computation time with the assumed accuracy.

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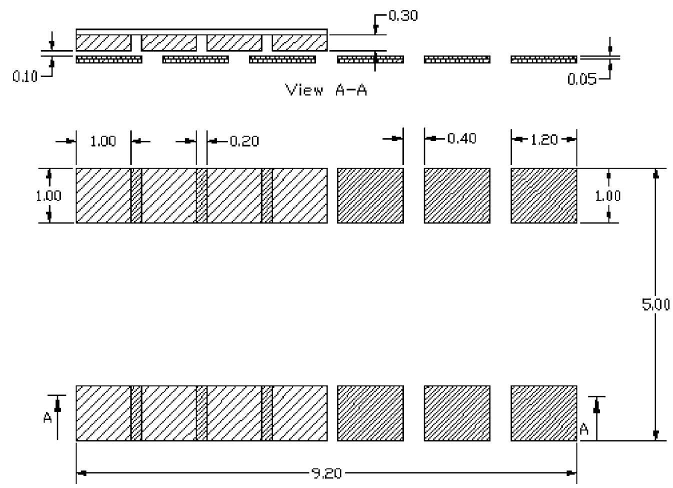

Fig. 1. Structure of linear micromotor.

II. Structure of Linear Micromotor

The structure of linear micromotor designed is shown in Fig. 1. It is a classical brushless micromotor with small scale. There is 1 linear micromotor in each side of the substrate. The primary is made of six coils, which is fabricated by using the UV lithography and copper electroplating technique.

There are four rare-earth SmCo permanent magnets in the secondary, with remanence of 3000 G and coercivity of 2600 Oe. To achieve stronger magnetic flux density in the linear motor's air gap, a yoke is added behind the magnets. The yoke and magnets can be electroplated on the substrate of the secondary by using the micromachining techniques.

III. Finite-Element Method Model and Computation Results

Fig. 2 is the finite-element method (FEM) model of a linear micromotor, which is made of the moving part and the coils. Around the moving part of a linear micromotor one thin air layer is built to calculate the thrust force using the CVW method. Besides these components, one air volume is also built to surround the whole linear micromotor. The electromagnetic field solution results are shown in Fig. 3.

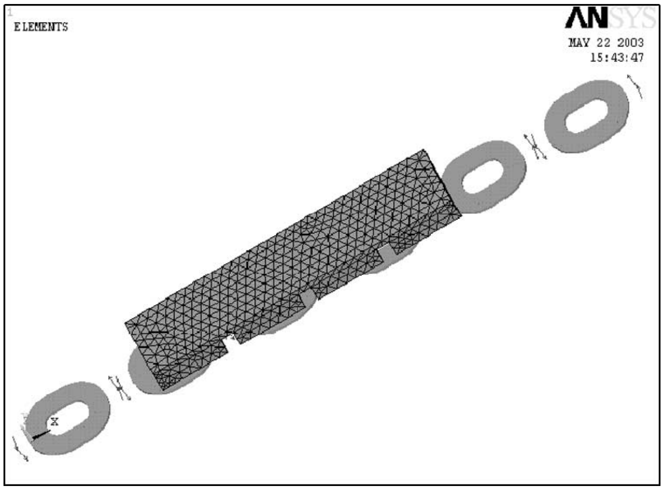

Fig. 2. FEM model of linear micromotor.

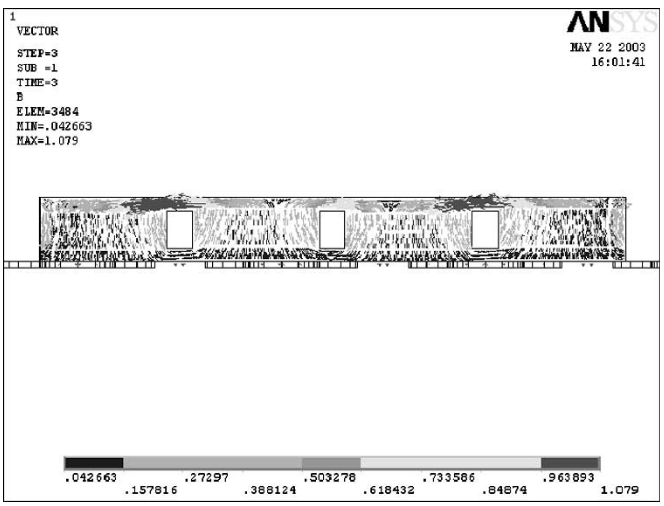

Fig. 3. Distribution of flux density in the linear micromotor.

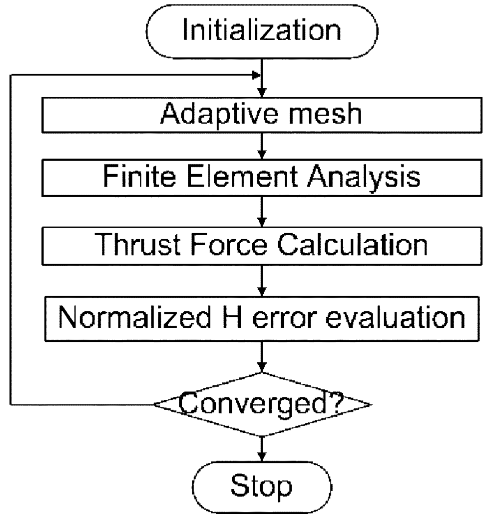

Fig. 4. Discretization process of the mesh.

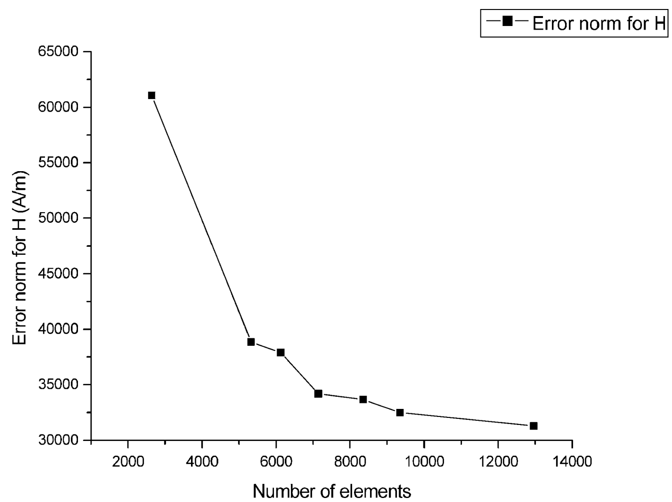

Fig. 5. Maximum values of normalized error norms of H versus the number of elements in sheath air layer.

IV. Thrust Force Analysis

The basic CVW equation for the force of an element in the air layer in the s direction is

$$F_s = \int_{\text{vol}} \{B\}^T \left\{ \frac{\partial H}{\partial s} \right\} d(\text{vol}) + \int_{\text{vol}} \left(\int \{B\}^T \{dh\} \right) \frac{\partial}{\partial s} d(\text{vol}) \tag{1}$$

where

- F_s force in element in the s direction;
- B flux density
- $\{\partial H/\partial s\}$ derivative of H with respect to displacements;
- s virtual displacement of the nodal coordinates taken alternatively to be in the X, Y, Z global directions;
- vol volume of the element.

The total force in the air layer surrounding the moving part is summed over the volume. The relative error measure is based on the difference in calculated fields between a nodal-averaged continuous field representation and a discontinuous field represented by each individual element's nodal field values. So, the relative error for each element is calculated as

$$H_{ei} = \frac{1}{n} \sum_{j=1}^{n} |H_j - H_{ij}| \tag{2}$$

where

- H_{ei} relative error for H (magnitude) for element I;
- H_j nodal averaged H (magnitude);
- H_{ij} H (magnitude) of element I at node j.

The relative error measure is normalized based on the maximum element nodal calculated field value in the currently selected element set

$$H_{nei} = \frac{H_{ei}}{H_{\max}} \tag{3}$$

where $H_{\max}$ is the maximum element nodal H (magnitude).

According to the normalized relative error of H, the elements with maximum and near maximum H_{nei} are selected. An adaptive mesh algorithm is applied to refine the selected elements and the other elements. After the refinement of the mesh, the

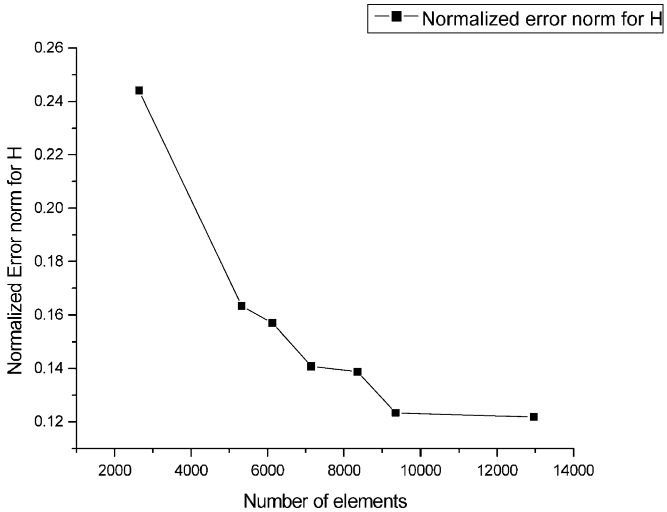

Fig. 6. Thrust force versus the number of elements in sheath air layer.

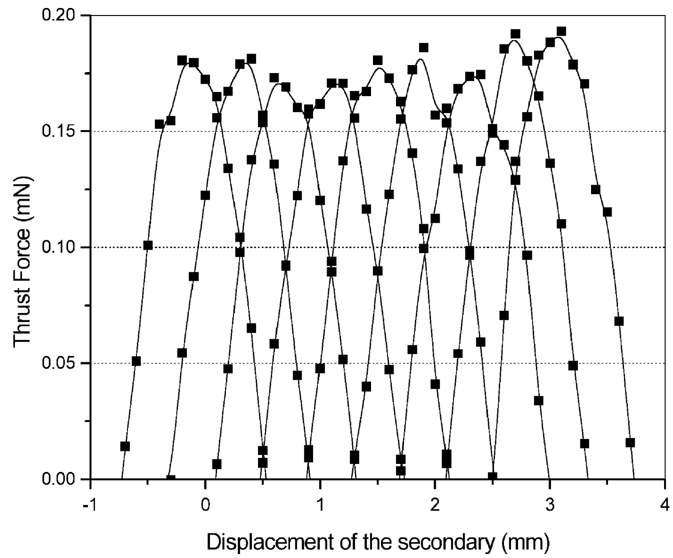

Fig. 7. Thrust force curves versus the displacement of the secondary.

normal finite-element analysis is performed and the H_{ei} and H_{nei} are calculated. The iteration of this discretization process is conducted repeatedly until the defined H_{nei} criterion is satisfied. The flowchart of the discretization process is shown in Fig. 4.

Figs. 5 and 6 show the maximum H_{nei} and thrust force versus the number of elements in sheath air layer, respectively.

On the basis of accurate thrust force calculation, the thrust force curve can be obtained when the secondary moves. Fig. 7 shows the thrust force curves versus the secondary's displacement, where each curve presents the thrust force versus the distance of the secondary moving when a definite coil is excited. From Fig. 7, it is noted that the thrust force can be kept at an approximate constant value of 0.16 mN when the coils are excited suitably, this means the linear micromotor can move smoothly.

V. Conclusion

This paper has investigated the accurate thrust force analysis of the linear micromotor by the H error evaluation and adaptive refine mesh method. This method refines different elements at different refining levels and avoids the refinement of all the elements at the same refining level. It greatly reduces the number of elements and thus requires much less computation time. In meanwhile, it still can obtain thrust force results with satisfactory accuracy. On the basis of analysis of accurate thrust force analysis, the smoothness of the thrust force is also studied with simulation results.

References

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