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Inventor: CHULKO KIM

NOTICE

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CODE 1008.2
NAVAL RESEARCH LABORATORY
WASHINGTON DC 20375

PATENT APPLICATION/TECHNICAL DIGEST PUBLICATION RELEASE REQUEST

FROM: Associate Counsel (Patents) (1008.2)
TO: Associate Counsel (Patents) (1008.2)

Via: (1) Chulho Kim (Code 6354)
(2) Division Superintendent (Code 6300)
(3) Head, Classification Management & Control (Code 1221)

SUBJ: Patent Application/Technical Digest entitled: **"PIEZOELECTRIC TORSIONAL VIBRATION DRIVEN MOTOR"** Request for release for publication.

REF: (a) NRL Instruction 5510.40C
(b) Chapter 6, ONRINST 5870.1C

ENCL: (1) Copy of Patent Application/Technical Digest

1. In accordance with the provision of references (a) and (b), it is hereby requested that the subject Patent Application/Technical Digest be released for publication.

2. It is intended to offer this Patent Application/Technical Digest to the National Technical Information Service, for publication.

3. This request is in connection with Navy Case No. 80,131

11/19
(date)

JOHN J. KARASEK
Associate Counsel (Patents)

FIRST ENDORSEMENT Date: 11/17/00

FROM: Chulho Kim (Code 6354)
TO: Division Superintendent (Code 6300)

1. It is the opinion of the Inventor(~~s~~) that the subject Patent Application/Technical Digest ~~(is)~~ (is not) classified and there is no objection to public release.

Inventor's Signature

SECOND ENDORSEMENT Date:

FROM: Division Superintendent (Code 6300)
TO: Classification Management & Control (Code 1221)

1. Release of Patent Application/Technical Digest (is) (is not) approved.

2. To the best knowledge of this Division, the subject matter of this Patent Application/Technical Digest (has) (has not) been classified.

3. This recommendation takes into account military security, sponsor requirements and other administration considerations and there in no objection to public release.

Division Superintendent

THIRD ENDORSEMENT Date:

FROM: Head, Classification & Control (Code 1221)
TO: Associate Counsel (Patents) (1008.2)

1. This Patent Application/Technical Digest is authorized for public release.

Ina Smallwood
Head, Classification, Management & Control

Docket No.: N.C. 80,131
Inventor's Name: Kim

PATENT APPLICATION

PIEZOELECTRIC TORSIONAL VIBRATION DRIVEN MOTOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to piezoelectric motors, and more specifically to piezoelectric torsional vibration driven motors.

2. Description of the Background Art

The use of piezoelectric ceramic materials such as lead zirconate titanate (PZT) is well known for applications for sensors, transducers, actuators, and other electromechanical devices.

Many actuators have been developed using electroactive materials, including the torsional actuator disclosed in U.S. Patent 6,020,674. This torsional actuator uses an even number of alternately poled segments of electroactive material which are arranged side by side. The segments are bound together in an integral structure, with conductors positioned between adjacent segments. Under an applied electric field, the torsional actuator produces large angular displacement and a high torque. Similarly, a torsional piezoelectric actuator is described in Glazounov, A.E. Zhang, Q.M., Kim, C. "Piezoelectric Actuator Generating Torsional Displacement from Piezoelectric d_{15} Shear Response" Applied Physics Letters 72, pages 2526-2528, 1998.

For some applications, a large rotational motion with a large torque output is demanded. For example, vibration and noise control systems for helicopter rotor blades require an actuator which can provide large amplitude rotational motion with a high torque.

Piezoelectric ultrasonic motors have been developed using traveling wave and standing wave theories which provide higher torque density than electromagnetic motors. An example of the current art in piezoelectric motor technology is provided in "Development of a Two-Sided Piezoelectric Rotary Motor for High Torque", T. S. Glenn, W.G. Hagwood, SPIE Volume 3041, 1997. These piezoelectric ultrasonic motors are of limited application, however, because they have either lower power density or lower efficiency than conventional electromagnetic motors.

A compact, simple, lightweight motor which uses a torsional actuator as a stator could provide high torque density, high power density, and high efficiency in response to an alternating electric field.

Therefore, it is an object of this invention to provide a piezoelectric motor with high torque density, high power density, and high efficiency.

It is an object of this invention to provide a compact and lightweight piezoelectric motor.

It is an object of this invention to provide a simple piezoelectric motor which converts an alternating electric field to torsional vibration and directly into rotary motion.

It is an object of this invention to provide a full cycle piezoelectric torsional vibration motor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG1a shows a torsional actuator and the relationship between the polarization of electroactive segments and the applied electric field.

FIG **1b** shows the relationship between the polarization and the applied electric field for the torsional actuator.

FIG **2** shows the frequency dependence of a torsional actuator under applied electric fields for different clamping conditions.

FIG **3** shows a one way roller clutch for use in a torsional electroactive motor.

FIG **4** shows a half cycle torsional electroactive motor using a torsional actuator.

FIG **5a** is a schematic of a full cycle torsional electroactive motor using a torsional actuator.

FIG **5b** is a cross sectional view of the actuator, rotor and housing shown in FIG **5a** at section AA.

DETAILED DESCRIPTION

A torsional motor as described herein includes a stator, a clutch, a rotor. A torsional actuator is used as the motor stator. **FIGs 1a** and **1b** illustrate the torsional actuator. Several torsional actuators which may be used for this purpose are described in U.S. Patent 6,020,674, incorporated herein in its entirety. The torsional actuator uses an even number of alternately poled segments **10** of electroactive material which are arranged side by side. The segments are bound together in an integral structure, with electrical conductors **30** positioned between adjacent segments. An electrically conductive epoxy or other conductive adhesive may be used to bond the segments together and to act as the conductor.

Each electroactive segment is continuously poled along its length, and the segments are arranged so that adjacent segments have the polarization direction opposite to each other. The conductive elements are connected electrically in parallel, allowing an electric field E to be applied to each segment in a direction perpendicular to the polarization P_s of each segment **10**.

The relationship between the direction of polarization and the applied field for adjacent segments is shown in **FIG 1a**. An applied electric field induces a shear deformation in each segment. The shear strain α is proportional to applied electric field E and the shear piezoelectric coefficient d_{15},

$$\alpha = d_{15} E \qquad \text{Equation (1)}$$

Due to the cylindrical symmetry of the actuator, the shear strain α is directly transformed into angular displacement of an end of a segment with respect to the other end of a segment, β, such that

$$\beta = \left(\frac{L}{R}\right)\alpha = \left(\frac{L}{R}\right)d_{15}E \qquad \text{Equation (2)}$$

where L is the length of the actuator segment, R is the radius of the actuator. By using an actuator with a large value of L/R, a large torsional displacement β can be achieved, even though shear strain α is usually quite small in piezoelectric materials.

If the length of the actuator, L, is greater than the radius of the actuator, R, then the torsional displacement of the end of the actuator β will be larger than the shear strain α induced in each segment of the actuator, and the actuator will be an effective amplifier of angular displacement. The value of L/R is therefore considered the geometric amplification factor.

When a voltage V is applied to the actuator segments, the electric field E in each segment will be:

$$E \approx \frac{nV}{\pi(R_1 + R_2)} = \frac{nV}{2\pi R} \qquad \text{Equation (3)}$$

The torque developed by the actuator, T, will be

$$T = \frac{d_{15} n V (R_1 - R_2)}{s_{44}^{E}} R \qquad \text{Equation (4)}$$

where R is equal to the average of the inner and outer radii of the actuator ($R = (R_1+R_2)/2$), n is the number of segments, and s^E_{44} is the shear elastic compliance at a constant electric field. Hence, although the angular displacement β increases linearly with the length of the actuator L, the torque T is independent of the length of the actuator.

The material selected for the actuator segments should have a high shear response under the limiting electric fields (the field limit before de-poling occurs) as well as a high shear piezoelectric coefficient d_{15} under operating conditions. The material should also have a low elastic shear compliance and a high de-poling shear stress.

Actuators with a polygonal cross section may be assembled using long segments having trapezoidal cross sections. Actuators with a circular cross section may be assembled using segments having a circular arc cross section. Other actuator configurations may be built, as will be apparent to those skilled in the art.

Example of a torsional actuator

An actuator was manufactured using PZT-5A material obtained from EDO Inc., which has a high maximum shear piezoelectric response (greater than 1,200 micro-strain). This material demonstrated a significant nonlinear behavior with respect to the field. The PZT-5A has a d_{15} coefficient at high fields (4.8kV) of 2,500 pC/N, compared to a d_{15} coefficient of 700 pC/N at low fields (less than 200 V). There is, however, no marked response (d_{15} change) to the shear load applied up to stresses of 10 MPa.

A continuous poling fixture was used to apply this polarization in the longitudinal direction. The continuous poling was applied by moving the two conductive rubber electrodes along the length of the segment (5 to 15 cm) at a rate of 0.2 to 1.0 cm per minute, after applying the desired electric field to one end. Moving the electrodes allows the segment to be exposed to sufficient electric field strength needed to approach full uniform spontaneous polarization while avoiding material breakdown which would be the result of applying a large voltage across the entire length of the segment.

A segment of PZT-5A was poled by moving two electrodes separated by a distance of 1.4 cm along the long segment at a rate of 0.2 to 1.0 cm per minute with 20kV between electrodes while the entire system was immersed in a dielectric oil bath heated to a temperature of 80 to 100 ° C. These long segments of PZT-5A exhibited a large d_{33} value of greater than 460 pC/N. This is more than 95% of the d_{33} value of shorter PZT-5A samples which were poled fully using a conventional poling method (~480 pC/N).

The continuously poled segments were assembled into a cylindrical actuator and were joined by a high shear strength conductive epoxy, which serves as an electrical conductor and to adhere the adjacent sides of the segments to one another. The epoxy was selected based on its high shear strength and a curing temperature below the Curie temperature of the material being joined. An example of a suitable epoxy is MB-10HT/S, which is then cured using a vacuum bagging process, which typically results in joints which are approximately 25μm in thickness and very uniform along the length of the joints. This process is described in "Piezoelectric Ceramic Assembly Tubes for Torsional Actuators," C. Kim, A. E. Glazounov, F. D. Flippen, A. Pattnaik, Q. Zhang, D. Lewis, SPIE Proceedings, Volume 3675, March 1999, incorporated herein in its entirety. Other methods of joining the segments and conducting an electric field may be used, however, the joining method must have sufficient shear strength to maintain the structural integrity of the actuator.

Other examples of torsional actuators and the continuous poling fixture are described in the report NRL/MR/6380–97-7997, "Composite Piezoelectric Assemblies for Torsional Actuators," C. Kim, T. Jensen, V. DeGiorgi, B. Bender, C. Cm Wu, D. Flippen, D. Lewis, Q. Zhang, V. Mueller, M. Kahn, R. Silberglitt, and L. K. Len, September 30, 1997, incorporated herein in its entirety. Additional examples of torsional actuators are described in "Piezoelectric Ceramic Assembly Tubes for Torsional Actuators," C. Kim, A. E. Glazounov, F. D. Flippen, A. Pattnaik, Q. Zhang, D. Lewis, SPIE Proceedings, Volume 3675, March 1999; "Piezoelectric Actuator Generating Torsional Displacement from Piezoelectric d15 Shear Response," A. E. Glazounov, Q. Zhang, and C. Kim, Applied Physics Letters, Volume 72, Number 20, May 1998, and "High Authority Piezoelectric Torsional Actuators," C. Kim, D. Lewis, C. Cm Wu, A. E. Glazounov, Q. Zhang, Proceedings of the Eleventh IEEE International Symposium on Applications of Ferroelectrics (IEEE ISAF), # 0-7803-4959-8/98, all incorporated herein in their entirety.

Equivalent circuit analogy around the resonant frequency, f_r shows that the resonant frequency dependence of the torsional angle β is given by:

$$\beta(f_r) = d_{15}E(L / R_1)Q_m \qquad \text{Equation (5)}$$

where d_{15} is the piezoelectric shear coefficient and Q_m is the mechanical quality factor of the actuator. The mechanical quality factor Q_m is an additional torsional angle amplification term, which can be utilized in piezoelectric ultrasonic motor development. In order to provide a large angular displacement β, a material having a high Q_m is chosen for the actuator segments. For example, in one embodiment, a hard piezoelectric ceramic material (APC-841, available from APC International, Ltd.) was selected as an actuator material because of its high Q_m value.

Torsional Motors

A torsional actuator as described above, with electroactive segments, having a length L and a radius R, can be used as the stator in a torsional motor. Such a torsional motor provides high torque and high efficiency. A torsional motor has several components, including a stator, a clutch, and a rotor.

When an alternating electric field is applied to a torsional actuator, if one end of the actuator is fixed, the other end will twist back and forth in response to the applied electric field. A one way clutch is used to transmit the angular displacement in one direction only to a rotor, ensuring the rotor turns in the same direction at all times. An example of a one way roller clutch which may be used is shown in **FIG 3**. The torsional actuator (not shown) is fixedly attached to the clutch cam **110,** so as the torsional actuator and cam **110** rotates in a counter-clockwise direction, the rollers **120** jam between the rotor **130** and the cam **110**, locking them together. This allows the angular displacement of the actuator to be transmitted to the rotor. As the actuator and cam **110** rotate in an opposite (clockwise) direction, the springs **140** are compressed by the rollers **120**, the rollers **120** slip, and the actuator and cam **110** is allowed to rotate freely, so no clockwise angular displacement of the actuator is transmitted to the rotor. Thus, the roller clutch transmits angular displacement of the actuator to the rotor only if the actuator and cam **110** move in the counterclockwise direction when the rollers **120** are wedged between the tilted slope of the cam **110** and the surface of the rotor **130**.

Half -cycle Motors

A cross sectional view of a half cycle torsional electroactive motor is shown in **FIG 4.** A torsional actuator **200** is fixed at one end **201** to a support member **210**, while the other end of the torsional actuator **202** is allowed to move freely in response to an electric field applied to conductors across the electroactive segments of the torsional actuator. The torsional actuator **200** is as described previously and as shown in **FIGs 1a** and **1b**. A one-way clutch **220** (typically having rollers, a cam, and springs) is used to transmit the angular motion of the torsional actuator **200** to the rotor **230** in one direction only. When an alternating electric field is applied to the torsional actuator **200**, the free end of the torsional actuator **202** will be angularly displaced in an amount β according to Equation **2** above. When the free end of the torsional actuator **202** is displaced in one angular direction, the one-way clutch **220** will transfer this motion to the rotor

230. When the free end of the torsional actuator **202** is displaced in the other direction, the one way clutch **220** is disengaged from the torsional actuator **200** and will not transmit the angular displacement of the torsional actuator's free end to the rotor **230**.

As shown in **FIG 4**, a shim **210** and bolt **215** are used to hold the fixed end of the torsional actuator **201** against a metal cylinder **240**, in order to maintain alignment with the clutch **220**. The metal cylinder **240** adds mass and reduces vibration of the shim **210** and the end of the actuator **201**. Of course, many other methods may also be used to maintain motor alignment and to reduce vibration in the fixed end of the torsional actuator for a half cycle torsional motor.

Optionally, another set of freely rotating rollers **260** keep the rotor **230** in alignment with the clutch **220** and the torsional actuator **200**.

The torsional motor may be operated at a resonant frequency f_r. If the half cycle motor is operated in a resonance mode, the actuator optimally has a length L equal to 1/4 λ, where the wavelength λ corresponds to the natural frequency f_r of the actuator. This allows the maximum angular displacement β to occur at the free end of the actuator, and allows the clutch to transmit maximum angular displacement from the torsional actuator to the rotor. The natural frequency of the actuator, f_r, is dependant on the material properties of the electroactive segments which make up the torsional actuator, and the length of the actuator, according to the following equation:

$$f_r = \frac{1}{4\,L\sqrt{\rho\left(s_{44}^{E}\right)}} \qquad \text{Equation (6)}$$

Referring again to **FIG 4**, the effective length of the torsional actuator (from the fixed end of the actuator to the rotor) is L = 1/4 λ. Optimally, the length of the cylinder **240** plus the effective length of the actuator (between the end of the actuator **201** and the clutch roller **220**) is equal to 1/2 λ, so the end of the shim **201** is a nodal point, and has very low vibration.

Thus, when driving the actuator tube at its resonant frequency, and accumulating the produced angular displacement by using a direct coupling between the actuator (stator) and rotor via the one way clutches, a high efficiency piezoelectric motor generates continuous rotation with precise control over angular positioning.

Full Cycle Torsional Motors

A full cycle torsional motor in which both ends of the torsional actuator transmit angular displacement can be used to increase power density, torque density, and efficiency. This full cycle motor transmits the displacement continuously to the rotor, without any half-cycle dead periods inherent in the half-cycle motors discussed above. A full cycle torsional motor has the advantage of compact size while providing twice the efficiency of the half-cycle motor. If the rotor, clutches, and torsional actuator are aligned, the torsional vibration of the electroactive segments will be transferred directly into rotary motion of the rotor.

Advantages provided by the full cycle torsional motor as described herein include an approximately ten fold improvement in power density over electromagnetic motors, and a twenty fold increase in power density over current piezoelectric motors. Such a full cycle torsional motor also provides an approximately thirty fold increase in torque density over current electromagnetic motors and a three fold increase over current piezoelectric motors, as illustrated in **Table 1** below.

Table 1.

Comparison of electromagnetic (EM) and PZT ultrasonic (US) motors

Row	*Type*	*Model/ Description*	*Maker*	*Stall Torque (Ncm)*	*Max. Speed (rpm)*	*Peak Eff. (%)*	*Mass (g)*	*Torque Density (Ncm/kg)*	*Power Density (W/kg)*
1	**EM**	**1319E003S/ Brush DC**	**Micro Mo**	**0.33**	**13,500**	**71**	**11.2**	**29**	**104**
2	**EM**	**FK-280-2865/Brush DC**	**Mabuchi**	**1.52**	**14,500**	**53**	**36**	**42**	**160**
3	**EM**	**Brush DC**	**Maxon**	**1.27**	**5,200**	**70**	**38**	**33**	**45**
4	**EM**	**Brushless DC**	**Aeroflex**	**0.98**	**4,000**	**20**	**256**	**3.8**	**4.0**
5	**EM**	**Brushless DC**	**Kannan**	**8**	**5,000**	**80**	**600**	**13**	**17**
6	**US**	**Standing wave, twist coupler**	**Kumada**	**133**	**120**	**80**	**150**	**887**	**~50**
7	**US**	**USR60, disk-type**	**Shinsei**	**62**	**105**	**23**	**230**	**270**	**16**
8	**US**	**EF 300/2.8L, ring-type**	**Canon**	**16**	**40**	**35**	**45**	**356**	**~5**
9	**US**	**Two-sided prototype**	**MIT**	**170**	**40**	**13**	**330**	**520**	**7.3**
10	**US**	**8-mm ring prototype**	**MIT**	**0.054**	**1,750**	**n/a**	**0.26**	**210**	**108**
11	**US**	**16-mm torsional actuator (projected results)**	**NRL**	**80.7**	**3,620**	**80**	**65**	**1,240**	**1,177**

The 16mm torsional actuator (row 11 of Table 1) will have superior power density and torque density compared to currently available electromagnetic motors (rows 1-5 of Table 1) and to currently available piezoelectric motors which rely on standing wave and traveling wave theories (rows 6-10 of **Table 1**).

A full cycle electroactive torsional motor driven by piezoelectric torsional vibration is shown in Figures **5a** and **5b**. A torsional actuator **51** can be fixed at its midpoint **58** to a housing **53** or other structure. Because only the midpoint is fixed, both ends of the actuator **51** are free to move in response to the application of an electric field across the electroactive segments. The torsional actuator **51** acts as a stator which generates high frequency torsional vibrations at both ends. When driving the actuator at a resonant frequency f_r, the midpoint of the tube is a nodal point and is stationary and both ends of the actuator oscillate in opposite directions with respect to each other. One way clutches are located at each end of the actuator **51**. This symmetric configuration allows the full cycle of the oscillating displacement to be transmitted to the rotor, **55**.

A one-way clutch **52** is attached to an end of the actuator **51**, so that the end of the actuator **51** and the clutch **52** move together as follows: The one-way clutch **52** is in contact with the rotor via clutch rollers so that the clutch transmits the angular displacement of the actuator **51** to the rotor only if the actuator moves in the clockwise direction as shown in **FIG 5a**. A second one-way clutch **54** is attached to the other end of the actuator **51**, so that this other end of the actuator **51** and the second one way clutch **54** move together as follows: This second one way clutch **54** is in contact with the rotor via clutch rollers so that the second one way roller clutch **54** transmits the angular displacement of the actuator **51** to the rotor **55** only if the actuator moves in a clockwise direction.

An alternating electric field at the resonant frequency of the actuator is applied to the actuator segments as described above. Thus, the first one-way clutch **52** is used to rotate the rotor in the clockwise direction for the half cycle period, while the other end of the actuator tube connected to the second roller clutch **54** is disengaged from the rotor. In the next half cycle period, the first one way roller clutch **52** is disengaged from the rotor while the second clutch **54** rotates the rotor **55** in the clockwise direction. This full cycle torsional motor design provides full cycle rotary displacement in one direction (clockwise in the example of **FIG 5b**). The revolution speed of the rotor will be a full cycle rotary angle multiplied by the resonant frequency. Optionally, rollers **56** and **57** may be attached to a housing **53**, or other structural member, to maintain the rotor shaft in a stable holding position.

The length L of the actuator for use in a full-cycle piezoelectric motor should be equal to $\lambda/2$, where λ corresponds to the natural frequency f_r of the actuator. This allows the maximum angular displacement β to occur at the free ends of the actuator, and allows the motor to transmit maximum angular displacement to the rotor. The natural frequency, f_r, of a segment is dependant on the length and material properties of the actuator segments according to Equation (6) above.

Alternatively, a full cycle motor can be built to operate in a non-resonant mode, in order to transmit higher force at a lower speed. In a non-resonant motor embodiment, the actuator is subjected to a low frequency, high electric field. It is not necessary that the length of the actuator segments be built to correspond to the natural frequency in the non-resonant mode. The twist angle per cycle is proportional to the L/R ratio and the torque is independent of actuator length, so the geometry of the actuator may be varied to achieve the intended result.

The above description of several embodiments of the invention is intended for illustrative purposes only. Numerous modifications can be made to the disclosed configuration, while still remaining within the scope of the invention. To determine the scope of the invention, refer to the following claims.

Docket No.: N.C. 80,131
Inventor's Name: Kim

PATENT APPLICATION

ABSTRACT

A high power and high torque density piezoelectric motor is developed using torsional actuator tube (stator) directly coupled to the rotor via one or two one way clutches. A cylindrical torsional actuator is comprised of a plurality of tubular piezoelectric ceramic segments poled along their length, aligned in alternate polarity and bonded together with intervening electrodes. When an alternating electric field is applied to the electrodes across adjacent segments to actuate the segments in their shear resonance mode, an end of the cylindrical actuator moves in a direction perpendicular to the length of the cylindrical actuator in response to the applied electric field. In a half cycle torsional motor, the angular motion of the end of the cylindrical actuator is transmitted to a rotor via a one way roller clutch positioned at one end of the cylindrical actuator. A full cycle motor has a second one way clutch positioned at the other end of the cylindrical actuator tube such that both ends of the tube vibrate in opposite angular directions. These rotary displacements contributed alternatively from both ends of the cylindrical actuator (stator) are selectively transmitted to the rotor in unidirectional rotary motion via a set of one-way clutches. The clutches are built into both ends of the stator tube in such an orientation that the minute strokes are accumulated by converting the high frequency mechanical vibrations into continuous (or step-wise) motion of the rotor. Thus the power generated in the piezoelectric element is converted directly into rotary motion of the rotor, and thus this coupling mechanism results in a highly efficient motor. Specific values of the torsional angle and torque can be tailored for each application, by varying the actuator material, geometry and the applied alternating electric field.

FIG. 1A

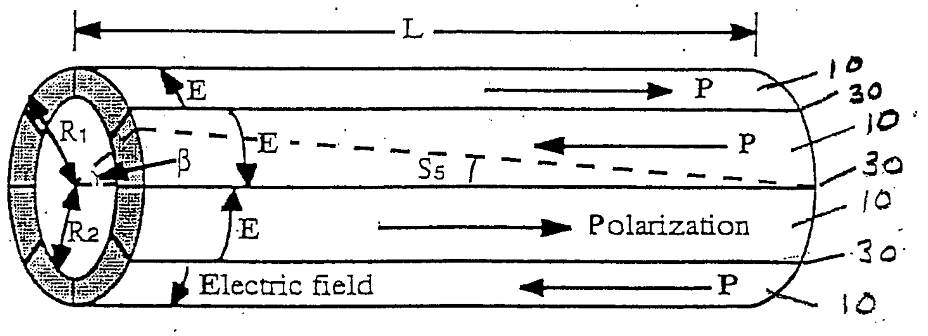
L
E
P
10
30
10
R1
E
P
β
30
S5
γ
10
R2
E
Polarization
30
Electric field
P
10

FIG. 1B

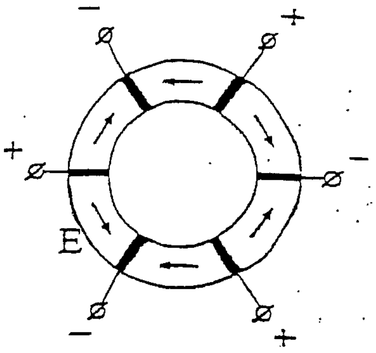
−
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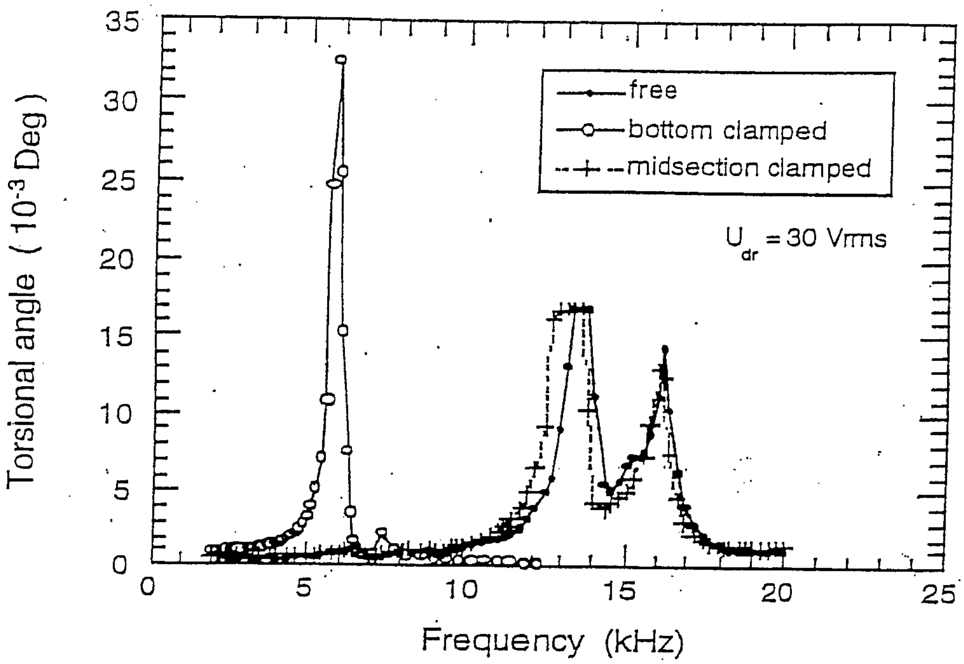
FIG. 2



Frequency dependence of the torsional angle. Different clamping conditions are compared for the same actuator.

FIG. 3

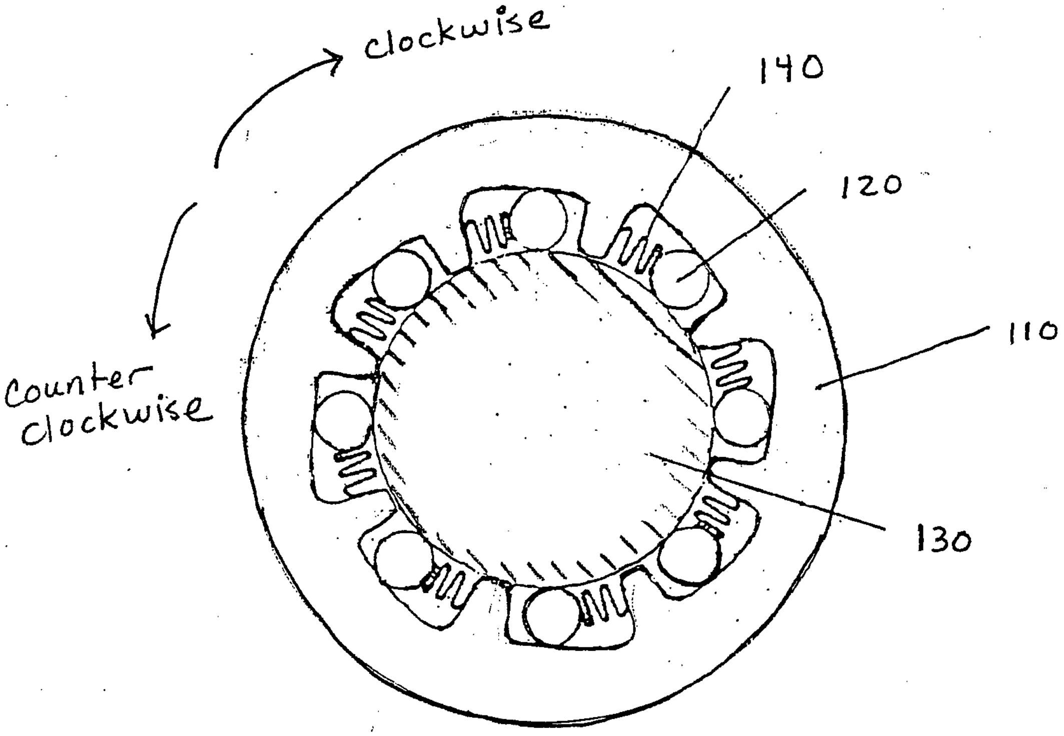


FIG. 4

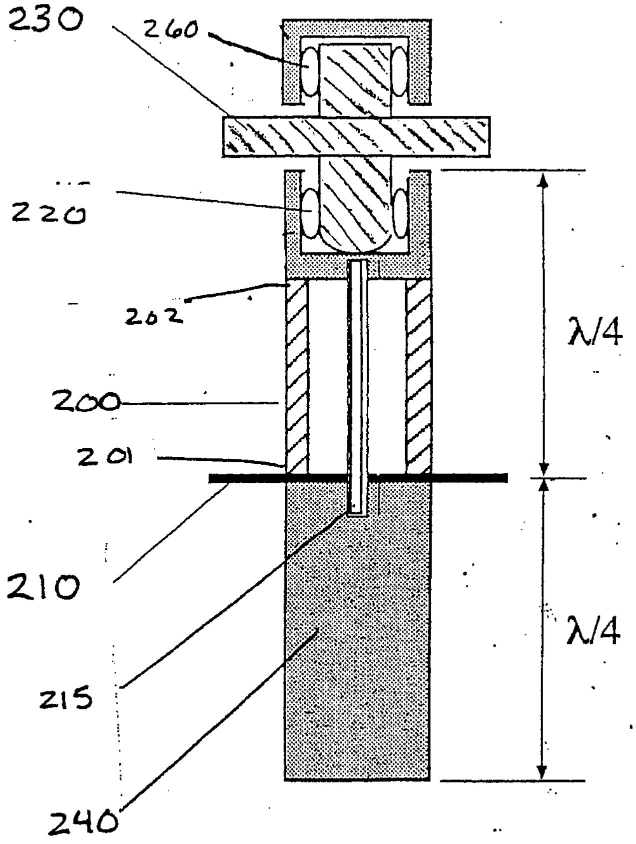


FIG 5a

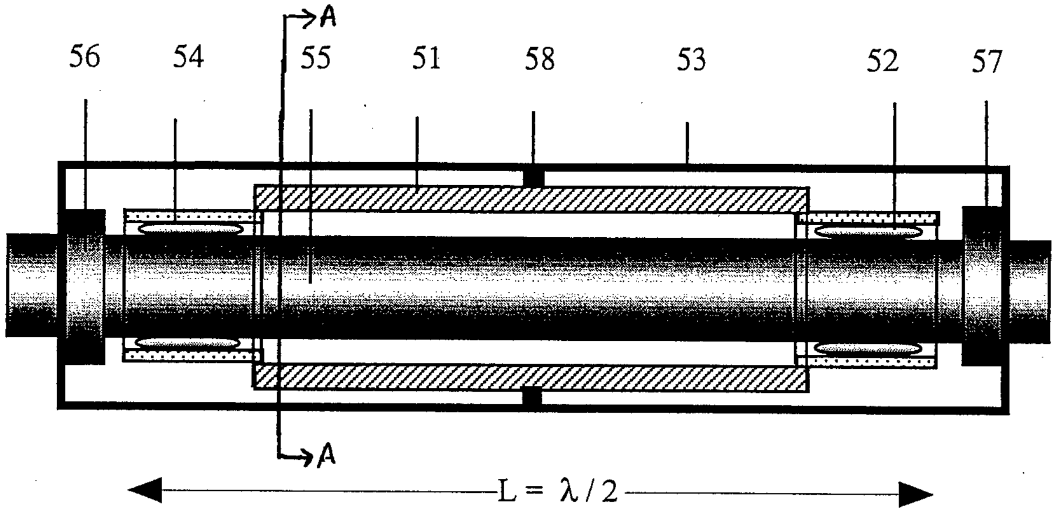


FIG 5b