REVIEW OF FLYWHEELS FOR ENERGY STORAGE WITH REFERENCE TO THEIR POTENTIAL FOR USE IN SPACE

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Summary

The current development status of flywheel energy storage systems is reviewed and their potential for use in space, where the requirements are similar to those of the electric vehicles (compact, light weight and long lived reliable secondary power units), is assessed.

Vacuum and zero gravity are advantages peculiar to space which will reduce some of the current problems but careful design will be needed to minimise the precessional effects of the gyroscopic forces.

It is concluded that, although the system appears to have potential for cycle lives well in excess of 20 000 at energy densities up to 50 W h/kg, developments are not, as yet, sufficiently advanced to make it worth considering a dedicated unit for space.

1. Introduction

Over the past few years two major applications have been 'driving' the development of energy storage: motive power for electric vehicles and peak power in civil power stations using energy that has been stored during periods of low demand. Desirable parameters for these applications are listed in Table 1 with the specified requirements for advanced space batteries.

The needs for space and for electric vehicles are not dissimilar but power generating stations need to store orders of magnitude more energy and the weight and volume of the system is largely irrelevant. Energy Storage Wheels (ESW), however, are considered to be potential contenders for both terrestrial applications. In this paper they are examined to determine their potential for use in satellites in Earth orbit. Two main types of orbit will be considered:

(a) Low Earth Orbit. In this case the satellite enters an eclipse once per orbit. The time spent in eclipse depends on the height of the particular orbit but for the large space platforms being considered for development in about 10 years' time it is about 0.5 h in a total orbit period of about 1.5 h. The main requirements are for a useful energy density of 50 W h/kg and a cycle life that will permit real lifetimes of between 2 and 4 years.

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TABLE 1

Energy storage requirements

	Space low earth orbit	Space geosync. orbit	Electric vehicles	Civil power stations
Gravimetric energy density (W h/kg)	50	150	60 - 130 - 300 [1]	–
Volumetric energy density (W h/l)	50 - 100	50 - 100	50 - 100	–
Gravimetric power density (W/kg)	25 - 50	100 - 150	200 [1]	–
Power (kW)	20 -200	5 - 20	25 - 150	>10 000
Energy (kW h)	20 - 200	6 - 25	50 - 400	>10 000
Cycles (1000s)	12 - 25	> 1	> 1 [1]	–
Life (years)	2 - 4	5 - 10	> 3	10 - 20

(b) Geosynchronous Orbit. Here, satellites have an orbital period of 24 h and maintain station over a given point on the equator. The main attraction of the orbit is that it is particularly useful for communications but to reach it requires the expenditure of much more energy to launch the satellite. All systems, therefore, must be as light as possible. Ideally one would like a battery with an energy density of the order of 150 W h/kg but, as the satellite is eclipsed on only about 40 days in each 6 month period (the length of the eclipse varying from 0 up to a maximum of just over 70 min per day), less than 1000 cycles are needed to guarantee continuous service for a real life of more than 10 years.

Nickel/cadmium is the only proven type of cell that can meet the life requirement for the low Earth orbit applications at the present time, but at the cost of accepting shallow discharges and, therefore, energy densities less than 20 W h/kg. Nickel/hydrogen cells give the promise of improved gravimetric energy density and are already achieving long cycle lives. Their disadvantage is a low volumetric energy density.

The ESW is an alternative that has some advantages:

(a) Useful energy density of up to 50 W h/kg.

(b) Cycle lives of 20 000 and more.

(c) a.c. Power generation — makes processing for all the different systems on board easier.

Energy is stored as angular momentum, and the wheel is charged by being accelerated up to high rotational velocities. It is discharged either mechanically, by providing power through a gear chain, or electrically by driving an alternator. For space use an electric motor charges the wheel and an alternator discharges it. A reversible motor/alternator can be made but dedicated units will probably prove to be the most effective.

Development is being funded both for load leveling and for electric vehicles. In the latter case there are two potential modes of use. It can either replace secondary batteries completely or it can be used in a hybrid system either with diesel engine or with a secondary electrochemical battery to provide the peak power demand [2]: ESWs can be designed with a capacity that is virtually independent of the load.

In the terrestrial environment, one of the major loss mechanisms of the flywheel is friction with the air. To achieve acceptable efficiencies it has to be maintained in an evacuated chamber. This introduces additional weight, a potential source of unreliability in the form of the pumps, and reduced efficiency as power is needed to maintain the vacuum. In space no such problems exist and the system is therefore inherently made more attractive, not least because the vacuum containment usually doubles the weight of the system [3]. With the savings that this permits, gravimetric energy densities of the complete system, including the bearings and the motor/alternator could exceed 50 W h/kg if the theoretical gravimetric energy densities of between 110 and 125 W h/kg [4, 5], using flywheels made from composite materials, can be converted into practice. Lifetimes well in excess of 20 000 cycles should be feasible for such a flywheel and can be predicted in advance with a far higher degree of certainty than is possible for electrochemical systems. The main limit is fatigue failure and in calculating the energy density of the flywheel 10^6 cycles were assumed for a wheel made from carbon fibre. Lower cycle lives would permit higher stresses and, therefore, could have higher energy densities.

2. Basic theory

The energy E of a flywheel is stored as angular momentum and is a function of its moment of inertia I, radius of gyration r, mass m; where I is given by:

$$I = mr^2$$

and angular velocity ω to give:

$$E = (mr^2\omega^2)/2\ .$$

For a given wheel the energy can be increased by raising the rotational velocity, but in doing this the stresses tending to destroy the wheel also increase until it disintegrates. The speed at which this will occur can be calculated from a knowledge of the tensile strength of the material from which the wheel is made. If σ is the maximum stress that a material will withstand and ρ is its density, it can be shown that the maximum angular velocity to which a loop of material can be taken is given by:

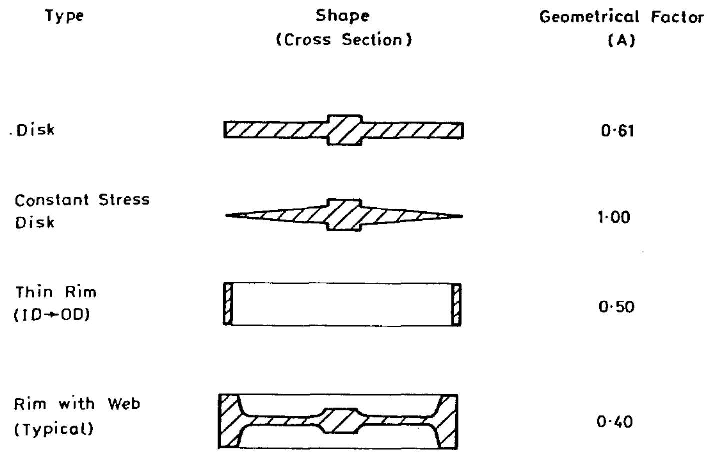

Fig. 1. Flywheels. Shapes and their respective geometry factors.

$$w = (\sigma/\rho)^{0.5}/r$$

and the maximum energy that can be stored, E_m, per unit mass is given by:

$$E_m = 0.5\,A(\sigma/\rho)\,.$$

σ/ρ is a figure of merit of a material and defines how effective it will be when made up into a flywheel and A is a geometrical factor determined by the shape of the particular wheel. Some of the forms that wheels can take, together with the 'factor' they produce, are shown in Fig. 1. Traditionally the most common form is that of a rim with a web support that can either be as radial spokes as used in the work of the AiResearch Manufacturing Company [6, 7] and of the Société Nationale Industrielle Aerospaciale [8], looped spokes such as those favoured by the William M. Brobeck and Associates [9, 10] or even a tapered disk [11].

From these equations several fundamental deductions can be made.

(a) The ratio of the strength of a material to its density defines the maximum gravimetric energy density that a flywheel made from it can have.

(b) Flywheels made from lightweight, high strength materials are likely to provide higher storage capacities than are those made from metals.

(c) In a flywheel made from prestressed concentric rings the limiting stresses will always be reached in the outer rings first.

(d) Although it is not acceptable to 'discharge' the flywheel completely, it is possible to reduce its speed to 25% of the peak value. As the stored energy is a function of the square of the rotational speed this is equal to a 'depth of discharge' of more than 90%.

(e) To achieve the potential of flywheels made from composite materials, their rotational velocities need to be high compared with metals. This means that the input/output controls must be considered much more carefully.

TABLE 2

Properties of some potential flywheel materials [12]

Material	Density (kg/m^3)	Design stress (MN/m^2)	Useful energy density (W h/kg)
Mild steel	7800	300	8
Mild steel (laminated)	7800	300	16
Maraging steel	8000	900	24
Titanium	4500	650	31
Wood	550	30	6
E-glass (60%)/Epoxy	1900	250	14
S-glass (60%)/Epoxy	1900	350	20
Carbon fibre (60%)/Epoxy	1500	750	52
Kevlar (60%)/Epoxy	1400	1000	76

The physical properties determine the potential performance of a given material. A range of candidate materials and their potential performance is given in Table 2.

3. Current status

Until a few years ago interest in energy storage by flywheels was low, as metal wheels were the only ones usually considered. These, as Table 2 indicates, have limited energy densities. They also tend to fail catastrophically, without warning, and release their energy instantaneously when the wheels burst. With the advent of two-phase (composite) materials in the form of fibres embedded in an otherwise homogeneous matrix, it has become possible to consider the development of ESWs with higher energy densities.

Much of the renewed effort has taken place in the USA and the Sandia Laboratories, Albuquerque has, since 1978, funded the development of four separate flywheel concepts. These are with Garrett AiResearch, Hercules, Rocketdyne/Rockwell and Brobeck. In addition, the Lawrence Livermore National Laboratory has been associated with the development of rotors at General Electric since 1978 [13].

The rotor concepts are:

(a) Garrett. A multi-ringed annular rim with two inner layers of S2-glass/epoxy on the inside diameter, 5 middle layers of Kevlar-29/epoxy and 8 outer layers of Kevlar-49/epoxy. The use of different materials enables the highest strength fibres to be used on the outer edge where the stresses are higher, and lower strength materials, that are cheaper, on the inner edge. The rim is supported on 4 spokes made of layered S2-glass/epoxy and Kevlar/epoxy and a hub made of carbon fibre/epoxy. The design is such that the outer diameter of the spokes is greater than the inner diameter of the unstressed rim. The latter, therefore, has to be prestressed to mount it onto the spokes and

sustains lower stresses when it is being rotated. The form this takes is shown in Fig. 2. Maximum gravimetric energy densities of 53 W h/kg have been achieved with this type of wheel, and with conservative rotor design to reduce the risk of failure, useful gravimetric energy densities of 27 W h/kg are obtained at 12.5 krpm in a rotor having 15 kW h of stored energy. A wheel designed for the near term electric vehicle was tested for 1000 cycles to 75% depths of discharge (25 krpm to 13 krpm) without failure. Air was then admitted to the vacuum enclosure surrounding the wheel while it was running at 26.25 krpm and friction heating resulted in the disintegration of the rim but with an acceptable rate of momentum transfer [14, 15].

(b) William M. Brobeck and Associates. A basic flywheel concept is being developed that can be used at different sizes either for electric vehicles [9] or for energy storage at residential premises [10]. The rim consists of an inner ring of S2-glass/epoxy and an outer ring of Kevlar-49/epoxy. It is supported on 64 spokes, each of which is one quarter of an ellipse, as shown in Fig. 3. The spokes are made of Kevlar-29/epoxy with an aluminium hub at the center. The design peak gravimetric energy density is 84 W h/kg at 55.9 krpm with 0.97 kW h of stored energy for the electric vehicle unit. From the dimensions given it is also possible to show that the peak volumetric energy density is 114 W h/l, assuming the disk to have constant thickness equal to the maximum value at the rim. The residential flywheel appears to be a more conservative unit operating at between 5.73 krpm and 2.86 krpm with a peak energy density of 33 W h/kg and storing up to 50 kW h. No tests of these wheels have been reported at the time of writing.

(c) Rockwell. This firm has been developing composite ESWs since 1968 but has also developed metal wheels that operated at 40 krpm with an energy density of 25.5 W h/kg and which failed, predictably, at 53 krpm when the stored energy density was 46.6 W h/kg. Their latest design has a rim of circumferentially wound carbon fibre/epoxy overwound tangentially with another layer of carbon fibre/epoxy. Predicted failure is at 30 krpm and at the operating maximum of 22 krpm, the energy density taking the total stored energy is 61.7 W h/kg. It is predicted that the useful energy density of the system will be 29.6 W h/kg [16] and in initial tests of the wheel the rated speed has been exceeded at 22.92 krpm with no problems.

(d) Hercules. This design is of a prestressed, contoured disk made from circumferentially wound AS-4 carbon fibre in a P1700 polysulphone polymer (thermoplastic resin) matrix mounted onto an aluminium hub [17]. The energy densities of the particular wheel have yet to be determined.

It is proposed that when these four concepts have each been fully evaluated the best will be chosen for future development.

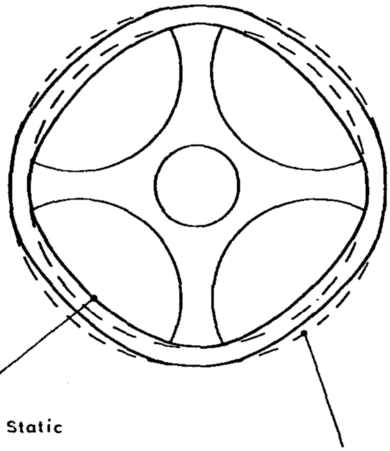

Fig. 2. Flywheels. Prestressed composite rotor of AiResearch.

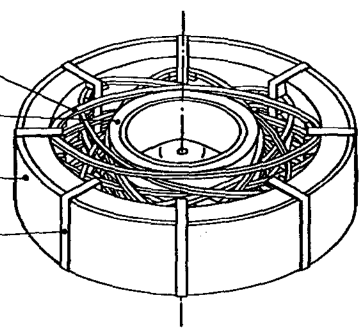

Fig. 3. Flywheels. Biannulate rim and multi-spoke design of William Brobeck & Associates.

The Lawrence Livermore National Laboratory and General Electric collaboration has led to the development of two further flywheel concepts. They are both based on building up a disk of several (> 20) layers of fibre composite, with each layer having the fibres rotated through a predetermined angle to the layer below. At LLNL a tapered disk of carbon fibres has a maximum energy density of 61.6 W h/kg, but for a flat disk made using S2-glass it is 66.9 W h/kg. During tests of the tapered disk, however, it did not reach its maximum operating speed and failed at 36 krpm although it was not predicted to fail until 50 krpm [13]. Failure analysis studies at GE [18] indicated that microcracks in the matrix material occur at lower operating speeds than those that can be withstood by the fibres and could cause premature disk failure. This, it was concluded, explained the failure of the LLNL disk at 36 krpm: matrix failure can be expected in such a disk at 30 krpm. The stacking procedure is to be modified in future disks to reduce the anisotropy in the strength. It is also proposed that the rim be redesigned with filament windings, which increases both the efficiency and the energy density of the

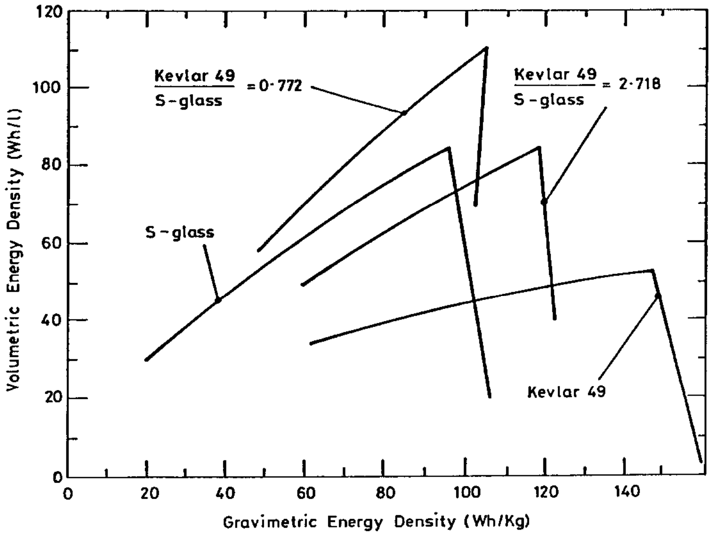

Fig. 4. Flywheels. Volumetric and gravimetric energy densities for S-glass and Kevlar 49 and ratios between (theoretical).

disk. A new moulding process for the disks using S2-glass/polyester sheet is also being developed in collaboration with Owens-Corning.

A study of how the volumetric and gravimetric energy densities of composite flywheels are inter-related was completed at the University of Nebraska–Lincoln [19]. It was shown that with S-glass one had a higher volumetric but a lower gravimetric energy density than with Kevlar. This is illustrated in Fig. 4.

Outside the USA the effort is much less in this field but interest in increasing.

In the Netherlands the Energy Research Foundation has sponsored, in cooperation with industry, research institutes, universities and the utilities, a 2 year feasibility study. This includes applications, development and construction problems, and the design of a hybrid flywheel unit of 0.7 - 1 kW h. It is hoped that a 10 kW h unit for static applications will be built [20]. At the University of Delft a 10 kW, 10 kW h complete, (quasi) static power system is being constructed [21]. Several types of flywheel are also being built such that any of them can be fitted into the system for evaluation. These include laminated wheels being built by the Netherlands Aircraft Factories Fokker. It is predicted that these will have an energy density of 26 W h/kg and 8 will be needed to give the 10 kW h called for if made of carbon fibre. Three types of wound fibre wheel are being developed at the Laboratory of Fibre Technology:

(a) E-glass rim on a modified Laval disk made from aluminium.

(b) E-glass rim with 6 E-glass spokes on an aluminium hub and which should have energy densities of 36 W h/kg and 65.7 W h/l.

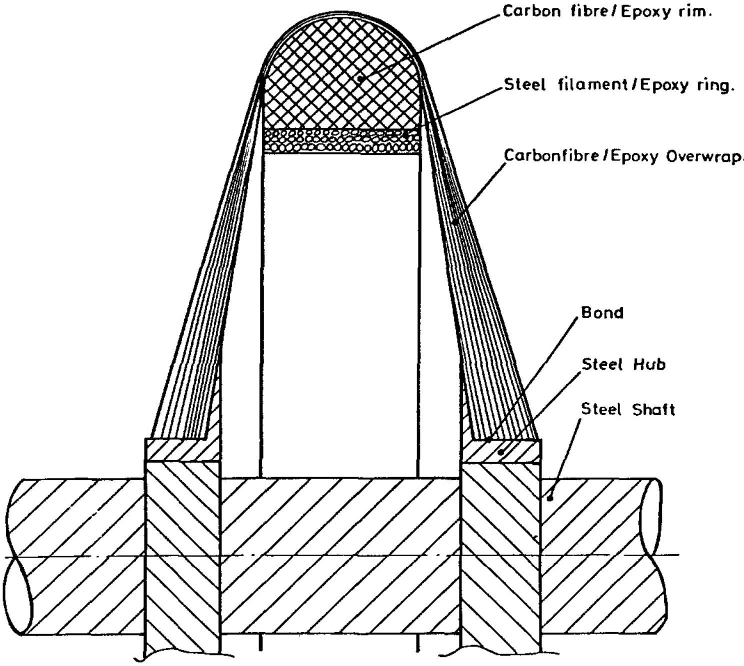

Fig. 5. Flywheels. Rotor design of University of Aachen and MAN-Neue Technologie.

(c) As (b) but with high strength steel fibre instead of the E-glass.

Finally, two Laval disks of maraging and of tool steel are being made by the central workshops of the university and should have energy densities of 23 W h/kg. Studies are also being made of the motor-generator for which a mass of 6 kg is predicted compared with the rotor mass of more than 250 kg in the case of type (b) above [21].

In Germany, following the 6 W h/kg forged steel disk flywheel installed in a bus by the Technical University of Aachen in 1973, work has started on the development of a hybrid (diesel/flywheel) drive system for city buses at MAN-Neue Technologie [22]. An annular rimmed flywheel has been designed using steel wire for the inner layer and carbon fibres for the outer layer. This is then overwrapped with a layer of carbon fibres as shown in Fig. 5. The theoretical energy density of this type of flywheel was computed to be 107 W h/kg and that with a safety factor of 50% it should store up to 71 W h/kg for lifetimes of 10 years or 10^7 cycles. In practice it was only capable of storing 23.4 W h/kg as its rotational speed was limited to 22 krpm due to lack of balance in the wheel.

A novel approach to the design is being made in Mexico that could prove to be useful for static systems but probably not for any other and certainly not for use in space. To overcome the need for a vacuum seal in the outer case, through which the torque has to be transmitted, it was proposed that the outer case be part of the rotating assembly. This rotates at low speed to limit air friction losses, and inside an epicyclic set of gears transmits the bulk of the energy to a central high speed rotor [23].

In Italy experimental studies have been made at the University of Cagliari with a 500 mm dia. flywheel having a rim made from a glass fibre (65%)/epoxy composite on a polyamide disk. It was designed to run at 25 krpm with an energy density of 50 W h/kg [24]. This was used for testing techniques of stress measurement in order that the theoretical predictions can be compared with the values observed in practice. Fiat are also carrying out some flywheel developments for load leveling applications using wire wound wheels of between 2 and 2.5 m in diameter.

There are also a number of theoretical studies of various aspects of the system being completed at these and at other establishments in other parts of the world. In addition, the growing interest in the field resulting from the practical achievements that have already been made have given rise to a number of surveys of potential applications, such as that in the Netherlands and a similar one in the UK [3, 4, 20], and the indications are that the effort is likely to increase.

4. Future developments

Flywheel energy storage must be considered to be a relatively new field. Most of the work that has been completed has served to define the problem areas, to prove the system's feasibility and to show that it is competitive with the other, more established, energy storage techniques. Little effort has been made to produce a commercially viable device.

One of the major problems in a flywheel intended for terrestrial use is the need to eliminate air friction. The outer case therefore has to be hermetic and it has to be continually pumped. This means that in a practical device the weight of the total system is at least double that of the isolated flywheel. Energy is also needed to drive the vacuum pumps but, in units greater than a few kW h, the loss is not significant. It is also a problem that does not arise in space and any case that is needed will only serve the purpose of preventing excess damage should the wheel fail.

Other problems remain and there are also areas where development is either essential or is needed to improve performance.

4.1. Structural materials

Theory and practice both confirm that the composite flywheels enable the stored energy to be maximised for a given weight. Many applications other than ESWs need stronger fibres and there is, therefore, a strong incentive to seek for them. One can only make a guess as to whether any will emerge but it does seem to be a reasonable possibility. Assembly methods of the known fibres are not, however, optimised, as evidenced by the range of differing techniques used. Only experimental tests will show which consistently achieve the best results, both in terms of the theoretical energy density and of the ease of maintaining a balanced wheel. The latter fact is particularly important in a device of this type and many of the tests have either failed or have been terminated due to the imperfect wheel balance.

It has also been shown, as described above, that the strength of the matrix material can be a significant factor in the ultimate strength of the wheel and one cannot degrade the strength of the fibre in proportion to the volume of the matrix. It is necessary, therefore, to concentrate some effort on the search for improved matrix materials that combine ease of construction, compatibility with and wetting of the fibres, and increased ultimate tensile strength.

4.2. Bearings

For terrestrial applications there are a number of possible bearing choices including, balls, roller, gas, and magnetic levitation. These have all been considered and various designs of each type assessed, but for space applications the magnetic bearings are likely to have advantages that make them the only ones worth considering. The zero gravity of space presents significant advantages to the designer of flywheels not enjoyed by the designer of units intended for terrestrial use, although means of constraining the wheel during the launch phase will have to be considered. The bearings do not have to carry the mass of the wheel, they only have to locate it. A study of a flywheel for space, using experience gained in the development of magnetic bearings for the gyroscopic inertial guidance systems of satellites, has been started in France where a 10 kW h, 10 kW, model is under development [8].

4.3. The motor/generator

Very few of the flywheel studies make any reference to the problems involved in mechanics of the input and output of the energy to the wheel, but it could be one of the major factors limiting the realisation of the flywheel's full potential. The technology of basic motor/alternators is well established and integration into a flywheel storage unit is not thought to present any difficulties except those resulting from the fact that the output of an alternator is a function of the angular velocity. This means that, on discharge, a flywheel is like a battery in which the load voltage varies significantly with the state of charge. On charge, also, the power input must be varied as the state of charge changes. Continuously variable speed electric drives which depend on control of the supply electronics exist, but there has been no demand for a variable speed motor which can also serve as an alternator in reverse. Producing one may present difficulties although it should be possible. The problems associated with the voltage and power variations during discharge may prove to be less easy to solve. One alternative is to use a variable ratio gearbox but these have proved to be very inefficient at the high speeds which this application requires. Other alternatives include both hydrostatic and hydrodynamic systems. The former consists of two motor/pumps with one connected to the flywheel and the other incorporating a motor/alternator. On discharge the flywheel unit pumps oil to drive the alternator unit, while on charge the 'alternator', now a motor, pumps the oil in reverse to drive the flywheel. The users of current equipment of this type complain of a rapid falling off of efficiency with usage. Maintenance and better oil filtration could reduce this, but it is still unlikely to be applicable in space despite an efficiency of about 80% that can be maintained down to about 20% of the rated power of the flywheel. It is also likely to carry a very severe weight penalty and will certainly be the item that will limit the life of the whole system. Hydrodynamic systems have also been in use for some time as torque convertors in the automobile but, on their own, cannot be considered to be suitable for the flywheel as the losses increase rapidly as speed increases. With gears to reduce the speed of rotation at their input they may prove to be the answer to providing a constant power output with varying rotor speed. The problems in this case will be in achieving a long, reliable life from such a mechanical system and development work will be needed.

4.4. Gyroscopic forces

In designing a system for use in satellites the gyroscopic forces will have to be considered, but the incorporation of a flywheel could be an advantage in a satellite intended to maintain a fixed orientation in space. The incorporation of two contra-rotating flywheels will eliminate most of the forces but some couple will remain unless they can be designed to rotate within each other. In either case, care will be needed to ensure that the velocities of the wheels are matched at all states of charge and discharge. Development of the necessary control systems will have to be undertaken.

5. Conclusions

This is a growing area of development, and the indications are that the growth will continue as it is becoming evident that it is a method of storing energy efficiently both in mobile and in static applications. Experimental flywheels have already been operated which have theoretical gravimetric energy densities (*i.e.* equivalent to the energy density of the cell assuming a 100% depth of discharge) greater than 100 W h/kg. Experimental tests of prototype flywheels have also shown that useful energy densities of greater than 30 W h/kg can be achieved and, already, much useful knowledge and understanding of the limits and failure mechanisms are being accumulated. At the present time, and with the current state of the art, any estimate of the ultimate potential of the flywheel system must be somewhat conjectural. With the effort that is being expended in so many establishments, however, it is reasonable to assume that the current limits will be exceeded and that 50 W h/kg is probably only a conservative estimate of the ultimate performance.

In terms of the volumetric energy density, the literature is not nearly so informative but from the dimensions that are occasionally quoted it appears to lie between 60 W h/l and 90 W h/l.

The flywheels themselves can be designed to have a very long cycle and real life. Typically, cycle lives in excess of 1 000 000 and 10 years are being referred to. These have not yet been achieved in practice but, as the system is controlled by physical laws rather than those of chemistry and electrochemistry, it is possible to predict failure modes and potential lifetimes with a far higher confidence level than is possible for normal batteries.

As mentioned above there is little in the 'flywheel' literature concerning the motor/generator and much more thought needs to be given to the problem of efficiently converting the kinetic energy of the flywheel into electrical energy at all possible rotor speeds. If it were to be assumed that a motor/alternator and associated electronics could be developed to this end the system seems to hold much promise, but at the moment it is impossible to assess the probability of success.

It must be concluded that the Energy Storage Wheel has a potential for space use similar to that for electric vehicles. The problems associated with the fatigue failure and extraction of the energy are similar but in space one has a far more attractive environment: a good vacuum and no gravitational forces on the bearings. One problem will, however, have to be given serious consideration in space. The precessional forces associated with a flywheel orbiting the Earth must be eliminated by the use of contra-rotating wheels. These must operate in the same plane, as far as is possible, and their rotational velocities must be matched at all states of charge and discharge. The problems do not seem to be insurmountable and therefore Energy Storage Wheels could be useful for application in low Earth orbits in the future.

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