

Review

Piezoelectric Inertia Motors—A Critical Review of History, Concepts, Design, Applications, and Perspectives

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Abstract: Piezoelectric inertia motors—also known as stick-slip motors or (smooth) impact drives—use the inertia of a body to drive it in small steps by means of an uninterrupted friction contact. In addition to the typical advantages of piezoelectric motors, they are especially suited for miniaturisation due to their simple structure and inherent fine-positioning capability. Originally developed for positioning in microscopy in the 1980s, they have nowadays also found application in mass-produced consumer goods. Recent research results are likely to enable more applications of piezoelectric inertia motors in the future. This contribution gives a critical overview of their historical development, functional principles, and related terminology. The most relevant aspects regarding their design—i.e., friction contact, solid state actuator, and electrical excitation—are discussed, including aspects of control and simulation. The article closes with an outlook on possible future developments and research perspectives.

Keywords: inertia motor; stick-slip motor; smooth impact drive; piezoelectric motor; review

1. Introduction

Piezoelectric actuators have long been used in diverse applications, especially because of their short response time and high resolution. The major drawback of these solid state actuators in positioning applications is their small stroke: actuators made of state-of-the-art lead zirconate titanate (PZT) ceramics only reach strains up to 2%. A typical piezoelectric actuator with 10 mm length thus reaches a maximum stroke of only 20 μm . Bending actuator designs [1] and other mechanisms [2] can increase the stroke at the expense of stiffness and actuation force ([3]; [4] (pp. 287–289)), but strokes of a few millimetres are hard to reach, even with such structures.

In piezoelectric motors, these small strokes are repeated at frequencies of up to several 100 kHz and are accumulated using different principles to achieve a macroscopic movement. This movement can be linear or rotary, and is principally unlimited. Orbital or spherical trajectories are relatively simple to realise. Compared to typical electromagnetic motors, piezoelectric motors provide large force or torque at small size, powerless holding-force, magnetic insensitivity, and are well-suited for miniaturisation [5,6].

Since the invention of the first piezoelectric motors in the 1940s [7], numerous piezoelectric motors have been developed and described in literature. Nowadays, it is difficult to keep track of the ever-growing variety of piezoelectric motors. This contribution does not aim to provide a general review or classification of piezoelectric motors, as many authors have done so before, e.g., [8]; [9] (pp. 27–33); [10]; [11] (p. 32); [12] (p. 414); [13] (p. 5); [14]; [15] (p. 9); [16–18]. The proposed classification schemas differ, and none of them comprises all motor variants described in literature. For this reason, there is no generally accepted detailed classification of piezoelectric motors. However, up to four common groups are usually recognised:

- Standing wave motors
- Travelling wave motors
- Walking piezoelectric motors
- Inertia motors

Standing wave and travelling wave motors are the oldest and best known piezoelectric motors. They are often summarised under the terms “ultrasonic motors” or “resonant motors” because resonant vibration of the stator at ultrasonic frequencies is usually used to obtain the desired vibration amplitude of contact points on the stator. These contact points drive the rotor through a friction contact. Walking piezoelectric motors operate below their resonance frequency, and follow the “clamp and feed” principle. One piezoelectric actuator is used to clamp the rotor, while another actuator moves it.

This contribution does not go into detail on these three motor types, but focuses on a detailed overview and critical review of the fourth group: piezoelectric inertia motors. These motors are often inferior to other piezoelectric motors in terms of force, velocity, or power. However, they have a simple mechanical design, are typically controlled by only one electrical signal per degree of freedom, and inherently provide a fine positioning capability with principally unlimited resolution. These characteristics are additional advantages for miniaturisation, and make inertia motors suitable for use in mobile phone cameras, cp., for example [19–25]. All of their many variants make use of the inertia of the driven part to drive it through an uninterrupted friction contact. The functional principle of two basic inertia motor designs is illustrated in Figure 1. These motors are also known as “stick-slip motors” because of the repeated transition between static and sliding friction that is present in many inertia motors. Figure 2 shows five piezoelectric inertia motors from the literature, illustrating the large variety of motor designs.

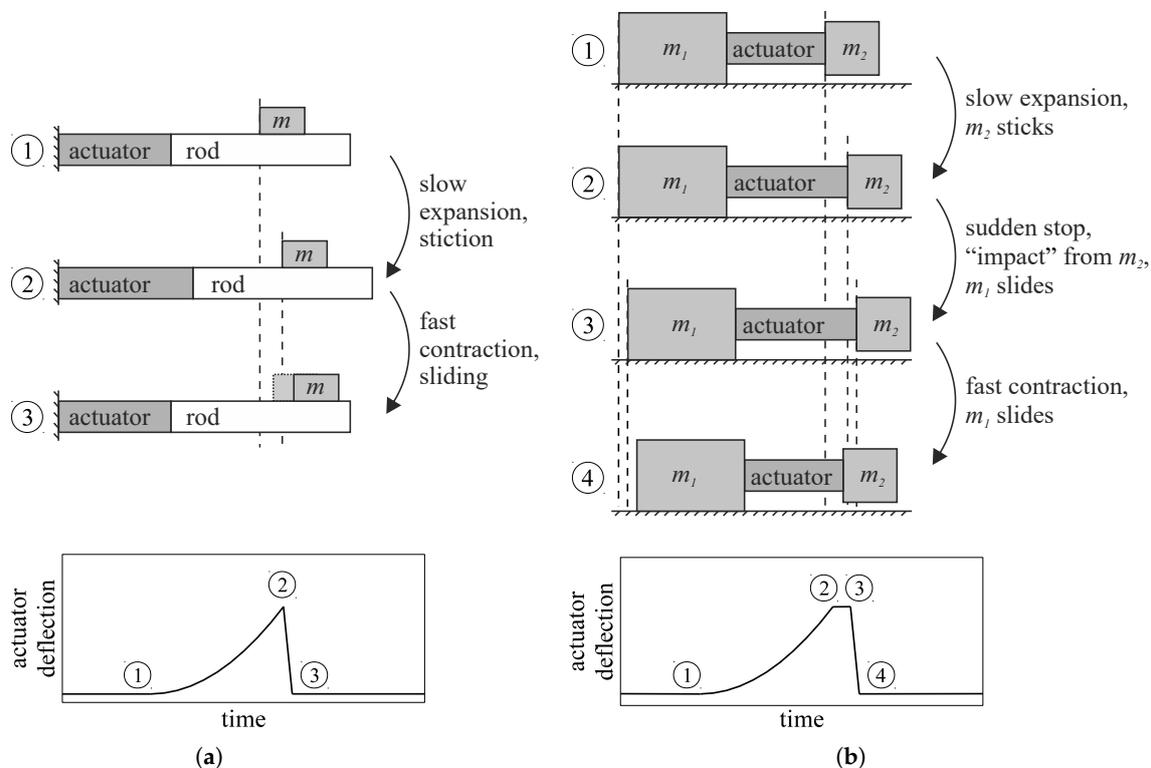


Figure 1. Schematic representation of the two basic designs of inertia motors and their functioning in classic “stick-slip” operation, including typical excitation signals. (a) Fixed actuator type; (b) Moving actuator type.

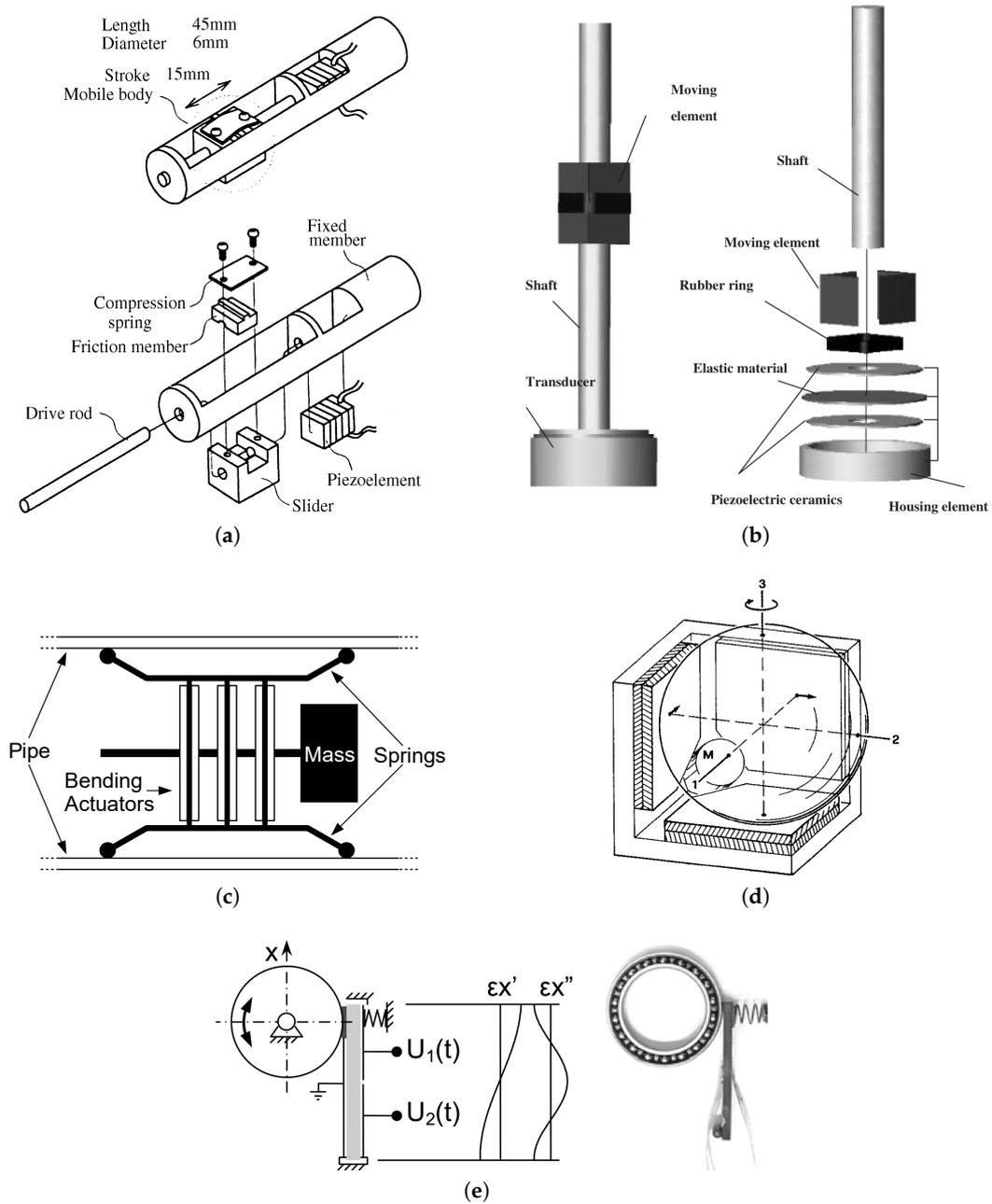


Figure 2. Some inertia motors from the literature, using different piezoelectric actuators and different mechanisms to generate normal force. (a) Fixed actuator motor with one linear axis using a piezoelectric stack actuator and a metal spring to generate normal force (Reprinted from [26] with permission from Wiley); (b) Fixed actuator motor with one linear axis using a piezoelectric bending actuator (two piezoelectric discs glued to a passive central disc) and a rubber spring to generate normal force (Reprinted from [27], Copyright 2006 The Japan Society of Applied Physics); (c) Moving actuator motor for linear movement inside pipes (cross-section), using three piezoelectric bending actuators and flat metal springs to generate normal force (as described in [28,29]); (d) Fixed actuator spherical motor with three rotational axes using piezoelectric shear actuators and a magnet (M) to generate normal force (Reprinted from [30] with the permission of AIP Publishing); (e) Schematic (left) and prototype (right) of a fixed actuator motor for resonant operation with one rotational axis, using a monolithic piezoelectric actuator and a helical spring to generate normal force (Reprinted with permission from [31]).

Zhang et al. [32] published a first review on piezoelectric inertia motors in 2012. Their contribution gives a broad overview of motors described in the literature, describes the structure and functional principle of different motors in detail, and lists some performance data. However, some of the explanations and discussions are rather brief, and some aspects and recent developments—especially regarding inertia motors operating at high frequencies and/or without phases of stiction—are not covered. So, this contribution can be seen as a complement to the review by Zhang et al. [32] on some aspects of piezoelectric inertia motors, offers an alternative view on some other aspects, and discusses several topics not included in the previous review.

With this aim, Section 2 discusses the historical development of piezoelectric inertia motors and their applications in positioning and force generation. In Section 3, the basic functional principles of fixed and moving actuator inertia motors are explained in detail. This includes a definition of four modes of operation, two of which use sliding friction (and not stiction) for generating propulsion. Based on these concepts, the different terms used in literature to describe this type of motor are discussed, and a general definition is proposed in Section 4. Section 5 takes a closer look at the most relevant aspects regarding the design of inertia motors. The friction contact, the solid state actuator, and the electrical excitation are each discussed in detail; this includes aspects of control and simulation. Section 6 closes the article with a summary and an outlook on possible future developments and research perspectives.

2. History and Application Review

2.1. First Developments

The invention of piezoelectric inertia motors is commonly attributed to Pohl [33,34] or Higuchi et al. [35]. Anders et al. [36] should be mentioned on par with these two. They presented their work [36] in July 1986 at the same conference as Pohl [33] (First International Conference on Scanning Tunneling Microscopy (STM'86) in Santiago de Compostela, Spain, 14–18 July 1986; Volume 181 of "Surface Science" contains the proceedings of this conference, which include [33,36]), and submitted and published a paper at almost the same time as him. However, their paper was met with far smaller response than Pohl's.

In a work published in 1984 [37], Higuchi described electromechanical micropositioning devices. In a work published in 1987 [35], he transferred their functional principle to piezoelectrically-actuated mechanisms, so these devices can be regarded as predecessors of piezoelectric inertia motors. In fact, Söderquist already described devices for fine positioning using electromagnetic and piezoelectric actuators in 1973 in a Swedish patent [38]. These devices resemble the electromagnetic motors proposed by Higuchi [35,37]. They are not inertia motors according to the above definition, but impulsive manipulators [39]. Yet, they can be regarded as the first predecessors of today's inertia motors, even though it is unlikely that Söderquist's patents were known to the later inertia motor developers.

2.2. Positioning Applications

The first piezoelectric inertia motors were developed for horizontal positioning (e.g., in microscopy). In the years following the above-mentioned first publications, several researchers developed inertia motors in a multitude of designs. Practically all of these developments focused on microscopy applications, many related to the then-new scanning tunnelling microscopes and other scanning probe microscopes [40–47]. Many developments were not intended for industrial production, but for use in the developers' own laboratories. Reported improvements of motor designs mostly concerned the maximum slope a motor could handle—using mechanisms to generate a gravity-independent normal force, vertical motion was soon achieved [44,48–50]—and the integration of multiple degrees of freedom into one device [30,42,49–52]. Since 1990, the number of publications regarding inertia motors has continuously increased. (A search on Google Scholar and Scopus on

12 February 2013 showed that the number of publications regarding piezoelectric inertia motors increased by a factor of about 30 between 1987 and 2012).

Positioning in laboratory applications like microscopy [53], cell manipulation [54–56], and micro or nano handling [57–61] is still a main area of application for piezoelectric inertia motors today. Many companies have specialised in fabricating precision inertia motors for such applications. Figure 3 presents a survey of the maximum velocities and forces of commercially available inertia motors. Depending on the design, actuation forces up to 22 N or velocities up to 70 mm/s are obtained, but most motors reach less than 10 N and 20 mm/s. Especially the velocity is low compared to other types of piezoelectric motors (cp. e.g., [14]).

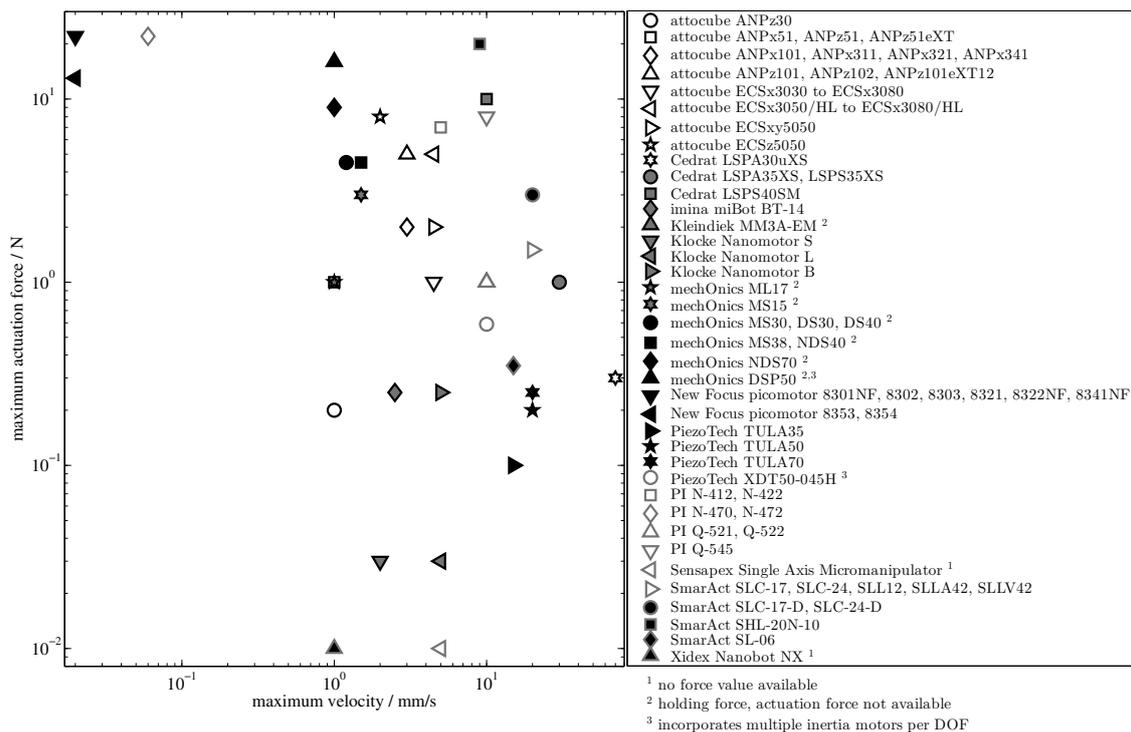


Figure 3. Maximum actuation force and velocity of commercially available translatory inertia motors. All are driven piezoelectrically, and apart from the imina miBot, all are fixed actuator motors. The Appendix A contains a list of companies.

Higuchi et al. [62] were the first to use inertia motors in a micro robot in 1990, and Saito and Nagano [63] described imaging applications in 1991. However, only in the late 1990s did the number of publications on non-microscopy applications of inertia motors began to grow significantly. Actual or intended positioning applications of inertia motors can be differentiated into two groups. This differentiation is often helpful when comparing inertia motors, as the desired motor characteristics differ significantly.

In one group of applications, high precision is of the highest priority; these applications will be called *precision applications* in the following sections. On the other hand, *velocity applications* prioritise high velocity and often low cost over precision. Application-oriented literature was focused on precision applications like micropositioning and microrobotics in the first years [57,64–67], and is nowadays dominated by velocity applications in miniaturised consumer goods [68], like zoom and autofocus mechanisms for miniaturised digital cameras as used in mobile phones [19–25]. Other investigated applications include braille cells [69] and discharge machining [70]. In commercial mass products, inertia motors provide zoom, focussing, and image stabilisation in digital cameras, for example by Sony [71], formerly Konica Minolta ([20]; [72] (p. 650203-7f)).

An inertia motor with a single fixed actuator can also move multiple objects, ranging from two masses—which can be moved independently by varying the driving signal [25]—to large numbers of microscopic particles [58]. To date, these remain niche concepts.

2.3. Force Generation

As the above survey shows, piezoelectric inertia motors are almost exclusively used in positioning applications with little to no force. Even in these applications, it is generally advantageous if a motor can provide a certain force, as this implies a certain robustness against disturbances such as wear and dirt. It also allows non-horizontal operation and fine-positioning applications where flexure hinges exert a small restoring force. Additionally, some of the positioning applications described above—such as cell manipulation [54–56] and micro or nano handling [57–61]—require a certain, yet usually low, force. One of the few examples where a larger force exerted by an inertia motor is used in an application is the indentation device developed by Rabe [73].

The force generated by an inertia motor has been investigated in only a few publications. It has been measured using different methods: making the slider move against a spring, the force is either determined from the deformation of the spring [61,74,75], or using a load cell connected to the spring [76,77]. Other authors make the slider move directly against a load cell [67,78–81], or the force is exerted to a part connected to a load cell instead of a slider [82]. (Bergander et al. [67] (p. 33) and Kang et al. [78] (p. 610) only state that they measured the force of the slider “with a precision balance” respectively “using a digital power gauge”. It is likely that this was done with direct contact between slider and measurement instrument.) Another option is to make the motor lift weights [83–85]. The force generation potential can also be estimated from the transient motor behaviour [86]. To what degree forces determined using these different methods with differing parameters can be compared has yet to be investigated. Recently, it has been shown that running the slider against a spring is a robust method of determining the force generation potential of an inertia motor, providing results independent of the spring stiffness as long it is sufficiently low ([87] (pp. 73–77), in short form also [77] (p. 7)). This method is also suited for non-iterative numerical simulation [87] (pp. 73–77). It thus appears as an advantageous measurement method for comparing the force generation performance of different inertia motors.

Controlled force generation with inertia motors has been investigated by Edeler et al. [79,88,89]. These works have shown that in the investigated motor, the generated force—determined using the spring method—depends on a number of parameters, such as slider mass, friction contact, pre-load, and excitation signal. An influence of the excitation signal on the generated force was also demonstrated for an inertia motor with a very different concept by Hunstig et al. [77,87]. Edeler and Fatikow [79] experimentally demonstrated for their motor that up to a maximum friction force, the producible force is approximately proportional to the friction force. This relationship was also shown theoretically for horizontally-acting high-frequency inertia motors by the author [87] (p. 92f).

3. Basic Functional Principles

All known realisations of piezoelectric inertia motors can be reduced to one of two basic designs. These are shown in Figure 1 with one linear degree of freedom (DOF) to explain their functional principle. The fundamental difference is whether the solid state actuator driving the motor is part of the fixed (“fixed actuator type”) or of the moving part of the motor (“moving actuator type”). A motor with multiple DOF can combine both types; for example, create linear motion with a fixed actuator, and rotation with a moving actuator [90]. Zhang et al. [32] additionally differentiate two types of “moving actuator” motor, based on which part of the motor (m_1 or m_2 in Figure 1b) is regarded as the object to be moved.

3.1. Fixed Actuator Type

Figure 1a shows the functioning of an inertia motor with fixed actuator and one translatory DOF in a simplified diagram with one phase of static friction and one phase of sliding friction. In the first step, the propulsion phase ①→②, the driving rod is moved with low acceleration in one direction. The mass m sticks to the rod, and is carried along because its inertial force is lower than the break-away force $\mu_0 F_N$, calculated from the coefficient of static friction μ_0 and the normal contact force F_N . In the second step, the retraction phase ②→③, the driving rod is moved back with high acceleration. The force required to carry the mass along is larger than the break-away force—the mass breaks loose and slides on the rod. If the retraction phase directly follows the propulsion phase, the mass continues to slide to the right due to its kinetic energy, while the rod returns to its starting position. If the mass is at rest before the retraction phase begins, it is moved to the left by the friction force, but this backward movement is smaller than the forward movement during the propulsion phase.

The result is an aggregate displacement of the mass, which can be arbitrarily multiplied by repeating the cycle described above. The first examples for such motors and the concept of their movement cycle consisting of alternating phases of static and sliding friction (“stick-slip”) are the motors by Anders et al. [36] and Pohl [34].

3.2. Moving Actuator Type

In inertia motors with moving actuator as shown in Figure 1b, a mass is attached to either side of the actuator. One of these masses is in contact with the underground and, through this contact, provides displacement of the whole motor. The functional principle of such a motor is shown in Figure 1b in a simplified form, with a stiction phase of slow extension (①→②) and a sliding phase of quick contraction (③→④). If the extension is sufficiently fast, the sudden stop at its end (②→③) can be utilised to generate additional displacement: the force required to instantly stop m_2 is larger than the break-away force; thus, m_1 breaks loose and the motor slides until its kinetic energy is dissipated in the friction contact. The total displacement per cycle is thus composed of up to two distinguishable steps. The first example of an inertia motor with moving actuator and the concept of its movement cycle was presented by Higuchi et al. [35].

Fixed and moving actuator motors share the advantages of inertia motors described in Section 1. Table 1 additionally lists some of their individual pros and cons. The main advantage of moving actuator motors is their “unlimited” displacement, while fixed actuator motors can generally be smaller and faster.

Table 1. Pros (+) and cons (–) of fixed and moving actuator inertia motors.

| Fixed Actuator Inertia Motors |
|--|
| + can use the kinetic energy of the slider for additional movement during/after retraction of the slider (relevant mostly in high-frequency operation) |
| + moving mass m can be very small, and has no effect on the frequency characteristics of the stator |
| + higher possible operation frequencies, thus higher possible velocities |
| – displacement limited by the length of the rod |
| Moving Actuator Inertia Motors |
| + additional motion can be generated by the “impact” of the mass m_2 (relevant mostly in low-frequency operation) |
| + does not require fixation |
| + displacement limited only by the surface it operates on and by the wiring |
| – requires a proper, well machined surface to operate reliably |
| – mass m_2 must be relatively large; this makes the motor heavy and limits excitation frequency and maximum velocity |

3.3. Modes of Operation

In a theoretical investigation of the idealised operation of inertia motors [91], four principally different modes of operation of fixed actuator inertia motors have been previously identified. Figure 4 shows the displacements and velocities of rod and slider of a motor as in Figure 1a driven with a parabolic sawtooth signal in these four modes of operation. They differ by two criteria: does the slider move in discrete steps or continuously, and is the propulsion of the slider achieved using stiction or by sliding friction only? The motor velocity in stick-slip operation or with discrete steps (Figure 4a–c) is limited principally, only continuous slip-slip operation (Figure 4d) allows very high velocities [91]. This is also true for real inertia motors which operate with multiple phases of stiction and sliding per cycle [92]. A drawback of slip-slip operation is that wear—which is influenced significantly by the applied excitation signal [92]—is generally higher than in stick-slip operation using similar excitation signals due to the increased sliding distance.

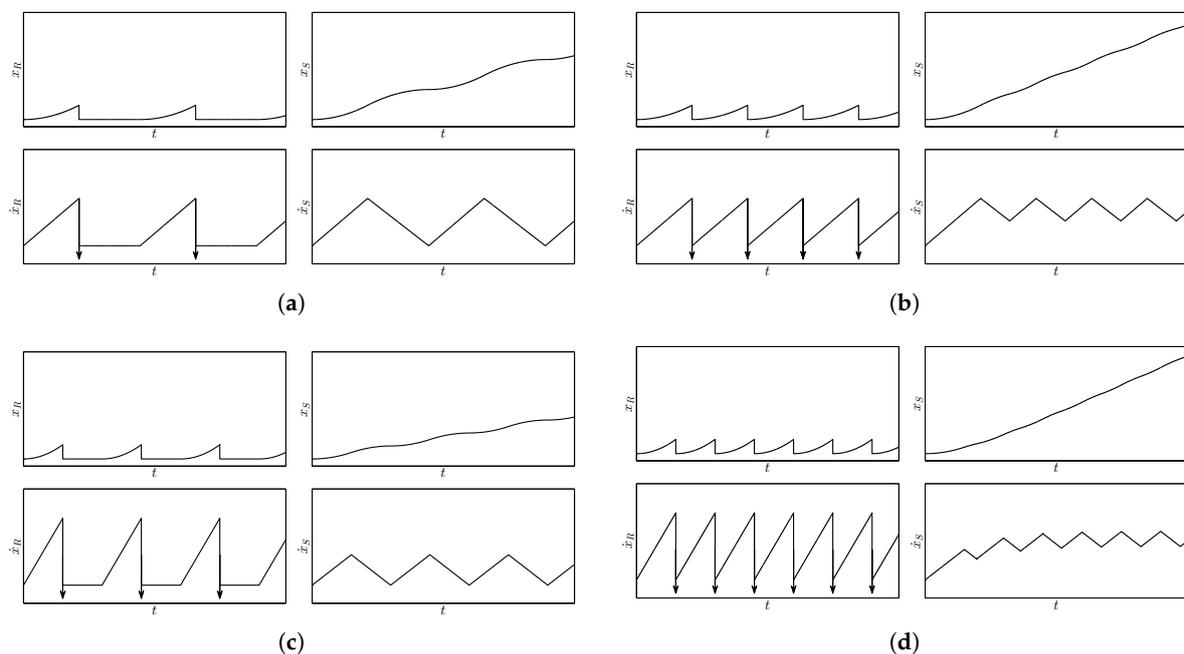


Figure 4. Simulated displacement (x) and velocity (\dot{x}) of rod (index R) and slider (index S) of a fixed actuator motor as in Figure 1a over time t in four modes of operation. All scales of the same type (time, displacement, velocity) are equal in all diagrams. (Diagrams from [91], reprinted with permission from Elsevier). (a) Discrete stick-slip operation: slider driven by stiction, at rest after each step; (b) Continuous stick-slip operation: slider driven by stiction, moves continuously; (c) Discrete slip-slip operation: slider driven by sliding friction, at rest after each step; (d) Continuous slip-slip operation: slider driven by sliding friction, moves continuously.

It is sometimes claimed in the literature that the coefficients of static and dynamic friction must be different for an inertia motor of either type to function (e.g., in [93] (p. 187)). It becomes clear that this is not necessary by taking a closer look at the slider movement in stick-slip operation (Figure 4a,b): in a horizontally operating motor as in Figure 1a, the *maximum* gradient of the rising flank (positive acceleration) of the slider velocity \dot{x}_S is

$$a_{0,\max} = \mu_0 F_c / m_S, \quad (1)$$

where μ_0 is the coefficient of static friction (stiction), F_c is the normal force in the contact between slider and rod, and m_S is the mass of the slider. The gradient of the falling flank (negative acceleration) is

$$a_d^- = -\mu_d F_c / m_S, \quad (2)$$

where μ_d is the coefficient of dynamic (sliding) friction. A velocity profile as in Figure 4a,b—where the average of \dot{x}_S over time is positive and the slider thus moves into the desired direction—can be achieved with almost any ratio of $a_{0,\max}$ and a_d . The rising flank does not have to be steeper than the falling flank; i.e., μ_0 does not have to be larger than μ_d . However, situations with $\mu_0 < \mu_d$ are very rare, can only occur with non-constant friction coefficients, and are not relevant in the practical applications of inertia motors. Thus, $\mu_0 \geq \mu_d$ is a valid assumption.

The same rationale can be applied to the “slip-slip” mode of operation (Figure 4c,d): if the acceleration of the driving rod is sufficiently high in the propulsion phase, the mass also slides in this phase, with the acceleration

$$a_d^+ = \mu_d F_c / m_S. \quad (3)$$

Equations (2) and (3) show that the acceleration of the mass is of equal magnitude in both directions, assuming constant μ_d and F_c . In continuous slip-slip operation, the mass is nevertheless accelerated over the first cycles, because with appropriate asymmetric driving signals, the opposing friction forces act for different lengths of time until the motor reaches its steady state, cp. Figure 4d. Such continuous slip-slip operation has been realised and described a few times [25,26,86,91,94] for fixed actuator motors.

Slip-slip operation is also possible in moving actuator motors, but has not been demonstrated in the literature to date. It must be noted that the actual movement cycle in an inertia motor of either type in any mode of operation can consist of a multitude of phases of static or sliding friction. It can thus be much more complex than in the principle explanations above.

The macroscopic stationary velocity \bar{v}_∞ of an inertia motor with a constant driving signal can be calculated as the product of its step size \bar{x}_∞ ; i.e., the displacement per cycle (typically ranging from several nanometres to some 10 μm) and its operation frequency f_1 (typically between 100 Hz and several 100 kHz):

$$\bar{v}_\infty = \bar{x}_\infty \cdot f_1 \quad (4)$$

Published velocities of inertia motors range from well below 1 $\text{mm}\cdot\text{s}^{-1}$ (especially in early setups for precise positioning [34,35,44]) to well over 100 $\text{mm}\cdot\text{s}^{-1}$ in current high-frequency motors, with the maximum of 750 $\text{mm}\cdot\text{s}^{-1}$ achieved by Nishimura and Morita [95]. It should be noted that the step size depends on the driving signal, and as such, can vary substantially in one motor. In particular, high-frequency motors operating in “slip-slip” mode in continuous operation show a very different step size when driven with only a single driving pulse (cp. Figure 4d), and in some motors, the step size can be modified to vary the velocity (cp. Section 5.3.4).

In the “stepping mode” described above, inertia motors can produce unlimited displacements (at least in principle), with a positioning resolution equal to the step size. The design of both types of piezoelectric inertia motors allows a second mode of operation often called “scanning mode” [67,96–99]. In this mode, the object to be moved (m in Figure 1a, m_2 in Figure 1b) is displaced by applying a DC voltage to the piezoelectric actuator. The resolution in this mode is typically below 1 nm [4,99–101], limited only by the resolution of the driving electronics. The stepping mode is an essential feature in many *precision applications* of inertia motors (cp. Section 2.2), while *velocity applications* mostly do not use the stepping mode. Combination of stepping and scanning operation into one controller has been demonstrated by Claeysen et al. [84].

4. Terminology and Proposed General Definition

As discussed in the above sections, numerous variants of piezoelectric motors exist. In the case of piezoelectric inertia motors, ambiguity starts with inconsistent naming in the literature. The movement cycle consisting of stick and slip phases as shown in Figure 1 has sparked terms like “stick-slip mechanism”, “drive”, “actuator”, or “motor” [41,51,97,102–107], which are mostly

used for fixed actuator motors. However, these terms are not always appropriate, and also not unambiguous. Firstly, if forward and backward movement of the actuator are sufficiently fast or superposed by high-frequency oscillations, there is no stable phase of stiction. Secondly, there are motors (e.g., the nanopositioner by Voigtländer et al. [108] or the “stick-and-clamp” mechanism by Lee et al. [109]) which use alternating phases of stiction and sliding for propulsion, but not the inertia of the driven object.

“Impact drive” is a common denomination for inertia motors with a moving actuator. This term was coined by Higuchi et al. [110], who for the first time used the fast stopping of a mass, which has an effect on a connected second mass (cp. Figure 1b) similar to an impact, to generate displacement in their moving actuator inertia motors [35]. Okamoto and Yoshida [26] picked up this term for their fixed actuator inertia motor, and expanded it to “smooth impact drive mechanism” (SIDM), a term also used later by other authors.

“Stick-slip drive” and “impact drive” are also occasionally used to differentiate inertia motors with fixed actuator from those with moving actuator ([111] (p. 36f); [112]). This differentiation seems justified, as only moving actuator inertia motors can use an “impact” on the motor to generate additional displacement, but this explanation is rarely found in literature [111] (p. 37f). The use of the different terms rather seems to have historical reasons: “impact drive (mechanism)” is used for moving actuator motors, and mostly by authors whose works are to different extents based on the early works of Higuchi et al. [35,110] on this type of motor; e.g., in [64,70,113–116]. The derived term “smooth impact drive mechanism” is used for fixed actuator motors by authors who directly or indirectly refer to the works of Okamoto, Yoshida et al. [26,117,118] (e.g., in [25,95,119,120]). On the other hand, “stick-slip drive” or similar has been used for inertia motors of any design, even if they clearly have a moving actuator; e.g., the motors of Niedermann et al. [41] and Smith et al. [51].

Zesch [65] differentiates inertia motors based on the ratio of the two moving masses. Referring to a schematic like Figure 1b, he writes: “In its general form—both m_1 and m_2 are non-zero—the inertial drive is known as *Impact Drive* [...] The setup, when m_1 decreases towards zero, is often called *Stick-Slip Drive*” [65] (p. 36). This differentiation is also found in the works of Breguet [66] (p. 12) and Driesen [121] (p. 56). In fact, m_1 and m_2 are of similar magnitude in most moving actuator motors, and the dynamics of fixed actuator motors can be improved by reducing the mass of the driving rod. However, a low mass m_1 is also beneficial for moving actuator motors, and a fixed actuator motor can—albeit with worse dynamics—also work with equal masses of driving rod and payload. It is thus questionable whether such a differentiation is meaningful.

One essential feature of this type of motor is independent from the design and the employed type of actuator: using the inertia of a mass to drive this mass through a friction contact with permanent or intermittent sliding. Many authors thus describe these motors as “inertial slider”, “inertial sliding drive”, “inertia slip drive”, “friction-inertia actuator”, or similar [32,42–44,47,49,122–128], also as a comprehensive term when differentiating between “stick-slip drive” and “inertial drive” [65,111,121]. Zhang et al. [32] (p. 674) criticise short terms like “inertia motor” as misleading, because they omit the friction necessary for the motor to function. (Sliding) friction is indeed essential in these motors. However, as it also occurs in other technically relevant piezoelectric motors (cp. e.g., [13,129,130]), it is not a suitable differentiating feature. So, in the search for a descriptive yet concise name for this type of motor, “inertia motor” appears to be the best candidate. It is thus used throughout this publication. This and similar terms are also occasionally used for (fictional) motors creating propulsion without repulsion, thus violating Newton’s third law of motion—“*actio est reactio*”. Such motors are found in science fiction, but have also been and still are being developed [131] and applied for a patent, for example by Davis [132] and Lasch [133]. As their supposed functional principle obviously violates fundamental physical laws, there are only a few critical discussions of such motors in the literature, like those by Adams [134] and Millis and Thomas [131]. It should be noted that also driving a body by using its inertia is not exclusive to inertia motors, but for example is also done in vibratory conveyors [135].

This discussion of terminology gives an indication of the diversity of inertia motors and of the difficulty of finding a clear yet comprehensive definition of this type of motor. The following general definition of an inertia motor has been proposed earlier by the author [87] (p. 9). It is based on studying more than 300 publications, and covers a wide range of motors with very different designs and for very different applications. It is formulated for a motor with one translatory DOF, but is just as valid for rotatory motors and motors with multiple DOF:

In an inertia motor, an actuator of limited stroke, acting essentially parallel to the motor axis, drives an object through an uninterrupted contact. The object can travel a distance larger than the actuator stroke. The inertia of the object is essential for its movement.

How any specific motor should be categorised is determined by its construction and by its electrical control. For example, the inertia motor stepping mode (cp. Section 3.3) is used as an alternative operating mode in several motors with a different preferred mode of operation ([108] (p. 10); [136]; [137] (p. 24)). Additionally, inertia motors with quickly changing normal force can operate like standing wave motors (cp. Section 5.1.1).

5. Design Aspects

The basic construction of inertia motors is simple: they consist of few parts which are easy to manufacture and are generally controlled by a single electrical signal per DOF. (In resonant motors like the one described by Tuncdemir et al. [138]—where different modes of vibration can be excited by varying the excitation signal—it is possible to (sequentially) use multiple DOF with only one electrical input.) In its simplest form, an inertia motor with one DOF as in Figure 1a consists of three parts: a solid state actuator and a driving rod, forming the stator of the motor, and a slider moving along the rod. The friction contact between rod and slider, the solid state actuator, and the electrical excitation are the most important aspects in the design of an inertia motor, and shall be reviewed in the following.

5.1. Friction Contact

Figure 5 shows a rigid body model of a simple translational inertia motor, which will be used in the following discussion of the friction contact: a slider of mass m_S hangs below the driving rod. $x_R(t)$ and $x_S(t)$ are the displacements of the rod and slider, respectively. The contact force $F_c(t)$ between rod and slider results from the gravitational force F_g and an external force $F_z(t)$, both acting on the center of gravity C of the slider. The friction force $F_f(t)$ acts between rod and slider. This contact has a tangential stiffness k_t .

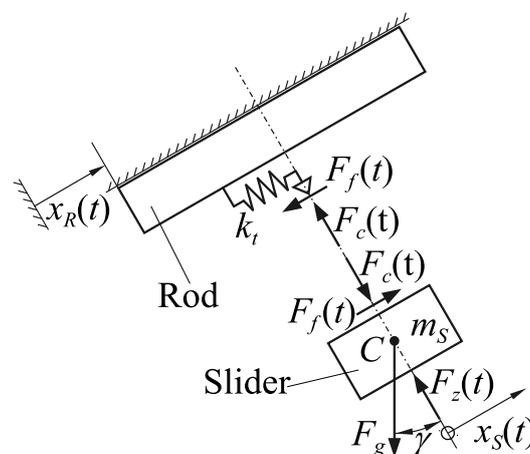


Figure 5. Rigid body model of a simple translational inertia motor.

5.1.1. Generation and Variation of Normal Force

In inertia motors operating horizontally or with small angles of inclination, the weight of the slider can produce sufficient contact force $F_c(t)$ if the slider is placed on top of the rod. However, most inertia motors incorporate an additional mechanism to generate normal force independent of gravity, which is indispensable in applications with larger angles of inclination. Generally, the normal force $F_z(t)$ produced by these mechanisms is constant over one actuation cycle. It is produced by permanent magnets (Figure 2d, [30,50]; [89] (p. 15f); [93,139–141]) or by elastic deformation, for example, of metal springs (Figure 2a,c,e, [26,31,44,75,76,142]) or rubber rings (Figure 2b, [27,77,138]). The normal force generated by all these mechanisms can change over time due to wear, ageing, or creep. A robust inertia motor construction must consider this by using appropriate design and material. In micro motors, it should also be possible to use adhesive forces as in the surface acoustic wave motor by Shilton et al. [143], but this has not been realised in an inertia motor to date.

The literature contains some examples of inertia motors with quickly changing normal force, realised by piezoelectric actuators [144], electromagnets [113,145], electrostatic forces [43,140,146], or inertial forces [147,148]. In all these motors, the normal force is increased in the propulsion phase, during which a large tangential force shall be transmitted, and/or decreased in the retraction phase, during which a low friction force is desired. Compared to these examples, increasing the normal force depending on the macroscopic position of the slider and the temperature using a shape memory actuator as proposed by Sasaki [21] is a slow process.

Normal force variation can also be achieved by the acceleration created by the primary actuator, without the need for a second actuator, in which case normal and translational force are coupled. This has been realised in moving actuator motors through a suitable geometric design by Rass and Kortschack [112], and by making the actuator exert a force with a certain normal component by Cheng et al. [149] and Wen et al. [150]. Such a setup can also be used in fixed actuator motors, where a suitable suspension of the slider—as in the motor by Li et al. [151]—can reduce the effect of the acceleration on the normal force. As this effect is geometrically determined, it is directional: when the motor moves in one direction, the normal force is increased during the propulsion phase and reduced during the retraction phase, as desired. The effect is negative when the motor moves in the other direction, which can even prevent bidirectional motion. Thus, this is an option to build an inertia motor with a *preferred direction of motion due to a direction-dependent normal force*.

Mechanisms for quickly changing the normal force can extend the field of applications of inertia motors, but also diminish two advantages of inertia motors: if equal bidirectional motion shall be possible, both construction and control of the motor are much more complex compared to a passive solution, and single signal control is no longer possible. The additional actuator for normal force variation consumes additional energy, which can offset possible energy savings from the normal force variation. These motors also work at the boundary of the inertia motor principle defined in Section 4: if the modulation of the normal force is large enough, the inertia in the translatory direction is no longer essential for the function of the motor. This is the case, for example, in the motors by Burisch et al. [144] and Wen et al. [150], or the vibratory conveyor by Frei [152], which consequently do not require asymmetric excitation signals: if the normal force is reduced to zero in the retraction phase, the motor operates with lift-off instead of sliding.

5.1.2. Friction Couple

Due to the finite tangential stiffness of real friction contacts—which can be included in contact models as a stiffness k_t as shown in Figure 5—a certain displacement between rod and slider is always required before sliding can occur. Sliding can only begin if

$$|x_R(t) - x_S(t)| > \mu_0 F_c / k_t. \quad (5)$$

In order to keep the amount of actuator stroke “lost” in the contact compliance to a minimum, it appears reasonable to use tangentially stiff contacts (i.e., high k_t) in inertia motors. Most inertia motors described in the literature—especially those designed for microscopy applications—use hard materials for the friction couple. Aluminum oxide (Al_2O_3 , sometimes as a ceramic, in most cases in crystalline form as corundum and its varieties sapphire and ruby) predominates [104,105,126,153–157], but quartz (SiO_2) [49,104,154], different glasses [105,158,159], or other ceramics [158] are also used. Combinations of one of these hard materials and metals are also common, mostly with steel [30,44,51,52,78,96,139,160,161] or bronze [49,162,163], sometimes also with other metals [49,164–166]. A steel–steel couple is also used sometimes [34,47,50,62,84,157], while couples of steel with other metals [167], of two relatively soft partners like bronze [168], or with a very soft partner like polytetrafluorethylene (PTFE) [169,170] or other plastics [84,118,138,171,172] are rare.

Some authors have experimentally compared different friction couples in inertia motors (e.g., [41,84,113,173–175]). Bergander [111] (pp. 81–105) compared contacts of sapphire hemispheres with differently coated surfaces of steel, aluminium, and silicone regarding wear. Edeler et al. [176] compared rough and polished steel, aluminium, and bronze surfaces in contact with ruby hemispheres. They observed larger steps with polished surfaces and harder materials [176]. Similarly, Claeysen et al. [84] observed larger steps with a steel–steel contact compared to a steel–polymer contact in most setups. While these observations confirm the intuitive expectation that tangentially stiff contacts are beneficial, the optimum friction couple appears to depend on the motor design, its excitation, and application. For example, Bergander [111] (pp. 81–105) found materials to compare differently with different normal forces, Ko et al. [175] observed that their high-frequency motor required different friction couples to reach its maximum velocity and its maximum actuation force, and the experiments by Claeysen et al. [84] (p. 625) showed a different influence of the moved mass on the motor velocity with different friction couples.

The characteristics of a friction contact are not only determined by the material couple, but also by the surface structure and treatment. Inertia motors in literature often use surfaces which have been polished to different degrees or even lapped, but many authors make no mention of the surface at all. Hardening surface treatments like anodising [124] are rarely described.

Wear in inertia motors—even though it is an aspect closely linked to friction—has barely been looked into apart from the investigation by Bergander [111], recent work by Dubois et al. [172], and investigations by Hunstig et al. [77,87,92] on the influence of the excitation signal. Wear is a critical aspect, especially if inertia motors are used commercially, as it can change the characteristics of the friction contact and thus the motor behaviour over time, resulting in final dysfunction [172]. Claeysen et al. [84] found a steel–steel contact became unreliable after 5000 full strokes of their motor. As a means to increase motor lifetime, Hata and Okamoto [177] proposed a “self-cleaning mode” in which the slider pushes wear debris off the driving rod, and recesses where debris can accumulate without disturbing the motor operation.

In most cases, sliding friction forces causing wear act directly between slider and rod in fixed actuator motors, respectively, between motor and working surface in moving actuator motors. Kortschack et al. [178] presented the first form of a moving actuator motor which was later refined [89] (p. 15), and in which the force acts through a rotating steel ball, so that the working surface is only affected by rolling friction.

Practically all inertia motors use dry friction contacts. There are only very few investigations of lubricated inertia motors, possibly because the well-known early motor by Pohl showed a significant loss of velocity and load capacity if lightly lubricated with machine oil [34]. Anantheshwara et al. [157] compared lubricated and dry steel–steel couples, using the same control signal for both cases. The fact that lubrication reduced the step size of their motor should not be seen as proof of a general disutility of lubrication in inertia motors, as two motors with different friction couples have different optimal control signals. In fact, the experiments by Furutani et al. [113] with steel couples and different lubrication fluids indicate that lubrication can be beneficial for different reasons. It increases the

uniformity of the contact, resulting in less variation of the step size and less movement of the slider perpendicular to the contact [113]. With lubrication, they achieve the same or a slightly higher velocity than without, and the lubricant additionally prevents corrosion. The viscosity of the lubricant seems to be irrelevant at the low investigated velocities [113]; the influence of lubrication on wear was not investigated. In the investigations by Bergander [111] (pp. 81–105), coating the steel surface—which is in contact with a sapphire counterpart—with solid lubricant molybdenum disulfide (MoS_2) was also beneficial for the repeatability of movements and reduced wear.

If the surface structure of either friction partner is structured directionally, the effective coefficient of friction is direction-dependent. In the investigations by Zhang et al. [81], such a surface increases—for equal driving signals—velocity and force for one direction of movement while decreasing the velocity for the other direction, with the force unmentioned. This is thus an option to build an inertia motor with a *preferred direction of motion due to a direction-dependent friction coefficient*.

Such motors can be advantageous in certain applications. However, like motors with a preferred direction of motion due to direction-dependent normal force (as discussed in Section 5.1.1), they work at the boundary of the inertia motor principle defined in Section 4: if the difference in friction force is large enough, the inertia in the translatory direction is no longer essential for the function of the motor.

5.1.3. Friction Contact Simulation

The development of mechatronic components (e.g., small electrical motors like the ones discussed in this work) nowadays almost always includes simulation, both in industry and academia. Simulation allows the prediction and optimisation of the performance and the identification of influencing parameters in the design phase. It thus helps to produce better products in less time.

To simulate the motion of an inertia motor, appropriate models of the solid state actuator, the dynamics of the moving parts, and the friction contact are required. The friction contact is the most difficult part to simulate, with its special conditions of small displacements, high relative velocity, and frequent direction changes. It requires an elaborate model choice, and shall thus be briefly discussed in this review.

In so-called “kinetic” friction models, the coefficient of friction is a function of the relative velocity v_r between the friction surfaces. Such kinetic models are sufficient for many technical applications. However, they cannot describe a number of effects observable in certain contacts, like a hysteresis between v_r and the coefficient of friction, an influence of the test conditions on the break-away force, and a tangential displacement in the friction contact during stiction (“micro-slip”). Numerous models, such as the “Dahl model” [179] and the “LuGre model” [180] have been developed to model some or all of these effects.

Liu et al. [181] present a recent survey of different friction models applied to inertia motors. There is no general result as to which model is best suited for this application. Altpeter [182] compared several friction models for the simulation of inertia motors, and concluded that applications with small displacements require complex friction models, while motors with larger displacements can be simulated with sufficient accuracy using kinetic friction models [182] (p. 24). Motors are regarded to have a small displacement if the actuator displacement is in the same order of magnitude or smaller than the “characteristic displacement”

$$s = \mu_0 F_c / k_t \quad (6)$$

with the break-away force $\mu_0 F_c$ and the tangential stiffness of the friction contact at rest k_t (cp. Figure 5).

All works that have so far investigated the friction contact in inertia motors in more detail and see the necessity for more sophisticated friction models concentrate on motors with step sizes in the nanometre range [66,124,182–184]. Kang [185], Chen et al. [107], and Peng and Chen [186] have used the elastoplastic friction model [187] to model inertia motors with step sizes in the range of 10 μm , but their contributions do not show an advantage of the used friction model over a classic Coulomb model. So, Altpeter’s thesis—that kinetic friction models are sufficient for motors with actuator displacements which are large relative to a characteristic displacement—remains unrefuted. In addition, experiments

performed by the author show that a “large displacement” inertia motor operating at relatively high frequencies can successfully be modelled using a kinetic friction model [77,87].

One aspect not covered by such models is the often-observed increase of the break-away force after a long period of standstill. This is only relevant in the moment of start-up after standstill, and can easily be overcome by an adapted starting signal, as proposed by Yoshida et al. [188].

In almost all contributions found in the literature, the friction partners are described as rigid bodies, and all modelling effort is put into the friction model. Teidelt et al. [184,189] take a different approach, and show that a kinetic model can be sufficient to model even an inertia motor with nanometre-sized steps if the mechanics of the contact are modelled with sufficient detail. We can conclude that there is no standard friction contact model for inertia motors to date. Thus, there is much room for further research.

5.2. Solid State Actuator

Their high bandwidth and robustness, and the ability to generate fast as well as slow bidirectional motion predestines piezoelectric actuators for use in inertia motors [190] (p. 176). Usually, lead zirconate titanate (PZT) ceramic actuators are used. Recently, Yokozawa et al. [119] presented the first inertia motor driven by a non-PZT piezoelectric actuator. As research on lead-free alternative materials progresses, we will see more such motors in the future. However, PZT is very likely to remain the dominant material in commercial applications for the coming years.

Different actuator designs can be used: axial actuators in monolithic (Figure 2e, [68,191]), stack (Figure 2a, [26,28]) or multilayer design [26,149,192], axial actuators with transmission mechanism [192,193], shear actuators (Figure 2d, [30,90,153,155,157]), bending actuators of different types (Figure 2b,c, [24,27,28,105,194]), and other designs developed especially for use in inertia motors [195]. There is no general rule as to which type of piezoelectric actuator is most beneficial for inertia motors, as this depends on the particular application. Bergander [111] (p. 39f) presents a short discussion of the pros and cons of different piezoelectric actuators in inertia motors, together with additional literature references.

If no nonlinearities must be considered (cp. Sections 5.3.1 to 5.3.3), standard models for piezoelectric transducers are sufficient for modelling the dynamic behaviour of the actuator in an inertia motor. Depending on the dynamics of the driving signal, a one-DOF model is often sufficient. For high-frequency excitation, two or more DOF can be required [82]. The details of such models are beyond the scope of this work, and shall not be reviewed here.

Inertia motors can also be designed based on other (non-piezoelectric) actuation principles. Electro- and magnetostriction are effects similar to piezoelectricity causing solids to deform in an electric or magnetic field, respectively. A comparison of the three effects can be found in [196]. The use of electrostriction in inertia motors has been proposed in several patent applications [197–202], but no realisation is known to date. Translatory and rotatory motors based on magnetostriction were investigated in the 1990s in NASA’s “Jet Propulsion Laboratory” [203,204]. Their ability to work at cryogenic temperature was seen as the main advantage over piezoelectric actuators which only reach very low strokes at very low temperatures [205]. Later, Zhang et al. [206] built a translatory magnetostrictive inertia motor, stating the high sensitivity of piezoelectric ceramics towards tensile and bending loads and their poor machinability (which would limit miniaturisation) as their motivation. Ueno et al. [207] argue similarly when presenting a magnetostrictive motor inspired by the “smooth impact drive” [117].

Yamagata et al. [208] presented an inertia motor using the fast thermal expansion and the relatively slow contraction of heated components. This actuation principle can only be applied effectively to small parts, because their fast heating can be achieved with moderate power, and their passive cooling occurs quickly enough for acceptable repetition rates and thus velocities. As they can be quickly heated, but not cooled, bidirectional operation requires a design with different heatable areas for different directions of motion, as shown by Yamagata et al. [208]. The heat is introduced by resistive

heating [208] or laser radiation [209–211], and electromagnetic waves are another option. The two last-mentioned options do not require an electrical connection to the moving parts, which can be advantageous in certain applications [208] (p. 144).

Apart from the examples described above, most motors resembling inertia motors and using, for example, electromagnetic or electrostatic forces are not inertia motors, but impulse manipulators [39]. Real non-piezoelectric inertia motors are rare, and as the above-mentioned cases show, have advantages over piezoelectric actuation only in very limited fields of application, like wireless or cryogenic operation. In all other applications, piezoelectric actuation is predominant, and this is likely to remain the case for the foreseeable future.

5.3. Electrical Excitation

5.3.1. Nonlinearities in Piezoelectric Actuators

The strain of PZT actuators is not only determined by the electrical voltage, but also depends on the temperature [212] (pp. 110–129) and on the mechanical boundary conditions, especially on the prestress of the actuator ([212] (pp. 110–129); [213] (pp. 97–112)). The voltage–strain relationship in piezoelectric actuators is often described by linear equations as a first approximation, but in fact shows several nonlinear effects. At large signals, the nonlinear behaviour is dominated by changes in the microscopic structure, which do not appear at small signals [214]. Piezoelectric actuators driving inertia motors in stepping mode operate with large voltage gradients; thus, large-signal nonlinearities are relevant. These mainly manifest in hysteresis and creep, illustrated in Figure 6: hysteresis (Figure 6a) results in a non-unique correlation of voltage and strain. If the voltage increases, the strain follows a different course than during a following voltage decrease ([215] (pp. 15–16); [216] (p.p. 24–29)). Creep (Figure 6b) means that after a quick change of voltage and strain, the strain continues to increase or decrease over time. The magnitude of this creep not only depends on the height of the voltage step, but also on the total applied voltage [213] (pp. 55–71). The strain first increases with an approximately logarithmically decreasing gradient, then—after a long time in the range of 1000 s—slowly decreases again [213] (pp. 55–71).

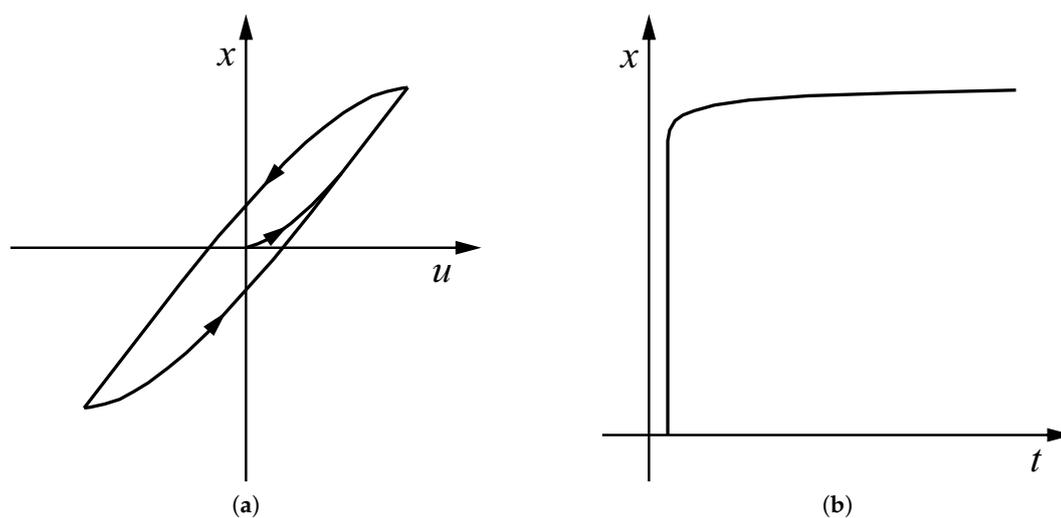


Figure 6. Qualitative illustration of the nonlinear large-signal behaviour of piezoelectric actuators (adapted from [215] (pp. 15, 17)). (a) Hysteresis between voltage u and deformation x ; (b) Creep of deformation x over time t after a voltage step.

Numerous publications deal with the modelling of these nonlinearities and their compensation in open-loop and closed-loop control of piezoelectric actuators in different applications; e.g., [213,215–229].

5.3.2. Open-Loop Operation

Using inverse models of the nonlinearities described above, they could also be compensated in open-loop inertia motors. However, the modelling and parameterisation is rather complex, and the benefit in stepping mode is very limited, as also found by Edeler et al. ([89] (pp. 94f, 128f); [183] (p. 79)): as the voltage either changes quickly or equals zero between steps, there is hardly any creep; hysteresis has little effect because the exact course of the deformation is not essential for the motor motion. This is one reason why no realisation of a model-based compensation of nonlinearities in the stepping mode of an inertia motor is found in the literature. Ha et al. [114] describe and simulate such a compensation, but show no experimental validation.

Hysteresis and creep are much more relevant during precise positioning with inertia motors in scanning mode. As an inertia motor in scanning mode is essentially a solid-state piezoelectric positioner, all open-loop compensation techniques developed for such actuators, described, for example, in [215,221–226,228,229], are applicable. Two additional options are discussed in the following stanzas.

One reason for hysteresis and drift is the fact that the charge on the actuator drifts if a constant voltage is applied. This behaviour can for example be described using a nonlinear capacitance [101,218]. Thus, charge-controlled driving is a way to significantly reduce hysteresis and creep without extensive control effort. This has been known since the early 1980s [230,231]. Charge-controlled driving of piezoelectric actuators is occasionally used in technical applications [232], but the realisation of simple and flexible charge amplifiers is not trivial, and continues to be an object of research [233–236]. Especially in low-frequency operation, most amplifier concepts show unacceptable drift ([101]; [215] (p. 2); [233]), and partly require actuator-specific calibration [101]. For these reasons, charge-controlled driving of piezoelectric actuators is far less common than voltage-controlled driving in both commercial applications and laboratories. Špillar and Hurák [234] have presented the only example of a charge-controlled piezoelectric inertia motor in the literature reviewed in this work.

Connecting a capacitor in series with the piezoelectric actuator reduces the effect of the actuator capacitance on the actuator charge, and thus constitutes another simple option for reducing hysteresis and creep [101]. Investigations by Minase et al. [101] show that an actuator may even show less hysteresis in such a setup than in a simple charge-controlling circuit. However, the additional capacitance also reduces the voltage at the piezoelectric actuator, and thus the stroke at equal input voltage [101,237]. Probably due to this major disadvantage, this technique is not used in inertia motors.

It can thus be stated that piezoelectric inertia motors in open-loop operation are generally driven with a voltage signal containing no compensation for piezoelectric nonlinearities.

5.3.3. Closed-Loop Operation

Closed-loop control is another option to compensate piezoelectric nonlinearity and other disturbances of the system. Two kinds of feedback control can be implemented in an inertia motor, as exemplified in Figure 7: the (slow) motor controller tracks a desired position or velocity by performing steps in either direction together with adjusting the step size and possibly also the frequency, thus compensating deviations in step size. The resolution of such a control is limited to the minimum step size. This type of controller can be realised without severe difficulties with an appropriate sensor and control electronics, and is available with many commercial inertia drives for fine positioning. Some examples of such controls from scientific literature are described and discussed by Liu et al. [181] (pp. 102–104).

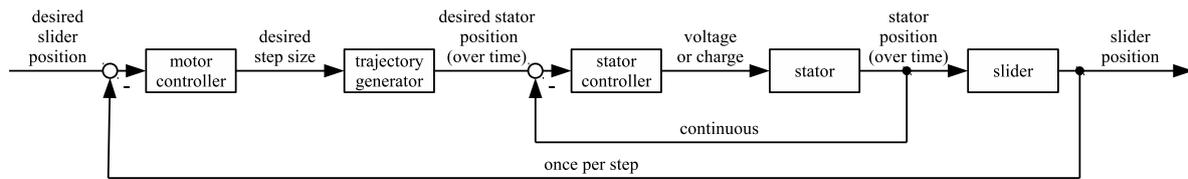


Figure 7. Schematic representation of an inertia motor incorporating a piezoelectric stator actuator, feedback-controlled with a (fast) stator control loop and a (slow) motor control loop.

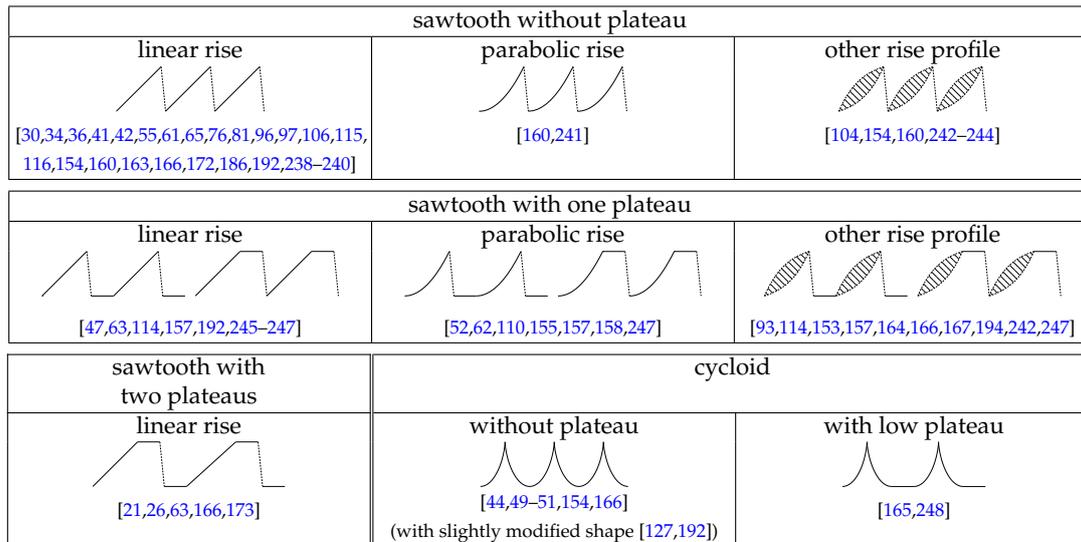
A (fast) stator controller would track the stator trajectory during each step, thus compensating, for example, piezoelectric nonlinearities, but not external influences such as a fluctuating friction force. While control electronics with sufficient bandwidth are currently available, the required sensor is the main issue limiting the use of such a control in inertia motors: it must possess sufficiently high resolution and bandwidth, and must not disturb the system. It would also have to be small and affordable for commercial applications, which disqualifies the laser vibrometers commonly used in laboratory experiments. Piezoelectric “self-sensing” as used by Chao et al. [127] could be one way to overcome this limitation, but offers only an indirect and thus less precise velocity measurement. For these reasons, and because piezoelectric nonlinearities have little effect in the stepping mode of an inertia motor (cp. Section 5.3.1), stator feedback control is not common in inertia motors.

5.3.4. Voltage Signals for Low-Frequency Operation

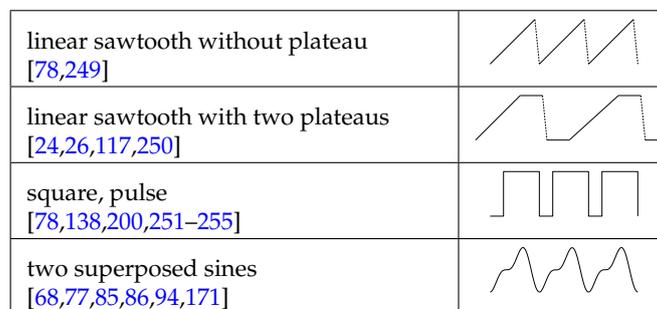
In stepping mode (cp. Section 3.3), all early inertia motors were driven with a periodic sawtooth signal with a slowly rising, respectively falling, voltage for the propulsion phase and a quickly falling, respectively rising, voltage for the retraction phase. Such a signal intuitively appears to be reasonable, and it is still used in most inertia motors. Over the years, different variants of this signal have been applied, differing mostly in the shape of the slow edge and by the existence of phases of constant voltage (“plateaus”) between the edges in some signals. Figure 8a contains a compilation of frequently used driving signals for low-frequency inertia motors, which shall be discussed in this section. (In a number of publications, particularly about early inertia motors, a “sawtooth” voltage signal is mentioned without further specification. Classically, this term describes a signal with linear rise and sharp drop. It is included as such in Figure 8a, assuming that otherwise the authors would have described the signal in more detail.)

Anders et al. [36], Pohl [34], and many after them have used a linearly rising voltage for the propulsion phase. Higuchi, Yamagata et al. [110,158] have shown that a parabolic rise of the voltage can be reasonable to reach a constant acceleration, and thus a constant inertial force. They also explain that the large acceleration occurring when the voltage stops increasing can be used to generate additional displacement in moving actuator motors (cp. Figure 1b). While this parabolic sawtooth is the ideal signal to reach high velocities with low-frequency stick-slip inertia motors [91], many other sawtooth-like signals with different shapes of the rising flank and with plateaus of constant voltage—to allow motor vibrations to settle—have also been used.

Renner et al. [44] regard the existence of two opposing acceleration peaks as the main disadvantage of a sawtooth excitation signal, and introduce a cycloid driving signal. Subsequently, this type of signal has frequently been applied—sometimes with variations to be able to generate the signal using analog circuits, as then digital-to-analog converters did not have the necessary dynamics [49]. For similar technical reasons, some authors have used simple driving circuits in which the slow edge of the signal is determined by the discharge curve of a capacitor [164,167,244].



(a)



(b)

Figure 8. Voltage signals for piezoelectric inertia motors with examples from literature. (a) Commonly used in low-frequency inertia motors; (b) Used in high-frequency inertia motors.

Matsuda and Kaneko [45] present a motor operating with single cosine waves. This demonstrates that an inertia motor in single-step operation does not necessarily require an asymmetric driving signal, but this signal remains unique in literature.

Several authors have compared different excitation signals [154,160,256], but come to different conclusions. While Bordoni et al. [122] only reach a smooth and reproducible motion with cycloid signals, Silveira and Marohn [163] found a sawtooth signal to produce larger and more uniform steps and to perform better at low temperatures than a cycloid signal. Stieg et al. [243] found different signals to be best suited for upward and downward vertical motion. Smith et al. [165] found sawtooth excitation to be most efficient, but mention that a cycloid signal was more effective with larger moving masses. Chang and Li [192] compared sawtooth, pulse, and cycloid excitation. They reached the largest steps using sawtooth excitation, and the highest velocity using pulse excitation. Anantheshwara et al. [157] compared different sawtooth signals experimentally, and concluded that a high slider velocity at the end of the propulsion phase leads to large steps—a result consistent with the analytical investigation by Hunstig et al. [91]. Neuman et al. [93] and Shrikanth et al. [247] obtained the same result in their numerical and experimental studies. Wang and Lu [166] investigated a motor which reached both larger maximum and smaller minimum steps with sawtooth excitation than with cycloid excitation. In contrast to the investigations referred to above, they conclude from a comparison of different sawtooth signals that a signal with decreasing acceleration in the propulsion phase and short phases of constant voltage before and after the steep edge are beneficial. They attribute this to creep of the piezoelectric actuator.

In motors operating with discrete steps, the velocity is the product of step size and frequency. Thus, there are different ways to adjust the velocity of such a motor: adjust the step size by adjusting the amplitude of the driving signal (“amplitude control”), adjust the frequency via the length of an idle period between the steps (“idle time control”), adjust the frequency by changing the length of one step (“step width control”), and combinations of these techniques. Their pros and cons have been discussed previously [257] (p. 940f). As idle time control is the only technique allowing the use of one optimised signal for any velocity, it should be preferred in most cases.

Any periodic signal can be described as a sum of sinusoidal oscillations (e.g., as a Fourier series). These oscillations are also known as the harmonics of the signal. The driving voltage signals for low-frequency inertia motors (cp. Figure 8a) differ substantially from a sine wave, and thus contain numerous harmonics of significant amplitude. Typical signal frequencies of low-frequency inertia motors range from several 100 Hz to some kHz. Thus, these motors emit audible noise at the signal frequency and its first harmonics, which can be a severe drawback in some applications.

5.3.5. Compensation of System Dynamics for Higher Velocity in Low-Frequency Operation

Self-oscillation of a system can generally be neglected if the frequencies of all significant harmonics of the excitation signal are low compared to the first natural frequency of the system. Typical low-frequency inertia motors have natural frequencies between some kHz and more than 100 kHz, and are driven with signal frequencies between several 100 Hz and some kHz, thus justifying this neglect to a certain degree.

The vibrations caused by the strong high-frequency harmonics of sawtooth and cycloid signals have already been observed by Pohl [34]. These vibrations have an effect on the motor operation, but can be neglected without dramatic effect, as long as they decay before the next excitation [66,115]. For this reason, some authors include decay phases in their excitation signals [47,164]. Compared to these vibrations (which stem from the piezoelectric actuator), the white noise generated in the sliding friction contact is small, and can be neglected in first approximations [258].

The literature contains different approaches to increasing the usable frequency range and thus the motor velocity. Bergander and Breguet [259] use the technique of “input shaping” [260] to modify the sawtooth input signal such that self-oscillation of the system is suppressed to a large extent. Teidelt [189] (pp. 60–63) used a similar approach. Zesch [65] also starts from a sawtooth signal and removes its higher harmonics to avoid any high-frequency excitation of the motor. Zou et al. [261] calculated the excitation signal using the inverted dynamic transfer behaviour of their motor. Hunstig et al. [262] independently developed a similar procedure, and applied it to an inertia motor ([77,87]; [263] (pp. 101–107)). Chao et al. [127] used feedback control with the actuator current as a feedback signal to reduce unwanted vibrations. The motor controller by Belly et al. [75] performs a frequency sweep and measures the step size to automatically determine the optimum driving frequency.

Some authors make explicit use of the actuator dynamics, even at relatively low frequencies, using for example square [170] or pulse signals [192], but such approaches to drive low-frequency inertia motors are rare.

5.3.6. High-Frequency Operation

The stators in low-frequency inertia motors as discussed above are generally driven with signals far below their first natural frequency. Their vibrational dynamics are either not considered at all or are regarded as a disturbance which must be avoided or compensated. On the other hand, the vibrational dynamics are an important part in the design of high-frequency inertia motors and are often essential for their functioning. This is what distinguishes low- and high-frequency inertia motors, rather than a fixed frequency limit.

High-frequency inertia motors commonly operate in “sliding only” mode; i.e., without any relevant phase of stiction and with multiple sliding phases per period. In this mode of operation,

the ratio between the times during which the friction force acts in either direction is the main factor determining the macroscopic velocity of the slider. To the author's knowledge, this basic relationship was first mentioned in literature by Morita et al. [94] (p. 189). It was independently used as the basis of a specialised simulation technique for such motors by Hunstig et al. ([87] (pp. 85–93); [264]).

Most high-frequency motors make use of resonant amplification by appropriate superposition of multiple eigenmodes. This allows large stator amplitudes, and thus high velocities, even with electrical excitation amplitudes as low as 0.8 V [171]. Earlier investigations [77,87,92,264] have shown that different (mechanical) signals are ideal, depending on the application. For example, high velocity is achieved with high frequency and few superposed harmonics, while the generated force increases with the number of harmonics. The electrical signal to achieve such vibrations can consist of superposed sines, but it is also possible to use, for example, sawtooth or square signals, as explained, for example, by Yoshida et al. [265]. Figure 9 demonstrates how a sawtooth-like vibration can be excited using a square driving signal: the “mechanical admittance” of a piezoelectric actuator can be defined as

$$\underline{Y}_{\text{mech}}(f) = \hat{v}_R(f) / \hat{u}(f), \quad (7)$$

where f is a frequency, $\hat{v}_R(f)$ is the complex actuator velocity, and $\hat{u}(f)$ is the complex excitation voltage. It is shown in Figure 9a (thick lines), plotted in amplitude and phase over frequency. Figure 9b shows a voltage square signal $u_{\text{sq}}(t)$ of duty ratio 0.8 (dash-dot line). Figure 9a shows the first five harmonics of this signal in the frequency domain (circles); a signal composed only of these five harmonics (dashed line) is also shown in Figure 9b for better understanding. Excitation of the actuator with this signal is represented in the frequency domain by the multiplication

$$\hat{v}_{R,\text{sq}}(f) = \underline{Y}_{\text{mech}}(f) \cdot \hat{u}_{\text{sq}}(f). \quad (8)$$

The resulting velocity is shown in Figure 9a (triangles), and in the time domain in Figure 9b (dotted line). Integration of this signal yields the desired sawtooth-like displacement $x_{R,\text{sq}}(t)$, indicated by the solid line in Figure 9b.

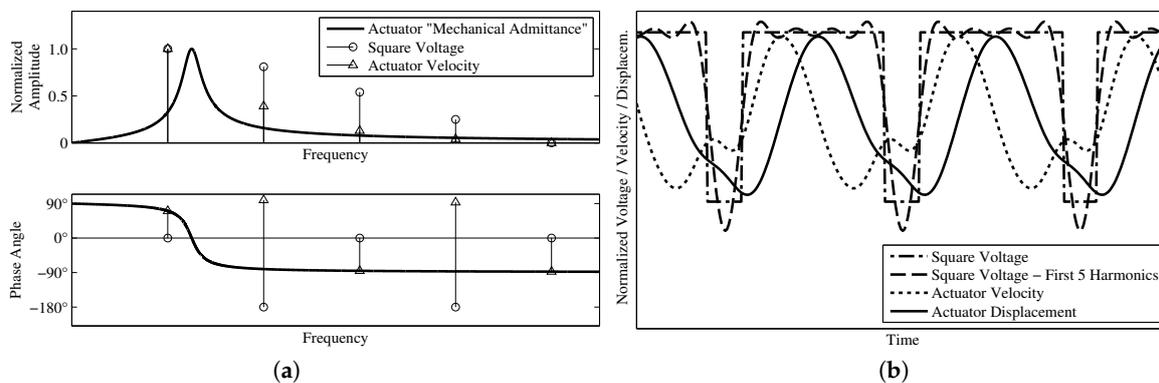


Figure 9. Example of the generation of a sawtooth-like actuator output from square pulse excitation. (a) Admittance and signals in the frequency domain; (b) Signals in the time domain. The frequency components (“harmonics”) of the voltage signal multiplied with the mechanical admittance of the piezoelectric actuator—both shown in (a)—result in a sawtooth-like displacement of the actuator shown in (b).

Square excitation signals are easily generated from direct voltage [266] (Figure 12), which is particularly relevant in battery-powered applications. A superposed sines signal has a precise frequency spectrum, which results in a more defined electrical excitation compared to a simple square signal. However, as eigenfrequencies shift, for example, due to temperature or load changes, the electrical signal would have to track these frequencies in order to obtain a steady vibration output. This issue has not been addressed to date in the literature reviewed in this work.

Figure 8b contains a compilation of different excitation signals for high-frequency inertia motors. High-frequency inertia motors are much rarer than the low-frequency variants to date. Their signal frequencies are typically in the ultrasonic range of 20 kHz and above. Thus, they operate silently, as long as no parasitic lower frequency vibrations are excited.

Suzuki et al. [80] present a motor where one of the two superposed sinusoidal vibrations is generated not by the stator, but by the actively excited slider. By proper utilisation of eigenmodes, it is also possible to realise special characteristics like a piezoelectric actuator positioned parallel to the driving rod or an out-of-phase driving of two rods using only one piezoelectric actuator, as shown by Vasiljev [267]. If the actuator—which may be split into several parts—is mounted so that it can excite different kinds of eigenmodes (e.g., longitudinal and bending modes), a motor can have multiple degrees of freedom with only one electrical input, as shown by Tuncdemir et al. [138,168].

As the frequency spectrum of the excitation is essential in high-frequency and especially in resonant inertia motors, their velocity can generally only be regulated by changing the excitation amplitude. With a suitable design, the frequency—and thus the velocity—can also be changed by inserting a phase of rest after each period [268].

6. Conclusions and Outlook

Piezoelectric inertia motors have a simple mechanical design, are typically controlled by only one electrical signal per degree of freedom, and inherently provide a fine positioning capability with principally unlimited resolution. The state-of-the-art as described in the above sections shows the variety of inertia motors and their potentially broad field of application due to these unique advantages. Nevertheless, there are only a few examples of these motors being applied commercially in larger quantities. Limited understanding of their functioning and optimal operation and a lack of comprehensive design rules are reasons for this. Further research and the dissemination of recent research results should help to overcome this shortfall.

Two main areas of application (cp. Section 2.2) are likely to dominate the future research on piezoelectric inertia motors. On the one hand, there will be efforts to further improve the precision of inertia motors for positioning applications, for example, by more detailed, comprehensive modelling including the friction contact, model-based compensation of disturbances, optimisation of the mechanical components, and refined driving strategies. Because they are easier to control, generally have a larger stroke in scanning mode, and have more options to adapt to changing environmental conditions [75], non-resonant inertia motors are likely to remain dominant in such applications. On the other hand, there will be efforts to improve the potential of simple fast inertia motors for commercial mass-production. Non-resonant inertia motors are unlikely to be competitive in such applications, because they tend to be bulkier and require more piezoelectric material to obtain the same velocity as resonant inertia motors. Recent developments of resonant inertia motors, like the integration of multiple DOF sharing one electrical input [16], small and tuneable designs [269], and strategies for the compensation of temperature-dependence [21,270] are promising. However, robust strategies for handling eigenfrequency shifts and a thorough comparison of the different electrical driving principles for resonant inertia motors are still missing in the reviewed literature. If superposed sine excitation shall prove its theoretical precision advantage over pulse excitation in commercial applications, tracking of multiple eigenfrequencies must be realised using low-cost electronics.

Next to these open questions, there are several other interesting research perspectives in the field of piezoelectric inertia motors. One topic which is of common importance to both fields of application, but which has been treated only very rarely in literature, is the reliability and repeatability of inertia motors. When presenting experimental results, most authors present either single or averaged curves without any mention of the deviation which was almost certainly observed. Neuman et al. [93] (p. 189) state that the standard deviation of their average velocity is below 5%. Curves obtained by the author [87] (pp. 135–141) indicate similar or lower standard deviation for most investigated parameter sets, but also show significantly larger fluctuation of momentary values. This can mostly be attributed

to the motor design, which is not aiming at high precision, but gives another indication that this topic deserves further study. Degradation over time was not investigated by either of the above studies, but should also be investigated to improve the fitness of inertia motors for technical applications. The studies by Bergander [111] and Dubois et al. [172] on wear in inertia motors and the investigations by Hunstig et al. [77,87,92]—which show a significant dependence of wear on the applied excitation signal—are only a start. Commercial producers of inertia motors may have already investigated these topics in more detail, but not documented this in publicly available literature.

Inertia motors are often used in positioning applications where the mechanical output power is of little interest. The same applies to the efficiency, defined as the ratio between output and input power. Both quantities have hardly been investigated in literature. Instead, the ratio between velocity and input power is sometimes used as an alternative measure of how well an inertia motor makes use of its input energy [92,271]. To the author's knowledge, there has been no research to date on inertia motors for power applications, and no known inertia motors provide mechanical outputs of more than a few milliwatts ([87] (p. 92); [258]). One possible reason for this is that electromagnetic motor technology is very mature and competitive at larger powers [5], even though other literature suggests that piezoelectric motors have an efficiency advantage up to about 30 W [272] (p. 257f). Much of the input power of an inertia motor is dissipated in the friction contact, and the wear rate in any given contact is roughly proportional to the friction power. Thus, efficiency is also closely connected to wear. Designing a high-power, high-efficiency inertia motor would thus bring about several interesting research questions, and may also open opportunities for currently unrecognised applications.

Resonant inertia motors with fixed actuator as they are known today share the disadvantage that a superposition of different eigenmodes of the stator inevitably results in a position-dependence of the stator velocity profile. This in turn makes the motor characteristics (e.g., velocity, force) vary along the travelling distance of the slider. Approximately constant characteristics can only be achieved in a relatively small area. Sophisticated designs could alleviate this drawback. Modifying the normal force to compensate this effect as suggested by Sasaki [21] is another option—with the disadvantages of modulated normal force, as discussed in Section 5.1.1.

An idea also brought up by Edeler [89] (p. 98) is to use so-called ultrasonic friction reduction [273,274] during the retraction phase. High-frequency vibrations of the stator would change the direction of the friction force for fractions of this phase, effectively reducing the average friction force. This provides a significant velocity increase in simulations [275], and has recently been shown to increase velocity and load capacity and reduce minimum operation voltage in a first realisation [120]. Still, many questions remain open: can this effect be used at the high frequencies required in resonant inertia motors? How to tune all involved eigenmodes in this case? What amplitudes are required? Is it more efficient than utilizing the required space and electrical energy to obtain a higher amplitude or frequency of the main stator vibration? Applying “friction-reducing” vibration to the slider instead of the stator could alleviate some difficulties in designing such a motor.

Another potential lies in the utilisation of the velocity-dependence of the friction force. If a friction coefficient can be realised which falls with rising relative velocity, the average friction force during the retraction phase will be lower than during the propulsion phase. This would allow higher velocities and driving forces. Hydrodynamic effects could be one possibility to obtain such a friction characteristic and at the same time use other possible advantages of lubrication (cp. Section 5.1.2). However, it must be investigated whether the well-known macroscopic effects (“Stribeck curve”) can also be observed at the small high-frequency swings in inertia motors. A positive indication for this is the fact that Qiu et al. [276] have observed a positive effect of lubrication in a piezoelectric standing-wave motor, and attributed it to hydrodynamic effects.

The number of lead-free inertia motors will grow with the availability and capability of alternative piezoelectric materials, but is unlikely to pose any new research questions specific to inertia motors. It may even simplify the design of precise inertia motors if the new materials show less nonlinearities

than PZT. Of course, if one of the new materials or another physical principle provides much more elongation at similar frequencies, this would change many of above considerations.

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Appendix A. Producers of Piezoelectric Inertia Motors

The following companies currently commercially offer piezoelectric inertia motors. All data for Figure 3 was taken from the specified web sites, accessed 8 January 2017.

- **Attocube Systems AG**, Munich, Germany, www.attocube.com
- **Cedrat Technologies**, Meylan, France, www.cedrat-technologies.com
- **Imina Technologies SA**, Lausanne, Switzerland, www.imina.ch
- **Kleindiek Nanotechnik GmbH**, Reutlingen, Germany, www.nanotechnik.com
- **Klocke Nanotechnik GmbH**, Aachen, Germany, www.nanomotor.de
- **mechOnics AG**, Munich, Germany, www.mechonics.de
- **Newport Corporation**, Irvine, CA, USA, www.newport.com
- **Physik Instrumente (PI) GmbH & Co. KG**, Karlsruhe, Germany, www.physikinstrumente.de
- **Piezoelectric Technology**, Seoul, Korea, www.piezo-tech.com/eng
- **Sensapex Oy**, Oulu, Finland, www.sensapex.com
- **SmarAct GmbH**, Oldenburg, Germany, www.smaract.de
- **Xidex Corporation**, Austin, TX, USA, www.xidex.com

The following companies no longer offer inertia motors:

- **OWIS GmbH**, Staufen, Germany
- **DCG Systems**, Fremont, CA, USA (formerly Zyvex Instruments)

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