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Energy Storage - Flywheel

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[list all tags]

This piece resulted from a challenge within the staff to write a collaborative post on emerging energy storage technologies. I left Chemistry back in high school but one technology that has long fascinated me led me to volunteer on a project: the flywheel. It seemed a good justification to study why industry hasn't developed many applications for these ancient mechanisms. The elusive quest for an answer to that question lead to a rather long writing, that justifies a post on its own. Hopefully this shall be the first of a series on energy storage.

Flywheels are very simple mechanisms. If you have a bicycle you can see how it works: lift one of its wheels from the ground and give it an impulse so that it starts spinning. If the wheel hub is in proper condition the wheel keeps on spinning for quite some time. In fact, were your bicycle in space and the wheel could spin for ever, all due to the law of energy conservation - the work employed by your hand on the wheel is stored as kinetic energy as the wheel spins. Here on Earth, the bicycle flywheel slowly grinds to a halt because air friction and hub imperfections slowly dissipate this energy.

Basic concepts

Flywheels are nothing more than discs or cylinders that spin around a fixed axis. The amount of energy a flywheel can store is proportional to its mass (m), the square of the speed at which it spins (w) and the square if its radius (r). The general equation for a solid disc is of this form:

$$E = 1/4 \cdot m \cdot r^2 \cdot w^2$$

Flywheels have been known to Man at least since the Neolithic, when the first potter's wheels were built. At the dawn of the Industrial Revolution flywheels started to be employed widely as mechanisms to translate the work of steam engines into constant rotational motion; this solution is still employed today in modern internal combustion piston engines. At face value, a flywheel presents several advantages when compared to chemical batteries:

- **Efficiency** – charge and discharge are made with very small losses; as an electrical storage system a flywheel can have efficiencies up to 97%;
- **Fast response** - flywheels can promptly store huge bursts of energy and equally rapidly return them;
- **Lifetime** – flywheels built in the XVIII century for the early rail industry still work today.
- **Maintenance/decommission** – flywheels are kept in vacuum containers, functioning with zero material wear in modern designs; they also do not pose the chemical recycling/decommission issues of conventional batteries.

The basic design of an electric storage flywheel is to attach it to an electric engine and enclose it in a vacuum container to avoid air friction. To store energy, the engine provides motion to the disc/cylinder, increasing the rotational speed of the flywheel; the kinetic energy can later be drawn by the engine to generate electricity, this way reducing the rotational speed of the flywheel.

First commercial applications, first disappointments

This design was the first to be used in commercial applications back in the 1950s in buses that used heavy steel flywheels as their sole energy storage mechanism; these vehicles got the name of Gyrobus. They were employed in routes with low passenger loads that didn't justify full electrification. Gyrobuses could travel about 5 Km on a full charge between recharging stations. Recharging would take no more than 3 minutes, since flywheels can easily absorb high voltage electrical currents. These buses were also equipped with regenerative braking systems that recharged the flywheel.

Commercial Gyrobus services were started in Switzerland connecting Yverdon-les-Bains and Grandson in 1953, and soon after services were initiated in several routes in the city of Kinshasa in the Belgian Congo; in 1956, another service was started in Belgium, linking Ghent and Merelbeke. With time several problems came up, mostly due to the huge weight of these machines – the Gyrobuses used in Congo weighed more than 10 tonnes. They were hard to drive, damaged roads and above all, were electricity guzzlers; a tram used on the same service could easily slash electricity consumption by a third. By the end of 1960, all of the Gyrobus routes mentioned above had been scrapped.

This early commercial experiment brought to light the main disadvantages of flywheels:

- **Weight** – alloy flywheels can easily weigh several tonnes; for transport applications this can be a serious issue, due to the added inertia they impose on acceleration and breaking;

- **Failure** – if a flywheel fails by some reason at high rotation, it disintegrates, sending shrapnel as fast as bullets in random directions; to prevent damage they be must kept within an armoured container, adding further weight to the system;

- **Bearings** – alloy bearings proved to wear out quite rapidly, at first reducing efficiency and later rendering the flywheel useless; Gyrobuses required constant service because of this;

- **Angular momentum** – the momentum stored in the flywheel will act against direction changes, which in transport can make turns a complex task.

For every engineering problem there's a solution (or thereabouts)

Though Gyrobuses haven't returned, research continued on the application of this technology; at the beginning of the 1990s there seemed to be engineering solutions to deal with all the issues above. The first big change was the introduction of new composite materials: they immediately tackled the weight issue but also ameliorated the container, these materials disintegrate into very small particles much easier to retain. Then the bearings issue was elegantly solved with magnets, creating a magnetic field that makes the flywheel levitate, thus spinning without any contacts with other parts (this requires a small consumption of electricity). Finally, the angular momentum has been addressed with the employment of gimbals, which, while not completely solving the issue, greatly reduce its effects.

All these solutions were employed by a company named Rosen Motors in a venture project aimed to produce a car without an internal combustion engine. The concept was based on a small gas turbine coupled with a composite electric flywheel for regenerative braking. In 1997 the first test run was made with the system installed in a Saturn production car; it covered 130 Km in about 2 hours, in what as an engineering breakthrough in many aspects, earning good reactions from several auto-makers. Months later the venture capital of $24 million ran out. Without a single auto-maker wishing to pursue the project the company was forced to fold.

Until today no commercial car has ever been fitted with a flywheel based regenerative system. Nevertheless, the research conducted by Rosen Motors proved that flywheel electrical storage had reached technological maturity, with many different potential applications opening up.

Many promises, few realizations

In the rail industry, flywheels have been used more extensively, though it can't be said their usage is widespread. They have been employed to store energy in electric locomotives to guarantee motion along non- electrified sections of rail lines and also to power small locomotives; beyond a few exceptions these solutions have remained mostly experimental. Flywheel powered trams can be particularly convenient in cities for they dispense with overhead electrification. Notwithstanding this fact, today there's only one commercial case to refer, in the Stourbridge line in London. Ever since 2002, 3 different units built by Parry People Movers have been tested, with 2 of them providing regular service since 2008. This sort of tram can also be fitted with diesel engines for longer distances; since the flywheel deals with all acceleration and braking, this engine can be designed to function at optimal revolutions per minute (rpm), thus being very small and efficient. So far the apparent success of these trams hasn't triggered any serious market penetration, though trial services and demonstrations have been run in other lines; a new trial service is set to start next month on the Mid-Hants Railway, also in Britain.

More recently, interest has been growing on the employment of flywheels as static batteries by the rail side. They can be used to stabilize the electric current feed to locomotives and also to store energy locomotives feed back to electric lines when braking. In 2009 the press reported a 5.2 million $ project to implement a rail-side 2.4 MW flywheel system on the West Hempstead line in Long Island, US. In parallel, the US company Urenco Power Technology, has been developing and testing smaller rail-side flywheels in the underground lines of New York, London, Tokyo and Lyon. Satisfied with the maturity of the system, at the beginning of this year a spin-off company was launched, Kinetic Traction Systems, with the specific aim of commercializing the technology.

Another US company has been working with similar objectives: Beacon Power, but with applications for the electrical distribution grid. The company developed a large scale flywheel that spins up to 16 000 rpm, with a maximum storage capacity of 25 kWh, that can be delivered back to the grid at maximum power rate of 100 kW (over 15 minutes). These flywheels are gathered in clusters that can be used together. Here's a video from 2009 describing the system:

Contrary to what this video suggests, Beacon Power seems quite healthy today, especially after the opening, already this year, of the first commercial flywheel farm, composed by 200 units and installed at Stephentown in New York. This flywheel farm has been deployed primarily as an electricity frequency stabilizer, a perfect match to the flywheel's prompt discharge/recharge characteristics; beyond that, the farm is used to store cheap electricity available in the grid during the night. The company maintains close collaboration with US government authorities through several development programs with broader aims at grid wide stability. The state of Pennsylvania also seems interested in this technology, with capital already committed to a flywheel farm. Further applications are being envisioned, particularly the marriage of flywheel farms with wind farms in order to decentralize load balancing; in this case the system will also be coupled to a thermal generator feed by diesel or gas, that once again can be greatly optimized by the prompt aid of flywheels. If there's an application where flywheels seem bound for serious market penetration it is this one; nonetheless, considering how long intermittent technologies have been penetrating the electricity production market, these seem yet small steps.

When fun meets technology

To fully understand the flywheel state-of-the-art, a final (and longer) story needs to be told. In recent years flywheels took a boost from an unexpected source: Formula 1. In a bid to “green” the sport and provide deeper technological transfer to the auto industry, the FIA introduced new rules for the 2009 season that allowed teams to optionally fit their cars with a regenerative electric storage system with a fixed maximum capacity. This system was baptised Kinetic Energy Recovery System - KERS. These new rules seemed to put those teams opting for the KERS at an advantage, but their late introduction gave little room for the new technology to be developed and absorbed, especially concerning the extra weight applied on the cars. The 2009 season ended up dominated by one of the low budget teams that opted to not even develop a KERS.

After this *débâcle* no F1 team used KERS in 2010, but a left over from 2009 brought the curiosity of many: while most teams opted for chemical batteries, the Williams team had developed a flywheel, that though not successful on track, seemed quite promising for the road. With maximum spinning rates of 60 000 rpm, the Williams flywheel presented itself as such an advantageous systems that the team set up a corporate arm to commercialize it.

At the beginning of 2010 the charismatic German marque Porsche commemorated the 110th anniversary of the first hybrid car in history, developed by its late founder Ferdinand Porsche, with the public presentation of a hybrid version of the track going flavour of its flagship. The Porsche 911 GT3 R Hybrid features two electric wheels at the front axle complementing the traditional 6 cylinder engine plus a KERS – the flywheel developed by Williams. This car made its race début that year at the 24 hours of Nurburgring held on the mythical 25 km circuit. Covering 25% more distance on each fuel tank, this car lead the race from the 14th to the 23th hour, with the thermal engine giving up its ghost 45 minutes from the chequered flag. The impact of this near feat was such that Porsche presented a new flywheel fitted race car in 2011, the 918 RSR, termed by the company as a "racing lab" for the technology, though so far it hasn't taken part in any race. This flywheel system is presenting such an advantage over traditional cars in endurance racing that it's actually becoming hard for these cars to be accepted by race organizers. In its latest version, the Williams flywheel has a maximum capacity of 340 Wh, but it can produce more than 200 hp (~ 150 kW). In time, the urge to "green" the sport and reduce energy consumption will likely force endurance race and championship organizers to set specific rules for regenerative systems, once and for all opening the doors to flywheels.

As much happened in 2011 in Formula 1, with improvements on KERS regulations resulting in most teams re-adopting it. This season the system is limited to 60 kW peak output and maximum storage of 100 Wh. The next big rules revision will come in 2014 when engines will take a huge downsize from 2.6 litres to 1.6 litres; this will be matched by an increase in flywheel peak output to 120 kW. Several companies are today developing flywheels to use in Formula 1 and motorsport in general. Notable among these is the Flybrid, which is coupled to the transmission, thus avoiding electric conversions with direct kinetic energy translation. Another charismatic car maker, Jaguar, is presently studying the introduction of the Flybrid system into its production cars. In the long run Jaguar aims at completely replacing the traditional combustion engine by small turbines functioning at constant, highly efficient regimes. Here's a corporate video on the application of the Flybrid to city buses:

So, why aren't flywheels popular?

Porsche owns Volkswagen, the largest car maker in Europe, and Jaguar is part of the Tata group, the largest car maker in India - could this be the dawn of a new wide-spread technology or just a curiosity restricted to 100,000 € plus cars? Answering this question may start by comparing flywheel state-of-the-art with present chemical battery solutions. This wasn't exactly a simple task, since data varies widely from source to source on certain technologies. For what it is worth, I stuck to the numbers found at Wikipaedia. Here's a compilation of energy density (energy per unit volume) and specific energy (energy per unit mass):

	Energy Density (Wh/l)	Specific Energy (Wh/kg)
Compressed Air	17	34
Supercapacitor	35	20
Lead Acid Battery	40	20
Nickel Metal Hydride	90	90
Lithium-Iron-Phosfate	220	110
Flywheel	210	120
Lithium-ion	440	175
Zinc-Air	1600	470

These are all round numbers that intend, above all, to present the relative positioning of each technology. Clearly flywheels do not present any drastic advantage above chemical batteries in terms of density, being somewhat above Nickel Metal Hydride, getting close to Lithium batteries but far from Zinc-Air batteries. The only advantage that flywheels may have in this regard is that they don't have funny names in their components; in the long run this may mean a cost advantage to flywheels: carbon is abundant, they have much longer lifetimes (more charge cycles per capital cost) and do not present the same recycling issues. But the lack of data, since presently few systems are in commercial operation, makes an assessment of this sort hard to perform. In any event, flywheels do not seem to be the most appropriate means of pure energy storage, hence it is not to be expected their success on applications of that genre.

Things start to look entirely different regarding specific power (power per unit mass) which tells how fast the system can store and/or deliver energy:

	Specific Power (W/kg)
Zinc-Air	100
Lithium-ion	300
Nickel Metal Hydride	600
Lithium-Iron-Phosfate	3000
Supercapacitor	3500
Flywheel	5000

Flywheels not only are clearly ahead of everything else, they also appear at the antipodes of those systems that are ahead in terms of energy density and specific energy. The conclusion is straightforward: for applications where energy must be made available fast and in large quantities, or likewise stored rapidly, and the overall energy capacity isn't critical, flywheels are at a clear advantage.

An illustration can be useful, coming again to transport applications. What amount of energy does a car dissipate when braking, say a vehicle weighing 1 tonne and moving at 100 Km/h? To answer this we must dig into the old high-school Physics trunk for the kinetic energy expression:

$KE = ½ \cdot m \cdot v^2$

Or in English: half the mass (*m*) times the square of velocity (*v*). In SI units the mass is 1000 kg and velocity is 27.(7) m/s; doing the math our illustration results into 385 kJ, or little over 100 Wh. Meaning that a flywheel with 1 kg and occupying about half litre could store the energy needed to bring a car moving at 100 Km/h to a standstill. Depending on how hard the brakes are stepped on, this energy can be produced in just a handful of seconds. If it takes 10 seconds, average power output of such braking will be 36 kW. While an 8 kg flywheel can easily deal with such power, a Lithium-ion battery would have to be much larger, weighting some 120 kg. This means a flywheel is useful even in fully electric cars, dealing with acceleration/deceleration, whilst a chemical battery package could be dedicated exclusively to vehicle range.

An answered question

I started preparing this post in the hope of finding an answer to the lack of commercial application of flywheels as a means of electrical or kinetic energy storage. With the writing finished, I can't say I achieved such an objective. There are a few commercial applications where flywheels are starting a shy market penetration, namely on the rail industry for regenerative braking and cable-less storage and as supporting infrastructure to load balancing within the electrical grid. But precisely where they seem to be more advantageous, in road transport, commercial applications simply do not exist. Car makers have so far chosen storage technologies for their hybrid solutions that seem to go against logic, preferring specific energy to specific power; especially so when the technology has been available for 15 years. Considering that only expensive car makers are developing flywheels (Jaguar, Porsche), could this be a cost issue? There isn't satisfactory data to answer that, but the flywheel's simplicity, long lifetime, and lack of rare and/or polluting materials seems to point against it. Nevertheless, the likely success of this technology on the electrical grid and rail industry, plus the unexpected push from motorsport may change things in the years to come.

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