US 20250264296A1

(19) United States
(12) Patent Application Publication
Wirth
(10) Pub. No.: US 2025/0264296 A1
(43) Pub. Date: Aug. 21, 2025

(54) **SPIN STABILIZATION OF PROJECTILES ACCELERATED BY ELECTROMAGNETIC FORCE**

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(21) Appl. No.: **18/581,611**

(22) Filed: **Feb. 20, 2024**

Publication Classification

(51) **Int. Cl.**
F41B 6/00 (2006.01)

(52) **U.S. Cl.**
CPC *F41B 6/003* (2013.01)

(57) **ABSTRACT**

An electromagnetic accelerator device which is configured to impart spin to projectiles fired from it. Various methods to accomplish this stabilization are proposed. The spin may be imparted physically using friction, inductively using an alternating magnetic field or inducing eddy currents in an armature, or by shaping the magnetic field or armature within the barrel of the device appropriately. The magnetic field(s) within such a device may be configured to impart a linear, as well as a rotational force, upon an armature which may be non-circular in cross-sectional profile, or non-axi-symmetric in physical shape or material properties.

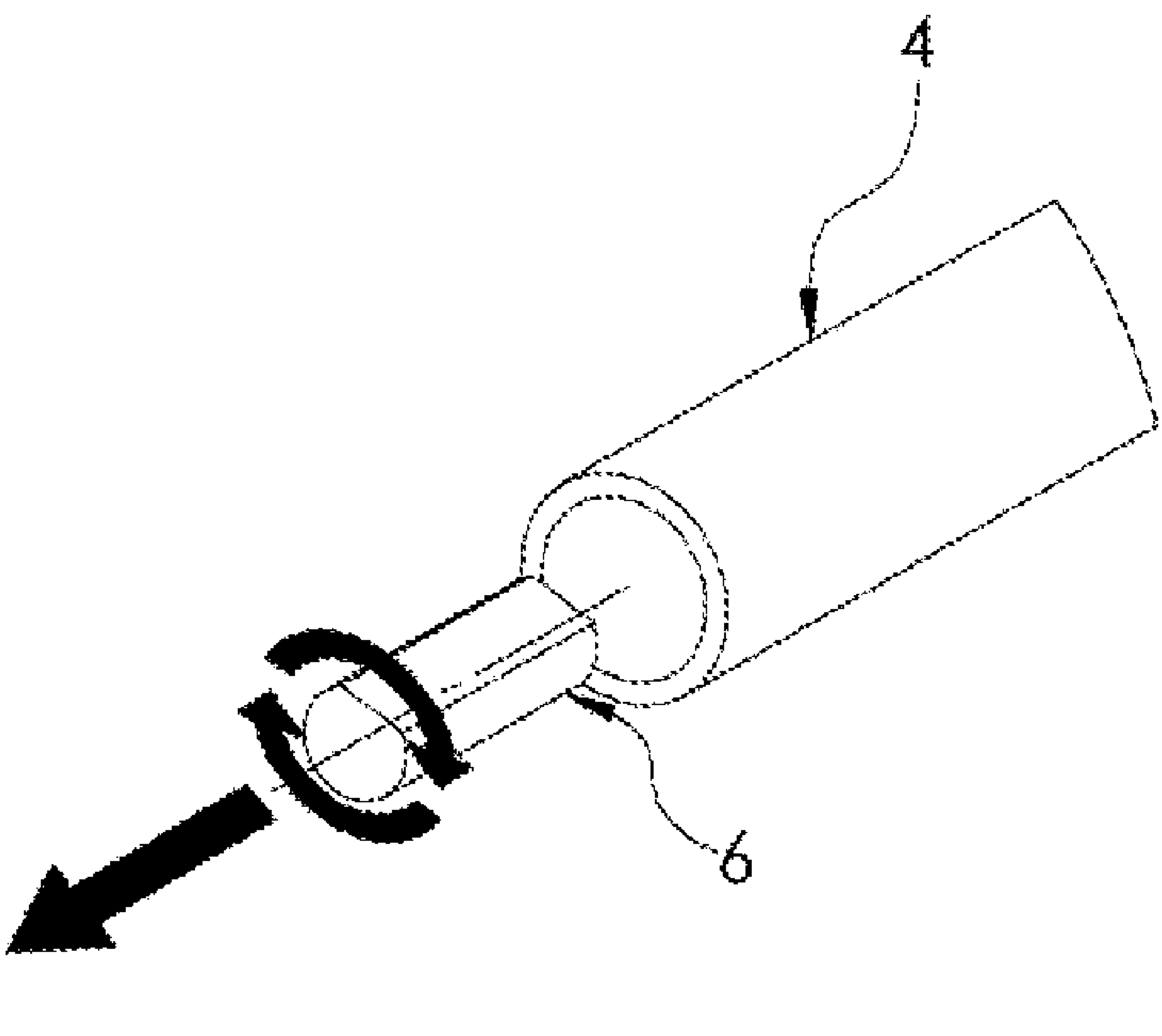


Fig. 1

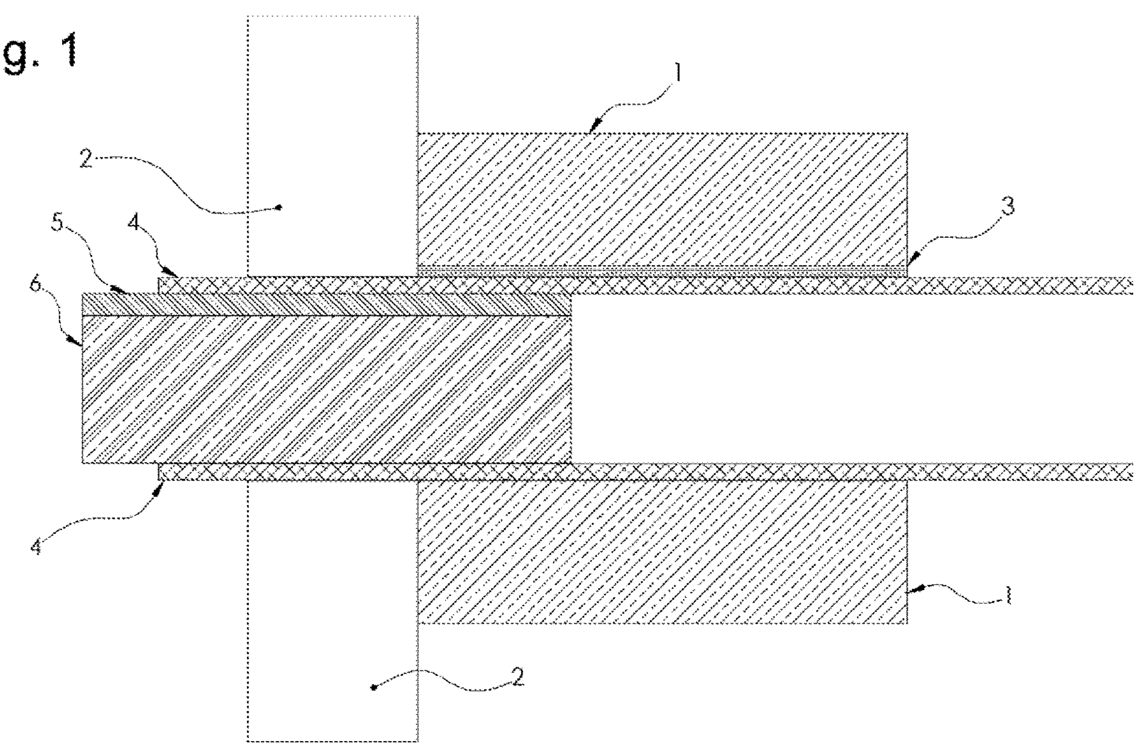


Fig. 2

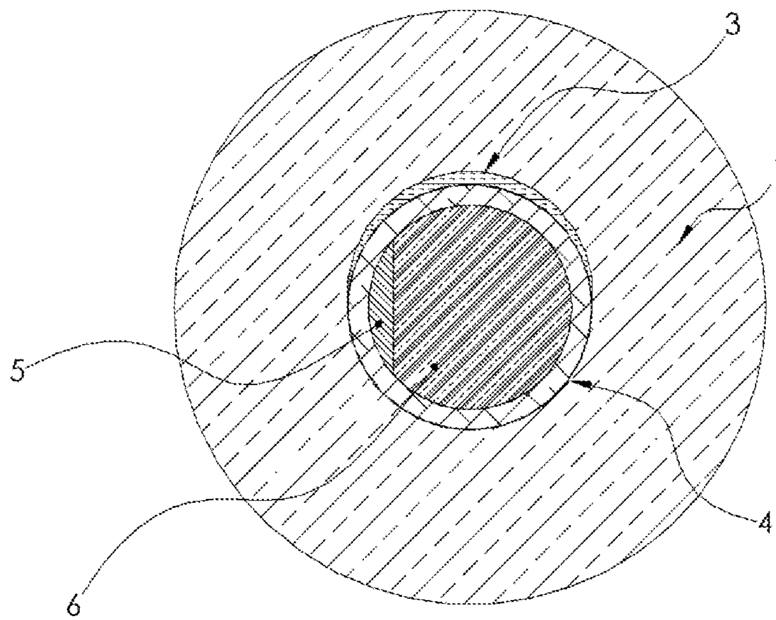


Fig. 3

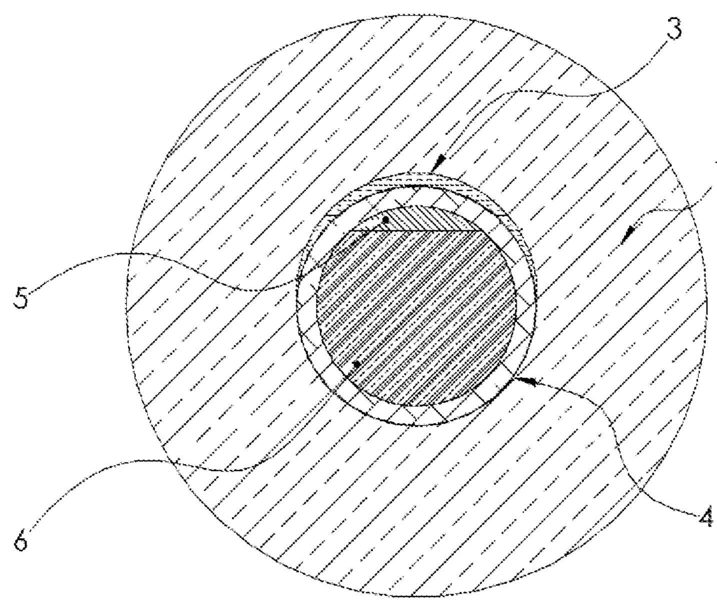


Fig. 4

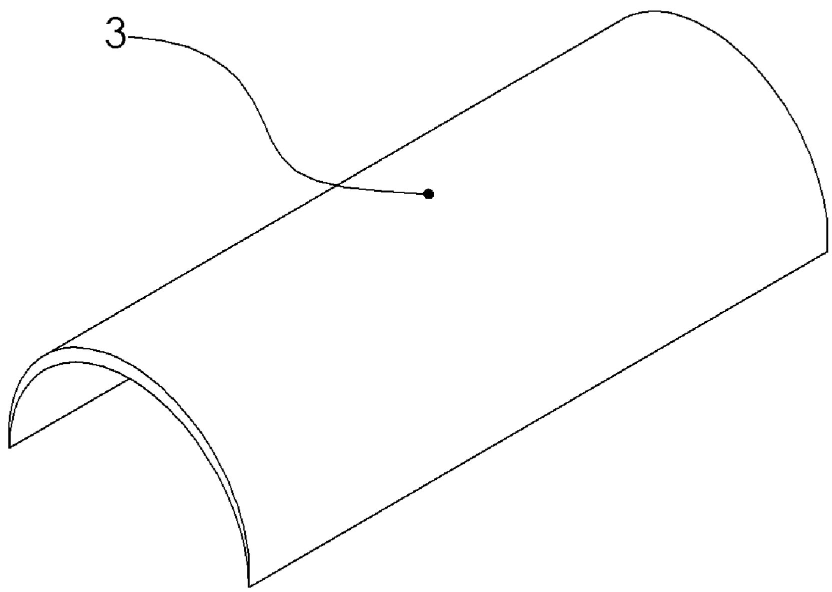


Fig. 5

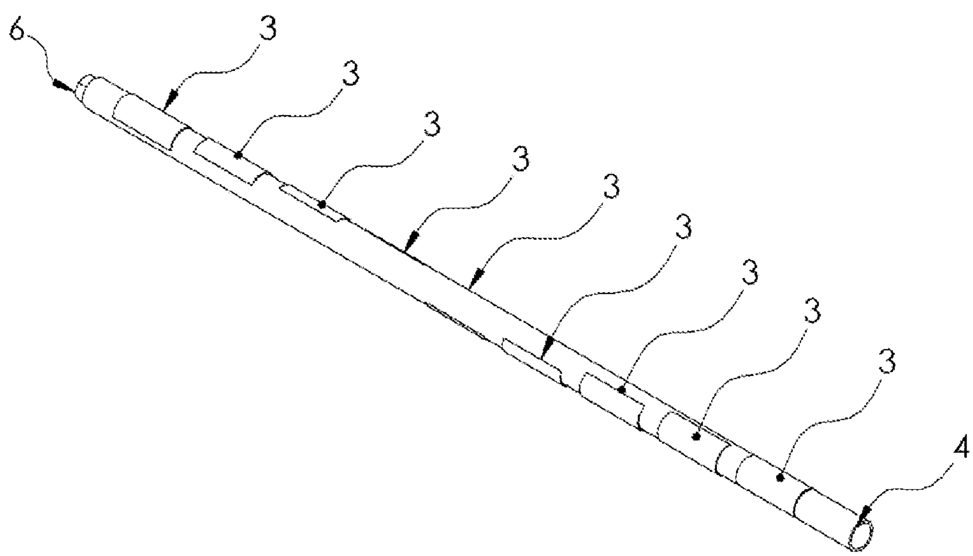


Fig. 6C

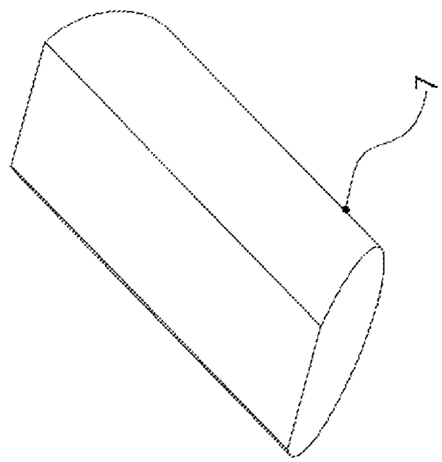


Fig. 6B

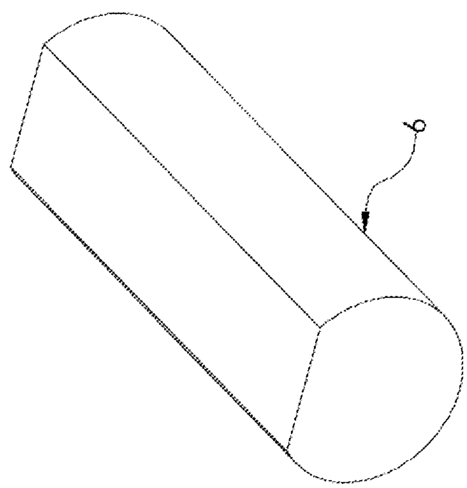


Fig. 6A

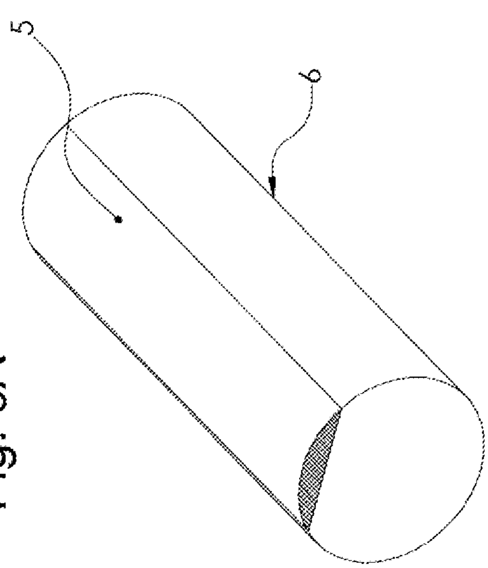


Fig. 7

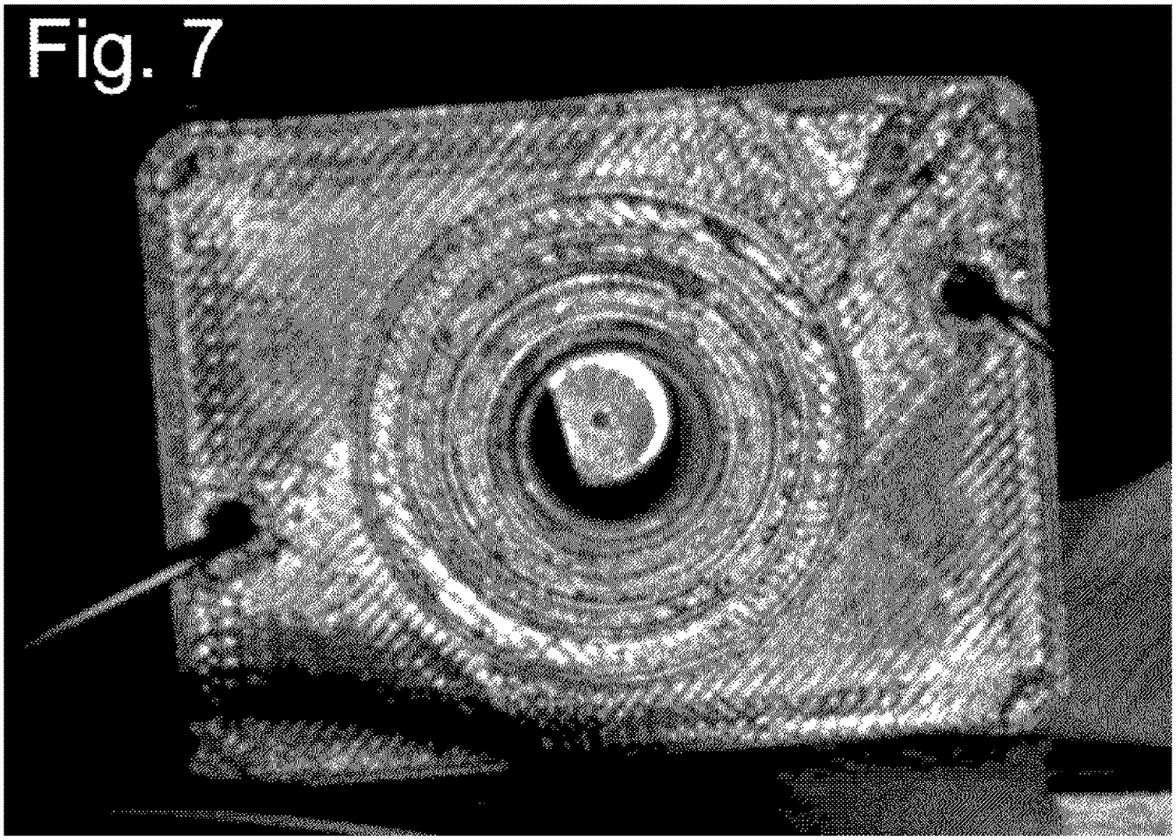


Fig. 8

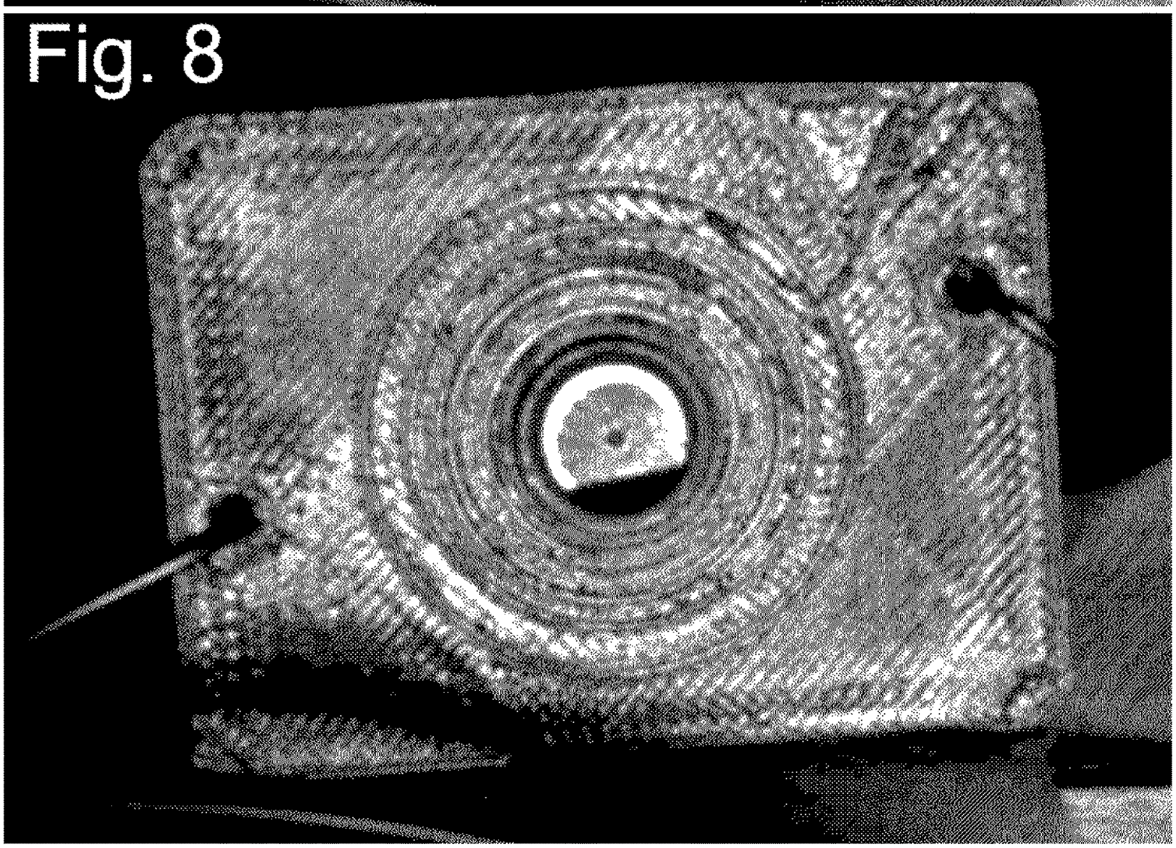


Fig. 9

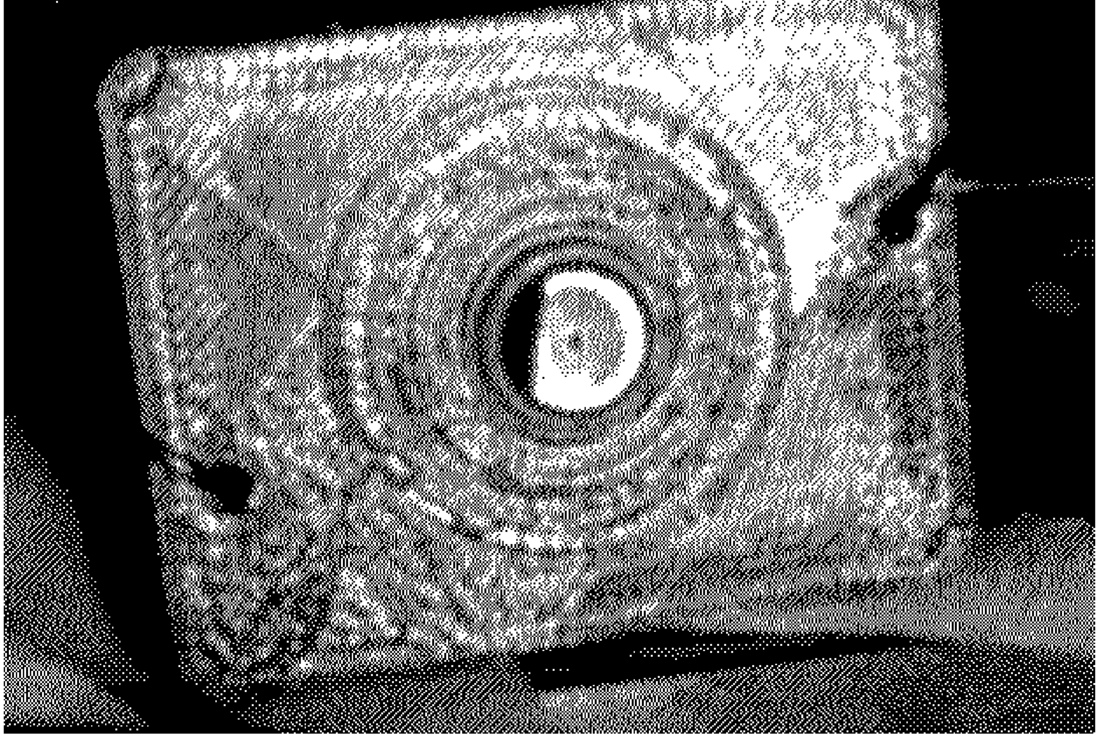
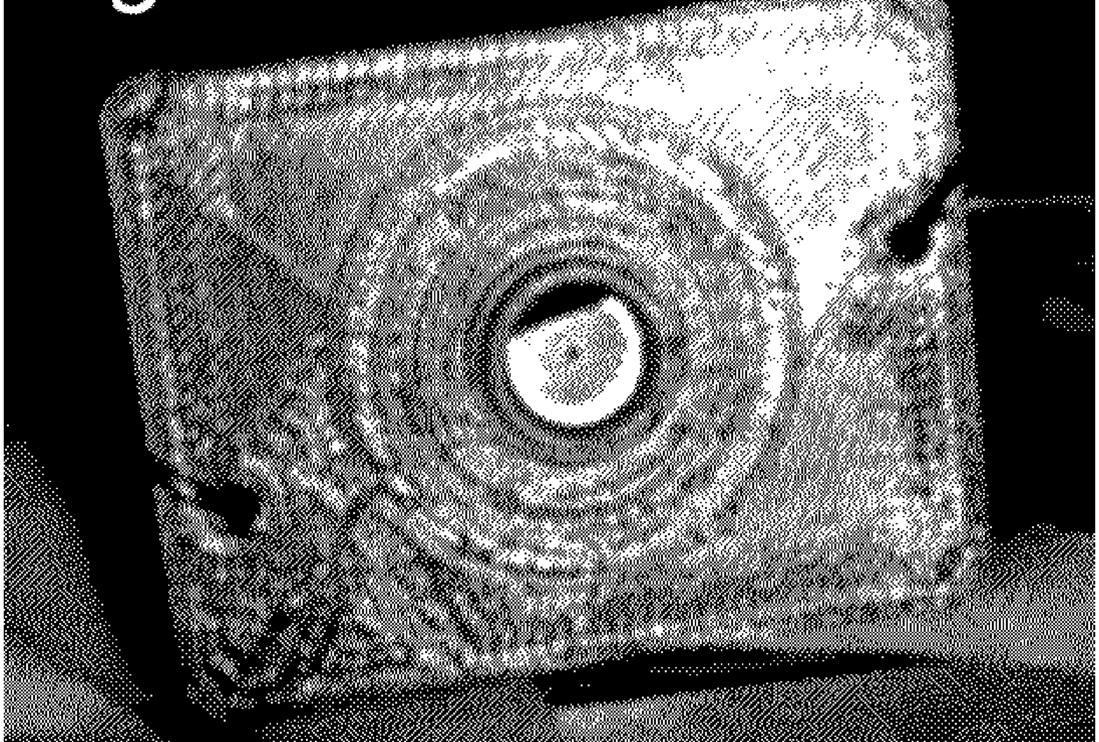


Fig. 10



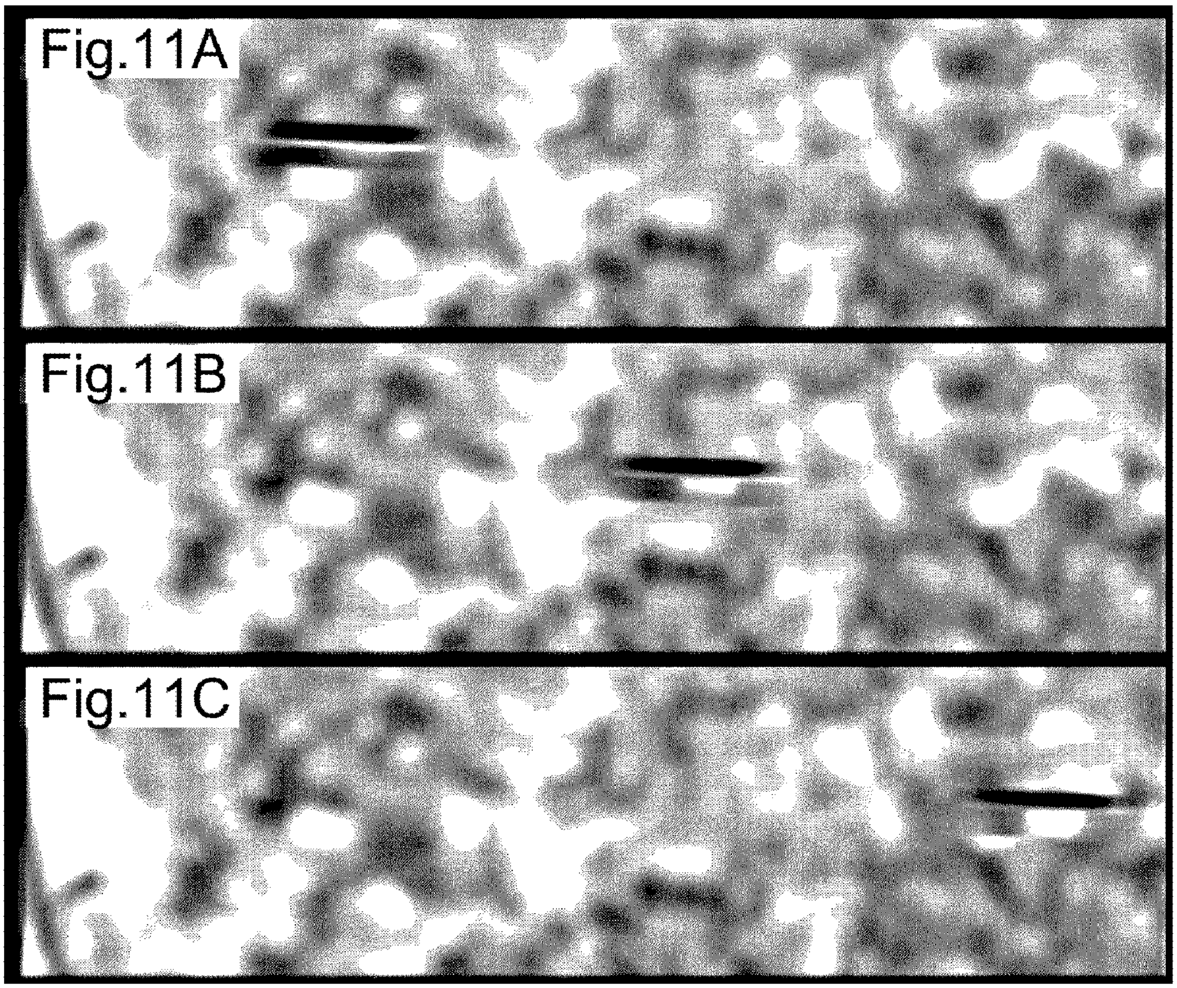


Fig.11A

Fig.11B

Fig.11C

Fig. 12

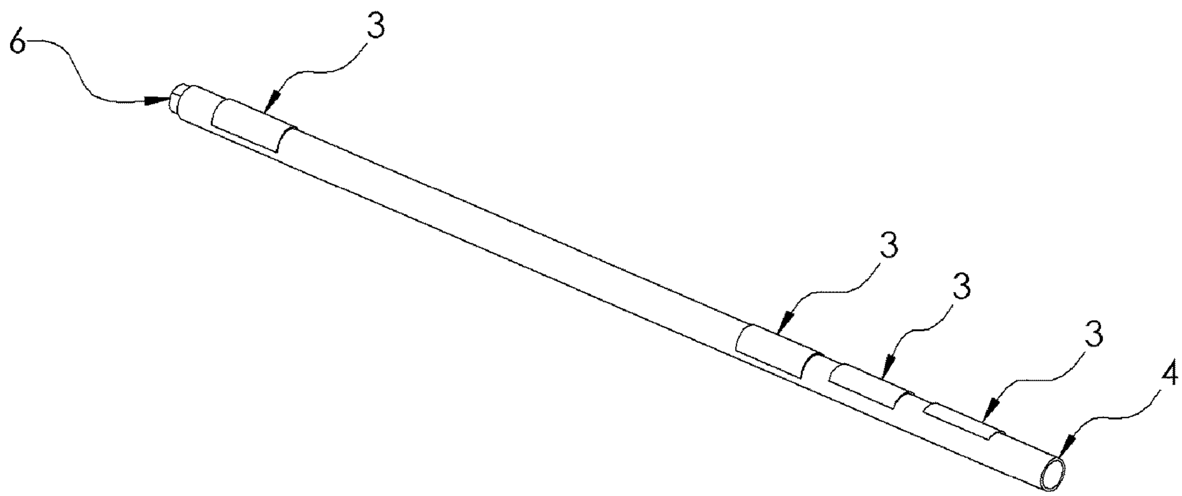


Fig. 13

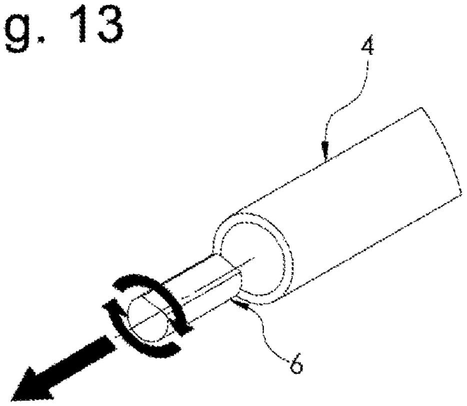


Fig. 14

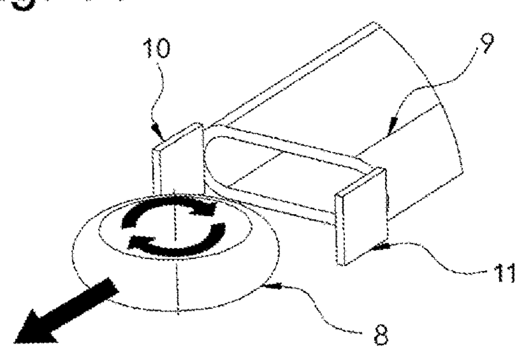


Fig. 15

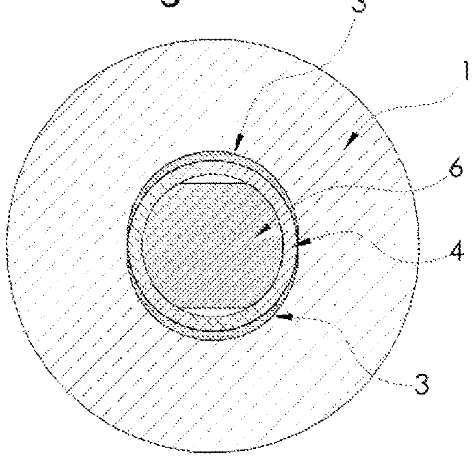


Fig. 16

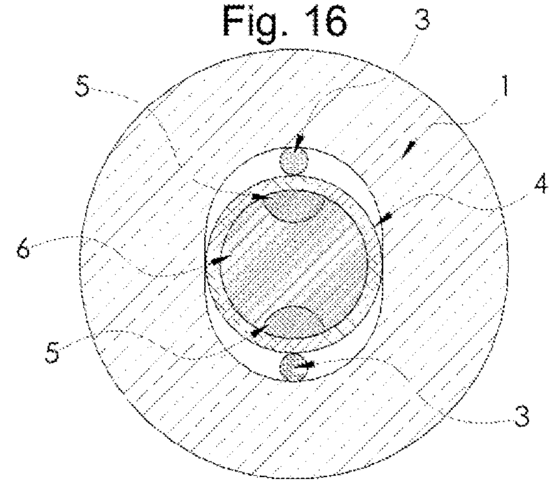


Fig. 17

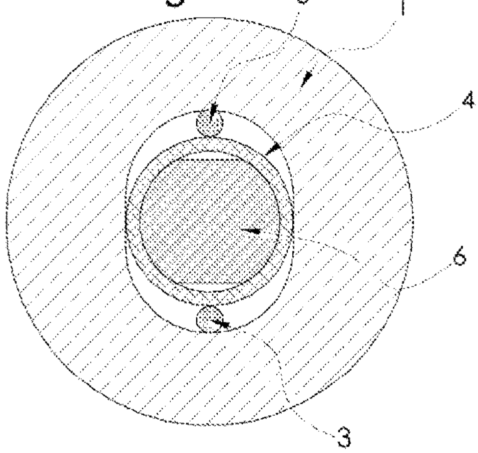


Fig. 18

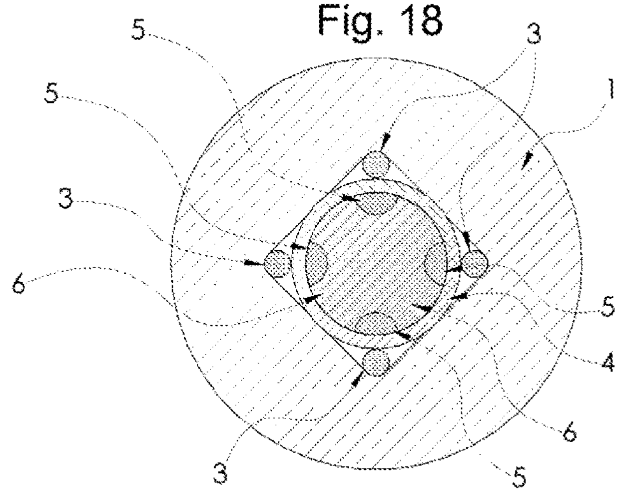


Fig. 19

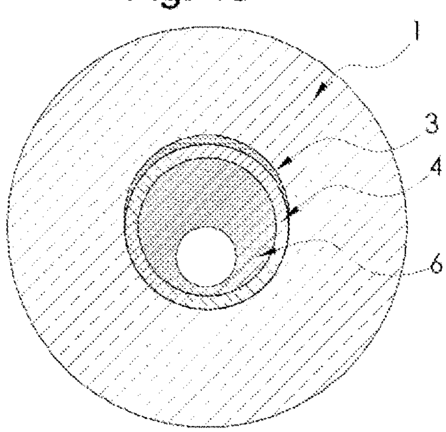


Fig. 20

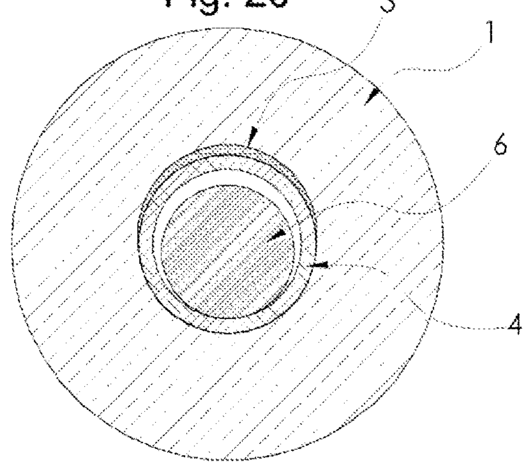
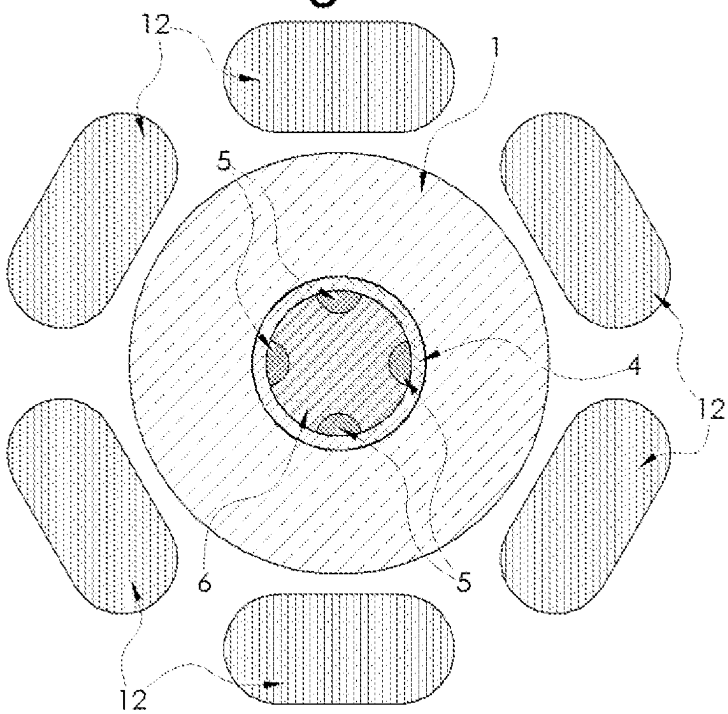


Fig. 21



SPIN STABILIZATION OF PROJECTILES ACCELERATED BY ELECTROMAGNETIC FORCE

TECHNICAL FIELD

[0001] This invention relates to a rifling system for an electro-magnetic launcher using at least one driving coil for accelerating a projectile.

BACKGROUND

[0002] The stabilization of projectiles in flight was a seminal hurdle in the development of historical small arms. Dating back to the 15^{th} century, the spin stabilization of projectiles was accomplished by the inclusion of internal grooves and/or polygonal turning on the internal surfaces of a hard steel firearm barrel, through which a soft (lead or copper jacketed) projectile passes through. As the soft projectile is accelerated by gas pressure, it deforms and mates with the hard steel grooves on the rifled barrel, imparting spin during its linear acceleration. Due to this spin stabilization, projectiles fired from such devices tended to be much more accurate than the prior smoothbore guns, allowing for higher repeatability, and military utility of the rifle over the prior art.

[0003] Electromagnetic accelerators offer some advantages over conventional firearms. Some can fire projectiles of arbitrary geometry, with few or no moving parts, some may generate no muzzle flash or noise, and many have far higher ammunition energy density than modern firearm magazines. They can also be recharged using any available source of electrical energy, thus reducing reliance on supply chains, and eliminating the requirement to transport explosive chemical ammunition.

[0004] However, electromagnetic accelerators are typically smoothbore and due to the unique electrical and mechanical construction of such devices, they are typically not configured to impart spin onto projectiles. Therefore projectiles fired from such accelerators in the prior art tend to tumble in flight, reducing their accuracy at any practical range.

[0005] Technological and material limitations of these devices typical design prevents them from being rifled in a similar fashion to that of firearms.

[0006] Those electromagnetic accelerators that do impart spin onto projectiles are typically either very large (in the case of military prototypes such as the US Navy's railgun), utilize expensive and challenging machining processes (such as helical railguns), or have complex projectiles featuring fins, aerodynamic tails, or spin-imparting discarding sabots.

[0007] Some of these devices have been designed such that a user may carry all components of the device, including the power supply, in a hand-held portable form factor. These portable accelerators are typically weigh less than 20 lbs as this approaches the limit of a system that is comfortable to carry by the average person. Some hobbyist prototypes have weighed in excess of 40 lbs, despite the limited ergonomics and utility of such systems.

[0008] Of these portable devices in the contemporary state of the art, those that have shown the most commercial success and practicality from a defense standpoint have used electromagnetic coils to generate force on a moving projectile. However, at this point their employment in a defensive capacity has been limited due to their relatively low muzzle velocity, as well as their limited accuracy, and low technological maturity.

[0009] If such devices could be designed such as to impart a rotational spin on their projectiles, their application space would be substantially widened and their relevance to the defense marketplace considerably increased, especially as devices with higher muzzle energy become available as the technology matures.

[0010] These coilguns, also known as "Gauss Rifles" (although such a term is typically a misnomer) consist of one or more electromagnet coils, which drive an armature (in this context also a projectile) to high velocities by sequentially turning on and off high-amperage electromagnet coils in a sequence to apply an accelerating force to an armature throughout its travel. This force results from either the attraction of a ferromagnetic projectile into the electromagnet coil(s) in front of it, or the repulsion of a conductive (but not ferromagnetic) projectile from the electromagnet coil(s) behind it. The former case is referred to as a "reluctance coilgun", and the latter referred to as an "inductance coilgun".

[0011] Coilguns in the contemporary state of the art consist of a single coil or multiple coils.

[0012] The present invention relates primarily to coilguns with more than one coil (also known as a "stage" when referred to in combination with said coil's requisite switching electronics).

[0013] In a coilgun, coils are connected to switches capable of controlling currents typically in excess of 100 A, and must be rated to withstand reverse voltages typically in excess of 100V, although the values for coil amperage and reverse voltage in contemporary systems are typically much higher. The switches used are typically of type relays, contactors, vacuum tubes, Metal On Silicon Field Effect Transistors (MOSFET), Insulated Gate Bipolar Transistors (IGBT), Silicon Controlled Rectifiers (SCR), Gate Turn-Off Thyristors (GTO), Insulated Gate Commutated Thyristors (IGCT), or MOSFET-Controlled Thyristors (MCT), or one of a number of other power electronic switches known to those of ordinary skill in the state of the art.

[0014] Such switches are typically actuated by a chain of gate drivers, shift registers, or other logic elements, with the projectile's position within the barrel sensed by optical gates, induction, reluctance, laser time of flight, microwave, or radar-based sensors, or other methods of positional determination known to those of ordinary skill in the state of the art. This position measurement is either directly used to actuate the switches, or is passed into a microcontroller which may perform some other functions based on such a position measurement and also may actuate the switches or monitor the activation of the switches.

[0015] In all forms of coilguns, it is advantageous for the barrel (the material between the current carrying electromagnetic coil and the moving projectile) to be thin, electrically insulating, and non-ferromagnetic. In some embodiments, this barrel may be entirely omitted, electing to use just the thin insulating enamel of the inner layer of the coil as a "barrel", because of the levitation and self-centering forces on the projectile as it is accelerated.

[0016] The projectiles in a reluctance coilgun must be ferromagnetic. These materials which typically consist of steel, iron, nickel, cobalt, permalloy, Hiperco, Permendur, ferrite, etc.; are generally much harder than materials that fulfill the requirements for a barrel (such as insulating polymers and composites). If mechanical grooves were to be fashioned in the barrel, they would quickly be worn down by mechanically harder projectiles passing through them.

[0017] While barrels fashioned from a ceramic material would theoretically fulfill the requirements above, such barrels tend to be very expensive and machining internal spiral grooves in such a hard material would be challenging. Ceramics also tend to have low impact resistance, which would lead to high failure rates in this particular application. Furthermore, the limited ductility and deformability of ferromagnetic materials (in the case of reluctance coilguns), and the extreme compressive forces placed upon inductance coilgun armatures further limit the economic feasibility of using ceramic barrels to impart rotational spin upon armatures.

[0018] Therefore, a different mechanism for imparting spin upon projectiles is desired, preferably one which does not rely on mechanical contact between the projectiles and the barrel, or upon complex aerodynamic projectile geometries.

[0019] Imparting angular velocity on an armature using magnetic fields has long been achieved in the field of electric motors using a variety of methods. The prior art contains a vast array of embodiments for converting alternating current (AC) or direct current (DC) into rotational mechanical motion. The majority of these electric motors use a linearly constrained, captive armature (i.e. axially confined between two pinions, bearings, journals, etc.) which is able to rotate radially around an axis but is disallowed from moving linearly along such an axis.

[0020] By contrast, a linear motor (such as a coilgun) is employed to convert electrical power, generally in the form of AC or pulsed DC into linear mechanical motion. The vast majority of these linear motors are employed as solenoids for mechanical automation and use a radially unconstrained, linearly actuated armature which is bounded on both the fore-stroke and back stroke (generally through the use of end-stops), and which generally employs a spring to return the armature to its initial position.

[0021] The imposition of angular velocity (spin) on an armature within a coilgun has not been studied in great depth compared with the imposition of angular velocity on more traditional rotary electric motors. The armatures of rotary electric motors generally have cages (in the case of AC induction motors), commutators (in the case of brushed DC motors or "universal" motors), permanent magnets, or integrated windings (in the case of brushless DC motors). The integration of such complex features into a disposable coilgun armature presents manufacturing challenges and reduces the commercial viability of such a system.

[0022] The ideal coilgun projectile is as simple as possible, and ideally geometrically agnostic as to allow the system to fire loose-tolerance projectiles or scrap ferromagnetic material. This is one of the key advantages to coilgun technology over conventional firearms and ideally this property should be preserved regardless of the system employed to impart spin to a projectile.

[0023] Since a conventional coilgun imparts no net rotational velocity on an axisymmetric armature (projectile), others have proposed methods for imparting rotational velocity via mechanical means. Such proposed methods have generally involved the mechanical coupling of an armature to a rotary electric motor prior to acceleration by the linear motor, thereby decoupling the linearly unconstrained armature from the linearly constrained rotary motor portion of the device. While this method of imparting rotary motion has been successfully demonstrated by others possessing reasonable skill in the state of the art, such devices are prone to mechanical failure, jamming, and difficulty in feeding rounds from a magazine into the device. Such devices also generate a great deal of noise-due to the high radial velocity required for effective spin stabilization (upwards of 10,000 rpm in many cases), and as such the rotary electric motor portion of the device adds a great deal of complexity and noise to a system that is ordinarily silent with few or no moving parts.

[0024] Other proposed methods have involved the addition of internal or external grooves or ribs on the barrel, friction-based or field-matching spiral grooves in the projectile, or other mechanical techniques. While some of these approaches have achieved some level of successful spin stabilization, all add significant complexity to the linear motor system, its armatures, or both. Furthermore, friction based approaches (such as grooving of the projectile/barrel) as stated earlier, presents a number of challenges both from a technological and economic point of view, however some friction-based approaches may be advantageous for certain specific projectile geometries.

[0025] Still other proposed methods have involved aerodynamic approaches to spin stabilization, including the addition of tail-fins, extendable aerodynamic draglines, bore holes, helical air scoops, discarding sabots etc., to the projectile in hopes that the airflow around the projectile may act to impart rotational velocity on the projectile. While some of these methods would undoubtedly succeed in imparting spin to a projectile, they are limited in practicality by 1) the low (subsonic) speed of reluctance coilgun projectiles which limits the force imparted by the rushing air, 2) the very long length required for such fins to exert a stabilizing effect on the low-subsonic projectiles, and 3) the complexity and cost of manufacturing such armatures which undercuts the aim of simplicity and the unique ability of coilguns to fire armatures with quasi-arbitrary geometries.

[0026] In view of the above, the imposition of rotational spin on coilgun armatures via a contact-less electromagnetic or electromotive force is a preferred solution as it retains the favorable characteristics of silent contact-less operation, adds no moving parts, necessitates less complex armatures, and does not cause additional wear on polymer barrels.

[0027] Since the prototypical coilgun consists of a power supply capable of delivering high amperage pulsed DC current, and is in many ways similar to a rotary electric motor, it is conceptually well-understood that such a system may be modified to impart rotational velocity upon an armature either sequentially before, after, or during the linear acceleration of the projectile using existing techniques of electro-motion. However, the practicalities of implementing such a system of contactless spin-stabilization have been elusive thus far and devising a system which is both reliable, and cost-effective to implement has not been demonstrated, especially within the emerging field of portable hand-held accelerators.

[0028] One potential approach to impart rotational velocity in conjunction with linear velocity may be achieved via electromagnetic induction, and the other via electromagnetic reluctance. In the present invention, the latter will be demonstrated and an alternate approach involving the former will be explained as well.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. **1** depicts a cutaway side-view of a single coil of an accelerator equipped with the proposed invention. The electromagnetic drive coil (**1**) is abutted against a spacer (**2**), and wrapped around a shim (**3**) which is supplanted to the barrel (**4**). Through this barrel, an insulator-shimmed or D-profiled (**5**) ferromagnetic armature (**6**) is allowed to pass freely as it is accelerated by a magnetic field generated by the drive coil (**1**). Due to the non-axisymmetric nature of the coil (**1**), which generates a non-axisymmetric field within the barrel (**4**), the rotationally unconstrained armature (**6**) experiences both an axial force towards the center of the drive coil (**1**) and also a net rotational force of the profiled section (**5**) toward the shim (**3**).

[0030] FIG. **2** depicts a cutaway cross-sectional view of the system of FIG. **1**, prior to switching on the drive coil (**1**). In this state, the profile or insulator side (**5**) of the armature (**6**) is oriented in a random (or different) radial direction with respect to the distorted drive coil (**1**) and its shim (**3**).

[0031] FIG. **3** depicts a cutaway cross-sectional view of the system of FIG. **1**, after the drive coil (**1**) is switched on. In this state, the profile or insulator side (**5**) of the armature (**6**) experiences a rotational force and orients the profile or insulator side (**5**) of the armature (**6**) radially towards the shim (**3**) of the drive coil (**1**).

[0032] FIG. **4** depicts one embodiment of a shim (**3**).

[0033] FIG. **5** depicts one configuration of a series of shims (**3**) placed in

[0034] different radial positions along the axis of a barrel (**4**), in such a manner as to impart a rotational force on the armature (**6**) continuously as it travels axially down the barrel (**4**). The drive coils (**1**), and spacers (**2**) are hidden in this view.

[0035] FIG. **6**A-C—Three potential embodiments of armatures (**6**) which may linearly accelerated and rotationally spun using the present invention. FIG. **6**A depicts a cylindrical armature (**6**) with a section of its material which has been replaced with an insulator or other material which is different in ferromagnetism (**5**) from the body of the armature (**6**). FIG. **6**B depicts an armature (**6**) where such material (**5**) has been removed completely. FIG. **6**C depicts a pointed armature (**7**) which also possesses a flat side similarly to the center figure.

[0036] FIG. **7**—A photograph which shows a single coil of an embodiment of the present invention where the shim (**3**) is on the bottom side of the figure, and the drive coil turned off.

[0037] FIG. **8**—A photograph which shows the rotational effect of powering on the system shown in FIG. **7**.

[0038] FIG. **9**—A photograph which shows a single coil of an embodiment of the present invention where the shim (**3**) is on the top side of the figure, and the drive coil turned off.

[0039] FIG. **10**—A photograph which shows the rotational effect of powering on the system shown in FIG. **9**.

[0040] FIG. **11**A-C—A series of photographs which show three snapshots from a high speed video taken of an armature similar in geometry to that of FIG. **6**B, after firing from an embodiment of the present invention involving a system of 9 drive coils with shims placed in an arrangement similar to that of FIG. **5**. FIG. **11**A is an armature in flight at T=0 ms, FIG. **11**B is the same armature in flight at T=10 ms, and FIG. **11**C is the same armature in flight at T=20 ms.

[0041] FIG. **12** depicts an alternate configuration of a series of shims (**3**) placed in different radial positions along the axis of a barrel (**4**), with some drive coils imparting an axisymmetric field and other drive coils imparting a non-axisymmetric field in such a manner as to impart an orientation-specific force on the armature (**6**) as it enters the barrel, and a rotational force as the armature (**6**) exits the barrel (**4**). The drive coils (**1**), and spacers (**2**) are hidden in this view.

[0042] FIG. **13** depicts the end result of the operation of the systems described herein, where an armature (**6**) exits the barrel (**4**) with its linear velocity along an axis parallel with that of the barrel (**4**) and its axis of rotation also parallel with the axis of the barrel.

[0043] FIG. **14** depicts the end result of the operation of an alternate embodiment of a system described herein, where a disc-shaped armature (**8**) exits an alternate geometry barrel (**9**) with a cross-sectional inner profile similar to that of the cross-sectional profile of the disc-shaped armature (**8**). The disc-shaped armature leaves its barrel with a linear velocity parallel with the direction of travel through the barrel (**9**), and its axis of rotation in this case is perpendicular with such axis of travel. In the drawn embodiment, the rotational force is imparted through the use of two plates which are imposed upon the armature as it leaves the barrel. One of such plates has a high coefficient of friction (**10**), and the other has a low coefficient of friction (**11**).

[0044] FIG. **15** depicts an alternate embodiment of the cross-sectional view of FIG. **3**, wherein a plurality of shims (**3**) are interposed between the inner surface of the drive coil (**1**) and the barrel (**4**), and an armature (**6**) features a plurality of cutouts which orient towards the shims (**3**) when the coil (**1**) is activated.

[0045] FIG. **16** depicts an alternate simpler embodiment of FIG. **15** wherein the shims (**3**) are circular in profile and an alternate embodiment of the armature (**6**) which features semi-circular cutouts (**5**) wherein an insulator or other material with different magnetic properties is secured.

[0046] FIG. **17** depicts yet another alternate embodiment of FIG. **16** wherein the projectile (**6**) may feature similar structural features to FIG. **15**.

[0047] FIG. **18** depicts yet another alternate embodiment wherein a plurality of shims (**3**) and corresponding cutouts (**5**) act to perform a similar function to the arrangements shown in FIGS. **15-17**.

[0048] FIG. **19** depicts yet another alternate embodiment of FIG. **3**, wherein a large cavity has been removed from the armature (**6**) which substantially changes its center of magnetism such that the non-axisymmetric drive coil (**1**) preferentially acts upon one side of the armature (**6**) to produce a rotational force.

[0049] FIG. **20** depicts yet another alternate embodiment of the current invention wherein an armature (**6**) substantially smaller than the bore of the barrel (**4**) is accelerated by a non-axisymmetric drive coil (**1**). In this alternate embodiment, the armature (**6**) is preferentially attracted to one side of the barrel (**4**). As the shim (**3**) position changes on subsequent coils, the armature (**6**) experiences a rolling motion around the inner circumference of the barrel (**4**) as it is accelerated.

[0050] FIG. **21** depicts an alternate embodiment of the apparatus wherein a plurality of rotary electromagnet coils

(**12**) are positioned around the length of the primary drive coil (**1**), and wound such that they act to create a magnetic field perpendicular to the axis of linear travel of the armature (**6**). Said rotary coils are actively switched by an external controller to induce a rotational force upon the armature (**6**).

DETAILED DESCRIPTION

[0051] The invention described herein improves upon the current state of the art by, in an embodiment, combining aspects of a rotary electric motor with a linear electric motor (i.e. a coilgun), to realize a device which may impart rotational spin onto an armature (**6**) simultaneously or sequentially to their linear acceleration.

[0052] The coilgun described herein contains multiple stages. Some (or all) of these stages may, in an embodiment, be configured to produce a non-axisymmetric magnetic field, the radial strength of which may vary in radial direction relative to other stages, or may be varied by time or position-dependent electronic control of an external field which acts by superposition to create a radially varying position of maximum field strength within the accelerator barrel (**4**) as the armature (**6**) is accelerated.

[0053] In an embodiment, the armature (**6**) may be physically, magnetically or materially shaped such that when the armature travels through the barrel of the motor, the armature experiences a torque tending to align the armature in an orientation which minimizes the reluctance of the drive coil-armature magnetic circuit. By advancing the angular position of the minimum reluctance orientation in subsequent drive coils, armature angular velocity is increased as the armature accelerates through the linear motor, achieving an angular velocity suitable for projectile spin stabilization.

[0054] A simple embodiment of the proposed invention is shown in a side-cutaway view FIG. **1**: wherein a cylindrical ferromagnetic armature (**6**), which has been machined to remove one radial side (**5**), and the material removed or may be replaced with a material of different electrical and/or magnetic properties. Such an armature fits within the barrel (**4**) of a linear electromagnetic motor. In the embodiment of FIG. **1**, the motor is a reluctance (attraction-based) solenoid, which consists of one stage (**1**), which has been shimmed by a small piece of material (**3**), or otherwise offset using other methods known to those of ordinary skill in the state of the art, which creates an off-center (i.e. non-axisymmetric) magnetic field within the barrel (**4**). In the embodiment shown in FIG. **1**, the strength of the magnetic field within the barrel (**4**) is stronger at the bottom, and weaker the at the top. The armature (**6**), if initially in any orientation other than with the altered section (**5**) placed at the top, will experience a net rotational force. In this embodiment, the system seeks to minimize reluctance of the drive coil-armature magnetic circuit by exerting a torque on the armature (**6**) in the direction of lowest gap between a high-saturation material and the radial side with highest magnetic flux (shown at the bottom of FIGS. **2** and **3**). This force is the rotational equivalent to the force which drives the armature in the axial direction into the center of the drive coil for a switched reluctance coilgun.

[0055] FIG. **2** shows a cross-sectional view looking down the barrel of the embodiment of the invention depicted in FIG. **1**, with the armature (**6**) at an initial position prior to powering on the drive coil (**1**). Upon powering on the coil (**1**), said armature (**6**) will experience a torque towards the orientation depicted by FIG. **3**.

[0056] Other alternate embodiments to achieve a similar net effect are shown in FIGS. **15-20**.

[0057] In an embodiment, this field may be created or augmented using one or a set of radial field coils as shown in FIG. **21**. Alternate embodiments may feature a different number of radial coils (**12**) or may utilize a dipole, halbach, multi-pole, or other configuration of field coils known to those of ordinary skill in the art, which act to exert a magnetic field in a perpendicular direction to that of the solenoid coils (**1**), which may be activated by a control system to distort the radial magnetic field within the barrel (**4**) via superposition of fields, to effect a net field similar to that of a shimmed solenoid coil shown in the FIG. **1-3** or **15-20**.

[0058] In an alternate embodiment, a non-axisymmetric field may be created by surrounding the system with a magnetic yoke. In yet another embodiment, the non-axisymmetric field may be created by an alternating current system designed to induce eddy currents in the armature (**6**). In an alternate embodiment, the system may be augmented with a shaded pole or AC induction motor stator to induce non-axisymmetric time-variant magnetic fields within the barrel (**4**), similarly inducing rotation of the armature (**6**).

[0059] The method of the present invention may be applied to induction (repulsion-based) coilguns as well as reluctance (attraction-based) coilguns. In an induction coilgun, the field created by the coil (**1**) would be axially similar in direction to the field induced within the armature (**6**). Because the fields of similar polarity would act to repel each other, the system would seek to maximize the distance between the side of the armature with maximal radial field intensity and the side of the barrel with maximal radial field intensity (the bottom side of FIG. **1-3**), thus resulting in the profiled side of the armature (**5**) to move to the bottom of the barrel, and the bulk of the armature (**6**) to experience a torque towards the top.

[0060] The system of the present invention may be used to accelerate axisymmetric (cylindrical) armatures (using the embodiment of FIG. **20**), or non-axisymmetric armatures, or armatures of other arbitrary geometry which may be configured to rotate along an axis parallel to the axis of motion/acceleration. In a preferred embodiment, maximal torque may be exerted on armatures of a non-axisymmetric geometry such as those depicted in FIG. **6**A-C.

[0061] In a preferred embodiment, the amount of material removed from the armature (**5**) and/or replaced with a magnetically non-interacting material, should be at least 10% of the total cross-sectional area of the armature, and preferably between 20-35% of the cross sectional area of the intact armature. For embodiments utilizing an axisymmetric armature (FIG. **20**), the armature (**6**) should be undersized by 10-35% of the area of the barrel (**4**).

[0062] In an embodiment, the maximum displacement of the shim (**3**) from the outer diameter of the barrel (**4**) (i.e. the distance between the internal surface of the drive coil (**1**) and the outer surface of the barrel (**4**)) is at least 0.05 multiplied by the outer diameter of the barrel (**4**). In a preferred embodiment, the maximum displacement of the shim (**3**) is between 0.05 and 0.3 multiplied by the outer diameter of the barrel. In an embodiment, the shim may be smooth/conformal (such as that shown in FIG. **1-5**, **7-10**, **12**, **15** or **19**), or round (such as shown in FIGS. **16-18**), or of one of many other geometric cross-sections implementable without undue experimentation by those of ordinary skill in the state of the art.

[0063] In an embodiment, the displacement of the shim (**3**) may be larger (0.15-0.3 times the outer diameter of the barrel) in the earlier (slower linear velocity) stages of a multi-stage accelerator, and smaller (0.05-0.15) in the later stages of said accelerator embodiment.

[0064] In an embodiment, such as that depicted by FIG. **14**, a system for imparting spin upon a disc-shaped armature (**8**) is depicted which rotates on an axis perpendicular to the axis of motion/acceleration. The application of rotational force may be via mechanical means (i.e. two contact plates (**10**, **11**) with different coefficients of friction which are imposed upon the transiting armature such as Teflon and sand-paper to create a differential torque on the transiting armature), or via a permanent magnet (**10**), or via an electromagnetic field acting upon the projectile in an asymmetrical or time-variant fashion as it transits or exits the accelerator, or in any of the above mentioned proposed systems upon an armature of non-axisymmetric geometry. A shaded-pole or homopolar motor may also be employed to produce the effect depicted in FIG. **14**.

[0065] In an alternate embodiment, a projectile may be surrounded by a soft, low-friction outer material such as Teflon, UHMWPE, or Acetal which mates with spiral-grooved rifling patterns on the inside of a barrel made from a harder material such as fiberglass, CFRP, aluminum, copper, stainless steel or any other suitable material for an electromagnetic accelerator barrel.

[0066] In an embodiment of a reluctance-based accelerator, the armature (**6**) may be fashioned from a ferromagnetic material such as cast iron, alloy steel, silicon steel, ferritic, duplex or martensitic stainless steel, hiperco, permendur KF49, permendur 2V, nickel, cobalt, magnetite, amorphous metals, neodymium-iron-boron based materials, samarium-cobalt based materials, iron-nitride based materials, or of any other material possessing high magnetic saturation and intrinsic or induced ferromagnetic properties. In an embodiment, the armature is comprised of a solid material. In an embodiment, the armature is comprised of laminated sheets of material, with the continuous sheets of such an embodiment running parallel to the direction of linear acceleration, to reduce eddy currents (which ordinarily reduce the performance of the coilgun).

[0067] In an embodiment of an inductance-based accelerator, the armature is composed of a non-ferromagnetic, electrically conductive material such as copper, aluminum, tungsten, brass, etc. In an embodiment, the armature may consist of multiple axial turns of conductive wire material, connected at both ends to form one or more loops through which induced current may travel.

[0068] In an embodiment, the profile (**5**) may be removed from the armature (**6**) entirely (leaving an air gap), or the profile (**5**) may be replaced by any insulator such as Acetal, Teflon, poly-ethylene, ceramic, epoxy resin, or one of many such low-friction high dielectric materials known to those of ordinary skill.

[0069] In an embodiment, a low-resistance single or multi-loop electric shunt may be placed within the removed/dielectric section (**5**) or around the long axis of the armature (**6**) to generate eddy currents and further enhance the rotational motion.

[0070] FIG. **4** depicts an embodiment of a simple shim (**5**) which may be used to distort the coil (**1**) to produce a non-axisymmetric field within the barrel (**4**). In a preferred embodiment, the shim (**5**) may be fashioned from a dielectric or insulator material such acrylic, poly-carbonate, ABS, phenolic, glass-fiber reinforced polymer composite, or other high strength insulating materials known to those of ordinary skill. In an embodiment, the shim (**5**) may consist of a single or multiple loops of insulated conductive wire, forming a variant of a "shaded pole" in order to produce a net distorted non-axisymmetric magnetic field. In an alternate embodiment, the shim (**5**) may consist of a ferromagnetic material. In an embodiment, the shape of the shim (**5**) may be similar to those depicted in FIG. **4**, a "half-moon" shape which fits snugly around the barrel, consisting of an extruded shape consisting of two tangential arcs with a distance between the arcs of between 5-25% of the barrel's outer diameter. In an alternate embodiment, the shape of the shim may be a single circular wire which is placed between the coil (**1**) and the barrel (**4**) as it is wrapped. In an embodiment, the shim (**5**) may run the entire axial length of the coil (**1**), or a portion of the axial length of the coil (**1**). In an alternate embodiment, the shim (**5**) may consist of any cross sectional shape which is non-axisymmetric. In an embodiment, the shim (**5**) may be removed prior to use of the device, leaving an air gap between the coil (**1**) and the barrel (**4**) on one side. In an embodiment, one or more shims (**5**) may be inserted onto the barrel (**4**) within the axial confines of a single coil (**1**). In an embodiment, the cross sectional width of the shim (**5**) may be equivalent to the outer diameter of the barrel (**4**), or less than the outer diameter of the barrel (**4**), or greater than the outer diameter of the barrel (**4**).

[0071] In an embodiment, the barrel (**4**) may consist of a tube fashioned from a polymer, ceramic, or metal material. In a preferred embodiment, the barrel (**4**) is fashioned from a high strength polymer such as glass-fiber reinforced composite polymer (GFRP), carbon-fiber reinforced composite polymer (CFRP), kevlar reinforced composite polymer, poly-carbonate, or one of many non-conductive polymeric materials with high strength known to those of ordinary skill in the state of the art. The barrel may also consist of the inner surface of the electromagnetic coils (**1**) themselves. In an alternate embodiment, the barrel (**4**) is fashioned from a non-conductive ceramic material such as aluminum oxide or silicon nitride. In an alternate embodiment, the barrel is fashioned from a non-magnetic metal such as aluminum, brass, tungsten, stainless steel, titanium or other material known to those of ordinary skill. In an embodiment, the barrel is circular in cross section. In an embodiment, the barrel (**4**) is non-axisymmetric in its external shape and the shim (**5**) features are molded directly into the barrel (**4**) during its manufacturing. In an embodiment, the barrel (**4**) is circular in its internal shape.

[0072] FIG. **5** depicts an embodiment of the present invention with the placement of shim (**5**) features along the barrel (**4**). In the depiction of FIG. **5**, the coils (**1**) and spacers (**2**) are removed for the sake of visibility. Such a linear arrangement may also apply to the cross-sectional embodiments of shims and coils depicted in many of the other figures. In an embodiment, the coils (**1**) are wrapped around the shim features (**5**) after affixing the shim features (**5**) to the barrel (**4**). In an embodiment, the shims are placed at different radial positions along the outside of the barrel to rotate a non-axisymmetric armature (**6**) incrementally with each passing stage. It is important to note that if radial field coils (**12**) are used to create the non-axisymmetric magnetic field described by the present invention, the use of shims (**5**) is not necessary.

[0073] In an embodiment of the system depicted by FIG. **5**, the shims are rotated less than 45 degrees per coil stage with respect to the stage prior. In an embodiment, the twist rate of the shims is at least one full 360 degree rotation per 36 inches of barrel length. In a preferred embodiment, the twist rate is approximately one full 360 degree rotation per 12-18 inches of barrel length. In alternate embodiments, the twist rate may be greater or lesser to achieve the desired effect and stabilization profile of the projectiles accelerated by the system. In alternate embodiments, some stages may be shimmed and others lack shims.

[0074] In an embodiment, the position of the shims may be matched to an ideal projectile size, shape, inertia, and geometry such that similar projectiles rotate at similar angular velocities within a barrel configured optimally for such projectiles, and other non-optimal projectiles exhibit less than optimal rotation within such a barrel.

[0075] In an embodiment, the radial position of armatures may be sensed using optical, inductance, conductance, pressure, capacitance, RF, or one of many other methods of absolute or relative position sensing known to those of ordinary skill. In an embodiment, the power to some coils may be increased or decreased in response to variations in the radial position of the projectile so as to achieve closed-loop control of projectile angular velocity.

[0076] In a prototypical embodiment of the invention, FIG. **7** shows a photograph of an armature turned approximately 90 degrees with respect to the shim side of the coil (where the shim side is on the bottom of the picture), and the drive coil is turned off, upon turning on the drive coil, the armature rotates to the configuration shown by FIG. **8**.

[0077] In a prototypical embodiment of the invention, FIG. **9** shows the system depicted by FIG. **7** where the coil (with shim) has been rotated 180 degrees and the shim side of the coil is now on the top. This photograph shows a similar physical setup to the diagram depicted by FIG. **2**. When the drive coil is turned on, the armature rotates to the configuration shown by FIG. **10**. This set of figures demonstrates that the rotation of the armature is independent of the effect of gravity and depends solely on the radial strength of the magnetic field within the barrel (determined by the shim position).

[0078] In a prototypical embodiment of the invention with a shimmed barrel similar to FIG. **5**, FIG. **11**A-C shows an armature in flight (with a geometry similar to FIG. **6**B) after being fired from such a system. The armature has been colored black on the curved side and left bare metal on the flat side. In the high speed photographs shown in FIG. **11**A-C, the armature can be seen traveling from left to right, and the rotation of the profiled armature is visible when FIG. **11**A is compared to FIGS. **11**B and **11**C.

[0079] In an embodiment, an axisymmetric projectile, which lacks a profile or section with different material properties (**5**), may be induced to spin by the introduction of non-axisymmetric external fields which act upon or create eddy currents within the projectile in a non-axisymmetric fashion. Such a system may employ "shaded pole" type features, or other non-axisymmetric features intended to exert torque upon a projectile without making physical contact with the projectile.

[0080] The use of any and all examples, or exemplary language provided is intended merely to better illuminate one or more embodiments and does not pose a limitation on the scope of any claimed subject matter unless otherwise stated. No language herein should be construed as indicated any non-claimed subject matter as essential to the practice of the claimed subject matter.

[0081] The use of the terms "a", "an", "said", "the", and/or similar referents in the context of describing various embodiments (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context.

[0082] When any phrase (i.e. one or more words) appearing in a claim is followed by a drawing element number, that drawing element number is exemplary and non-limited on claim scope.

[0083] Within this document, and during prosecution of any patent application related hereto, any reference to any claimed subject matter is intended to reference the precise language of the then-pending claimed subject matter at that particular point in time only.

[0084] Every portion (e.g. title, field, background, summary, description, abstract, drawing, figure, etc.) of this document, other than the claims themselves and any provided definitions is to be regarded as illustrative in nature and not as restrictive. The scope of the subject matter protected by any claim of any patent that issues based on this document is defined and limited only by the precise language of that claim (and all legal equivalents thereof) and any provided definition of any phrase used in that claim, as informed by the context of this document.

1. An apparatus comprising:

a) one or more of an electromagnetic coil which may impart a linear accelerating force and/or a rotational torque onto an armature by means of an electromagnetic field; and

b) a force, or a superposition of forces, is exerted upon the armature differentially depending upon its material properties, and/or its position within the electromagnetic field generated by the apparatus; and

c) at the armature, a torque is exerted as a result of a non-axisymmetric quality of said magnetic field in at least one portion of the apparatus for at least some portion of the time which said armature spends within said apparatus; and

d) an external surface of said armature which lacks helical groove or helical rib features.

2. The apparatus of claim **1**, wherein the armature is non-axisymmetric in its physical shape, material properties, electrical properties, or magnetic properties; and/or the electromagnetic field generated by the electromagnetic coil is essentially non-axisymmetric in intensity.

3. The apparatus of claim **1**, wherein the apparatus in its entirety weighs less than 100 lbs.

4. The apparatus of claim **1**, wherein the armature lacks aerodynamic fins or spiral groove features.

5. The apparatus of claim **1**, wherein the magnetic field is generated by three or more coils.

6. The apparatus of claim **1**, wherein the armature is constructed primarily from a ferromagnetic material.

7. The apparatus of claim **1**, wherein the armature is constructed primarily from an electrically conductive material within which a transitory electrical current is induced while the armature is within the apparatus, and said electrical current creates a magnetic field which interacts with the electromagnetic field generated by the apparatus.

8. The apparatus of claim **1**, wherein the electromagnetic coil surrounds a barrel fashioned from non-magnetic material, and within said barrel there exists an internal bore through which the armature may pass, and when the armature is positioned within said internal bore, the cross section of the internal bore consists of less than 90% by area of a material which interacts with the electromagnetic field of the apparatus.

9. The apparatus of claim **1**, wherein a cross section of the armature does not substantially change in shape along an axis parallel to its linear acceleration.

10. The apparatus of claim **1**, wherein the electromagnetic coil(s) are switched on or off by a control system in response to the armature's angular position.

11. The armature of claim **6**, wherein the ferromagnetic material is selected from the group consisting of: Permendur KF49, Permendur 2V, ferrite, iron, steel, or steel alloys.

12. The control system of claim **10**, wherein the angular position of the armature is provided by electrical, optical, mechanical, radio frequency, or magnetic signals generated by the armature as it passes through a barrel of the apparatus.

13. A system comprising a linear electromagnetic motor which imparts a linear force upon a non-captive projectile; and during or after such linear acceleration, the system also imparts a rotational force upon said projectile through the use of electromagnetic, electrostatic, mechanical, or other means; and the projectile leaves the system rotating on one axis.

14. The system of claim **13**, wherein the projectile exits the system rotating about an axis that is parallel to its direction of travel.

15. The system of claim **13**, wherein the projectile exits the system rotating about an axis that is perpendicular to its direction of travel.

16. The system of claim **13**, wherein the control system may be configured to engage a series of external electromagnetic coils in a pre-programmed timed sequence, or in response to feedback from optical, mechanical, radio frequency, or magnetic signals generated by the armature, to create a superposition of fields which acts to impart a rotational torque upon said armature.

17. The system of claim **13**, wherein the system imparts a rate of rotation upon the projectile greater than one rotation per three feet of the projectile's linear travel.

18. A means for imparting spin upon a non-captive armature accelerated by electromagnetic force.

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