Mechanical modeling and analysis of V-shaped LUM mechanical drift

Ranran Geng1*, Chenguang liang2, Zhiyuan Yao3, Jiacai Huang1

1 Industrial Center, Nanjing Institute of Technology, Nanjing, 211167, China
2 State Key Laboratory of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, 210016, China
*Corresponding author’s e-mail: rrgeng@nuaa.edu.cn

Abstract. The flexible clamping component is used to support the stator of linear ultrasonic motors (LUM). It distinctly improves the vibration characteristics of the motor and simplifies the structure, nevertheless brings the mechanical drift phenomenon. In order to improve the positional accuracy and structural stability of the V-shaped LUM, this paper studies the mechanical drift mechanism of the LUM with clamping component. Mechanical model of the motor with flexible clamp which occur mechanical drift is established, and the mechanism as well as control methods are analyzed. Based on the model, the mechanical drift experiments of clamping components with different stiffness are carried out. The experimental results show that the mechanical drift is obvious when the stiffness of the two flexible clamps are different, while the mechanical drift hardly occur when using the clamping components with tremendous tangential stiffness. Therefore, a kind of straight beam clamping LUM is proposed. The research indicate that the new motor has little mechanical drift, better running performance and higher structural stability, which can be used in the precision positioning of the mechanical devices.

1. Introduction
Linear ultrasonic motor (LUM) was developed since the early 1980s[1]. It is a new type of motor which uses the reverse piezoelectric effect of piezoelectric ceramics to actuate ultrasonic vibration of the stator. Through the friction between the stator and the slider, the slight vibration of the stator is converted into the linear motion of the slider. LUM has plenty of advantages such as simple structure, fast response, power self-locking, and is not subject to electromagnetic interference[2]. It can directly export linear motion and thrust, at the same time it has good control performance. Therefore, LUM has a broad application prospect in the aerospace, military equipment and many other fields[3–5].

With the perfection of the mechanism research and the structural design method, the output force and velocity of LUM has been significantly improved[6-8]. Nowadays, the stability of the construction and operation mechanism has become the research emphasis. Normally, when the LUM is powered off, the slider should be locked and motionless due to the pre-pressure between the stator and slider. But experiments show that the slider will drift a certain distance within a period of time after the motor stops running[9]. In this paper, the phenomenon is called mechanical drift of the LUM.

The mechanical drift will cause positioning error and seriously influence the accuracy of various devices[10-12]. The impacts of mechanical drift on precision motion platforms have received much attention from researchers. There are many papers study on the analysis and error compensation method of mechanical drift. Chakraborty proposed a physical mechanical drift model of the
micromachined vibratory gyroscope[13]. Then Xu and Zhou analyzed the periodic drift error and random drift compensation of the MEMS gyroscope respectively[14,15]. Leonard et al. developed the stability and drift theory of relative equilibria or mechanical systems with rigid motion symmetry[16]. Wang et al. investigated a new method to measure and compensate for the drift between the cantilevers and sample surfaces in atomic force microscope[17].

So far, the mechanism of LUM drift has not been identified due to the lack of systematical descriptions and studies. In order to improve the positioning accuracy and decrease the adverse effects of mechanical drift, the mechanism study of LUM drift is proposed in this paper. Based on a V-shaped LUM with the flexible clamp, the paper studies the mechanism of mechanical drift. Firstly, the mechanical model of drift is established according to the structure of LUM. Then the mechanism of the formation and function of mechanical drift are analyzed through the model. Analysis shows that the structure of the clamping component is the main factor affecting the mechanical drift. Then the mechanical drift experiments of clamping components with different stiffness are conducted in order to verify the theoretical results. Finally, the control method of LUM mechanical drift is put forward.

2. Drift mechanical model of LUM
The mechanical model shows that the cause of mechanical drift is about the different stiffness attenuation coefficients of the two sides of the clamps. The internal reason is about the asymmetric structure of the clamps which includes the asymmetric physical properties and the asymmetric geometry. Due to various factors such as clamping materials and processing, as well as the influence of motor operation on itself, the asymmetry of clamping on both sides resulted in the occurrence of mechanical drift after the long operation in practice. In order to prove the above analysis, clamping components with different stiffness were designed. The mechanical drift phenomenon is studied through their combined actions.

2.1. Drift mechanism analysis
There are many kinds of LUMs with various structural forms and different output characteristics. A V-shaped LUM using two sandwich-type was firstly put forward by Kurosawa[18] and then improved by some other researchers[19,20]. Figure 1 shows the structure of the improved V-shaped LUM stator. The frame, driving foot, vibration blocks and flexible clamp are all fabricated from metal materials. The design of the flexible clamping component can eliminate the clearance and friction that exist in the traditional motors and can also leads to simplification of the processing and assembly of the device. By applying the flexible clamping components, both the output velocity and the efficiency of the LUM are increased, meanwhile the running state becomes more stable. The output force, no-loaded velocity and displacement resolution are 15N, 471mm/s and 50nm respectively. It has been used in the precision motion platforms and micromanipulators[21,22].

![Figure 1. Structure of V-shaped LUM stator](image-url)
Piezoelectric ceramics have the electromechanical transfer behaviour which is characterized by creep and hysteretic effects, especially when used as actuators[23]. But the piezoelectric ceramics used in the LUM are installed between the metal vibration blocks, hence they have little creep effect on the whole structure. On the other hand, many metal structures have the phenomenon of room temperature creep. When the elastomer subjected to the constant load which is lower than the yield strength at room temperature, in addition to the elastic deformation, the deformation of the elastomer will continue to occur with the extension of time, which is regarded as one form of the plastic deformation[24-26]. From the qualitative perspective, this phenomenon of plastic deformation is mainly caused by the dislocation movement inside the metal materials. That will affect the key characteristics of precision components, the accuracy and long-term stability.

It can be speculated that the mechanical drift is related to the internal structure material creep of LUM. The room temperature creep of metal is the main and dominant factor for the mechanical drift of LUM since the most components of the LUM are made of metallic materials. In addition, the structural form of metal materials can significantly affect the mechanical drift level. Therefore, the aim of mechanical drift study is to discover the structure which has main influence on mechanical drift and correspondent influence rules.

2.2. Mechanical model
As shown in Figure 1, the structure of the V-shaped LUM indicates that the clamping component suffers most of the stress and strain in all the components, while the stiffness is the smallest. The clamping component is the easiest to occur creep, hence it is the main component to cause the mechanical drift of LUM.

Figure 2 shows the mechanical model of the LUM. The moving direction of the slider, i.e. the tangential direction is defined as the x axis, while the normal direction is defined as the y axis. According to the practical situation, pre-pressure $F_P$ along the y axis should be applied between the stator and slider. When the motor is out of running state, there is no force in the x axis. Given the electric excitation on the stator, the slider will run a linear motion along the x axis through the friction between the stator and slider. The driving force applied on the slider along the x axis is defined as $F_1$, and the reactive force applied on the stator is defined as $F_2$, which is particularly effect on the clamping component. These two forces form an equilibrating force system, resulting the motor running in a balance state. When the motor stops running, there is no acting force between the stator and the slider along the x axis. The acting force only exists in the y axis. However, as time goes by, the force exerted in the clamping component on the stator will change due to the creep of the clamping component. The balance of the stator will be broken and the contact force between the stator and the slider will be changed, leading to the movement of the slider, which is the mechanical drift phenomenon.
In order to further study the mechanical drift phenomenon of the motor, the stator structure after running is abstracted to a physical model as shown in Figure 3. In the model, the stator is assumed as a rigid structure while the two clamps are assumed as elastic components. The stator is supported by the elastic components and is subjected to the normal contact force of the rotor. One end of the elastic components is connected to the stator while the other end is fixed on the pedestal of the device.

![Figure 3. Physical model](image)

Since the actuator can only move in one direction which is defined as the x axis, therefore, the mechanical drift and the interaction between the stator and the clamping part only occur in the x direction. Assume that the stiffness in the x direction of the left and right elastic components in the initial state are $k_1$ and $k_2$, and the compression deformation are $\Delta x_1$ and $\Delta x_2$ respectively. The pressure in the x direction of the elastic component is $F$, which is the friction force between the stator and the slider. After a period of time, the material of the clamp will creep. At this time, the stiffness of the two elastic components become $k_1'$ and $k_2'$. The stator moves $\Delta x$ to the right, which is the drift distance. According to the force-balance principle, there is

$$k_1'\Delta x_1 = k_2'\Delta x_2 = F$$  

(1)

$$k_1' (\Delta x_1 - \Delta x) = k_2' (\Delta x_2 + \Delta x)$$  

(2)

Combine the above equations, $\Delta x$ can be expressed as

$$\Delta x = \frac{(k_1' - k_2')F}{k_1' k_2'}$$  

(3)

$$\Delta x = \frac{k_1' - k_2'}{k_1' + k_2'} F$$  

(4)

The stiffness attenuation coefficients of the left and right clamping components are defined as

$$\eta_1 = \frac{k_1 - k_1'}{k_1}$$  

(5)

$$\eta_2 = \frac{k_2 - k_2'}{k_2}$$  

(6)

Then there is

$$\Delta x = \frac{\eta_2 - \eta_1}{k_1' + k_2'} F$$  

(7)
In the equation, $F$ is constant. The above analysis indicates that when $\eta_1=\eta_2$, the drift distance $\Delta x=0$, and when $k_1$ or $k_2\to\infty$, the drift distance $\Delta x\to0$. Therefore, there are two methods to reduce the mechanical drift of the motor. One is to make the stiffness attenuation coefficient of the left and right clamping components equal, while the other is to increase the tangential stiffness of the clamping component.

3. Experimental analysis

The mechanical model shows that the cause of mechanical drift is about the different stiffness attenuation coefficients of the two sides of the clamps. The internal reason is about the asymmetric structure of the clamps which includes the asymmetric physical properties and the asymmetric geometry. Due to various factors such as clamping materials and processing, as well as the influence of motor operation on itself, the asymmetry of clamping on both sides resulted in the occurrence of mechanical drift after the long operation in practice. In order to prove the above analysis, clamping components with different stiffness were designed. The mechanical drift phenomenon is studied through their combined actions.

3.1. Experiments with different rigidity flexible components

According to the flexible clamping structure actually used in the LUM, three flexible components with different rigidity are processed as shown in Figure 4 and taken as experimental objects. Arc-shaped flexible components with thickness of 0.6mm, 0.9mm and 1.2mm are shown from left to right, and are recorded as 1, 2 and 3 respectively. Apparently, their stiffness is $k_1 < k_2 < k_3$. The experiments were conducted to test whether the clamps with different stiffness combinations would generate mechanical drift under the action of internal pressure.

![Figure 4. Three flexible components with different rigidity](image)

The mechanical drift experimental device of the flexible components is shown in Figure 5. One side of each component is fixed on the slider along the motion direction, while the other side is fixed on the pedestal at the same height as the slider. Both the slider and the support are fixed on a metal base plate. A glass probe is fixed in the middle of the upper surface of the slider along the direction perpendicular to the slider motion for determining the position of the slider motion. After applying pressure on the flexible components, the whole device should be immediately placed under the microscope. Then we make a mark at the tip of the probe as the initial position on the microscope screen. It can be observed from the experiment that the deformation accumulation in the process of mechanical drift in the initial minutes should account for the majority of the entire deformation. Therefore, we let the device sit for about 30 minutes, and then observe the particular position of the probe tip and made a second mark. According to the change of two marked positions, the actual displacement of the slider is obtained, which is the mechanical drift distance. The measurement results of mechanical drift distance on the microscope screen are shown in the Figure 6.
From these figures above, it is clear that the mechanical drift occurs when using different clamping components on two sides. When the device is equipped with components 1 and 2, the probe tip mechanically drifted 2.31 microns along the slider motion direction. When the device is equipped with components 3 and 1, 3 and 2, the probe tip mechanically drifted 2.31 microns and 3.65 microns respectively. Each combination applied the same force on the slider during the experiments and is measured ten times respectively. The experimental results show that the mechanical drift will occur when the arc-shaped clamping components with different rigidity along the tangential direction are installed on both sides of the slider, which is consistent with theoretical analysis.

3.2. Experiments with straight beam clamping component
Through the mechanical model and experimental analysis, we can generalize the following two schemes to control the mechanical drift of the LUM. The first is to apply the same clamping components to clamp on both sides of the stator, hoping to control the mechanical drift by ensuring
that their stiffness is exactly the same. However, due to the material, processing, assembly, motor running and other factors and influences, it is impossible to ensure the clamping components on both sides of the motor keep the same state during the operation all the time in practice.

Therefore, a second scheme that greatly increase the tangential stiffness of the clamp on one side is put forward. A new kind of clamping component which has straight rod shape is designed, as shown in Figure 7, which is recorded as part 4. Obviously, the tangential stiffness $k_4$ is much greater than that of the previous arc-shaped clamping components.

The straight beam clamping components were processed and the mechanical drift experiments were conducted to verify if it is helpful to solve the problem of drift. The experimental results show that the tip of the probe barely move after using the new straight beam clamping component, whether the clamping component on the other side is flexible or not. The pictures above showed that after using the new straight rod clamp, there are no large displacements. The mechanical drift phenomenon has been significantly alleviated.

![Figure 7. Straight beam clamping component](image)

4. Mechanical drift comparison of LUMs with different clamping components

According to the analysis of the above experimental results, it can be concluded that the straight beam clamping component structure can improve the stability of motor device. Therefore, the LUM with straight beam clamp on one side is designed to conduct mechanical drift contrast experiments with the original arc-shaped clamping components. Figure 8 is LUM stator with straight beam clamp on one side.

![Figure 8. LUM stator with straight beam clamp](image)

According to the results of frequency sweep and experimental debugging, the working frequency of the two kinds of motors are both at about 39.4 kHz. The mechanical drift experiments of the two kinds of motors were performed and compared. First, the two kinds of motors were connected to the
actuators respectively. After setting up the working frequency, the probes were stuck on the two motors rotor, i.e. the slider. Then, drive the motors run for the same period of time. When the motors stopped running, the devices were placed under the microscope immediately to observe the movement of the probe tip. The experimental device of the motor mechanical drift is shown in Figure 9, and the experimental results of motor mechanical drift on the microscope screen are shown in the Figure 10.

![Experimental device of motor mechanical drift](image)

**Figure 9.** Experimental device of motor mechanical drift

![Experimental results of motor mechanical drift](image)

**Figure 10.** Experimental results of motor mechanical drift

It can be seen from Figure 10 that the mechanical drift phenomenon of the straight beam clamp LUM has hardly occurred, while the arc-shaped clamp LUM is obvious. The mechanical drift experiment was repeated 10 times for each type of motor. By analyzing the experimental results, all the data show that the motor with the arc-shaped clamp can be found having mechanical drift of 2-4 microns, but the motor with the straight beam clamp does not drift. The phenomenon is consistent with the previous clamp drift experiments and analysis.

5. **Conclusions**
The mechanical drift phenomenon will cause positioning error and influence the stability of the high precision devices. In this paper, the mechanical drift of V-shaped LUM is deeply studied and
researched. Firstly, the mechanical model of the flexible clamp LUM stator is established and analyzed. It is concluded that the mechanical drift can be effectively suppressed by theoretically ensuring the same stiffness attenuation coefficient of the flexible clamps on both sides or using clamping components with large tangential stiffness. Then, based on the mechanical model, the mechanical drift experiments of clamping components with different stiffness are carried out. The results prove that the mechanical drift is obvious when the stiffness of the two flexible clamps are different, while the mechanical drift hardly occur when using the clamping components with great tangential stiffness. Lastly, a LUM stator with straight beam clamp is put forward. The experimental results indicate that the new type of motor can not only satisfy the basic performance of the motor, but also obviously restrain the mechanical drift, improving the precision and stability of the motor.

Acknowledgments
Authors wishing to acknowledge the Natural Science Foundation of Jiangsu Province, grant number BK20191018; the Scientific Foundation of Nanjing Institute of Technology, grant number YKJ201858.

References
[1] Sashida, T. (1982) Trial construction and operation of an ultrasonic vibration driven motor. Oyo Butsuri, 6: 713-718.
[2] Zhao, C. (2007) Ultrasonic Motors Technologies and Applications. Publisher: Beijing: Science Press, China.
[3] Izuhara, S., Mashimo, T. (2018) Design and evaluation of a micro linear ultrasonic motor. Sensors and Actuators A: Physical, 278: 60-66.
[4] Ming, Y., Richardson, R. C., Levesley, M. C., et al. (2004) Performance improvement of rectangular-plate linear ultrasonic motors cx using dual-frequency drive. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 51:1600-1606.
[5] Zhou, S., Yao, Z. (2014) Design and optimization of a modal-independent linear ultrasonic motor. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 61:535-546.
[6] Tanoue, Y., Morita, T. (2020) Opposing preloads type ultrasonic linear motor with quadruoper stator. Sensors and Actuators A: Physical, 301: 3773-3776.
[7] He, Y., Yao, Z., Dai, S., et al. (2019) Hybrid simulation for dynamic responses and performance estimation of linear ultrasonic motors. International Journal of Mechanical Sciences, 153: 219-229.
[8] Yin, Z., Dai, C., Chen, Z., et al. (2020) Modal analysis and moving performance of a single-mode linear ultrasonic motor. Ultrasonics, 108: 1227-1237.
[9] Sha, J., Yao, Z., Geng, R. (2012) Mechanical Drift of Ultrasonic-Linear-Motor-Driving Motion Platforms. Applied Mechanics and Materials, 190: 1311-1316.
[10] Li, G., Yaxian, L., Chunling, J. (2018) Numerical simulation and verification on impact damage mechanical property of drift ice on diversion tunnel. Transactions of the Chinese Society of Agricultural Engineering, 13: 17.
[11] Poulin, A., Rosset, S. (2019) An open-loop control scheme to increase the speed and reduce the viscoelastic drift of dielectric elastomer actuators. Extreme Mechanics Letters, 27:20-26.
[12] Wang, Y., Lian, Z., Cui, X., et al. (2020) Visual sensing based ultra-high precision motion control with compensated mechanical drift across different stages. IEEE/ASME Transactions on Mechatronics, 25:1422-1431.
[13] Cakrabartı, I. (1996) Analysis of mechanical drift error in the JPL/UCLA micromachined vibratory gyroscope. Massachusetts Institute of Technology.
[14] Xu, J., Zhang, H., Sun, J. (2007) Periodic error compensation for quartz MEMS gyroscope drift of INS. Chinese Journal of Aeronautics, 20: 539-545.
[15] Zhou, J., Song, C., Zhuang, H. (2011) Square root unscented Kalman filter for MEMS gyroscope random drift compensation. Journal of Central South University (Science and Technology), 42: 469-472.

[16] Leonard, N. E., Marsden, J. E. (1997) Stability and drift of underwater vehicle dynamics: mechanical systems with rigid motion symmetry. Physica D: Nonlinear Phenomena, 105: 130-162.

[17] Wang, Y., Wang H., Bi S. (2014) Real time drift measurement for colloidal probe atomic force microscope: a visual sensing approach. AIP Advances, 4: 057130.

[18] Kurosawa M. K., Kodaira O., Tsuchitoi Y., et al. (1998) Transducer for high speed and large thrust ultrasonic linear motor using two sandwich-type vibrators. IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 45: 1188-1195.

[19] Zhou, L., Yao, Z., Li, X., et al. (2019) Modeling and verification of thermal-mechanical-electric coupling dynamics of a V-shape linear ultrasonic motor. Sensors and Actuators A: Physical, 298: 111580.

[20] Li, X., Yao, Z. (2018) Analytical modeling and experimental validation of a V-shaped piezoelectric transducer with a flexible joint for generating an elliptical motion. Precision Engineering, 52: 55-63.

[21] Geng, R. R., Mills, J. K., Yao Z. Y. (2016) Design and analysis of a novel 3-DOF spatial parallel microgripper driven by LUMs. Robotics and Computer-Integrated Manufacturing, 42: 147-155.

[22] Geng, R. R., Yao, Z. Y., Mills, J. K. (2015) LUM-driven micromanipulator for cell wall perforation. International Journal of Mechatronics and Automation, 5: 86-91.

[23] Chen, C., She, C. (2015) Creep effect analysis at the friction interface of a rotary ultrasonic motor. International Journal of Applied Mechanics, 7: 1550031.

[24] Maier, V., Merle, B., Göken, M., et al. (2013) An improved long-term nanoindentation creep testing approach for studying the local deformation processes in nanocrystalline metals at room and elevated temperatures. Journal of Materials Research, 28: 1177.

[25] Daghig, V., Khalili, S. R., Farsani, R. E. (2016) Creep behavior of basalt fiber-metal laminate composites. Composites Part B: Engineering, 91: 275-282.

[26] Meraj, M., Pal, S. (2017) Nano-scale simulation based study of creep behavior of bimodal nanocrystalline face centered cubic metal. Journal of Molecular Modeling, 23: 309.