Simulation study of T-shaped piezoelectric linear ultrasonic motor based on PZT piezoelectric ceramics

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Abstract: In this paper, the T-shaped structure of linear ultrasonic motor was studied by means of establishing a THREE-DIMENSIONAL model of mechanical structure through SolidWorks and completing relevant simulation analysis through ANSYS Workbench. The finite element simulation analysis consists of four part: i. modal analysis, it determines the working mode and ensures that the frequency difference between the two working modes is as small as possible; ii. Harmonic response analysis furtherly verifies that the resonant response occurs at the operating mode frequency; iii. transient dynamic analysis demonstrates that the motion trajectory of the motor stator driving foot meets the theoretical requirements of ellipse shape. iv. drive signal and prototype are tested to verify the simulation analysis.

1. Introduction
Linear Ultrasonic Motor (LUSM), rely mainly on the PZT resonant motion of the piezoelectric ceramics, which is produced by the driving voltage, to actuate vibration of the stator drive the load [1]. According to the resonance characteristics of piezoelectric ceramics, it mainly occurs in the ultrasonic frequency band, so the piezoelectric linear motor can be optimized into a piezoelectric linear ultrasonic motor [2]. The advantages of the piezoelectric linear ultrasonic motor include: miniaturization, large torque, fast response, high precision, No need for transmission mechanism, no external interference and other advantages [3].

2. Methods
This design of the T-shaped linear ultrasonic motor is depicted as in FIG 1. It is consisted of the three Langevin vibrators with holes at the junction. The purpose of the openings aims to prevent the mutual interference when vibrated.

Figure 1 T-type linear ultrasonic motor
3. Results & Discussion

3.1. Use of PZT piezoelectric ceramics in linear ultrasonic motors

![Vibration mode piezoelectric ceramics](image1)

![Piezoelectric laminated structures](image2)

This design mainly uses the stretching vibration of the piezoelectric ceramic along the thickness direction to make the Langevin vibrator produce longitudinal vibration, so as to realize the movement of the linear ultrasonic motor [4].

In order to obtain a larger amplitude under the same voltage amplitude, piezoelectric layer by layer structure can be used [5].

3.2. Establishment of equivalent circuit model of linear ultrasonic motor

The basis of the linear motion of the linear ultrasonic motor is that it can produce elliptical motion at the end of the stator driving foot and ensure that the phase difference of the excitation signal in the X and Y directions of the Langevin vibrator is 90°.

![Equivalent circuit diagram of linear ultrasonic motor](image3)

In the equivalent circuit diagram of the linear ultrasonic motor, $R_d$ is equivalent to the dielectric loss of the piezoelectric ceramic, and $C_d$ is equivalent to the dielectric constant and size of the piezoelectric ceramic. $R_d$ and $C_d$ are real electrical quantities, constitute the static equivalent parameters. $R_m$ is equivalent to the loss and temperature caused by friction coupling, $C_m$ is equivalent to the stiffness of the linear ultrasonic motor, and $L_m$ is equivalent to the mass of the linear ultrasonic motor. $R_m$, $C_m$, and $L_m$ are analogies of mechanical quantities and constitute dynamic equivalent parameters [6].

In order to display the resonance characteristics of piezoelectric ceramics more intuitively, the resonance frequency admittance circle is established according to the equivalent circuit [7].

The total admittance of the circuit is equivalent to $Y$, the static admittance is equivalent to $Y_d$, and the dynamic admittance is equivalent to $Y_m$. The relationship between $Y$ and $Y_d$ and $Y_m$ is as follows:

$$Y = Y_d + Y_m = G + jB = (g_d + g_m) + j(b_d + b_m)$$

$$Y_d = j\omega C_d$$

$$Y_m = \frac{1}{R_m + j\omega L_m + \frac{1}{j\omega C_m}}$$
In equation (1), \( g_m \) is dynamic conductance, and \( b_m \) is dynamic susceptance, where \( g_m \) and \( b_m \) can be solved via the following equation:

\[
g_m = \frac{R_m}{R_m^2 + \left(\omega L_m - \frac{1}{\omega C_m}\right)^2} \quad \text{(4)}
\]

\[
b_m = \frac{1}{\omega C_m} - \omega L_m \quad \text{(5)}
\]

\[
G = \frac{R_m}{R_m^2 + \left(\omega L_m - \frac{1}{\omega C_m}\right)^2} \quad \text{(6)}
\]

\[
B = \frac{1}{\omega C_m} - \omega L_m + \omega C_d \quad \text{(7)}
\]

The solution can be derived from the equation:

\[
\left( G - \frac{1}{2R_m} \right)^2 + (B - \omega C_d)^2 = \left( \frac{1}{2R_m} \right)^2 \quad \text{(8)}
\]

It can be seen from equation (8) that the final solution is a circle expression. This circle uses conductance as the X axis and susceptance as the Y axis, so the characteristic circle is called the admittance circle, (see FIG 5).

![Figure 5 Admittance circle characteristic diagram](image)

Because the mechanical quality factor of the ultrasonic motor is relatively large\(^{[8]}\), the following relationship must be satisfied: \( f_m = f_s = f_r \), \( f_n = f_p = f_a \).

Therefore, the specific values of the parameters \( R_m, C_m, L_m \) and \( C_d \) can be determined:

The solver is:

\[
C_m = \left( \frac{f_n^2}{f_m^2} - 1 \right) C_d \quad \text{(9)}
\]

\[
L_m = \frac{1}{4\pi^2f_m^2C_m} \quad \text{(10)}
\]

Where \( F_m \) and \( F_n \) values obtained by ANSYS simulation. Thus, the specific parameters of the components in the equivalent circuit can be determined.

### 3.3. Simulation analysis of linear ultrasonic motor

#### 3.3.1. Stator modal analysis
FIG 6 strain contours at different modalities linear ultrasonic motor

FIG 6 (a) shows the deformation state in the first-order mode, which is the reciprocation in the vertical direction; FIG 6 (b) shows deformation under the second-order mode. It is expressed as the back and forth motion in the horizontal direction.

By continuously adjusting the size of the circular hole at the joint of the Langevin vibrator and the thickness of the fixing part, the frequencies of the first-order mode and the second-order mode of the stator are as close as possible. The vibration mode at this time is the working mode.

3.3.2. Simulation analysis of the resonance frequency of the motor stator

FIG 7 displays the resonant response of the stator at different frequencies, the horizontal axis represents a frequency range, the vertical axis represents displacement of the stator drive foot at the end. When the frequency is 41.585KHz, the foot end of drive motor stator acquires maximum displacement. That is to say, the frequency is corresponding with the frequency of the working mode under modal analysis.

As is shown in FIG 8, the red line is the displacement curve resonant response, the green line exhibits the resonant response phase curve of motor stator under varied frequencies. It can be found that the phase of the motor stator at the first-order and second-order frequency has changed 90°. This phase change ensures that the motor can produce two-dimensional motion.

3.3.3. Trajectory stator Simulation Analysis

The transient dynamic analysis on the stator at the operating mode frequency point was performed. We applied time-varying sine load force and cosine load force in the X and Y directions respectively and obtained the graphs of the displacement in the X and Y directions with time. According to the FIG 9, it can be clearly seen that X-direction displacement and the Y displacement direction is present with a 90° phase lag.

FIG 10 shows the drive terminal trajectory simulation. The entire trajectory resembles an ellipse. It shows that the motor of this structure can meet the structural requirements of the linear ultrasonic motor as well as generate resonance under the excitation frequency of the driving signal to drive the load.
3.4. Experiment and analysis

The experimental platform is set up shown in FIG 11. The experimental platform consists of four parts: drive system module, PC, oscilloscope and ultrasonic motor.

It is necessary to ensure a certain phase difference between the three-channels drive signals. Specifically, the two phase signal applied to motor stator must keep a 180° phase difference. To obtain the phase difference signal, we can reverse the positive and negative output terminal of DDS chip. The test results were shown in FIG 12 (a).

In addition to ensuring the two phase difference of signal on X-axis, the phase difference of two excitation signals on X-axis and Y axis needs to be 90° as well. The specific test result was exhibited in FIG 12 (b).

In order to determine the optimal working state of the output performance of the prototype, the relations among the output speed of the motor under different driving voltages, different driving frequencies and different pressures were studied respectively. And the related results can contribute to determining the optimal working condition of the motor.

The driving signal can generate a continuously adjustable voltage signal with a peak-to-peak value of 0~110V. Therefore, the relationship between the output speed of the motor and the input voltage can be determined by adjusting the value of the voltage. In order to ensure the reliability of the experiment, a certain pressure is applied through the pre-stressed bolt, the driving frequency is set to the resonance frequency obtained by ANSYS simulation, and the phase difference is set to 90°. It can be clearly seen from Figure 13 that the voltage and speed of the linear ultrasonic motor shows a certain linear relationship.
The frequency of the driving signal, whose frequency is at 30KHz~60KHz, is in the ultrasonic frequency band, and the frequency is continuously adjustable. By continuously adjusting the input frequency, the relationship between the output speed of the motor and the input frequency can be obtained. In order to ensure the reliability of the experiment, the voltage amplitude of the driving signal is set to 100Vp-p, and the phase difference is set to 90°.

It can be clearly seen from Figure 14 that the drive frequency starts to increase at 30KHz. As the frequency increases, the output speed first increases and then decreases. When the driving frequency point gradually coincides with the resonance point of the piezoelectric ceramic sheet, the output speed of the motor reaches the maximum.

![Figure 13 Voltage amplitude-velocity curve](image1.png) ![Figure 14 Frequency-Velocity response curve](image2.png)

**4. Conclusions**

We conducted the research on the mechanical structure of the T linear ultrasonic motor. In this paper, the mechanical structure model is established by SolidWorks software, and was imported into ANSYS Workbench finite element analysis software for relevant analysis. We carried out modal analysis, harmonic response analysis and transient dynamics analysis in this research. By adjusting the modal analysis and correlation structure of the stator, and the pair of second order modal frequency differential required modality to reduced 45HZ; by harmonic response analysis to determine the first order, second order mode of vibration aliasing frequency finally determined as the motor frequency. 4 1.585KHz; stator obtained by driving the foot terminal transient dynamics analysis can produce elliptical motion, further verifies the rationality of the design.

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