Simple Ceramic Motor . . . Inspiring Smaller Products

D. A. Henderson
New Scale Technologies, Inc., Victor, NY 14564, USA
Dhenderson@newscaltech.com

Abstract:
A new linear piezoelectric motor is presented called the SQUIGGLE® motor. Ultrasonic vibrations in a threaded nut directly rotate and translate a threaded screw. The newest model is only 1.55 X 1.55 mm square and 6 mm long and uses less than 0.1 Watt to produce 20 grams of force at 5 mm per second. High linear force, power, precision and low cost make SQUIGGLE motors ideal for emerging micro motion applications including: mobile phone cameras, micro fluidic devices, implantable drug pumps, deformable mirrors for adaptive optics, and basic laboratory research including MRI, vacuum and cryogenics.

Keywords: piezoelectric, ultrasonic, motor, screw, nut, micropositioning, focus, zoom

Introduction

A new patented[1] piezoelectric linear motor called the SQUIGGLE motor uses ultrasonic standing wave vibrations in a threaded nut to directly rotate a screw. This unique operating principle "wraps" the vibration motion of the nut around the screw threads to directly produce linear movement without requiring additional mechanical conversion. The thread friction is not parasitic but is used to directly rotate the screw. The threads multiply linear force and position resolution and reduce linear speed. The result is a tiny high-force motor capable of sub-micrometer stepping and velocity control without the need for a position sensor and high speed servo control loop. Additional features include precise off-power hold and a manual adjustment option by turning the screw.

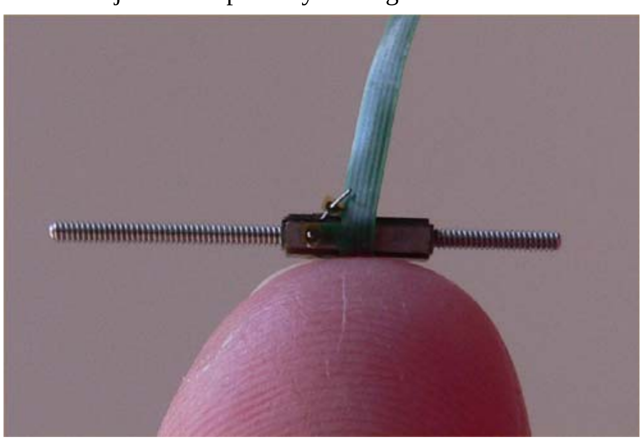

Fig. 1: *SQUIGGLE Linear Motor only 1.55 x 1.55 x 6 millimeters*

The nut vibration is sometimes described as a "hula hoop", wobble or orbiting motion. A small axial preload maintains constant contact between the nut and screw threads which causes the tangential friction force to rotate and translate the screw. Two orthogonal bending vibrations are combined to create the orbital motion. The two bending modes are created using orthogonal piezoelectric plates bonded to the outside of the metal nut.

This linear motor is a novel implementation of previous rotary motors using hula hoop vibrations. The first wobbling ultrasonic rotary motor was conceived more than 60 years ago by Williams and Brown (1948)[2]. This motor uses an orbiting stator to engage a round shaft or gear where tangential contact produces rotation. In 1995 a hula hoop rotary motor was demonstrated by Morita[3] which uses a thin walled piezoelectric cylinder. A miniaturized rotary motor, using two piezo plates and a hollow metal tube, was demonstrated by Koc, Catagay and Uchino[4] in 2002.

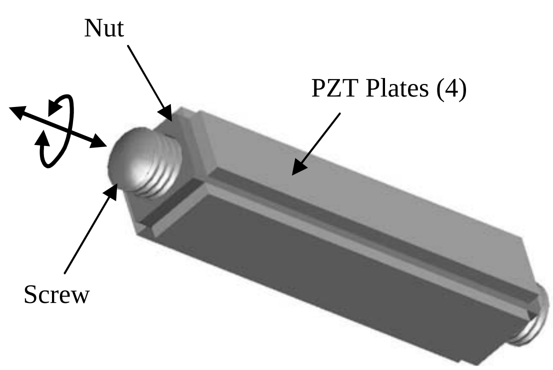

Fig. 2: *Squiggle Motor – A Vibrating Nut Turns a Screw*

Motor Operation

The PZT plates are bonded to flat surfaces on the outside of the metal tube at 90 degree spacing. The poling directions are aligned such that a common drive voltage on opposite pairs of plates produces opposing strain. The opposing d_{31} strain is parallel to the plate surface and bends the nut. The bending strain is applied at a frequency matched to the first bending resonance frequency of the

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tube. At this mechanical resonant frequency a small PZT strain is amplified by the Q of the mechanical system. By symmetry the resonant frequency of the orthogonal PZT plate pairs is matched. The hula hoop vibration mode is created by generating PZT strain in orthogonal plate pairs at the resonant frequency with 90 degree phase shift.

The PZT plates are activated to achieve the wobble motion using a two-phase electrical drive with a fixed frequency and +/- 90 degree phase shift. Drive frequency and amplitude depend on the motor model and vary from 40 to 200 kilohertz and 20 to 200 volts respectively. Both sinusoidal and square driving waveforms have been demonstrated. Positive 90 degree phase shift produces forward movement and negative 90 degrees produces reverse movement.

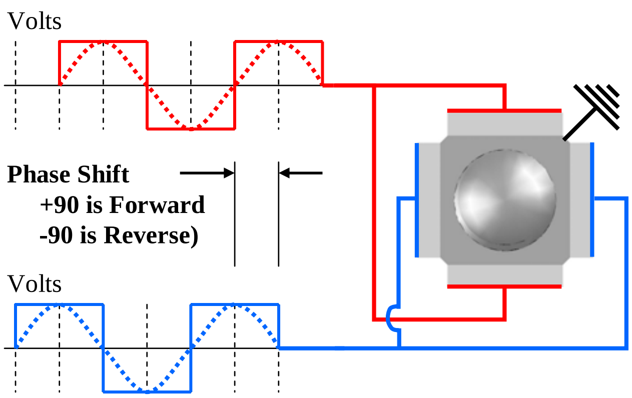

Fig. 3: *Two-Phase Motor Drive Signals (Sinusoidal or Square Wave)*

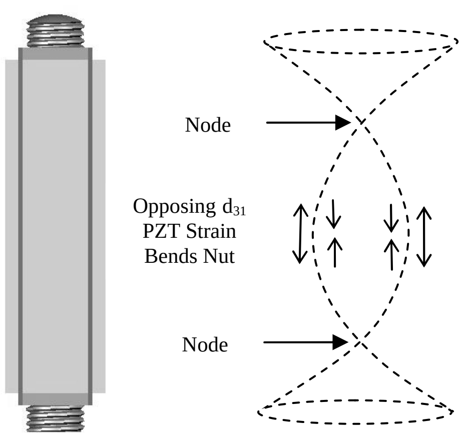

Fig. 4: *Motor Vibration Mode Shape (Called "Hula Hoop" Wobble or Orbiting)*

This motor design is highly scaleable to very small dimensions. Since its invention in 2003, the size and operating power have been reduced by an order of magnitude. This table summarizes the miniaturization achieved:

Motor Specifications	Dec 2003	Feb 2006
Diameter (mm)	8	1.55 x 1.55
Length (mm)	20	6
Screw Diameter (mm)	4.75	0.9
Stroke (mm)	50	10
Force (grams)	500	20
Speed (mm/sec)	2	5
Resolution (μm)	0.02	0.50
Frequency (kHz)	~ 40	~ 150
Voltage	100-200	20-40
Motor Power (Watts)	1	0.1

Applications

The smallest SQUIGGLE motors offer a unique size, power and precision capability that can not be matched by conventional electromagnetic (EM) DC or stepper motors. EM motors become dramatically less efficient below 6 mm diameter and require operation at higher speeds. This higher rotation velocity requires even more gear reduction which leads to even lower efficiency, reduced accuracy and increased size. EM motors have reached their practical limit of miniaturization.

When compared with other piezoelectric ultrasonic motors the Squiggle motor is half the size and provides ten times more force and position resolution. This excellent power and precision makes it ideal for emerging micro motion applications including mobile phone cameras, micro fluidic devices including implantable drug pumps, deformable mirrors for adaptive optics, and basic laboratory research including cryogenics and vacuum.

Mobile Phone Cameras

The explosive growth of world-wide mobile phone camera sales is creating a new market for more than one billion tiny motors per year. Today's fixed optics cameras must be replaced with moving optics to achieve better image quality. Tiny motors are needed to move micro lens assemblies to create auto focus and optical zoom in phone cameras that are one quarter the size of digital still cameras. This new market demand can not be satisfied by conventional EM motor technology.

In contrast to EM motors, the Squiggle motor is small enough for phone cameras and achieves sub-micrometer precision with many millimeters of stroke, high force, low power and competitive pricing. The "screw is the motor" and directly produces linear motion which eliminates 90 percent of classic camera mechanism parts including the gears, cams, barrels and levers. The movement is silent and the motor operates over a wide temperature range. No grease or other lubrication is used that can freeze or contaminate the optics. The mechanical design holds position with zero power and withstands very high shock loads because the metal threads support the load not the piezo ceramic plates. SQUIGGLE motors use only a few simple parts and are cost competitive with stepper motors. To compliment this very small motor, single chip ASIC drive circuits are being commercialized by several IC companies in 2006. These drive chips are powered by the 3 volt phone battery and output up to 40 volts to the motor.

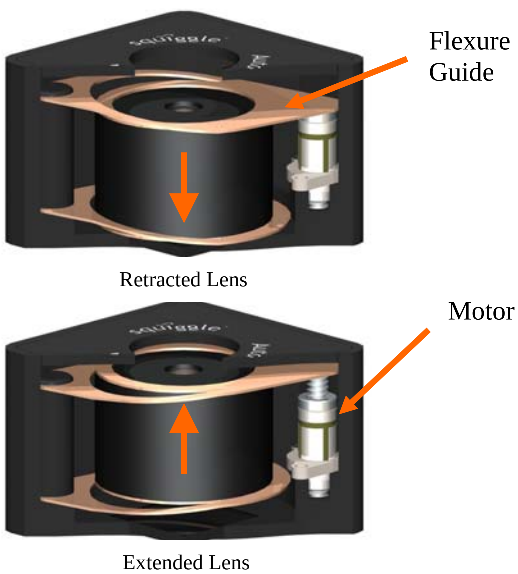

Fig. 5: *SQUIGGLE AF-Only Camera Module*
Less Than 10 X 10 X 8 mm

SQUIGGLE motors meet the demanding miniaturization and performance requirements for both AF and OZ. The pace of miniaturization is formidable. In 2006, AF-only cameras as small as 8.5 x 8.5 x 6.1 mm with 2MP sensors will be introduced. Cameras with AF and OZ are under development and will achieve image quality comparable to digital still cameras inside a mobile phone but use a volume less than 10 x 10 x 20 mm.

These are some typical requirements for auto focus (AF) and optical zoom (OZ) motion in phone cameras.

Motion Specifications	**Phone Camera Module**	
	AF	**OZ**
Force (grams)	10 - 20	
Stroke (mm)	0.25 - 2	5 - 10
Resolution (µm)	1	5
Repeatability (µm)	5	10
Speed (mm/sec)	1	5
Voltage	Less than 40	
Power (Watts)	Less than 0.5	

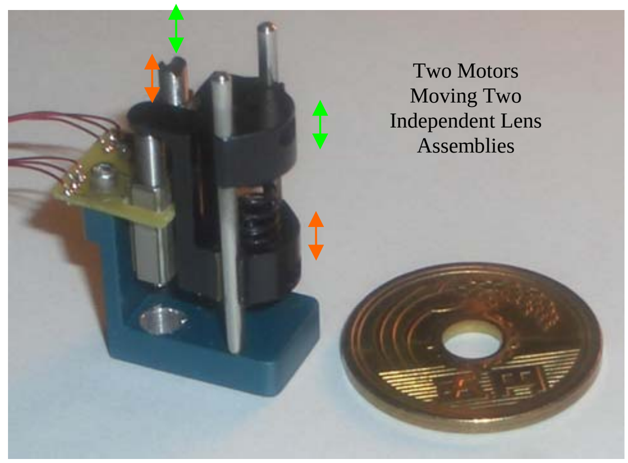

Fig. 6: *SQUIGGLE AF and OZ Module Demo*
Less than 10 x 14 x 25 mm

Cryogenic Positioning

With only minor design changes SQUIGGLE motors operate continuously from ambient to cryogenic temperatures of 4 degrees K. This wide operating temperature range is enabled by these fundamental characteristics of ultrasonic motors:

- Operation at resonance requires “hard” PZT material and peak electric fields well below the dielectric material limit.
- “Hard” PZT performance degrades at cold temperatures. However, the loss is much less than higher strain “Soft” piezo ceramics.
- Much of the lost PZT performance can be regained by increasing the drive voltage and the corresponding electric field.
- At resonance the motor vibration amplitude is highly dependent on the Q of the mechanical system. At cold temperatures the mechanical Q increases to offset some of the loss in piezoelectric performance.

Fig. 7: *Cryogenic SQUIGGLE motor using Cylindrical PZT Design*

Cryogenic motors solve critical challenges in research, aerospace and defense applications including: NMR, low-light cooled cameras and deep infrared space-based telescopes.

Medical Devices

Like other piezoelectric ceramic motors the SQUIGGLE motor generates no magnetic fields and can be constructed entirely of non-ferromagnetic materials. No coils, magnets or iron cores are needed. Special motors using non-magnetic stainless steel, bronze and titanium have been demonstrated.

Non-magnetic SQUIGGLE motors are safe for use in Magnetic Resonance Imaging (MRI) systems because they are not attracted by high magnetic fields. In addition, this motor has demonstrated compatibility with the MRI imaging process when stationary and moving. MRI safe and image compatible motors are especially valuable for implantable medical devices. Today patients with implanted devices are typically prevented from having an MRI scan.

Implantable medical device applications being considered include: drug pumps, biopsy tools, fluid collection, "smart pills", optical scanning, and adjustable valves/shunts where precision movement, dosage control and long battery life are essential.

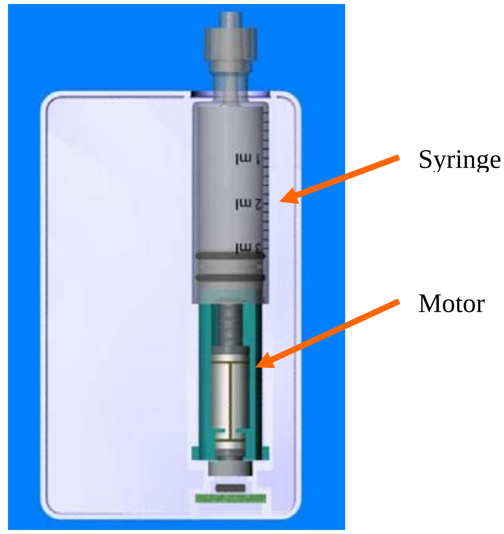

Fig. 8: *Drug Pump Showing the SQUIGGLE Motor Pushing a Syringe*

Outlook

The demand for tiny high-performance linear motors is accelerating due to the exploding market for mobile phone cameras. Very soon this new "killer application" will raise the ultrasonic motor industry to a manufacturing scale comparable with conventional stepper and DC motors. Today SQUIGGLE motors satisfy the critical requirements for auto focus and optical zoom based on their competitive size, force, precision, power and cost. At the same time this new technology has room for additional miniaturization and future SQUIGGLE motors will enable even smaller products.

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