International Journal of Engineering, Science and Mathematics
Vol.7Issue 3, March 2018,
ISSN: 2320-0294 Impact Factor: 6.765
Journal Homepage: http://www.ijmra.us, Email: editorijmie@gmail.com Double-Blind Peer Reviewed Refereed Open Access International Journal - Included in the International Serial Directories Indexed & Listed at: Ulrich's Periodicals Directory ©, U.S.A., Open J-Gage as well as in Cabell's Directories of Publishing Opportunities, U.S.A

Design and Analysis of Flywheel for different Geometries and Materials

S.S Pawar*
Veeraj Pardeshi**
Vinayak Khade***
Sumaiya Sayed****
Chandrakant Katara*****

Abstract

A heavy rotating wheel which increases the momentum and provides greater stability or acts as a reservoir of available energy is termed as a 'Flywheel'. The rotational speed of the rotor coupled with the material strength of flywheel directly determines the kinetic energy level that could be produced.This paper mainly focuses on investigating the effects of flywheel geometries and various materials on the capacity of flywheel storing / delivering of maximum kinetic energy. In this paper, the flywheel is redesigned for a given dimensions and geometries of three cross-sections namely; rectangular, diamond-shaped and elliptical using 3D modelling software SOLIDWORKS 2015. After performing series of finite element analysis, it was observed that with the change in flywheel geometry and its material, there is a significant effect on the performance with a reduction in weight of the flywheel. This paper particularly examines the three different geometries of flywheel coupled with two different materials namely Cast Iron and Graphene.It was found that diamond shaped flywheel stores specific kinetic energy of 21545.69 KJ/kg. It was also observed that there was reduction in the weight of the flywheel by 88%.

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Keywords:

Energy storing capacity,
Flywheel geometry,
Finite Element Analysisand
Graphene.

Author correspondencing:

Veeraj Pardeshi,
Department of Mechanical Engineering
A.C. Patil College of Engineering, University of Mumbai, Kharghar, Navi Mumbai, India

1. Introduction

Based on the traditional kinetic energy equation, the kinetic energy of a system varies linearly with the mass but directly proportional to the square of the velocity as shown in equation (1),

$$K = \frac{1}{2}mv^2 = \frac{1}{2}mr^2\omega^2 \quad (1)$$

where K is the Kinetic energy, m is mass, r is Radius, v is velocity and ω is the angular velocity. Here, itcould be seen that the energy stored grows faster with velocity than with mass. It is preferred to have a light, high-speed flywheel than a heavy, low-speed flywheel. For centrifugal loading,the stresses inducedare found to be related to the velocity as shown below:

$$\sigma = \rho v^2 = \rho r^2\omega^2 \quad (2)$$

*Department of Mechanical Engineering, A.C. Patil College of Engineering, University of Mumbai,Navi Mumbai, India
**Department of Mechanical Engineering, A.C. Patil College of Engineering, University of Mumbai,Navi Mumbai, India
***Department of Mechanical Engineering, A.C. Patil College of Engineering, University of Mumbai,Navi Mumbai, India
****Department of Mechanical Engineering, A.C. Patil College of Engineering, University of Mumbai,Navi Mumbai, India
****Department of Mechanical Engineering, A.C. Patil College of Engineering, University of Mumbai,Navi Mumbai, India

where ρ is mass density and σ is normal stress. The above equation explicates the stresses induced in the flywheel due to centrifugal loading are also proportional to the square of the velocity. From equations (1) and (2), we can conclude that a flywheel should be made up of a material that has high strength characteristic in order to produce high rotational speed.

The energy crisis of 1970's was imminent to a significant era in development of flywheels as the need to search for an alternative energy storage surfaced. Substantial amount of money was invested by government of different nations for the further development of flywheels as an efficient energy storing system. Researchers began intensively investigating fibre reinforced composites for energy storage applications. One of such research works was done by Edward et.al. [1].The aim of their research was to design a composite flywheel using Kevlar-49/Epoxy. Materials such as Kevlar epoxy, Gr epoxy, Boron Epoxy, S-glass epoxy, E-glass epoxy were studied and comparisons were made between these materials on the basis of density, young's modulus, thickness, Poisson's ratio etc. The authors noted that Kevlar epoxy was most desirable material as it had low density, high specific strength property and stored large amount of energy per unit weight.In 2000, objective of an article, by Jinhua Huang & Georges M Fadel, was optimization of heterogeneous flywheel [2]. In this paper, they have demonstrated how to apply Kumar and Dutta's modeling techniques to two different kinds of heterogeneous flywheels, one consisting of a finite number of distinct material and another consisting of two or more primary materials with continuous volume fraction variation. With this methodology, graphical display, volume mass and various stress calculations of homogenous and heterogeneous HD's and HC's could be easily realized [3], [4].Jerome Tzeng, Ryan Emerson, Paul Moy published a paper which focused on designing composite flywheels for energy storage [5]. This paper proposed a comprehensive study with the intent to design a high-performance flywheel, especially for long term durability as well as developing the analytical codes for predicting the elastic and visco-elastic behaviour of flywheel design. An optical strain technique was developed to validate the flywheel design and construction. A design proposed by considering long term behaviour of flywheel such as stress relaxation, fatigue, creep and fracture of composites.

In an article by Mehmet Ali Arslan, attempts were made to design a flywheel for improved energy storage using finite element analysis [6]. In this paper, six different geometries, material strength and rotational speeds were compared in order to get optimum energy storage. The study solely focused on exploring the effects of flywheel geometry using ANSYS and the problem objective was formulated in terms of specific energy value and its maximization through the selection of the best geometry among the predetermined six cross sections.

Research concerning optimization of flywheel to develop an efficient energy storing system has led to exploration and findings of new materials which may be far superior than their rival materials. In 2011, a study by Dale A.C Brownson et al., investigated various concerns regarding applications of graphene in energy storage/generation devices [7]. The study stated that utilisation of graphene for energy devices has made a diverse impact and within energy related themes, graphene has great potential.

In 2013, a research by S.M. Choudhary & D.Y. Shahare focused on design optimization of a thresher by smartly designing the flywheel using Cast Iron [8]. In this paper they compared different geometries of flywheel keeping the material and load constant for von-mises stresses and deformation. The method used was FEM and geometries of flywheel compared where solid type, rim type, web type and arm type. The authors concluded that the maximum stresses induced in the rim and arm junction and smart design of flywheel has a significant effect on its specific energy performance. At around same time, another research with an aim to design a flywheel using E-glass epoxy composite, was published by Akshay P. Punde& G.K. Gattani [9].They compared E-glass epoxy and grey cast iron in terms of von-mises stress and deformation. Finite Element Analysis Method was used to compare the output results of two materials. The authors noted that E-glass epoxy produces lesser stress value compared to Grey Cast Iron.

A similar attempt was made by Pagoti Lokesh & B. Ashok Kumar in an article published in 2015, where they analysed flywheel using grey cast iron and S-glass epoxy [10]. They compared S-glass epoxy and grey cast iron in terms of von-mises stress and deformation. The softwares used for the design and analyses were Catia and ANSYS. By the observations, it was concluded that S- glass epoxy is more effective material with less deformation and less equivalent stress when compared to grey cast iron.

In 2016, a paper with an aim to design composite flywheel material for high-speed energy storage, was published by Michael A. Conteh& Emmanuel C. Nsofor [11]. In this paper, lamina and laminate mechanical properties of materials suitable for flywheel high-speed energy storage were evaluated using analytical studies. Along with analytical studies results were also evaluated on CADEC-online software. By the observations it was concluded that, in order to obtain higher flywheel energy density, material having higher strength and lower density is required.

As seen from exhaustive literature survey, it is observed that more energy is stored at the higher speeds and to allow the flywheel to rotate at high speeds without occurrence of failure, we need materials that could undertake large operating stresses. It is also clear that geometry of the flywheel controls the energy storage capability of the flywheel and optimizing the geometry can lead to reduction of loads and thus increase the durability of the flywheel.

2.Objectives

- To study the behaviour of the flywheel for change in the cross-sectional area to get the optimal kinetic energy storage capacity per unit mass.
- To design the flywheel by using different materials to find the maximum rotational speed the system can sustain.
- To study behaviour of flywheel with different geometries and materialsincombination in terms of stress, strain, deformation, kinetic energy and rotational speed.

3.Methodology

Flywheel design and analysis requires a number of steps to be followed sequentially to reach the objectives defined. This includes all the necessary stages of flywheel design and its dynamic study using finite element method.The methodology to be followed to design flywheel using different geometries as well as different material is listed below:

1. Selection and dimensions of Flywheel:The first step to be taken is to get the dimensions of the existing flywheel. To do this,it is necessary to finalise the type of application to be chosen.
2. Design of flywheel:On board working condition, the flywheel of thresher machine is considered. While designing of flywheel, the design parameters that were kept constant are; inner diameter, outer diameter and thickness of flywheel. The cross-section of the flywheel was varied in order to achieve an optimum design with commensurate weight reduction.
3. 3D Modelling of Flywheel Using SOLIDWORKS:After getting the dimensions of the flywheel, a 3-D Model of these manifolds was created on SOLIDWORKS workbench.
4. Selection of Material:After the studing of existing material as well as composite materials, 2-3 composite materials were short-listed along with one popular existing material by WRM method.
5. Theoretical Calculations:On the basis of the thorough research done during the literature survey, the boundary conditions on the system are defined. Accordingly, theoretical calculations to find kinetic energy of the solid flywheel were carried out.
6. Simulation Using FEA:Simulation of the design was done for the Cast Iron ASTM-30, the short-listed composite materials and Advance Material using Finite Element Analysis software ANSYS WORKBENCH.
7. Results Calibration and Conclusion:The simulation results are compared with theoretical values on the basis of various factors and the best design wasfinalized based on results.

4.Selection of flywheel and its dimensions

The machine used to separate the comb from the grain is known as thresher machine in agriculture sector. The flywheel that is present in thresher machine is made up of single solid disk ofcast iron material. The specifications of flywheel selected are asmentioned in Table 1.

Table 1. Dimensions of Flywheel

Mass of Flywheel (m)	72 kg
Outer Diameter (Do)	500 mm
Inner Diameter (Di)	50 mm
Thickness (t)	50 mm
RPM	750

5. Design of Flywheelfor optimization

A little consideration shows that the variation in flywheel cross-section can results in variation of flywheel's rotational speed and kinetic energy storing capacity. While re-designing the flywheel, the design constraints like inner diameter, outer diameter and thickness is kept as constant, and variations were made precisely in the cross-section of flywheel which reduces further the weight of the flywheel. The re-designed cross-sections of flywheel are as shown in Figure 1.

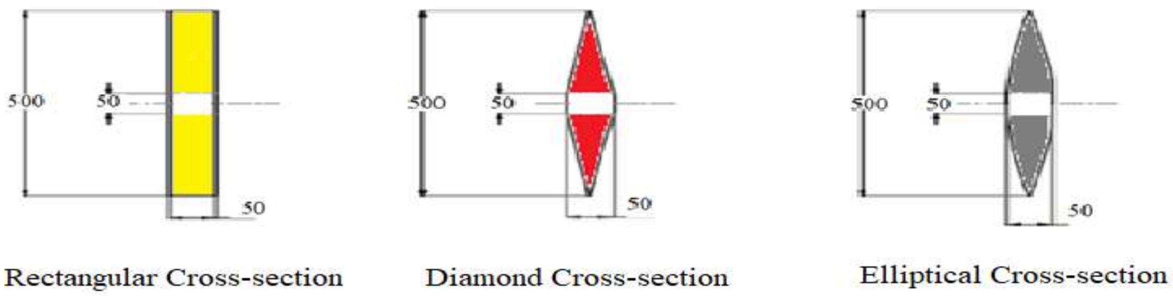

Figure 1. *Cross-sections of theflywheel*

For the designing and modelling purpose, a solid modelling software, SOLIDWORKS 2015 is used. It makes use of parametric feature-based approach for creating models and assemblies. The present as well as re-designed geometries of flywheel are as shown in Figure 2.

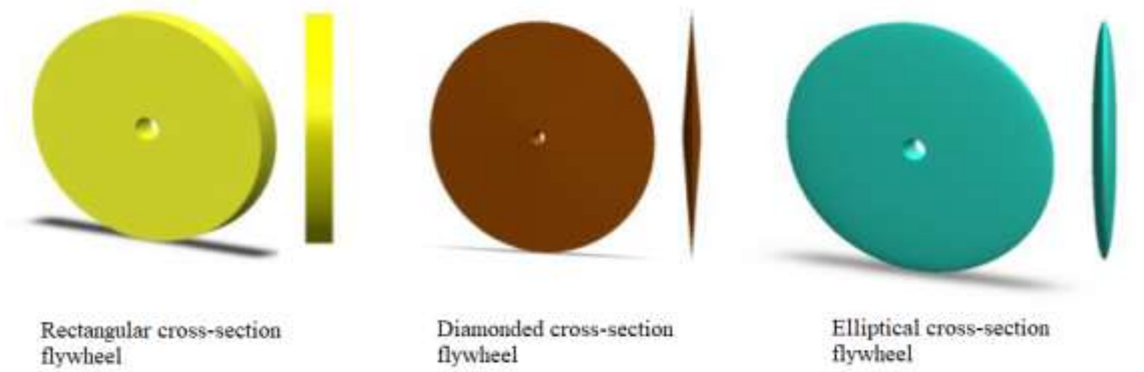

Figure 2.*Parametric models of flywheel*

6.Material Selection

Flywheel's kinetic energy depends upon the mass moment of inertia of the cross-section geometry which consecutively depends on the material of the flywheel. For this research work, various composite materials were studied and on the basis of the density, yield strength and Young's modulus of the materials, Graphene having more favourable properties, was chosen for further study.

Table 2. Material Properties

Material	Young's Modulus E, GPa	Poisson's Ratio, ν	Density, Kg/m^3	Yield Strength σ_y, MPa
Cast Iron ASTM-30	101	0.23	7510	260
Graphene	90	0.33	2190	2500

7. Theoretical Calculations

7.1. For Solid disk flywheel made of Cast Iron ASTM-30.

a. Angular velocity,

$$\omega = \frac{2\pi N}{60} = \frac{2\pi * 7796}{60} = 816.395 \text{ rad/sec}$$

b. Mass moment of inertia,

$$I = \frac{1}{2}mr^2 = \frac{1}{2} * 72.992 * (0.250)^2 = 2.281 \text{ kg} - \text{m}^2$$

c. Maximum kinetic energy,

$$KE = \frac{1}{2}I\omega^2 = \frac{1}{2} * 2.281 * (816.395)^2 = 760.14 \text{ KJ}$$

7.2. For Solid disk flywheel made of Graphene.

a. Angular velocity,

$$\omega = \frac{2\pi N}{60} = \frac{2\pi * 306071}{60} = 32051.68 \text{ rad/sec}$$

b. Mass moment of inertia,

$$I = \frac{1}{2}mr^2 = \frac{1}{2} * 24.298 * (0.250)^2 = 0.759 \text{ kg} - \text{m}^2$$

c. Maximum kinetic energy,

$$KE = \frac{1}{2}I\omega^2 = \frac{1}{2} * 0.759 * (32051.68)^2 = 389864.21 \text{ KJ}$$

8. Simulation using FEA

Finite Element Analysis (FEA) is a numerical method used for solving problems in engineering and mathematical physics. Finite Element Method and Analysis is used to determine the maximum rotational speed the flywheel can attain without undergoing any failure and the amount of kinetic energy the flywheel can store at that maximum rotational speed. ANSYS is a Computer Aided Finite Element Modelling (FEM) and Finite Element Analysis (FEA) tool developed by ANSYS Inc. In the Graphical User Interface (GUI) of ANSYS Workbench, one can generate 3D models, FEA models, perform analysis and generate results of analysis.With the help of ANSYS Workbench, Static Structural module is used to determine the maximum rotational speed and Explicit Dynamics module is used to determine the kinetic energy the flywheel can store at that maximum rotational speed.

8.1. Input data and Boundary Conditions:

Static Structural:

1. Providing displacement of "0mm" along the X-component on the interior surface of the flywheel geometry while keeping the Y-component and Z-component as free.
2. Provide rotational speed on the flywheel geometry along the X-component while providing the Y-component and Z-component with 0 rpm (i.e. Motion is fixed).

Explicit Dynamic:

1. In the "Detail of Angular Velocity" provide angular speed along X-component while providing the Y-component and Z-component with 0 rpm (i.e. Motion is fixed).
2. Provide displacement of 0 mm along X-component on the interior surface of the flywheel geometry while keeping the Y-component and Z-component as free.

8.2. Flywheel analysis using ANSYS:

- Meshing
  Element size: Default
  Span Angle Center: Coarse
  Minimum Edge Length: 50mm
  Nodes: 3312
  Element: 2349

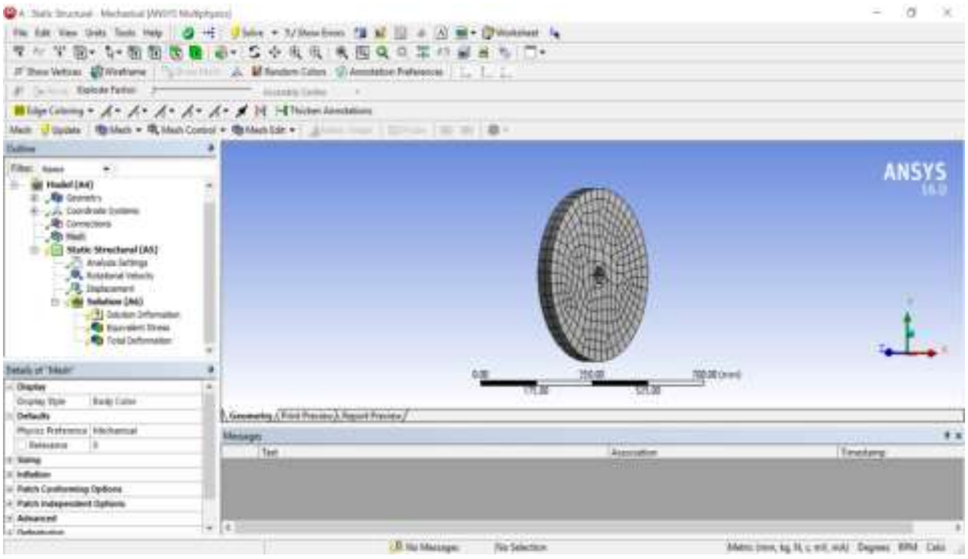

Figure 3. *Meshing*

Iteration 1: Rectangular Cross-sectioned Flywheel with Cast Iron ASTM-30.

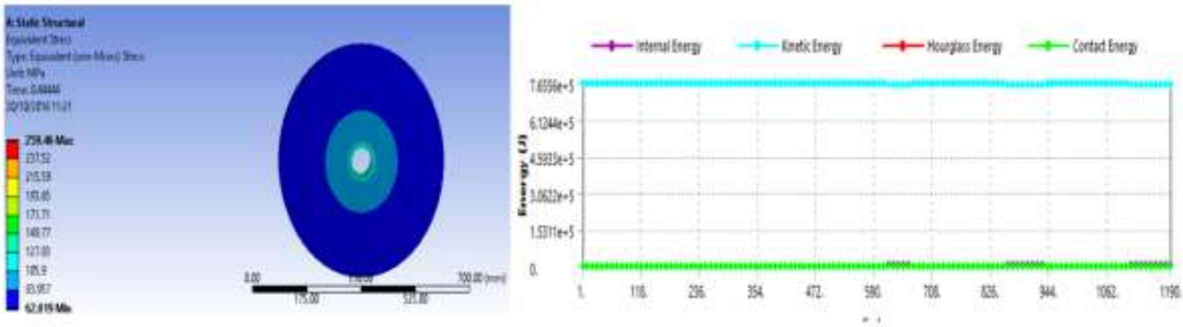

Figure4.*Stress distribution and Kinetic energy graph for Rectangular cross-sectioned flywheel with Cast Iron ASTM-30*

Iteration 2: Rectangular cross-sectioned flywheel with Graphene.

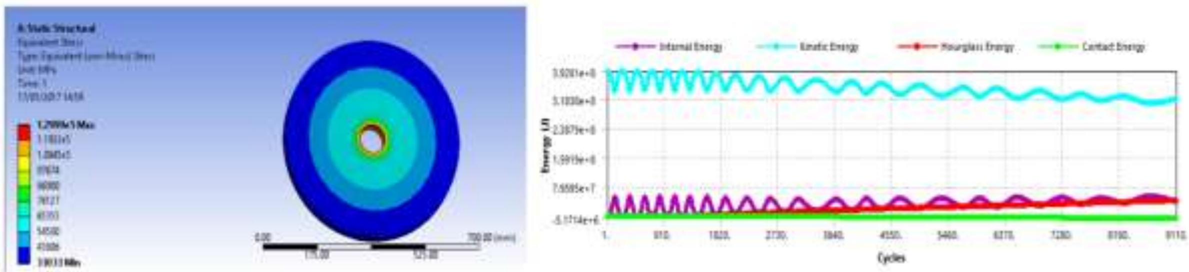

Figure5. *Stress distribution and Kinetic energy graph for Rectangular cross-sectioned flywheel with Graphene*

Iteration 3: Diamond cross-sectioned flywheel with Cast Iron-ASTM 30.

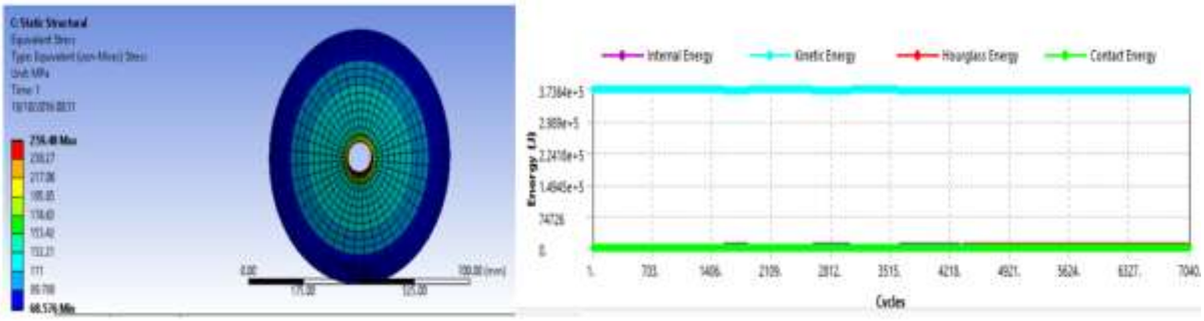

Figure 6.*Stress distribution and Kinetic energy graph for Diamond cross-sectioned flywheel with Cast Iron ASTM-30*

Iteration 4: Diamond cross-sectioned flywheel with Graphene.

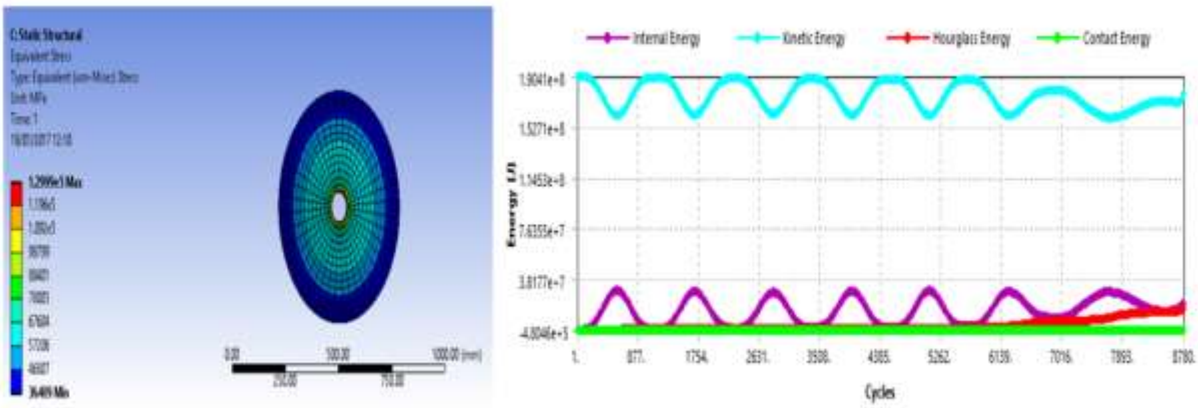

Figure7. *Stress distribution and Kinetic energy graph for Diamond cross-sectioned flywheel with Graphene*

Iteration 5: Elliptical cross-sectioned flywheel with Cast Iron-ASTM 30.

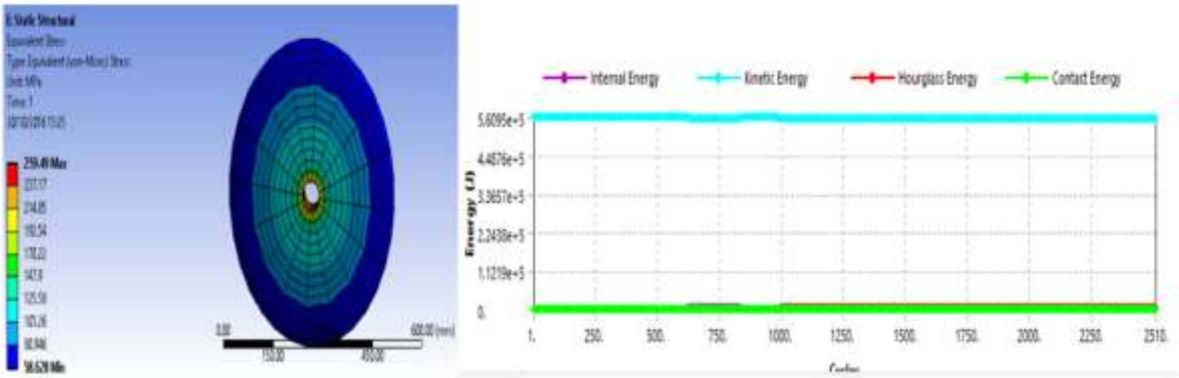

Figure8. *Stress distribution and Kinetic energy graph for Elliptical cross-sectioned flywheel with Cast Iron ASTM-30*

Iteration 6: Elliptical cross-sectioned flywheel with Graphene.

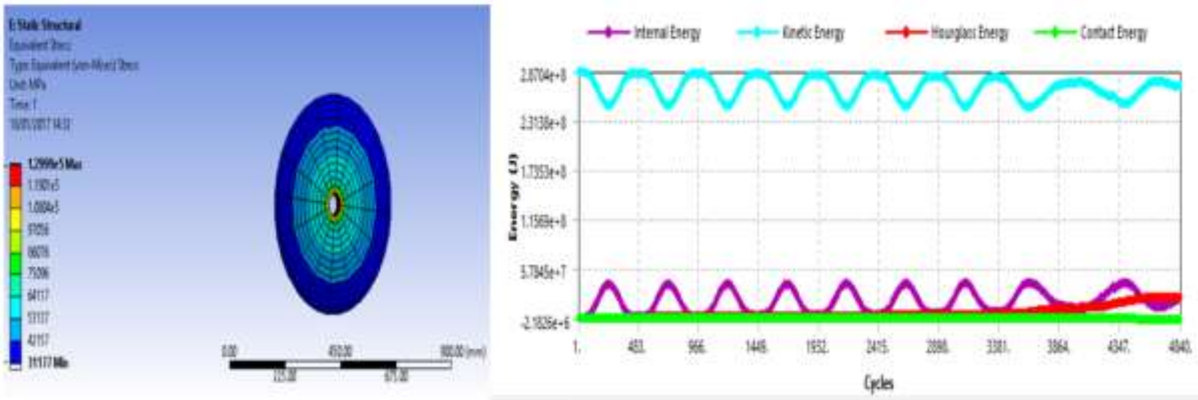

Figure9. *Stress distribution and Kinetic energy graph for Elliptical cross-sectioned flywheel with Graphene*

9. Results, Deviation and Cost Analysis

9.1. Results

Table 1. Results

Geometry	Material	Mass (kg)	Speed (RPM)	Stress (MPa)	Kinetic Energy (KJ)	Kinetic Energy per kg (KJ/kg)
Rectangular Cross-sectioned flywheel	Cast Iron ASTM 30	72.992	7796	259.46	766	10.49
	Graphene	24.298	306071	129999	392810	16166.35
Diamond cross-sectioned flywheel	Cast Iron ASTM 30	26.543	11543	259.48	374	14.09
	Graphene	8.8375	451630	129999	190410	21545.69
Elliptical cross-sectioned flywheel	Cast Iron ASTM 30	50.244	9018	259.49	561	11.17
	Graphene	16.726	353565	129999	287040	17161.31

9.2. Deviation

The deviation table is showed below to validate theoretical results and analytical results for Rectangular cross-sectioned flywheel made up of Cast Iron ASTM-30 and Graphene.

Table 2. Percentage deviation

Theoretical Kinetic Energy (KJ)	Analytical Kinetic Energy (KJ)	Deviation (%)
760.14	765.56	0.7
389864.21	392810	0.7

9.3. Cost Analysis

Cost analysis is a systematic approach for estimating the strengths and weaknesses of alternatives; it is used to determine options that provide the best approach to achieve benefits while preserving savings. The costs taken into consideration are material cost and manufacturing cost. The moulding cost is not taken into consideration since it's a one-time expenditure. The cost analysis is done only for the diamond-shaped or triangular cross-sectional flywheel design. According to the above results, as we can see in table 5, diamond-shaped flywheel is the best and optimum design of flywheel in terms of specific kinetic energy storing capacity and as well the maximum rotational speed it can attain.

Table 3. Cost analysis.

Flywheel	Mass (kg)	Material cost (Rs)	Manufacturing cost (Rs)	Total Cost (Rs)
Cast Iron ASTM 30	26.543	2070	1200	3270
Graphene	8.8375	57,500	1200	58,700

10. Conclusion and Future scope

The results of this research work showed that the flywheel with diamond-shaped cross-sectional geometry and made of graphene stores maximum kinetic energy per unit mass compared to all other combination of geometry and material. It is observed that the mass goes on decreasing from present geometry to modified geometries, thus increasing flywheels maximum rotational speed, and hence maximum kinetic energy to corresponding rotational speed. This new design of flywheel saves weight by 88% as compared to existing flywheel design which is significant. In the design of flywheel, there is still room for research, especially when the performance is primary objective. The operating conditions impose quite narrow margin of energy storing limitations, even slim amount of improvements may contribute in overall weight reduction. Till time, the use of flywheel was restricted to low speed application due to inability of existing flywheel material to withstand high rotational speed. This study clearly depicts the importance of flywheel geometry design selection and its contribution in the energy storage performance. Problem and objective is formulated in terms of kinetic energy per unit mass and its maximisation through the selection of best geometry among the three predetermined cross sections. With the use of composite material, it is possible to develop a flywheel which can give maximum kinetic energy at very high rotational speeds.

By knowing the mathematical formulas of the new geometry created it can help to optimize the performance of flywheel and it will also be helpful for carrying out fabrication of the flywheel. Using the available technology at hand, one could very well make fast but crucial improvements in the advanced research requiring flywheel utilization.

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