Chapter 6
Mechanical Energy Storage

6.1 Introduction

There are two basic types of energy storage that result from the application of forces upon materials systems. One of these involves changes in potential energy, and the other involves changes in the motion of mass, and thus kinetic energy. This chapter focuses upon the major types of potential energy and kinetic energy storage. It will be seen that it is possible to translate between these two types of energy, as well as to convert these energies to heat or work.

6.2 Potential Energy Storage

Potential energy always involves the imposition of forces upon materials systems, and the energy stored is the integral of the force times the distance over which it operates. Thus

$$\text{Energy} = \int (\text{force})\,(\text{distance}) \tag{6.1}$$

Consider the application of a tensile stress upon a solid rod, causing it to elongate. This is illustrated simply in Fig. 6.1.

The stress σ is the force per unit cross-sectional area, and the resultant fractional change in length $\Delta x/x_0$ is the strain ε.

In metals the strain is proportional to the force, and this can be represented as a stress/strain diagram, as shown in Fig. 6.2. The proportionality constant is the Young's modulus Y, and this linear relation is called "Hooke's Law."

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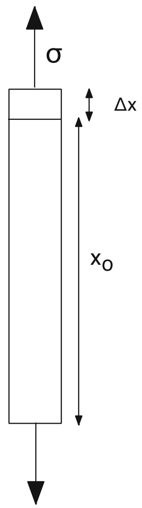

Fig. 6.1 Simple example of the elongation of a solid rod as the result of an applied tensile force upon its ends

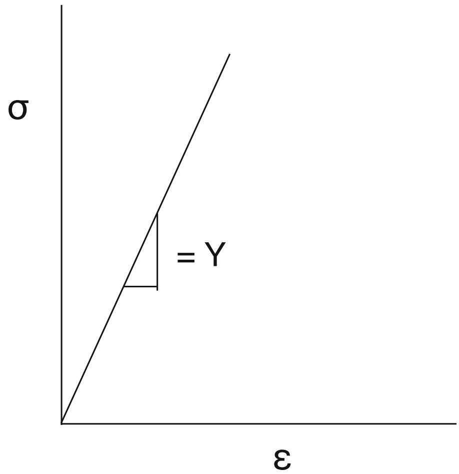

Fig. 6.2 Schematic stress/strain diagram for an elastic metal

If this mechanical deformation is elastic, the work *W* that is done on the spring is the area under the stress/strain curve. This is obviously proportional to the magnitude of the applied stress. That is

$$W = \frac{1}{2}\sigma\varepsilon = \frac{1}{2}Y\varepsilon^2 \tag{6.2}$$

If this mechanical process is reversible without any losses, the work is equal to the amount of stored energy in this simple system.

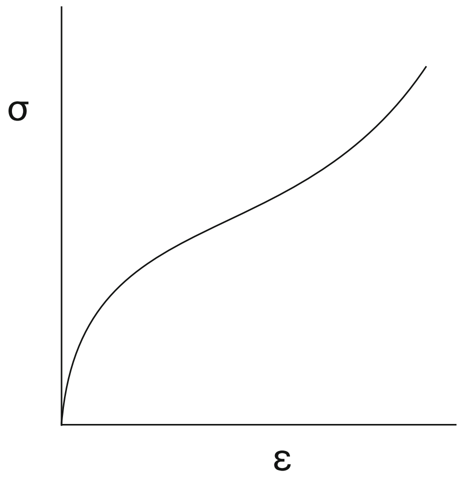

Fig. 6.3 Schematic stress/strain curve for rubber

In metals and ceramics Young's modulus is a constant up to a critical value of the stress, called the yield point. This is because the interatomic forces in such materials are linear at small displacements. At higher values of stress, however, there can be plastic (nonreversible) deformation, and then, ultimately, fracture.

In polymers and rubbers Young's modulus can vary with the value of the strain, due to the action of different physical processes in their microstructures. An example of a stress/strain curve for a common rubber is shown schematically in Fig. 6.3.

The deformation of a metallic spring in a mechanical clock, and the use of stretched rubber bands to power model airplanes are simple examples of this type of stored mechanical potential energy.

6.3 Energy Storage in Pressurized Gas

Everyone who has had to pump up a bicycle tire knows that that process requires work, and that the required force becomes greater as the pressure increases. If there is a leak, or the valve is opened, the gas stored in the tire is released. This is a simple example of the storage of energy in a gas.

It is possible to store energy by making use of the elastic properties of gases in a manner similar to that of the elastic properties of solids.

This can be readily understood by consideration of the ideal gas law, or the equation of state of an ideal gas, that can be written as

$$PV = nRT \tag{6.3}$$

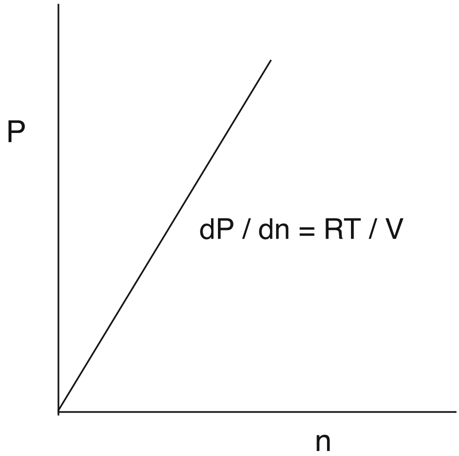

Fig. 6.4 Elastic behavior of gas under pressure

where P is the absolute pressure of the gas, V its volume, n the number of moles, R the gas constant, and T the absolute temperature. The value of R is 8.314 J mol^{-1} K^{-1}, or 0.082 l atm K^{-1} mol^{-1}. Using this latter value, the volume of a mole of gas can be readily found to be 22.4 l at 273 K or 0 °C.

For a constant volume, such as that of a bicycle tire, the pressure is proportional to the amount of gas (air), n, that has been pumped into it. This can be simply represented as shown in Fig. 6.4, which is seen to be directly analogous to Fig. 6.2.

Gases can be compressed and stored in simple mechanical tanks, so long as the pressure is not so large as to cause mechanical damage. This is one of the ways in which the hydrogen used as the fuel in the fuel cells that are being developed for the propulsion of vehicles is contained. Such tanks have been traditionally made of high-strength metals, but carbon fiber composite materials, which can have greater strength and lighter weight, are becoming more attractive for use at high pressures.

The tanks that are used to store gaseous hydrogen to power the fuel cells in the automobiles currently under development can operate up to a pressure of 10^4 psi. One of these autos carries a total of 8 kg of hydrogen in its tanks.

Another alternative for this purpose is to store the hydrogen in solid metal hydride materials. That topic will not be discussed at this point, however. It appears in Chap. 8.

It is also possible to store gases under elevated pressure in underground cavities, if they are gas tight. This is the case for some large salt caverns, depleted oil wells, or underground aquifers.

Since this process is generally close to adiabatic if these are done rapidly, heat is given off during compression, and there is cooling during expansion. Some sort of heat transfer system must be employed to take care of this problem. This can be a serious consideration. For example, compression to a pressure of 70 atm can produce a temperature of about 1000 K. This can cause the overall efficiency of a pressure storage system to be significantly reduced.

6.4 Potential Energy Storage Using Gravity

Instead of depending upon the elastic properties of solids or gases, there are energy production and storage methods that are based upon gravitational forces

One example that is familiar to many people is a type of clock that is driven by the gravitational force on a mass, or “weight.” Some of these are called “grandfather clocks,” and others are “cuckoo clocks.” These types of clocks evolved from the realization by Galileo in the early 1600s that the period of the swing of a pendulum is independent of its amplitude, and that this phenomenon might be used for timekeeping. This led to the invention of the pendulum clock by Christiaan Huygens in 1656, which was shortly followed by the invention of the anchor escapement mechanism by Robert Hooke in 1657.

“Cuckoo clocks” driven by weights have been produced in the Black Forest area of Germany since the middle of the 1700s. They typically include a moving bird, and a small bellows is used to make bird call sound. These have been popular tourist items for some time.

These pendulum-regulated clocks are driven by the action of gravity upon a weight, instead of a metallic spring. This mechanism is illustrated schematically in Fig. 6.5.

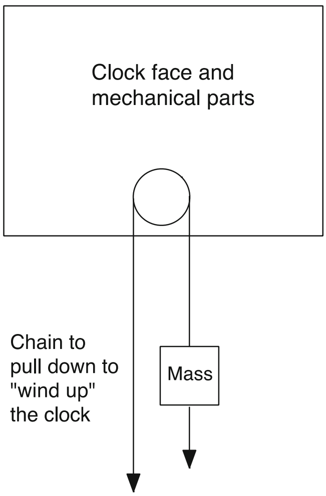

Fig. 6.5 Schematic illustration of the mechanism used to provide energy to pendulum-regulated clocks

In these cases the potential energy involves attractive forces between two bodies, W_{pot}, where

$$W_{\text{pot}} = -G\frac{Mm}{r} \tag{6.4}$$

G is the gravitational constant, $6.67 \times 10^{-11}\ \text{m}^3\ \text{kg}^{-1}\ \text{s}^{-2}$, M is the mass of the earth (5.98×10^{24} kg), m is the mass being moved, and r is the distance between their centers. Thus

$$\Delta W_{\text{pot}} = -GMm\left(\frac{1}{r+\Delta r} - \frac{1}{r}\right) = mg\Delta r \tag{6.5}$$

where

$$g = GMr^{-2} = 9.81\,\text{ms}^{-2} \tag{6.6}$$

6.5 Hydroelectric Power

Water is evaporated from the earth's surface by solar energy as part of the global climate cycle. This evaporation is partly from the land masses, but primarily from the world's oceans. The moisture rises and condenses to form clouds in the sky, which are transported by the global air circulation. This moisture can later precipitate in the form of rain or snow, sometimes at higher elevations. The water from the rain and snow that fall at high altitudes can be stored in reservoirs, from which it can be run through turbines to lower elevations, producing electricity.

This "hydroelectric power" is a major source of electrical energy in a number of countries, including Switzerland and Norway. It is also an important component of the total energy picture in parts of the USA.

One of its major advantages us that the flow through the turbines can be turned on and off in response to the current need. This is not instantaneous, however, for there is a start-up time for the turbines of the order of a few minutes.

There are some disadvantages to this method of energy acquisition and storage as well, for the large reservoirs and their related water collection areas can require a considerable amount of real estate, and this can become a political problem. In addition, the dams, themselves, can be quite expensive.

The use of the gravitation force on collected water to produce energy can also involve much smaller scale facilities. Years ago there were many small waterwheels that were driven by falling water to provide either mechanical or electrical output. These were generally located on smaller waterways, and often used modest millponds to store the water before it was fed onto the water mills.

Another form of hydroelectric energy production takes advantage of the tidal rise and fall of the ocean surface as the result of the gravitational forces of the moon and sun, coupled with the effects of the earth's rotation. Variations in the wind can also have a temporary effect.

The gravitational effect of the moon would theoretically cause the surface of the ocean to rise about 54 cm at its highest point, if it were to have a uniform depth, there were no land masses, and the earth were not rotating. The gravitational effect of the sun is somewhat smaller, theoretically producing an amplitude of about 25 cm under comparable conditions. Tides rise and fall with a cycle time near 12 h, with their magnitudes dependent upon the relative positions of the sun and the moon. Tides with the greatest amplitudes occur when the sun and moon are in line, and are called "spring tides." Those with the smallest amplitudes are "neap tides."

Tidal amplitudes vary greatly from place to place as well, depending upon variations in local ocean depth as well as the nearby underwater land mass topography. In some locations the difference between low and high tide is quite large. Examples include some areas near the English Channel, along the coast of New Zealand, and in the Bay of Fundy and Ungava Bay in Eastern Canada.

Programs have been initiated to make use of the large variations in water level is several locations by the construction of "impoundment ponds" that admit and release seawater through turbines. The power that is generated in this way is, of course, periodic, related to the timing of the tides.

6.6 Pumped-Hydro Storage

A modification of hydroelectric storage and power is called "pumped-hydro" storage. The general configuration in this case involves water storage facilities at two different elevations. They can either be natural or artificially constructed, and can have a wide range of sizes. They could include underground caverns, old mine shafts, volumes formerly occupied by oil, or newly excavated volume.

Water can be run through turbines from the upper one to the lower one, producing electricity, as in simple hydroelectric power systems. But then water can be pumped back up to the storage area at the higher elevation, effectively recharging the system. In some cases this involves the use of two-way turbines. This can make sense if the price of electricity varies significantly at different times of the day or the week. This type of energy storage can be especially useful in connection with daily peak shaving and load leveling, as well as weekly and seasonal variations in the energy demand.

This scheme is illustrated schematically in Fig. 6.6.

Whereas the efficiency of large-scale water-driven turbines can be quite high, even over 95 %, the efficiency of the dual-cycle reversible storage system typically is about 80 %. There are other losses, of course, such as water evaporation from one or both of the reservoirs, leakage around the turbine, and losses due to friction of the moving water.

There are many such pumped-hydro storage systems in the world. Some of them are listed in Table 6.1.

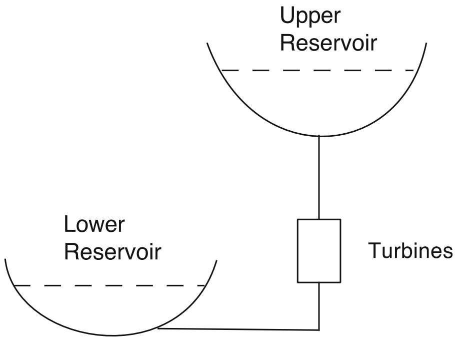

Fig. 6.6 Schematic illustration of a pumped hydro system

Table 6.1 Examples of large pumped hydro systems

Country	Name	Capacity (MW)
Argentina	Rio Grande-Cerro Pelado	750
Australia	Tumut Three	1500
Austria	Malta-Haupstufe	730
Bulgaria	PAVEC Chaira	864
China	Guangzhou	2400
France	Montezic	920
Germany	Goldisthal	1060
	Markersbach	1050
India	Purulia	900
Iran	Siah Bisheh	1140
Italy	Chiotas	1184
Japan	Kannagawa	2700
Russia	Zagorsk	1320
Switzerland	Lac des Dix	2099
Taiwan	Mingtan	1620
United Kingdom	Dinorwig, Wales	1728
United States	Castaic Dam	1566
	Pyramid Lake	1495
	Mount Elbert	1212
	Northfield Mountain	1080
	Ludington	1872
	Mt. Hope	2000
	Blenheim-Gilboa	1200
	Raccoon Mountain	1530
	Bath County	2710

6.7 Use of the Kinetic Energy in Moving Water

It is possible to extract power from moving water by the immersion of a water-driven propeller or turbine. This could be done in flowing rivers, where the flow is relatively constant with time. It also can be done in locations in which there are significant tidal currents. In this case, however, the current, and thus the power available, are periodic, with rather substantial periods between.

Whereas this may appear to be rather simple, some practical matters require attention. These include seawater corrosion and the growth of barnacles and other biological species on underwater surfaces. Some recent designs involve retractable propellers that can be periodically cleaned.

6.8 Kinetic Energy in Mechanical Systems

In addition to potential energy, it is also possible to store kinetic energy. This is energy that is related to the motion of mass. This will be discussed in two parts, linear motion of a mass, and rotational motion of mass. More information on this topic can be found in [1].

6.8.1 Linear Kinetic Energy

The kinetic energy E_{kin} related to a body in linear motion can be written as

$$E_{\text{kin}} = \frac{1}{2} mv^2 \tag{6.7}$$

where m is its mass, and v its linear velocity.

A simple hammer is an example of this principle. The kinetic energy in its moving mass is utilized to drive nails, as well as for other purposes.

A somewhat more exotic example involves hybrid automobiles. In some of the current hybrid internal combustion/electric vehicles an electric motor/generator in the drive train drives the wheels. It is fed from a high-rate battery (sometimes called a "supercapacitor") that is recharged as needed by an efficient internal combustion engine.

When the vehicle is slowed down, or braked, the motor/generator operates in reverse, and some of the vehicle's kinetic energy is converted to electrical energy that is fed back into the battery. This energy can then be used subsequently for propulsion. The amount of this recovered energy is typically about 10 % of the basic propulsion energy in urban driving. This system is shown schematically in Fig. 6.7.

A variant on this model is the "plug-in hybrid," in which the net energy consumed from the battery is replaced by the use of an electrical recharger when

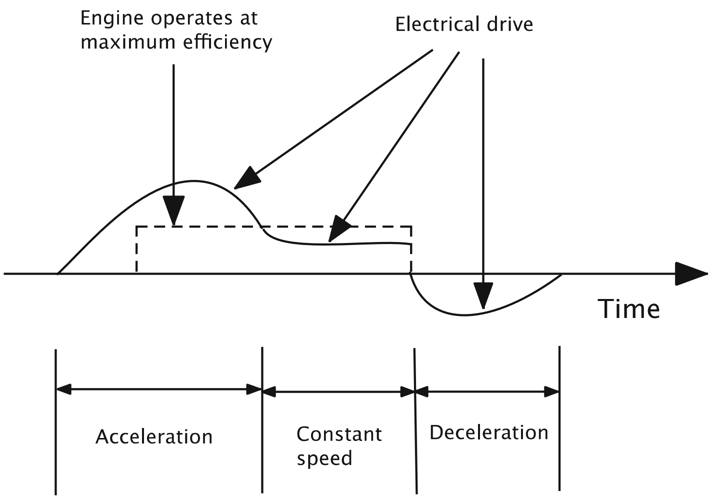

Fig. 6.7 Schematic representation of the interaction between the internal combustion engine and the battery in a hybrid vehicle

the vehicle is not being used. This might involve connection to the electrical system of a home overnight, for example. There is further discussion of this topic in Chap. 24.

6.8.2 Rotational Kinetic Energy

Kinetic energy is also present when a body is rotated. In this case,

$$E_{\text{kin}} = (1/2)I\omega^2 \tag{6.8}$$

where I is the moment of inertia and ω is the angular velocity.

Flywheels can be used for the purpose of storing kinetic energy, and there are ready methods whereby this mechanical energy can be converted to and from electrical energy.

The moment of inertia of a rotating body can be expressed as

$$I = \int \rho(x) r^2 \mathrm{d}x \tag{6.9}$$

where $\rho(x)$ is the mass distribution, and r is the distance from the center of rotation.

Thus the magnitude of the kinetic energy in a rotational system is increased if the rotational velocity ω is large and I is large. The latter can be achieved by having a large mass at a large value of r.

Consideration must be given to the strength of the material from which the flywheel is constructed, for it must be able to withstand the centrifugal force. This can be represented schematically as shown in Fig. 6.8.

The centrifugal force is given by

$$\text{Force} = (\text{mass})(\text{acceleration}) = mr\omega^2 \tag{6.10}$$

Flywheels can have a variety of shapes. One optimization strategy is to use a disc design in which the stress is the same everywhere. If the material with which the flywheel is constructed is uniform, this results in a shape such as that illustrated schematically in Figs. 6.9 and 6.10.

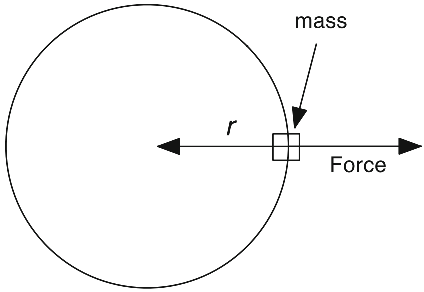

Fig. 6.8 Schematic representation of the centrifugal force operating on a mass in rotation

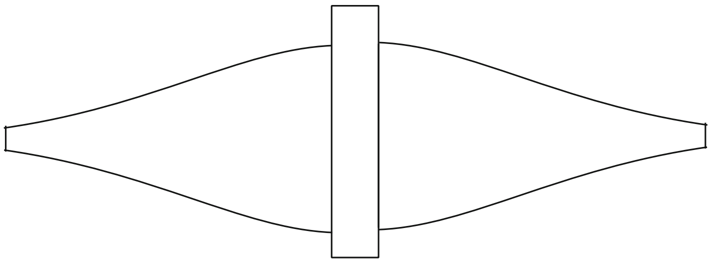

Fig. 6.9 Schematic drawing of the cross section of a disc upon a central shaft in which the centrifugal stress in the disk is the same everywhere

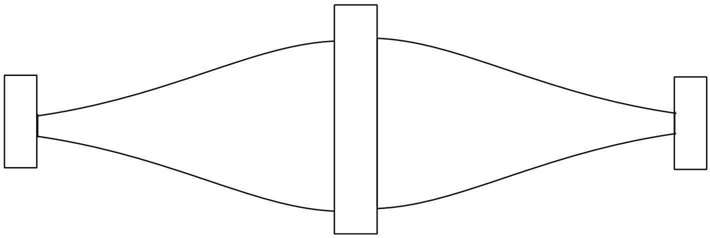

Fig. 6.10 Constant stress disk with constant-thickness outer rim

The local thickness b is given by

$$b = b_0 \exp\left[(\text{constant})\left(r^2\right)\right] \tag{6.11}$$

The radial strain causes tangential strain, and thus tangential stress. Thus if such a flywheel were to be reinforced by use of high strength carbon fibers, this is done by placement of the fibers around the outside, so that they carry the tangential force.

In this case, the specific energy, the kinetic energy per unit mass, in the flywheel is given by

$$\frac{E_{\text{kin}}}{\text{mass}} = \frac{\sigma_{\max}}{\rho} K_{\text{m}} \tag{6.12}$$

where $\sigma_{\max}$ is the maximum allowable stress, ρ is the material density, and K_{m} the shape factor. Note that the ratio $\sigma_{\max}/\rho$ leads to a strength-to-weight ratio, not just the material's strength.

Some values of the shape factor are given in Table 6.2.

Because of the advantage of operation at as high a stress as possible, there is a tendency to construct high performance flywheels of fiber reinforced materials, either Kevlar or carbon. These materials are, however, not isotropic, so that simple disc shapes are not practical. Instead, constant stress central shapes with high stress rims are often used. By use of such materials it is possible to achieve energy storage values as high as 200 kJ/kg in modern flywheels. A range of flywheel types, and their characteristics are shown in Table 6.3.

Table 6.2 Values of the shape factor for several simple disc shapes

Shape	K_{m}
Brush shape	0.33
Flat disk	0.6
Constant-stress disc	1.0
Thin rim only	0.5
Thin rim on constant-stress disk	0.6–1.0

Table 6.3 Examples of flywheel characteristics

Object	K, shape factor	Mass (kg)	Diameter (m)	Angular velocity (rpm)	Energy stored	Energy stored (kWh)
Bicycle wheel	1	1	0.7	150	15 J	4×10^{-7}
Flintstone's stone wheel	0.5	245	0.5	200	1680 J	4.7×10^{-4}
Train wheel, 60 km/h	0.5	942	1	318	65,000 J	1.8×10^{-2}
Large truck wheel, 18 mph	0.5	1000	2	79	17,000 J	4.8×10^{-3}
Train braking flywheel	0.5	3000	0.5	8000	33 MJ	9.1
Electrical power backup flywheel	0.5	600	0.5	30,000	92 MJ	26

It should be pointed out that flywheels can be dangerous. If they get out of balance or begin to come apart, parts can become very-high-velocity projectiles. Thus it is safer to construct them of many small pieces. This is the reason for the circular brush shape concept. They are generally housed in very robust steel containment, and large units are placed underground for safety reasons.

Flywheels also store energy in the form of mechanical strain potential energy—like springs—due to the forces upon them. The magnitude of this potential energy is small, for example, 5 %, compared to their kinetic energy, however.

Another consideration in the use of flywheels is rate at which energy can be added or deleted. That is, their power.

The maximum power that can be applied or extracted is determined by the mechanical properties of the central shaft. The maximum torque τ_{max} that can be withstood can be expressed as

$$\tau_{max} = \tfrac{2}{3}\pi\sigma_s R_0^3 \tag{6.13}$$

where R_0 is the shaft radius and σ_s is the maximum shear strength of the shaft material.

The torque involved in a change in the rotational velocity of the flywheel

$$\tau = I\frac{d\omega}{dt} \tag{6.14}$$

for a disk of radius R and thickness T,

$$\tau = \frac{\pi}{2}\rho T R^4 \frac{d\omega}{dt} \tag{6.15}$$

The maximum possible acceleration can be obtained by setting this value of τ equal to the value of τ_{max} calculated above:

$$\frac{d\omega}{dt} = \frac{4}{3}\left(\frac{\sigma_s}{\rho R T}\right)\left(\frac{R_0}{R}\right)^3 \tag{6.16}$$

The power is the rate of change of the kinetic energy. So the maximum power is

$$P_{max} = \frac{\pi}{2}\rho\omega T R^4 \frac{d\omega_{max}}{dt} = 2\frac{\pi}{3}R_0^3\sigma_{max} \tag{6.17}$$

for the case in which the strength of material from which the shaft is made is the same as the strength of the flywheel material.

But the maximum rotational velocity of a flywheel is related to the strength of its material by

$$\omega_{max} = \frac{1}{R}\left(\frac{2\sigma_{max}}{\rho}\right)^{1/2} \tag{6.18}$$

To see the magnitudes involved, consider a flywheel with a weight of 4.54 kg, $R = 17$ cm, $T = R_0 = R/10$, $\sigma_{max} = 1.5 \times 10^6$ lb/in.^{2}, and $\rho = 3.0$.

If $\omega_{max} = 1.6 \times 10^6$ rad/s, the maximum power, P_{max} is 5×10^8 W, or 10^6 W/kg

This is a very large number. Thus flywheels are very good at handling high power, and therefore energy transients. For comparison, the power per unit weight of a typical battery might be of the order of 100 W/kg.

Aerodynamic drag can be substantial in high-velocity flywheels. As a result, they are typically operated under vacuum conditions.

6.9 Internal Structural Energy Storage

It is also possible to introduce a different type of mechanical energy into solid materials by plastically deforming them such that changes occur in their microstructure. These can involve changes in the concentrations or distributions of dislocations or crystallographic point defects during mechanical deformation or irradiation. In some extreme cases, such as heavy forging at elevated temperatures, this can become quite evident, for it can be seen from color changes that the extensive mechanical deformation causes the internal temperature to rise. Although at least some of this energy can be recovered upon annealing, this increase of the internal energy in solids is not readily reversible, and is therefore not of interest for the types of applications that are generally considered in this text.

Reference

1. Genta G (1985) Kinetic Energy Storage. Butterworths, London