Investigations of output performances of a V-shaped linear standing-wave piezoelectric motor

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Abstract. A V-shaped linear piezoelectric motor was constructed and the output performances were valued by the output speed and thrust force. The effects of working conditions (i.e. the applied voltage and the preload) on the output performances were analyzed. Results showed that the effects of applied voltage and preload on the output speed and thrust force are not monotonic, which is different from the previous views. The related illustration and discussion are provided as useful suggestions for further investigations. Lastly, complex factors are discussed for the output performances and service behavior of linear piezoelectric motors.

1. Introduction
Piezoelectric technology is well known for the various engineering applications especially for the detection, driver [1] and harvester [2] et al. High speed, high power, and high efficiency output are desirable for the development of transducers, actuators and motors [3]. Linear piezoelectric motors own many advantages for advanced engineering applications, which aroused the attention from different fields [4]. Specifically, standing-wave piezoelectric motors gradually come into the views for it may realize the high efficiency. Furthermore, piezoelectric motors are compact, often fitting where nothing else will, and have the nanometer resolution and direct friction drive with zero backlash [5]. These merits are critical to recommend them when traditional motor technologies fail to meet the limited space or high performance demands.

Linear piezoelectric ultrasonic motors are expected to be large output force actuators because that piezoelectric elements have the ability to put out large force [6]. Using two piezoelectric elements in an orthogonal arrangement, and several kinds of linear motors have been proposed [7]. Kurosawa et. al [8] reported a piezoelectric motor with a sandwich-type transducer, which achieved very high speed and large thrust. The output mechanical power is also larger than that of previous ultrasonic linear motors. This transducer is developed for linear actuator and is applicable to rotational motors.

As well known, there are several factors affecting the performance of piezoelectric motors. Structural design and optimization, material properties (including piezoelectric and friction materials), and the control strategies are critical to the improvement of service performances. Hitherto most literature on linear piezoelectric motors reported the optimize parameters of output performance. There is enough blank for illustration of the output performances and the service lifespan of linear piezoelectric motors. Little is known to design and illustrate the performance map of linear piezoelectric motors for different performances and different applications. This approach has led to a serious lack of global performance data for piezoelectric motors developed by different researchers.
and their groups. With the continuous improvement of the control strategy, the author believes that the motor performance testing and evaluation in the laboratory phase will require more standard and comprehensive data as a support.

2. Experimental detail

2.1. Apparatus and materials
A schematic diagram of the experimental apparatus is shown in Fig. 1. The device comprises a stator, driver, reversing arrangement and stents. The device implements replaceable contact interfaces of LUSM, which consists of the replaceable driving tip and slider. The V-shape vibrator of standing-wave motor is composed of two Langevin transducers. The triangular amplification enhances the advantages of high speed and large thrust. In this study, the driving tip made of 45# carbon steel, and the stator is made of aluminum alloy 2A12. The working principle of standing-wave linear piezoelectric motor(LUSM) is illustrated in literature [9]. According to modal and harmonic analyses, the vibration model of V-shape vibrator consists of both symmetric and antisymmetric vibrations by longitudinal tension-and-compression [10]. Symmetric vibration results in vertical vibration, whereas antisymmetric vibration results in horizontal vibration. Horizontal and vertical displacements generate the elliptical locus of the driving tip.

![Figure 1. Experimental sketch of the linear piezoelectric motor and the vibrator.](image)

2.2. Experimental methods
As shown in Fig. 1, the experimental device is composed of vibrator, shell, actuator, base and elastic connector. The V-shape vibrator is assembled in the housing made of 2A12, and the shell is connected to the base through an elastic supporting part (composed of four groups of springs, screws, nuts and gaskets). The movable nut fixed at the I-beam through the six angle screws, and the slider connected with I-beam, while the linear unit (HINWIN) fixed on the base. When the driving tip contact the slider, the movement of the slider generated through friction process, which carries a reciprocal movement of the I-beam with the slide block on the linear unit. The friction coefficient of the linear element is small, and the friction coefficient is less than 0.004. The test device controls the size of the preload by adjusting the compression of four springs. Before the tests, the stiffness coefficient of the preload spring regulated and calibrated by weight. When the pressure changes in the range of 5-30 N, the length of the spring decreases with the increase of external pressure, and the stiffness coefficient of the spring is about 5.2 N/mm. The thrust force derives from the average tangential force generated by friction, which used to evaluate the load of linear motors. At the specific driving voltage and frequency, the pull force of the spring is approximated as the output thrust of the motor, which indirectly monitors the variation of the thrust with the driving conditions.
3. Results and Discussions

3.1. Effects of applied voltage

The effect of drive voltage on output performance is shown in Fig. 2. When the driving voltage is higher than the starting voltage, the output speed of the piezoelectric motor increases linearly with the increase of the driving voltage. The thrust force increases gradually when the driving voltage is increased, but the thrust force decreases when the voltage is further increased. The output power of the piezoelectric motor increases first and then decreases with the increase of the driving voltage. The change trends of the output power and the efficiency are similar to that of the thrust. The output power gets the maximum at about 150V, and the output efficiency of the friction interface is maximum at about 140V.

The reason is that the driving voltage increases the elliptical motion trajectory, which restricts the effective boundary of the stator contact and further affects the driving characteristics of piezoelectric motors. In addition, the antifriction effect of ultrasonic vibration plays an important role in the driving process. The normal and tangential components of inertia force increase with the increase of driving voltage. From the point of view of elastic deformation coordination, the increase of normal inertia force is equivalent to the decrease of the stiffness of the contact interface, thus making the elliptical track of the contact interface fall. The friction force transmission requires greater effective friction to make the driving process. When the tangent force increases with the increase of the voltage, the dynamic boundary and the friction time of the contact processing are prolonged, and the contact intermittency between the vibrator and the slider is strongly disturbed, resulting in the drop of the output thrust.

![Figure 2](image)

**Figure 2.** Variation in the output performances of SWUM against the applied voltages.

The relations of the speed characteristics of linear piezoelectric motor and the control variables are nonlinear, which are serious problems for accurate speed control [11]. In this study, data of the output performances approval this statement.

3.2. Effects of preload

The preload has an important influence on the performance of the ultrasonic motor. The resonant frequency of stator and piezoelectric ceramic is closely related to the preload, and the resonance frequency increases with the increase of preload. In addition, with the increase of preload, the reduction of ultrasonic vibration on the contact interface decreases. Under different preload, the friction and friction coefficient between the contact surfaces are different, which ultimately changes the output performance of piezoelectric motors.

Output speed and thrust are two important characteristic parameters of piezoelectric motor. The effect of preload on the output performance of piezoelectric is shown in Fig. 3. With the established working conditions (excitation frequency and voltage amplitude given), the output speed decreases with the increase of preload. It can be seen that when the driving voltage is the same, increasing the preload reduces the output speed of the motor. Therefore, when the friction interface is designed, the
preload should be adjusted to make the motor work in the best performance state. The effect of preload on the output thrust is different from the velocity, and the output thrust increases first with the increase of preload. After reaching its critical value, the thrust will decrease with the further increase of preload.

A preload action is applied between the contact interface of the stator and the contact between the contact and the guide. When the preload increases, the contact boundary and contact area increase, to a certain extent, increase the friction force and increase the thrust force of piezoelectric motor. When the preload exceeds a critical value, the contact depth of the stator is increased, resulting in the falling of the contact and reducing the friction transfer efficiency. In addition, too much preload makes the elliptical track extrusion deformation, reduces the effective driving boundary and is not conducive to power transmission, and makes the thrust force drop.

![Graphs showing output force, speed, power, and efficiency against preload.](image)

**Figure 3.** Variation in the output performances of piezoelectric motor against the preloads.

There is a boundedness of monotone change of the output performances of linear piezoelectric motor. For instance, the output speed increased with the applied voltage. This trend is a basic common sense that is well known by many engineers and scholars. However, little known that the increase trend is not always change monotonously (see Fig. 4). It should be note that the boundedness of monotone change of output performances with the working conditions such as the applied voltage and preload. Besides, an important issue is that the reported data of output performances were discrete, which is clearly different from the engineering applications. It should provide the true curve of output performances (the output speed and/or the thrust force) with time. Based on the output performances, many issues and strategy would be necessary for further development and utilization.

![Graph showing nonlinearity change of output performance with applied voltage.](image)

**Figure 4.** Illustration of the nonlinearity change of output performance with applied voltage.

3.3. Compound effects of applied voltage and preload

Furthermore, the compound effects of the applied voltage and preload on the output performances are illustrated. For the given friction pairs and the exciting frequency, the contour maps of output performances of linear piezoelectric motors are provided, as shown in Fig. 5. Note that the variation trend of the output speed is different from that of the thrust force. It is clearly that the output speed increase with the applied voltage. For the given preload, the applied voltage has a dominant effect on the output speed. This result agrees with the aforementioned result as shown in Fig. 2. Differently, the effects of the preload and applied voltage on the thrust force are complex. The thrust force increase first and then decrease when the preload or applied voltage increase.
The greater applied voltage is, the greater the vibration displacement, the greater the ellipse trajectory. The larger the preload, the greater the indentation depth, the larger the contact region between the elliptical track and the slider. In addition, the properties of friction materials have important effects on vibration characteristics, contact characteristics and friction and wear properties, especially the elastic modulus and hardness of materials. The complex effects is illustrated in Fig. 6. In other conditions, the greater the modulus and hardness of the material, the smaller the deformation of the material, the influence of the contact action of the stator is shallow, and the local damage caused by the stress concentration of the material is small. Therefore, the excitation conditions, preload and material properties have a direct influence on the contact boundary conditions of the stator, and then influence the performance and wear behavior through the friction transfer process.

Figure 5. Compound effects of applied voltage and preload on the output performances.

Figure 6. Illustration of the complex effects of working conditions on the output performances of linear piezoelectric motors.
4. Conclusion
For the specific structure of the piezoelectric motor, the traditional view is that with the increase of driving voltage, the output speed of piezoelectric motor will increase linearly. In this study, note that the driving voltage and the preload should regulate in a suitable selection range. The monotonic increasing trend is interpreted as the local curve approximation without regarding the boundedness. In addition, the effect of the preload on the output speed is different from that of the thrust force. When the preload increases, the thrust force of the linear piezoelectric motor exhibits an upward convex parabola change, while the output speed decreases linearly. The output power and efficiency differ from the variation of output speed and thrust force. The effects of the applied voltage and the preload on the output performances of the piezoelectric motor are different. In addition, the complex effects of output performances analyzed for further application and better service.

Acknowledgments
This work was financially supported by National Natural Science Foundation of China (51705210, 51705211), China Postdoctoral Science Foundation (2016M601728), Jiangsu Planned Projects for Postdoctoral Research Funds (1601050C), and Jiangsu University Scientific Research Staring Foundation of Senior Talent (15JDG148, 16JDG037). The authors are indebted to these financial supports to accomplish this research.

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