United States Patent

Rabenhorst

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[54] **FIXED ELEMENT ROTOR STRUCTURES**

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[52] **U.S. Cl.** **74/572,** 74/5

[51] **Int. Cl.** **F16h 33/02**

[58] **Field of Search** 74/572, 5; 15/179, 181

[56] **References Cited**

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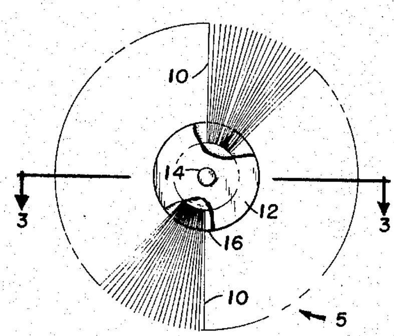
[57] **ABSTRACT**

The invention relates to inertial energy storage devices wherein a central hub holds a multiplicity of anisotropic filaments, the filaments extending from the hub in fixed relation thereto and in parallel planes perpendicular to an axis of rotation through said hub. Each filament extending from the central hub is so disposed within the structure that the stress component imposed on said filament acts uniaxially along its length.

21 Claims, 13 Drawing Figures



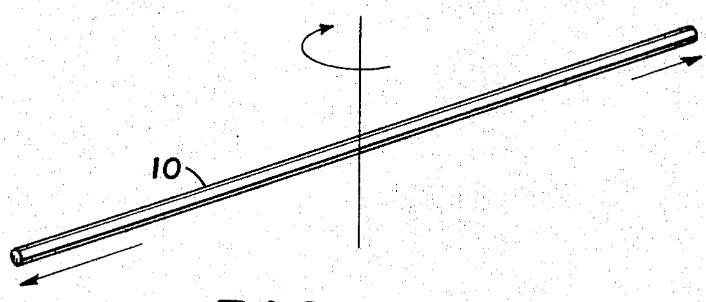


FIG. 1

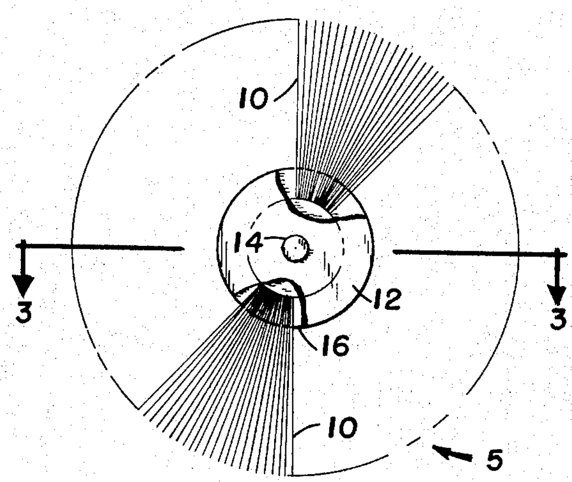


FIG. 2

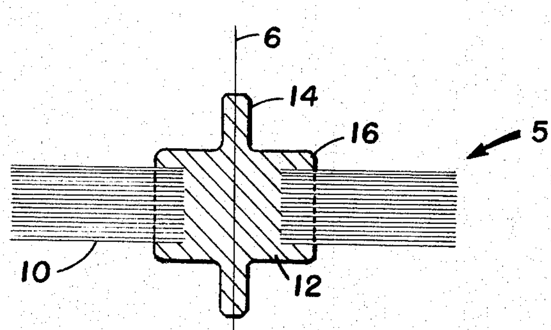


FIG. 3a

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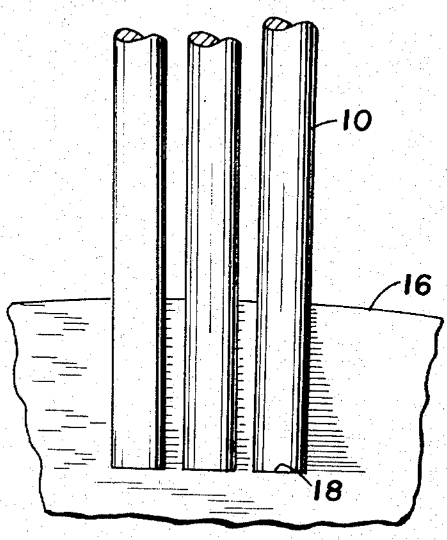

FIG. 3b

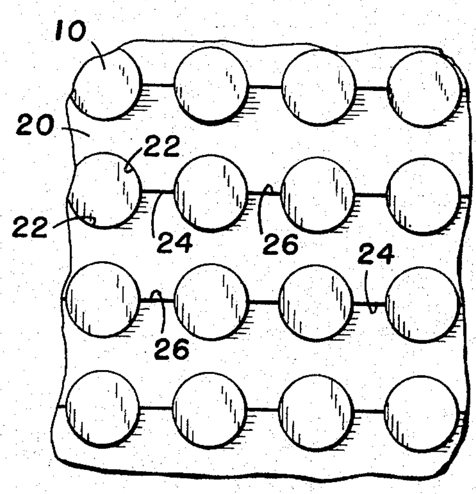

FIG. 4

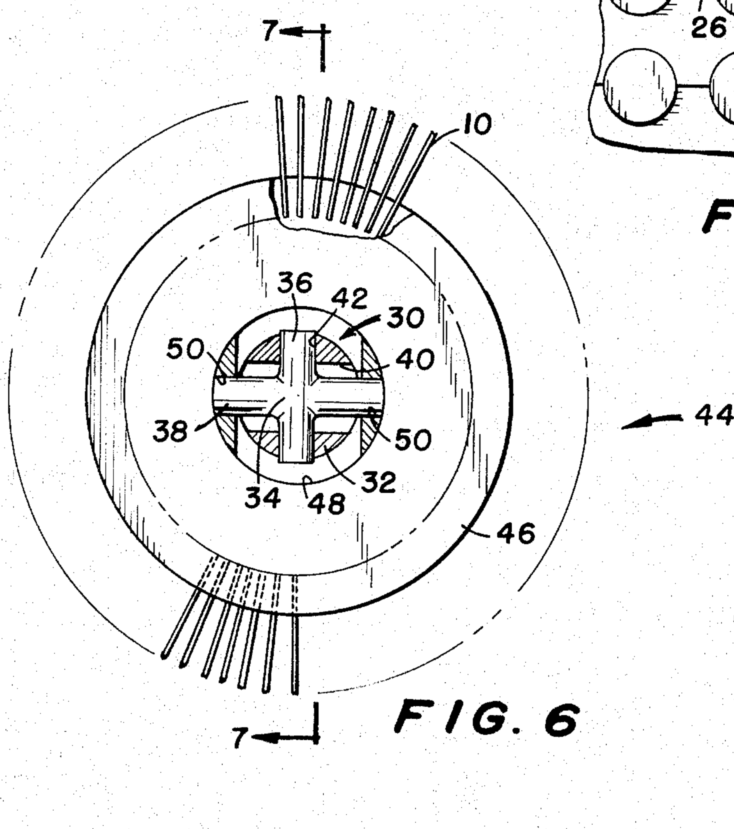

FIG. 6

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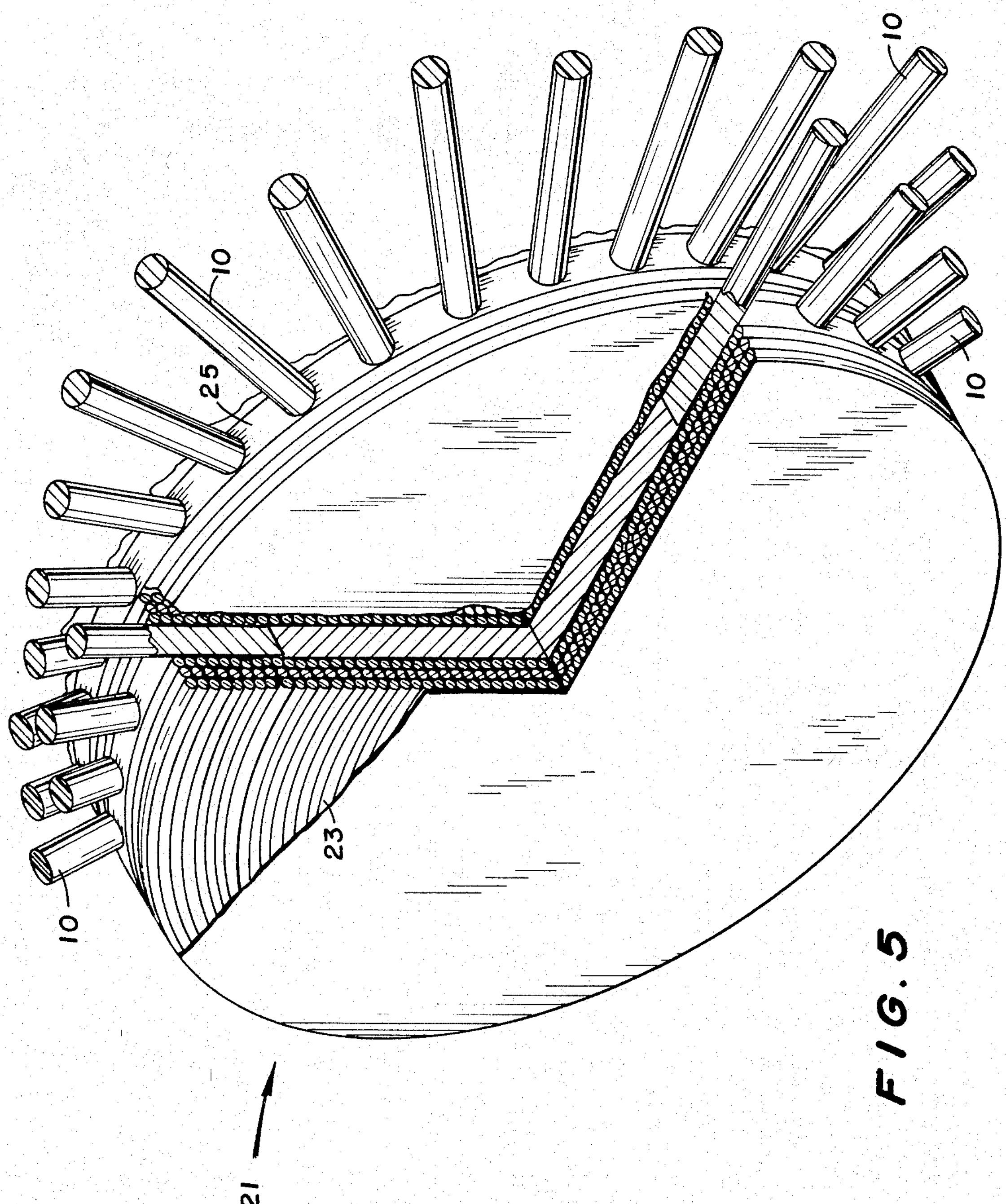

FIG. 5

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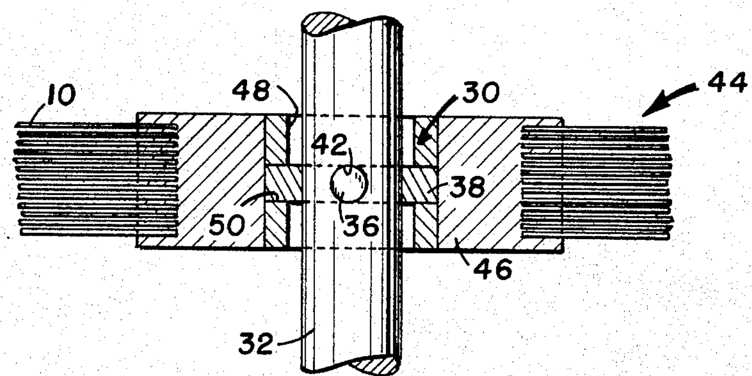

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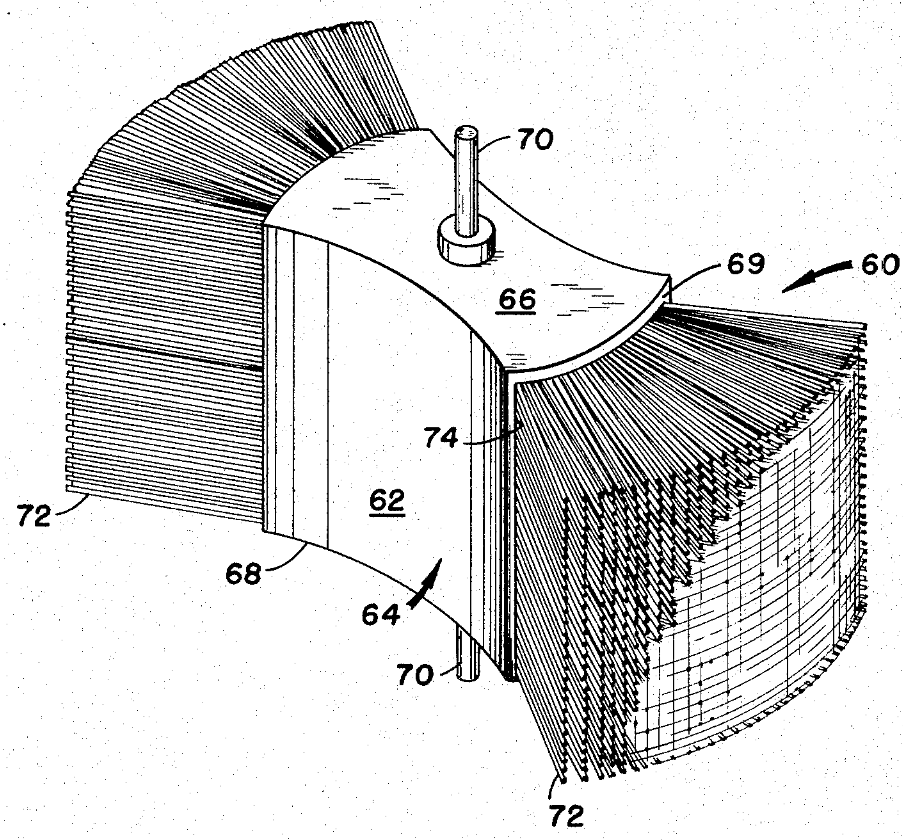

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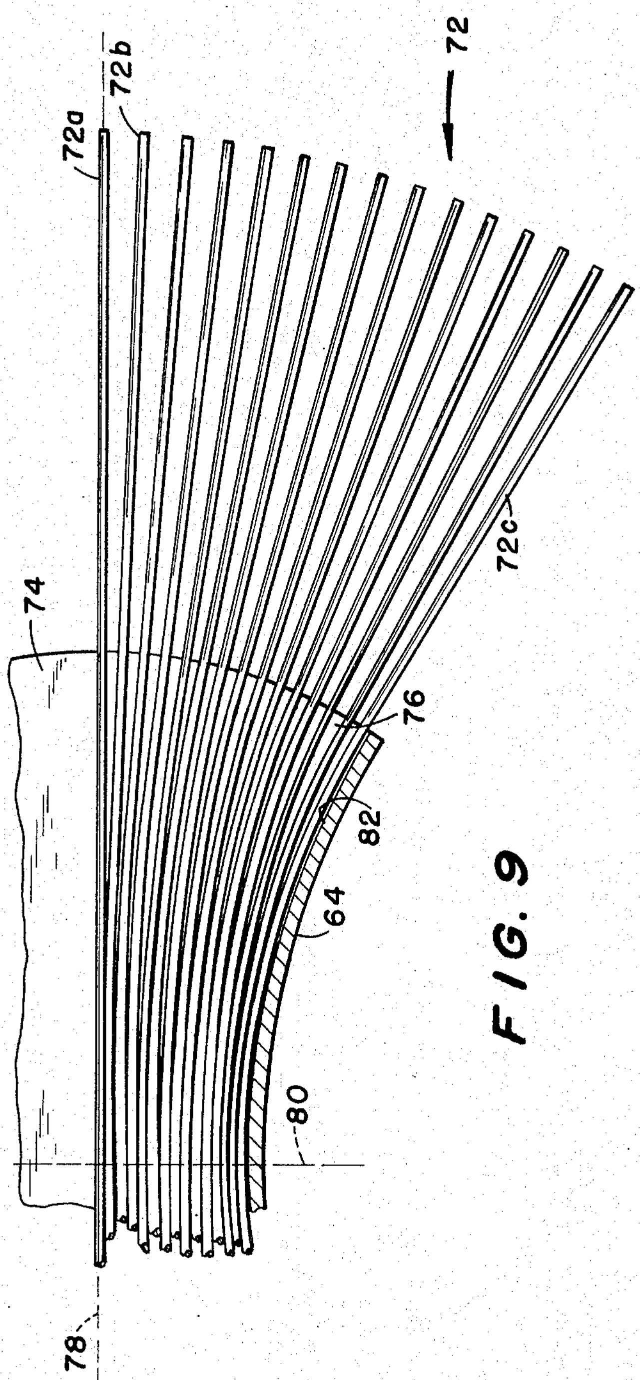

FIG. 9

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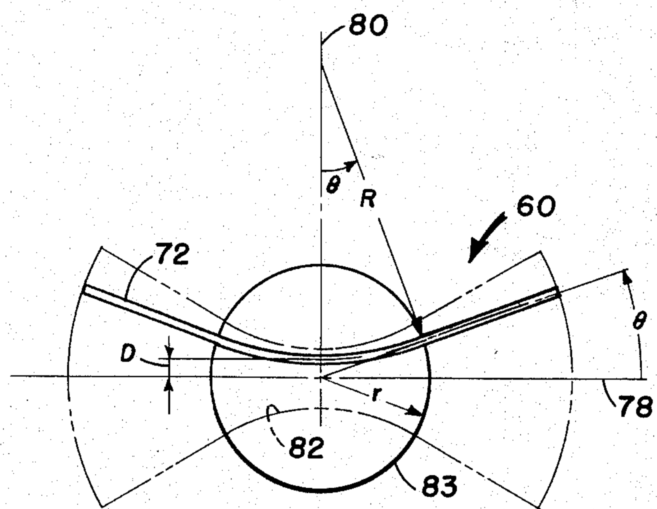

FIG. 10

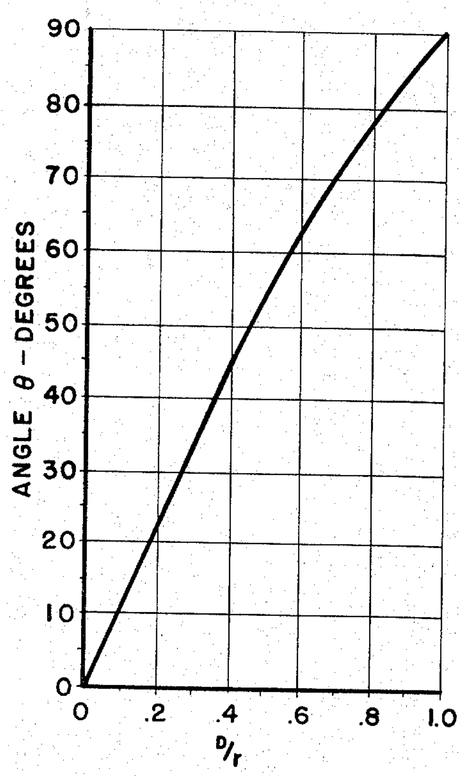

FIG. 11a

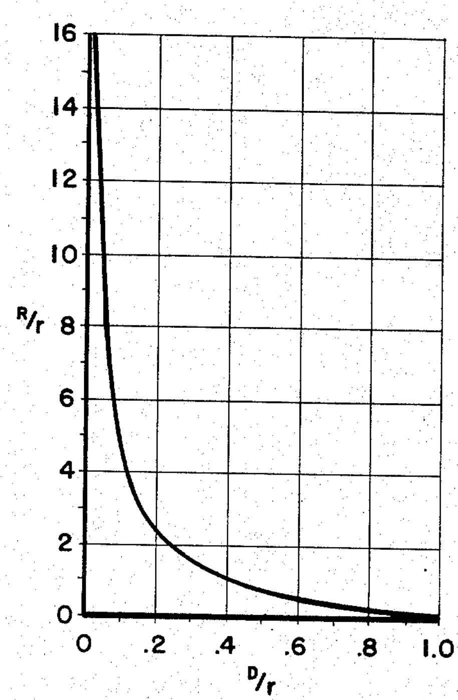

FIG. 11b

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FIXED ELEMENT ROTOR STRUCTURES

STATEMENT OF GOVERNMENT INTEREST

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

CROSS-REFERENCE TO RELATED APPLICATION

The present invention comprises a novel modification of the invention described in co-pending U.S. Pat. application, Ser. No. 60,047, filed July 31, 1970, entitled "Filament Rotor Structures", by the same inventor.

BACKGROUND OF THE INVENTION

A. 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 use as a home emergency power supply unit.

B. 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 inertial energy storage device offers substantial improvement in useable energy density due not only to the advantageous utilization of the high uniaxial strength of filamentary materials, but also to the more efficient packaging density provided by the invention. The structure of the invention permits maximum utilization of the uniaxial strength of each filament while packaging a multiplicity of filaments within an extremely compact volume.

The significance of the present energy storage device is best understood by its application to the urban vehicle. Although flywheels have been used in short-range vehicles, such as in the Swiss Oerlikon bus and in the British Gyreacta transmission, those devices produced only about three 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, it can be charged at any reasonable rate. Thirdly, it 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 energy source in an urban vehicle.

SUMMARY OF THE INVENTION

In a first embodiment, the invention provides a high performance inertial energy storage device wherein a central hub holds a multiplicity of uniaxial filamentary elements in radiating disposition to the hub. In particular, straight anisotropic rods or composite rods of filamentary or "whisker" materials are disposed around the periphery of the central hub in substantially parallel relation to the major stress component acting on the rods during rotation thereof. As is the case with other "flywheel" devices, the performance of the present invention is directly proportional to the specific strength of the material used in its construction. By utilizing the large specific strengths of filamentary materials, i.e., by aligning the individual filaments substantially parallel 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. Since the invention allows the filaments in the device to be in line with the respective force vectors generated by their own rotating masses, virtually all of the available strength of the filamentary materials is effectively used, thereby maximizing "-packaging density" (watt-hrs/pound and watt-hrs./unit vol.) without performance degradation.

In a second embodiment of the invention, a central hub having arcuate internal support surfaces holds a multiplicity of anisotropic elements in fixed, pre-determined positions within the energy storage device, the elements being supported and held in position by the internal surfaces and by matrix materials within the hub. Each element is "fanned" within the device to an arcuate position, the radius of curvature of the element being dependent on the location of the element within the hub.

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

It is a particular object of the invention to provide a rotary energy storage member comprised of anisotropic filaments or rods radiating from a central hub, each said filament being substantially parallel to the major local stress component acting thereon.

A further object of the invention is to provide a rotary energy storage member comprised of anisotropic filaments or rods held in fixed positions within a central hub, the filaments each being "fanned out" to a predetermined curvature.

Another object of the invention is to provide an energy storage device which can be readily and efficiently made from a large number of small discrete rod-like elements in order to minimize the likelihood of simultaneous failure of all such elements and thus maximize the safety of the device.

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

A still further object of the invention is tor provide a "densely packaged", 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

FIG. 1 is an enlarged perspective view of a single, essentially uniaxial filament illustrating the major stress component acting on the filament during rotation thereof;

FIG. 2 is a plan view of a "circular brush" rotor fabricated according to the invention, the rotor being shown partly broken away to illustrate filaments aligned along local stress vectors;

FIG. 3*a* is a section of the circular brush rotor of FIG. 2 taken along line 3—3 thereof;

FIG. 3*b* is an enlarged detail elevation of a portion of the rotor of FIG. 3*a;*

FIG. 4 is an idealized detail plan view of a greatly enlarged portion of the peripheral surface area of the hub;

FIG. 5 is a perspective of a modified rotor in which the hub and rods are laminated together in alternating fashion to build up a rotor structure;

FIG. 6 is a plan view of another modification of the invention, the rotor employed being fitted with a gimballing device to provide attachment to a rotatable shaft;

FIG. 7 is a section of the rotor of FIG. 6 taken along line 7—7 thereof;

FIG. 8 is a perspective of still another embodiment of the invention illustrating a rotor having diverging, or "-fanned" out elements;

FIG. 9 is an enlarged detail plan view of a portion of the hub and of the elements comprising the rotor of FIG. 8;

FIG. 10 is a schematic illustrating the relationships for determining the position of each element within the rotor; and

FIGS. 11*a* and 11*b* are charts showing graphically the relationships shown in FIG. 10.

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. Isotropic materials, such as solid steel, have most often been used in the construction of "-kinetic energy" structures, or "flywheels". However, the best isotropic material exhibits only a small fraction of the strength-to-density of anisotropic materials, such as music wire, Fiberglas or boron filaments, for example. It will thus be understood that a flywheel rotor configured to maximize the anisotropic strength characteristics of uniaxial filamentary or whisker materials is capable of increased performance relative to flywheels composed of isotropic materials. In a first embodiment, the present invention not only provides a rotary structure comprised of straight anisotropic filamentary material which maximizes performance and also permits considerably increased rotor weight within a given volume, hence more energy per volume, relative to prior straight filament rotor structures. This increase is primarily due to the inclusion within the present rotor structure of a circular hub and anisotropic elements around the full periphery of said hub. Additional advantage is provided by the ability of the present structure to allow alignment of each radial element in the structure along the local stress vector acting on said element.

For illustration of the concept embodied in the invention, a single filament or thin rod 10 is shown in FIG. 1 to be spinning about an axis normal to its longitudinal axis. If the diameter of the filament 10 is infinitely small, the total stresses in it are directed along its length from its spinning axis toward its ends, i.e., the direction of the centrifugal forces acting on it, said centrifugal forces, for the situation described, being the only forces acting on it during rotation. If the filament 10 were the only element in a flywheel or rotating structure, all of its allowable strength at its center would contribute to the kinetic energy of such a flywheel. However, in order to obtain a rotary structure of sufficient mass to possess utility, a plurality of filaments have previously been bound together in mutually parallel or near parallel relation by suitable hub means. While producing substantially improved energy storage structures, such filament rotary structures are subject to minor loads which are not directed along the longitudinal axes of the filaments, such loads tending to reduce the energy storage capability of the structures. In the embodiments of the present invention, the filaments are disposed within the rotary structure so that the local stress vector acting on each filament is effectively directed along its longitudinal axis.

A "circular brush" rotor is seen at 5 in FIGS. 2 and 3*a* to comprise a plurality of filaments 10 radially extending from a central cylindrical hub 12. The hub 12 has two centrally mounted shaft members 14 extending from either end thereof, the longitudinal axis extending through the shaft members **14** being coincident with the axis of rotation **6** of the rotor **5**. The hub **12** may be formed of any essentially isotropic material having high specific strength or may be formed from layers of filament-wound composite materials joined into a laminate in a manner to be described further hereinafter. The filaments **10** are chosen from a variety of anisotropic materials having essentially uniaxial load bearing capabilities, e.g., Fiberglas, graphite, quartz, or boron filamentary rods.

The filaments **10** extend radially from the cylindrical surface **16** of the hub **12** around the full periphery of said hub. As can be seen more readily in FIG. 3*b*, each filament **10** has its inner end portion secured in a hole **18** in the surface **16** of the hub **12**. The inner ends of the filaments **10** are preferably secured in the holes **18** by a suitable adhesive, such as epoxy. Since the inner ends of the filaments **10** extend into the holes **18** for a finite distance and adhere to the walls of said holes over the full areas of mutual contact, a bond of sufficient strength to prevent "pull-out" of the filaments during high-speed rotation of the rotor **5** is planes The filaments **10** are seen in FIG. 3*a* to extend radially from the hub **12** in successive planes perpendicular to the axis of rotation **6** of the rotor **5**, co-planar filaments **10** extending inwardly toward a co-planar point lying on said axis of rotation. Essentially, if each filament **10** were extended inwardly to the center of the rotor **5**, the filaments would meet at points along the axis of rotation **6**. Thus, if a plane is taken through the rotor **5** perpendicular to the axis of rotation **6**, each filament **10** lying in that plane is coincident with a radius extending from the geometrical center of the plane, said geometrical center lying on the axis of rotation **6** of the rotor **5**.

The holes **18** in which the inner ends of the filaments **10** are held may be formed by chemical milling, stamping, or in some other suitable manner. However, a particular manner of accomplishing attachment of the elements to the hub is indicated in FIG. 4. In this view, the hub **12** is composed of successive disc-like layers **20**. Semi-cylindrical depressions **22** are pressed into upper and lower faces **24** and **26** of the layers **20**, except the top and bottom surfaces of the uppermost and lowermost layers, respectively, so that the depressions **22** of one layer **20** confront those of adjacent layers, the longitudinal axes of said depressions **22** extending radially from the geometrical centers of the faces **24** and **26**. The inner ends of the filaments **10** are then placed into confronting semi-cylindrical depressions **22** of adjacent layers **20**. The diameter of the filaments **10** may typically be 0.03 inch, the layers **20** having a thickness of 0.04 inch to provide maximum packaging with reasonable separation between successive layers of filaments. The lateral displacement from center-line to center-line of the filaments **10** may also reasonably be 0.04 inch. The disc-like layers **20** may be vacuum welded along adjoining upper and lower faces **24** and **26** to assure high strength for the hub **12**.

The actual number of the filaments **10** per unit area of the cylindrical surface **16** is determined by the capacity of the hub **12** to withstand the combined loading on said filaments within said unit area and the loading due to the rotation of the hub itself. Typically, uniaxial Fiberglas rods of the dimensions noted above, i.e., 0.03 inch diameter, prove useful with the "laminated" disc hub **12** composed of high strength steel.

In the modification of FIG. 5, a high strength, lightweight hub **21** is formed by alternately bonding together layers of the filaments **10** and filament-wound sheets **23**. The layers of filaments **10** and sheets **23** are laminated together with an epoxy adhesive **25** to give solid bi-axial laminar strength properties to the hub **21**. The hub **21** therefore has greater strength-to-density and less weight than a hub fabricated from isotropic material.

The rotor of the present invention may be gimballed, as shown in FIGS. 6 and 7, to minimize gyroscopic precession loading on the rotor and on bearings used to support shafting holding the rotor. The internal gimbal device shown generally at **30** avoids the necessity for otherwise having large external gimbal rings and associated bearings. More importantly, rotor shaft **32** does not have to be gimballed, enabling its output to be used directly. The gimbal device **30** is seen to comprise a cruciform member **34** having shaft pins **36** extending therefrom along the minor axis of the member and gimbal pins **38** extending along the major axis of said member. The cruciform member **34** is disposed within a transverse opening **40** in the shaft **32**, the shaft pins **36** having their outer ends rotatably received within aligned bearings.

A circular brush rotor **44** is fitted with a hub **46** having an axial channel **48** disposed therein for receiving the shaft **32**. The ends of the gimbal pins **38**, which extend longitudinally from the transverse opening **40**, are rotatably received within aligned bearings **50** disposed in the wall which defines the channel **48**. The rotor **44** is thus fully gimballed in the axial channel **48**. For any foreseeable vehicular application in which the rotor **44** is to be used with a stationary vertical spin axis, reasonable gimbal limits, allowing tilting of the hub, are provided by the internal gimbal device **30**.

FIGS. 8 and 9 illustrate still another embodiment of the invention, i.e., a rotor, shown generally at **60**, which has elements contoured into a "fixed-fanned brush" shape. The rotor **60** comprises a unitary central hub **62** having arcuate side walls **64** curved toward each other and spaced by flat, parallel upper and lower walls **66** and **68**, the walls **66** and **68** terminating in arcuate edges **69**. Shaft members **70** are attached to the walls **66** and **68** and extend above and below said walls on the axis of rotation of the hub **62**. An assembly of anisotropic filament-like elements **72** extends through a central longitudinal cavity **74** in the hub **62**, the elements **72** being held in fixed, predetermined positions within said hub. As can be seen more clearly in FIG. 9, the elements **72**, except elements **72***a* at the exact midpoint of the assembly which are straight, are held in fixed, precontoured, arcuate positions within the hub **62** by a matrix material **76**, such as epoxy. The shape of each element **72** is determined by means to be described hereinafter.

Although FIG. 9 shows for simplicity only a portion of one co-planar layer of elements **72** in the rotor **60**, the actual structure of the rotor may be appreciated by reference to axes of symmetry **78** and **80**. The longitudinal axis of symmetry **78** is coincident with the longitudinal axis of the rotor **60**, the pattern of the elements **72** shown to the right of the axis **78** in FIG. 9

being duplicated in mirror image to the left of said axis 78. Similarly, the pattern of the elements 72 above the transverse axis of symmetry 80 in FIG. 9 is duplicated in mirror image below the axis 80. The longitudinal and transverse axes of symmetry 78 and 80 intersect at the geometrical "midpoint" of the axis of rotation of the rotor 60. The structure of the rotor 60 is completed by "building up" in stacked relation a plurality of layers of the pattern of elements 72 thus described.

The elements 72 and 72*a* may be of the same length or, alternately, one or more of the elements 72*a* may be made longer than the remaining elements 72 as a safety measure. The additional loading on an "extra long" element 72*a* would cause that element to fail first if the speed of the rotor 60 exceeded design limitations. By being disposed centrally in the structure, failure of the element 72*a* would not produce substantial imbalance while providing a warning of excessive speed or imminent rotor failure.

Straight elements 72*a*, contained in a plane perpendicular to the upper and lower walls 66 and 68 and extending through the longitudinal axis of symmetry 78, remain straight during rotation of the rotor 60, thereby fully utilizing the inherent strength-to-density of said elements 72*a* to carry the tension loading, or stress, which is directed along the length of said elements. The elements 72 on either side of the straight elements 72*a* thus described are held in contiguous relation along the transverse axis of symmetry 80, each element 72 diverging from the axis 80 in progressively greater degrees of curvature, i.e., the inner elements 72 having a greater radius of curvature than the outer elements 72, the element 72*b* adjacent to the straight element 72*a* having the largest radius of curvature and the outermost element 72*c* having the smallest radius of curvature. The inner surfaces 82 of the side walls 64 of the hub 62 are formed with a radius of curvature equal to that of the outermost elements 72*c*. Thus, midportions of the elements 72*c* are contiguous to and are supported by the surface 82 of the wall 64 along the full length of said wall. The remaining elements 72 are held in place and supported by the matrix material 76 which surrounds the midportions of said elements within the central cavity 74.

As can be seen with reference to FIGS. 9 nd 10, those portions of the elements 72 which extend externally of the hub 62 are aligned along extended radii of an imaginary circle 83 defined in part by the arcuate edges 69 of the hub 62. The elements 72 must be positioned within the hub 62 with the proper curvature in order for the portions of the elements 72 external of the hub to be directed as described. Although the straight elements 72*a* are the only elements within the rotor 60 which are positioned to permit maximum utilization of the strength-to-density of the elements, proper choice of the radii of curvature of the remaining elements 72 allows utilization of a significant portion of the strength-to-density of said elements, thereby resulting in a rotor 60 of manageable dimensions wherein the tension load on each element 72 is carried by the element itself.

The position of each of the elements 72 within the hub 62 may be determined from the relationships illustrated in FIG. 10. In FIG. 10, a single element 72 is schematically shown in its predetermined location within the rotor 60, the displacement of the element 72 from the axis of rotation being taken as normal from the longitudinal axis of said element to the longitudinal axis of symmetry 78. That portion of the element 72 extending beyond the circle 83, which circle is defined in part by the arcuate edges 69 of the hub 62, lies along an extended radius r of the circle 83 drawn to the point of intersection of the longitudinal axis of the element and said circle. The tangent to the circle 83 through the aforementioned point of intersection defines the radius of curvature R of that portion of the element 72 lying within the hub 62. In particular, the radius of curvature R is that portion of the tangent lying between the aforementioned point of intersection on the circle 83 and the intersection of the tangent with the extended transverse axis of symmetry 80. The angle θ between the radius of curvature R and the extended transverse axis of symmetry 80 is identical to the angle defined by the longitudinal axis of symmetry 78 and the extended radius r with which the element 72 aligns beyond the circle 83.

The relationships between the above described values define the position of the element 72, which relationships are shown graphically in FIGS. 11*a* and 11*b*. FIG. 11*a* shows the relation between the angle θ and D/r, while FIG. 11*b* illustrates the relation between R/r and D/r. For a given displacement D and radius r, the radius of curvature R of each element 72 may be determined from either FIG. 11*a* or 11*b*. Alternatively, given the displacement D and the radius r, the radius of curvature R for the given element 72 may be directly determined from the relationship:

$$R=\frac{1}{2}\left(\frac{r^2}{D}-D\right). \tag{1}$$

In practice, the stress loss encountered due to bending of the elements 72 should be limited to 20 percent or less to maintain performance capabilities of the rotor 60. The following relationship allows determination of the maximum desirable radius of curvature R for a given element 72:

$$S=tY/4R \tag{2}$$

where:

S = Bending stress loss;

t = thickness of an element;

Y = modulus of elasticity of the material;

R = radius of curvature.

The rotor 60 may be gimballed according to the principles described in the previously mentioned co-pending patent application Ser. No. 60,047, by the present inventor.

It is to be understood that the foregoing description of the invention is illustrative, and that various modifications to the structure and manner of fabrication of the rotors disclosed herein may be made without departing from the scope of the invention.

I claim:

1. An energy storage device having an axis of rotation extending transversely therethrough, comprising

a plurality of anisotropic, filament-like members having maximum strength-to-density along their longitudinal axes, the longitudinal axes of portions of said members extending radially from the axis of rotation of the device, hub means for holding the members in planes perpendicular to the axis of rotation of the device, the axis of rotation of the device being coincident with the longitudinal axis of said hub means,

the hub means being comprised of disc-like layers of material, adjacent layers having confronting semi-cylindrical depressions in the upper and lower faces thereof, the confronting semi-cylindrical depressions cooperating to receive portions of each of the members within the hub means and said layers clamping said portions of said members in said depressions.

2. The energy storage device of claim 1 wherein the adjacent layers are joined along respective upper and lower faces.

3. An energy storage device having an axis of rotation extending transversely therethrough, comprising

a plurality of anisotropic, filament-like members having maximum strength-to-density along their longitudinal axes,

hub means for holding the members in planes perpendicular to the axis of rotation of the device, the axis of rotation of the device being coincident with the longitudinal axis of said hub means and the longitudinal axes of the members being aligned along radii emanating from points along the axis of rotation, the members being disposed around the full periphery of the hub means,

the hub means being comprised of disc-like layers of material, adjacent layers having confronting semi-cylindrical depressions in the upper and lower faces thereof, the confronting semi-cylindrical depressions cooperating to receive portions of each of the members within the hub means and said layers clamping said portions of said members in said depressions.

4. An energy storage device having an axis of rotation extending transversely therethrough, comprising

a plurality of anisotropic, filament-like members having maximum strength-to-density along their longitudinal axes, the longitudinal axes of portions of said members extending radially from the axis of rotation of the device, and

hub means comprising layers of parallel planar spiral wound filaments disposed in alternation with respect to parallel layers of radially extending filament-like members.

5. The energy storage device of claim 4 wherein the members are disposed around the full periphery of the hub means.

6. The energy storage device of claim 4 and further comprising matrix means disposed between the sheets and the members to bond said sheets and members into a unitary structure.

7. An energy storage device having an axis of rotation extending transversely therethrough, comprising;

a plurality of anisotropic, filament-like members having maximum strength-to-density along their longitudinal axes, the longitudinal axes of portions of said members extending radially from the axis of rotation of the device;

hub means having an axial channel extending therethrough, the longitudinal axis of said channel being coincident with the axis of rotation of the device, the hub means further having aligned bearings in the walls of the axial channel,

a shaft extending through the axial channel, the longitudinal axis of the shaft being disposed coincident with the axis of rotation of the device, the shaft having a transverse opening formed therein and further having aligned bearings formed in the walls of said transverse opening, and

a cruciform member disposed within the transverse opening and having pairs of gimbal pins, one pair of said pins being rotatably received within the bearings in the shaft and the other pair of said pins, the axes of which are disposed at right angles to the axes of the first-mentioned pair of pins, being rotatably received within the aligned bearings in the hub means, thereby allowing said hub means to tilt relative to the shaft.

8. An energy storage device having an axis of rotation extending transversely therethrough, comprising,

a plurality of anisotropic, filament-like members having maximum strength-to-density along their longitudinal axes, the longitudinal axes of portions of said members extending radially from the axes of rotation of the device, and

hub means comprising arcuate side walls, the side walls being curved toward each other and toward the axis of rotation of the device.

9. The energy storage device of claim 8 wherein the filament-like members are held by the hub means in fixed, predetermined positions, portions of the members within said hub means being arcuate.

10. The energy storage device of claim 9 wherein the portions of the members extending externally of the hub means are straight and aligned along radii emanating from the axis of rotation of the device.

11. The energy storage device of claim 9, wherein the radius of curvature of the fixed arcuate portion of each of the members is dependent upon the distance of said member from a plane taken through the longitudinal axis of the device and perpendicular to the transverse axis thereof, the radius of curvature of each said member being determined according to the relationship:

$$R=\frac{1}{2}\left(\frac{r^2}{D}-D\right)$$

where:

R = radius of curvature of a given member;

r = radius of the hub means; and

D = distance from the given member to the said plane.

12. The energy storage device of claim 9 and further comprising matrix means for maintaining the members in fixed positions within the hub means.

13. An energy storage device having an axis of rotation extending transversely therethrough, comprising,

a plurality of anisotropic, filament-like members having maximum strength-to-density along their longitudinal axes, the longitudinal axes of portions of said members extending radially from the axis of rotation of the device, and

hub means for holding portions of the filament-like members,

the members disposed in a plane through the longitudinal axis of the device and perpendicular to the transverse axis thereof being straight and the members on either side of said plane having portions within the hub fixed in predetermined arcuate configurations.

14. The energy storage device of claim 13 and further comprising matrix means for maintaining the members in fixed positions within the hub means.

15. The energy storage device of claim 13 wherein the portions of the members extending externally of the hub means are straight and are aligned along radii of the hub means.

16. The energy storage device of claim 13, wherein the radius of curvature of the fixed arcuate portion of each of the members is dependent on the distance of said member from the said plane, the radius of curvature of each said member being determined according to the relationship:

$$R=\frac{1}{2}\left(\frac{r^2}{D}-D\right)$$

where:

R = radius of curvature of a given member;

r = radius of the hub means; and

D = distance from the given member to the plane.

17. 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 axes 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, the longitudinal axes of major portions of said members extending radially from the axis of rotation of the device.

18. The energy storage system of claim 17, and further comprising

hub means having an axial channel extending therethrough, the hub means further having aligned bearings in the walls of the axial channel, the shaft extending through the axial channel and having a transverse opening formed therein and further having alined bearings formed in the walls of said transverse openings, and

a cruciform member disposed within the transverse opening and having pairs of gimbal pins, one pair of said pins being rotatably received within the bearings in the shaft and the other pair of said pins, the axes of which are disposed at right angles to the axes of the first-mentioned pair of pins, being rotatably received within the aligned bearings in the hub means, thereby allowing said hub means to tilt relative to the shaft.

19. The energy storage system of claim 17, and further comprising hub means for holding the members in planes perpendicular to the axis of rotation of the device.

20. The energy storage system of claim 19 wherein the members are disposed around the full periphery of the hub means.

21. The energy storage system of claim 20 wherein the hub means is formed with a plurality of radially directed holes extending from the surface of said hub means inwardly toward the axis of rotation of the structure, each hole receiving therein a portion of one of said members.

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