A non-resonant piezoelectric linear motor with alternating normal contact force

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To develop a piezoelectric linear motor with high precision, large stroke and strong thrust, a non-resonant piezoelectric linear motor with alternating normal contact force is developed. The motor adopts four piezoelectric stacks to excite the non-resonant state vibration of two driving feet, which alternately push the mover to generate unidirectional motion. On the basis of working principle analysis, the structure of the motor is designed and manufactured. The testing results show the feasibility of the motor. The operating results also shows that the flatness of the contact surface greatly affect the performance of the motor. The design criteria of the motor are proposed, which provides a basis for optimization of the motor.

1. Introduction

Piezoelectric linear motors (PLMs) have many advantages, such as high resolution, fast response, no electromagnetic interference and power-off self-locking[1-4]. In recent years, it has become a hot research topic and attracted the attention of scholars. It′s widely used in integrated circuits, bioengineering, precision machinery[5-8] etc.

PLMs can be classified into resonant types[1, 9-10] and non-resonant types[11-14] by the vibration state of the stator of a motor during operation. In the early researches, limited by the small output strain of piezoelectric materials, the resonant motors were mainly studied. Resonant motors use the resonance effect of stator composed of piezoelectric material and metal elastomer[15-16]. Driven by high-frequency signals, this type of motor amplifies the mechanical strain of the order of nanometer to micron meters with the help of structural resonance, which was converted into one-way linear motion of the mover through friction coupling. It has the advantages of simple structure, small size, easy to realize mass production16 etc. Resonant motors have become one of the main development directions of low power linear motors. Besides, the output characteristics of the motor in resonance state is highly dependent on the environment, leading to a significant frequency nonlinearity. The environment temperature will cause the change of material geometry, which will change the natural frequency of the motor, and the environmental humidity will affect the friction between the driving foot and the actuator[17]. As a result, the utilization of resonance leads to the instability output characteristics of resonant motors, and raises higher demands on their drive and control systems[18-19].

With the development of manufacturing technology of piezoelectric ceramics, piezoelectric stacks were invented. A piezoelectric stack is composed of several pieces of piezoelectric ceramics, which is mechanically connected in series and electrically connected in parallel. It can produce larger deformation under lower voltage[20]. Non-resonant piezoelectric linear motors utilize piezoelectric stacks as the driving elements21[-22], so it inherits the characteristics of piezoelectric stacks. A stator can generate enough amplitude to drive a mover without the stator reaching resonance state, and the stability of the motor is significantly improved. In general, the stability of non-resonant piezoelectric linear motors would be better, and it would achieve large stroke as well as high resolution[23]. Its output speed is linear with the driving voltage and frequency, which is good for control.

Non-resonant PLMs are driven by the friction between driving foot and mover to realize the stepping motion[24]. According to the change of normal contact force between driving foot and mover, non-resonant PLMs can be classified into constant normal contact force mechanisms and alternating normal contact force mechanisms. Non-resonant PLMs with constant normal contact force include inertial type[25-27] and tangential differential type[28-29], it′s the contact force on the contact surface between driving foot and mover always remains unchanged, and the vibration direction of piezoelectric vibrators are parallel to the moving direction of mover. So, this kind of motor has the characteristics of simple structure and easy to integrate. Besides, it requires high excitation signal, and its driving force is small. In one action cycle, the conversion efficiency of friction is low.

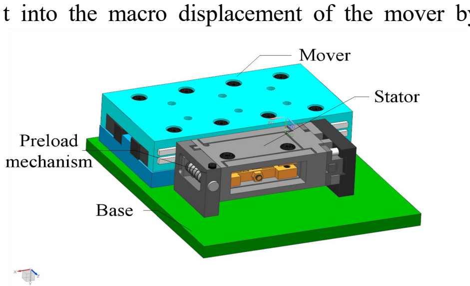
The driving feet of non-resonant PLMs with alternating normal contact force have vibration components in the tangential and normal directions[30-31]. The normal vibration component makes the contact force change periodically, and the tangential vibration component transforms the vibration into one-way motion. The driving feet of this motor alternately act on mover, which has a large stroke and a large thrust. Its step size is controlled by the amplitude of driving feet and the step′s precision is controllable[32]. As one of the alternating motors, inchworm motor[33-36] works by using inchworm actuator. When inchworm motor works, the two clamping mechanisms alternately lock the mover, and cooperate with the actuator to realize the stepping motion. However, inchworm motors have complex structure, and higher requirements for machining accuracy and assembly accuracy. The driving feet are far away from each other, so it is difficult to achieve alternate action. When the driving feet have little wear, the preload will change, and the motor performance will be affected.

In order to solve the above problems, this paper proposes a kind of bipedal differential stepping PLM, which belongs to the alternating normal contact force type. The design structure and principle are introduced, and the prototype of the motor is designed and manufactured. The experimental test of the prototype verifies the feasibility.

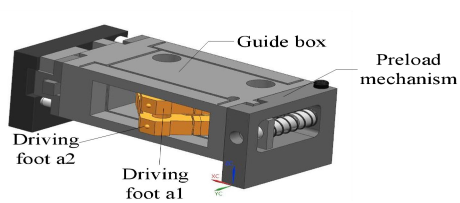
2. Construction of Motor

2.1 Structure of motor

Fig.1(a) shows the model of the PLM, which mainly consists of a stator, a mover, a preload mechanism and a base. The mover, the stator and the preload mechanism are fixed on the base by screws. Fig.1(b) shows the model of the stator, which consists of a guide box and driving feet, the preload mechanism is located on the side of the stator. Two driving feet are fixed in the guide box by screws and stacked to reduce the distance between the two driving feet, which makes the alternate action of two driving feet easier to achieve. Each module cooperates with each other to transform the micro amplitude of two driving feet into the macro displacement of the mover by friction.



(a)Model of piezoelectric linear motor



(b) Model of stator

Fig. 1 Construction of Motor

2.2 Operation Principle

Four piezoelectric stacks are driven by sinusoidal signals with DC bias, and the phase difference between two adjacent signals is 90°. It is known that the deformation of the piezoelectric stacks is approximately proportional to the applied voltage.

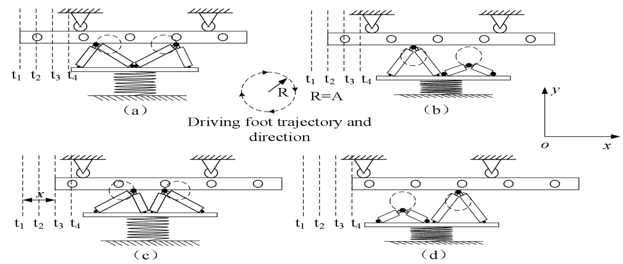


Fig. 2 Operation circle of the motor

At t = t_1, the left driving foot starts to contact the mover. Under the action of friction, the mover and the left driving foot move along the positive direction of *x*-axis. The right driving foot starts to break away from the mover and move along the negative direction of *x*-axis, and the stator moves along the negative direction of *y*-axis to compress the preloading spring.

At t = t_2, the left driving foot reaches the apex of *y*-axis, and the right driving foot moves to the farthest from the mover. At this time, the speed of the mover driven by the left driving foot reaches the maximum, and the compression of the preloading spring reaches the maximum.

At t = t_3, the right driving foot starts to contact the mover. Under the action of friction, the mover and the right driving foot move along the positive direction of *x*-axis, and the left driving foot starts to move away from the mover and along the negative direction of *x*-axis. At this time, the displacement of the mover along the positive direction of *x*-axis is 2A, and A represents the trajectory radius of the driving feet.

At t = t_4, the right driving foot reaches the apex of *y*-axis, and the left driving foot moves to the farthest position from the mover. At this time, the speed of the mover driven by the right driving foot reaches the maximum again, and the compression of the preloading spring reaches the maximum.

When the motor recovers from the state at t_4 to the state at t_1, the displacement of the mover along the positive direction of *x*-axis is 2A, and the motor completes one cycle of action. In this way, the motor runs periodically. In one cycle, the two driving feet alternately drive the mover to realize one-way movement, and the movement distance is 4A.

3. Conclusions

To develop a PLM with high precision, large stroke and strong thrust, a double feet differential stepping PLM with alternating normal contact force is proposed. The working principle of the motor is introduced, the motor′s operation model is established, and the motor′s structure is designed. In order to verify the feasibility of the motor, a prototype is made and tested. By testing the amplitude of two driving feet, the correctness of the motor installation is verified, and a method to verify the correctness of the motor installation is obtained. From the observation of th e motor's output characteristic experiment, the position relationshi p between two driving feet and the contact surface is studied, a nd a design criterion of the motor is obtained, that is, the flatne ss tolerance zone of the contact surface should be less than the amplitude of the motor's driving feet. The feasibility of the mo tor is verified by experiments. The research and analysis show t hat friction load and preload have a great impact on the motor performance. In the future work, the influence of friction load a nd preload on the motor performance will be studied.

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