FLYWHEELS AND SUPER-FLYWHEELS

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Keywords: Flywheel, super-flywheel, energy storage, composites.

Contents

Summary

This chapter introduces the use of the flywheels for mechanical energy storage. The need for flywheels is discussed and the amounts of energy stored by different techniques are compared with that stored by flywheels. Some historical information is given and previous work is briefly surveyed. Then design of clasical flywheels is introduced. The design of super flywheels made out of composite materials are discussed and theory for multi-hyperbolic and multi-rim flywheels are presented..

1. Introduction

Strorage of energy is necessary in many applications because of the following needs:

- Energy may be available when it is not needed, and conversely energy may be needed when it is not available.

- Quality of the available energy may not meet the characteristics of the required energy, such as when an intermittent energy supply is available whereas a smoother energy supply is needed like in internal combustion engines.
- The needed energy may exhibit some peaks where the supply may be uniform in character.
- Smaller size power plants can be used if peak power requirements can be handled by stored energy.

For one or more of the above reasons energy storage is needed.

Energy can be stored in many ways. Some of these alternative ways of storing energy are listed below in Table 1 [1]:

Storage type	**Specific energy (Wh/kg)**
Compression of gases	7.7
Hydraulic accumulator	7.7
Elastic deformation:	
Steel spring	0.09
Natural rubber band	8.8
Electrochemical reaction:	
Lead-acid battery	17.9
Nickel-cadmium battery	30.6
Kinetic energy:	
Maraging steel flywheel	55.5
4340 steel flywheel	33.3
Composite flywheel	213.8*
*Using longitudinal strength of Kevlar without any shape factor	

Table 1. Energy Storage Types.

It is seen that the kinetic energy storage using flywheels provides the highest specific energy compared to other alternatives. Especially, the flywheels manufactured by using composite materials provide the most efficient means.

2. Applications

Flywheel, being among the oldest inventions of mankind, has been defined as a heavy wheel used to oppose and moderate any fluctuation of speed in various kinds of machinery. Archeologists claim that they have found one in the Middle East estimated to be 5500 years old. It was apparently used as a potter’s wheel to keep it spinning between the occasional kicks of the potter’s foot. This striking example indicates that the principle of the flywheel, that a spinning wheel can store mechanical energy, has been understood long before Newton formalized the basic principles of mechanics.

Since their usage in the ancient potter’s wheel, flywheels have found various applications that contributed to the mechanical developments leading to the Industrial Revolution. The steam engines powering the factories and mills of those days could not have functioned without the steadying influence of their flywheels. The same argument is similarly valid for the modern internal combustion engines of automotobiles, trucks and diesel locomotives which rely upon energy stored in flywheels to continue the rotation of the crankshaft between the pulses of energy delivered by the pistons. The power cycle of a single piston engine is very irregular. Power is generated for about 35% of the cycle and the average power output is only about 20% of the peak power. So a large flywheel is needed to smooth the output power. Internal combustion engines have flywheels that are an integral part of the engine design. Automobile engines have flywheels which also function as a clutch plate and as a gear for starting the engine electirically. This flywheel maintains smooth operation of the engine at low speeds. While the vehicle is moving, the flywheel serves no useful energy-storage purpose, because the mass of the vehicle itself acts to smooth the power variations from the motor. For the same reason the steam engines on trains do not need flywheels because the momentum of the train serves to smooth the engine's power production. On airplane engines, the propeller serves as a flywheel, in addition to providing propulsion.

A common application of flywheels is encountered in machinery showing sudden torque and power requirements. A typical example for such a case is the shear or punch press. Here, the function of the flywheel is to reduce the size of the driving motor by storing energy when demand is less than supply and releasing it during the peak power requirement.

Figure 1 [1] shows a typical construction of a flywheel for a motor/generator application where the speed of the rotating assembly needs to be constant under variable load to avoid changes in frequency of the generated electricity.

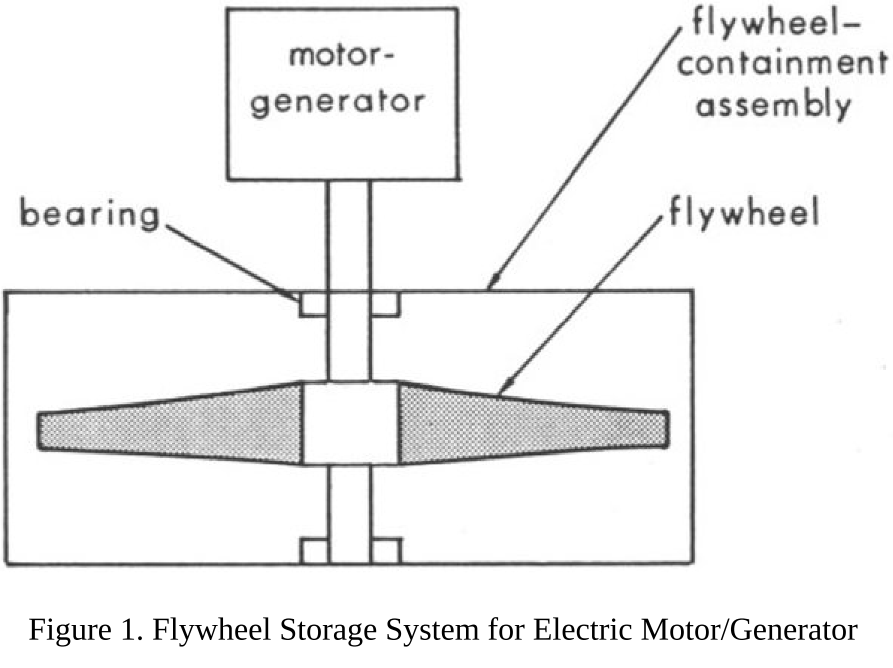


Figure 1. Flywheel Storage System for Electric Motor/Generator

Figure 2 shows a flywheel/heat engine hybrid configuration [2] where the pulses of the internal combustion engine can be smoothed out by the inertial storage capacity of the flywheel. Application of flywheels to trolleybuses to save the kinetic energy of the vehicle during braking was demonstrated in Denmark [3], [4] in the prevous century. However it has not achieved widespread application.

Knoblauch et al. [5] explained in detail an interesting application of a large flywheel to fusion experiments. It weighs 223 tons, is 5.5 m in length and 2.9 m diameter and rotates at 1200 rpm.

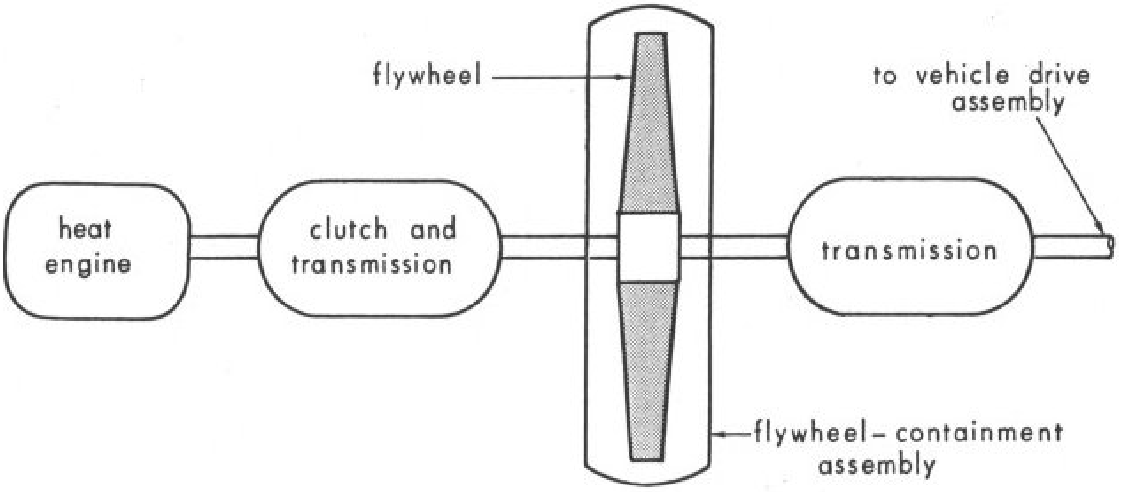


Figure 2. Flywheel/Heat-Engine Hybrid Configuration

Super flywheels built in the recent years have improved characteristics such that they can store more energy per unit weight. They also rotate at higher speeds and have shapes different from the conventional ones which have a thick rim, a thin web, and a thick hub. Some of the new designs are shown in Figure 3. They can use homegeneous and composite materials. The speeds can go up to 50 000 rpm.

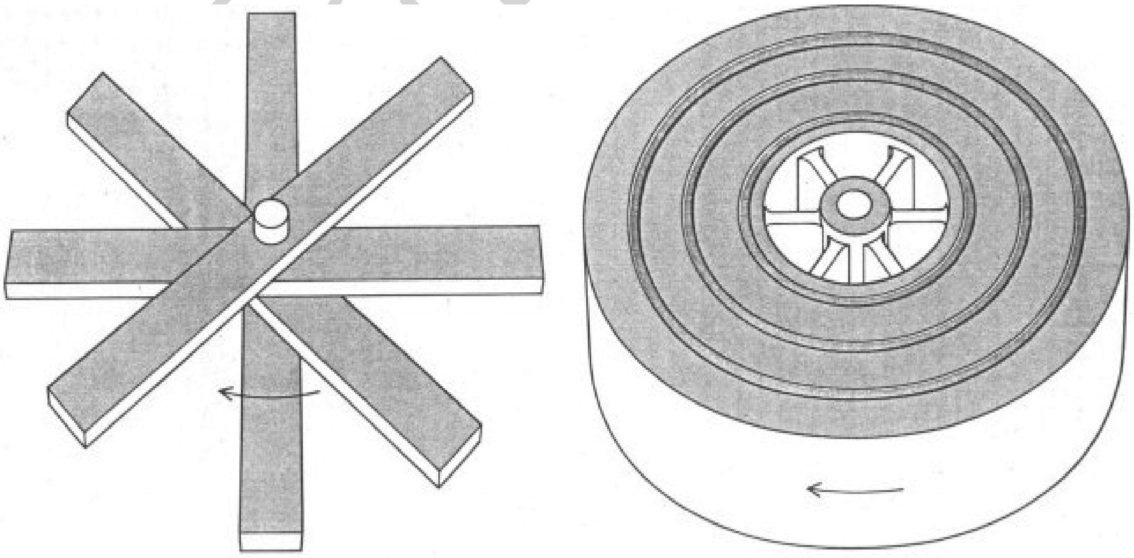


Figure 3. New Designs for Super Flywheels.

3. Flywheel Design

A typical modern flywheel construction is given [2] in Figure 4. Flywheel, being a high-speed rotating disc, is generally contained in a sealed vacuum canister in order to minimize the drag losses. Magnetic levitation system can be used to reduce the frictional losses in bearings. In certain cases fluid or air bearing may also be used. The gyroscopic precession loads on the bearings may be minimized by using internal gimbal arrangement in the design of the superflywheel. For extra protection for safety against disintegration, another shield may also be used.

The kinetic energy stored in a flywheel is given by

$$KE = ½\, I\, \omega^2$$

or the change in kinetic energy

$$\Delta E = \frac{1}{2}\, I\, (\omega_2^2 - \omega_1^2)\ , \qquad (1)$$

where I is the mass moment of inertia of the flywheel about the axis of rotation and ω is the angular velocity.

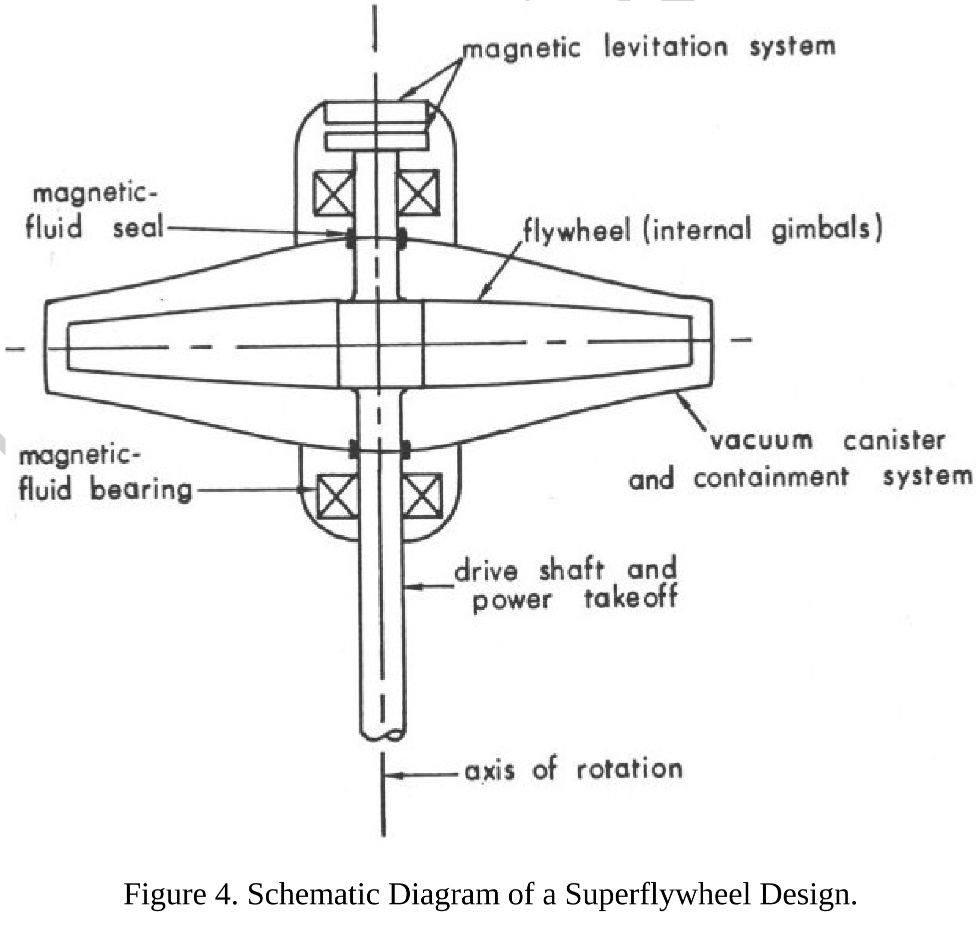


Figure 4. Schematic Diagram of a Superflywheel Design.

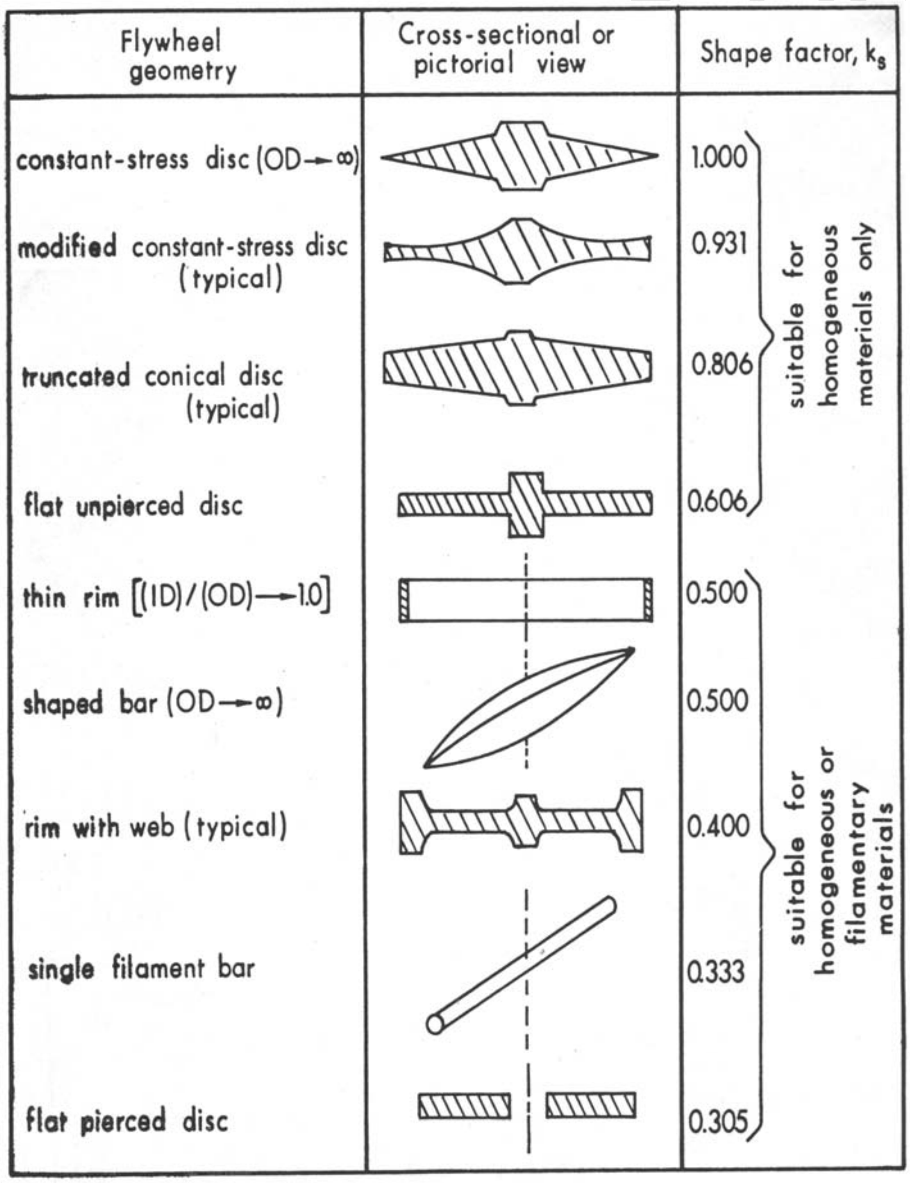
The maximum specific energy (per unit mass), $KE_{\max}$, that can be stored in a flywheel is given by

$$KE_{max} = k_s\,(\sigma_{\max} / \rho)\,, \qquad (2)$$

where $\sigma_{\max}$ is the maximum tensile strength of the flywheel material, ρ is the flywheel-material density and k_s is the shape factor which depends on the rotor geometry. In Table 2, cross sections and shape factors are provided for different flywheel designs [2].

It is observed that the constant stress design provides the highest energy storage capability. Table 3, on the other hand, provides the data on maximum specific energy stored in thin rim flywheels as a function of different materials [2].

4. Historical Perspective of Flywheel Design



Flywheel geometry	Cross-sectional or pictorial view	Shape factor, k_s	
constant-stress disc (OD → ∞)		1.000	suitable for homogeneous materials only
modified constant-stress disc (typical)		0.931	
truncated conical disc (typical)		0.806	
flat unpierced disc		0.606	
thin rim [(ID)/(OD) → 1.0]		0.500	suitable for homogeneous or filamentary materials
shaped bar (OD → ∞)		0.500	
rim with web (typical)		0.400	
single filament bar		0.333	
flat pierced disc		0.305	

Brush

Flywheel

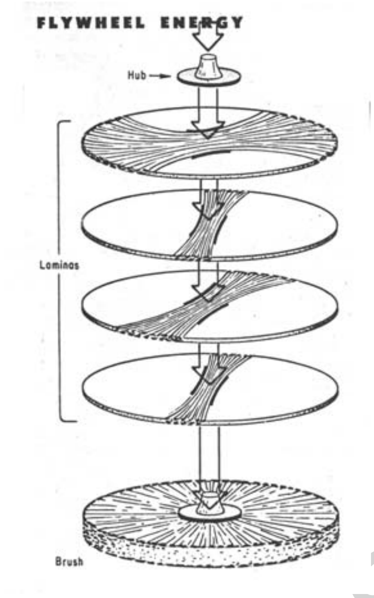


Table 2. Different Flywheel Design

The higher speed allows storage of larger energy in a flywheel. However centrifugal forces increase with the square of the rotational speed. Hence strength analysis of flywheels is the limiting factor of its design. Stresses in a rotating isotropic disk have been studied since the beginning of the twentieth century intensively by many researchers like Grubler, Donath, Grammel, Bishop, Haigh and Murdoch.

Material	**Maximum specific Energy storable in a thin-rim flywheel (k_s=1/2), Wh/lb**	**Relative maximum Specific energy Storable in any Flywheel design**
aluminum alloy	10	1
maraging steel	22	2.2
EE-glass	86	8.6
carbon fiber	98	9.8
S-glass	120	12.0
polymer-fiber (PRD-49)	159	15.9
fused silica	395	39.5

Table 3. Specific Energy Storable in Flywheels

Axially symmetric systems of appreciable thickness using the three-dimensional equilibrium equations were analyzed which resulted in two coupled partial differential equations. Their results showed a 10% change in the maximum stress with a 15 fold increase in computer-time compared to the two-dimensional analysis.

Seireg and Surana [6] have analyzed the stresses in a rotating pierced disk by a two dimensional approach. They have developed a computer program to optimize the rotor according to several design criteria related to minimizing the maximum and average stresses. Later they have extended this study to disks with integral shafts [9]. Others utilized a method using the computer to determine the stresses in a rotating disk with stress free boundaries. They concluded that a two dimensional analysis is sufficient as long as there are no abrupt changes in the thickness.

Later, laminated and polarly orthotropic unpierced flywheels in plane stress were considered. Using a uniform strain failure criterion, an optimal shape yielding constant strain has been determined as a function of the degree of anisotropy. Others analyzed the multi-rimmed flywheel configuration assuming plane stress and attempted to obtain suitable stress distributions by a trial and error procedure on the computer. An extension of this study has considered temperature stresses as well, and has given performance surfaces of energy per unit weight, swept volume and costs for rotors constructed from two rings.

In flywheels, energy loss is estimated to be 3.6 percent of the storage capacity per day. Because of other causes of energy loss, this represents about the highest tolerable loss. The required vacuum to keep losses below this level would be about 10^{-3} torr ($1.3\text{x}10^{-1}$ Pa).

Optimal design procedures for the isotropic multi-hyperbolic and the composite multi-rim flywheels were studied by Soylu and can be found in [7].

Practical knowledge can be found in the publications of Post and Younger [8]. Another aspect of flywheel design is estimation of losses [9]. The following detailed considerations on the strength analysis and design optimization of flywheel are based on reserch results which are summerized in [10].

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Biographical Sketch

Prof. Kaftanoglu graduated Mechanical Engineering Dept. (ME) of the Middle East Technical University (METU) Ankara with high honors (1960) and received D.I.C., Ph.D. degrees of Imperial College, University of London (1966). After research and teaching years in England and Canada (1964 – 69) he joined ME Dept. of METU. He had important duties as Chairman of ME Dept. (1973 – 77), Founder Director of the Centre for Computer Aided Design, Manufacturing and Robotics (1984 – 1992), Director of the Graduate School for Natural and Applied Sciences (1984 – 87) and Vice-President (1987 – 1992) at METU where he is still active. He has received various awards and has honorary editorial responsibilities of professional Journals.