Linear Ultrasonic Motor for Absolute Gravimeter

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ABSTRACT:

Thanks to their compactness and suitability for vacuum applications, linear ultrasonic motors are considered as substitutes for classical electromagnetic motors as driving elements in absolute gravimeters. Still, their application is prevented by relatively low power output. To overcome this limitation and provide better stability, a V-type linear ultrasonic motor with a new clamping method is proposed for a gravimeter. In this paper, a mechanical model of stators with flexible clamping components is suggested, according to a design criterion for clamps of linear ultrasonic motors. After that, an effect of tangential and normal rigidity of the clamping components on mechanical output is studied. It is followed by discussion of a new clamping method with sufficient tangential rigidity and a capability to facilitate pre-load. Additionally, a prototype of the motor with the proposed clamping method was fabricated and the performance tests in vertical direction were implemented. Experimental results show that the suggested motor has structural stability and high dynamic performance, such as no-load speed of 1.4m/s and maximal thrust of 43N, meeting the requirements for absolute gravimeters.

Key words: linear ultrasonic motor, absolute gravimeter, clamping method, design

1. Introduction

A precise knowledge of the magnitude of the Earth's gravitation field and its variation is crucial for various aspects of science and technology, [1-3]. It can be acquired with a high-precision absolute gravimeter and used for earthquake prediction, exploration of mineral resources and as essential reference for aircraft navigation and missile guidance.

The absolute gravimeter is regularly placed at different locations to observe the local geomagnetic field variations, so it is best to be light and portable, [4-5]. A free-fall absolute gravimeter assesses the level of gravity value by measuring the distance and time of a free fall of a body in vacuum. Such a device is designed to produce a stable and repeatable motion of a free-falling body, [6]. Traditional absolute gravimeters commonly use electromagnetic motors as driving device, which can lead to complicated and heavy structures. Electromagnetic motors are complex structures themselves and they need also mechanical transmission components to provide rectilinear motion directly. A linear ultrasonic motor as a replacement for an electromagnetic motor as the driving device could provide a rectilinear motion directly in the vacuum without transmission components, simplifying the instrument and making it

lighter.

A linear ultrasonic motor developed in 1980s is a new type of micro motor that can be used in many fields such as aerospace and precision driving thanks to its compact structure, quick response and other advantages, [7]. In 1970s, Japanese scholars were first to suggest a travelling-wave linear ultrasonic motor [8], with an exciter and a vibration absorber to produce a travelling wave in a beam to drive a slide. However, this type of motor is inefficient since the whole beam vibrated generating excessive power loss during its operation. In 1998, Japanese scholars Kurosawa et al. proposed a standing-wave linear ultrasonic motor, composed of two mutually perpendicular Langevin transducers, [9-10]. It achieved a good output performance thanks to its simple and compact structure, high driving efficiency and an obvious vibration node as a clamping point. Since then, a standing-wave linear ultrasonic motor attracted significant attentions and was used for a V-shape linear ultrasonic motor with a continuous variable cross-section designed by Yang Dong and Yao Zhiyuan in 2008 [11]. This type of a continuous variable cross-section replaced the one with the sudden changes to improve transmission efficiency of a vibration wave in the stators [12].

Thanks to their ability of working in vacuum, ultrasonic motors can be used as driving elements instead of traditional electromagnetic motors in various extreme environments [13]. In recent years, ultrasonic motors were used in Micro-lander for Mars Exploration in United States [14]. The main reasons that NASA adopted ultrasonic motors as actuators for the joint of manipulators are that the reliability of the ultrasonic motor in a vacuum is high, and they are more stable [15-16].

However, poor output performance of current linear ultrasonic motors limits their application in absolute gravimeters. As the driving device of an absolute gravimeter, it should always be under a measured object and avoid collisions with a free-falling body. It means that its output acceleration must be greater than that of gravity in the process of moving down. Additionally, in the uplink process, the measured object should be lifted stably back to its original position, which needs a higher output power and more stable operation. In addition, to meet the market demands, the motor should also be simply to install and maintain, and the pre-load loading device should be calibrated and easily adjusted.

Designers of linear ultrasonic motors have always paid more attention to the structural design and a choice of vibration model. Still, a structure and an installation position of a clamping element, which is an essential connection component between ultrasonic motors and external parts, have a significant impact on output properties and efficiency of the motors. Early designs of ultrasonic motors used a spring as its clamping elements, and the pre-load was applied to the axis of symmetry of the stator. This clamping method had a complex structure, and the gap between components was not easy to eliminate, limiting the improvement of output performance. Furthermore, the fact that the stator had only two support points also led to instability of the motor's structure. In order to eliminate these

negative factors, Hu was first to bring a flexible hinge (arc) clamping into the structural design of ultrasonic motors in 2011, [17]. This method included moving the clamping point from the axis of symmetry to two sides of the stator and applying pre-load by the flexible arc instead of the spring. As the number of support points increased to three, the structure of motor became more stable. However, experiments showed that the levels of normal and tangential rigidity of the flexible arc clamping were of the same order of magnitude, and low tangential rigidity constrained potential improvement in terms of output power and velocity. Additionally, the deformation of the flexible mechanism could cause a drift of the motor. To further improve the output characteristics of V-shape linear ultrasonic motors so that it could meet technical requirements of the absolute gravimeter, a novel clamping method-single-end hinge clamping-is proposed. A mechanical model of stator with single-end hinge clamping is suggested, and it is proved that the clamping could provide high tangential rigidity with an appropriate normal rigidity. Based on this idea, a prototype was designed and manufactured and its output performance was compared with that of original motors in experiments. Subsequently, an absolute gravimeter with an ultrasonic motor as driving device was designed, effectively simplifying the structural complexity.

2. Structural design of linear ultrasonic motor for absolute gravimeter

2.1 Principle and structure of absolute gravimeter

A free-fall absolute gravimeter was developed rapidly in recent decades. Currently, a typical commercial absolute gravimeter usually consists of two parts: its upper part is a falling-body container while its lower part is a damping structure. Taking A10 Absolute Gravimeter produced by Micro-g LaCoste of USA as an example, in its falling-body container, a three-side corner cube is used as a test object. When it begins to fall freely from the top of the chamber, a light source from a stable wavelength laser device is split and partly reflected from the corner cube. A photosensitive diode detects the untreated fringe signal reflected parallel by the corner cube. These signals can be calibrated for the corresponding time and distance, so that the level of acceleration of the test object (i.e. the acceleration of gravity) can be obtained. A schematic of process is shown in Fig. 1.

Figure 1. Measurement principle(modified after[3])

The falling-body container is a vacuum chamber, which includes the test object, the drag-free cart and mechanical transmission devices (Fig. 2). For A10 Absolute Gravimeter, a servo motor used as driving element is installed outside of the vacuum chamber because it cannot operate in vacuum, and the drag-free cart is driven by it through a shaft.

Figure 2. Schematic diagram of falling-body container

To further simplify the structure of absolute gravimeter, it is proposed to adopt ultrasonic motors instead of traditional ones as a driving element. It can be placed in the vacuum chamber and drive the drag-free cart directly. In this case, the mechanical transmission devices can be removed, reducing considerably the structural complexity and making the instrument lightweight and portable. A structure of the novel absolute gravimeter is presented in Fig.3. A stator of the ultrasonic motor is installed on the base of the vacuum chamber to drive the slide guide used as a rotor. The drag-free cart is fixed on the slide guide. When the test object falls, the drag-free cart drops with an acceleration more than g at first and always maintains its position below the test object in the whole downlink process. When the test object reaches the bottom of the vacuum chamber, the drag-free cart should catch it gently and uplift it back to

the initial position stably. This requires for the output force of ultrasonic motor in the uplink process to exceed the weight of test object (about 20N).

Figure 3. Structure of novel absolute gravimeter with linear ultrasonic motor

In summary, as driving element of the absolute gravimeter, the linear ultrasonic motor should reach the following technical requirements:

1. A falling distance is 50 mm.
2. The drag-free cart maintains its position below the test object in downlink process.
3. The output thrust of the ultrasonic motor in the uplink process should be more than 20 N.
4. The ultrasonic motor can stably operate in vacuum.
5. It is easy to install, remove and maintain the motor.

2.2 Structure design of linear ultrasonic motor for absolute gravimeter

Existing V-shape linear ultrasonic motors could not meet the requirements of the driving element for the absolute gravimeter. In fact, their insufficient output characteristics of prevented their application in many fields [18-19]. In order to solve this problem, many researchers focused on the structural design and mode selection of the stator [20], while less attention was paid to the clamping method of the stator that also affects significantly the output performance of the ultrasonic motor.

As an essential component connected to external parts, the clamping element is used to support the structure of the stator, ensure flexibility of its contact with external parts. The structure and installation position of clamping has a significant effect on the output characteristics and the stability of ultrasonic motor. The existing research shows that with appropriate normal rigidity of the clamping element, an increase in its tangential rigidity could improve the motor's output performance [21].

According to a design criterion for clamping elements, and also taking a simple and easy-to-test method for applying pre-load into consideration, a novel clamping method of a

V-shape motor - a single-end-hinge type clamp-is proposed.

Figure 4. Overall structural design of motor

As shown in Figure 4, a stator of the V-shape ultrasonic motor is formed by two mutually perpendicular continuous variable-section Langevin transducers. When the motor is in operation, the transducers A and transducer B are excited by two sinusoidal signals with the same frequency and a 90° phase difference. The vibration modes excited by these signals result in an elliptic motion of the stator's driving foot. The driving foot of the stator is pressed on the slider under a certain pre-load. In the upper half of the elliptic motion, the driving foot is in contact with the slider to drive it into linear motion. While in the lower half of elliptic motion, the slider is not in contact with the driving foot, but continues moving forward due to inertia. By repeating these sequences, the elliptic motion of the stator can be converted into the linear motion of the slider [22]. An opposite motion can be achieved when reversed excitation signals are applied. It is clear from Fig.4 that the clamping element consists of a stator support, a fixed hinge end and a pre-load applying end. Stretching of a spring can be changed by adjusting a bolt, controlling the level of pre-load. Before the motor is operation, the pre-load between the stator and the slider can be applied by tightening the bolt to rotate the stator support around the fixed hinge end. This clamping method can improve vibration characteristics and structural stability of the motor, and increase its output power and efficiency as well. Besides, it is convenient to apply and adjust pre-load according to various occasions and requirements, thus improving controllability of the motor.

2.3 Mechanical modal of single-hinge-end clamp

To illustrate feasibility of the single-hinge-end clamp, its mechanical model is considered. As shown in Figure 5, connecting a hinge fulcrum, a contact point of the stator and the slider, and the point of action of pre-load loading forms a triangle rotating around the hinge fulcrum.

When force F was exerted on the pre-load loading end, pre-load F_n would be applied to the contact point of the stator and the slider. A distance between the point of action of the pre-load loading end and the hinge fulcrum is equal to $2l$, and the sides of the isosceles triangle are connected at angle α .

Figure 5. Mechanical model of novel clamping element

Let the value of the spring's rigidity be K , and assume it is placed at the angle of 45° with axis x (Fig.5). Then its elongation of is

$$d = \frac{F}{K} . \quad (1)$$

Application of tangential force F_t to the driving foot would produce tangential displacement S_t . So, tangential rigidity of the system can be defined as

$$K_t = \frac{F_t}{S_t} . \quad (2)$$

From the moment balance condition

$$F_t \cdot h = F \sin 45^\circ \cdot 2l . \quad (3)$$

At this point, the triangle would rotate around the hinge fulcrum and produce a small angle, $\Delta\alpha$. According to the relationship between displacements and employing the arc-length formula, we obtain

$$\frac{l}{h} = \frac{s}{S_t} \cdot \frac{d}{\sqrt{2}l} . \quad (4)$$

Then, the relationship between tangential rigidity and that of spring can be deduced

$$K_t = \frac{2l^3}{\sqrt{l^2 + h^2} h^2} K . \quad (5)$$

Applying a similar procedure to a case of normal force F_n , the relationship between normal rigidity and that of spring can be obtained

$$K_n = 2K \quad (6)$$

The above analysis shows that normal rigidity of the single-hinge-end clamp is constant, and two times higher than rigidity of the spring. Tangential rigidity is related to distance h between the contact point of the stator and slider and the hinge fulcrum, as well as distance $2l$ between latter and the point of action. Considering the overall size of the stator, for a given l , tangential rigidity increases as h decreases.

3. Assessment of output performance

Based on the theoretical analysis above, and taking both the structure dimensions and installation requirements into account, a prototype ultrasonic motor with a single-hinge-end clamp was designed and manufactured (see Fig.6).

Figure 6. Prototype motor

To test the output performance of the new motor and compare it with that of the flexible-arc clamping motor (shown in Fig.7), experiments were performed with a special set up presented in Fig.8.

Figure 7. Flexible-arc clamping V-shape motor

In tests with this set up, the motor was installed on the motion platform and a linear

guide was used as a slider. When the slider was driven by the motor, a laser speed sensor placed on the motion platform recorded the speed of the slider and sent it to a computer. The output speed of the motor was measured for various pre-loads, driving frequencies and loads. In order to obtain the output thrust, a fixed pulley was installed on the motion platform. A rope was used to connect the slider and the weights; the latter were considered to be equal to the output thrust. The output power was also measured alongside the thrust.

Figure 8. Experimental setup

The effect of pre-load on output velocity and thrust of a motor with a top-top voltage of 350V was studied, the respective results are presented in Figure 9.

(a)

(b)

Figure 9. Effect of pre-load on output velocity (a) and thrust (b)

Apparently, with the same voltage and pre-load, the levels of output velocity and thrust of the novel one-end-hinge motor are higher than those of the original one. For instance, at the pre-load of 85N, the no-load velocity of the proto type motor reached its maximum magnitude of 955mm/s, nearly 2.7 times larger than that of the original motor. While the highest output thrust of 43N was achieved at pre-load of 175N; it was 2.15 times higher than the original one. These results showed vividly that the improved design for the clamping method was efficient.

For the case of pre-load is 85N, corresponding to the highest no-load velocity of the motor, the relationship between the output thrust and output velocity is presented in Fig.10.

Figure 10. Relation curve between output thrust and output velocity

Maximum power of the novel motor reached the level of 20W with the input voltage being 350V, and the corresponding current was measured to be 0.25A, the efficiency of motor reached 32.3%.

According to Figures 9 and 10, the level of errors of output performance was smaller with a pre-load in a range between 65 N to 175 N. That is because the parasitic vibration was more prominent at low pre-loads, while the used vibration was restrained when the pre-load was too large. Hence, employing pre-loads from the optimal range could improve the operation stability of the motor. To confirm the output performance of the novel motor, more experiments were conducted as described below.

Asymmetry of the novel clamping method may lead to different output performances of the motor in two directions, and, as a result, affect its application. So, a comparative experiment of output velocities for the two directions was conducted. The relations between the output velocity and frequency for two directions are shown in Figure 11 with the input voltage of 350 V and the pre-load of 85 N.

Figure 11. Relation between output velocity and frequency for two directions

According to Figure 11, asymmetry of the one-hinge-end clamping method affects the output velocities for two directions, but the difference is not considerable. Actually, there are many other factors influencing the velocity difference for these directions, e.g. roughness of contact surfaces. This directional difference cannot be avoided even for completely symmetrical motors. Still, the suggested ultrasonic motor can operate with a high speed in both directions in a large range of frequency, hence, it can meet different requirements of operation.

For practical applications, the level of output power of the motor is not the most important technical parameter. Its stability, tunability and performance under loads play a more important part.

The output velocity and output thrust measured at various frequencies for different levels of pre-load of 85 N, 120 N and 150 N are shown in Figure 12.

(a)

(b)

Figure 12. Effect of frequency on output velocity(a) and thrust(b) at various pre-load levels

Figure 12 demonstrates that the exciting frequencies necessary to achieve best output performance of the motor differs somewhat at various pre-load levels. Generally, the motor can operate stably in a frequency range between 39.5 to 41.5 kHz. In summary, the range for both exciting frequency and pre-load for the novel motor are sufficiently large. So, the novel motor can meet different operation requests by fine-tuning these two parameters for various applications.

Subsequent tests studied performance of motor under load; pre-loads of 85 N and loads of 10 N and 20 N were selected. The measured output velocities for various frequencies are shown in Figure 13.

Figure13. Relation between output velocity and frequency at various loads

For the case of the 10 N load, the output velocity of the motor could stably exceed 300 mm/s within the exciting-frequency range between 39 to 41.5 kHz. For the exciting frequency between 39 to 40 kHz, the output velocity could even be higher than 500 mm/s. Although, increasing the load to 20 N led to the decrease of the output velocity, the motor could still operate stably in a rather large range of the exciting frequency; the small level of errors of the output velocity showed that motors operated stably. All the obtained results demonstrated that the novel motor could perform well under loads.

As the stroke of the linear guide and the measurement range of the laser speed sensor used in the tests were limited, the obtained output velocity of motor is not the maximum value. It was proved with further speed-testing experiments conducted. The motor was installed on a platform to drive a rotor, and a rotating speedometer was used to measure the motor's velocity after achieving a stable operation regime. The results showed that the highest velocity of the motor without load was 1400 mm/s.

As the driving element of an absolute gravimeter, the ultrasonic motor will be used to provide a motion in a vertical direction. So the output performance of the motor in this direction was measured. With a falling distance of 65 mm, input voltage 350 V and pre-load 85 N, the respective velocities of the slider and the free-falling body were measured and presented in Figure 14.

Figure14. Velocities of slider and free-falling body in downlink process

Figure 14 demonstrates that when the free-falling body falls in the downlink process, under the combined effect of gravity and output thrust, the slider drops with an acceleration higher than g at first, hence its speed increases rapidly. The resistance increases with speed, so the slider's acceleration decreases, with its speed eventually becoming constant. But the falling distance is limited. With the slider's acceleration decreasing and the maintained acceleration of the free-falling body, the distance between them decreases. Still, in the whole downlink process, the slider can always maintain its position below the free-falling body. Since the motion of the slider has no effect on the fall of the free-falling body, accuracy of the measured acceleration of gravity can be guaranteed.

For the uplink process, the slider should uplift the body back to its initial position stably to conduct a next experiment. In our test, a load of 20 N is applied to the motor to imitate gravity of the free-falling body. The relation displacement-time in the uplink process is shown in Figure 15.

Figure15. Relation between displacement and time in uplink process

According to Figure 15, the motor can drive the slider back to its initial position with a 20 N load. It demonstrates that in the uplink process, the motor can overcome the gravity of the free-falling body, and uplift it stably back to its initial position for the next measurement.

In summary, compared with the original flexible-arc clamping motor, the single-hinge-end clamping motor has a better output performance, higher stability and tenability; its performance at loads and in vertical direction also improved. Thus, the novel motor can be used as the driving device of the absolute gravimeter.

4. Conclusions

Aiming to resolve the limitations related to free-fall absolute gravimeter, such as the complex structure and its large size, a novel absolute gravimeter based on an ultrasonic motor was proposed. In order to meet the technical requirements of the driving device for the absolute gravimeter and improve the output performance of V-shape ultrasonic motors, a novel clamping method, based on a single-hinge-end scheme, was suggested. Its mechanical model proved theoretically that it could meet the design criterion and improve the output performance of the motor. Considering the overall motor's dimensions and challenges of its installation, a prototype was designed and manufactured, and a series of experiments was performed to compare it with the original motor. The experiments showed that the suggested single-hinge-end clamp effectively improved the output characteristics of ultrasonic motors. The achieved maximum output force was 43 N, and the maximum output velocity 1.4 m/s. The motor can also provide a stable motion in vertical direction. Besides, the new motor is convenient to install and adjust, and it fully meets the requirements for the driving device of the absolute gravimeter.

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