Design of flywheel for improved energy storage using computer aided analysis

A Project Report
Submitted in partial fulfilment for the award of the degree
Of

BACHELOR OF TECHNOLOGY
IN
MECHANICAL ENGINEERING

By
Michael Mathew (10503047)
Under the guidance of
Prof. N.Kavi
Professor, Department of mechanical engineering

Department of Mechanical Engineering
National Institute of Technology
Rourkela,769008 (2008-2009)

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CERTIFICATE

This is to certify that the thesis entitled, "Flywheel geometry design for improved energy storage using computer aided analysis" submitted by Sri Michael Mathew in partial fulfilments for the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

Date:

Prof. N.Kavi
Dept. of Mechanical Engineering
National Institute of Technology
Rourkela - 769008

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I place on record and warmly acknowledge the continuous encouragement, invaluable supervision, timely suggestions and inspired guidance offered by our guide ***Prof. N.Kavi,*** *Professor, Department of Mechanical Engineering, National Institute of Technology, Rourkela, in bringing this report to a successful completion.*

I am grateful to ***Prof. R.K.Sahoo****, Head of the Department of Mechanical Engineering, for permitting me to make use of the facilities available in the department to carry out the project successfully. Last but not the least I express my sincere thanks to all of my friends who have patiently extended all sorts of help for accomplishing this undertaking.*

Finally I extend my gratefulness to one and all who are directly or indirectly involved in the successful completion of this project work.

Michael Mathew (10503047)

Abstract:

Flywheels serve as kinetic energy storage and retrieval devices with the ability to deliver high output power at high rotational speeds as being one of the emerging energy storage technologies available today in various stages of development, especially in advanced technological areas, i.e., spacecrafts. Today, most of the research efforts are being spent on improving energy storage capability of flywheels to deliver high power at transfer times, lasting longer than conventional battery powered technologies. Mainly, the performance of a flywheel can be attributed to three factors, i.e., material strength, geometry (cross-section) and rotational speed. While material strength directly determines kinetic energy level that could be produced safely combined (coupled) with rotor speed, this study solely focuses on exploring the effects of flywheel geometry on its energy storage/deliver capability per unit mass, further defined as Specific Energy. Proposed computer aided analysis and optimization procedure results show that smart design of flywheel geometry could both have a significant effect on the Specific Energy performance and reduce the operational loads exerted on the shaft/bearings due to reduced mass at high rotational speeds. This paper specifically studies the most common five different geometries (i.e., straight/concave or convex shaped 2D

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CHAPTER 1

Introduction of flywheel

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1.1 Introduction

A flywheel is a mechanical device with a significant moment of inertia used as a storage device for rotational energy. Flywheels resist changes in their rotational speed, which helps steady the rotation of the shaft when a fluctuating torque is exerted on it by its power source. flywheels have become the subject of extensive research as power storage devices for uses in vehicles. flywheel energy storage systems are considered to be an attractive alternative to electrochemical batteries due to higher stored energy density, higher life term, deterministic state of charge and ecologically clean nature.

Flywheel is basically a rechargeable battery. It is used to absorb electric energy from a source, store it as kinetic energy of rotation, and then deliver it to a load at the appropriate time, in the form that meets the load needs. As shown in Fig1, a typical system consists of a flywheel, a motor/generator, and controlled electronics for connection to a larger electric power system.

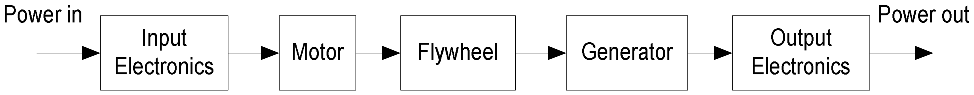

Figure 1.1Basic components of flywheel wheel energy storage system

The input power may differ from the output power in its temporal profile, frequency, or other attributes. It is converted by the input electronics into a form appropriate for efficiently driving a variable-speed motor. The motor spins the flywheel, which stores energy mechanically, slowing down as it delivers energy to a load. That decrease in mechanical energy is converted into electrical form by the generator. A challenge facing the motor and the generator designer is to size the system for the amount of storage (energy) and delivery rate (power) required and also to minimize losses. The output electronics convert the variable-frequency output from the generator into the electric power required by the load. Since the input and output are typically separated in a timely manner, many approaches combine the motor and generator into a single machine, and place the input and output electronics into a single module, to reduce weight and cost.

Modern high-speed flywheels differ from their forebears in being lighter and spinning much faster. Since the energy stored in a flywheel increases only linearly with its moment of inertia but goes up as the square of its rotational speed, the tradeoff is a good one. But it do raise two issues: flywheel strength and losses caused due to air friction. To keep from flying apart, modern flywheels are complex structures based on extremely strong materials like carbon fibers.

1.2 Flywheel Origins

The origins and use of flywheel technology for mechanical energy storage began several hundred years ago and developed throughout the Industrial Revolution. One of the first modern dissertations on the theoretical stress limitations of rotational disks is the work by Dr.A.Stodola, whose first translation to English was made in 1917. Development of advanced flywheel begins in the 1970s.

1.3 Comparison among Alternative Forms of Energy Storage

Chemical batteries are widely used in many applications currently. But there are a number of drawbacks of chemical batteries.

1. Narrow operational temperature range. The performance of the chemical battery will be deteriorated sharply at high or low temperature.
2. Capacity decreases over life. The capacity of the chemical battery cannot be maintained in a high level all through its life, the capacity will decrease with time goes on.
3. Difficulty in obtaining charge status. It is not so easy to know the degree of the charge of the chemical battery because the chemical reaction in the battery is very hard to measure and control.
4. Overcharge and over-discharge. Chemical battery can neither be over-discharged nor be over-charged, or its life will be shorted sharply.
5. Environmental concerns. Many elements of the chemical battery are poisonous, they will do harm to the environment and the people.

Obviously, the presence of the shortcomings of the chemical batteries makes them not-so-appealing to the users nowadays. Instead, flywheel energy storage system become potential alternative form of energy storage.

Table.1.1 Comparison among two energy storage systems

	Lead-acid battery	Flywheel battery	
Storage mechanism	Chemical	Mechanical	
Life(years in service)	3-5	>20	
Technology	Proven	Promising	
Number of manufacturers	~700	~10	
Annual Sales(US $millions)	~7000	~2	
Temperature range	Limited	Less Limited	
Environmental concerns	Disposal issues	Slight	
Relative size (equivalent power/energy)	Larger	Smallest	
Price, per kilowatt	\$50-\$100	\$400-\$800	

Table1 shows the comparison among chemical battery and flywheel energy storage system . Given the state of development of flywheel batteries , it is expected that costs for flywheel can be lowered with further technical development. On the other hand, electrochemical batteries already have a tremendous economy of scale that has driven costs down as far as they are likely to go.

Besides what have been mentioned in table1, there are also some other potential advantages that flywheel energy storage system has over chemical battery. Refer to:

1. Higher energy storage density. The flywheel battery whose speed exceeds 60000r/min can generate more than 20Whrs/lbm energy . But the energy storage density of the nickel-hydrogen battery is only 5-6 Whrs/lb.

2. No capacity decreases over life. The life of the flywheel battery depends mainly on the life of power electronic devices and can reach about 20 years.

3. No overcharge and over-discharge. The performance of the flywheel battery is not influenced when it is discharged heavily, and the overcharge can be avoided with assistance of power electronic devices.

4. Since mechanical energy is proportional to the square of the flywheel speed, the stored energy level indicator is a simple speed measurement. In addition, the charge of the flywheel battery can be restored in several minutes, but it will take about several hours for chemical battery to charge.

1.4 Theoretical analysis

Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

$$E_k = \frac{1}{2} \cdot I \cdot \omega^2$$

where

ω is the angular velocity, and

I is the moment of inertia of the mass about the center of rotation.

- The moment of inertia for a solid-cylinder is $I_z = \frac{1}{2}mr^2$,
- for a thin-walled cylinder is $I = mr^2$,
- and for a thick-walled cylinder is $I = \frac{1}{2}m({r_1}^2 + {r_2}^2)$.

where *m* denotes mass, and *r* denotes a radius. More information can be found at list of moments of inertia

When calculating with SI units, the standards would be for mass, kilograms; for radius, meters; and for angular velocity, radians per second. The resulting answer would be in Joules

The amount of energy that can safely be stored in the rotor depends on the point at which the rotor will warp or shatter. The hoop stress on the rotor is a major consideration in the design of a flywheel energy storage system.

$$\sigma_t = \rho r^2 \omega^2$$

where

σ_t is the tensile stress on the rim of the cylinder

ρ is the density of the cylinder

r is the radius of the cylinder, and

ω is the angular velocity of the cylinder.

1.5 Applications

1.51Transportation

In the 1950s flywheel-powered buses, known as gyrobuses, were used in Yverdon, Switzerland, and there is ongoing research to make flywheel systems that are smaller, lighter, cheaper, and have a greater capacity. It is hoped that flywheel systems can replace conventional chemical batteries for mobile applications, such as for electric vehicles. Proposed flywheel systems would eliminate many of the disadvantages of existing battery power systems, such as low capacity, long charge times, heavy weight, and short usable lifetimes.

Advanced flywheels, such as the 133 kW·h pack of the University of Texas at Austin, can take a train from a standing start up to cruising speed.

The Parry People Mover is a railcar which is powered by a flywheel. It was trialed on Sundays for 12 months on the Stourbridge Town Branch Line in the West Midlands, England during 2006 and 2007, and will be introduced as a full service by the train operator London Midland in December 2008 once two units have been ordered.

1.52 Uninterruptible power supply

Flywheel power storage systems in current production (2001) have storage capacities comparable to batteries and faster discharge rates. They are mainly used to provide load leveling for large battery systems, such as an uninterruptible power supply for data centers.

Flywheel maintenance in general runs about one-half the cost of traditional battery UPS systems. The only maintenance is a basic annual preventive maintenance routine and replacing the bearings every three years, which takes about four hours.

1.53 Amusement ride

The Incredible Hulk roller coaster at Universal's Islands of Adventure features a rapidly accelerating uphill launch as opposed to the typical gravity drop. This is achieved through powerful traction motors that throw the car up the track. To achieve the brief very high current required to accelerate a full coaster train to full speed uphill, the park utilizes several motor generator sets with large flywheels. Without these stored energy units, the park would have to invest in a new substation and risk browning-out the local energy grid every time the ride launches.

1.54 Motor sports

The FIA has re-allowed the use of KERS (see kinetic energy recovery system) as part of its Formula 1 2009 Sporting Regulations. Using a continuously variable transmission (CVT), energy is recovered from the drive train during braking and stored in a flywheel. This stored energy is then used during acceleration by altering the ratio of the CVT. In motor sports applications this energy is used to improve acceleration rather than reduce carbon dioxide emissions—although the same technology can be applied to road cars to improve fuel efficiency.

1.55 Flywheel energy storage systems are widely used in space, hybrid vehicles, military field and power quality. Space station, satellites, aircraft are the main application field in space. In these fields, flywheel systems function as energy storage and attitude control. For the applications in hybrid vehicles and military field, flywheel systems are mostly used to provide pulse power. But for power quality application, flywheel systems are widely used in USP, to offer functions of uninterruptible power and voltage control.

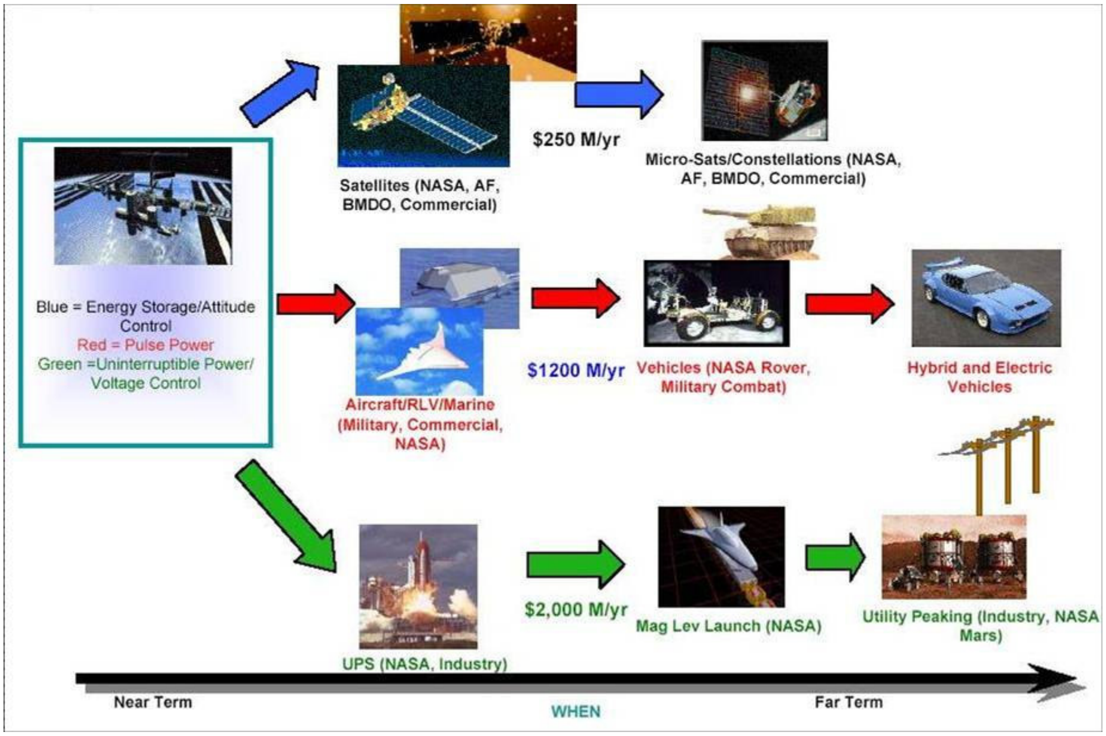

Figure 1.2 Applications of Flywheel Energy Storage System

Figure 3 shows an example of NASA on the FESS development. The blue arrows represent energy storage combined with attitude control, which mostly used in space stations, satellites, and so on. Red arrow represents pulse power, which are used in aircrafts, combat vehicles and hybrid electric vehicles. green arrow represents uninterruptible power & voltage control, which is used in UPS, aircraft launch and utility peaking. From the figure, we can see that NASA's near term researches on flywheel are mostly concentrated on space applications, but the far term researches are turning to industry applications gradually.

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1.6 Advantages and disadvantages

1.61 Advantages

Flywheels store energy very efficiently (high turn-around efficiency) and have the potential for very high specific power(~ 130 W·h/kg, or ~ 500 kJ/kg) compared with batteries. Flywheels have very high output potential and relatively long life. Flywheels are relatively unaffected by ambient temperature extremes. The energy efficiency (ratio of energy out per energy in) of flywheels can be as high as 90%. Typical capacities range from 3 kWh to 133 kWh. Rapid charging of a system occurs in less than 15 minutes.

1.61Disadvantages

Current flywheels have low specific energy. There are safety concerns associated with flywheels due to their high speed rotor and the possibility of it breaking loose and releasing all of it's energy in an uncontrolled manner. Flywheels are a less mature technology than chemical batteries, and the current cost is too high to make them competitive in the market.

CHAPTER 2

Literature survey

2.1 Recent developments

Mission critical technology programs are recently focused on storing energy more efficiently using flywheel than rechargeable chemical batteries while also providing some control advantages. Flywheel is essentially a simple device for storing energy in a rotating mass has been known for centuries. It is only since the development of high-strength materials and magnetic bearings that this technology is gaining a lot more attention. Exploration of high-strength materials allows designers to reach high operating speeds, yielding more kinetic energy. Using magnetic bearings make it possible to reach high operating speeds providing cleaner, faster and more efficient bearing equipment at extreme temperatures. Recently designed flywheels could offer orders of magnitude increases in both performance and service life and in addition, large control torques and momentum storage capability for spacecraft, launch vehicles, aircraft power systems and power supplies

The flywheel system mainly consists of flywheel rotor, motor/generator, magnetic bearings, housing and power transformation electronic system In the development of the flywheel, current researches have focused on increasing the performance while meeting the safety considerations, i.e., material, housing and bearing failures. Investigation of energy storage and failure considerations starts with the calculation of kinetic energy.

2.2Theoretical analysis

The kinetic energy stored in a rotating mass is given as,

$$E_k = \frac{1}{2} I \omega^2 \quad [\mathrm{J}] \tag{1}$$

$$I = \int x^2 \mathrm{d}m_x \quad [\mathrm{kg\,m^2}] \tag{2}$$

where x is the distance from rotational axis to the differential mass $\mathrm{d}m_x$.

where I is the mass moment of inertia and ω is the angular velocity. Mass moment of inertia is obtained by the mass and geometry of the flywheel and given as,

For solid cylindrical disk, I is given as,

(3)

$$I = \frac{1}{2} m r^2 \quad [\mathrm{kg\,m^2}]$$

where m is the mass and r the radius of the flywheel. Specific energy $E_{k,m}$ is obtained by dividing E_k by the mass to give:

(4)

$$E_{k,m} = \frac{1}{4} r^2 \omega^2 \quad [\mathrm{J/Jkg}]$$

If $E_{k,}$ is multiplied by the mass density ρ of the flywheel the energy density is obtained:

(5)

$$E_{k,v} = \frac{1}{4} \rho r^2 \omega^2 \quad [\mathrm{J/m^3}]$$

In this context, the design challenge is to maximize either $E_{k,m}$ or $E_{k,v}$, while satisfying the stress constraints. Tangential and radial stresses are given for cylindrical flywheel geometry [10] where the outside radius (r_o) is assumed to be large compared to the flywheel thickness (t) $r_o \geqslant 10t$;

(6)

$$\sigma_t = \rho \omega^2 \left(\frac{3+\upsilon}{8} \right) \left(r_i^2 + r_o^2 + \frac{r_i^2 r_o^2}{r^2} - \frac{1+3\upsilon}{3+\upsilon} r^2 \right)$$

(7)

$$\sigma_r = \rho \omega^2 \left(\frac{3+\upsilon}{8} \right) \left(r_i^2 + r_o^2 - \frac{r_i^2 r_o^2}{r^2} - r^2 \right)$$

After careful examination of these formulations, it could be observed that mainly three fully-coupled design factors have significant effect in the overall performance of flywheels as depicted in Fig. 1.

- Material strength; basically stronger materials could undertake large operating stresses, hence could be run at high rotational speeds allowing to store more energy.

- Rotational speed; directly controls the energy stored, higher speeds desired for more energy storage, but high speeds assert excessive loads on both flywheel and bearings during the shaft design.

- Geometry; controls the Specific Energy, in other words, kinetic energy storage capability of the flywheel. Any optimization effort of flywheel cross-section may contribute substantial improvements in kinetic energy storage capability thus reducing both overall shaft/bearing loads and material failure occurences.

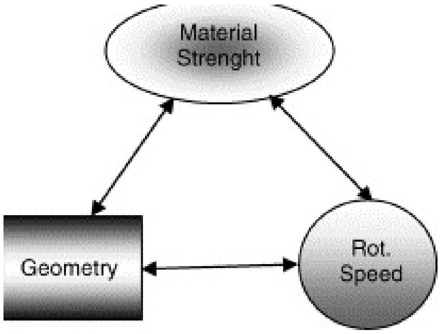


Fig. 2.1. Fully-coupled flywheel operating characteristics.

2.3 Algorithm

- *Step 1*, a fully parametric model of the flywheel is created to be inputted to ANSYS [13] (a finite element modeling and analysis software) to form the desired geometry.

- *Step 2*, model obtained in Step 1 is analyzed using ANSYS/LSDYNA [13], an explicit code, to obtain the stored kinetic energy and mass of the flywheel.

- *Step 3*, the same model is also analyzed using ANSYS, an implicit code, and overall stress distribution of the flywheel obtained and critical stresses and regions identified.

- Finally, using kinetic energy, mass and maximum stress of the flywheel obtained in Steps 1–3, an optimization is performed to come up with the maximum obtainable Specific Energy level, meantime making sure that the maximum equivalent stress is less than the maximum allowable yield stress by adjusting rotational speed (rpm) of the flywheel. Note that the higher rpm level means the better kinetic energy level could be reached.

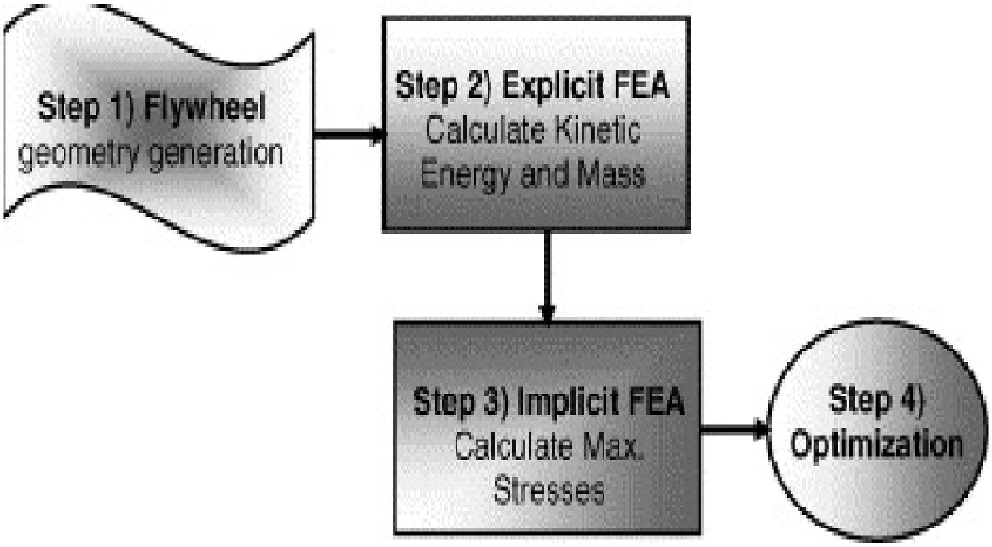


Fig 2.2 Finite element analysis procedure flow chart.

2.4 Design

Proposed fully parametric model shown in Fig. 3, where *t* is the thickness (*t* = 5.08 cm or 2″) and *h* is the radius of the flywheel (*h* = 14.605 cm or 5.75″). Two dimensional (2D) flywheel geometry is constructed with the total of 10

(X, Y) coordinates by varying coordinates 1 to 8 only in X direction to be less/equal to h. Y axis shows the axis of rotation according to the right hand rule. Although many materials with better strength and low density are available in the market, to serve the purpos of this study, an example material properties of AISI 1006 Steel (cold drawn), with modulus of elasticity of E = 205 GPa, density of ρ = 7.872 g/cc, Poisson's ratio of υ = 0.29 and yield stress of σ_Y = 290 MPa, is adapted in all cases.

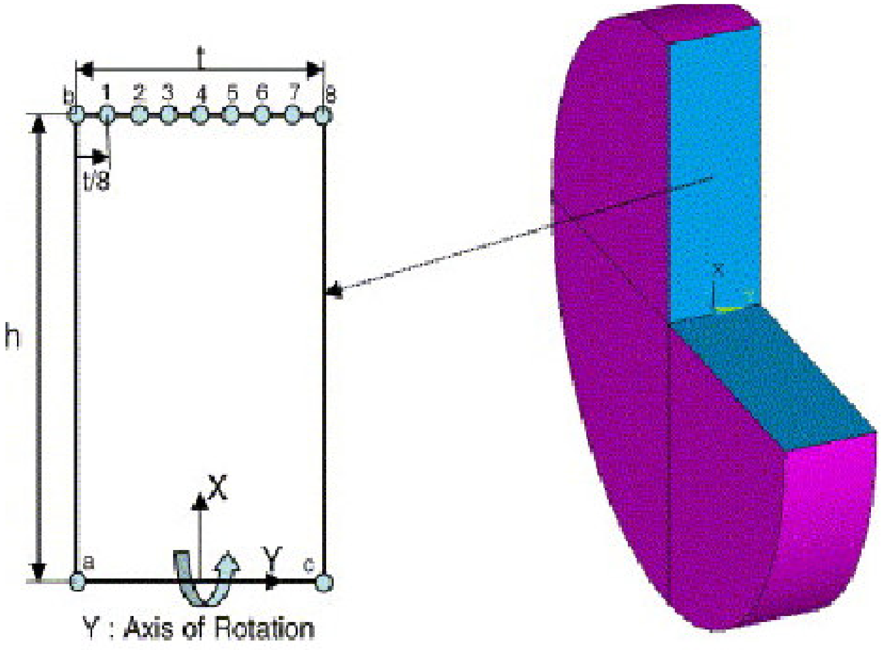
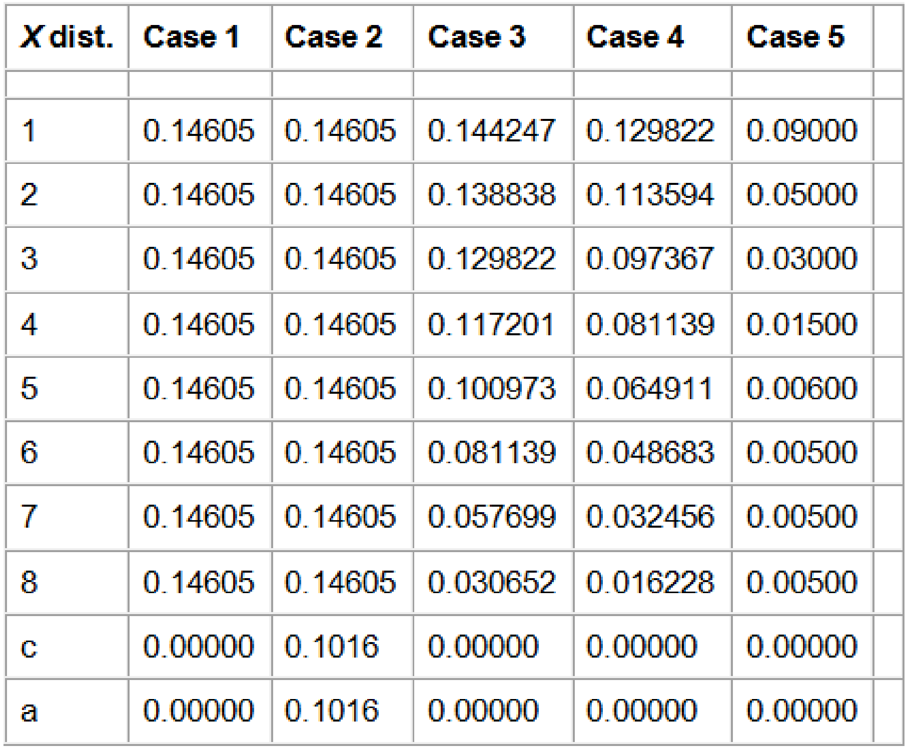


Fig 2.3 2D and 3/4 view of solid flywheel model (case 1).

Table 2.1Tabulated *X*-coordinates for all cases.

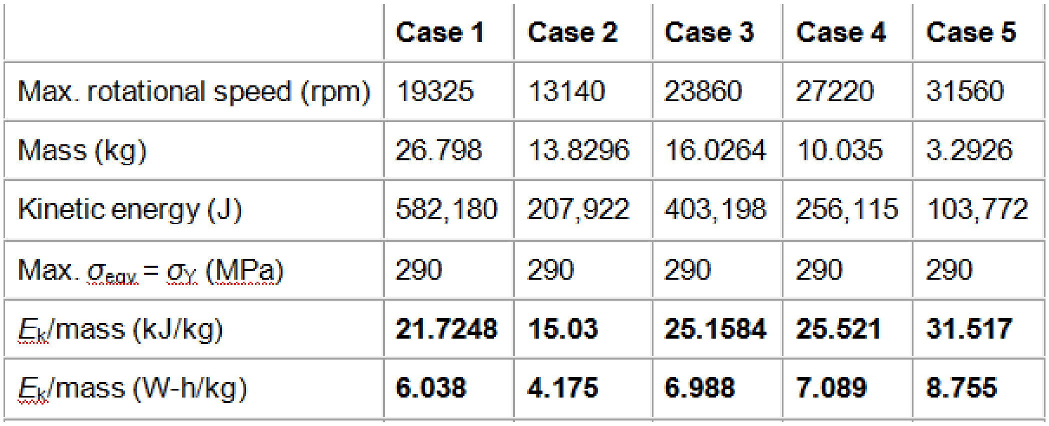


***X* dist.**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	
1	0.14605	0.14605	0.144247	0.129822	0.09000	
2	0.14605	0.14605	0.138838	0.113594	0.05000	
3	0.14605	0.14605	0.129822	0.097367	0.03000	
4	0.14605	0.14605	0.117201	0.081139	0.01500	
5	0.14605	0.14605	0.100973	0.064911	0.00600	
6	0.14605	0.14605	0.081139	0.048683	0.00500	
7	0.14605	0.14605	0.057699	0.032456	0.00500	
8	0.14605	0.14605	0.030652	0.016228	0.00500	
c	0.00000	0.1016	0.00000	0.00000	0.00000	
a	0.00000	0.1016	0.00000	0.00000	0.00000	

2.5 Conclusion

After the successful application of proposed procedure outlined in the previous section, all four steps are executed and equivalent stress distribution contours are obtained for all six geometries. Kinetic Energy, mass and maximum equivalent stress obtained in step 2 and 3, are also presented in Table 2. The maximum stress criterion is used as failure criterion. This implies that after the optimization in step 4, maximum allowable Equivalent stresses could be as high as (red colored area), σ_Y = 290 MPa, for AISI 1006 Steel (cold drawn, even material). Minimum Equivalent stresses are calculated to be in the range of 120–200 MPa, therefore they are considered to be within the safe stress interval.

Table 2.2 Result



	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Max. rotational speed (rpm)	19325	13140	23860	27220	31560
Mass (kg)	26.798	13.8296	16.0264	10.035	3.2926
Kinetic energy (J)	582,180	207,922	403,198	256,115	103,772
Max. $\sigma_{eqv} = \sigma_Y$ (MPa)	290	290	290	290	290
E_k/mass (kJ/kg)	**21.7248**	**15.03**	**25.1584**	**25.521**	**31.517**
E_k/mass (W-h/kg)	**6.038**	**4.175**	**6.988**	**7.089**	**8.755**

CHAPTER 3

Computation

3.1Aim

Flywheel geometry design for improved energy storage using computer aided analysis. This paper specifically studies the most common five different geometries and ranks according to their energy storage performance using the proposed procedure.

3.2 Computational analysis

Proposed fully parametric model shown in Fig. 3.1, where t is the thickness (t = 5.08 cm or 2″) and h is the radius of the flywheel (h = 14.605 cm or 5.75″). Two dimensional (2D) flywheel geometry is constructed with the total of 10 (X, Y) coordinates by varying coordinates 1 to 8 only in X direction to be less/equal to h. Y axis shows the axis of rotation according to the right hand rule. Although many materials with better strength and low density are available in the market, to serve the purpos of this study, an example material properties of AISI 1006 Steel (cold drawn), with modulus of elasticity of E = 205 GPa, density of ρ = 7.872 g/cc, Poisson's ratio of υ = 0.29 and yield stress of σ_Y = 290 MPa, is adapted in all cases.

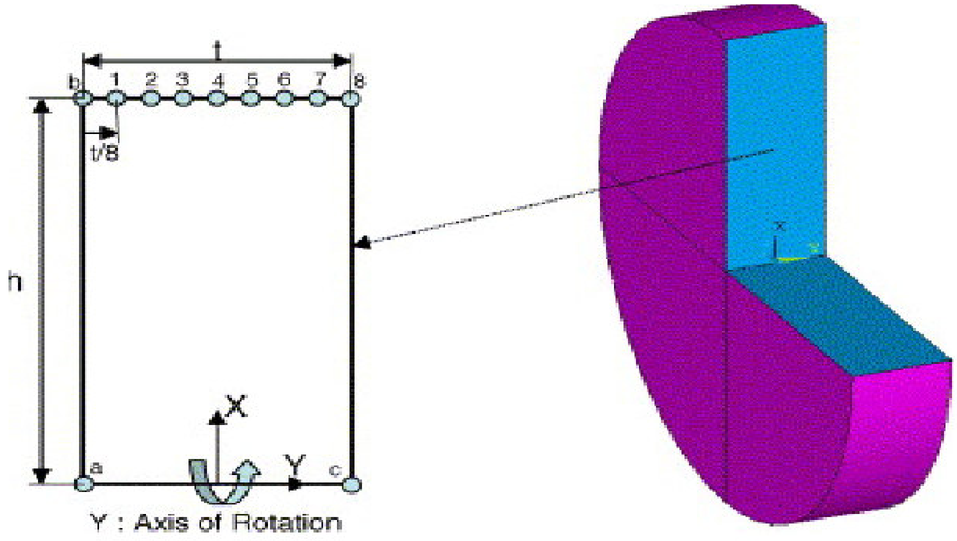


Fig. 3.1. 2D and 3/4 view of solid flywheel model (case 1).

Although there is an infinite number of a possibility for 2D cross-section selection, the procedure outlined in the previous section, applied to first, solid disk as base 2D geometry. Next, the annular disk geometry is chosen with an inner radius of 0.1016 m. In the test runs using various inner diameter sizes performed worst in terms of high stress levels, even at lower rotational speeds. Therefore only single configuration is documented here. Third and fourth cross-sections are chosen out of concave and triangular shaped functions, respectively. Final cross-section is selected to be composition of convex lines.

Step 1:Five different flywheel designs are made.

Step 2:A program is made to compute the maximum angular velocity that each design can handle.

Step3:maximum kinetic energy and specific energy of each cases are found out.

Step4:The best design is found comparing the specific energy of each designs.

Case1:

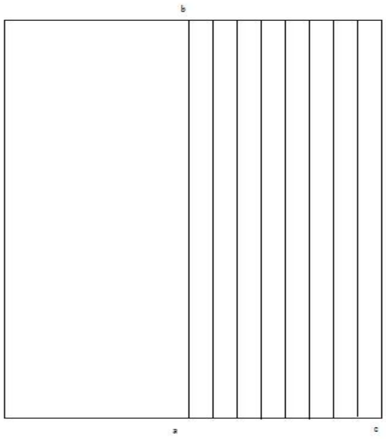
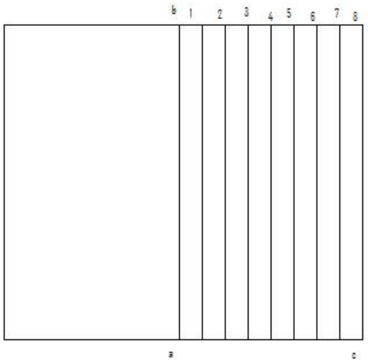


Fig 3.2:2D view of design 1

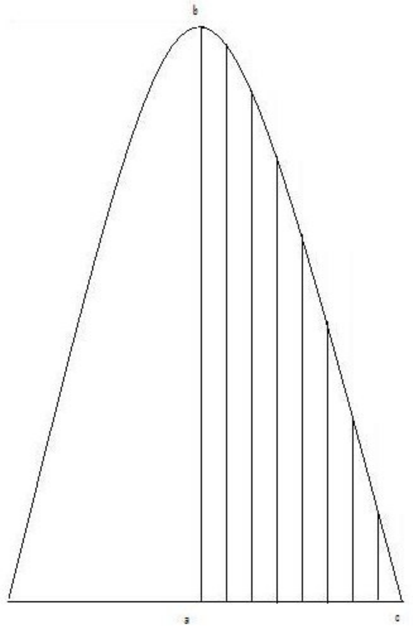
Case2:

Fig 3.2:2 D view of design 2



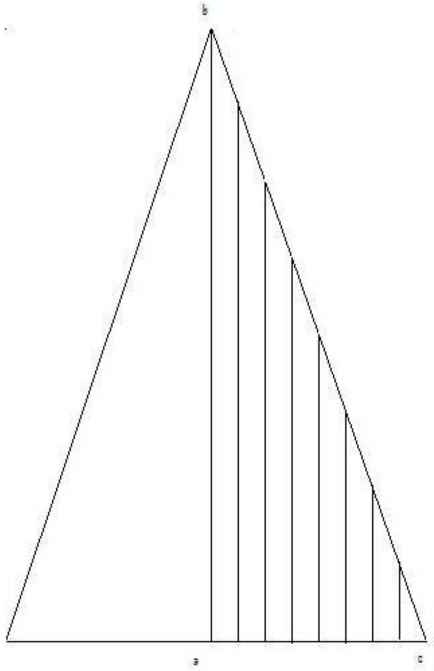
Case3:

Fig 3.4:2 D view of design 3



Case4:

Fig 3.5:2 D view of design 4



Case5:

Fig 3.6:2 D view of design 5

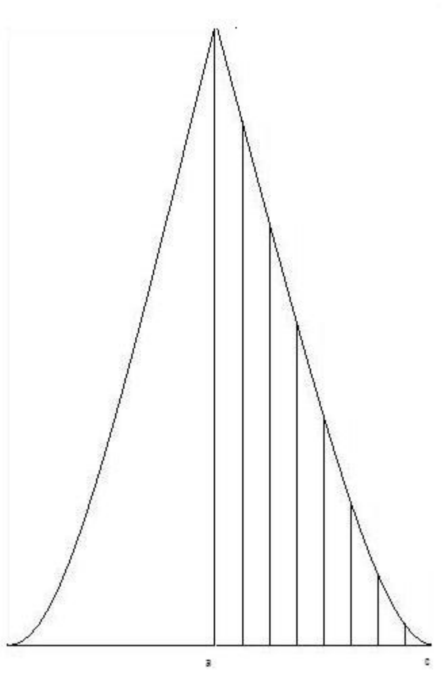
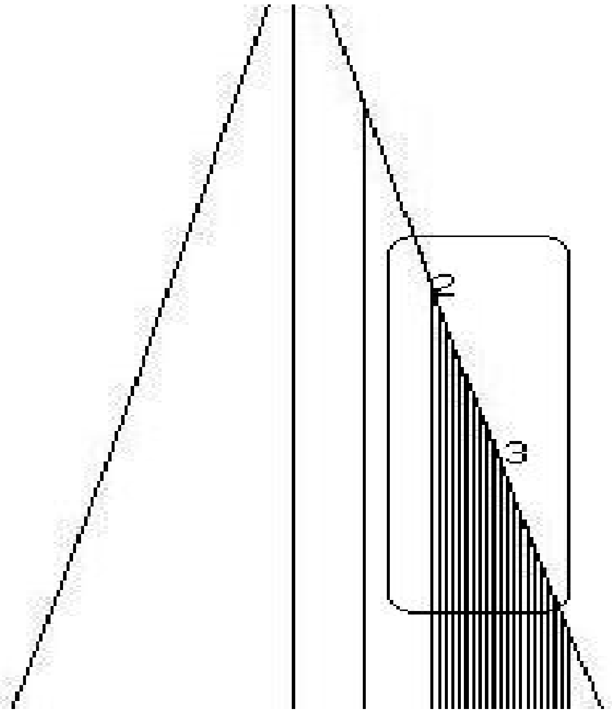


Table 3.1.

Tabulated *X*-coordinates for all cases

***X* dist.**	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	
1	0.14605	0.14605	0.144247	0.129822	0.09000	
2	0.14605	0.14605	0.138838	0.113594	0.05000	
3	0.14605	0.14605	0.129822	0.097367	0.03000	
4	0.14605	0.14605	0.117201	0.081139	0.01500	
5	0.14605	0.14605	0.100973	0.064911	0.00600	
6	0.14605	0.14605	0.081139	0.048683	0.00500	
7	0.14605	0.14605	0.057699	0.032456	0.00500	
8	0.14605	0.14605	0.030652	0.016228	0.00500	
c	0.00000	0.1016	0.00000	0.00000	0.00000	
a	0.00000	0.1016	0.00000	0.00000	0.00000	

Fig 3.7:dividing of the cross-section area of design 5



A program is made to compute the maximum angular velocity each design can tolerate.

Program:To find the max angular velocity

```
#include<iostream.h>
#include<conio.h>
void main()
{
int node[10]
float density,w1,w2,w[10],wfinal,u,ri,ro,r,ys;
ys=290000000;
density=7872;
u=0.29;
r=0.14605;

for(int i=0;i<8;i++)
```

```
{
cout<<"Enter the value of ri for node"<<i+1<<endl;
cin>>ri;
cout<<endl<<"Enter the value of ro for node"<<i+1<<endl;
cin>>ro;
w1=(ys/(density*((3+u)/8)*(ri^2+ro^2+ri^2*ro^2/r^2-((1+3*u)/(3+u))*r^2))^0.5;
w2=(ys/(density*((3+u)/8)*(ri^2+ro^2-ri^2*ro^2/r^2-r^2))^0.5;
if(w1<w2)
w[i]=w1;
else
w[i]=w2;
cout<<endl<<"w[i+1]="<<w[i];
if(i==0)
wfinal=w[i];
else
{
if(wfinal>w[i])
wfinal=w[i];
}
}
getch();
clrscr();
}
```

3.3 Output

```
Result
Case 1
Enter the value of ri for node1
0
Enter the value of ro for node1
0.14605
Enter the value of ri for node2
0
Enter the value of ro for node2
0.14605
Enter the value of ri for node3
```

```
0
Enter the value of ro for node3
0.14605
Enter the value of ri for node4
0
Enter the value of ro for node4
0.14605
Enter the value of ri for node5
0
Enter the value of ro for node5
0.14605
Enter the value of ri for node6
0
Enter the value of ro for node6
0.14605
Enter the value of ri for node7
0
Enter the value of r0 for node7
0.14605
Enter the value of ri for node8
0
Enter the value of ro for node8
0.14605
wfinal=19325
```

Case 2

```
Enter the value of ri for node1
0.1016
Enter the value of ro for node1
0.14605
Enter the value of ri for node2
0.1016
Enter the value of ro for node2
0.14605
Enter the value of ri for node3
0.1016
Enter the value of ro for node3
0.14605
Enter the value of ri for node4
0.1016
Enter the value of ro for node4
0.14605
Enter the value of ri for node5
0.1016
Enter the value of ro for node5
0.14605
```

```
Enter the value of ri for node6
0.1016
Enter the value of ro for node6
0.14605
Enter the value of ri for node7
0.1016
Enter the value of ro for node7
0.14605
Enter the value of ri for node8
0.1016
Enter the value of ro for node8
0.14605
wfinal=13198
```

Case 3

```
Enter the value of ri for node1
0
Enter the value of ro for node1
0.144247
Enter the value of ri for node2
0
Enter the value of ro for node2
0.138838
Enter the value of ri for node3
0
Enter the value of ro for node3
0.129822
Enter the value of ri for node4
0
Enter the value of ro for node4
0.117201
Enter the value of ri for node5
0
Enter the value of ro for node5
0.100973
Enter the value of ri for node6
0
Enter the value of ro for node6
0.081139
Enter the value of ri for node7
0
Enter the value of r0 for node7
0.057699
Enter the value of ri for node8
0
Enter the value of ro for node8
0.030652
wfinal=24002
```

Case 4

```
Enter the value of ri for node1
0
Enter the value of ro for node1
0.129822
Enter the value of ri for node2
0
Enter the value of ro for node2
0.113594
Enter the value of ri for node3
0
Enter the value of ro for node3
0.097367
Enter the value of ri for node4
0
Enter the value of ro for node4
0.081139
Enter the value of ri for node5
0
Enter the value of ro for node5
0.064911
Enter the value of ri for node6
0
Enter the value of ro for node6
0.048683
Enter the value of ri for node7
0
Enter the value of r0 for node7
0.032456
Enter the value of ri for node8
0
Enter the value of ro for node8
0.016228
wfinal=27225
```

Case 5

```
Enter the value of ri for node1
0
Enter the value of ro for node1
0.09000
```

```
Enter the value of ri for node2
0
Enter the value of ro for node2
0.05000
Enter the value of ri for node3
0
Enter the value of ro for node3
0.05000
Enter the value of ri for node4
0
Enter the value of ro for node4
0.01500
Enter the value of ri for node5
0
Enter the value of ro for node5
0.00600
Enter the value of ri for node6
0
Enter the value of ro for node6
0.00500
Enter the value of ri for node7
0
Enter the value of r0 for node7
0.00500
Enter the value of ri for node8
0
Enter the value of ro for node8
0.00500
wfinal=31640
```

CHAPTER 4

Results and future prospects

4.1 Results

The maximum angular velocities attained by the designed flywheels are found from the output of the program, From we can find the kinetic energy and the specific energy that the flywheel can store.

Table4.1

Result of the experiment:

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Max. rotational speed (rpm)	19325	13198	24002	27225	31640
Mass (kg)	26.798	13.8296	16.0268	10.035	3.2923
Kinetic energy (J)	583,780	210,437	403,501	256,418	110,892
Max. $\sigma_{eqv} = \sigma_Y$ (MPa)	290	290	290	290	290
E_k/mass (kJ/kg)	**21.725**	**15.043**	**25.38**	**25.54**	**33.2**

Examining the results shows that using the annular solid disk flywheel yields the lowest Specific Energy performance no matter what the inner hole radius is chosen. Solid disk performs better than the annular disk but highest shaft load is expected since the flywheel mass in this case is the largest. By adopting simple modifications to the geometry, flywheel specific energy performance could be improved as demonstrated in Case 3 through 5, especially in Case 5 performance of the flywheel performs 50% better than Case 2. One more thing to note that, Case 5 cross-section also exerts fewer shafts load than Case 1 through 4, since its mass is the smallest . Although this improvement is to be thought small, it still could be crucial for mission critical operations, which require long lasting service life and efficiency.

4.2 Discussion

In space power applications where solar inputs are the primary thermal source, energy storage is necessary to provide a continuous power supply during the eclipse portion of the orbit. Because of their potentially high storage density, flywheels are being considered for use as the storage system on the proposed orbiting space station. During the past several years, graphite fiber technology has advanced, leading to significant gains in flywheel storage density. With these high strength graphite fibers, operational storage densities for flywheel storage modules applicable to the space station power storage could reach 200 kJ/kg. This module would also be volumetrically efficient occupying only about 1 cu m. Because the size and mass of the flywheel storage module are controlled by the storage density, improvements in specific energy can have a significant impact on these values. With the improvements anticipated within the next five years, operational storage density on the order of 325 kJ/kg may be possible for the flywheel module.

Although we can increase the specific energy of a flywheel this leads to the complexity in the shape and cost of production will rise. Since the use of flywheel as rechargeable batteries is still at a premature stage already the cost of production is high.

Further modifications can be done on the designs and still better designs can be found out using this method.

The computer aided program simplifies the calculations that are complex and time consuming.

4.3: Conclusions

In this design of flywheels, there is still room for research, especially when the performance is the primary objective. The operating conditions impose quite narrow margin of energy storing limitations, even slim amount of improvements may contribute in the overall success. This study clearly depicts the importance of the flywheel geometry design selection and its contribution in the energy storage performance. This contribution is demonstrated on example cross-sections using computer aided analysis and optimization procedure. Overall, the problem objective is formulated in terms of Specific Energy value and its maximization through the selection of the best geometry among the predetermined five cross-sections. Using the available technology at hand, we could very well make fast but crucial improvements in the advanced research areas requiring flywheel utilization, where engineers are frequently confronted with the limitations on magnetic bearing load carrying capacity, size limitations and efficiency.