Analysis of vibration characteristics of cylindrical linear induction motor

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Abstract. Due to the non-periodic operation of the cylindrical linear induction motor, the vibration characteristics cannot be studied by the conventional steady-state method. In this paper, the finite element modal analysis method is used to describe the natural vibration characteristics of linear motor with different connection conditions, and the contribution factors of modal on the overall vibration are quantitatively analyzed. Besides, the modal change law of linear motor is analyzed, and the transient dynamics method is used to investigate the transient forced vibration characteristics of the linear motor during the movement of the mover. The research shows that the elastic connection can greatly reduce the natural vibration frequency of the linear motor; when the excitation force is applied, the mover bracket is the most easy to vibrate; the motion of the mover has little effect on the linear motor mode, and the difference is reflected in the different mode of stator because of the different relative position of mover and stator.

1. Introduction

Cylindrical linear induction motors have been widely used in reciprocating mechanisms due to their structural symmetry, good thrust characteristics, high primary winding utilization, no lateral edge effects and single-sided magnetic pull forces [1-3]. Due to the longitudinal edge effect and the non-periodic operation of the cylindrical linear induction motor, large thrust pulsations will be generated, resulting in velocity fluctuations and structural vibration [4]. Structural vibration will generate noise, reduce the accuracy of control and transmission performance. Therefore, it is of great significance to study the vibration mechanism of cylindrical linear induction motor.

In [5], the transient electromagnetic vibration of the permanent magnet brushed DC motor is calculated by the modal superposition method. However, with the movement of the cylindrical linear motor mover, the modal state will change accordingly. So modal superposition is not useful to transient vibration characteristics analysis. In [6], the modal and natural frequencies of the secondary core of the permanent magnet linear switch motor are analyzed by finite element simulation, but the electromagnetic force of the cylindrical linear induction motor acts on both the primary and secondary, and the primary and secondary are connected through the friction plates, so both of them should be considered. In [7], the influence of rubber stiffness on the linear motor flutter of metro vehicles is studied. It is found that the greater the rubber stiffness, the higher the motor flutter frequency. This paper focus on the transient vibration characteristics of cylindrical linear induction motors with additional rubber vibration isolators that there are few researches on currently.

In this paper, the natural vibration characteristics of the motor under three different connection modes, rigid connection, elastic connection and no connection is explored, and the contribution of
each mode of the motor is extracted under different excitations. For the non-periodic operation of the linear motor, considering the movement of the mover, the modal change law of the motor is applied, and the transient structure method is used to analyze the forced vibration law of the motor.

2. Cylindrical linear motor

2.1. Structure and materials

The cylindrical linear induction motor model is shown in Figure 1. The finite element model was established through Spaceclaim, and the modal analysis, harmonic response analysis and transient dynamics analysis will be conducted by Ansys-Workbench. The motor is connected to an external device through a vibration isolating device, so the influence of the vibration isolating device on its vibration characteristics needs to be investigated.

![Figure 1. Stator and mover of cylindrical linear motor.](image)

The secondary stator is divided into an inner conductive layer and an outer magnetic conductive layer, the primary mover is divided into brackets, friction plates, cores, windings, glue layers and sleeves. The modal analysis material parameters are shown in Table 1.

| Component         | Density (kg/m³) | Young’s modulus (Gpa) | Poisson’s ratio |
|-------------------|-----------------|-----------------------|----------------|
| Conductive layer  | 8933            | 100                   | 0.35           |
| Magnetic conductive layer | 7850          | 200                   | 0.3            |
| Bracket           | 4620            | 96                    | 0.36           |
| Friction plate    | 1000            | 7.84×10⁻³             | 0.47           |
| Iron core         | 7850            | 200                   | 0.3            |
| Winding           | 8900            | 100                   | 0.35           |
| Glue layer        | 1000            | 7.84×10⁻³             | 0.47           |
| Sleeve            | 4620            | 96                    | 0.36           |

2.2. Transient operation characteristics

Different from the steady-state operation of the rotating motor, the working mode of the linear motor is the non-periodic and short-time pulse working system, so the amplitude and frequency of the electromagnetic force are time-varying. For the moving primary linear induction motor, the position of the primary mover changes momentarily, resulting in instantaneous changes in the bearing parts and constraints of the stator. Therefore, the electromagnetic force and vibration characteristics of the cylindrical linear induction motor are transient.

3. Modal analysis theory

The modal is the natural vibration characteristic of the mechanical structure, and each modal has a specific natural frequency, a damping ratio, and a mode shape. These modal parameters can be obtained by numerical calculation or experimental analysis. The process of identifying these modal parameters is modal analysis [8]. In this paper, the finite element method is used to calculate the modal parameters of a cylindrical linear motor. Reference [9] discussed the linear stationary system
modal analysis theory based on the finite element method. Then the difference between rigid modal and elastic modal, and the modal contribution analysis theory is discussed below.

3.1. Rigid modal and elastic modal
Reference [10] shows that a rigid material refers to a material that does not undergo deformation, neither elastic deformation nor plastic deformation, and there is no rigid material in practice. Materials with very high modulus of elasticity can be considered as rigid materials before yielding. Elastic material refers to a material that is deformed by force and can be completely recovered by deformation. The elastic modulus is used to measure the deformability of a material. If the slope of the stress-strain curve (elastic modulus) of a material is constant, it is called a linear elastic material.

The rigid body has 6 degrees of freedom: 3 translational degrees of freedom and 3 rotating degrees of freedom. When moving, any straight line of the rigid body is always parallel to their initial position; when rotating, the mass elements in the rigid body make a circular motion around the same straight line. Any complex movement of a rigid body is a superposition of these two basic movements. Elastomers have an infinite number of degrees of freedom and therefore have a variety of elastic deformation motion forms. If no deformation occurs during the movement of the elastomer, it can be called rigid body motion. In general, the movement of an elastomer can be seen as a combination of rigid body motion and elastomeric motion.

The rigid body modal is similar to the definition of rigid body motion. The mode shape that does not deform inside the structure is the rigid body modal, and the mode shape that is deformed inside the structure is the elastic modal.

3.2. Modal contribution analysis theory
The mode shape is the inherent state of vibration, and the modes are not coupled to each other [11]. The vibration response caused by the structure under external excitation can be understood as a linear superposition of various modes of orders [12].

It can be seen from equation (1) that the vibration response of the system under the excitation of external force \( F(t) \) is \( \{x\} \). The vibration response can be expressed as [13]:

\[
\{x\} = q_1\{j_1\} + q_2\{j_2\} + \ldots + q_n\{j_n\} = \{q\} \times [J]
\]

(1)

Where \([J]\) is the mode matrix and \(\{q\}\) is the vector consisting of the participation factor of each vibration mode [14].

In actual modal analysis, modal truncation is often performed, that is, the influence of higher-order modes on vibration is ignored. Therefore, \([J]\) is usually not a square matrix, and equation (1) is an overdetermined equation. The least squares method can be used to approximate the modal participation factors:

\[
\{q\} = ([J]^T[J])^{-1}[J]^T\{x\}
\]

(2)

Normalize the modal participation factor:

\[
Q_r = \frac{|q_r|}{\sum_{r=1}^{n}|q_r|}
\]

(3)

Among them, \(Q_r\) represents the contribution ratio of the \(r\)-order mode to the overall vibration.

4. Simulation results and analysis

4.1. Steady-state vibration characteristics of linear motors
In the three connection modes of no connection (free boundary), rigid connection (without vibration isolator) and elastic connection (with vibration isolator), the mover is located in the middle of the stator, and the first 30 modes of the linear motors are shown in Figure 2. In the non-connected state, the modal reflects the natural vibration characteristics of the linear motor. The first six modes are rigid body modes, no deformation occurs, and the natural frequencies of each mode are below 600 Hz.
When rigidly connected, the degrees of translations and rotations freedom are restrained by fixed constraints. The modes of each order are elastic modes. The natural frequencies are between 200 Hz and 800 Hz. When elastically connected, the modal vibrations are concentrated on the rubber isolators. The natural frequencies of the modes are greatly reduced, less than 100Hz. The cylindrical linear motor can be equivalent to a rigid body with a small modulus of rubber. Therefore, the vibration isolator can greatly reduce the natural vibration frequency of the linear motor.

The excitation force is applied to the inner wall surface of the stator magnetic conductive layer, the amplitude is 7000N and the excitation frequency is 10Hz, 100Hz, 200Hz, 300Hz, 350Hz, 400Hz, respectively. The top 30 mode contribution of the linear motor is shown in Figure 3.

When the excitation frequency is 10 Hz, the linear motor mainly undergoes translation, vibration of the front and rear ends of the stator and vibration of the mover bracket. When the excitation frequency is 100Hz and 300Hz, the 9th-order mode has the greatest influence, and the vibration mode is the vibration of the mover hexagonal bracket. When the excitation frequency is 200Hz, the 9th and 22nd modes have the greatest influence, and the vibration modes are the vibration of the mover hexagonal bracket. When the excitation frequency is 350Hz, the 9th, 21st, and 22nd modes have the greatest influence, and the vibration modes are the vibration of the mover hexagonal bracket. When the excitation frequency is 400 Hz, the 16th order mode has the greatest influence, and the 16th order mode of the linear motor corresponds to the natural frequency of 398.61 Hz. Therefore, the 400Hz excitation force causes the linear motor to resonate, and the main vibration part is the stator front end. In summary, the excitation near the natural vibration frequency may cause the linear motor to resonate; the 9th and 22nd modes are relatively easy to excite, and the corresponding mode is the vibration of the mover hexagonal bracket.

Replacing the mover hexagonal bracket material from titanium alloy to structural steel, and increasing the Young's modulus by about two times. Applying 7000N, 350Hz excitation force on the inner wall surface of the stator magnetic conductive layer, the vibration amplitude of the mover hexagonal bracket is reduced from 0.021829mm to 0.0027383mm, which is reduced by 87.45%. When the amplitude, frequency and action position of the disturbance force change, the forced vibration characteristics of the motor will change accordingly. However, for the known specific conditions, the modal superposition method can be used to solve the vibration response, and the modal contribution

Figure 2. Modal under three installation conditions.
analysis method can be used to find a number of key modes. It is possible to achieve the purpose of vibration and noise reduction through local optimization.

Figure 3. modal contribution under different excitation.
4.2. Transient natural vibration characteristics of linear motors

The modal analysis is performed considering the two states of the linear motor, with mover and with no mover. The typical mode comparison is shown in Figure 4 and Figure 5. It is obvious that the mover imposes a constraint on the stator deformation. During the working of the linear motor, the mover moves from the front end to the rear end of the stator, and instantaneously restrains the different positions of the stator, thereby affecting the overall mode of the linear motor.

**Figure 4.** Typical vibration with mover.    **Figure 5.** Typical vibration without mover.

According to the four relative positions shown in Figure 6, the modal analysis of the cylindrical linear induction motor is carried out. The natural frequency changes of the 10th-13th mode and the 20-22nd mode are extracted as shown in Figure 7 and Figure 8. As the mover moves from the front end to the back end, the natural frequency of each mode of the linear motor does not change much, but there are two laws of change: the natural frequencies of each order in Figure 7 are approximately axisymmetric, and the corresponding mode is the stator cylinder wall deforming. Regard the stator as a regular cylinder, and the motion path of the mover is the side end - the middle part - the side end. Therefore, the constraints of the mover at the corresponding positions on the front and rear ends can be equivalent; The natural frequencies of each order in Figure 8 are almost the same, and the corresponding vibration mode is the vibration of the mover bracket. It can be seen that the natural vibration characteristics of the mover are little affected by the relative positions of the mover and the stator.

Considering the non-periodic operation characteristics of linear motors, it is found that the transient natural vibration characteristics are not much different from the steady-state natural vibration characteristics. Each order modes are quite close to the corresponding natural frequencies, and the modal of the mover is hardly changed with the motion of the mover, the difference is that the deformation of the stator is different due to the different constraints of the stator.

![Schematic diagram of four relative position.](image)

**Figure 6.** Schematic diagram of four relative position.
4.3. Transient forced vibration characteristics of linear motors

It is known from 3.2 that the transient vibration characteristics of a linear motor are reflected by the stator. Therefore, this section uses the transient structure method to analyze the forced vibration of the stator. As the mover moves from the front end to the rear end, in addition to applying a displacement constraint at the corresponding position of the stator, an electromagnetic force is applied thereto, and the electromagnetic force is the most important factor causing the vibration of the linear motor. Considering the edge effect, the area that electromagnetic force affects is slightly longer than the length of the mover cover. Since each point of the stator is subjected to a time-varying distribution force, it is complicated to characterize every force strictly. In order to analyze the forced vibration characteristics without considering the real electromagnetic vibration source, the stator stress is simplified: according to the four relative positions shown in Figure 6. Apply a simple harmonic force as shown in Figure 9 to the stator, and the positive direction is the direction of gravity.

The displacement response curves of the front end, the base, the top, the middle section of the stator, the rear end of the cylindrical linear motor is shown in Figure 10. The harmonic response analysis can only obtain the steady-state vibration response, while the transient structure method
characterizes the transient response curve of each component. Moreover, the components in the positional relationship from the front end to the rear end tend to have a decreasing amplitude of the forced vibration. When the mover moves to position 4, the front end, the base and the top are weakened, so the amplitude of the three components first increases and then decreases; the rear end is weak because of the small force in the first half of the linear motor operation, when the traction moves to the position 4, the force is sharply increased, so the amplitude of vibration is also rapidly increased; the force in the middle section of the stator is relatively uniform, so the amplitude of deformation is evenly increased.

Figure 9. Linear motor transient load force. Figure 10. Displacement curve of component.

It can be seen that the transient structure method can characterize the transient forced vibration characteristics of a linear motor. When the electromagnetic vibration source of the cylindrical linear induction motor is further determined, the transient forced vibration of the linear motor can be performed according to the actual electromagnetic excitation.

5. Conclusions
In this paper, the influence of the rubber vibration isolator on the natural mode of the cylindrical linear induction motor is considered, and the transient forced vibration analysis considering the transient operation characteristics of the linear motor is carried out. There are the following conclusions:

(1) The rubber vibration isolator can greatly reduce the natural vibration frequency of the linear motor, and the deformation of the device with the rubber vibration isolator will be concentrated on the vibration isolator.

(2) Regardless of the movement of the mover, the most vulnerable part of the cylindrical linear induction motor is the mover bracket. Increasing the stiffness of the bracket can effectively reduce the vibration of the bracket.
(3) Considering the motion of the mover, the linear motor mover mode does not change with the relative position of the mover and the stator. While the stator modal has a small difference due to the different constraint positions, but the difference between the overall modal and the natural frequency is not large.

(4) Transient structure method can effectively describe the transient forced vibration characteristics of cylindrical linear induction motor.

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