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MAGNETOSTRICTIVE DIRECT DRIVE MOTOR

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Abstract

Highly magnetostrictive materials such as Tb.3Dy.7Fe2, commercially known as TERFENOL-D, have been used to date in a variety of devices such as high power actuators and linear motors. The larger magnetostriction available in twinned single crystal TERFENOL-D, approximately 2000 ppm at moderate magnetic field strengths, makes possible a new generation of magneto-mechanical devices. NASA researchers are investigating the potential of this material as the basis of a direct micro-stepping rotary motor with torque densities on the order of industrial hydraulics and five times greater than that of the most efficient, high power electric motors. Such a motor would be a micro-radian stepper, capable of precision movements and self-braking in the power off state. Two motor prototypes are being developed and competed against each other, one based on the proven "Inch Worm" technique and the other based on entirely new "Roller Locking" principle which eliminates pounding and the need for active clamping.

The thrust of this paper is to juxtapose innovative mechanical engineering techniques on proper magnetic circuit design to reduce losses in structural flexures, inertias, thermal expansions, eddy currents and magneto-mechanical coupling, thus optimizing motor performance and efficiency. Mathematical modelling techniques will be presented, to include magnetic, structural and both linear and non-linear dynamic calculations and simulations. In addition, test results on prototype hardware will be presented, including some promising early results.

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MAGNETOSTRICTIVE DIRECT DRIVE ROTARY MOTOR

1. Introduction

The performance of robots in space will ultimately be limited by the motors which drive them. These electromagnetic motors are limited in their torque density, hence they depend on high speed to generate power. This means that they must derive torque and force multiplication through gear reduction systems. And this in turn, means that the size of the motor/drive system must grow and that the efficiency and reliability of the system as a whole must decrease. Also, since most high performance electromagnetic motors today are servo type and not steppers, they must either use brakes or must keep the power on the hold position. This serves to reduce the duty cycle, reduce system efficiency and create heat. It also leads to limit cycling. On the other hand, adding a brake also increased size and complexity and reduced reliability. And, even if current stepping motors could be brought up to performance standards of servo motors we would still have the problem of needing gear reduction and a brake (because the magnetic holding force is too weak to ensure adequate safety margins with the power off. An entirely new approach, the magnetostrictive direct drive motor is needed to redress the inadequacies described above.

Magnetostriction may provide a means of developing an electric motor with power densities on the order of industrial hydraulics (> 5 times present electric motors) and with a frequency response in the sonar range (6 KHz per inch of length). The magnetostrictive motors would be inherently self braking with the power off thus power, efficiency and safety would be improved. In addition to their space applications, such motors/actuators would have major spin-offs into the commercial and industrial sectors.

Several concepts based on magnetostrictive drives have been attempted, all with varying degrees of success. In this paper two distinctly different approaches, one using magnetostrictive drive and clamping rods (inch worm principle:prototype A) and one using magnetostrictive drive rods and a roller locking system for clamping (prototype B) are described.

2. Literature Review

Several magnetostrictive devices have been developed, most of which are linear motors. Linear motors operate on the "inch Worm" principle such as is described in [1 - 8]. The motion generated in these devices is limited because of the nature of the materials typically used, (magnetostrictive or electrostrictive), the length of the translator and because electrical power must be provided to the active (and moving) portion of these motors. The Harvard motor described in reference [3] is rotary motor. However the principle used does not appear to lend itself to being developed into a practical motor due to several inherent disadvantages. First, the device is too bulky and the inertia of the rocker and the distance it must travel is a limiting factor on speed. Secondly, the force and torque are reduced because standard magnetic attraction techniques are used to power the device and the advantages of magnetostriction are used only in clamping. The ultrasonic motor illustrated in [5] is a magnetostrictive adaptation of the family of piezoelectric ultrasonic motors developed by Panasonic as described in reference [4]. This type of motor is limited in its torque output because the coupling between the elastic body and the rotating body is ultimately a frictional one. It is most appropriate as a piezoelectric system which places a premium on compactness and simplicity and in which torque can be modest. It is not particularly compact when magnetostrictive rods are used and as stated before, its torque capability is limited.

2.1 Disadvantages of Prior Art

Although Inch Worm technique is straight forward and proven it has several disadvantages. The "Inch Worm" technique has excessive coil losses because it requires dedicated active magnetostrictive elements to clamp. It also has critical tolerances on the clamping elements and it is difficult to get the clamping elements to adjust for wear without a prohibitive sacrifice in torque output. It is difficult to prevent large losses of torque and travel due to structural deflections. Also a lot of magnetostrictive material is required, some for the drive elements and some for the clamping elements. And, the system is bulky because of the excessive number of active elements, the coil windings which go with them and the magnetic shielding required to keep the fields of each element from interfering with each other.

The "Kiesewetter" technique [2] is prone to excessive wear. Since it depends on an interference fit, this device will not retain its clamping power as it wears out. The large number of drive coils makes the electronics extremely complex as it must excite these coils, one by one. Thus the task of making a rotary motor based on this principle is formidable. Although the forces generated through this motor are large, the speed is low as linear stroke is limited.

The "Ultrasonic Motor" is torque limited because it has a frictional coupling between the elastic body and the drive. Also, it requires a number of magnetostrictive elements. While it is compact as a piezoelectric motor, that advantage is lost when magnetostrictive elements are used. All-in-all, it seems most appropriate as a piezoelectric motor.

2.2 Motor Design Goals

Current robot motors are very high speed; but have weak torque compensated by using a transmission with extensive gearing. Since safety brakes are also required in these joints, these brakes must be located to act on the motor itself or the drive shaft on the motor side of the transmission to give them sufficient holding leverage. All these additions, compensations and restrictions lead to complications, lower reliability and controls problems. The magnetostrictive motor addresses these concerns by developing outstanding torque density and is self-braking with the power off. This permits the power to be taken directly off the drive shaft, eliminating brakes and transmissions. The magnetostrictive phenomenon using the material Terfenol-D shows promise because it generates impressive forces (> 4 ksi) and has excellent frequency response (6 KHz for 0.25 in. dia. rod). However, it also has three significant drawbacks, it has a very short stroke (0.001 in./in.), low magnetic permeability (5) [8] and low magnetomechanical coupling coefficient of 0.7 resulting in fifty percent efficiency. These drawbacks present formidable engineering challenges. Power lost in heat reduces the current in the Terfenol coils and thus affects the Terfenol performance. Earlier attempts to design a magnetostrictive rotary motor have not been successful due to inherent properties of Terfenol-D. Small stroke limits the rotary speed of motor. The supporting structure has to be carefully designed as Terfenol rods are hard, brittle and sensitive to fracture and hence enable to withstand shear and bending loads. This requires precision mechanical engineering which had been lacking in earlier attempts to design the rotary motor. Following design goals are set forth for the rotary motor after giving due consideration to the requirements of space applications and inherent advantages offered by Terfenol-D.

- Direct drive/compact package-high torque density
- Fail safe holding torque self locking with power off
- Microradian-size steps leading to precision control
- No limit cycling
- Simple/reliable-minimal number of moving parts
- Outstanding agility-high frequency response

3. Approach

Two prototypes based on Inch Worm and Roller Locking principle respectively are designed and are enumerated as follow.

3.1 Inch Worm Principle

The motor incorporates mechanically prestressed Terfenol-D rods for clamping and driving the drive discs, permanent magnets for magnetic bias and magnetic fields generated by electrical coils.

The Magnetostrictive motor has two important modules, namely a pole pair and a drive element. Pole pair is essentially a clutch device and its function is to either lock or unlock drive disc. The top and bottom drive discs are splined to the shaft. Drive element, transfers a torque to output shaft through drive disc and a pole pair. These two modules are as shown in Fig. 1. A pole pair having 'C' shaped cross section holds a number of Terfenol rods. The top and bottom flanges of a pole pair has number of slots resulting into number of cantilevers. Each pair of cantilever is associated with a clamping Terfenol-D rod and serves the purpose of prestressing the Terfenol rods and allow the expansion of Terfenol rods under magnetic field. Mechanical compressive prestress is adopted to raise the magnetostriction of Terfenol and to keep the Terfenol rod from tensile stress condition because of its relative low tensile strength.

When the Terfenol rods are energized through electric coils, they expand and deflect the cantilevered flange of the pole pair to make a firm contact with both the drive discs. Under no load condition this is achieved by the magnetic bias provided by the permanent magnets provided at the both the ends of the Terfenol rods. By adding permanent magnets to the pole pair the neutral position of the Terfenol rods can be shifted. Thus, when power is off, motor is self locked preventing any possibility of back driving under load. The self locking feature of this motor is attractive as it eliminates the additional device to lock the motor under no load, a requirement which renders conventional motor applications in space relatively costly as it limits the payload capacity of robots. Another advantage of the permanent magnetic bias field here is that now the maximum current needed in the coil is reduced by a factor of 2 and thus the coil losses by a factor of 4. By adding magnetic flux return to the pole pair design, the required current values can again be reduced by a factor of 2 resulting in a coil loss decrease by a factor of 16 compared to the no permanent magnets, no magnetic flux return design.

The drive discs can be unlocked if needed by driving the Terfenol rod in opposite direction. Two such pole pairs in the form of 150^{o} circle sectors are used in this motor. These pole pairs are coupled together by two 'U' springs as shown in Fig. 2. and react against each other in a sequential manner.

The drive elements are enclosures for another set of Terfenol rods assembled in such a way that they are perpendicular to those in the pole pairs. Drive elements are mounted on stator (casing) of motor. The free ends of Terfenol rods rest on vertical flanges on pole pairs. Thus, when expanded they react against the pole pairs. Two such sets of rods react diametrically opposite against a pole pair simultaneously to generate a torque.

The basic principle of the Magnetostrictive motor is to mechanically clamp two parallel drive discs through a set of Terfenol rods in a pole pair. Driving the drive discs by two parallel sets of Terfenol rods in drive elements generate a torque acting in the plane parallel to that of the drive disc. The net result of this is to rotate the shaft through a step of the order of micro-radian. The Magnetostrictive motor incorporates two sets of pole pairs and two sets of drive elements which react against each other in a sequential manner to function as a micro-stepper motor. The cycle of events which control the motion of the motor is shown schematically in Fig. 3 and is self explanatory. Prototype 'A' designed for 60 ft-lbs of torque at 30 r.p.m. is shown in Fig. 2.

3.2 Roller Locking Principle

Fig. 4 (a) illustrates the prototype 'B' concept. The drive assembly consists of two concentric races, in which one is circular (drive drum - which is positively connected to output shaft) and other cylinder having cams on its outer rim (drive cam cylinder - which is free to rotate on shaft) with a roller above each cam. Relative rotation which wedges the rollers between the narrow portion of the cam and the circular surface of the outer race forces both races to rotate together, while relative rotation in the opposite direction frees the rollers. For proper locking action, without backlash or slip the condition for self locking $\alpha \leq 2\phi$ must be satisfied. Here α is the angle between tangents to the cam contour and to the roller surface at contact points and $\phi = \tan^{-1} \mu$ (coefficient of friction).

Fig. 4 (b) shows the proposed design in half scale and give an idea of its size and complexity. In order to provide dual directional motion two sets of drive rods and a modified drive cam cylinder is incorporated in the design. The top half of the drive cam cylinder has cam oriented in such a way as to generate counterclockwise (CCW) motion. The bottom half of the drive cam cylinder has cam oriented in reverse fashion to facilitate motion in clockwise (CW) direction.

Under the influence of a magnetic field each of one pair of magnetostrictive rods (A) expands approximately 0.001 in/in. with great force. The opposing rods (B) contract approximately 0.001 in./in. Thus we have a rotational motion of the drive cam cylinder. This drive cam cylinder is coupled to the drive drum by conical rollers. These rollers are lightly preloaded so there is no backlash between the drive cam cylinder and the drive drum. As the drive cam cylinder rotates CCW, the CCW drive rollers try to roll up the CCW drive cams on the drive cam cylinder; but are immediately pinned between the drive drum and the drive cams and the rollers locks generating positive motion in CCW direction. At the same time, the magnets above the CW rollers are activated. Following this, the CW rollers first roll, disengaging from both the drive cam and the drive shaft drum, and then are each pulled up against the magnetized plate. Thus, a preferential CCW torque and motion is established. When the magnetic field in the expanding rod set (A) collapses, the system returns to neutral and the cycle can start again (except that the CW rollers are effectively nonparticipatory). When the magnetic field is excited at high frequency the system cycles in a rapid ratcheting motion generating relatively high rpm.

Following the above procedure using the magnetostrictive rod pair (B) as the drive source, results into a CCW ratcheting motion. The torque produced by the magnetostrictive rods is oscillatory while that emerging from the output shaft is unidirectional (but reversible).

4. Expected Performance

The performance of the motor can be evaluated by number of benchmarks like torque, speed, efficiency, wear and life etc.

4.1 Prototype A

The torque of prototype A depends on various parameters such as torque arm, materials, no of Terfenol rods per pole pair, no of shoes per pole pair etc. For 0.25 inch diameter Terfenol rod, 4 nos per pole pair, the clamping torque is 40 ft - lbs. The drive torque each drive module is 34 ft - lbs. The motor is expected to work without slip as clamping torque is higher than the drive torque.

4.1.2 Frequency Response

The frequency response depends on inertia torque caused by load acceleration or deceleration, the inertia of the load, the operating speed and the angle of acceleration. The pole pairs, clamping rods and associated windings contribute to the no load inertia. The inertias of top and bottom drive discs and shaft together with no load inertia determine the full load frequency response of the motor. The results based on data taken from Fig. 2 is tabulated in Table 1.

The individual oscillating and rotary moment of inertias and their sum total calculated from the data taken from Fig. 2 is shown in Table 1.

Table 1: Polar Moment of Inertia (J) of Oscillating and Rotary Members

			J (ft lb sec^2)
Member	Each	No	Total
Clamping Module	1.82459E-04	2	3.64918E-04
Clamping Rod	9.75629E-05	8	3.90251E-04
Clamping Rod Coils	1.78697E-05	8	7.14788E-05
Top Drive Disc	1.144019E-04	1	1.144019E-04
Bottom Drive Disc	3.1896918E-04	1	3.1896918E-04
Shaft	1.76529E-06	1	1.76529E-06
			ΣJ_{osc} = 1.28837E-03

$\Sigma J_{rot} = 0.43553E-03$
$\Sigma J \quad = 1.7235E-03$

Where,
ΣJ_{osc} = inertia of oscillating parts
ΣJ_{rot} = inertia of rotary parts
ΣJ = total inertia

Table 2 shows the no load and full load frequency response of prototype A.

Table 2: No Load and Full Load Frequency Response of Prototype A

T (60 ft - lbs)				
Loading	Acceleration α (rad/sec^2)	time T(seconds)	Frequency f_m (Hz)	rpm n
No Load	27167.585	2.65842E-4	3761.6199	68.967981
Full Load	20304.439	3.07484E-4	3252.1979	59.627908

4.1.2 Deflections

The top and bottom drive discs are the only members susceptible to excessive deflections. However, the top drive disc is protected by wear compensation mechanism. In view of this bottom drive disc is made heavier to withstand the major deflections. The deflection of bottom drive disc should not exceed more than that of the expansion of the drive rods. The deflection of bottom drive disc is computed from the formula [9] for the case of flat circular disc fixed at the center and free at the outer rim. The maximum deflection of the bottom drive disc is 6.9837 μ inches.

4.1.3 Wear

There are a large number of variables which affect wear. Structural properties of the material, hardness, state of lubrication, load/pressure, sliding velocity, sliding time, surface temperature rise, size, finish, clearance and ambient temperature are the various parameters which affect wear. The most important and independent ones are the load and the velocity as these are dictated by the system requirements. Analytical technique for wear prediction is based on engineering model for zero wear [10]. Zero wear is taken to be wear of such a magnitude that the surface finish in the wear track is not significantly different from the finish in the unworn portion. Non zero wear would be a change in the contour which is greater than the surface finish. The condition for zero wear for N passes is given by following equation.

$$\gamma = \left(\frac{2*10^3}{N}\right)^{\frac{1}{9}} \gamma_R \tag{1}$$

$$\tau_{max} = Kq_o \sqrt{(0.5)^2 + \mu^2}$$

$$\gamma = \frac{\tau_{max}}{\tau_y}$$

where,

$\gamma_R = 0.52$ for 2000 passes

q_o = pressure between drive disc and top and bottom flanges

τ_{max} = Shear stress

τ_y = Yield strength in shear

Evaluating the above equation for N we get N = 6.15042 E17 passes. Considering no load frequency of prototype of 3761.6199 Hz, drive discs have zero wear.

4.2 Prototype B

Torque capacity for a given geometry of drive drum and drive cam cylinder and their material properties is established by three considerations: Hertz contact stresses, hoop stresses and deflections. Prototype B design shown in Fig. 4 is arrived at after many iterations to satisfy these requirements. The motor is designed to deliver 60 ft-lbs at 36 rpm at no load speeds.

4.2.1 Frequency Response

No load inertial limitations involve the rollers and drive cam cylinder. We can neglect the drive drum and drive shaft because they store kinetic energy and serve as flywheel. The frequency response of motor under no load depends on the inertia of oscillating parts of motor.

The individual polar moment of inertias calculated from the data taken from Fig. 4 is shown in Table 3.

Table 3: Polar Moment of Inertia (J) of Oscillating and Rotary Members

Member	Each	No	Total
			J (ft lb sec^2)*E-06
Rollers	2.15368E-06	14	30.15152
Drive Cam Cylinder	872.45618E-06	1	872.45618
Drive Drum	515.57294E-06	2	1031.14590
Shaft	31.2213E-06	1	31.22120

$\Sigma J_{osc} = 902.6077$

$\Sigma J_{rot} = 1062.3671$

$\Sigma J = 1964.9748$

Where,

ΣJ_{osc} = inertia of oscillating parts

ΣJ_{rot} = inertia of rotary parts

ΣJ = total inertia

Table 4 shows the no load and full load frequency response of prototype B.

Table 4: No Load and Full Load Frequency Response of Prototype B

T (60 ft - lbs)				
Loading	Acceleration α (rad/sec^2)	time T(seconds)	Frequency f_m (Hz)	rpm n
No Load	66474	2.45303E-4	4076.5910	155.7139
Full Load	30534.7	3.61936E-4	2762.9194	105.5355

4.2.2 Structural Stresses and Deformations

As the motor drives, the drive rollers roll slightly, deform and the drum stretches until the structural reactions balance the torque forces. As a rule of thumb this equality of forces should occur before the total deflections exceeds the fifty percent cam rise or Terfenol rod expansion so that useful motion at maximum torque can be achieved. At maximum torque, structural deformations are primarily due to contact and hoop stresses induced in the roller, drive drum and drive cam cylinder. The contact stresses can be reduced by increasing the number of rollers but beyond a certain point it does no good to add additional rollers, since the controlling resisting force that determines torque carrying capacity is the hoop strength and rate of stretch of the drive drum and drive cam cylinder and not the number of rollers involved. The contact stresses and strains and Hoop stresses and strains are computed using appropriate formulae's [9] and are as shown in the following table.

Table 5: Contact and Hoop Stresses for Prototype B

	Stresses (ksi)		Deformations (μ inches)	
	Contact σ_c	Hoop σ_h	Contact δ_c	Hoop δ_h
Roller	-	-	2.65	-
Drive Cam Cylinder	112	2.9	0	60
Drive Drum	74	6.4	0.2548	38

$\Sigma\,\delta = 101\ \mu$ inch.

Current industry standards limit Hertz stress to 450 ksi because Brinelling occurs at 650 ksi for steel hardened to Rc 58-62. Using cam radius larger than roller helps minimize Hertz stresses. The elastic limit for high strength alloy steel S.A.E. 52100 is 175-240 ksi. The allowable flexure in a half stroke is 136 μ-in. Thus, deformations appear to be manageable.

4.2.3 Wear

Since the wear of various components of roller drive affect the performance and the replacements of these components are impractical, wear and wear predictions are of major concern. Referring to equation (1) for this case following relationship apply.

$$\tau_{max} = \frac{\sigma_{cmax}}{3}$$

where,

$\gamma_R = 0.54$ for 2000 passes

σ_{cmax} = Contact stress

Evaluating the above equation for N we get N = 2.03119 E08 passes. Which relates to life of 188 hours without any significant wear on the cam which is the most vulnerable member of the prototype B for wear.

5. Experimental Results

5.1 Prototype A

Type A motor was brought to prototype recently and even with undersized drive rods has yielded a record (for its size of 10.25 X 4.50 X 4.25 inches) 9 ft-lbs of torque directly off its shaft at 0.5 rpm. The device used 600 watts of power. Rotary motion was achieved and the motor ran smoothly. There was none of

5.1 Prototype A

Type A motor was brought to prototype recently and even with undersized drive rods has yielded a record (for its size of 10.25 X 4.50 X 4.25 inches) 9 ft-lbs of torque directly off its shaft at 0.5 rpm. The device used 600 watts of power. Rotary motion was achieved and the motor ran smoothly. There was none of the pounding that had been expected. The holding torque was on the same order of magnitude as the drive torque. And the step resolution was equally outstanding, 800 micro-radians for a full cycle. This being a proof-of-principle prototype, no effort was made to control its weight (39 lbs.). Low speed (0.5 rpm) is due to excessive internal inertia and the fact that underpowered Terfenol rods which were available were used.

5.2 Prototype B

Type B is undergoing the latest of several iterations in detailed design, each of which has improved its performance. Performance of 60 ft-lbs maximum torque at 36 rpm no load speed, 0.4 hp and step sizes ranging from 10 to 800 μ-rad is expected from a compact package of overall dimensions of 5 X 5 X 6 inch high. This would be a major statement in the state-of-the-art in electric motors. The critical first step is to prove the principle. A commercial roller-locking device will be used to build a unidirectional motor to achieve this objective. The prototype will have weaker drive rods and so will be somewhat slower than the production motor; but a significant improvement over prototype A is expected.

6. Applications

The development of a magnetostrictive direct drive, micro-stepping motor would constitute a fundamental improvement in the state-of-the-art of electric motors, particularly for space applications. Research on prototype B has yielded an important by product - a Roller Locking Brake which shows promise in significantly extending the state-of-the-art in low power, high performance brakes. A second "spin-off" has also been discovered because of the obvious possibilities presented by the Roller Locking Brake. This new product involves a Dual Roll Wrist which needs only one motor and two Roller Locking Brakes to achieve two concentric degrees of rotational freedom about a single axis if a conventional motor is used or one motor and one Roller Locking Brake if a magnetostrictive direct drive motor is used. This will prove very important in space robotics where fastening/grasping and manipulation by rotation must be accomplished at the robot wrist. A host of minor latches and mechanisms and caging devices would also benefit by using magnetostrictive direct drive motors. In addition to their space applications, such motors/actuators would have major spin-offs into the commercial and industrial sectors. In addition to robotics, materials handling equipment such as cranes, elevators and conveyor belts seems uniquely suited to the high torque, self-locking and braking capabilities of magnetostrictive motors.

7. Discussions

As reported earlier, motor B appears to have much more potential than motor 'A' because of our experience with prototype A, particularly as concerns speed. The prototype A demonstration was highly successful in the achieving record torque output (9 ft-lbf) for its size and in precision microsteps (800 μ-radians for a full step). It was not as successful in its no load speed (0.5 rpm) primarily because all the clamping coils were mounted on pole pairs, contributing to the total oscillating inertia. Troubleshooting the prototype 'A' design found numerous instances where the inertial components of the motor could be reduced. For example, the heavy coils of the clamping elements can be inertially decoupled from the Terfenol clamps and this, alone, will raise the speed significantly with very little real impact on motor design. But; it is better still to eliminate the clamping elements completely. Thus, the development effort is now turning towards bringing type B motor to prototype. The increased sensitivity to no load speed (and efficiency), has resulted into improved type 'B' motor design. Wherein major effort has been to reduce oscillating inertias for better frequency response.

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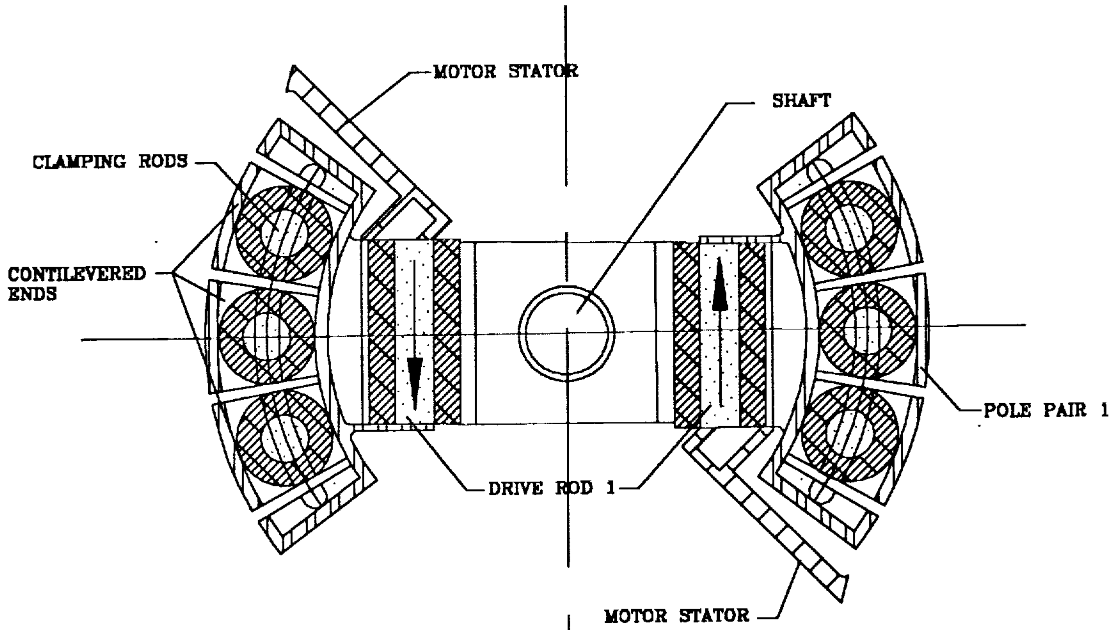

CLAMPING (POLE PAIR) AND DRIVE MODULE

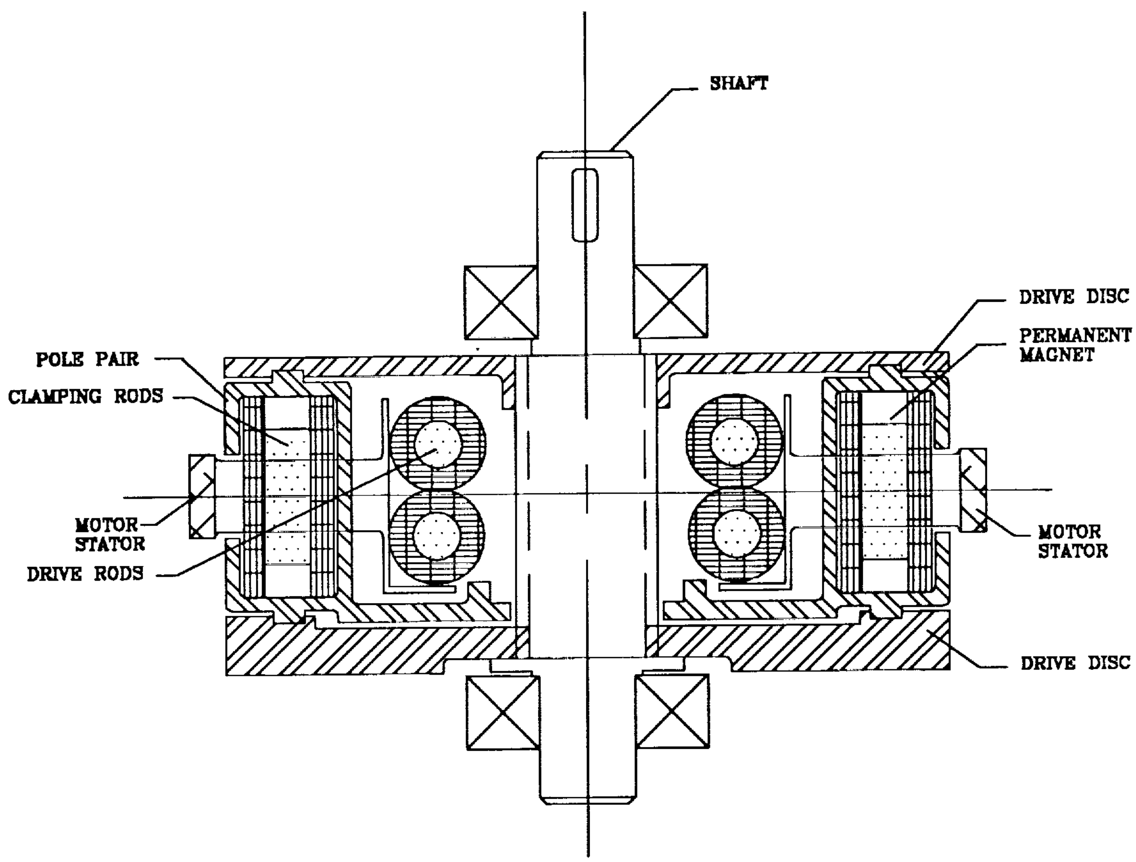

FIG. 1 CONCEPTUAL DESIGN OF PROTOTYPE 'A'

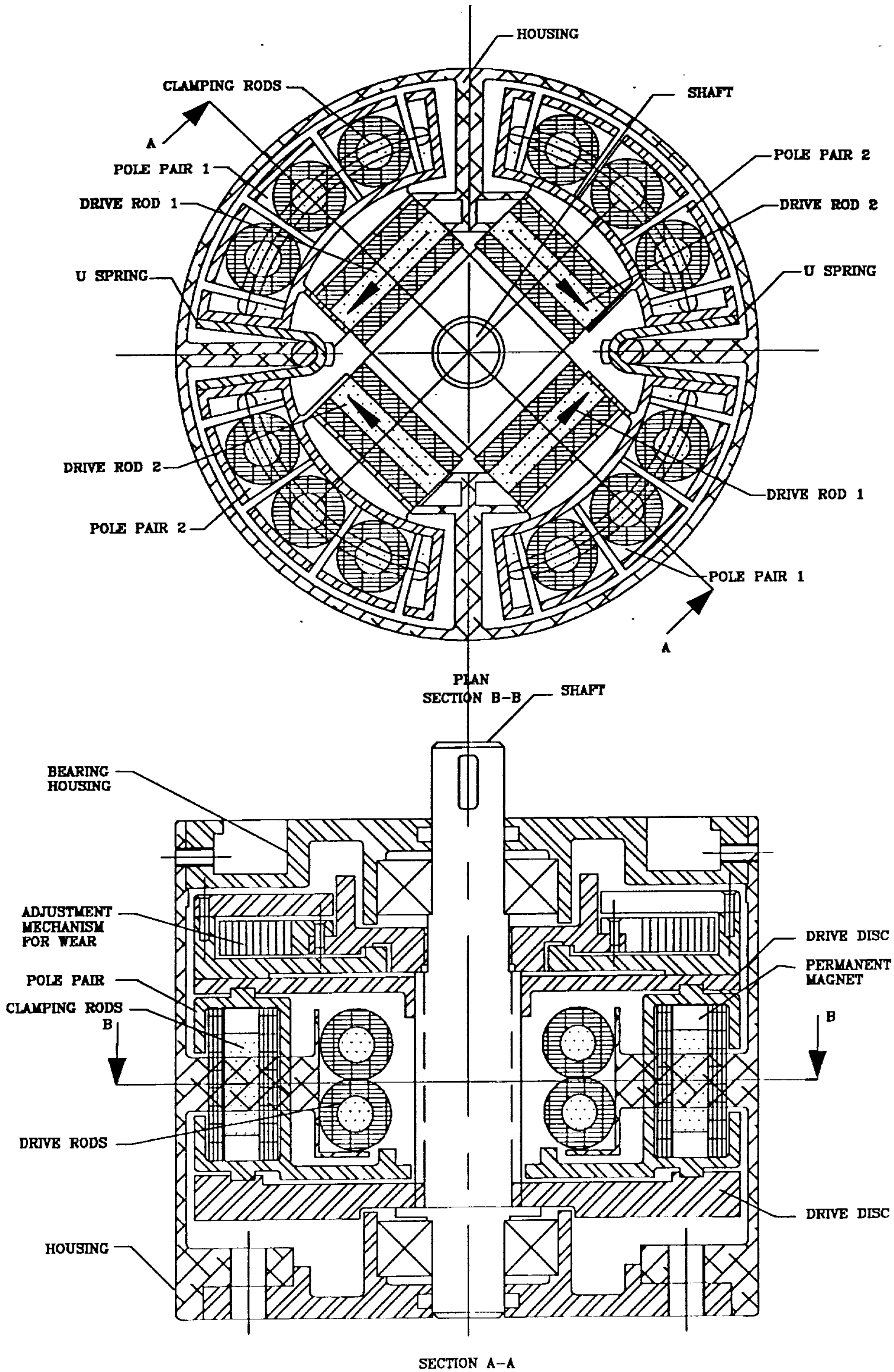

FIG. 2 PROTOTYPE 'A'

SCALE: 1:2

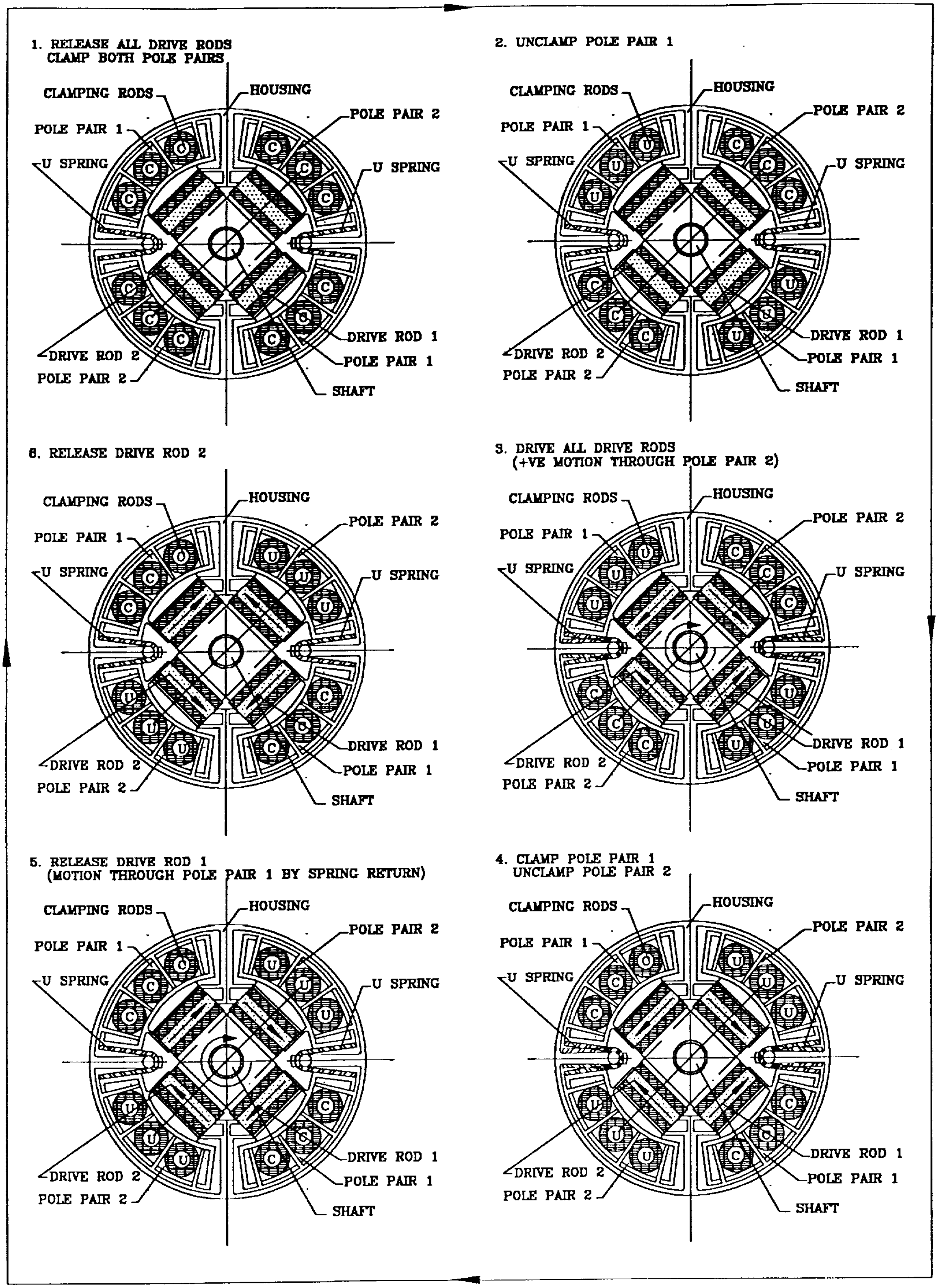

FIG. 3 PROTOTYPE 'A' MOTION CYCLE

SCALE: 1:2

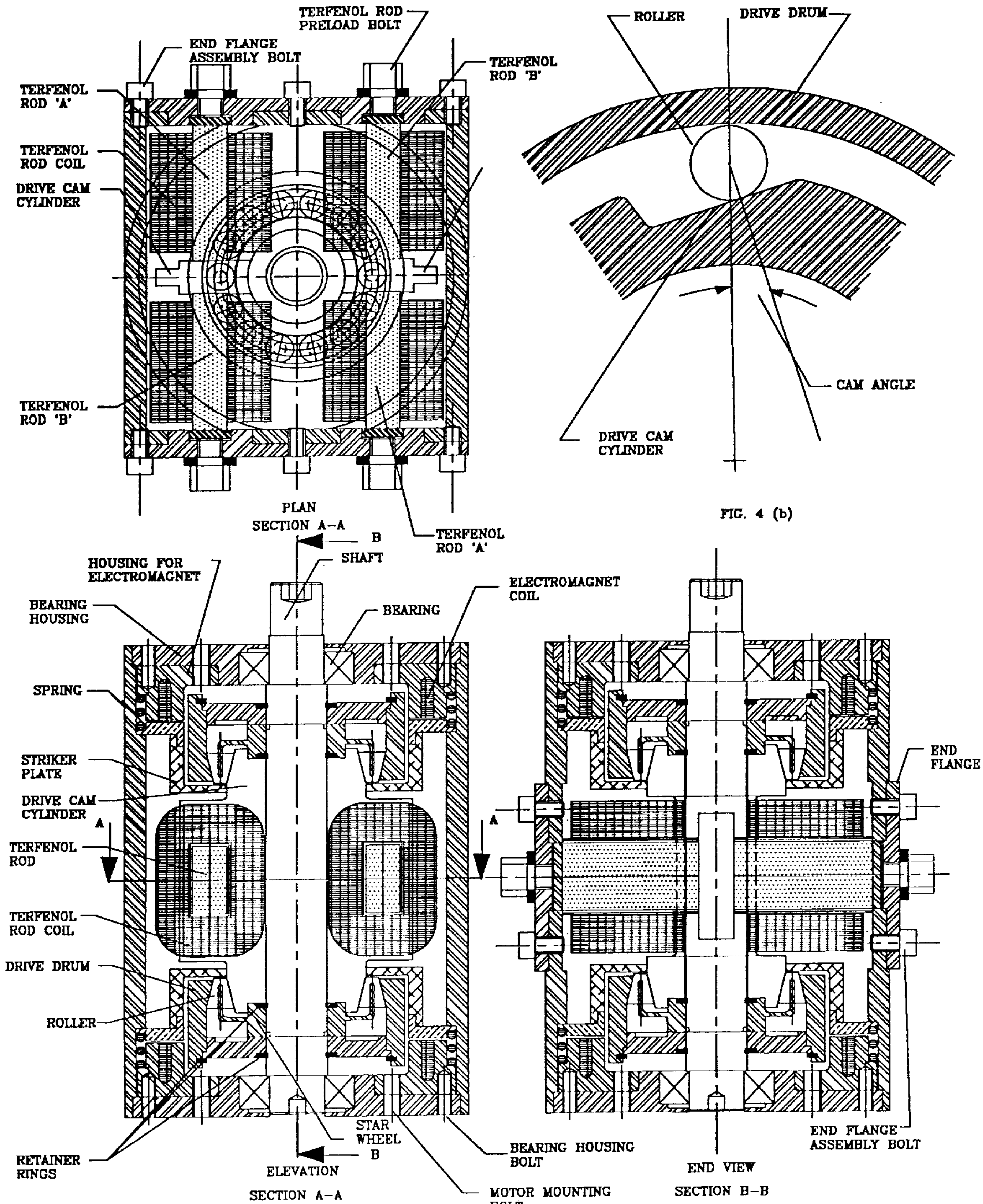

FIG. 4 PROTOTYPE 'B'

SCALE: 1:2