United States Patent

Rabenhorst

[15] **3,672,241**

[45] **June 27, 1972**

[54] **FILAMENT ROTOR STRUCTURES**

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[73] Assignee: **The Johns Hopkins University,** Baltimore, Md.

[22] Filed: **July 31, 1970**

[21] Appl. No.: **60,047**

[52] **U.S. Cl.** **74/572,** 161/60

[51] **Int. Cl.** **F16c 15/00**

[58] **Field of Search** 74/572; 156/296, 297; 161/168, 161/172, 60, 239, 247; 15/179, 180, 181, 182, 186, 187, 188, 198

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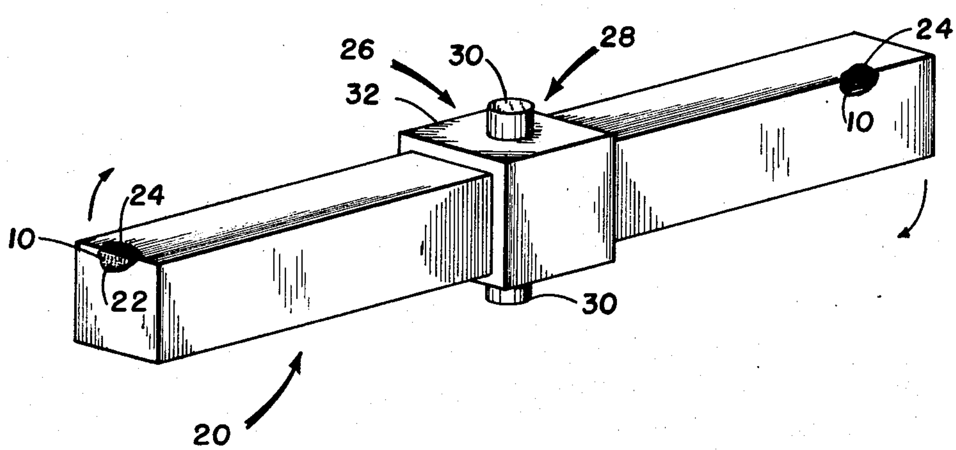
Primary Examiner—William F. O'Dea
Assistant Examiner—F. D. Shoemaker
Attorney—John S. Lacey

[57] **ABSTRACT**

A rotational energy storage device comprising in its basic form a rotor or "flywheel" structure constructed of straight anisotropic filamentary members, the members being disposed in substantially parallel relation to the major stress component acting on the structure. Each filamentary member is essentially loaded along its longitudinal axis, thereby permitting maximum utilization of high strength-to-density uniaxial properties of the member.

26 Claims, 24 Drawing Figures



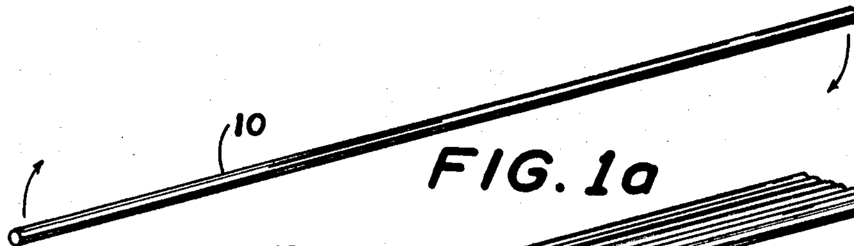


FIG. 1a

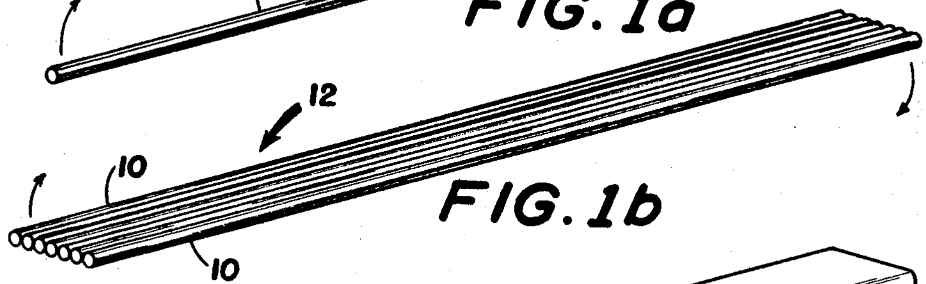


FIG. 1b

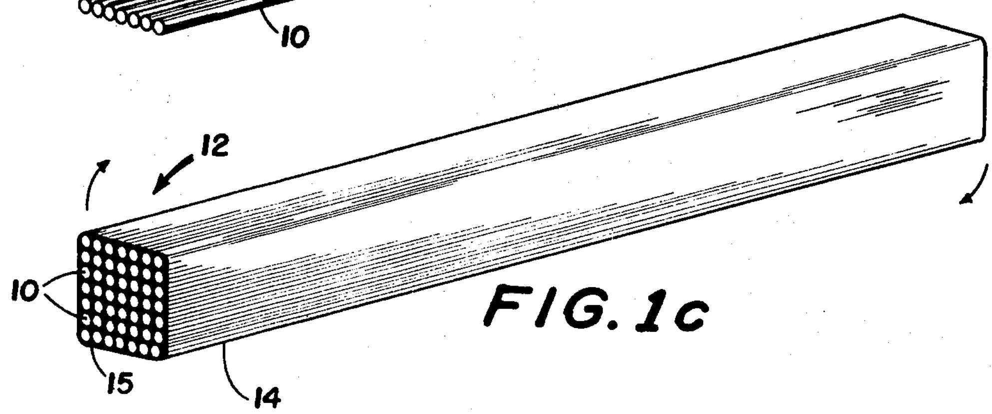


FIG. 1c

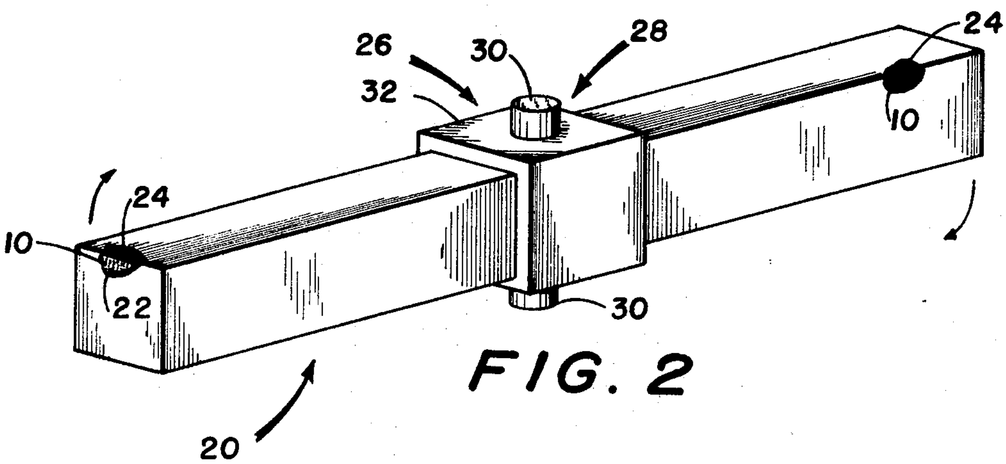


FIG. 2

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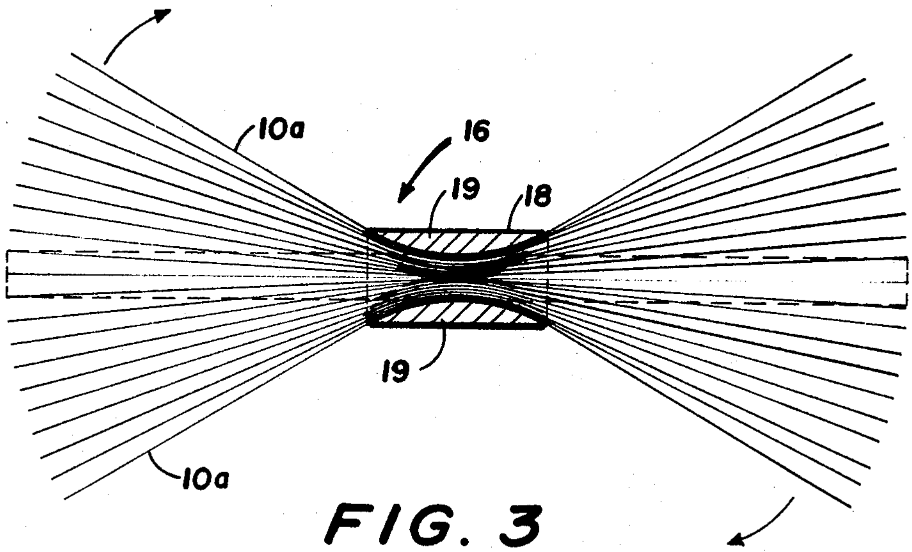

FIG. 3

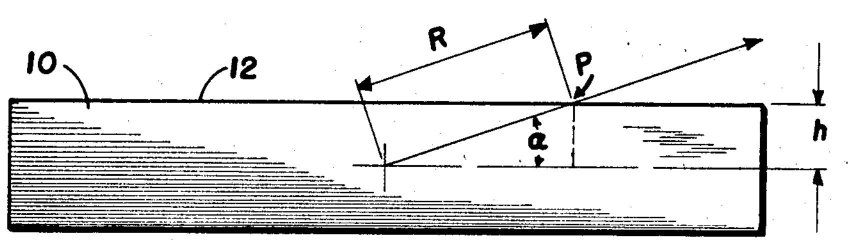

FIG. 4

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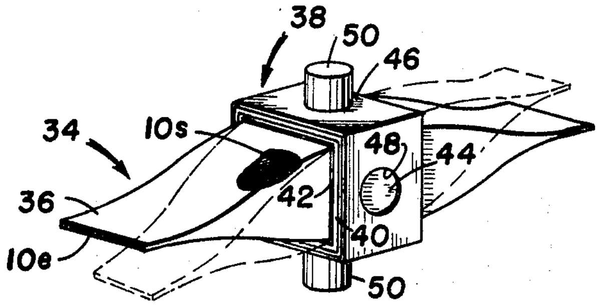

FIG. 5a

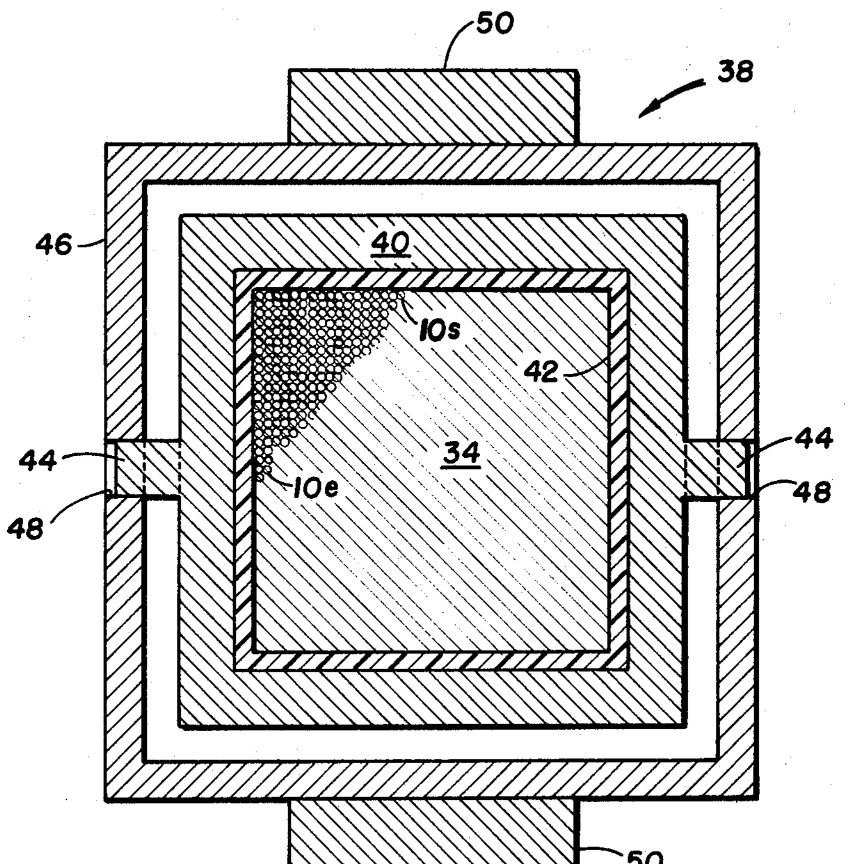

FIG. 5b

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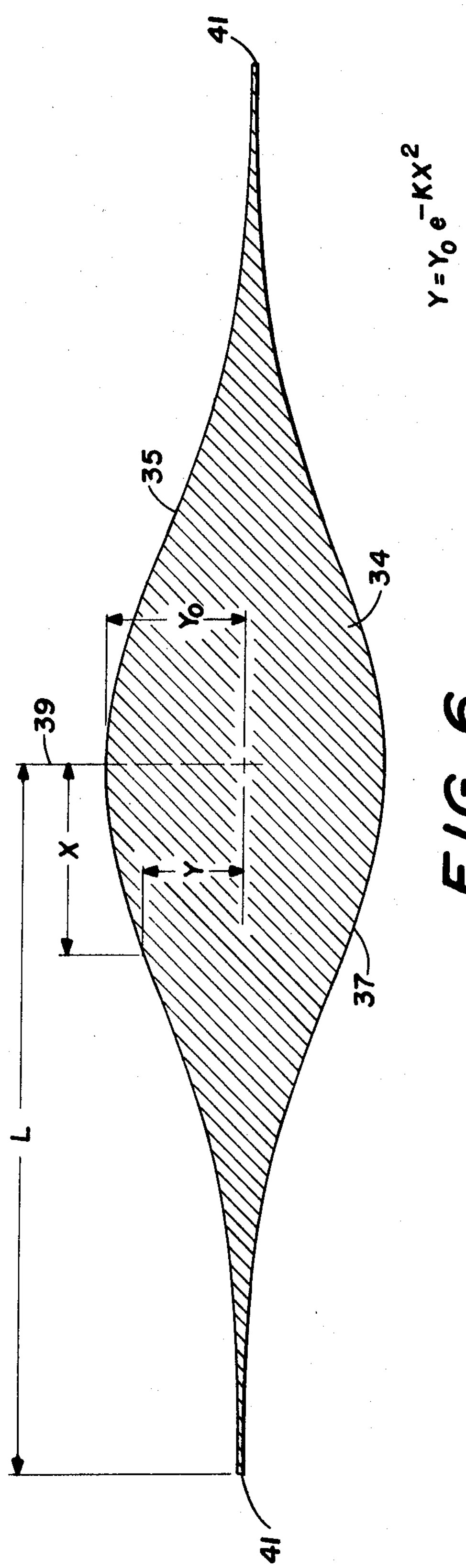

FIG. 6

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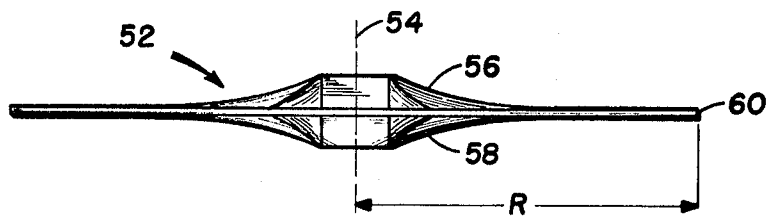

FIG. 7a

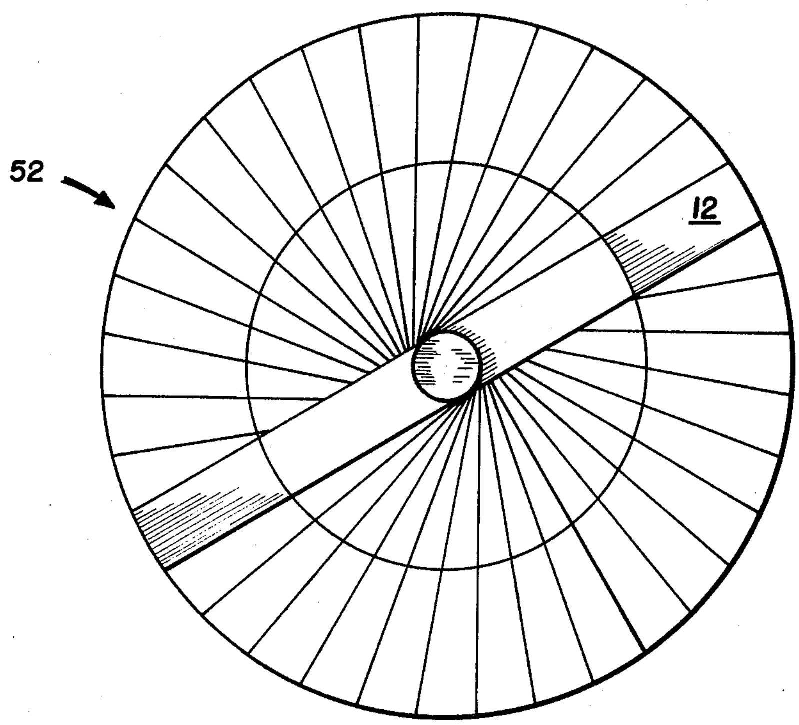

FIG. 7b

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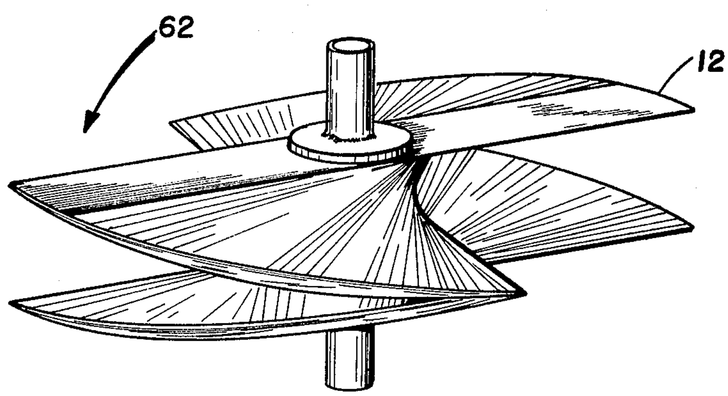

FIG. 8a

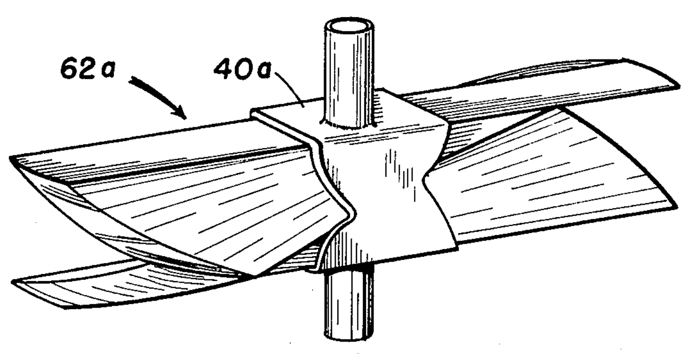

FIG. 8b

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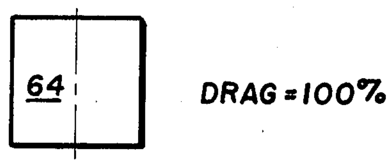

FIG. 9a

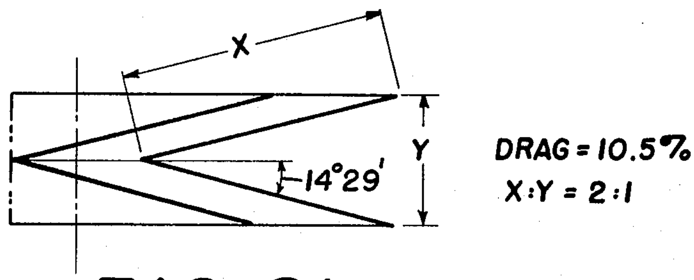

FIG. 9b

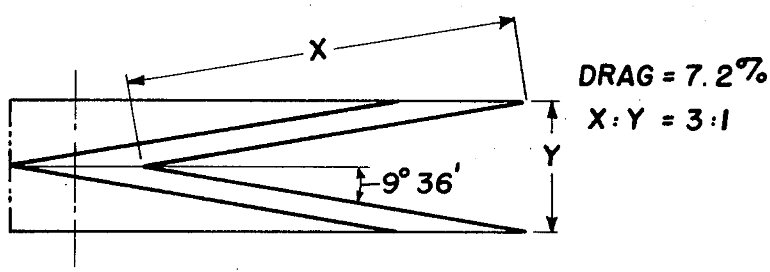

FIG. 9c

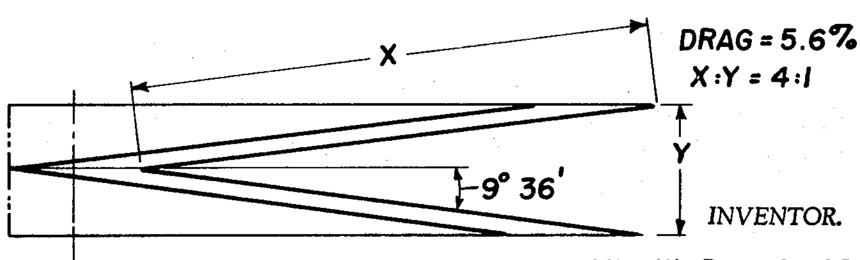

FIG. 9d

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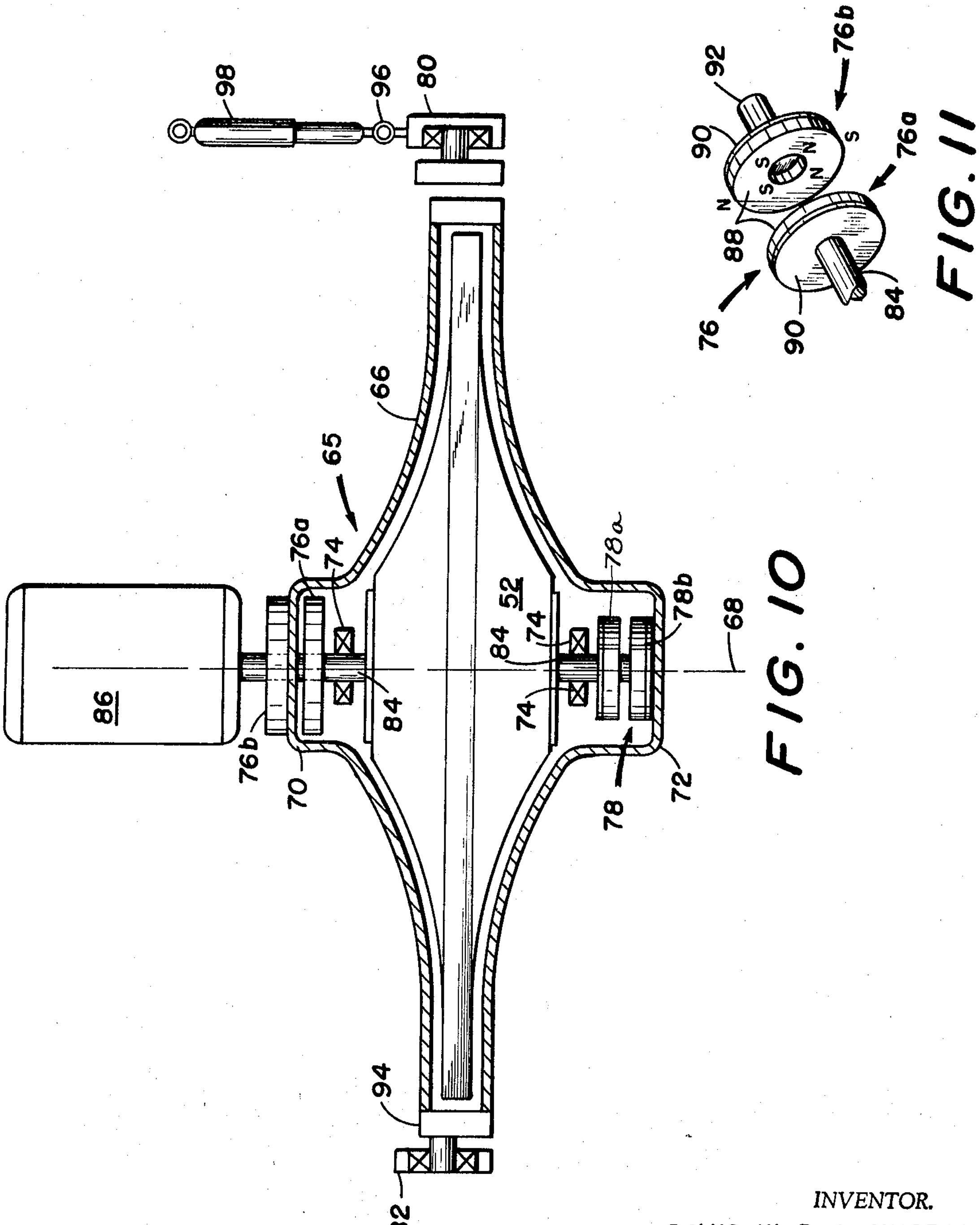

FIG. 10

FIG. 11

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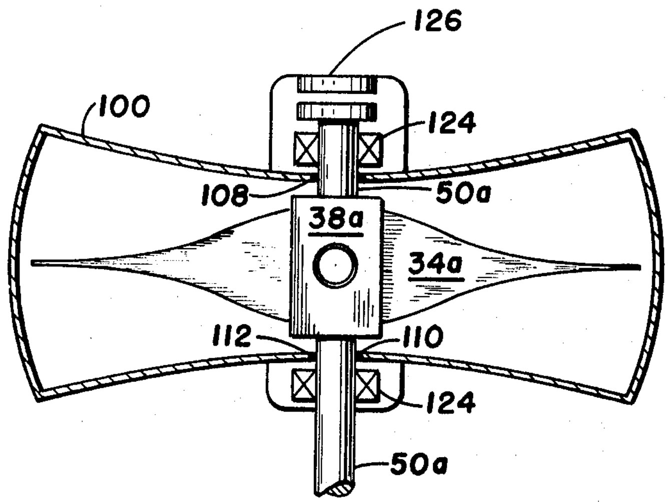

FIG. 12

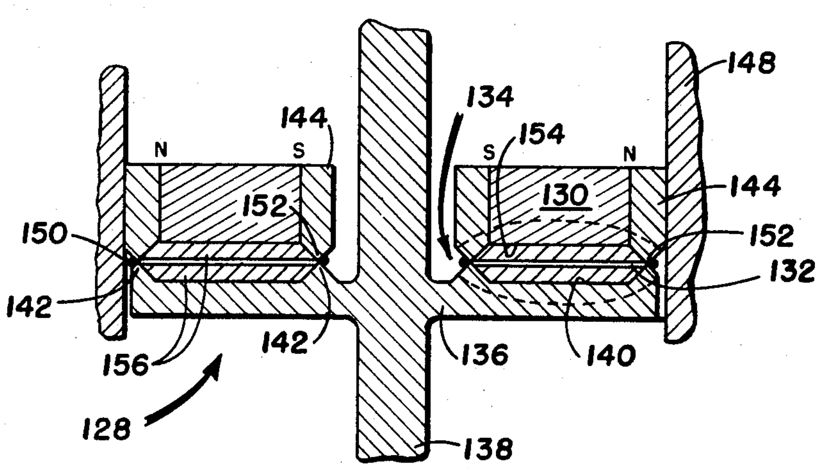

FIG. 13

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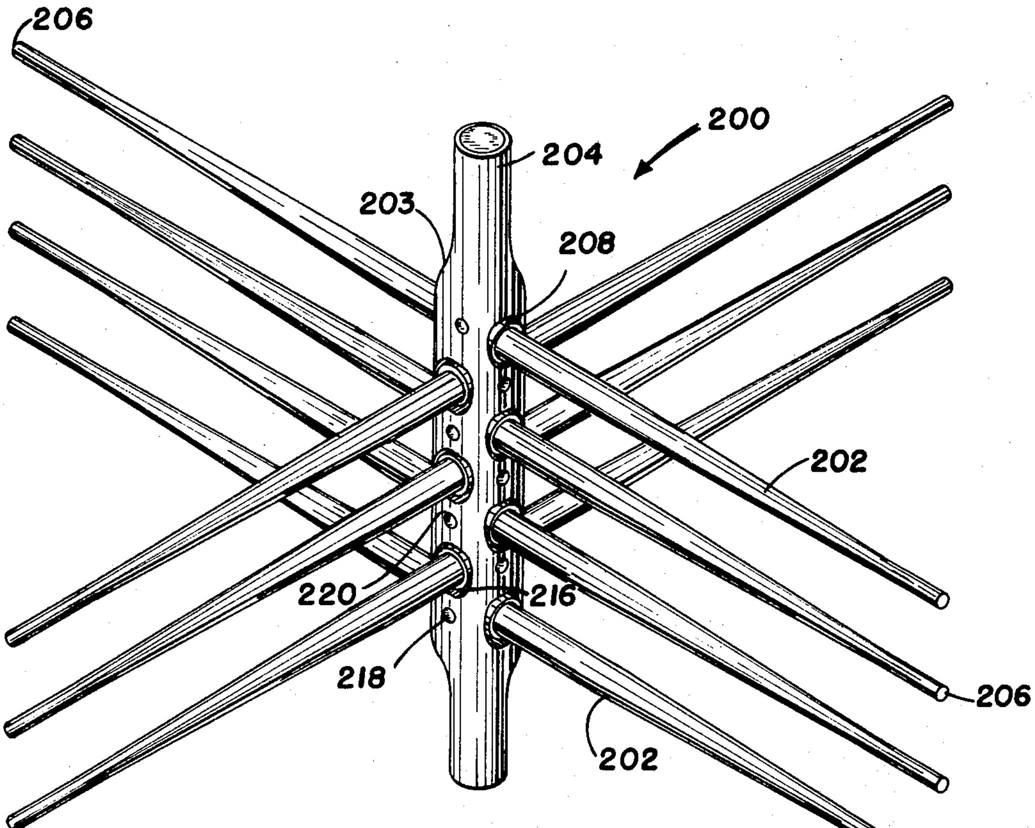

FIG. 14

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FIG. 15a

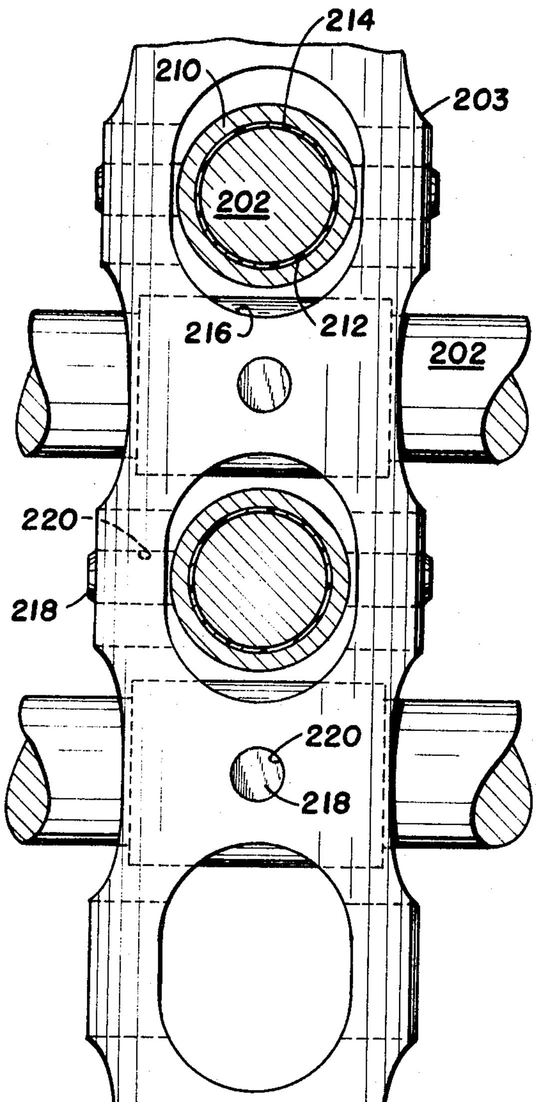
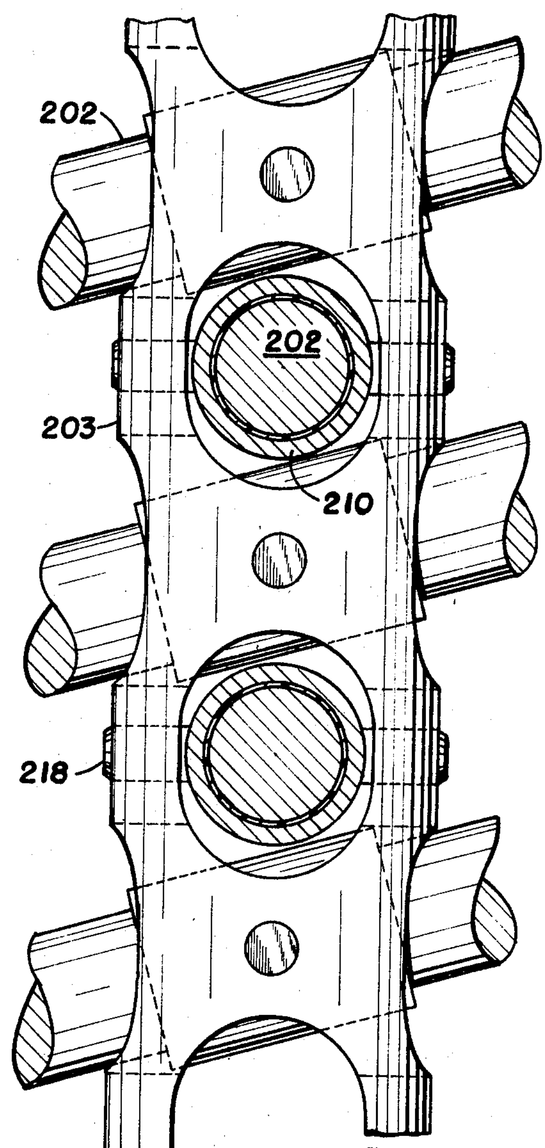


FIG. 15b



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FILAMENT ROTOR STRUCTURES

The invention herein described was made in the course of or under a contract or subcontract thereunder, with the Department of the Navy.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to energy storage devices, such as flywheels, and particularly to performance-optimized high-speed rotary structures. Application of the invention ranges from use as the sole power source of a quiet, pollution free urban vehicle to powered portable hand tools.

2. Description of the prior art

The flywheel has been used for centuries as an efficient energy storage device. Since the flywheel is an inertial device governed by the laws of kinetic energy, maximum performance is attained at maximum speed, the performance being generally quadrupled with a two-fold increase in speed. The speed of the rotating body, however, cannot be increased beyond its bursting limit. In the prior art, three general flywheel configurations are predominant, namely, the flat disc type characterized by smooth parallel surfaces between the hub and the periphery; the rim type having a massive peripheral portion secured to the hub by spokes or a solid wheel portion; and the more recently developed optimized disc.

Materials used to fabricate high-energy flywheels must have large specific strengths (strength/density) to enable the structure to be rotated at a high velocity. High strength steel has ordinarily been chosen as flywheel material. However, the strength/density ratio of an isotropic steel structure is substantially less than that obtainable with modern anisotropic filamentary materials. High strength filaments typically exhibit substantially greater strength-to-density characteristics over the best isotropic materials, such as steel or titanium. Only a small portion of this strength advantage can be used in the prior art flywheels due to the inherent isotropic stresses in these structures. In the rim type flywheel, stresses normal to the wound filaments exist at all locations other than the outer edge. Additionally, the problem of attachment of the rim to the hub, requiring additional weight, has been a principal factor inhibiting further development of this flywheel structure.

The present rotational energy storage device features flywheel rotor structures capable of substantial improvement in useable energy density, primarily because a much higher percentage of filament specific strength is useable. Characteristic of the present rotor structure is the use of straight anisotropic filamentary material arranged in the structure so as to permit maximum utilization of the filament strength in its axial direction.

The significance of the present energy storage device is best understood by its application to the urban vehicle. Although flywheels have been previously used in short-range vehicles, such as in the Swiss Oerlikon bus and in the British Gyreacta transmission, these devices produced only about 3 watt-hours per pound. Thus, energy density of the devices was even lower than that of available lead-acid batteries at the same discharge rate. However, certain characteristics of flywheels caused their use in preference to storage batteries, despite the problems then encountered in the use of flywheel structures. Firstly, the flywheel can be charged and discharged virtually an infinite number of times without degrading performance. Secondly, the flywheel can be charged at any reasonable rate. Thirdly, the flywheel can be discharged at any rate within the design limitations of ancillary equipment without degrading performance. These capabilities are largely responsible for the proposed use of flywheels in pollution-free urban vehicles. In most previous proposals, the rapid discharge capability of the flywheel has been primarily used to lend increased acceleration power to the vehicle in order to minimize the overall size of the main propulsion power plant. The present energy storage device provides a power plant of sufficient energy density to also enable its economic and practical use as the primary source in an urban vehicle.

SUMMARY OF THE INVENTION

The invention primarily concerns a number of rotor structural configurations which form the major component of a high performance energy storage device. The several rotor configurations actually described herein, and those other configurations which follow from the description, are related in their use of high strength uniaxial filament-like materials to comprise the rotor structure. In particular, straight anisotropic filament or "whisker" materials are not only disposed substantially parallel to each other over the entire length of the rotor but are also substantially parallel to the major stress component acting on the rotor. Like any other flywheel device, the performances of the present rotor configurations are directly proportional to the specific strength of the material used in construction. By taking maximum advantage of the large specific strengths of filamentary materials, i.e., by aligning these filamentary materials substantially parallel to each other and to the major stress component which acts along the axis of each individual filament, a dramatic energy density increase in the total structure results, thus making a flywheel-type structure useful to a wide variety of applications beyond the capabilities of prior art rotary energy storage devices.

In the straight filament rotor configurations disclosed herein the low stresses which exist normal to the filaments are supported by a suitable matrix material or by a combination of a relatively few added filaments disposed normal to the principal filaments and potted in a suitable matrix material. For certain applications using high strength continuous filaments, such as ordinary music wire or boron filaments, a matrix is not required to maintain the filaments in alignment. In such a device, the filament bundle is secured in a central hub, which, when rotated, causes the filaments to fan out and align along respective force vectors generated by their own rotating masses. In such a configuration virtually all of the available strength of the material is effectively used at the maximum stress point (center of rotation).

In order to accommodate the extremely high rotational speeds of which the present device is capable, the performance limits of the bearings which support the rotating shaft must be maximized. Additionally, the rotating member must be maintained in a vacuum to reduce aerodynamic drag losses, thus presenting the necessity for a high-speed rotary seal or a passive magnetic coupling to drive the rotor through the wall of the vacuum chamber. Bearing and sealing functions can be provided through use of a combination of magnetic fluid seals, magnets, and bearings which allow operation of the rotating member under these conditions.

Accordingly, it is a primary object of the invention to provide a high power-density energy storage device which also has a high energy density capability.

It is another object of the invention to provide rotary structures capable of higher rotative speeds for higher energy outputs than have been previously available.

It is a further object of the invention to provide a rotor structure comprising substantially parallel high strength filamentary materials aligned along the major stress component acting on the structure.

Yet another object of the invention is to provide an energy storage device capable of operating at an abnormally high rotation speed with minimal aerodynamic and bearing drag losses.

A further object of the invention is to provide an energy storage device which can be readily and efficiently made from a large number of small autonomous rod-like components to minimize the likelihood of simultaneous failure of all components, thus maximizing the safety of the device.

It is also an object of the invention to provide a rotor structure having inherent gimballing capability about a stationary spin axis to minimize gyroscopic loads on the rotor and its spin bearings.

A still further object of the invention is to provide a safe, efficient, economical high performance and pollution-free energy storage device useful in an urban vehicle for alleviating the increasing contribution of motorized vehicles to noise and air pollution problems.

Additional objects, advantages, and uses of the invention will become apparent from the following detailed description of the preferred embodiments thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1***a*, *b*, and *c* are enlarged perspective views of the sequential build-up of an embodiment of the invention, FIG. **1***a* showing a single, essentially uniaxial filament which forms the basic unit of the uniaxial strip of FIG. **1***b*, which strip in turn comprises the secondary structural unit of the composite bar of FIG. **1***c;*

FIG. **2** is a perspective of a "bar" rotor fabricated according to the invention;

FIG. **3** is a plan view of a rotating "brush" rotor fabricated according to the invention, the rotor being shown with filaments aligned along local stress vectors, the unspinning rotor being shown in phantom;

FIG. **4** is a schematic illustrating the fanning load operating on a point on a filament in a rotor constructed according to the invention;

FIG. **5***a* is a perspective of an optimized bar rotor fitted with an internal gimbal, a portion of the rotor being cut away to illustrate the increasing length of the filaments which are shown to be enlarged in the cut-away portion;

FIG. **5***b* is a cross section taken through the geometrical and mass center of the embodiment of the invention shown in FIG. **5***a;*

FIG. **6** is a section taken longitudinally through the optimized bar rotor shown in perspective in FIG. **5***a;*

FIG. **7***a* is an elevation of a disc rotor constructed according to the invention;

FIG. **7***b* is a plan view of the disc rotor of FIG. **7***a;*

FIGS. **8***a* and **8***b* are perspectives of "wedge" rotors fabricated according to the invention, the rotor of FIG. **8***b* being fitted with a hub conforming to the cross sectional dimensions of said rotor;

FIGS. **9***a*, **9***b*, **9***c*, and **9***d* are schematics illustrating the relative drag of wedge rotors having varying half-angles as compared to the square block shown in FIG. **9***a;*

FIG. **10** is a partial section of an energy storage system useful with the present invention and having bearings within an associated vacuum can;

FIG. **11** is a perspective of a magnetic coupling device useful with the system shown in FIG. **10**;

FIG. **12** is a partial section of an energy storage system useful with the present invention and having magnetic liquid seals which allow use of bearings disposed externally of an associated vacuum can;

FIG. **13** is a cross-section of a magnetic fluid bearing useful to prolong the charged life of the present invention;

FIG. **14** is a perspective of an internally gimballed multiple rotor energy storage device structured according to the invention; and,

FIGS. **15***a* and **15***b* are elevations of a portion of the device of FIG. **14**, the device being shown in a precessed mode in FIG. **15***b*.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The performance, i.e., the stored kinetic energy of a rotating body, is directly proportional to the useable specific strength of the material used in the fabrication of the body.

Prior flywheels of optimum configuration composed of isotropic material such as solid steel have only a small fraction of useable strength to density compared with modern filamentary materials. A common uniaxial filamentary material, fine high-grade music wire, while not the most advantageous material for fabrication of the present rotor structure, has a useable specific strength of 1,500,000 lbs-in/lb, or about three times that of solid steel. A flywheel rotor configured to take maximum advantage of the anisotropic strength characteristics of uniaxial filamentary or whisker materials is capable of increased performance relative to flywheels composed of isotropic materials.

The term "anisotropic" is generally defined as exhibiting properties with differing values when measured along axes taken in different directions. For the purposes of this disclosure, "anisotropic" is applied to a material to denote the property of strength along axes taken in different direction within the material. In particular, the term relates to a material having maximum strength along one particular axis thereof. For the filamentary materials or thin rods used in the present rotor structures, the axis of the material along which said material has maximum strength is the longitudinal axis of the material.

Considering the single filament or thin rod **10** shown in FIG. **1***a* to be spinning about its major axis, the specific energy of the filament **10** is given by:

$$E_{sp} = 32.2\ I\ S\ A/W^2R \qquad (1)$$

where:

E_{sp} = specific energy: foot-pounds per pound
I = moment of inertia: slug-ft^2
S = allowable stress: lb/in^2
A = rod cross section: in^2
W = weight: lb
R = one-half the spinning radius: ft

or,

$$E_{sp} = 32.2\ (IA/WR)\ (S/W) \qquad (2)$$

As is the case with prior art flywheels composed of isotropic materials, it is apparent from Equation (2) that the specific energy of the filament **10** is also a function of the specific strength (S/W) of the filament material. Similarly, the actual energy storage capability of a flywheel rotary device is given by Equation (1).

If the diameter of the filament **10** is infinitely small, the total stress in the filament is directed along its length, i.e., the direction of the centrifugal force acting on the filament **10**, which, for the situation described, is the only force acting on the filament during rotation. If the filament **10** were the only element in a flywheel or rotating member, all of its allowable strength at its center contributes to the kinetic energy of this single element flywheel. If the effective shape of the filament **10** were optimized according to the principles described hereinafter for total rotor optimization, performance of the single filament rotor would be substantially increased.

In practice, the single filament **10** would have insufficient mass for most energy storage applications. However, FIGS. **1***b* and **1***c* illustrate the build-up of a flywheel rotary member according to the present invention. In FIG. **1***b*, a plurality of single filaments **10** are aligned substantially parallel to each other to form a layered unidirectional strip **12**. The width of the strip **12** is held to a low proportion of its length, such as 1:10 or 1:20 in order to minimize that force which acts to spread the filaments **10** apart due to the impossibility of aligning each filament **10** along the centrifugal force vector acting on the strip **12**. Referring briefly to FIG. **4**, the magnitude of the fanning load, L_f, at a point P on a filament **10** will be

$$L_f = SR \sin \alpha \qquad (3)$$

where S is the operating filament stress, R is the spinning radius of the point P where the fanning load is being determined, and α is the angle between the centerline of the strip **12** and a line connecting the center of rotation and the point of interest. Since $\sin \alpha = h/R$, Equation (3) can be written:

$$L_f = SR\ h/R \qquad (4)$$

or

$$L_f = Sh \qquad (5)$$

Thus, the magnitude of the fanning load on a given filament on the spinning strip **12** will be the same at any point on the filament.

The strips **12** are stacked to form a rotor bar **14** of a desired total weight and potential performance shown in FIG. **1***c*. The filaments **10** in the rotor bar **14** may be bonded together by a matrix **15** such as silicone rubber, epoxy, metal or a plastic or elastomeric material. The bar **14** in FIG. **1***c* is shown in the simple shape of a rectangular solid, although the bar shape may be optimized to provide greater energy storage capability, as will be described hereinafter. Optimization of the shape of each filament **10** according to the principles described for optimization of the total bar rotor would yield increased performance but at a substantial increase in production cost and effort.

Referring to FIG. **2**, a "bar" rotor **20** fabricated in essentially that fashion indicated for the bar **14** of FIG. **1***c* is shown. Straight, parallel, essentially uniaxial filaments **10** are bonded together in a matrix **22** of metal, plastic, or elastomeric material capable of supporting the fanning loads generated by the rotating mass of each filament **10**. The matrix **22** may also bond to the rotor **20** one or more layers **24** of filaments having their axes disposed normal to the filaments **10**. These layers **24** could be only one filament thick and could be regularly disposed throughout the rotor **20** to give additional resistance to fanning load stressing. However, the ratio of filaments in the layers **24** must remain low relative to the number of filaments **10** in order to maximize the useable strength of the filament material. The rotor **20** consisting of bonded filaments **10** in the simplified form of a rectangular solid is bonded within a rectangular, sleeve-like hub **26** composed of steel or other high strength material. The hub **26** has an integral shaft **28** comprised of upper and lower shaft members **30** which extend normal to and from the upper and lower major plane surfaces **32** of the hub **26**, which surfaces **32** are substantially parallel to the filaments **10**. The rotor **20** may be additionally secured within the hub **26** by means of an epoxy-type adhesive or by a high strength filler compound such as those materials used to form the matrix **22**. On rotation of the "bar" rotor **20**, the principal load, F, on the rotor **20** is aligned along the longitudinal axis of the rotor, i.e., along and parallel to the filaments **10**. Rotor spin-up and power takeoff is accomplished in a known fashion through the hub **26** and associated shaft **28**. The use of certain continuous filamentary materials, such as music wire, boron filaments, etc., to form the rotor bar **14** do not require a matrix to maintain the filaments **10** in operative disposition. As shown in the "brush" rotor **16** in FIG. **3**, the filaments **10a** are allowed to fan out and align themselves with the local centrifugal force vector acting on each filament. As shown in phantom in FIG. 3, the loose filaments **10***a* are clamped together substantially tangentially between two rounded abutments **19** which form walls of a hub **18**, which internally rounded walls are substantially parallel to the axis of rotation of the rotor **16**. The filaments **10***a* remain substantially parallel in a bar shape until rotation commences. On rotation of the rotor **16**, the filaments **10***a* fan out symmetrically around the longitudinal axis of the rotor and line up precisely with the respective force vectors generated by their own rotating masses. The filaments **10***a* contacting that small portion of the perimeter of the abutments **19** holding the filaments when the rotor is at rest, fan out and virtually impress themselves against the full length of the perimeter of the abutments **19**, i.e., assuming the shape of the abutments to be advantageously formed to approximate the shape assumed by the filaments under the operating conditions. The hub **18** could alternatively be cylindrical rather than the external rectangular solid shown in FIG. 3. In either event, the length of the hub **18**, i.e., that dimension parallel to the longitudinal axis of the rotor **16**, should be at least twice as great as the width or diameter of the hub. The strength degeneration of the filaments **10***a* caused by the moderate bending of each filament as it passes through the hub **18** is negligible.

If music wire filaments having a useable specific strength of 1,500,000 lbs/in² are utilized in the "brush" rotor **16**, the energy storage capability is nearly twice that of a disc flywheel of optimized shape and constructed of isotropic steel such as is disclosed by Call in U.S. Pat. No. 3,496,799. The energy storage capability of the "brush" rotor, though greater than the capabilities of previous flywheels, would be less than that of a theoretically optimized anisotropic disc due to the difference in effectiveness of the two configurations. A practical optimized disc configuration using anisotropic material will also be described hereinafter.

The actual energy storage capability of the "brush" rotor **16** and of the simple "bar" rotor **20** of FIG. **2** is given by Equation (1). By substituting appropriate values in Equation (1), it is seen that the "brush" rotor **16** is capable of storing at least 16 watt-hours per pound, taking the usable strength of music wire to be about 70 percent of the tensile strength of the material (600,000 lbs/in²). Such a value would apply to mechanical energy storage systems not subject to personnel hazard restrictions nor exposed to more than a few thousand cycles of operation. Since factors other than specific strength of a material govern the specific energy content of a particular rotor configuration, the usable strength of a material will not always be the same proportion of the specific strength for all materials. If the "bar" rotor **20** were constructed of laminated high strength glass filaments and if appropriate allowances were made for personnel safety factors, handling degradation, static fatigue, cyclic fatigue, filament volume, and filament alignment, then the allowable strength could be as low as 25 percent of the tensile strength of the material. Even so, the glass filament "bar" rotor **20** would still have twice the specific energy capability of the music wire "brush" rotor **16** by virtue of its greater specific strength at the design condition.

The performance of the "bar" rotor **20** may be optimized in a fashion illustrated in FIGS. **5***a* and **6** so that the major stress component acting on the rotor is constant along its length. As seen in the drawings and particularly in the sectional view of FIG. **6**, an optimized bar **34** has oppositely facing surfaces **35** and **37** defined by respective lines of rotation having an effective radius L and which are substantially mirror images across a longitudinal centerline of the bar **34**. The surfaces **35** and **37** produced by the lines of rotation are characterized by a generally reverse curvature in the cross-sectional profile seen in FIG. **6**, the surfaces being essentially convex near the center of rotation **39** of the bar **34** and sloping to a substantially concave shape near the ends **36** of the bar. Thus, the shape of the bar **34** is seen to generally decrease in thickness from a maximum at and around the center of rotation **39** to a minimum at the ends **36** of the bar. To achieve maximum rotor optimization, the thickness of the ends **36** would continuously diminish to infinity, thus practically producing a razor sharp edge. Practical considerations dictate forming the ends of the bar into a substantially square cut edge such as is shown at **41** in FIG. **6**.

Generally, constant stressing of the bar is approximated when the cross-sectional thickness of the bar diminishes non-uniformly from a maximum thickness to a minimum thickness according to the relation

$$y = y_o e^{-kx^2} \qquad (6)$$

where

y_o = one-half of the bar thickness at its center of rotation,
y = one-half of the bar thickness at any point on the surface of the bar,
e = the base of the natural system of logarithms, i.e., 2.71828...
x = the spinning radius of the point
k = a numerical constant for a particular configuration

Equation (6) yields a family of coordinates which explicitly defines the cross-sectional profile of the rotor **34** best shown in FIG. **6**. The constant, k, in Equation (6) may be any real number. However, values of k greater than 100 or less than 2.5 yield impractical rotor configurations. The rotor shaping yielded by Equation (6) can be practically approximated by either two cones joined at their bases and symmetrical across the axis of rotation or two regular pyramids joined at their bases (not shown). The rotor **34** could alternatively be shaped according to Equation (6) but having square or circular axial cross-sections at any distance from the axis of rotation of the rotor.

This optimized bar **34** will yield at least 50 percent greater performance than the bar rotor **20** described previously. The rotor **34** may be initially formed as a rectangular solid with straight, parallel filaments in the manner of the "bar" rotor **20** of FIG. **2**. However, the rectangular bar is machined to the shape shown in FIGS. 5*a* and 6, thereby causing the filaments to have increasing length as is illustrated by enlarged filaments **10***s* shown in a cut-away portion of the rotor **34**. The maximum load on the shorter filaments **10***s* at and near the center of rotation of the optimized bar **34** is distributed over a greater number of filaments which are not as heavily loaded as the full length filaments **10***e* shown enlarged at the ends of the rotor **34**. Stated in another fashion, the short filaments **10s** act to increase the load carrying capability of the longer center filaments **10***e* through additional shear load in the matrix. If each filament **10***s* and **10***e* of the rotor **34** were optimized in shape according to Equation (6), maximum performance optimization would be obtained.

The optimized bar **34** pictured in FIGS. 5*a*, 5*b*, and 6 also serves to illustrate an internal gimbal arrangement, shown generally at **38** in FIG. 5*a* and in section in FIG. 5*b*, which minimizes gyroscopic precession loads on the bearings used to hold the shaft supporting the bar **34** and on the rotating bar. In the bar configuration, the internal gimbal arrangement **38** described avoids the necessity for otherwise having large external gimbal rings and their associated bearings. More importantly, the rotor shaft does not have to be gimballed, enabling its output to be used directly. The gimbal arrangement **38** is seen to comprise a hollow box-like internal hub **40** which generally, assumes the shape of the rotor cross-section. The hub **40** is preferably constructed of steel or other high strength material. The optimized bar **34** is centered within the hub **40** and held therein by means of an elastic sleeve **42** disposed over that portion of the bar's surface held within the hub. The elastic sleeve **42** is contiguous to the bar **34** on the inner surfaces of the sleeve and contiguous to the inner surfaces of the hub **40** on the outer surfaces of the sleeve to form a tight fitting within the hub **40**. The sleeve **42** is made of elastic material in order to effect a better fit within the hub without inducing local stress concentrations. The sleeve **42** could well be fabricated from non-elastic material if this protection were not required in a particular application. As can be better seen in the sectional view in FIG. 5*b*, the hub **40** has two gimbal pins **44** extending from its opposite vertical faces, the pins **44** being aligned through the mass (and geometrical) center of the bar and hub combination. The pins **44** can be formed integrally with the hub **40** for increased structural strength.

A hollow box-like external hub **46** having four rectangular faces mountably encloses the bar **34** and hub **40** combination described above. The external hub **46** has two cylindrical recesses **48** disposed in and centered on its opposite vertical faces for receiving the gimbal pins **44**. The pins **44** extend into the recesses **48** a sufficient distance to provide positive gimbal mounting of the bar **34** and hub **40** combination within the external hub **46**. Anti-friction or elastomeric bearings (not shown) can be fitted into the recesses **48**, if required. Stud shafts **50** extend from the opposite horizontal faces of the hub **46** and are aligned through the mass (and geometrical) center thereof. The hub **46** and shafts **50** are formed integrally with the hub and are made of steel or other easily worked high strength material. The gimbal limits of the bar **34** are determined primarily by the relative dimensions of said bar **34** and the external hub **46**, particularly the clearance provided between the bar and hub and the length of the horizontal faces of the hub. For any foreseeable vehicle application wherein the flywheel is disposed therein with a vertical spin axis, reasonable gimbal limits are easily provided by the arrangement **38**. The gimbal arrangement **38** is easily adapted to the "brush" and gimballing rotor **16** of FIG. 3 and to the "bar" rotor **20** of FIG. 2. Geometrical modification of the internal and external hubs **40** and **46** allows shaft attachment to and gimballing of the various rotor shapes and configurations which can be fabricated according to the invention.

The optimized bar **34**, although capable of high energy storage capacity, is subject to aerodynamic drag losses directly proportional to the pressure and gas density within the vacuum can in which it is being rotated. For any given partial vacuum now practically maintainable ($\approx 10^{-4}$ torr), it can be shown that a disc shaped rotary member reduces drag losses by at least one order of magnitude, i.e., compared to a straight bar configuration having essentially the same diameter, volume, weight and rotary speed. The drag of the optimized bar is also about three times less than the straight bar, but must be operated at a higher speed to achieve its greater performance. Additionally, the volume of the vacuum can enclosing the disc-type rotor is substantially smaller than is possible for a non-optimized bar rotor.

A "disc" rotor **52** fabricated according to the present invention is shown in FIGS. 7*a* and 7*b*. The shape of the "disc" rotor **52** is coincidentally similar to that disclosed by Call in U.S. Pat. No. 3,496,799. Call provides a disc flywheel composed of isotropic material with an optimized generally lenticular shape which produces a substantially uniform stress throughout the flywheel mass during rotation.

The "disc" rotor **52** is seen to progressively decrease in thickness from a maximum at and around the hub or center of rotation **54** to a minimum at the circumferential tip **60**. This configuration is built up by bonding together a plurality of the unidirectional strips **12** previously shown in FIG. 1*b*.

The strips **12** are stacked in an offset sequence, the geometrical center of each rectangular strip **12** being coincident with the center of rotation **54** of the rotor **52**. The strips **12** may be initially stacked into a rectangular solid with the four edges of each strip **12** being aligned with the edges of the other strips **12**, the resulting structure then being "fanned out" by offsetting each said strip **12** a finite angular distance from the immediately adjacent strips **12**. By continuing the relative angular offset of adjacent strips **12** around a full 360° angle, the geometrical relationship shown in FIG. 7b is produced. The strips **12** are then bonded into a matrix to maintain them at the proper angular offset. As an idealized and simplified example, if the rotor **52** were comprised of twelve of the strips **12**, then each strip **12** would be "fanned out" from the aligned rectangular solid described above at an angle of 30° relative to the adjacent strips **12** in the rotor **52**, thereby forming a disc-shaped member having maximum thickness at or around the center of rotation **54** and minimum thickness at the circumferential tip **60**. At the center of rotation **54** the thickness of the rotor **52** is comprised of a finite contribution from each of the strips **12** comprising the rotor. At the circumferential tip **60**, the thickness is comprised of the finite contribution of a relatively smaller portion of the strips **12**, thereby yielding a differential thickness which results in the generally lenticular shape shown in FIG. 7*a*. The filaments comprising the strips **12** are substantially aligned within the rotor **52** with the local centrifugal force vector acting on each filament, thereby providing an energy storage capacity consistent with the maximum useable specific strength of the filaments themselves. Hub mounting means (not shown) for power takeoff and flywheel spin-up may be provided by bonding metal hubs to either side of the hub or center of rotation **54**.

A bi-directional fanning of the strips **12** produces a "-wedge" rotor **62** shown in FIG. 8*a*. The aerodynamic drag on the rotor **62** can be shown to be about equal to the drag acting on the optimized "disc" rotor **52**. However, the advantage of the wedge configuration is that its straighter filaments are more nearly lined up with the radial force vector. Although a vacuum can surrounding the "disc" rotor **52** can be made smaller than that required for the "wedge" rotor **62**, all of the uniaxial filaments comprising the "wedge" rotor can be straight and aligned virtually parallel to the local centrifugal stress vector acting on each filament. The "wedge" rotor **62** is seen to result from a buildup of the unidirectional strips **12**, one of the strips **12** being at first slightly and regularly offset relative to the next lower strip **12** in a counterclockwise direction, and the strip build-up then being reversed to a clockwise direction.

Aerodynamic drag acting on the "wedge" rotor **62** depends on the slope of the surface of the strips **12**, i.e., the magnitude of the relative offset between said strips **12**. This factor is more easily discussed by consideration of the half-angle between the line defining the fanning surface and a line normal to the axis of rotation through the wedge caused by the reversal in strip buildup. As seen in FIGS. **9a**, **9b**, **9c**, and **9d**, drag varies significantly in proportion to the half-angles shown taken through the cross-sections of several representative wedge shapes. Assuming the rectangular body **64** of FIG. **9a** to have a normalized drag of 100 percent, the "wedge" rotor of FIG. **9b**, having a half-angle of 14°29′, exhibits a relative drag of 10.5 percent. Progression to lower half-angles produces reduced drag, but eventually produces dimension problems of greater severity, since the filaments tend to separate tangentially when elongated under the radial stress vector.

FIG. **8b** illustrates a "wedge" rotor **62a** having a hub **40a** shaped to accommodate the wedge shape of the rotor in the manner indicated hereinabove.

For purposes of illustration, FIG. **10** shows a state-of-the art energy storage system **65** capable of use with the present energy storage device. The "disc" rotor **52** is shown in this view as the energy storage device, but, with alteration of the shape of certain components of the system **65**, any configuration of the present energy storage device may be used in the system. The system **65** comprises a hermetically sealed vacuum can **66** which generally follows the shape of the rotor **52** except near the axis of rotation **68** of said rotor where the can **66** is provided with integral cylindrical extensions **70** and **72**. The extensions **70** and **72** both accommodate dry bearings **74** and respectively accommodate a plate **76a** of a magnetic coupler **76** and a magnetic suspension device **78**. The bearings **74** are burnished with MoS_2 or other suitable dry lubricant, and function without additional lubrication in the vacuum environment within the can **66**. The dry bearings **74** are completely unloaded for the static situation by the permanent magnetic suspension device **78** and are only loaded in a dynamic operating environment, such as in a vehicle. Low vapor pressure lubricating oils can also be used at these modest vacuum pressures. However, if the system **65** is installed in a vehicle with the spin axis vertical, then x and y axis gimbals **80** and **82** act to relieve gyroscopic precessional loads caused by pitching and turning of the vehicle. Operation of the flywheel with the system **65** thus disposed does not effect vehicle turning, nor does vehicle turning affect the flywheel, since the vehicle turns around the spin axis of the rotor **52**.

The rotor **52** is mounted on a two-piece shaft **84** coinciding with the spin axis of the rotor. The shaft **84** is journaled at each end in the bearings **74** and terminates at its upper end at the plate **76a** of the magnetic coupler **76** and at its lower end at permanent magnet **78a** of the magnetic suspension device **78**. Plate **76b** of the magnetic coupler **76** is disposed outside of the vacuum can **66**, the plate **76b** being driven in this instance by an electric motor **86**, said plate **76b**, in turn, driving the plate **76a** which spins the rotor **54** without direct connection through a non-magnetic portion of the vacuum can **66**. By utilizing such an indirect drive system, high speed rotating seals are not required; thus the operating pressure inside the vacuum can may be held lower than might otherwise be possible.

The magnetic coupler **76** is shown in greater detail in FIG. **11**. The coupler **76** comprises the two plates **76a** and **76b** which each consist of a multipole magnet **88** and an iron backing **90**, the backing **90** of the plate **76a** being attached to the shaft **84** and the backing **90** of the plate **76b** being joined to a shaft member **92** coupled to the electric motor **86**. The present energy storage device, because of its high speed and low torque characteristics, is especially suited for use with the coupler **76**. Since the magnetic coupler **76** is not novel and is well-known in the art, further description thereof is not given herein. However, it should be noted that, despite the advantages of a hermetically sealed vacuum can and the improved vacuum condition thus made possible, the coupler **76** has the relative disadvantage of losing lock between the plates **76a** and **76b** if design torque is exceeded, and will not relock without a full restart.

Returning to FIG. **10** and the system **65** the vacuum can **66** is provided with a safety ring **94** and a gimbal frame **96**. A shock absorbing suspension **98** stabilizes the system **65**. If the internal gimballing arrangement **38** of FIGS. **5** and **6** is used with an aptly sized vacuum can, the external gimbals **80** and **82** may not prove necessary for most applications. In the system shown, compensation for precession resulting from the earth's rotation can be provided either in the form of springs, slight friction, or by locating the gimbal axes slightly above the swung center of gravity, so that the system **65** will be self-compensating.

Spin-up of the rotor **52** is accomplished as described previously. Power take-off is similarly accomplished. In this instance, the electric motor **86** becomes a generator converting mechanical energy to electrical energy for efficient conduction to electric motors, such as at the wheels of a vehicle. Power take-off can just as easily be accomplished by means of hydraulic motors and pumps, or an all mechanical system could also serve in place of the electric motor **86**.

Certain applications are better accomplished by using a turbine or internal combustion engine (with an over-riding clutch) as the driving motor. In the hybrid installations the engines could be much smaller than usual, since the flywheel would provide all of the extra power required for acceleration of the vehicle. Using the instant concept, the flywheel in such a hybrid vehicle would only weigh about 1 percent of the vehicle weight. At a can pressure of 10^{-4} torr, the rotor **54** could be run for several days despite bearing losses. By comparison, the useable power for the flywheel used in the Oerlikon bus was diminished in a few hours.

The safety hazard of the present energy storage device is minimized relative to conventional flywheels since the present structure comprises a large number of relatively small highly stressed components. A rotor having a total energy content of 25,000,000 ft-lbs, would constitute a formidable hazard if it were fabricated of a single piece of isotropic material and were to fail at the rated speed. However, fabrication of the present rotor **52** from music wire strands 0.003 inch in diameter would result in a kinetic energy on a single strand of wire of only 1 to 2 ft-lbs. In any conceivable rotor configuration, the matrix strength will be only a small percentage of the strength of the filamentary material, thus resulting in a relatively progressive failure, rather than the instantaneous failure occuring with single-piece flywheels.

The high rate of rotation possible with the present energy storage device results in low torque, since the torque varies indirectly with the rotation speed of the flywheel for a given power level. For example, an embodiment of the present energy storage device capable of producing 50 horsepower at 35,000 rpm would exert a torque of only 7.5 ft-lbs. For the music wire rotor **52** described above, the torque exerted on each wire would be only 3×10^{-7} ft-lbs. The low torque would have a negligible effect on the rotor as well as on a vehicle in which the rotor could be used.

The most significant factor governing the performance of the present energy storage device is the usable specific strength of the filamentary or whisker material used in its construction. Presently available wire material is in almost every instance stronger along its length than the parent material in bulk form. Steel wire is available having a tensile strength of 600,000 lbs/in². Other wire material, such as beryllium wire, actually exceeds the specific strength of steel wire. More exotic filamentary and whisker material now available includes fiberglass, graphite, boron, tungsten-carbide, etc. These available materials have been developed because of the need for high strength, high temperature, and, usually, lightweight materials. However, the present use requires only the high specific strength characteristic, since the high temperature capability is not required.

Most filamentary and whisker materials described, unlike the wire materials, must be bonded into a suitable matrix. The matrix material can be the epoxy or polyester resins or metals, such as aluminum and magnesium. However, in the high vacuum environment necessary for efficient operation of the present device, a matrix material relatively free of out-gassing is required to avoid degrading the vacuum. Protection of a normally out-gassing matrix with a thin layer of vacuum deposited metal or other low vapor pressure material is found to be useful.

Unlike any battery, the performance of the present energy storage device is virtually unaffected by the number of charge/recharge cycles, the ambient temperature, or by the rate of charge or discharge. The efficiency of energy storage is virtually 100 percent, since the only losses are the aerodynamic losses on the spinning rotor in the vacuum environment and the losses resulting from bearing drag, which should be minimal at the zero loading of the magnetic suspension. The overall efficiency of an energy storage system using the present device is substantially greater than the efficiency of batteries, presently available flywheel systems, or any other known energy storage system.

An energy storage system configuration which utilizes the present energy storage device and which overcomes certain disadvantages of the system **65** described hereinabove is shown in FIG. 12. The system shown is seen to utilize an optimized bar **34***a* spinning in a vacuum environment maintained by a vacuum can **100** having flared ends defined by the gimbal limits of the bar **34***a*. The bar **34***a* is gimballed internally in the same fashion previously described for the bar **34** of FIGS. 5*a* and 5*b*. In this system configuration, shaft members **50***a* actually pass through openings **108** and **110** in the upper and lower portions of the can **100**, the openings **108** and **110** being circular and having their centers coincident with the axis of rotation of the bar **34***a*. Magnetic fluid seals **112**, such as those described by Rosensweig in U.S. Pat. No. 3,215,572, allow operation of the bar **34***a* at the necessary vacuum within the can **100**. The seals **112** provide sealing between the internal vacuum in the can **100** and ambient air with virtually no leakage (less than 10^{-11} cm/sec). The seals **112** not only permit rotation in a low drag environment, but also allow the placement of bearings externally of the vacuum can **100**, where available high speed bearings and conventional high speed lubrication may be used.

Since there is no solid contact between the seal **112** and the rotating shaft, the contribution of the seal to the overall drag is extremely low and can actually be calculated according to:

$$P=(\pi/4)\,\eta\,N\,(\delta'/\delta)\,D^3\,\omega^2\,l$$

where:

η = viscosity of seal fluid: poise
N = Number of stages
D = Diameter: cm
ω = Rotating speed: rad/sec
δ = seal gap
δ' = seal width
P = Drag: dyne-cm/sec

Referring again to FIG. 12, high speed bearings **124** are disposed externally of the vacuum can **100**. Since the drive shaft i.e., the lower shaft member **50***a* also extends externally of the can **100**, rotor spin-up and power take-off is accomplished in a more direct fashion than is possible with the system **65** of FIG. 10. Loading on the bearings **124** is minimized to reduce bearing drag by providing complete gravity unloading of said bearings through the use of a passive magnetic suspension **126**. The magnetic suspension **126** accommodates only the static load situation, the dynamic loads being accommodated by the conventional bearings **124**.

FIG. 13 illustrates the general concept underlying an unconventional bearing **128** which can be expected to exhibit reduced drag loss capability and have a virtually infinite operating life. The bearing **128** is completely passive and avoids solid contact between any moving parts. The bearing **128** generally provides stability in three planes through the use of a permanent annular ring magnet **130**. The magnet **130** provides stability in two planes, while stability in the third plane is provided by a fluid **132**, such as air sealed by magnetic fluid which is trapped by the magnetic field of the magnet **130**. An arrangement of concentric magnetic fluid seals shown at **134** similar to the seal **112** previously described assists in entrapment of the fluid **132**.

The bearing **128** may be used in the system of FIG. 12 with the conventional high speed bearings **124** primarily to obtain lower drag loss in the static loading condition to minimize rotor run-down time. The bearing **128** shown is seen to have an annular plate **136** formed integrally with a rotating shaft **138**, which shaft **138** also provides the shaft support for the spinning rotor and serves for rotor spin-up and power take off. The plate **136**, composed of magnetizable material, has an annular depression **140** formed in one face thereof and defined by two raised concentric beveled ridges **142**. Opposing the ridges **142** and held fixedly at a finite distance therefrom are concentric annular pole pieces **144** held in spaced relation by and contiguous to the annular ring magnet **130**. The magnet **130** and pole piece **144** combination is fixedly attached to a stationary support **148** and surrounds a portion of the rotating shaft **138**. A ferromagnetic fluid **150**, which comprises the concentric fluid seals **134**, is held magnetically in the finite space between the ridges **142** and beveled edges **152** of the pole pieces **144**, thus sealing a chamber **154** defined by the ridges **142** and edges **152**. This sealing function is accomplished in the same fashion as that described for the seal **112** of FIG. 12. The chamber **154** is reduced in volume by the provision of non-magnetic filler members **156** on either side of the chamber **154**. The structure described thus produces a reduced chamber **154** which holds the previously mentioned fluid **132**. The fluid **132** within the chamber **154** is trapped and held at moderate pressures for indefinite periods. An operable bearing **128** typically seals a 0.005-inch gap of air at pressures near 3 psi within the chamber **154**. Provision of a plurality of chambers allows scalable staging of the bearing **128** to a desired loading capability. The bearings **128** are usually arranged in opposing pairs in order to conveniently maintain axial stability.

FIG. 14 depicts a multiple rotor energy storage device **200** which combines a number of advantageous features of the present invention. The device **200** is seen to comprise a plurality of optimized cylindrical rotors **202** individually gimballed on an enlarged portion **203** of a rotary shaft **204** according to the internal gimbal arrangement previously shown in FIGS. 5*a* and 5*b*. Each rotor **202** is constructed according to the invention, being composed of a large number of filaments having their respective longitudinal axes disposed parallel to the longitudinal axis of the rotor. The rotors **202**, as shown, are cylindrical in cross section, having a greater diameter at and near the center of the rotor and tapering symmetrically to reduced end portions **206**. It should be understood that the rotors **202** could take shapes other than the tapering cylindrical form shown, the cylindrical shape being used mainly for illustrative purposes.

The rotors **202**, as better seen in FIGS. 15*a* and 15*b*, are individually gimballed on the shaft **204**. Each rotor **202** has an internal hub **208** comprising a hollow cylinder **210** which receives the rotor through an axial opening **212** in the cylinder **210**. Each rotor **202** is preferably held within the cylinders **210** by means of an elastic sleeve **214** disposed over that portion of the rotor's surface held within the cylinder, i.e., in the fashion previously described for the embodiment of the invention shown in FIGS. 5*a* and 5*b*. Each rotor and hub combination is centered within one of a number of substantially oval-shaped ports **216** regularly disposed in the enlarged portion **203** of the shaft **204**. The ports **216** are interdigitated along the length of the portion **203**. Thus, if the rotors **202** were numbered along the shaft **204**, those rotors occupying even-numbered positions would be mutually parallel. Similarly, those rotors **202** occupying odd-numbered positions would be mutually parallel. Any odd-numbered rotor would be spatially perpendicular to any even-numbered rotor.

Each cylinder **210** has two gimbal pins **218** extending from diametrically opposite points thereon, the pins **218** being aligned through the mass (and geometrical) center of the rotor and hub combination. The pins **218** are rotatably received within recesses **220** disposed in the shaft **204**, two each of the recesses **220** being aligned and centered on opposite sides of each of the ports **216**. The longitudinal axis of each pair of aligned recesses **220** is perpendicular to the longitudinal axis of the ports **216**. As is clearly seen in FIG. **15***a*, the ports **216** may have portions of their volume shared with the perpendicular ports **216** on either side thereof. Although this space sharing arrangement is not necessary, it does allow the most compact positioning of rotors **202** per unit length of shaft **204**.

FIG. **15***b* illustrates the degree of freedom allowed by the internal gimbal arrangement, the magnitude of this motion being dependent on the design parameters desired for a particular application. Using the device **200** shown, the shaft **204** need not be externally gimbaled to avoid precessional loading. Of course, the device **200** could be constructed without the internal gimballing feature, i.e., each rotor **202** could be fixed on the shaft **204**. In such an event, the shaft itself would then be externally gimbaled. The structure of the device **200** also allows provision of a useful safety feature. If one of the rotors **202** were longer than the remaining rotors, the longer rotor would fail prior to the attainment of the design limitations of the device **200** itself. That is, the stresses on the longer rotor under a certain set of operating conditions are greater, thus maximizing the probability of a relatively safe failure of this single rotor rather than the substantially simultaneous failure of a number of the rotors. The failure of the longer rotor, or of any individual rotor, signals shutdown of the device **200** to prevent further failure. In any event, failure of several of the rotors **202** is an unlikely occurrence, the device **200** being substantially more safe at rotation rates approaching design limitations than the other embodiments of the invention described herein.

Uses of the present energy storage device too numerous to mention are possible. Rotor configurations other than those explicitly described but which embody the uniaxial, anisotropic filaments disposed substantially parallel to each other and to the major stress component acting on the filaments are also possible. Thus, the invention may be practiced in fashions other than that specifically outlined herein without departing from the invention as defined by the following claims.

I claim:

1. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, comprising,

a plurality of straight anisotropic filament-like members, the longitudinal axes of said members being disposed parallel to each other;

matrix means for bonding the members together; and,

a coating of low-vapor pressure material disposed over the surface of the structure.

2. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, the structure comprising a plurality of straight anisotropic filament-like members, said members being formed into strips, the members within any given strip being parallel, and wherein the strips are disposed within the structure at an angle with respect to certain other strips of parallel members.

3. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, comprising,

a plurality of straight anisotropic filament-like members, the longitudinal axes of said members being disposed parallel to each other; and wherein the members are formed into a substantially rectangular unit having a length at least ten times greater than its width.

4. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, comprising,

a plurality of straight anisotropic filament-like members, the longitudinal axes of said members being disposed parallel to each other;

and wherein the members are formed substantially into a cylindrical unit of a length at least ten times greater than its diameter.

5. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, comprising,

a plurality of straight anisotropic filament-like members, the longitudinal axes of said members being disposed parallel to each other;

and wherein said structure has a symmetrical cross-sectional profile defined by opposed surfaces about the axis or rotation,

said structure having a relatively thick center portion around said axis and relatively thin end portions, said surfaces of said profile each having the shape of an exponential curve and being symmetrical about a plane extending through the geometrical center of the structure and perpendicular to the axis of rotation.

6. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, comprising,

a plurality of straight anisotropic filament-like members, the longitudinal axis of said members being disposed parallel to each other;

and wherein said structure is symmetrically contoured in cross-section about said axis of rotation and has a center portion of maximum thickness around said axis and end portions of minimum thickness at the end portions,

the center portion of the structure having a cross-sectional thickness diminishing non-uniformly from said maximum to said minimum according to the relation:

$$y = y_0 e^{-kx^2}$$

wherein:

y_0 = one-half of the thickness of the structure at the axis of rotation

y = one-half of the thickness of the structure at any point on the surface of the structure

e = the base of the natural system of logarithms

x = a spinning radius of a point on the surface of the structure

k = a numerical constant.

7. The energy storage structure of claim **6** wherein k is in the range of numerical values between 2.5 and 100.

8. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, comprising,

a plurality of straight anisotropic filament-like members, the longitudinal axes of said members being disposed parallel to each other; and wherein each member is shaped according to the relation:

$$y = y_0 e^{-kx^2}$$

wherein:

y_0 = one-half of the thickness of the structure at the axis of rotation

y = one-half of the thickness of the structure at any point on the surface of the structure

e = the base of the natural system of logarithms

x = a spinning radius of a point on the surface of the structure

k = a numerical constant.

9. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, the structure comprising a plurality of initially straight anisotropic filament-like members having maximum strength-to-density along their longitudinal axes, said members being oriented within said structure with the longitudinal axis of each member disposed substantially parallel to the longitudinal axis of the structure, said structure further comprising,

hub means for holding the members at their centers of rotation, rotation of the structure causing the members to fan out, each said member aligning substantially along the local principal stress vector acting thereon.

10. The energy storage structure of claim **9** wherein the members are initially formed substantially into a rectangular unit having a length at least ten times greater than its width.

11. The energy storage structure of claim **9** wherein the members are initially formed substantially into a cylindrical unit having a longitudinal dimension at least 10 times greater than its diameter.

12. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, the structure comprising a plurality of anisotropic filament-like members, said members being formed into strips, the members within any given strip being parallel, and wherein the strips are formed into a generally disc shape comprising two opposing surfaces and a circular peripheral edge, the structure being symmetrically contoured in cross-section about said axis of rotation, and having a center portion of maximum thickness and edge portions of minimum thickness.

13. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, the structure comprising a plurality of anisotropic filament-like members, the structure being formed into a generally disc shape,

a multiplicity of the members being bonded together into flat strips and having the longitudinal axis of each member oriented therein substantially parallel to adjacent members,

the strips further extending through and perpendicular to the axis of rotation and being bonded together in a regularly offset angular relation to each other whereby each strip contacts at least one other strip on at least one of its surfaces.

14. The energy storage structure of claim 13 wherein adjacent strips are maintained in contacting relation with each other over major portions of their surfaces.

15. An energy storage structure rotatable about an axis of rotation extending transversely therethrough, the structure comprising a plurality of essentially anisotropic filament-like members having maximum strength-to-density along their longitudinal axes,

the members being bonded together into a plurality of essentially flat strips and having the longitudinal axis of each member oriented therein substantially parallel to the longitudinal axis of the strip, the strips extending through and perpendicular to the axis of rotation and progressively and successively surmounting each other and being built-up and bonded together in a regularly offset angular relation to each other with certain of said strips extending in a counterclockwise direction and certain other of said strips extending in a clockwise direction.

16. In an energy storage system

a rotatable shaft,

an energy storage structure having its midpoint mounted for tilting movement on the shaft and having an axis of rotation coincident with the axis of rotation of the shaft when the longitudinal axis of a cross-section taken through the structure is perpendicular to the shaft,

said structure comprising a plurality of anisotropic filament-like members having maximum strength-to-density along their longitudinal axes.

17. The energy storage system of claim 16 wherein the filament-like members are oriented within the energy storage structure with the longitudinal axis of each said member disposed along a principal stress vector acting on the filament during rotation of the structure.

18. An energy storage structure rotatable about an axis extending transversely therethrough, comprising,

a multiplicity of anisotropic filaments having maximum strength-to-density along their respective longitudinal axes, the filaments being oriented within said structure with the longitudinal axis of each said filament disposed along the vector summation of the principal forces acting on the filament during rotation of the structure.

19. The energy storage structure recited in claim 18, including means engaging the structure at its midpoint and mounting said structure for rotation about said axis.

20. In an energy storage system,

a shaft rotatable around a stationary axis, and

a plurality of energy storage rotary structures mounted on the shaft, and having axes of rotation coincident with the axis of rotation of the shaft when the longitudinal axes of respective cross-sections taken through the structures are perpendicular to the shaft,

each of said structures comprising a plurality of straight, filament-like members, said members being oriented within each structure with their longitudinal axes disposed substantially parallel to the longitudinal axis of a section of the rotary structure taken parallel to the member.

21. The energy storage system of claim 20 and further comprising

hub means on each of the rotary structures, and pin gimballing means on each of said hub means,

the shaft having a plurality of ports for receiving one each of said rotary structures therethrough and a plurality of recesses perpendicular to, aligned with and communicating with each of said ports for receiving said pin gimballing means, the rotary structures being capable of pivotal displacement around said gimballing means to relieve precessional loading on the shaft.

22. In an energy storage system, a rotatable shaft and,

an energy storage structure having its midpoint mounted for tilting movement on the shaft and having an axis of rotation coincident with the axis of rotation of the shaft when the longitudinal axis of a cross-section taken through the structure is perpendicular to the shaft,

said structure comprising a plurality of anisotropic filament-like members oriented with their longitudinal axes parallel to each other.

23. The energy storage system of claim 22 and further comprising,

internal hub means on the said structure,

pin gimbaling means on said internal hub means, and

external hub means formed with the shaft for receiving the energy storage structure therethrough, said external hub means having recesses therein for receiving said pin gimballing means, the energy storage structure being capable of pivotal displacement around said gimballing means to relieve precessional loading on the shaft.

24. The energy storage system of claim 23 and further comprising an elastic sleeve disposed around the said structure and between said structure and said internal hub means.

25. An energy storage structure comprising a plurality of anisotropic filament-like members rotatable about an axis extending transversely therethrough,

said structure having a generally wedge-like cross-section with wedge-shaped leading and trailing surfaces,

the structure being symmetrical about a plane extending through the geometrical center of said structure perpendicular to the axis of rotation.

26. An energy storage structure rotatable about an axis extending transversely therethrough, comprising,

a plurality of anisotropic filament-like members arranged with their longitudinal axes parallel, and

hub means including arcuately shaped spaced walls,

said hub means engaging said members with the mid-portions of said walls in engagement with the mid-portions of said members,

the members fanning out on rotation of the structure whereby the portions of said members within said hub means will bear against said walls and be supported thereby.

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