Design and Research on a Biped Clamp and Pull Piezoelectric Linear Motor Based on Inchworm Principle

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Abstract. The piezoelectric linear motor based on piezoelectric ceramic stack has a potential in high-tech field’s application such as optical waveguide packaging. Mechanical properties of piezoelectric linear motors in the existing researches still need to be improved. So have designed double foot clamping type piezoelectric linear motor based on the principle of inchworm, and analyzed the working principle. The performance analysis of the driving mechanism shows that the relationship between the amplitude of driving mechanism and voltage values is positively proportional, and the influence of frequency on its amplitude is not big. The performance of the clamping mechanism was studied through experiments. First, verified the feasibility of the principle, tested the amplitude and found that the amplitude increases with the increase of the voltage, but due to the influence of clamping mechanism modal, amplitude tends to be zero as frequency increase to a certain extent. Second, amplitudes of the driving foot in two clamping mechanism were compared to ensure the consistency of amplitude of each driving foot, and the magnification of driving mechanism displacement was obtained by clamping mechanism in the practical work. Analyzed the rail vibration caused by driving foot and the prototype speed characteristics and load characteristic, and obtained speed characteristic curve are, in which, the speed of the motor increases with increasing voltage, but will not be able to continue to increase when the voltage reached to 60V, and the related curve between frequency and speed is similar to the frequency characteristic curve of the clamping mechanism, which is mainly due to the impact from the clamping mechanism modal. Obtained the maximum output of the motor power is 1.8 N through the load characteristic experiment.

1. Introduction
The piezoelectric linear motor is one of the many piezoelectric actuators, which has the advantages such as simple structure, high positioning accuracy, diversified design forms and other advantages. In recent years, it has received wide attention from the scholars both at home and abroad [1-6]. Many piezoelectric linear motors with the applications of laminated piezoelectric ceramic have been put forward by the scholars from both at home and abroad, such as inertial impact type [7-9], which has the advantages such as simple structure, easy to realize the sports; inchworm type [10-12] has advantages of high resolution, large output force and so on.

This study uses laminated piezoelectric ceramic as driving element, the movement mode of “clamp-drive-clamp”, developed a large stroke, high resolution, capable of self-locking inchworm type piezoelectric linear motor, and realized to reduce the motor assembling and machining precision through superposition of two kinds of amplification principles and the improved design of guide rail. Through
the design research, provided a drive with large thrust, high precision, large travel for the workbench with six degrees of freedom, which contributed to the development of precision PZT platform.

2. Motor structure
A good model of the motor assembly shows as figure 1. In order to observe the internal structure, remove the cover on the guide rail. The first step of the motor assembly process is to install two driving mechanism inside two clamping mechanisms, driving mechanisms (1&3) are fixed by screws, the other end fixed by a special stud, and two flexible foot installed at two ends of the driving mechanism 2, which can effectively eliminate the influence of bending moment on the driving mechanism, and two flexible feet fixed by two stud. The driving mechanism is arranged in the inner part of the clamping mechanism, the preload depends mainly on the screw to achieve. Different preload may make different amplitude, which will have an effect on the operation of the motor.

![Figure 1. The whole assembly model of the motor.](image1)

![Figure 2. The structure of biped clamp type piezoelectric linear motor.](image2)

11- clamping mechanism 1, 12- clamping mechanism 2, 21-drive mechanism 1, 22- drive mechanism 2, 23- drive mechanism 3, 31&32- flexible foot, 4- rail.

3. Experimental Study on the Driving Mechanism and the Clamping Mechanism

3.1. The performance of drive mechanism
Signal generator generates 100 Hz square wave, its peak value is 2.5V. After amplified by power amplifier, its value into 50 v, the signal is applied to the stack of the driving mechanism, the amplitude is measured by laser displacement sensor, then feedback it to the PC, the data obtained is shown in Figure3. According to the obtained data, the amplitude of the driving mechanism is about 2 μm, the vibration is basically stable, and the displacement is obtained, which has proved the feasibility of the driving structure.

Generally, the motor speed is adjusted by adjusting voltage and frequency, so the change of the driving mechanism is especially important. It is respectively studied that the relationship between voltage, frequency and displacement. The frequency of the signal generator 100Hz is unchanged, so as to obtain a series of displacement data by adjusting the voltage, the relationship between voltage and displacement as shown in Figure4. There is basic linear relationship between displacement output of the driving mechanism and the voltage, when the output voltage changing, the displacement is relatively stable. In addition, displacement is also increasing with the change of voltage; the displacement output range is relatively large, which meets requirements of the motor operation.

Similarly, signal generator’s voltage 5V remains stable, the voltage to pass the power amplifier is 100V, may obtain a series of displacement data by changing the frequency, the relationship between frequency and displacement as shown in Figure5. When the frequency is smaller, displacement output of the driving mechanism starts with a floating some, but with the increase of frequency, it finally tends to be stable, maintained at about 5μm. Therefore, when the frequency changes, the displacement of the driving mechanism is basically stable, which will not have a significant impact on the motor.

The experimental results show that the performance of the drive mechanism is good, and it can meet the requirements of the motor when the voltage and frequency change.
3.2 The performance of clamping mechanism

The clamping mechanism can realize clamping and releasing the clamp or not is related to whether the normal operation of motor. When adjusting the voltage and frequency of the motor, the amplitude of the clamping mechanism is also changed, so it is necessary to research the change. Researches the performance by taking a clamping mechanism for experiment, keeps the frequency of the signal generator 150Hz, changes the value of the voltage, and obtained a series of amplitude data, The relationship of the voltage and amplitude is shown in Figure 6. The amplitude of the clamping mechanism is also increasing with the increase of the voltage, which shows a linear relationship between them, only one point is small, which may be caused by the experimental error. Therefore, when the voltage changed, the mechanism of the clamp amplitude can work stably.

Similarly, signal generator’s voltage 5V remains stable, the voltage to pass the power amplifier is 100V, may obtain a series of displacement data by changing the frequency, the relationship between frequency and amplitude as shown in Figure 7. When the frequency being before 160Hz, curve is almost a straight line, the amplitude increases with the increase of frequency, and when the frequency is more than 160Hz, Increased range of the amplitude of the clamping mechanism becomes large, when the frequency exceeds 200Hz, the amplitude decreases sharply, and almost is zero. The first-order natural frequency of the clamping mechanism is 173Hz, when the working frequency is close to the first-order natural frequency, the resonance phenomenon happened, which led to the rapid increase of amplitude. When the frequency continues to increase, due to the second order natural frequency of clamping mechanism is 225Hz, and interference between the second order modal and the first order modal happened, which resulting in a clamping mechanism cannot work normally, thus the amplitude decreases sharply, and is almost zero.

Through the above experiments, it is known that the performance of clamping mechanism is satisfied with the work demand of the motor, but should pay attention to the size of the frequency when the motor works to avoid clamping mechanism can’t run normally caused by the high frequency and affects the motor work.
3.3 Amplitude comparison of clamping mechanism driving foot

The amplitudes of four driving feet in clamping mechanism are consistent or not will directly affect whether the motor can move stably or not. Using the same experimental apparatus and the principle, generates a square wave signal with the signal generator (bias signal), which is amplified to 100V by the power amplifier, the frequency is 10Hz, one end of the clamping mechanism is fixed by the vise, the end of driving foot is hanging, then shooting the laser at the drive foot to be measured, the sampling period is 200 μm. In order to measure the magnification of the clamping mechanism, when tests the amplitude of the clamping mechanism, at the same time also need to measure the amplitude of the driving mechanism. The measured data are shown in Table 1.

| Driving foot       | Frequency(μm) |
|--------------------|---------------|
| Clamping mechanism 1 | 76.71         |
| Clamping mechanism 2 | 75.214        |
| Drive mechanism     | 74.432        |
|                     | 73.886        |
| Drive mechanism     | 9.342         |

The clamping mechanism adopts the same structure, the driving mechanism also uses the same, through the data in the table we can see that the amplitudes are different for different clamping mechanism driving foot, and amplitudes of two driving feet belongs to the same clamping mechanism are also different, summarize the reasons as follows: the preload of piezoelectric ceramics for each clamping unit is not exactly the same; the error processing makes the clamping mechanism have small deformation; the different test points, the laser playing position will be a little discrepancy, magnification corresponding of different positions is different; There may be a random error and systematic error in the test. But because the gap is not particularly large, the little influences the operation of clamping mechanism. The influence to the operation of the clamping mechanism is not obvious.

3.4 Analysis of vibration induced by driving foot

To realize stable clamping and release clamp by clamping mechanism, the consistency requirements to the amplitude of the driving foot is relatively high, at the same time, because the guide is also designed a flexible structure, the rail vibration caused by the driving foot also have requirements for consistency. And because the rail vibration amplitude is very small, the tiny difference of vibration can’t be measured by ordinary measuring method, it is necessary to design an experiment: in the same working conditions, when the vibration of each clamping mechanism happened, measure out the amplitude transfer to the rail from it. By adjusting preload screw of the clamping unit repeatedly, amplitude of, makes the amplitude measured on the rail be as close as possible. The following is amplitude data from guide rail vibration caused by the clamping mechanism 1, 2. Data are 3.9μm, 4.6μm.
4. Motor experiment and result analysis

4.1 Speed characteristics of the motor under no-load condition

The relationship between the motor speed and frequency is measured, as shown in Figure 10. With the increase of the frequencies of the motor, the motor speed increases, this is due to the effect of excitation frequency on the amplitude of the piezoelectric stack is very small, the speed of the motor mainly depends on the excitation frequency, and the amplitude of the increase speed is also growing, it reaches the maximum speed when the frequency is 160 Hz, after that the motor is close to stop. When approaching the first order natural frequency of the clamping mechanism, the clamping mechanism will resonate, which leads to the increase of amplitude change, thereby affecting the speed increasing rate becomes larger. When the frequency increased to greater than first order natural frequency of the clamping mechanism, because the first order mode and second modes state interferes with each other, and the amplitude of the clamping mechanism tends to zero, then the motor will not be able to run.

![Figure 10. Speed and frequency.](image1)

![Figure 11. Motor speed and voltage.](image2)

![Figure 12. Motor load characteristic curve.](image3)

With the same experimental device, frequency of 150 Hz square wave signals are respectively applied to three driving mechanisms by the signal generator, the signal is shown in Figure 13, the relationship between the motor speed and voltage is measured by adjusting the voltage. The speed is measured using the same way with the above. The relationship between the motor speed and voltage is measured as shown in Figure 11.

As the figure, the no-load speed of the motor increases with the increase of the voltage, which is due to the output amplitude of laminated piezoelectric ceramics increases with the increase of the voltage and frequency constant, in each cycle, dynamic displacement of stator drive divided moving body to move forward has the relationship with the amplitude of the laminated piezoelectric ceramic, and the larger the amplitude, the greater of the displacement of divided moving body in a cycle. When the voltage reached to the 60 V, the motor speed tends to be stable, and no longer increases, the reason is that the amplitude of driving mechanism cannot continue to increase with the voltage increasing. The amplitude of driving mechanism increases with the increase of the voltage, but in practical work, because some pre tight is applied to the driving mechanisms when assembly, when the voltage increases continually to a certain extent, driving mechanism cannot continue to increase because of the preload. On the other hand, when the motor running, the end of realized clamp need to be supported by the static friction force, when the voltage is too high, driving force generated by the intermediate driving mechanisms is too large, causing sliding friction of the clamping end, thus the relative movement happened, and velocity cannot continue to increase.

4.2 Motor load characteristic test

The square wave bias signals with peak 100 V, frequency of 150 Hz are respectively applied to three driving mechanisms in the experiment, by adding weights to adjust the load, the measured motor load characteristic curve as shown in Figure 12. With the increase of load, the motor speed has been decreased continually; the change trend is similar to a quadratic curve. The measured maximum output force of the motor is 1.8 N.
5. Conclusion

The amplitude of the driving mechanism is directly proportional to the voltage, and the frequency has little effect on the amplitude.

The amplitude of the clamping mechanism increases with the increase of the voltage, but due to the influence of natural mode of clamping mechanism, the amplitude will tend to zero when the frequency increases to a certain extent. The amplitudes of the driving feet of two clamping mechanisms were compared with each other respectively, which ensured the consistency of amplitude of each driving foot, also obtained the displacement magnification of the driving mechanism caused by the clamp a mechanism in the actual work.

Analyzed the guide rail vibration caused by driving foot, and ensure that the vibration of the rail caused by each driving foot is little difference by the adjustment of the pre tightening force of the driving mechanism.

The motor speed increases with the increase of voltage, but will not be able to continue to increase when the voltage is 60V; relationship curve of the frequency and the speed is similar to the frequency characteristic curve of the clamping mechanism, which is mainly due to the modal impact of the clamping mechanism. The maximum output force of the motor is 1.8N.

The plan to improve the clamping mechanism is to increase flexural rigidity of the lever amplification arm of the clamping mechanism. The first-order natural frequency is changed to 388.83Hz. The scheme to improve the guide rail is to reduce the stiffness. The bits on both sides of the flexure hinges are removed, only the middle part is left, which effectively reduce the stiffness, and processing is also convenient. The improved scheme not only effectively increases adjustable range of the frequency when the motor is running, and effectively improve the power output of the motor.

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7. References

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