

Survey of the Various Operating Principles of Ultrasonic Piezomotors

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Abstract:

Piezoelectric ultrasonic motors have been known for more than 30 years. In recent years especially, a large number of different designs have been developed, both for rotation and linear drives. This talk will provide a definition of piezoelectric ultrasonic motors and classify their different operating principles. The operation of each type will then be explained, commercially available implementations described and the advantages and disadvantages of each discussed. The goal is to provide an international perspective on the current state of development of piezoelectric ultrasonic motors.

Keywords: piezomotor, PZT, ultrasonic motor, travelling-wave, standing-wave, piezoelectric actuator

Introduction

There is today a large variety of drive designs exploiting motion obtainable from the inverse piezoelectric effect. Ultrasonic piezomotors have a very special place among such devices. These motors achieve high speeds and drive forces, while still permitting the moving part to be positioned with very high accuracy. Such characteristics make these motors of great interest for many companies who make precision devices for which these drives are, in many cases, irreplaceable.

Piezoelectric Motors

Piezoelectric actuators are electro-mechanical energy transducers; they transform electrical energy into motion using the inverse piezoelectric effect. The travel range of a simple piezo actuator is very small, being limited by the maximum possible deformation of the piezoceramic material. **Piezoelectric motors** are electro-mechanical drive systems in which the limited displacement of a piezoceramic element is converted into the unlimited rotary or translatory motion of a rotor or slider. The displacement of the piezoceramic in the desired direction of motion is transferred to the rotor or slider over an intermittent frictional coupling.

The story of the piezomotor began, presumably, in 1942. In that year, Alfred L.W. Williams und Walter J. Brown of Brush Development Company reported having built a "Piezoelectric Motor," for which they received the first patent from the US Patent Office in 1948. Their invention comprised a process for converting a multi-phase electrical signal into mechanical motion using the piezoelectric phenomenon. They used different types of piezoelectric bending actuators, so

arranged that their vibrational motion was converted into rotary motion of a shaft and gear.

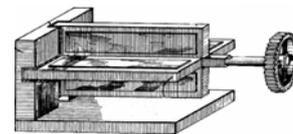


Fig. 1 Piezoelectric motor of L.W Williams and Walter J. Brown [1].

Since then, there have been numerous developments in the field of piezoelectric motors. They can be classified by working principle, geometry, or the type of oscillation excited in the piezoceramic. Fig. 2 shows a classification based on a mix of these possibilities, chosen from a pragmatic point of view.

We make first an overall distinction between quasi-static motors and the ultrasonic motors on which we wish to concentrate our attention here.

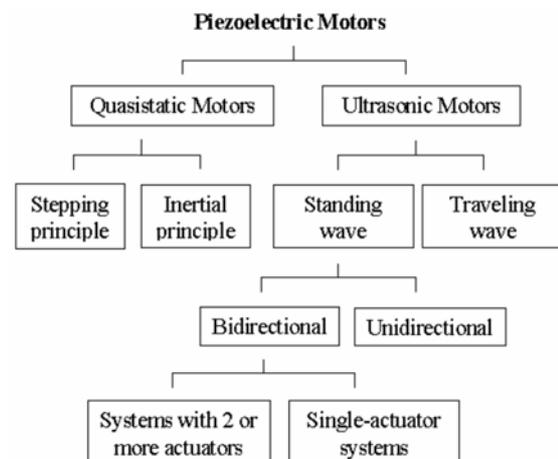


Fig. 2 Classification of piezomotors

Quasi-static Piezomotors

The quasi-static piezomotors operate on either the clamping principle or the inertial principle. In clamping-type motors, the rotor or slider is passed “hand-over-hand” between two sets of clamping and driving actuators. At any point in time, the set of actuators that is moving in the drive direction is the set that is clamped to the slider or rotor, while the other set is unclamped and moving “backwards,” preparatory to “taking a new bite.”

In inertial-type motors, inertia and the difference between the static and dynamic friction coefficients is used (the frictional force on the slider is reduced when slippage generated by the slider’s inertia occurs). During the slower displacement of the actuator in the drive direction, the slider follows the actuator with no slippage. In the next phase, the actuator moves in the opposite direction so rapidly that the slider, unable to follow due to its inertia, lets the actuator slip back beneath it.

What these motors have in common, is that they operate well below the resonant frequency of their piezoceramic actuators.

Clamping-type Motors

The first design for a clamping-type piezomotor was the Inchworm[®] motor proposed by Burleigh Instruments, Inc. in 1974. [2]. Fig. 3 shows how the Inchworm[®] motor works.

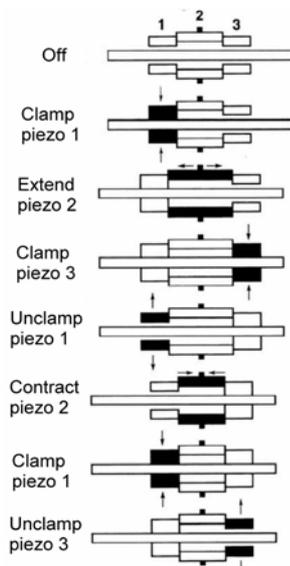


Fig. 3 Working principle of the Inchworm[®] Motor [2], 1974

The desired motion is obtained by the sequenced activation of three piezoelectric actuators. The two outer actuators (Numbers 1 and 3) can clamp the slider and can be activated independently of one another. The central actuator (Number 2) is used to

change the distance between the two outer actuators and thus to drive the slider.

Fig. 4 shows the design of the quasi-static Piezo Walk Drive[®], another system operating in the quasi-static mode.

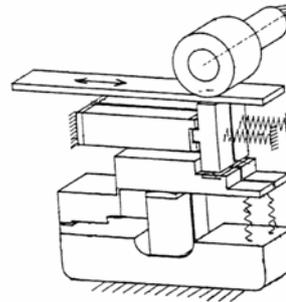


Fig. 4 Piezo Walk Drive [3], 1993

The Piezo Walk Drive[®] has two legs and four actuators. Two of the actuators are responsible for the (forward or backward) drive motion, and two for (alternately) engaging and disengaging the legs. As with a person walking, continuous forward or backward motion is possible. The two legs are parallel to each other and are pressed against the runner via levers. Each drive piezo can move the runner forwards or backwards by about 15 μ m. As one drive piezo approaches the end of its travel, the other clamp piezo will engage the other leg so that its drive piezo can take over. There is always at least one leg engaged with the runner, and manufacturing tolerances are fully compensated.

Fig. 5 shows a piezo drive for precision engineering or optical devices. [4].

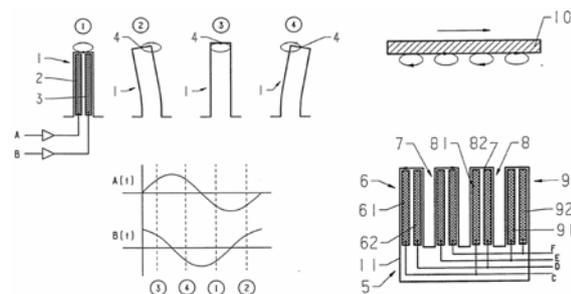


Fig. 5 Piezoelectric motor [4], 1994

This drive consists of a number of drive elements pressed against a slider. Each drive element is a piezo bimorph. The plates in the bimorph are electrically isolated and can be controlled independently. Exploiting the differential expansion or contraction of the bonded plates in the bimorph, the free end can be made to follow a trajectory with components in the lengthwise and bending directions as shown. If the two plates are excited with sine wave signals 90° out of phase, the free end will trace an elliptical pattern and drive the slider.

The polarity of the phase difference will determine the direction of motion of the slider.

Fig. 6 shows a piezoelectric stepper motor from the Swedish company PiezoMotor Uppsala AB. [5]. Both the drive unit and the working principle are the same as in [4]

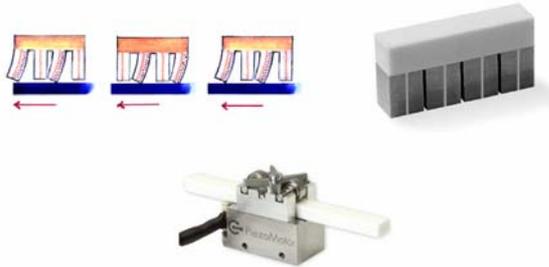


Fig. 6 Piezoelectric motor from PiezoMotor Uppsala AB [5]

Inertial Principle

The miniature piezomotor from Konica Minolta shown in Fig 7 works using the inertial principle. A thin metal shaft is attached to the piezo actuator, and the moving part is clamped to it. When the piezo expands or contracts with low acceleration/deceleration, the moving part moves with it, held by friction. At higher accelerations/decelerations, the inertia of the moving part prevents it from following and it slides.

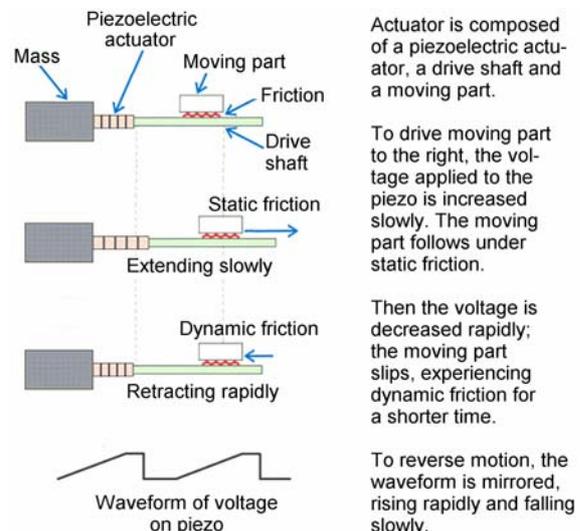


Fig. 7 Konica Minolta piezomotor [6]

The piezomotors from New Focus, which appeared more than ten years ago, work on the same principle. In them, the piezoelectric element acts directly on the clamp holding the shaft, causing the shaft to rotate.

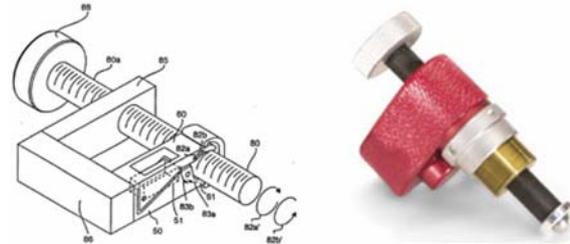


Fig. 8 Piezomotor from New Focus Inc.[7]

Ultrasonic Piezomotors

An **ultrasonic piezomotor** is one in which electrical energy is converted by the inverse piezo-effect to obtain oscillation of the piezo actuator at one of its resonant frequencies in the ultrasonic range, and this oscillation used in conjunction with a smooth frictional contact to obtain unlimited motion of the moving part. The increase in oscillation amplitude of the actuator due to resonance means that a lower drive voltage can be used. The working frequencies of ultrasonic motors range from 20 kHz to 10 MHz. The amplitude of the actuator motion is in the range of 20 to 200 nm.

In ultrasonic motors, the oscillations of the actuator result from excitation of different vibration modes (acoustic waves) in the actuator shape. The desired modes determine the shape and proportions of the actuator. The design of the ultrasonic motor is also dependent on that of the frictional components. The large number of different eigenmodes of a resonator, the combinations of different vibration modes and the design of the frictional contact lead to a large number of different possible ultrasonic motor designs.

Ultrasonic piezomotors can be divided into two groups, standing-wave motors and traveling-wave motors.

In traveling-wave motors, the superposition of multiple standing waves creates a traveling wave. Points on the active surface of the stator trace elliptical trajectories. Such traveling waves can only exist along an unbounded continuum. Resonators with circular geometry offer such a continuum for traveling waves. Traveling-wave piezomotors therefore usually have a stator in the form of a disk, ring or hollow cylinder. The best-known designs for traveling-wave piezomotors employ either a circular bending wave or a pseudo-longitudinal wave.

Standing-wave motors operate on the principle of micro-impulses. The motion is transferred to the rotor as the summation of a series of microscopic pushes or impulses. The micro-impulses are directed at an angle to the surface of the rotor. Standing-wave motors can further be divided into single-mode and bimodal motors.

In addition, ultrasonic motor designs can be classified as unidirectional or bidirectional.

The first piezoelectric ultrasonic motor was introduced by V. V. Lavrinenko in 1965 [8]. It consisted of an ultrasonic piezoelectric plate pressed against a smooth rotor. The year before, as candidate at the Polytechnic Institute in Kiev, Ukraine, USSR, he had observed rotation of piezoceramic crystals in their holders in the course of research with piezoelectric transducers. This observation led to the construction of the first ultrasonic piezomotor, which was registered by the issuance of a Soviet patent for a type of "Electric Motor" in 1965 [8].

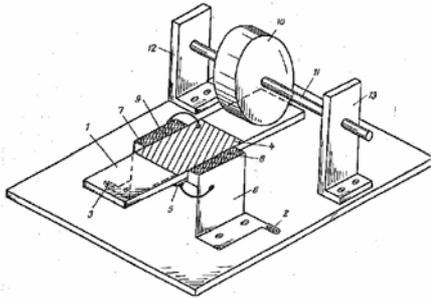


Fig. 9: V. Lavrinenko's ultrasonic piezomotor [8]

Unidirectional Motors

That invention [8] marked the beginning of systematic investigation and basic research in the area of ultrasonic piezomotors in the USSR. The research group at the Kiev Polytechnic Institute began working out the basic principles and design parameters of what was at that time a completely new type of electro-mechanical energy conversion device: the ultrasonic piezomotor. Further work on this motor led to recognition of fundamental design principles for ultrasonic motors, which were detailed in 1975 in a US Patent on "Piezoelectric Motor Structures" [9] and in similar additional patents [10]. Fig. 10. shows an ultrasonic motor with a piezoceramic plate as oscillator (stator). The piezoelectric plate is excited in the longitudinal mode. The front edge of the oscillator is pressed against the rotor with a spring. Motion is imparted to the rotor by a series of micro-impulses.

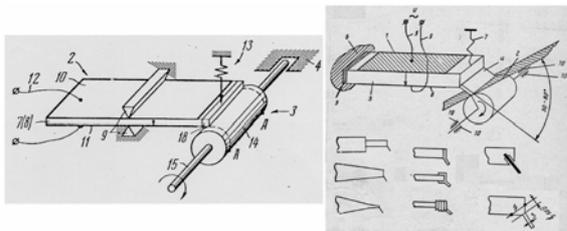


Fig. 10 Simplest design for an ultrasonic piezomotor 1975

The ultrasonic motors developed in the 70's also included unidirectional lamina motors. The mono-mode lamina ultrasonic motor uses the radial vibration mode of a piezoceramic cylinder or ring. Metallic laminae, or vanes, are attached to the oscillator; they convert the radial oscillation of the resonator to a rotary motion of the rotor. A bending wave is created in the laminae, which, in combination with the radial oscillation of the resonator, excites elliptical motion of the lamina tips.

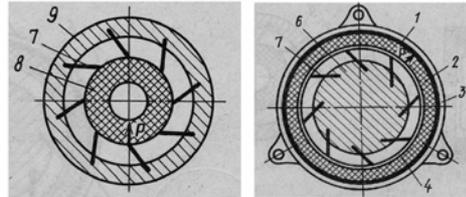


Fig. 11 Actuator with attached laminae 1974[11]

Fig. 12 shows a photo of a factory-built video recorder, the "Elektronika 552 Video," manufactured by the Positron company in 1982.



Fig. 12 Example of the "Elektronika 552-Video" a factory-built video recorder with an ultrasonic motor to power the drive axis, 1982

Bidirectional Motors

While many rotary applications need to move only in one direction, for linear motion, bidirectional drives are required. This can be obtained either using two separate actuators excited with a phase difference, or by superimposing two oscillations in a single resonator. Linear ultrasonic motors are, with very few exceptions, standing-wave motors. They produce their motion using a standing wave excited in the stator. The stator is either of a hybrid construction consisting of several actuators, or employs a single actuator.

As already mentioned, elliptical motion for driving a slider can be generated in an ultrasonic motor by the superposition of two non-parallel, out-of-phase oscillations. Simplest is perhaps to use separate actuators, which can also be separately controlled. This simplest design is shown in a layout from 1980 in Fig. 13 The connecting piece joining the two actuators traces an ellipse and imparts motion to the slider across a frictional interface [12].

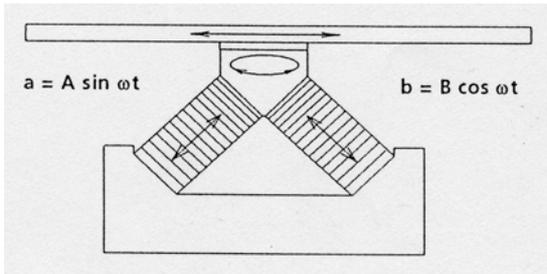


Fig. 13 Simple principle for an ultrasonic Motor

A very interesting design for a rotary motor with two piezoactuators was developed by Prof. Uchino (Fig. 14) [13],[14],[15].

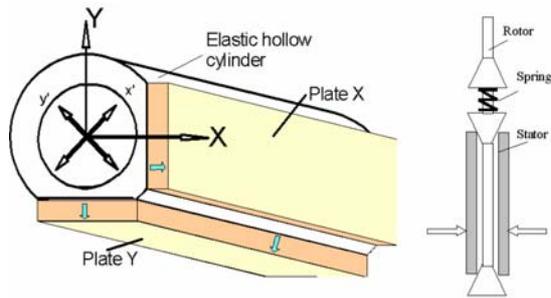


Fig. 14 Piezomotor using bending mode of a hollow cylinder

Piezoelectric plates are pressed against the surface of the metal cylinder as shown. They are then excited with a phase difference, exciting a wobbling motion in the cylinder, like the wobble of a hula hoop. This design is characterized by its compactness and low manufacturing costs. The SQUIGGLE Motor from New Scale Technologies, Inc. operates on this principle.

Micro-Impulse Drives with Piezoceramic Plate Actuators

Fig. 15 shows an ultrasonic motor with diagonally arranged electrodes on the main face of the plate-shaped actuator. [17].

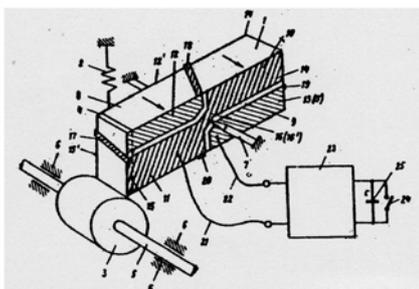


Fig. 15 Motor with diagonally arranged electrodes on a plate-shaped actuator 1976

A longitudinal or bending mode (L1B2) of this actuator is excited, permitting the motor to change direction.

Another L1B2 ultrasonic motor design, shown in Fig. 16, is that of Prof. Bansiavichus [18]. In it, the piezoelectric plate actuator is excited in a longitudinal and a bending mode simultaneously. The direction change of this motor is effectuated by switching the diagonally arranged electrodes.

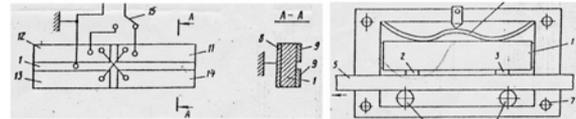


Fig. 16 Prof. Bansiavichus' ultrasonic motor, 1977

Fig. 17 shows an L1B2 ultrasonic motor from Nanomotion Ltd. [19]. This motor has an ultrasonic actuator similar to that of Prof. Bansiavichus' motor, with the exception that the pusher is located on the end of the piezoelectric plate.

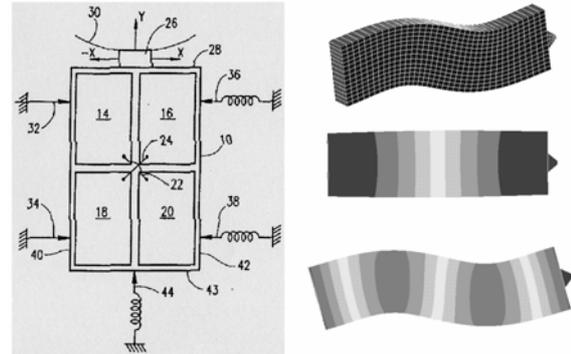


Fig. 17 Schematic representation of an ultrasonic motor 1994

Fig. 18 shows the design of a 2-phase linear motor from Physik Instrumente (PI), its piezoelectric actuator plate lying lengthwise with two attached friction tips [20].

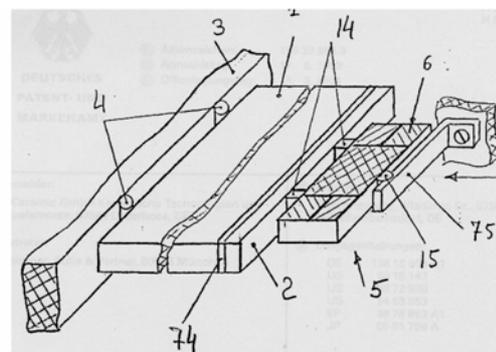


Fig. 18 Two-phase motor from Physik Instrumente (PI) based on longitudinal and bending standing waves in the actuator plate, 1999

This motor operates on the basis of simultaneous electrical excitation of longitudinal and bending standing waves in the actuator.

Fig. 19 shows a 2-phase ultrasonic linear motor from Physik Instrumente (PI) in which the actuator is excited with two longitudinal standing waves; one of the waves covers the actuator in the lengthwise direction while the other spreads out in the height direction [21].

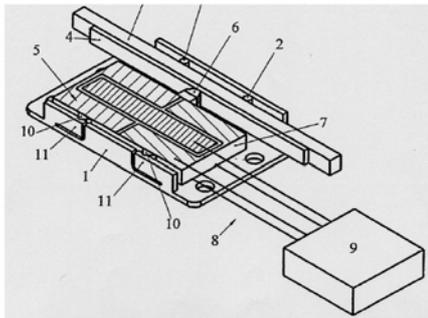


Fig. 19 Two-phase motor from Physik Instrumente (PI) with two longitudinal standing waves in the actuator plate, 2001

Fig. 20 shows the simplest of the well-known ultrasonic motors [22],[23] developed by Physik Instrumente (PI). The actuator of this motor has a common drain electrode and two excitation electrodes. This motor operates on the basis of the (1,3) excitation of an asymmetric standing wave in the actuator.

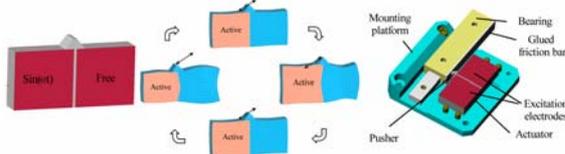


Fig. 20 Single-phase motor from Physik Instrumente (PI) with an asymmetric standing wave in the actuator plate, 2004

Fig. 21 shows a new ultrasonic micromotor from PI. [24].

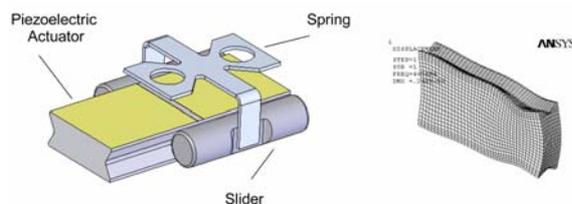


Fig. 21 CAD design of the newly developed ultrasonic piezoelectric micromotor

Ultrasonic Motors with Cylindrical Stator

Another variation uses a torsional mode and a true longitudinal mode in a piezoelectric cylindrical stator. The superposition of the two modes imparts elliptical trajectories to points on the ends of the tube. This motion can be used to turn a rotor pressed against the end face.

Fig. 22 shows different variations on actuators for such motors [25].

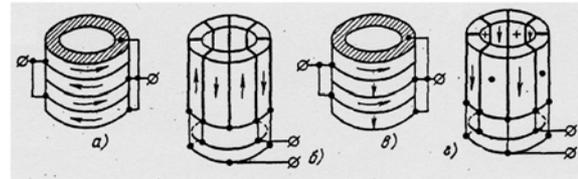


Fig. 22 Cylindrical stators for ultrasonic motors, 1980.

Fig. 23 shows a rotating-standing-wave ultrasonic motor based on excitation of a bending wave. [26]. The stator of the ultrasonic motor consists of a piezoceramic ring, a bonded metallic resonator and pushers attached to the resonator. A bending wave with characteristics depending on the desired direction of motion is excited. The pushers move along inclined, linear trajectories, and thus drive the rotor, which is pressed against them. This ultrasonic motor design has been used by Seiko for a pocket watch.

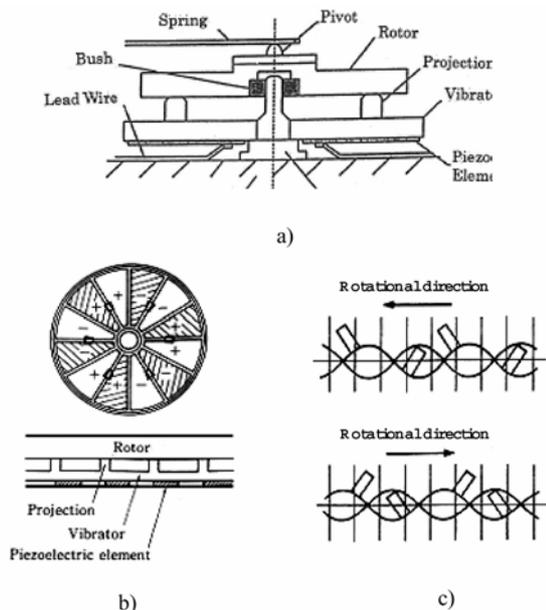


Fig. 23 a) Motor structure b) Electrode and friction tip locations c) Standing wave and rotor direction

Fig. 24 shows the design of a single-phase rotational motor developed by Physik Instrumente (PI) with a cylindrical actuator [27] employing the tangential-axial vibration modes. The figure also shows a

computer simulation which elucidates the working principle of the motor.

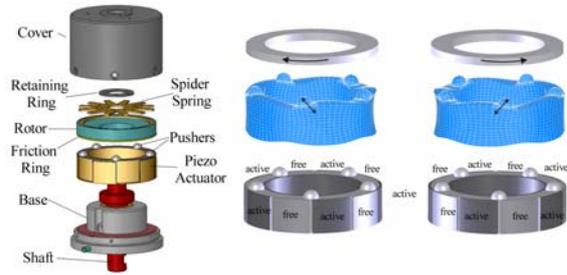


Fig. 24 Design and working principle of a single-phase motor from Physik Instrumente (PI) with cylindrical actuator using tangential-axial standing waves 2004

Traveling Wave Motors

In 1982 T. Sashida invented an ultrasonic motor based on the use of traveling waves [28]. In this motor, the elliptical trajectories of the points on the friction surface result from a traveling bending wave formed from two standing bending waves. Fig. 25 illustrates the design such a traveling-wave motor, made by the Shinsei Corporation.

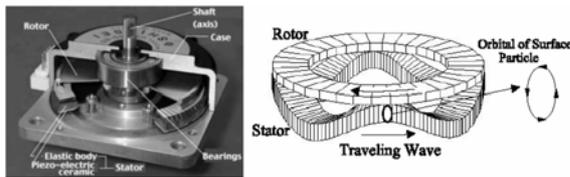
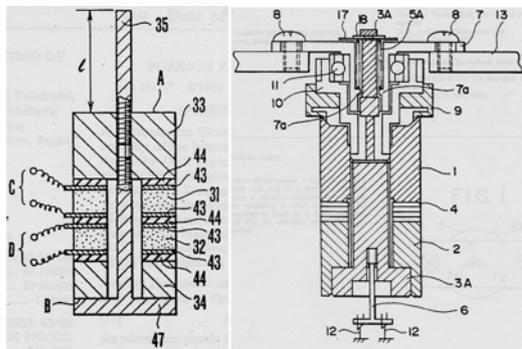


Fig. 25 Photograph and working principle of an ultrasonic motor using traveling bending wave, from the Shinsei Corporation, 1983

Fig. 26 shows an ultrasonic motor with composite actuators [29],[30]. In these motors, piezoelectric disk exciters are pressed between metallic resonators. The motor uses the bending mode.



1989 1991
Fig. 26 Motor variations with composite actuators
The drawings in Fig. 27 illustrate the working principle and the design of a 3-phase motor from

Physik Instrumente (PI) using longitudinal traveling waves on the circumference of a piezoceramic hollow cylinder. [31].

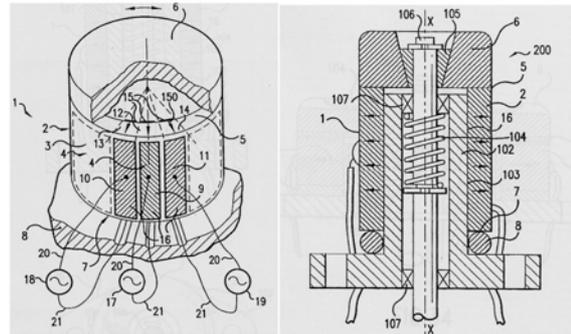
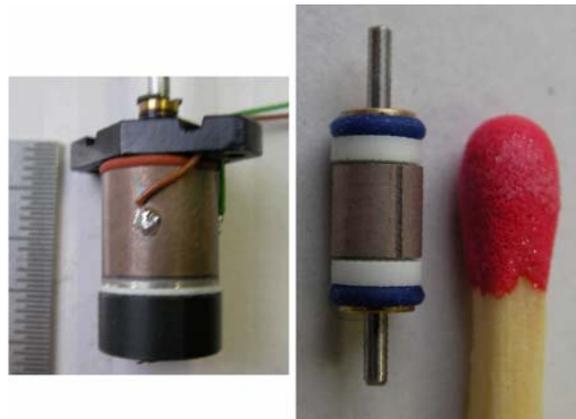


Fig. 27 Motor design using longitudinal traveling waves, 1995

The actuators of these motors are excited with longitudinal traveling waves consisting of the superposition of three longitudinal standing waves. Fig. 28 shows prototypes of 3-phase motors from Physik Instrumente (PI) using longitudinal traveling waves.



1994...2000
Fig. 28 Prototypes of miniature traveling wave motors from Physik Instrumente (PI)

Conclusions

Ultrasonic motors already have a long development history behind them. Many different implementations and working principles have been developed, will be improved, and patented. The basic principles shown here are only an incomplete selection. They all have one basic principle in common:

A piezoelectric element is excited in an eigenmode in such a way that at an extraction point, a particular motion component is obtained. The motion amplitudes are small, but given the high frequency, the moving part can achieve speeds of up to 1 m/s.

Piezoelectric ultrasonic motors have characteristics which make them far superior to conventional electromagnetic motors in certain market segments (for example, non-magnetic versions, high power-down holding forces, high positioning accuracy).

The greatest potential, however, will be in the area of automation and miniaturization, where compact and inexpensive motors with acceptable efficiency are required. The deciding factor is the price at which these motors can be produced in large quantities. The new developments demonstrate that motors can be built from very few parts, and that price can thereby become an argument for USMs.

It can be assumed that USM development has achieved the necessary breakthroughs, and that USMs will be of increasing importance in industrial products in the near future.

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