How to Determine the Size of Longitudinal-flexural Mode Linear Ultrasonic Motor

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Abstract. Linear ultrasonic motor is more and more widely used. Based on the coupling of longitudinal and flexural mode, the piezoelectric stator induces the elliptical locus of contact points to drive the rotor. Now, how to determine the size of a linear ultrasonic motor is still an important problem. Here, we use Shi’s structure of the linear ultrasonic motor and reconstruct the finite element model by the parametric design language of APDL to execute modal, harmonic, transient and contact analyses. We find the frequency of longitudinal mode is only related to the length of the piezoelectric stator and the frequency of flexural mode is related to the length and width of the piezoelectric stator. Based on the results, we put forward a simple strategy to design the linear ultrasonic motor. We find that viscous damping is important to the coupling. Suitable viscous damping gives a large frequency band where the longitudinal and flexural modes are inspired simultaneously. Our results also give a minimum limit of the number of substeps in a period in transient analysis.

1. Introduction
As a new type of actuators, ultrasonic motors have many advantages such as quick response, direct-drive and no electromagnetic interference. Many ultrasonic motors have been applied to accurate positioning devices, medical instruments, and aviation spacecraft. The core of ultrasonic motors is the piezoelectric stator which is composed of piezoelectric ceramics [1]. Owing to the inverse piezoelectric effect [2], the high-frequency voltage inspires the high-frequency vibration of the piezoelectric stator. Subsequently, through the frictional contact between the piezoelectric stator and the rotor, the high-frequency vibrational piezoelectric stator drives the rotor to move [3]. Based on the movement output way, ultrasonic motors are divided into linear ultrasonic motors (LUMs) and rotational ultrasonic motors (RUMs).

But how to design the linear ultrasonic motors is still a difficult problem. Now, a lot of theoretical and practical works have been raised to study the dynamic behavior of linear ultrasonic motors. For experiment, the samples are time-consuming and the tests are complicated and expensive. For theory, the piezoelectric coupling effect, complex structure, and complex boundary condition make it difficult to get the explicit results [4]. For simulation, the finite element model is easy to get the dynamic behaviors of linear ultrasonic motors although considering the piezoelectric coupling and contact [3]. To determine the size of linear ultrasonic motors, we must compare the results of different-sized linear ultrasonic motors. At the traditional analysis process, a lot of time is spent on the modeling.
In this paper, we use the parametric design language of APDL to model and simulate automatically. Through the modal analysis, we obtain the relationship between the frequency of longitudinal and flexural mode and the size of linear ultrasonic motors. Collaborating with MATLAB, we determine the suitable size parameters quickly. Then, we do the harmonic and transient analyses to verify the elliptical locus of contact points of the piezoelectric stator. In harmonic analysis, a suitable stiffness coefficient is determined. In transient analysis, we find the important role of the number of substeps and give a minimum limit in piezoelectric analysis. Finally, we use the parameters based on the above analyses and execute the contact analysis to create a constant motion of the rotor.

2. Finite Element Model of the Linear Ultrasonic Motor

Here, we take the structure of linear ultrasonic motor in Shi’s paper [3] as a starting point. The structure is shown in Fig.1 (a). The linear ultrasonic motor is composed of a piezoelectric stator and a rotor. The piezoelectric stator is composed of a rectangle with length L and width W and two semi-circles with radius R. The rotor is a rectangle with length L and width W1. The position of semi-circles is determined by the distance xL, where x is a scale factor. The brown represents the piezoelectric ceramics. The dark blue represents the bronze. The material parameters can be found in [3]. In our simulation, we fix the height of overall structure H=1mm, the width of rotor W1=0.5mm, the radius of semi-circles R=1.5mm and the scale factor x=0.33. The important parameters which influence the dynamic behavior of the piezoelectric stator are the length L and height W. We take L=38.8mm, W=12.2mm as the initial parameters.

![Figure 1. Schematic representation of the structure. (a) The size parameters of the piezoelectric stator and the rotor are listed. The height of the overall structure is H. The brown represents the piezoelectric ceramics. The dark blue represents the bronze. (b) The finite element model of the linear ultrasonic motor. We apply different voltage boundary conditions on the square points in the rectangles. The red rectangles represent sinusoidal alternating voltage. The blue rectangles represent cosine alternating voltage. On the reverse, all nodes have a zero voltage.](image)

Fig.1 (b) shows the finite element model. To inspire the longitudinal and flexural mode simultaneously [3], the sinusoidal alternating voltage is applied on the nodes in red rectangles. The cosine alternating voltage is applied to the nodes in blue rectangles. The voltage of nodes to the reverse is fixed at zero. The basic principle has been explained. Next, we use this model to start our analyses. In modal, harmonic and transient analyses, we only consider the piezoelectric stator. In contact analysis, the overall structure is included. The APDL files can be found at https://github.com/ChenAiYan/lum.

3. The relationship between the size and frequency

Firstly, we execute the modal analysis to find the suitable size of the linear ultrasonic motor. We define the frequency of longitudinal mode as \( f_l \), the frequency of flexural mode as \( f_b \). The suitable size is the structure whose \( f_l \) is close to \( f_b \) [3]. We change W and L alone to investigate the influence of size. Fig.2 (a) shows \( f_l \) and \( f_b \) decreases with the increase of L. Furthermore, the speed of decrease of \( f_b \) is larger than that of \( f_l \). So, if \( f_l \) is larger (smaller) than \( f_b \), we can increase (decrease) L to actuate \( f_b \) to close \( f_l \). Fig.2 (b) shows W has little effect on \( f_l \). \( f_b \) increases with the increase of W. So, we can
change $f_b$ through W individually. Based on the results in Fig.2, we give a simple strategy to determine the size of the linear ultrasonic motor. Firstly, we decide the working frequency $f$ according to the actual needs. Then, we change L to let $f_1$ close to $f$. Due to the little effect of W on $f_b$, we change W to let $f_b$ close to $f$. In our simulation, we get the best size parameters $W=38.8\text{mm}$ and $L=12.2\text{mm}$ and the frequencies $f_1=34698.6\text{Hz}$ and $f_b=34684.8\text{Hz}$. The difference between the two frequencies is only 13.8 Hz.

![Figure 2](image1.png)

**Figure 2.** The influence of the size of the piezoelectric stator on the longitudinal frequency $f_1$ and the flexural frequency $f_b$. (a) W is fixed. With the increase of L, $f_1$ and $f_b$ decrease. The speed of the decrease of $f_b$ is larger than that of $f_1$. (b) L is fixed. With the increase of W, $f_1$ is almost constant and $f_b$ increases.

4. **The influence of the stiffness coefficient and the number of substeps in one period**

In harmonic analysis, we include the viscous damping. Rayleigh damping is the most common viscous damping in piezoelectric analysis and the stiffness coefficient $\beta$ is enough to simulate the piezoelectric dumping [5]. So, the mass coefficient is set to zero. We compute the displacement of the contact point between the piezoelectric stator and rotor. Fig.3 shows the displacement $u_x$ along the x-axis and $u_y$ along the y-axis at different stiffness coefficients. At low $\beta$, the displacements are small at all frequencies. At high $\beta$, the displacements are very large at resonant frequencies. But $u_x$ and $u_y$ have little overlapping between the two resonant frequencies. We can’t find a suitable frequency where $u_x$ and $u_y$ are large simultaneously. At middle $\beta$, the displacements aren’t small. And there is a frequency band where $u_x$ and $u_y$ are all large enough. So, we choose the stiffness coefficient $\beta = 5 \times 10^{-8}$ and the voltage frequency $f_v = 32950\text{Hz}$.

![Figure 3](image2.png)

**Figure 3.** The influence of the stiffness coefficient on the displacement of the contact point. (A) $\beta = 5 \times 10^{-7}$. At low frequency, $u_x$ and $u_y$ have a large difference. At high frequency, $u_x$ and $u_y$ are gradually approaching. (b) $\beta = 5 \times 10^{-8}$, $u_x$ and $u_y$ have peaks at different frequencies. Between the two resonant frequencies, $u_x$ and $u_y$ have a large overlapping. (c) $\beta = 5 \times 10^{-9}$, $u_x$ and $u_y$ have highly significant peaks at different frequencies. But there is little overlapping between the two resonant frequencies.

In transient analysis, the simulations last 200 periods with sinusoidal and cosine alternating voltages. We find the number of substeps in one period is important to the displacements of contact
point. Fig. 4 (a) shows the displacement $u_x$ at different number $N$. At the low number of substeps ($N=10, 20$), we find $u_x$ in envelope curves vibrates with time and approaches stable slowly. The stable value is smaller than that of large number $N$. The simulations with low $N$ don’t inspire the displacements of the piezoelectric stator completely. At the large number of substeps ($N=40, 80, 160$), the stable value is large and not sensitive to $N$. Compared to Fig. 3 (b), the stable value of $N=40$ is very close to the displacements in the harmonic analysis. So, $N=40$ is the minimum number of substeps in the piezoelectric analysis which can capture the dynamic behavior of the piezoelectric stator enough.

Through the above modal, harmonic and transient analyses, we determine the size of the piezoelectric stator, the frequency of alternating voltages, the stiffness coefficient, and the number of substeps in transient analysis. Then, we execute the contact analysis based on the above parameters. Similar to the simulation in [3], the contact friction coefficient is set to 0.2. We choose the per-force 5N, the amplitude of voltages 100V. The mean displacement of the rotor is shown in Fig. 4 (b). In the beginning, $U_x$ decreases to negative which indicates the rotor moves to the negative $x$-axis. This may be owing to the mismatch at the initial contact. At a long time, $U_x$ increases with time linearly and the velocity keeps constant. The rotor moves to the positive $x$-axes at a constant velocity. The results prove the usefulness of the structure of the linear ultrasonic motor.

**Figure 4.** The influence of the number of substeps on the displacements of contact points in transient analysis. (a) With the increase of $N$, $u_x$ in envelope curves increases. At $N=10$ (blue), $u_x$ in envelope curves vibrates for a long time before approaching stable value. At $N=20$ (yellow), $u_x$ in envelope curves reaches a stable value which is smaller than the maximum value. For $N=40$ (green), $N=80$ (red), and $N=160$ (purple), $u_x$ in envelope curves increases with time and reaches a stable value. Moreover, the value difference between the three curves is little. (b) In contact analysis, the mean displacements $U_x$ of rotor decreases in the beginning and increases linearly with time subsequently.

5. Conclusion

In summary, we draw on the Shi’s structure of linear ultrasonic motor to study the relationship between the frequency of longitudinal and flexural mode and the length and width of the piezoelectric stator. We find the frequency of longitudinal mode is only dependent on the length. The frequency of flexural mode is dependent on the length and width. Based on the results, we give a new strategy to design the linear ultrasonic motor. The length is determined by the frequency of the longitudinal mode and the width is determined by the frequency of the flexural mode. In harmonic analysis, we find a suitable stiffness coefficient. In transient analysis, we find the important role of the number of substeps. Our results give a minimum number of substeps $N=40$. Finally, we use the parameters determined by the modal, harmonic and transient analysis to execute the contact analysis. The results give a constant velocity of the rotor and prove the usefulness of the simple design strategy.

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