Electromagnetic Mechanical Coupling Analysis of Linear Motor Used in Machine Tools

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Abstract. The finite element model of the linear motor machine tool was established by the finite element software, and the multi-field coupling analysis and modal analysis of the linear motor for the machine tool were carried out. The deformation amount of the machine tool driven by linear motor under multi-field coupling was obtained. At the same time, the force cloud diagram, the first 6th modal analysis of the important components (machine base), the natural frequency and vibration mode of the base are all obtained. The result shows that the natural frequency is much lower than the excitation frequency, so it can effectively avoid the resonance phenomenon. This article can provide reference for the application of linear motor on machine tools.

1. Introduction

Without any other intermediary transmission mechanism, linear motors can convert electrical energy directly into mechanical energy for linear motion. Due to its simple structure, non-contact, no wear, fast response, high precision, wide stroke range and many other advantages [1-2], it is used more and more widely, especially in fields such as machine tools [3], free piston engines [4], linear compressors [5].

The process of machine tool driven by linear motor is the result of the co-coupling of electric field, magnetic field and mechanical field. So the influencing factor is no longer defined by a single factor. Therefore, it is very necessary to perform multi-field coupling analysis on linear motor driven machine tool.

2. Model of the machine tool driven by linear motor

The machine tool driven by linear motor, comprising a work table, a slider, a guide rail pair, a linear motor, a permanent magnet seat, a permanent magnet, a foundation, and hexagon socket screws, which are mechanically assembled. A 3D geometric model can be modeled as shown in Fig.1.

In order to reduce the amount of analysis and shorten the analysis time, the three-dimensional model is moderately simplified in this paper. The bolts and screws are all omitted, and the chamfering and rounding are both simplified. The final grid is shown in Fig. 2.
3. Electromagnetic mechanical multi-field coupling analysis

The main parameter properties of the setup material are shown in Table 1. The current excitation is added on the section of the middle winding. The magnitude of the three-phase current is 0A, 5A, -5A at this moment, and then the current is applied to the corresponding winding.

Table 1. Three Scheme comparing.

| Part             | material | Density (kg/m$^3$) | Elasticity modulus (Gpa) | Poisson's ratio | Conductivity S/m |
|------------------|----------|--------------------|--------------------------|-----------------|------------------|
| Workbench        | 45       | $7.89 \times 10^3$ | 210                      | 0.31            |                  |
| Guide            | GCr 15   | $7.8 \times 10^3$  | 208                      | 0.3             |                  |
| Mover            | Epoxy resin | 450               | 150                      | 0.32            |                  |
| Winding          | Copper   | $8.9 \times 10^3$  | 120                      | 0.38            | $5.8 \times 10^7$ |
| Foundation       | HT 200   | $7.9 \times 10^3$  | 120                      | 0.25            |                  |
| Permanent magnet seat | 10   | $7.9 \times 10^3$  | 205                      | 0.28            |                  |
| Permanent magnet | Ndfeb 15 | $7.4 \times 10^3$  | 147                      | 0.3             | $6.25 \times 10^7$ |

Figure 1. 3D geometric model.

Figure 2. Mesh of the linear motor.
3.1. Winding and permanent magnet magnetic field distribution

Fig. 3 shows the winding and permanent magnet magnetic field distribution. The coil generates a magnetic field under the excitation of the current, and the magnetic field density distribution is uniform. The magnetic field density distribution of the permanent magnet is also substantially uniform, and the maximum magnetic density surrounds the circumference.

Figure 3. Winding and permanent magnet magnetic field distribution.

3.2. Vector magnetic field density of permanent magnets

Figure 4 is the magnetic field vector density diagram of a pair of opposing permanent magnets. From Fig. 4, it can be seen that the vector of a pair of permanent magnets is opposite, the vector magnetic density is substantially equal, and its alternating distribution is consistent with the polarity distribution requirement of the permanent magnets. And at the same time, the values are roughly equal, so it is consistent with the predicted results.

Figure 4. Winding and permanent magnet magnetic field distribution.

3.3. Result of coupling analysis

The coupling simulation results can be shown in Fig. 5, where (a) is the result of the coupling deformation, and (b) is the coupling equivalent stress. From Fig. 5 (a), it can be found that the deformation of the permanent magnet is open. This is because the applied current is three-phase alternating current, and the magnetic field generated by the energized current is the same as the magnetic field of the permanent magnet at the moment. So it has a repulsive effect, there is such an open deformation, which is still a reasonable solution.
It also can be observed from Fig. 5 (b), the equivalent stress of each component is all very small, and the maximum equivalent stress is 13-19 MPa which is found around skeleton part (mover). Because it is much lower than that of epoxy resin, the deformation and stress had a limited impact on the linear motor.

![Coupling deformation](image1) ![Coupling equivalent stress](image2)

**Figure 5.** Coupling simulation.

4. Machine tool foundation modal analysis

The role of modal analysis is to identify the modal parameters of the system, and provide a basis for structural vibration analysis, vibration fault diagnosis and prevention, and optimization of structural dynamic characteristics. So to some extent, the ANSYS workbench modal analysis can be used to replace the experiment.

As a supporting component, the foundation is an important part of the machine tool. In order to avoid resonance, it is very necessary to perform modal analysis on the foundation.

At present, the maximum speed of the milling cutter in our school is 15 000 r/min. And the frequency of the machine tool foundation will be calculated via Eq. (1).

\[
f = \frac{n}{60} = \frac{15000}{60} = 250 \text{Hz}
\]  

Where \( f \) is the frequency of the machine tool foundation, \( n \) is the Spindle speed.

![1-st-order](image3) ![2-nd-order](image4)

(a) 1-st-order    (b) 2-nd-order
The results of the machine tool foundation modal are shown in Table 2. The maximum self-induced natural frequency of the machine tool foundation is 250 Hz, and it is far below the working frequency. The minimum working frequency of the first 3rd order frequency is 866 Hz, and it is 3.4 times more likely to the maximum self-induced natural frequency of the machine tool foundation. So resonance phenomenon does not occur.

**Table 2.** The first sixth order modal natural frequency and vibration shape

| Order | Frequency /Hz | Vibration shape                                               | Maximum deformation/mm |
|-------|---------------|---------------------------------------------------------------|------------------------|
| 1     | 866           | Swing inward on the support of the guide rail (GR)            | 13.6                   |
| 2     | 1006          | Local torsional deformation of the GR                         | 19.5                   |
| 3     | 1523          | Bending and torsional of the GR                               | 21.0                   |
| 4     | 1852          | Swing deformation around the z-axis x positive direction of   | 18.9                   |
|       |               | the GR                                                        |                        |
| 5     | 1961          | Swing around the z-axis x direction of the GR                 | 22.9                   |
| 6     | 2244          | Swing and torsional deformation in the x-direction around     | 24.9                   |
|       |               | the z-axis of the GR                                          |                        |

**5. Conclusion**

Through model of machine tools driven by the linear motor drive, the coupling simulation analysis of electric field, magnetic field and stress field and modal analysis were carried out by the software ANSYS workbench, and the following conclusions were obtained:

1. The finite element model of linear motor machine tool is established by coupling method, and the electromagnetic-magnetic field-mechanical field coupling analysis is carried out to calculate the shape variable and equivalent stress cloud map at certain moment, which provides reference for structural optimization.
(2) The first sixth order of modal analysis was performed on important components (machine foundation) to calculate the natural frequency and vibration mode. The natural frequency is much lower than the self-induced frequency, so it can effectively avoid the generation of resonance phenomenon.

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References
[1] Y. Fujimoto, T. Kominami, H. Hanmada. Development and analysis of a high thrust force direct-drive linear actuator[J]. IEEE Transactions on Industrial Electronics. 56 (2009) 1383-1392
[2] X. Shi, S. Chang. Extended state observer-based time-optimal control for fast and precise point-to-point motions driven by a novel electromagnetic linear actuator. Mechatronics. 23 (2013) 445-451
[3] J. Dai, S. Chang, L. Liu. Optimization analysis of Electromagnetic Linear Actuators radial array permanent magnets. International Journal of Applied Electromagnetics and Mechanics. 47 (2015) 441-451.
[4] R. Mikalsen, A.P. Roskilly. The design and simulation of a two stroke free-piston compression ignition engine for electrical power generation. Applied Thermal engineering. 28 (2008) 589-600.
[5] J. Kim, J. Ieong. Performance characteristics of a capacity-modulated linear compressor for home refrigerators. International Journal of Refrigeration. 36 (2013) 776-785.