Review

A review of long range piezoelectric motors using frequency leveraged method

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ABSTRACT

This paper provides a comprehensive review of the literature regarding precision piezoelectric motors over long ranges based on the principle of repeating a series of small periodic step motions, named “frequency leveraged motors” in this paper. A summary of recent research into frequency leveraged motors is presented. Work is classified into three categories by different frequency driving methods, including ultrasonic motors, quasi-static motors (non-resonant motors), and motors combined resonant and quasi-static operations. Pros and cons of each motor type are discussed in term of their principle, structure, and performance. In addition, future perspectives and improvements of the frequency leveraged motor are also provided. It is summarized in such a way can provide a better understanding of the core characteristics of each type of long range piezoelectric motor. Moreover, it also aids in determining successful designs, suitability for applications and further research areas.

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1. Introduction

A piezoelectric motor is a device that creates a linear or rotary motion by means of converse piezoelectric effect. It aims to move an object over a certain distance with a high resolution and accuracy [1–6]. Piezoelectric motors with long motion range, high resolution, compact size, high speed and high bandwidth are desired in various applications, such as the manipulation of biological specimens, semiconductor equipment, optical element alignment and measuring instruments.

The piezoelectric motor usually works with the piezoelectric actuator to achieve long motion range [6]. Piezoelectric actuators refer to actuators made of piezoelectric materials such as lead zirconate titanate (PZT), which can provide motion with extremely fine resolution (sub-nanometer) but with a small travel range (several micrometers) [6]. To overcome this drawback, a number of efforts have been made for magnifying the output displacement of PZTs. Basically, there are three different displacement amplifying methods: internally leveraged method, externally leveraged method, and frequency leveraged method [2]. The internally leveraged method uses the internal structure of the PZT to generate amplified displacement, while the externally leveraged method uses the external mechanical component to amplify the displacement of the PZT. The frequency leveraged motor amplifies the displacement by using the frequency performance of the PZT to drive the motor in a series of small steps. A typical application of the internally leveraged method is the stacked multilayer PZT [3–10]. However, the travel range of stacked PZTs is still limited (several tens of micrometers order). Thus, to improve displacement of the PZT, externally leveraged mechanisms have been widely employed using amplification mechanisms. The typical type is the compliant mechanisms, which are flexible monolithic structures that transmit motion and/or force through elastic body deformation mechanisms. Flexure hinges are usually utilized as a displacement amplifier in these mechanisms to enlarge the stroke of the PZT [11–14]. Even though the flexible mechanism can realize nanometer and relatively large motion ranges, the amplification factor of the mechanism stroke is limited, resulting in difficulty achieving further larger motion ranges (such as millimeter level). In addition, such a mechanism for long travel range not only needs a large size of magnification mechanism, but also requires long PZTs with necessary strokes [15–17]. On the other hand, the actuating technique of a frequency leveraged motor is to drive the moving element by repeating the step motion of the PZT itself. By accumulating the displacement over many periods of the driving voltage applied to the PZT, it can generate long range movement through repetition and accumulation of micro-deformations of the PZT. Compared with the internally leveraged and externally leveraged methods, frequency leveraged motors can provide longer travel ranges (millimeters or more) without increasing the internal structure of the PZT or using external amplification mechanisms. Therefore, frequency leveraged motors have great potential to be designed with a simple structure and a compact size, which might be attractive for long travel range applications in micro-surgery, insect scaled robots and micro-positioning stages [18].

In this paper, frequency leveraged motors are classified into three groups by their frequencies of operation: ultrasonic motors, quasi-static motors (also called non-resonant motors), and motors combined resonant and quasi-static operations. Usually, an ultrasonic motor utilizes the mechanical resonance at high frequency to increase output motion, whereas quasi-static motors are operated at low frequency with a stable response [19,20]. The motor combined resonant and quasi-static operations is an emerging motor which utilizes the advantages of both operations by merging them into a single system. The whole classification system of frequency leveraged motors is shown in Fig. 1. Based on different wave propagation methods, the ultrasonic motors can be classified into standing wave type motors and traveling wave type motors. On the other hand, quasi-static motors are based on either the clamping drive principle or the inertia drive principle [19,20]. In the clamping drive principle, the motor is driven by clamping and feeding PZTs step by step. The typical motors of this type include inchworm mechanisms, seal mechanisms, and walking drive mechanisms. In the inertia drive principle, inertia and friction force are utilized to drive the motor over a long motion range. Two typical types of inertia motors are impact drive mechanisms and smooth impact drive mechanisms.

Correspondingly, this paper is organized as follows. In Section 2, piezoelectric ultrasonic motors are classified into standing wave type motors and traveling wave type motors. In Section 3, quasi-static motors are categorized into two main types. One is clamping and feeding mechanisms, which include inchworm mechanisms, seal mechanisms, and walking drive mechanisms. The other is inertia drive mechanisms, which include impact drive mechanisms and

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**Fig. 1.** Classification of frequency leveraged motors.

<table>
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<th>Frequency leveraged motors</th>
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<tr>
<td>Ultrasonic motors</td>
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<tr>
<td>Standing wave</td>
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<td>Quasi-static motors</td>
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<td>Clamping drive</td>
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<td>Motors combined resonant</td>
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<td>Impact drive mechanisms</td>
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<td>Smooth impact drive</td>
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<td>Inchworm mechanisms</td>
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<td>Seal mechanisms</td>
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<td>Walking drive mechanisms</td>
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<tr>
<td>Resonant and quasi-static</td>
</tr>
<tr>
<td>Operations</td>
</tr>
</tbody>
</table>

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smooth impact drive mechanisms. In Section 4, we introduce several motors combined resonant and quasi-static operations which attempt to utilize their advantages but mitigate their weaknesses. Conclusions and future research directions of frequency leveraged motors are given in Section 5.

2. Piezoelectric ultrasonic motors

2.1. Principle of the piezoelectric ultrasonic motor

An ultrasonic motor is a motor powered by the ultrasonic vibration excited at resonance. This vibration energy can produce a driving force to a stator. A rotor or slider, placed against the stator, can be then driven by using the frictional contact between the stator and the rotor/slider. The displacement of an ultrasonic motor can be accumulated by converting the vibrations into the motion of the rotor/slider.

A piezoelectric ultrasonic motor obtains a standing wave or traveling wave (surfing wave) produced by resonantly excited PZTs. Hence, piezoelectric ultrasonic motors can be divided into two groups according to wave propagation methods, standing wave type motors and traveling wave type motors. To induce the mechanical movement for rotating or sliding motion, an elliptic motion of the stator should be formed by mechanical waves. As shown in Fig. 2(a), the stator of a standing wave type motor is composed of a PZT and a vibratory piece. The vibratory piece generates bending and the PZT is excited with alternating voltage, resulting in elliptical trajectories at the tip of the stator. From A to B, the stator contacts to the slider/rotor and thus pushes the slider/rotor for slight movement. From B to A, the stator is released from the rotor, and no movement is transmitted to the slider/rotor. Therefore, long range traveling can be achieved by repeating the elliptic motion.

Fig. 2(b) shows the principle of a traveling wave type motor. Unlike the standing type motor which utilizes one elliptical motion generated in the stator, every point on the stator face of the traveling wave type motor follows an elliptical trajectory. Therefore, a surface particle of the contact surface of the stator can draw an elliptical locus and cause intermittent movement of the slider/rotor. Generally, a traveling wave can be generated by combining two standing waves with 90° phase difference. Traveling wave in the opposite direction can be generated by changing the phase difference to −90°.

2.2. Standing wave type motors

2.2.1. Different vibration modes of standing wave type motors

Since different resonant vibration modes are the basis of design for standing wave type motors, the classification according to the vibration modes is thought to essentially reflect the characteristics of these motors. In general, typical vibration modes used in standing wave type motors can be classified into five major categories as follows.

(1) Circumferential bending vibration mode

Fig. 3(a) shows the circumferential bending vibration mode of a membrane-like stator. The stator is usually coated with an exciting PZT. When the PZT is excited at the resonant mode, the axial displacement of the stator vibrates as a function of the circumferential. Motors of Sashida’s type belong to this category.

(2) Bending vibration mode

Bending vibration mode is characterized by bending deformations perpendicular to a longitudinal axis of the stator (see Fig. 3(b)).

(3) Radial vibration mode

As shown in Fig. 3(c), in the radial vibration mode, the displacement of the stator is in the radial direction. Generally, to achieve elliptical motion, radial modes are always combined with bending modes.

(4) Longitudinal/axial vibration mode

The displacement of the longitudinal vibration mode is in the axial direction (see Fig. 3(d)). Longitudinal vibration modes are usually combined with torsional or bending modes.
(5) Torsional vibration mode

Fig. 3(e) shows the mode of the torsional vibration. It is angular vibration excited by shear deformation of the upper part of the stator. Torsional vibration modes are commonly used in combination with other orthogonal modes.

2.2.2. Standing wave type motors of different composite vibration modes

In general, the elliptical motion of standing wave type motors is usually created by coupling at least two vibration modes. Therefore, the standing wave type motors in this paper are classified based on the way of combination of different vibration modes.

(1) Motors using orthogonal bending vibration modes

As shown in Fig. 4, two orthogonal bending modes of the beam can be isolated by driving the PZT at the correct frequencies. For example, a single PZT with multiple electrodes can be employed in this structure. When the electrodes are driven by two driving signals simultaneously, two orthogonal bending modes are created. Therefore, the tip of the beam rotates with an elliptical path in the X-Y plane. The rotation direction can be reversed by reversing the phase of the electrical sources.

The first bending vibration type ultrasonic motor was developed by Kurosawa et al. [21]. In their research, the motor was constructed by using bending vibrations of a short cylinder with free–free ends. The motor was designed to have a size of 20 mm in diameter and about 75 mm in length. It could also realize a high mechanical output of more than 1 W. Its revolution speed without load was 200 or 300 r/min. This motor had been widely used in the auto focusing model of Canon’s “EOS” camera series.

Subsequently, Morita et al. used a thin-film PZT deposited by a hydrothermal method onto the surface of a titanium tube and then successfully developed a cylindrical ultrasonic motor (2.4 mm in diameter and 10 mm in length) [22]. Electrodes were formed in four places on the PZT layer in a circumferential direction to excite bending vibration modes. The rotor on the stator could achieve bidirectional movement with maximum revolution speed of 295 rpm. Furthermore, Morita et al. improved this design in 2000 [23]. The thin-film PZT was deposited by the hydrothermal method on a small tube as before. By using an “improved nucleation process”, the dimensions of the stator were miniaturized to be 1.4 mm in outer diameter, 1.2 mm in inner diameter, and 5.0 mm in length. Therefore, with a 17% volume of the previous motor, the smaller motor can achieve a maximum velocity of 680 rpm and a maximum torque of 0.67 µNm.

In collaboration with Samsung Electromechanics, Korea, Koc et al. [24] proposed an alternative bending mode motor by using two orthogonal bending modes of a hollow cylinder. The outside surface of the cylinder is flattened on two sides at 90° to each other. Two rectangular piezoelectric plates were bonded on each surface, respectively. Since the cylinder combined the circular and square cross sections, the stator had two degenerated bending modes of slightly different resonance frequencies. Therefore, both modes could be excited when only one PZT plate was excited at a frequency between the above two bending modes. Then, an elliptical motion could be generated at the stator tip, and the rotation direction could be reversed by exciting the other PZT element. Another commercial product is the SQUIGGLE motor developed by New Scale Technologies [25]. Four PZTs of the motor were attached to a nut (stator), with a mating screw (shaft) inside. By using orthogonal bending modes driven by the PZTs, a wobbling motion could be created in the nut, which could be converted to a linear displacement through the screw. According to Newscale’s reports, the SQUIGGLE motor has found applications in medical devices, lab-on-chip microfluidic pumps, and micro optical instruments.

(2) Motors using longitudinal-bending composite vibration modes

The working principle of a longitudinal-bending ultrasonic motor is shown in Fig. 5. By combining a longitudinal and a bending vibration mode, a desired elliptic motion can be produced. Tomikawa et al. proposed a linearly self-moving longitudinal-bending ultrasonic motor in 1989 [26]. The first longitudinal and fourth bending modes were utilized to form a multi-mode vibrator. Therefore, elliptic motion in the same direction could be generated at both ends of the vibrator. In 1990, Ohnishi et al. developed a π-shaped linear ultrasonic motor [27]. Two multilayer PZTs were fixed at the two leg parts of the π-shaped frame. When the two PZTs were driven with a 90° phase difference, longitudinal and lateral bending modes of the leg parts could be stimulated. As a result, an elliptical motion was synthesized to drive the guide rails of the motor.

To realize miniaturization of ultrasonic motors, Suzuki et al. [28] developed a new type piezoelectric micro motor which employed a flat spring to adjust contact conditions. The structure had miniaturized the motor to as small as 2 mm in diameter and 0.3 mm in height. The stator with three cantilever oscillators glued to three PZTs had a flat configuration. When a PZT stimulated vibration and flexion of the cantilever oscillator, elliptical movements at the free
end of the cantilever oscillator could be created and transferred to the rotor. The micro motor could be operated at approximately 1800 rpm at 14 Vp-p when the contact pressure was set to be 1.6 MPa.

A different use of a longitudinal-bending coupling vibration mode was proposed by Aoyagi et al. [29]. In their design, the stator consisted of a stainless steel vibrator sandwiched between two thin PZT plates. As the PZTs excited the fundamental axial and second order bending modes in the vibrator, an elliptical motion could be delivered at the contact point with the rotor. With a stator vibrator 0.55 mm thick, a shaft 1.5 mm in diameter could be driven over 8000 rpm.

(3) Motors using longitudinal-torsional composite vibration modes

Fig. 6 shows the operation principle of a longitudinal-torsional ultrasonic motor. Longitudinal vibration in the axial direction and torsional vibration in the circumferential direction are excited simultaneously. As a result, an elliptic motion is generated at the tip of the stator. An example of this class was developed by Kurosawa et al. in 1991 [30]. The stator consisted of two kinds of PZTs which were driven by separate electric signals. One PZT was operated in the torsional vibration mode to drive the rotor, and the other was operated in the longitudinal vibration mode to control the frictional force. The vibration displacement of the latter is perpendicular to that of the former, and they were excited simultaneously. Therefore, an elliptical motion was produced at the end of the stator. Unloaded speed of the motor was measured to be 100 rpm, and the maximum output torque was 7 kg cm.

The design by Watson et al. [31] is a recent example of this class of motors. The motor used coupled axial-torsional vibration derived from a helically cut stator. The stator was a metallic tube with diameter of 0.25 mm and length of 1 mm. The motor could be driven at a maximum angular velocity of 1295 rpm with a torque of 13 nNm. The proposed micro motor could be used in areas of “in vivo” surgery and micro-robotics.

Compared with other kinds of ultrasonic motors, a longitudinal-torsional hybrid ultrasonic motor has merits of larger torque and stability at lower speeds. It has good controllability and drives the motor precisely, so it is suitable for use in some potential fields, such as aeronautics and astronautics. However, the coupled axial/torsional hybrid design is complex and difficult to fabricate, making them unsuitable for use as a micro/milli-scale motor.

(4) Motors using radial-bending composite vibration modes

Compared with the longitudinal-bending ultrasonic motors, a radial mode of a radial-bending ultrasonic motor is used instead of the longitudinal mode. As shown in Fig. 7, combined with a bending vibration mode, a radial-bending ultrasonic motor usually employs a ring-like structure to vibrate in the radial direction. Therefore, based on the similar principle as a longitudinal-bending motor, the elliptic motion is generated in a specified direction which is dependent on the bending vibration mode.

An example of a radial-bending spherical motor was proposed by Aoyagi et al. [32]. In their research, the motor was designed with a sandwich structure in which a spherical rotor was held by two stators. A disk shaped vibrator could excite a radial vibration mode and two bending vibration modes. The three vibration modes were perpendicular to each other. By combining the radial vibration mode and one bending mode, the spherical rotor could rotate around X- or Y-axis. In addition, Z-axis rotation could be generated by combining the two bending vibration modes. The spherical motor was suitable for use in multi-degree-of-freedom (multi-DOF) joints of robots or manipulators.

In 2011, Lu et al. put forward a rotor-embedded-type spherical motor [33]. Unlike the former sandwich structure, a single annular stator vibrator was fabricated with a spherical inner surface in their novel design. The rotor is embedded into the center of stator to rotate around three axes. With a monolithic construction, the motor used fewest components to realize a simple, lightweight, compact structure. Compared to the sandwich-type motor, this novel one could eliminate harmful vibration without any support and preload components for the stator.

In addition, there are standing wave type motors based on some other composite vibration modes such as torsional-bending vibration mode [34], longitudinal-shear vibration mode [35] and radial-torsional vibration mode [36]. Therefore, compared with the traveling wave type motors, standing wave type motors are superior in their various design and construction. The structure of them is less complicated and more suitable for miniaturization. It should be noted that the comparatively large outputs of this type are obtained by the piezoelectric strain amplified at resonance, which varies with different vibration modes. The speed of operation is also determined by the resonant conditions. The service life operated at resonance of the motors should also be considered during design.

2.2.3. Multi-DOF standing wave type motors

As elaborated above, a single-DOF motion is excited by a coupling vibration mode, which usually needs two resonance vibration modes excited simultaneously. On the other hand, a multi-DOF ultrasonic motor is driven by a single stator with several coupling vibration modes. It is required multiple resonance vibration modes (three or more) to generate several different coupling vibration modes (two or more), resulting in multi-DOF motion
correspondingly. Therefore, compared with the multi-DOF motion by superposing several single-DOF motors, a multi-DOF ultrasonic motor has a simple and compact structure, which is desired in many micro-mechatronic systems.

Considerable work has been done in an attempt to realize multi-DOF ultrasonic motors. The most common multi-DOF ultrasonic motors are planar, cylindrical and spherical types. Planar type ultrasonic motors, also known as surface motors, can generate two (XY motion) or three (XYθ motion) DOFs in a flat and damping free surface. They are preferred in the applications of planar micro-positioning. Many researchers used only composite longitudinal-bending vibration modes to move the motor straight in any direction on the XY plane [37,38]. A cylindrical type ultrasonic motor is a 2-DOF motor which can move along and around the Z-axis. A lot of research has been done to realize linear and rotary motion. One example of this was proposed by Iwatsuki et al. [39]. The stator reported in their research could move a shaft along and around the Z-axis by combining different longitudinal and bending modes of the corresponding PZTs. However, a pair of identical ultrasonic motors was employed in the design and might increase the total volume. In 2009, a compact ultrasonic motor with a cubic stator with a through-hole was proposed by Mashimo et al. [40]. The stator consists of a metallic cube with four PZTs adhered to its sides. The rotary motion was generated by a vibration mode which excited three waves along the circumference of the through-hole. The linear motion was generated by combining the first longitudinal mode and the second longitudinal mode. Later, the design was also miniaturized by Mashimo et al. in 2014 [41]. The volume of stator was design to be approximately 1 mm³, which was one of the smallest among currently existing motors. Spherical type ultrasonic motors are widely used in spatial positioning applications. A ball is used in this type as the rotor. There are several methods to construct a spherical type motor. Takemura et al. developed a bar-shaped ultrasonic motor capable of generating rotations of a spherical rotor around X-, Y- and Z-axis [42]. Rotation around the X- or Y-axis was excited by combining a longitudinal vibration mode and a bending vibration mode, while the rotation around Z-axis could be produced when the two bending modes (one in Z-X plane and one in Y-Z plane) were combined. In Aoyagi et al. research [43], three bending vibrations were applied to rotate a spherical rotor. Rotations in three orthogonal directions could be realized by combining two of the three bending vibrations. Aoyagi et al. also modified this design by using two composite radial-bending vibration modes to rotate the spherical rotor around the X- or Y-axis, and by combining two bending vibration modes to generate Z-axis rotation [32]. They also further advanced the motor to be an all-in-one structure in 2011 [33].

Tables 1 and 2 summarize the performance data of the reviewed standing wave type motors. Classification in such a way can provide a good understanding of the operating principle, construction, applications and performance of standing wave type motors.

2.3. Traveling wave type motors

The most famous type of the traveling wave type motors are known as “surfing” motors. In the influential work of Sashida [44], the travelling wave was induced by a thin piezoelectric ring. A ring-shaped elastic body was bonded to the piezoelectric ring. A ring-shaped rotor in contact with the elastic body could be driven in both directions by exchanging the sine and cosine voltage inputs. The rotor could be driven continuously by the traveling wave and the abrasion on the contact surface could be decreased. Compared with conventional electromagnetic motors, this motor could be silently driven with a propagating wave frequency of 44 kHz without any reduction mechanism such as gears. In addition, the thin design of the motor made it suitable for integrating into a camera as an auto-

focusing mechanism. In 1985, Canon installed the motor compactly in its EF 300 mm f/2.8 L lens. Most of Canon’s “EOS” camera series have already been replaced by the ultrasonic motor of Sashida’s type [45].

The “surfing” traveling wave type motors can provide high speed and high output force operation due to the small amplitude and high frequency waves. However, the complex design limits their miniaturization to a scale of a few millimetres. For example, without a sufficient buffer gap between the adjacent electrodes, electrical poling process easily initiates cracks on the electrode gap due to the residual stress concentration.

Another type of traveling wave type motor is the surface acoustic wave (SAW) motor [46–48]. A SAW, also known as a Rayleigh wave, is an acoustic wave traveling along the surface of an elastic material. It is a coupled wave of the longitudinal wave and the shear wave which has normal displacement component to a boundary. As it moves across the surface, each surface point in the elastic medium moves along an elliptical locus. The first SAW motor was reported by Kurosawa et al. in 1996 [46]. A 127.8° Y-rotated X-propagating piezoelectric substrate (LiNbO₃) with two pairs of interdigital transducers (IDT’s) was used for the SAW propagation. By exciting SAW in X- or Y-axis direction, a slider can be driven to move two-dimensionally in the plane. The driving frequency of the planner motor was around 10 MHz, which could produce a maximum transfer speed of 200 mm/s. The miniaturization of the SAW motor was investigated by Shigematsu and Kurosawa in 2006 [47]. In their study, the stator of the motor was miniaturized to be 3 mm × 12.5 mm × 0.5 mm using a 100 MHz driving frequency. An arbitrary axis rotating SAW micro motor was reported by Tjeung et al. [48]. To achieve arbitrary rotating motion, the substrate material of the motor was PZT rather than LiNbO₃ due to the anisotropic nature of the material. A micro metal sphere as the rotor was placed onto a blind hole drilled on the PZT surface. It was verified that the maximum rotation speed and torque achieved were 1000 rpm and 14 μNmm respectively.

SAW motors are suitable for precision positioning (nanometer) due to their very high-frequency SAW driving mechanisms. They also have great potential for high speed, high output force and quick response operation in a wide range of applications. Operating frequency of SAW motors is far higher than the common ultrasonic motors. It means that the operating wavelength of a SAW motor is far shorter and more convenient for miniaturization. However, further miniaturization is also restricted due to the necessity to fabricate complex IDT’s. In addition, the efficiency of SAW motors is still not so high, which is less than 10% at present. High wear rate induced by high-frequency operation is another hurdle to their commercialization.

2.4. Performance analysis and perspective

Compared with other types of motors, especially conventional electromagnetic motors, piezoelectric ultrasonic motors have many merits, including lightweight, compact size, high resolution (rotational types) or speed (linear types), self-braking without power, no noise, and electromagnetic immunity. Due to high driving torque at low speed, ultrasonic motors need no deceleration mechanism. Therefore, by using piezoelectric ultrasonic motors, micro mechanical systems can be realized for precise positioning over long strokes. The demerits of ultrasonic motors include necessity for a high frequency power supply, drooping torque-speed characteristics, and control complexity due to multiple input signals. It is required that the motor should have special frequency, amplitude and phase of driving signals. The driving signals should be adjusted appropriately to keep a stable output when the operational environments change, such as temperature, humidity and
pre-load. Therefore, it is difficult to tune the resonator and adjust the pre-load of an ultrasonic motor [49,50].

One of the greatest potential directions in future work is the miniaturization and integration of ultrasonic motors. A miniature ultrasonic motor is demanded in many micro areas, such as in miniature zoom lens, micro-robotics and micro surgery. Therefore, the driving mechanisms and stator design should continue to be reduced in scale, and possible lightweight materials should be investigated to obtain a large torque-to-weight ratio. To get a higher output and new motor designs, improving and developing manufacturing processes will continue to be an active area of research. On the other hand, further research into PZT fabrication and PZT materials cannot only generate larger vibration amplitudes and higher outputs, but also construct new types of micro motors. Since the movement of an ultrasonic motor is generated through the frictional coupling between the stator and the slider/rotor, wear and fatigue on the contact surface is an inevitable problem. Therefore, it is necessary to investigate low wear frictional materials for improving the durability of ultrasonic motors. In addition, the improvement of adhesive materials and adhesive bonding techniques can also improve the motor’s adaptability to environmental conditions and the stability of its performance. Additionally, the improved PZT materials and bonding techniques could potentially increase the efficiency of ultrasonic motors.

3. Quasi-static motors (non-resonant motors)

An ultrasonic motor is driven by using the resonance of the stator, which has difficulties of tuning the resonator and adjusting the pre-load. Therefore, to drive the moving element within a larger bandwidth of the driving frequency, some quasi-static motors (non-resonant motors) have been proposed in recent decades. Generally, there are two positioning modes of these motors. The first is a long stroke mode. At high frequencies, the PZT is actuated rapidly and repeatedly in a series of small steps. The motor can therefore achieve a theoretically unlimited travel range by accumulating each stroke of the step motion. The second positioning mode is a fine positioning mode. When a slowly changing DC voltage is applied to the PZT, nanometer scale positioning can be achieved within the stroke of the PZT. Therefore, without any external mechanical magnification components, a quasi-static motor is capable of coarse positioning as well as fine positioning with simple construction and a compact size.

There are several ways for a quasi-static motor to achieve a macroscopic motion from a very small strain generated by the PZT itself. Two main groups are classified based on different operation principles: clamping and feeding mechanisms and inertia drive mechanisms. In a clamping and feeding mechanism, long travel range is achieved by repeating sets of clamping and feeding motions of a number of PZTs. On the other hand, the motion range of an inertia drive mechanism is extended by utilizing inertia and friction force.

3.1. Clamping and feeding mechanisms

3.1.1. Inchworm mechanisms

An “inchworm” mechanism is a type of clamping and feeding mechanism which imitates the movement of the inchworm in nature. It can deliver nanometer-precision positioning over a long motion range. Piezoelectric inchworm motors presented in the literature can be categorized into three groups. In the first group, the body of the actuation mechanism can move through a fixed guide way, which is known as a “walker” [51,52]. The “pusher” is the second configuration. Here, the shaft moves through a fixed actuation mechanism body [53,54]. The third technique can be referred to as the hybrid “walker-pusher”, which mixes the actuation methods of the two previous groups [55,56].

An inchworm mechanism usually consists of three PZTs. The central one is used as a feeding mechanism to produce displacement along the motor shaft, while the other two serve as clamps. As shown in Fig. 8, the actuation sequence of a “walker” inchworm mechanism is similar to that of an inchworm in nature. On the other hand, the principle of a “pusher” is shown in Fig. 9. The motion of the shaft can be achieved by coordinating sequential activation of the feeding and clamping PZTs. One complete cycle is as follows: (i) PZT 3 releases its grip on the shaft; (ii) PZT 2 expands to move the shaft to the left; (iii) PZT 3 clamps the shaft; (iv) PZT 1 relaxes its clamp of the shaft; (v) PZT 2 contracts to feed the shaft to the left again; (vi) PZT 1 clamps the shaft and the cycle begins again. Fig. 10 shows the principle of a “walker-pusher” inchworm mechanism.

Table 1
Performance of standing wave type motors.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>Vibrating mode</th>
<th>Stator type</th>
<th>Stator size (mm)</th>
<th>Velocity</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kurosawa et al. [21]</td>
<td>1989</td>
<td>Orthogonal bending</td>
<td>Sandwich type</td>
<td>20 × 50</td>
<td>100 rpm</td>
<td>150 Nm</td>
</tr>
<tr>
<td>Morita et al. [22]</td>
<td>1991</td>
<td>Orthogonal bending</td>
<td>Thin-film PZT on tube</td>
<td>2.4 × 10</td>
<td>295 rpm</td>
<td>N/A</td>
</tr>
<tr>
<td>Morita et al. [23]</td>
<td>2000</td>
<td>Orthogonal bending</td>
<td>Thin-film PZT on tube</td>
<td>1.4 × 5</td>
<td>680 rpm</td>
<td>670 Nm</td>
</tr>
<tr>
<td>Koc et al. [24]</td>
<td>2002</td>
<td>Orthogonal bending</td>
<td>Tube with two flattened sides</td>
<td>2.4 × 10</td>
<td>360 rpm</td>
<td>1.8 Nm</td>
</tr>
<tr>
<td>Tomikawa et al. [25]</td>
<td>1989</td>
<td>Longitudinal-bending</td>
<td>Flat rectangular type</td>
<td>50 × 10 × 3.6</td>
<td>240 mm/s</td>
<td>25 Nm</td>
</tr>
<tr>
<td>Ohnishi et al. [26]</td>
<td>1990</td>
<td>Longitudinal-bending</td>
<td>π-shaped</td>
<td>≈36 × 15 × 5</td>
<td>300 mm/s</td>
<td>10 N</td>
</tr>
<tr>
<td>Suzuki et al. [27]</td>
<td>2000</td>
<td>Longitudinal-bending</td>
<td>Three cantilevers glued to PZTs</td>
<td>2.4 × 10</td>
<td>1800 rpm</td>
<td>3.2 Nm</td>
</tr>
<tr>
<td>Aoyagi et al. [28]</td>
<td>2004</td>
<td>Longitudinal-bending</td>
<td>Thin plate with a vibrating piece</td>
<td>16.2 × 2.5 × 0.55</td>
<td>8000 rpm</td>
<td>6.06 Nm</td>
</tr>
<tr>
<td>Kurosawa et al. [29]</td>
<td>2005</td>
<td>Longitudinal-bending</td>
<td>Sandwich type</td>
<td>20 × 10</td>
<td>100 rpm</td>
<td>586 Nm</td>
</tr>
<tr>
<td>Watson et al. [30]</td>
<td>2009</td>
<td>Longitudinal-bending</td>
<td>Helically cut tube</td>
<td>0.24 × 0.88</td>
<td>1295 rpm</td>
<td>13 Nm</td>
</tr>
<tr>
<td>Aoyagi et al. [31]</td>
<td>2004</td>
<td>Radial-bending</td>
<td>Disk type</td>
<td>60 × 1</td>
<td>N/A</td>
<td>91 Nm</td>
</tr>
<tr>
<td>Lu et al. [32]</td>
<td>2004</td>
<td>Radial-bending</td>
<td>Single annular stator</td>
<td>58 × 14</td>
<td>N/A</td>
<td>15 Nm</td>
</tr>
</tbody>
</table>

Table 2
Performance of multi-DOF standing wave type motors.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Year</th>
<th>DOF</th>
<th>Vibrating mode</th>
<th>Size (mm)</th>
<th>Velocity</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shi et al. [33]</td>
<td>2009</td>
<td>Planar</td>
<td>Longitudinal mode, bending mode</td>
<td>210 × 210 × 30</td>
<td>960 mm/s</td>
<td>103 N</td>
</tr>
<tr>
<td>Yan et al. [34]</td>
<td>2012</td>
<td>Planar</td>
<td>Longitudinal mode, bending mode</td>
<td>30 × 50</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Iwatsuki et al. [35]</td>
<td>1996</td>
<td>Linear-rotary</td>
<td>Longitudinal mode, bending mode</td>
<td>350 × 300 × 36</td>
<td>2700 rpm, 160 mm/s</td>
<td>N/A</td>
</tr>
<tr>
<td>Mashimo et al. [36]</td>
<td>2008</td>
<td>Linear-rotary</td>
<td>Three-wave mode, longitudinal mode</td>
<td>14 × 14 × 14</td>
<td>160 rpm, 63 mm/s</td>
<td>N/A</td>
</tr>
<tr>
<td>Mashimo et al. [37]</td>
<td>2014</td>
<td>Linear-rotary</td>
<td>Three-wave mode, longitudinal mode</td>
<td>1 × 1 × 1</td>
<td>2500 rpm</td>
<td>20 Nm</td>
</tr>
<tr>
<td>Takemura et al. [38]</td>
<td>2000</td>
<td>Spherical</td>
<td>Longitudinal mode, bending mode</td>
<td>1 × 10 × 32</td>
<td>183 rpm</td>
<td>5 Nm,</td>
</tr>
<tr>
<td>Aoyagi et al. [39]</td>
<td>2002</td>
<td>Spherical</td>
<td>Bending mode</td>
<td>20 × 20 × 3.25</td>
<td>1200 rpm</td>
<td>N/A</td>
</tr>
</tbody>
</table>
The clamping PZTs are fixed on the base as that in the "pusher" mechanism, while the feeding PZT serves as the moving shaft as in the "walker" mechanism. The feeding PZT can expand and contract to moving forward when the clamping PZTs alternately clamp it in a well-defined order.

Therefore, by repeating sets of clamping and feeding motions, the shaft can be driven continuously over a long range. The direction of the shaft can be reversed by exchanging the clamping sequence of the two clamps. The stroke of each cycle is limited by the maximum displacement of the central PZT. Theoretically, there is no range limitation of an inchworm motor, but it still depends on the length of the guide way.

Many investigations have been conducted to construct various inchworm motors. The first example of a "walker" inchworm motor was developed by Brisbane et al. in 1968 [31]. This motor used three cylindrical PZTs, two for clamping and one for feeding. The motor could produce an increment step size down to 5 μm with a claimed actuation speed of 50 mm/s. The first "pusher" inchworm motor was patented by Burleigh Instruments Inc. in 1975 [53]. It could provide a nanometer resolution and 200 mm motion range. An output force of 15 N is achieved at a speed of 2 mm/s. Hsu et al. introduced the first patented "walker-pusher" inchworm motor in 1966 [55]. A piezoelectric tube was utilized to create the forward motion, while the clamping mechanisms used two annular wedge surfaces inclined to the shaft's axis such that the wedged members could prevent motion in either direction. It could produce an unloaded velocity of 6.3 mm/s at 60 Hz and approximately 38 mm/s at 400 Hz. Another famous "walker-pusher" inchworm motor was developed by Locher et al. in 1967 [56]. The motor used clamping elements to engage a "clam-claw" mechanism resulting in an individual step as small as 13 μm.

Since the performance of the clamping mechanisms decides the feasibility of inchworm motors, design of better clamping mechanisms is part of the focus in inchworm motor development. To guarantee enough clamping force, many researchers used flexure structures or compliant mechanisms to enlarge the PZT elongation. In 1999, Roberts et al. designed a linear inchworm motor operating inside a metal tube [57]. The clamping mechanism of the motor could expand to push a piston outwards and allow four quadrants to splay apart thus gripping against the inside surface of the metal tube. In the design of Li et al. [58], each clamping mechanism consisted of a tubular PZT, a compliant mechanism with three identical flexural arms and a pre-load mechanism. Ma et al. proposed a kind of inchworm motor with a symmetry leveraged flexible hinge displacement amplification mechanism [59]. Experimental results showed that the clamping force of the mechanism was 17 N, and the bearing capacity was 11 N.

In addition to linear inchworm motors, rotary inchworm motors were also proposed by some researchers. Ohnishi et al. developed a rotary inchworm motor in 1990 [60]. Three pairs of longitudinal PZTs were utilized as the clamping mechanisms, while a torsional PZT served as the feeding mechanism. The rotor could rotate based on a similar actuation sequence to a linear inchworm motor. In 1995 [61], Duong et al. proposed a rotary inchworm motor with no torsional PZT used. The motor consisted of two clamping mechanisms to provide the holding force and a swinger to provide angular motion. The swinger consisted of one PZT and a flexure mechanism which generated rotation about the center of the motor, while the clamping mechanisms alternately gripped the rotor. Li et al. proposed a rotary motor with nine PZTs [62]. The stator included two
layers connected by flexure hinges. Each layer employed three PZTs to push three clamping units respectively. Three other PZTs were utilized to produce the torque between the upper layer and the under layer of the stator. A rotary inchworm motor utilizing a Y-shaped stator and ring rotor was proposed by Zhou et al. in 2014 [63]. One PZT was employed and the Y-shaped stator could be treated as three beams to clamp the rotor alternately. It was verified that the motor could achieve a maximum rotational velocity of 26.3 rpm and a stall torque of 96 μNm.

On the other hand, development has been done to construct multi-DOF inchworm motors. Yan et al. developed a 3-DOF mobile robot utilizing a rhombic flexure hinge mechanism in 2006 [64]. One PZT was used to drive the robot, while four electromagnetic legs were utilized to clamp the robot. By controlling the legs to clamp and release appropriately, the robot could achieve large stroke translation and rotation with high resolution on a platform. In 2011, Torii et al. proposed a tripod robot with three PZTs and three electromagnets [65]. The deformation of the PZTs moved the robot, while the adhesion of the electromagnets held the robot on a magnetic floor. Another 3-DOF inchworm mechanism was developed by Fuchiwaki et al. in 2010 [66]. The mechanism was composed of four PZTs as feeding mechanisms and a pair of electromagnets as clamping mechanisms.

Inchworm mechanisms have many advantages, e.g., high resolution positioning, compact size, no backlash, etc. Strictly speaking, the inchworm motor is also a friction-type motor, which pushes the shaft through friction at the interface of the clamp and the shaft.

Fig. 10. Working principle of a “walker-pusher” inchworm mechanism.

Fig. 11. Working principle of a “seal” mechanism.

The load capacity of the inchworm motor depends on the static friction between the clamp and the shaft. Compared to other friction drive mechanisms, the clamping mechanism of an inchworm motor can generate a higher driving force and a quasi-static operation. It also reduces wear due to the clamping operation when the shaft is stationary. However, in the meantime, the clamping operation and relatively large volume reduce the PZT driving frequency. An inchworm mechanism needs at least three phases, causing its operation to be complex. The discontinuous clamping operation may also cause vibration to the shaft. In addition, the mechanisms, especially the chucks, seem to be hard to miniaturize. High precision in manufacturing is also a challenge so that the clamps work reliably.

3.1.2. Seal mechanisms

A seal mechanism is another clamping and feeding mechanism, which is very similar to the inchworm mechanism but with only one clamping mechanism. As shown in Fig. 11, a seal mechanism is composed of one PZT and two friction elements (1 and 2). Friction element 1 is a passive device and applies a constant frictional force. Only friction element 2 is controlled by an on-off action, causing a clamping-releasing operation at the base. The frictional force should be designed as:

\[ F_{2\text{off}} < F_1 < F_{2\text{on}} \]

where \( F_1 \) is a constant frictional force between friction element 1 and the base, while \( F_{2\text{on}} \) and \( F_{2\text{off}} \) are frictional forces in the cases of clamping and releasing friction element 2, respectively. The actuation sequence of the seal mechanism is as follows: (i) The friction element 2 is off; (ii) Due to \( F_{2\text{off}} < F_1 \), the PZT expands to move the friction element 2 to the right when the friction element 1 keeps stationary; (iii) The friction element 2 is turned on; (iv) The PZT contracts to move the friction element 1 to the right because \( F_{2\text{on}} \) is bigger than \( F_1 \). The moving direction can be reversed by exchanging the extension and contraction of the PZT in the sequence above.

Furutani et al. developed an L-shaped seal mechanism with 3-DOFs in 2002 [67]. This mechanism consisted of two controlled electromagnets connected by two PZTs. An electromagnet with constant friction was used to connect the two PZTs at a right angle. By controlling the two controlled electromagnets with an on-off action, the mechanism could move with micrometer order steps in the x-, y- and \( \theta \)-directions.

Compared with the inchworm mechanism, a seal mechanism using passive devices decreases the number of controlled actuators but still retaining the same performance as the inchworm mechanism [67,68].
3.1.3. Walking drive mechanisms

Another type of clamping and feeding mechanism is a “walking drive mechanism”. It simulates the walking motions of a biological species. A walking drive mechanism usually uses a series of the same driving elements (at least two “legs”), each of which can clamp and feed the moving element separately. During the long walking motion, the mechanism can be alternately supported and driven by the legs step by step.

The working principle of a walking drive mechanism is shown in Fig. 12. The motion of one leg can clamp and feed the mechanism independently. When or before the feeding of one step is finished, the clamping of the next step is initiated. This means that the clamping and feeding of the next step can also be carried out concurrently before the previous step finishes. Therefore, two or more legs should be used to accomplish an overlap of the motion patterns. Similar to walking motions in animals or human beings, this mechanism can be driven in a continuous motion by repeating sets of clamping and feeding operations of the legs.

In 1997, Shamoto et al. proposed a walking drive mechanism driven by three “legs” [69]. Each leg consisted of a clamping PZT and a feeding PZT. By shifting the phases of the legs, the clamping and feed motions were repeated alternatively in a way similar to walking motions in animals. At least two clamping mechanisms clamped and guided the shaft rigidly at any time. Therefore, the mechanism could be driven continuously over a long stroke. Based on the walking drive principle, Shamoto et al. also proposed an XY and 6-axis walking drive mechanisms in 1997 and 2000, respectively [70,71].

Pan et al. developed a motor for translating a prism using six shear-mode PZTs [72]. Each PZT consecutively sheared and slid backward along the prism, while all the six PZTs simultaneously returned to their original position and drove the prism forward. On the other hand, a “piezolegs motor” was developed by Piezomotor Uppsala AB [73]. It consisted of four PZT legs and a drive rod pressed against the legs by a pre-load. Based on a bimorph working principle, the legs could elongate or bend in a two-dimensional plane. Therefore, the motor could perform a walking movement by synchronizing the movement of each pair of the four legs. Since the motor is non-resonant, it is easy to scale up and down in size. Many “piezolegs motors” have been commercialized for various applications, such as tuning and aligning lenses, high-precision auto-focusing, precision positioning in lab-on-a-chip or semiconductor industries, and manipulating samples in a Scanning Electron Microscope (SEM) or Transmission Electron Microscope (TEM) [73].

In general, an inchworm mechanism has a simpler structure. However, the motion is intermittent due to only one feeding actuator. The feeding actuator must stop when changing the clamping actuators to hold the shaft. Therefore, the clamping and feeding motion is not simultaneous but with a sequential alternation. Compared with the inchworm mechanism, the clamping motion of one leg of the walking drive mechanism can be carried out during its feeding phase. Hence, the leg can cooperate with the movement of the shaft fed by other legs. In addition, the leg can clamp or release the shaft at any time when other legs feed the shaft. It means that the shaft is fed by several legs or at least one leg during the entire movement. Therefore, the walking drive mechanism can move continuously and smoothly with high rigidity.

All the typical types of the aforementioned mechanisms are based on the sequenced operation of clamping and feeding. A clamping and feeding mechanism is capable of providing a large force with high efficiency, but it is characterized by low speed due to the low working frequency in the quasi-static state. The mechanism needs at least one clamping mechanism as well as one feeding mechanism to operate, which is too complicated in both structure and control. In addition, the reliability and applications of the mechanism in small space and weak signal measurements all become severe issues [74].

3.2. Inertia drive mechanisms

3.2.1. Impact drive mechanisms

An impact drive mechanism (IDM) is a method utilizing static friction and the impulsive inertial force caused by the rapid deformations of a PZT. As shown in Fig. 13, this mechanism is composed of a main body, a PZT and an inertial mass. The main body is placed on a guide surface, while the inertial mass is not in contact with the guide surface. When the PZT expands slowly, the mass moves forward while the main body keeps stationary due to the static friction on the guide surface. Then, the PZT shrinks quickly to generate an impulsive force and the main body gets the momentum of the mass. At this time, the inertial force generated by the mass exceeds the maximum static force of the main body. Consequently, the main body moves forward against static friction. By repeating these steps, the main body can move forward in infinite distance continuously. The backward motion can be obtained by reversing the sequence of extension and contraction of the PZT.

The impact drive mechanism was first proposed by Higuchi et al. in 1990 [75,76]. In his patent [75], several impact drive mechanisms with multi-DOFs were proposed, including XY and XY0 stages. In the paper of Higuchi et al. [76], one rotating joint was constructed by an arm with a shaft, a spring and a stand. A pair of PZTs with inertial masses was connected to the arm. Based on an impact friction drive, the PZTs could rotate the joint with a velocity of 0.048 rad/sec when the pulse rate was 1.2 kHz at 80 V. A three-DOF joint was also proposed in the paper. The arm was supported by a ball-joint mech-
anism. The cross section of the arm was an equilateral triangle, and the sides were attached with six PZTs and six inertial masses. Based on an impact friction drive, the PZTs could generate a couple of forces around the rotating axes of X, Y, and Z. Then, Higuchi et al. also proposed a four-DOF micro robot arm based on the two joints above. The IDM developed by Higuchi et al. have already been commercialized and being used in many institutes, such as for smooth insertion of a micro pipette into the cytoplasm in case of sperm injection or DNA transplantation [77]. Cedrat technologies developed a Stepping Piezo Actuator (SPA) based on the principle of IDM [78]. The displacement of the PZT was magnified by an external elliptical shell, and a clamping mechanism was used to generate friction force. Several customized SPAs have been developed by Cedrat Technologies to meet various environments (medical MRI, space... ) and customers’ needs. Yamagata and Higuchi et al. also developed an XY0 positioning table for use in an ultrahigh vacuum [79]. The table has a hexagonal shape with six PZTs and masses connected to the inside wall of the body. By utilizing friction and the inertial forces caused by rapid deformations of the PZTs, the table could be driven in the directions of X, Y, and θ. Nomura et al. proposed an impact drive mechanism that could provide X, Y, and θ motions [80]. Four PZTs were connected to the main body and the inertial mass. By alternating the phase shift of the PZTs, this mechanism could generate not only translational displacement in X and Y directions but also a rotational one, θ. To construct an impact drive rotary precision actuator, Zhang et al. used one end-loaded piezoelectric cantilever bimorph and one inertial mass as an actuating unit [81]. Two actuating units with a symmetrical layout were used to rotate the actuator. By slow bending and rapid restoration, the piezoelectric bimorph could rotate the actuator with a theoretically unlimited working range. As the deformation magnitude at the free-end was more than 10 times that of a stacked PZT, a heavier end-mass could be easily driven by the piezoelectric bimorph. Hence, the actuator was thought to be able to possess heavy load driving ability.

Unlike other friction-type motors, the impact drive mechanism only moves in the “slip” period and stands through the static friction period. The inertial force is used to overcome the frictional force to actuate the main body. Since the PZT and the inertial mass move with the movement of the main body, the whole system is a “self-moving” mechanism. It should be noted that the inertial mass of the IDM must be relatively large for effective transmission to the moving body, resulting in reduced resonance frequency of the stage. Besides, it is impossible to utilize the stroke of the PZT itself to move the moving body. This is because the static friction force should be overcome to move the main body. It is required relatively large voltage to generate enough impact force, which limits the minimum positioning displacement of the main body.

3.2.2. Smooth impact drive mechanisms

The initial smooth impact drive mechanism (SIDM) was modified from the construction of an impact drive mechanism by Yoshida et al. in 1999 [82]. As shown in Fig. 14, the inertial mass of the IDM is modified to become a friction element, which contacts with the guide surface. The frictional force on the friction element is much larger than that on the moving body. Therefore, when the PZT expands slowly, the friction element keeps at the original position and the moving body moves forward. When the PZT contracts rapidly, the moving body and the friction element are dragged simultaneously. The moving body can move a small displacement with respect to its original position. Hence, a long forward stroke is obtained by repeating the above operations. The whole mechanism of the initial SIDM is self-propelling and can be driven using a fine positioning mode by using the displacement of the PZT itself. By utilizing the principle of the mechanism, Morita et al. developed a three-DOF parallel link mechanism in 2002 [83]. The mechanism employed three SIDMs for positioning in X, Y, and θ directions over a long stroke with fine positioning resolution. In previous research by the authors [84], a pair of PZTs and friction elements with a symmetrical layout was employed to support and drive a moving body. Therefore, the moving body didn’t need to contact with the guide surface to obtain a relatively smooth movement.

Subsequently, Yoshida et al. also improved the SIDM by using a friction element to transmit the movement of the PZT to a moving body [85]. As shown in Fig. 15, one end of the PZT is mounted on a base and the other is attached to the friction element. The moving body is placed on the friction element by a pre-load mechanism. In the long stroke mode, the PZT is driven by a saw-tooth wave voltage of slow increase and rapid decrease. When the PZT is driven slowly, the moving body can be moved by the frictional force. Then, the applied voltage rapidly decreases and the PZT shrinks very fast. The moving body cannot follow the fast motion of the friction element and remains in place due to its inertia. Therefore, the moving body can obtain an unlimited displacement by continuously repeating these operations. On the other hand, in the fine positioning mode, a slowly changed DC voltage is applied to the PZT. Due to the static friction between the moving body and the friction element, the moving body can move with the movement of the PZT itself without slippage. Therefore, the moving body can demonstrate the same positioning faculty of the PZT itself, which is at nanometer level. The SIDM developed by Yoshida et al. was much smaller and could be installed in many mobile devices. Konica Minolta Opto has already mass-produced SIDMs in several applications such as autofocus actuators for mobile camera lens and image stabilizing unit of cameras called “Anti-shake” [86]. A number of SIDM-based commercial motors have also been developed by Physik Instrumente for precision positioning [17].
To construct a multi-DOF SIDM, Zhang et al. developed a rotary-linear motor by superimposing a linear SIDM and a rotary SIDM [87]. In the rotary SIDM, two PZTs were situated along the tangential direction of the motor system, and two corresponding friction pieces were placed against the perimeter of the rotary cylinder. Therefore, based on the same principle of a linear SIDM, the rotary SIDM could move with an unlimited angular displacement. To avoid the large size of the stacked structure, Gao et al. constructed a compact linear-rotary stage by utilizing two L-shaped driving units [49]. Each driving unit consisted of two PZTs and a friction element made by permanent magnet. The two PZTs were aligned along the axial direction and tangential direction of the moving body, respectively. Hence, based on the principle of SIDM, the stage could move along the axial and tangential directions with large motion ranges. It should be noted that the permanent magnet employed as the friction element could generate constant contact force without any pre-load mechanisms, which greatly simplified the SIDM-based stage configuration. Subsequently, a second-generation linear-rotary micro-stage whose volume was no more than 1 cm³ was constructed in Gao’s lab [50]. In 2013, a compact XY micro-stage was also proposed by using the same L-shaped driving unit by Gao’s lab [88].

Some other deformation modes of the PZT were also used to construct a SIDM-based motor. One typical type is referred to as “stick-slip” motor utilizing shear deformation of the PZT [89–93]. The principle is shown in Fig. 16. A moving body is supported and actuated by a deformable PZT leg. During the slow deformation of the leg, the moving body follows the leg owing to frictional force, whereas it slips due to its inertia when the PZT leg abruptly shrinks backwards. Compared with the “piezolegs motor”, which needs at least two legs actuated alternately, the “stick-slip” motor can be actuated by only one leg because of a smooth frictional drive [89]. In the research of Breguet et al. [90], two PZT legs in shearing mode were employed to drive the moving body simultaneously. They proposed and fabricated several stick-slip micro-manipulators including a 6-DOF platform, a sample holder for AFM, two 3-DOF mobile micro-robots, a 4-DOF micro-Electric Discharge Machining (EDM) machine, a micro-assembly system and a micro-telemanipulation system for biological specimens. These manipulators had several DOFs and were easy to integrate into complex mechanical systems. Zesch et al. proposed a rotational motor relying on the stick-slip effect [91]. The rotor of the motor was supported by 5 ruby hemispheres glued on top of 3 shear PZTs. The PZTs could move the ruby hemispheres tangentially to the rotor’s circumference, thereby causing rotation of the axle. A spherical motor which could be rotated about two or three orthogonal axes was proposed by Howald et al. [92]. Three PZT tubes or shear PZTs were aligned perpendicular to each other. Therefore, the spherical motor could be rotated about any desired axis through its center. Zou et al. designed a rotary motor by utilizing three PZT bimorph actuators mounted at 120° angles from each other [93]. A steel ball was attached to the top of each actuator and a glass disk was placed on the steel balls. Therefore, the disk could be rotated over unlimited angular range when the three PZT bimorph actuators were actuated in the stick-slip operation. Morita et al. reported a rotational motor using a hollow-cylinder torsional actuator [94]. The torsional actuator was made of multi-layer PZTs. To excite torsional displacement, the poling directions of the PZTs were aligned in a circumferential direction. Therefore, the rotor on the torsional actuator could be driven continuously when a saw-tooth wave voltage was applied to the actuator. The research of Han et al. showed the feasibility of making an impact rotary motor based on a tubular piezoelectric fiber actuator with helical electrodes [95]. In their further study [96], a cylindrical torsional actuator with grooved helical electrodes planted on its side face was developed. The motor could rotate at a speed of 22.5 r/min with a braking torque of 0.1 mN·m, and the stall torque could reach up to 1.6 mN·m.

In addition, some researchers have also used disk-type PZTs in the SIDM. In 2006, Kang et al. invented a tiny linear motor using the vibration of a PZT transducer [97]. The transducer consisted of two PZT disks with a metal disk between them. A shaft was mounted to the top PZT disk and a mobile element was compressed to the shaft. Long range linear motion of the mobile element could therefore be achieved by successive smooth friction driving. A similar mechanism developed for braille displays was also found in Ref. [98]. A linear motor using a unimorph structure PZT disk was developed by Jun et al. [99]. The disk was fabricated as a ring shape and a shaft was positioned in the hole of the disk. A saw-tooth wave voltage was applied to the disk by utilizing the principle of SIDM. As a result, the shaft moved smoothly with a long travel range.

Both the IDM and SIDM utilize an inertial force and a frictional force to drive the moving element over a long motion range, and many publications called them “inertia motors”. Compared with the IDM, the SIDM might be superior in respect of its positioning resolution. An SIDM can demonstrate the same positioning resolution of the PZT itself due to the driving static force between the PZT and the friction element. With the IDM, the moving body is driven using impact step motions. In other words, the frictional force plays a positive role for the actuation movement in the SIDM, whereas the inertia force plays a positive role in the IDM. In addition, a typical SIDM usually consists of two separate moving systems. One is the PZT and the friction element, the other is the moving body. Each of these can move independently. This allows the resonant frequency in the first system to be designed separately as high as possible. Therefore, the SIDM usually has a wider bandwidth with less vibration. However, unlike the unlimited motion range of the IDM because of its self-moving characteristic, the travel range of the SIDM is always limited by the length of the friction coupling mechanisms.

An inertia motor is rather simple made superior by its compact structure, simple operation, and accurate step capability compared with other types of motors, but it is not very rigid and prone to vibration [74]. In addition, its speed, output pushing force, and efficiency are fairly low because of its quasi-static operation, friction coupling mechanism, and sliding friction dissipation. For example, compared to the ultrasonic motors, the inertia motor is simpler, but the holding force is 1/10 smaller. In Table 3 we summarize the performance data of typical quasi-static motors reviewed according to classification to provide an easy reference for review.
3.3. Performance analysis of inertial motors

Generally, it is assumed that the inertial motor is actuated in “stick–slip” mode and is also called a “stick–slip” motor in some literature [89–93]. The moving body of the motor is classically regarded as being driven in small steps which are composed of a stick phase and a slip phase, between the friction partners. However, strictly speaking, the “stick–slip” mode involving friction and sliding only occurs at a specific frequency. Actually, the inertia motor can also operate in “slip–slip” mode without any static friction phase [82,100]. This means that the movement of an inertia motor not only occurs at a low specific frequency, but can be driven using a high bandwidth under resonance. In a “stick–slip” mode, it should be operated at a specific frequency exactly to obtain static friction in the “stick” phase and dynamic friction in the “slip” phase simultaneously. When the driving frequency becomes larger, the moving element is driven by dynamic friction force instead of static friction force, even in the previous “stick” phase. Therefore, slippage also occurs not only in the “slip” phase, but also in the previous “stick” phase. This phenomenon is called a “slip–slip” mode because slippage occurs in both phases. In this mode, the amount of the displacement of each step is determined by the difference between the forward slippage and the backward slippage. Although backward slippage occurs throughout the motion, the moving body moves forward continuously because the duration of its forward force is longer than that of its backwards force. The maximum velocity reachable in “stick–slip” mode is limited, while “slip–slip” operation allows inertia motors to be driven at higher frequencies for higher velocities.

Although the velocity of the inertia motor could be improved during the “slip–slip” mode, this movement might be not “smooth” at a low driving frequency. This is because only partial slippage occurs in the backward “slip” phase, and the moving body partially follows the backward motion of the PZT. Therefore, the moving body moves forward with vibration due to its partial backward motion. When the driving frequency becomes high enough, the moving body moves forward so fast that it cannot follow the backward movement of the PZT. Therefore, no vibration occurs and the moving body moves forwards smoothly and fast, which is desired for inertia motors. In Zhang et al. research [87], five cases were described for identifying the relationship between the output displacement of the moving body and the PZT according to stick and slip dynamic conditions.

On the other hand, some researchers have used a saw-tooth voltage to drive the PZT in order to obtain slow expansion and rapid contraction of the PZT. However, the output displacement of the PZT is distorted by the non-flat transfer function of the apparatus such as the PZT, the electronic circuits and the mechanical components. The distorted output displacement of the PZT is not efficient for the impact friction motion because it may reduce the velocity and cause undesirable motion of the moving body. To enhance the velocity of the moving body, the waveform of the voltage should be optimized to generate a quasi-sawtooth output displacement. In Yoshida et al. research [82], a rectangular voltage was reported for driving the SIDM. In the authors’ research [50], the desired voltage waveform at each frequency was calculated by inverse Laplace transformations.

Some other performances of inertia motors were also investigated in numerous publications. The movement performance of the IDM on fluid lubricated surfaces was investigated by Furutani et al. [101]. It was verified that the movement of IDM on a fluid lubricated surface was almost the same as that on a dry surface when the fluid lubricant was thin and the device moved slowly, and appropriate fluid lubricants could make the movement stable. In [102], it was found that the performance was not affected by exposure to dust and humidity. However, slight lubrication with machine oil resulted in a significant reduction in driving speed and maximum load. The effect of frictional force on driving speed is also found in literature. In [82], the driving speed changed little with the increasing of the frictional force, and began to decline when the frictional force reached a certain value. The thermal effect on inertia motors was investigated by Li et al. [103]. Their experiments further showed that a temperature rise reduced the displacement of the motor at low voltage, while there was no significant change at high voltage.

4. Motors combined resonant and quasi-static operations

Traditionally, ultrasonic motors are operated at resonance thereby achieving high speed, while quasi-static motors are driven
at off-resonance and may generate higher force/torque and resolution but cannot generate significantly high speed. To take advantage of the merits of both approaches, the recent trend is to combine the resonant and quasi-static operations together.

In Mang et al.'s research [104], a piezoelectric motor was constructed by merging quasi-static and resonant operations into a single system. The motor could be operated over the whole frequency from 0 Hz up to 10% above resonance. Therefore, the motor could demonstrate high torque in quasi-static operation and high rotation speed at resonance. To combine the fast positioning capability of resonant motors with a stepping function enabling fine positioning in the nanometer range, Devos et al. designed an ellipse-shaped linear drive unit by means of only two PZTs [105]. In the resonant mode, the horizontal and the vertical vibration modes were used to create an elliptical motion. In the stepping positioning mode, the motor operated as a walking drive based on the inchworm principle. Therefore, by combining the resonant and the stepping positioning modes, the motor could achieve a high speed of more than 100 mm/s and position accurately and smoothly at very low speeds. Based on the same driving concept, Devos et al. also built a planar piezoelectric drive by employing four PZTs for a desired planar motion [106].

Because of the low mechanical quality factor and heat generation of multi-layered PZTs, the traditional SIDM operated at off-resonant frequency is not suitable for sufficient high-speed movement. Several attempts were made to increase the driving frequency of the SIDM up to its resonance, which could improve the driving speed and thrust significantly. Since a saw-tooth voltage cannot generate a saw-tooth shaped displacement in the vicinity of resonance [107], some researchers used an uneven rectangular voltage wave to drive the SIDM at the resonant frequency. Another method is to combine two resonant frequency modes [108]. Tunedemir et al. designed and manufactured a translational-rotary motor by using a single actuator [107]. Translational and rotary motions were obtained at two distinct resonant frequencies by means of SIDM applied on slanted PZTs. To generate a saw-tooth shaped displacement profile, the SIDM was driven by an asymmetric square wave voltage at the resonant frequency. Compared with the SIDM driven at off-resonance, the SIDM driven at resonance not only reduced the power requirement but also enhanced the efficiency. In 2012, Morita et al. proposed a resonant-type SIDM to introduce the high speed and high thrust operation [108]. A quasi-sawtooth movement was generated by combining the first and third longitudinal resonant vibration modes. The ratio of the first and third vibration resonant frequencies was adjusted to be 1:2 by a bolt-clamped Langvinis transducer. Therefore, the motor could be driven with a high speed of 280 mm/s. In 2014, a resonant-type inertia linear motor based on wavefront synthesis was proposed by Pan et al. [109]. The motor’s stator driven by PZT plates could produce a quasi-sawtooth shaped motion by combining the second and the first resonant modes. In addition, the driving speed as well as the output power could be potentially enhanced with optimized design. Their lab also proposed a piezoelectric motor combined the resonant actuation of ultrasonic motors with the control mechanism of inchworm motors to utilize their advantages but mitigate their weaknesses [110]. Based on the synchronized switching-mode operation of harmonic vibration, the prototype demonstrated higher output force than ultrasonic motors, and higher efficiency than the motors with sliding friction coupling mechanism.

5. Conclusions

In this paper, a critical review of long range piezoelectric motors using frequency leveraged method is presented. The work is classified into three groups by actuation frequency, including ultrasonic motors (resonant motors), quasi-static motors (non-resonant motors) and motors combining resonant and quasi-static operations. According to different wave propagation methods, ultrasonic motors have been classified into standing wave type motors and traveling wave type motors. The standing wave type motors have been discussed according to different combinations of vibration modes. Also, two typical types of traveling wave type motors have been introduced. Quasi-static motors have been classified to be clamping and feeding mechanisms and inertia drive mechanisms. Various clamping and feeding mechanisms have been introduced according to their basis of operation, including inchworm mechanisms, seal mechanisms, and walking drive mechanisms. Impact drive mechanisms and smooth impact drive mechanisms, which are two main typical types of inertia drive mechanisms, have also been discussed. Some issues of movement performance and driving methods for inertia motors have been clarified. In addition, pros and cons for each type of motor have been discussed in this paper. Finally, recent attempts at constructing a motor by combining the resonant and quasi-static operations are also reviewed. The current state of frequency leveraged motors summarized in such a way can help researchers and engineers to design long range piezoelectric motors with improved performance.

Future research directions are suggested as follows:

1. Since almost all the frequency leveraged motors utilize frictional force to repeat an intermittent movement to obtain a long motion range, frictional behavior varies depending on pressure and contacting surfaces. Applications are limited to light duty, and open-loop repeatability is limited. Therefore, fabrication and materials at the contact surface should be further investigated. The optimized friction coupling can not only improve the wear and fatigue of the contact surface but also enhance the driving speed, repeatability and load capacity.

2. Another significant potential in the future is the miniaturization of the frequency leveraged motors. Therefore, optimization of structural design, lightweight material and novel manufacturing processes will continue to be active areas for the future.

3. Design of new driving mechanisms also plays an important role in the future. It is expected that more and more novel structures will be developed based on the principles of frequency leveraged motors.

4. Innovation of new driving principles and methods should continue to be explored.

References


