

Static, and Dynamic Analysis of Flywheel Using FEM

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Abstract

A flywheel is a power-accumulating device primarily used in automotive applications to control speed fluctuations and ensure smooth power delivery. This study focuses on material selection aimed at increasing output torque and energy storage capacity while simultaneously reducing weight, vibration, and stress. The main challenges involve stress effects on the flywheel, which arise due to critical vibrations, low torque output, limited energy storage capacity, and excessive weight. In this research, a flywheel used in four-wheelers was analyzed and designed based on dimensional specifications and operational requirements. Typically, flywheels are manufactured from AISI 4340 alloy steel, but in this study, they were replaced with unidirectional CFRP composite material. The performance characteristics of both materials were evaluated using the commercial FEA software ANSYS 19.2. To determine stress, frequency, velocity, and acceleration, static, torque, and dynamic analyses were conducted under simulated real-world conditions. Based on these results, output torque and energy storage capacity were calculated using analytical methods. The findings revealed that a 23% reduction in weight led to a 3.6-fold increase in energy storage capacity and a 4.48-fold increase in output torque. As a result, both static and torque-induced stresses were significantly reduced, and the rotational speed increased when CFRP was used instead of steel.

Keywords: CFRP, Dynamics, FEA, Flywheel, Static, Steel.

Introduction

Energy is a key part of any modern automotive industry and is essential for its growth. Today's 4th Industrial Revolution has seen a high demand for energy. The increase in energy demand and its impact on the environment have led to an increased reliance on renewable energy. There are four categories for energy storage purposes, which are electrical, electronic, electrochemical, mechanical, and thermal systems. In the mechanical industry, particularly automotive systems, the most widely used kinetic energy storage systems are flywheel energy storage systems (FESS). Flywheel energy storage systems (FESS) are a sustainable energy storage source because they are non-polluting, can withstand unlimited charge/discharge cycles, and have a high power-to-weight ratio compared to other energy-storing devices (1). Moreover, it is a mechanical energy storage device, consisting of a rotating mass around an axis, typically used in an automotive engine, power press, or machining and manufacturing sector. A flywheel works as a kinetic energy-storing device (2) and stores energy

under its own inertia. It releases energy when demand for energy exceeds supply and absorbs and stores energy when delivery of energy exceeds demand (3).

In recent years, based on a report by the World Health Organization (WHO), urban air pollution has been identified as the leading cause of premature deaths of 7 million people worldwide annually (4). Because day by day, there is increasing usage of a greater number of vehicles for human and goods transport. As a result, automotive manufacturers are facing the technological challenge of increasing engine efficiency and reducing exhaust emissions. Here, the challenge is to obtain low emissions with enhanced performance of engine efficiency. The vehicle weight is the main cause of high emissions, so reducing the weight of the vehicle (5) is the major task for the current automotive industry. The flywheel is the heaviest one of the weight components in the automotive. Also, a heavy flywheel requires more input energy to start up until speed comes to slow down, and it produces

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less acceleration. The energy-storing performance of a flywheel can be enhanced by making it with high-strength materials with optimal shape and dimensions and operating at high speeds (6). Some industrialists suggest composite materials for flywheels, while others use metals and alloys. Therefore, it is important to understand how to select flywheel materials, determine optimal dimensions, and consider all factors affecting FESS performance. The use of composite materials for FESS applications can further increase the energy-saving potential (7). The properties of composites such as CFRP, such as high strength in the fiber direction, low density, and flexibility in tailoring material properties, make them a promising choice for FESS material. On the other hand, metal FESS has advantages over the other materials, such as being easy to manufacture at low cost. Various studies have reviewed flywheel energy rotors with different structural configurations and materials, concluding that it remains challenging to enhance the energy storage capacity of a single machine in practical applications (8). Investigations into the thermal performance and windage loss of high-speed flywheel energy storage systems (FESS) have demonstrated that a 40% reduction in operating pressure can lead to a 20% decrease in surface temperature and a 30% reduction in windage losses (9). Research on hydraulic variable

$$e = \frac{E}{m} = K (U / \rho)$$

Where e is being specific energy, E is total energy, m is the mass of the flywheel, U is the ultimate strength of the material, and ρ is the density of the material. Also, the K - shape factor depends on flywheel design and dimension. From this eqn. (1), it could be seen that less density with high specific strength materials provides high specific energy. The specific strength of some isotropic materials, Carbon Steel, Al alloy, and Ti alloy was found to be a maximum of 66Wh/kg. But, in the case of composites such as unidirectional CFRP, it provides 240Wh/kg. From that, we could understand that the maximum specific energy of CFRP was higher than that of metals by a factor of 4–5 on average. Steel flywheels perform best at low rotational speeds below 10000 rpm and store energy in the short term when decelerating or braking (16).

The CFRP material FESS can withstand higher operating speeds and stresses compared to the

inertia flywheels has shown that they offer a simple and safe method of energy storage for AC power systems (10). Failure analysis of flywheel gears in marine diesel engines has revealed that cracks can develop at the gear root due to high stress concentrations under overload conditions (11). In addition, optimization of hybrid composite flywheel rotors—by varying rotational speed and rim thickness—has shown that the cost of a single metal rim can be up to 2.7 times higher than that of a composite rim (12). Extensive research on steel flywheels and other automotive structures has primarily focused on optimizing geometric profiles and improving efficiency through the use of simulation software tools (13–15). In the present study, a unidirectional CFRP flywheel (FESS) is proposed as a replacement for conventional steel flywheels, with the goal of achieving improved efficiency and reduced weight. While several studies have investigated and compared CFRP and steel flywheels, the present work specifically focuses on the unidirectional material properties of CFRP reinforced with aluminum alloy.

The materials researcher has predominantly used the specific energy as a performance measure to compare FESS-optimized designs. The specific energy at burst speeds condition is taken into consideration for choosing the material, which is given by the relation:

$$[1]$$

other conventional material FESS. Furthermore, composite materials weigh less than steel flywheels, and they can be used in high-speed FESS and can handle speeds up to 100,000 rpm (17). Traditionally, composite materials have been more expensive than steel; however, with advances in technology and the availability of materials, they are now cost-competitive (18). CFRP flanges with steel core material flywheels were investigated for CFD analysis, and it was concluded that they can withstand high heat loads (19). The properties that guide the selection of alternative materials for flywheel applications include cost, ultimate strength, density, and heat resistance. These properties were measured for each alternative, and the weights of their importance were determined using the variance method. It was concluded that AISI 4340 material was suitable for flywheel applications. Unidirectional CFRP plates reinforced with aluminum foils were investigated

and found to exhibit improved mechanical properties, making them suitable for high-speed and torque applications (20). Thus, this material is used to replace steel in this study.

Methodology

The materials used in this study are AISI 4340 alloy steel (19) and Carbon reinforced polymer (20). Analysis of this study mainly focused on simulation using FEA for both material flywheels. Based on the FEA results, an analytical approach has been

carried out. Figure 1 shows the flowchart for the sequence and method of analysis for this work.

The required material parameters are listed in Table 1. Figure 2 displays the flywheel dimensions from the 4- stroke petrol engine FEA model. It shows the front view and the right-side view. The solid disc with a section cut flywheel is composed of three parts, namely, the rim, the center portion with six holes, and the hub. In order to improve the accuracy of the comparison using finite element analysis, both materials' flywheels have been the same dimension.

Table 1: Properties of Steel and CFRP

S.NO	PROPERTIES	UNIT	Steel	CFRP
1	Density	Kg/m ³	7850	1750
2	Modulus of Elasticity	GPa	196	148.98
3	Poisson's ratio	-	0.29	0.297
4	Tensile Yield strength	MPa	470	155
5	Tensile Ultimate strength	MPa	745	2741

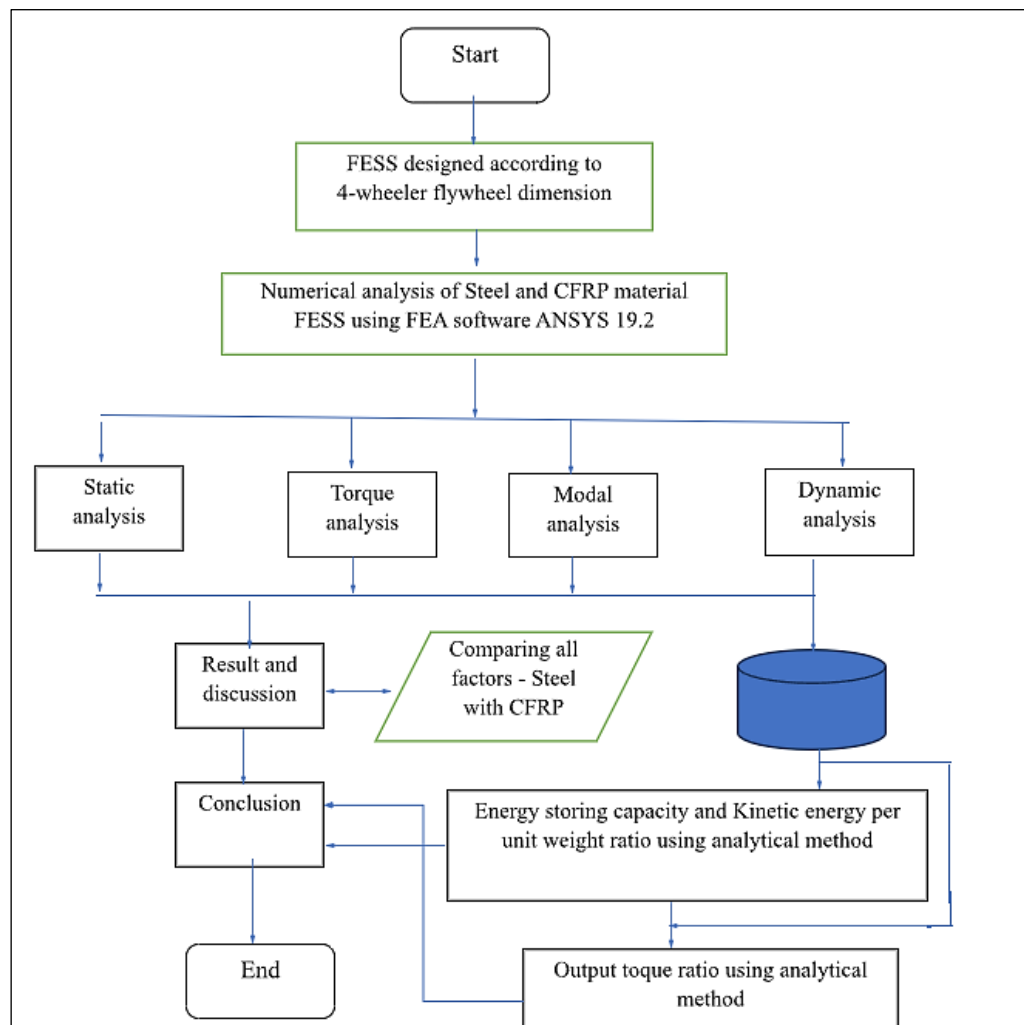


Figure 1: Diagram for the Analysis of FESS Using FEA and Analytical Methods

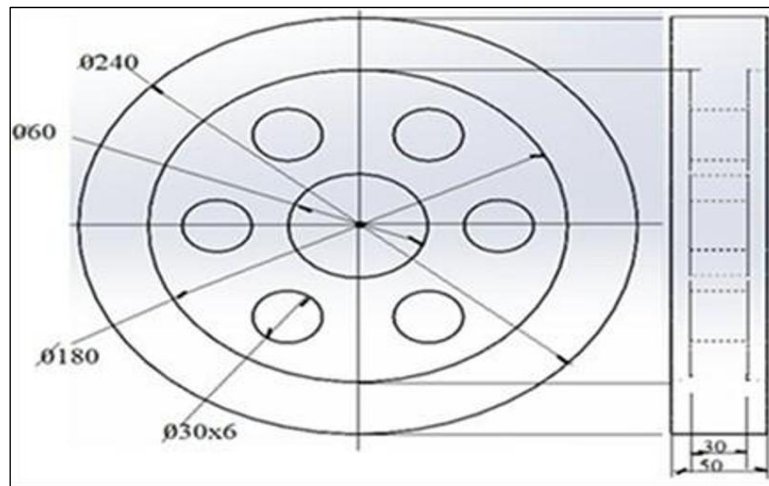


Figure 2: CAD Model of Flywheel (All Dimensions are in cm)

Energy and power developed by angular momentum- L inertia- J and angular velocity of flywheel- ω , radius and mass of flywheel- r, m .

The general equation becomes, $L = J \cdot \omega = m \cdot r^2 \cdot \omega$.

[2]

If angular moment changes with respect to time (dL/dt), a torque will be produced. In eqn. [1], it could be seen that the quantity changes of L do not give any impact of producing torque.

Also, Torque, $T = dL/dt$

[3]

From this eqn. [2] producing torque is based on angular velocity and it describes that energy should be stored in closed rotating system.

Power produced by flywheel, $P = T \cdot \omega$.

[4]

In this flywheel application, if angular momentum is caused by a change in mass or radius, the resulting torque must change the angular velocity. But, in this analysis, the mass will be reduced because of material replacement. If, however, we keep speed as a constant value, producing output torque and angular velocity leads to an exchange of energy over time, i.e., it leads to an exchange of power. This implies that output torque and angular velocity are directly proportional to the exchange of power.

In this work, the materials for consideration are steel and CFRP. Steel (19) is the orthotropic materials, and CFRP is unidirectional composite lamina (20).

A generalized stress analysis for the flywheel. First, for a single ring of cylindrically anisotropic material, the analysis is a simple extension of the isotropic case. In this case, both materials are to be considered as isotropic material. The displacement-strain relations for this axisymmetric problem are,

$$\epsilon_r = dU/dr \quad [5]$$

$$\epsilon_\theta = U/r \quad [6]$$

The stress-strain relations in polar co-ordinates are;

$$\epsilon_r = (\bar{\nu}_r / E_r) - (V_{\theta r} \bar{\epsilon}_\theta / E_\theta) \quad [7]$$

$$\epsilon_\theta = (\bar{\epsilon}_\theta / E_\theta) - (V_{r\theta} \bar{\epsilon}_r / E_r) \quad [8]$$

Where r and θ are polar coordinates, U is radial displacement, ϵ_r and ϵ_θ are radial and tangential stresses, and $\bar{\nu}_r$ and $\bar{\nu}_\theta$ are radial and tangential strains. E_r is elastic modulus in the r -direction and E_θ elastic modulus in the θ -direction. $V_{\theta r}$ and $V_{r\theta}$ are Poisson's ratios, which characterize the compression in the r -direction due to tensile stress in the θ -direction. Poisson's ratio, which characterizes the compression in the θ -direction due to tensile stress in the r -direction. From these

equations 6 and 7, it can be seen that materials with lower Young's modulus produce lower stress in radial and tangential directions. As a result, the above formula can be used to find the stress and strain for composite flywheels made of any rings. The selection of materials can be obtained based on the kinetic energy storage per unit weight and kinetic energy storage per swept volume. Furthermore, the value of kinetic energy stored per unit weight of a flywheel is proportional to the

ratio of the composite ultimate tensile strength and density (21).

Static Structure Analysis of Flywheel

The static analysis for the flywheel is crucial for design and materials selection, which is essential to ensure structural stability and prevent failure

during operating conditions. The static structure analysis of the flywheel was analyzed under no loading condition. The actual boundary condition i.e., fixed remote displacement has been applied in the flywheel. To ensures accurate results for the complex geometry, tetrahedral elements were used in the analysis.

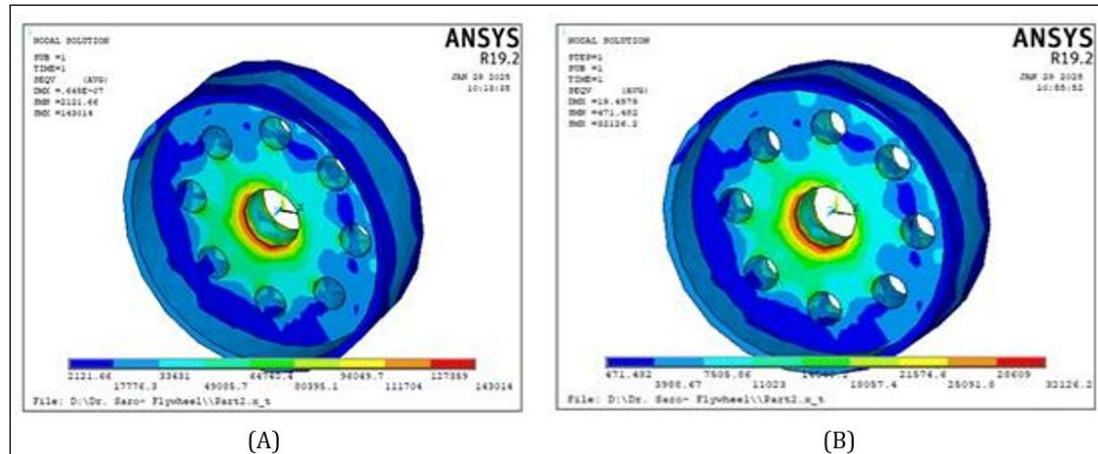


Figure 3: Static Stress Analysis: (A) Stress Steel, (B) Stress-CFRP

The center hub of the flywheel was restrained, and inertia loads due to gravity were applied. The offset distance also applied according to the actual model condition (X-10 cm, Y-0 cm, Z-0 cm). Figure 3 shows the stress value for steel and CFRP flywheels under no loading conditions (13).

Torque Analysis of Flywheel

In this section, a torque study has been conducted because it determines the flywheel's ability to manage torque variations and improved quietness

of the engine due to noise and vibration created by the drivetrain. The torsional vibration and friction between the hub and bearing are not considered here. The theoretical analysis of torque produced by the bearing under static conditions is taken into account (22). Therefore, resultant stress (normal and radial direction) is considered here. A torque load of 10000 Nm was applied at the inner surface of the hub of the flywheel to obtain stress due to torque load, and the outer surface of the rim was restrained. It is given in Figure 4.

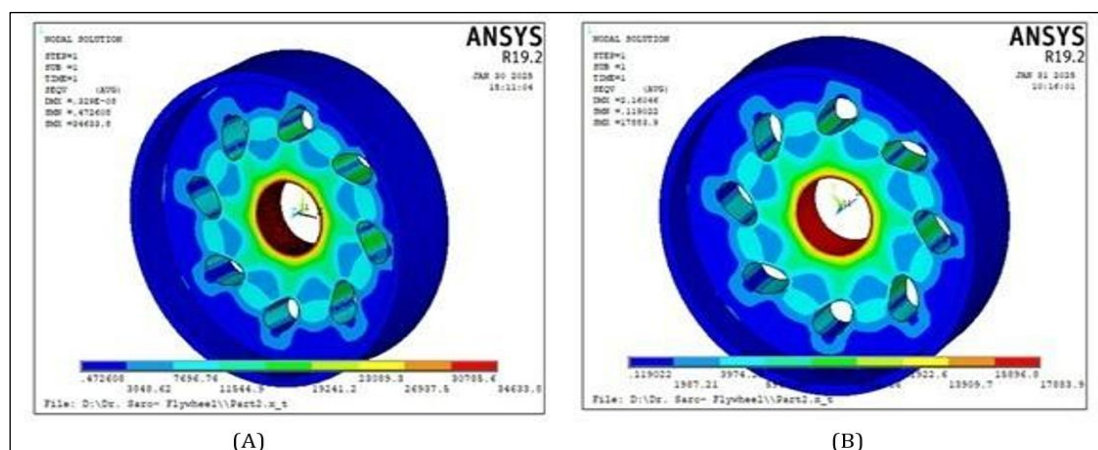


Figure 4: Torque Analysis, (A) Stress due to Torque- Steel, (B): Stress due to Torque- CFRP

Modal Analysis of Flywheel Model

The modal analysis provides the vibrational behavior of the flywheel, which involves natural frequencies and mode shapes. These is done by

solving the eigenvalue problem. In this section, identify potential resonance frequencies and how it responds to those frequencies for the current dimension and materials condition. Also, it

describes mass, damping and stiffness properties of flywheel materials. Vibration monitoring is an important issue when a flywheel is in motion. The structural vibration of a flywheel can be expressed as a linear combination of each order of natural frequency modes, with the lower frequency modes

having the greatest influence on the structural vibration. Thereby, the vibration characteristics of structural analysis generally consider the first 1 to 5 modes. This study obtained the first 5 natural frequencies taken, and the 5th mode for both materials is presented in Figure 5.

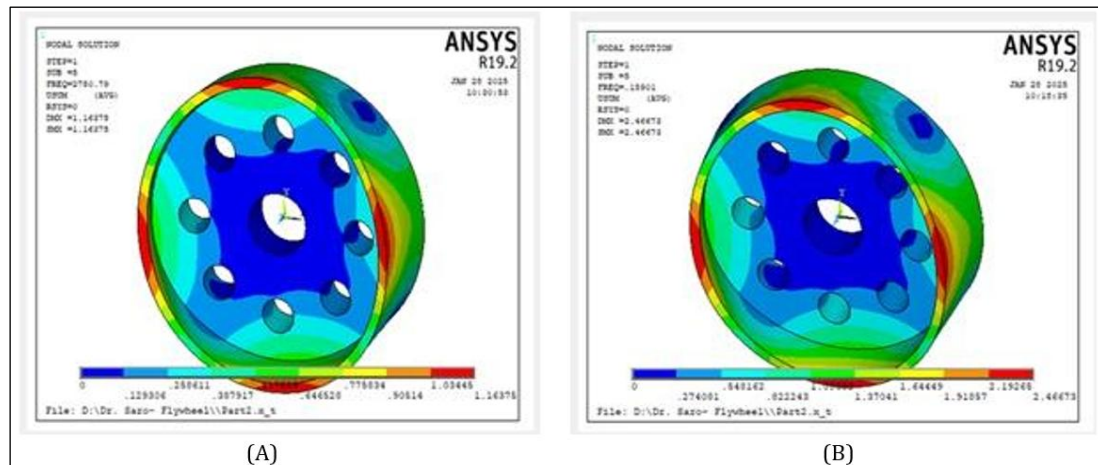


Figure 5: Vibrational Analysis: (A) 5th Mode – Steel, (B) 5th Mode- CFRP

Dynamic Analysis

Dynamic analysis of a flywheel refers to the process of examining how a flywheel behaves under rotation conditions with input velocity. The flywheel design and shape factor for both materials are the same. In order to compare the energy content of a flywheel made up of these two materials, dynamic analysis has been carried out. Normally, metal flywheels have a high kinetic energy storing capacity due to their ability to fabricate a better shape factor. Thus, it is clear that there is a need to validate output velocity for steel and CFRP. The following boundary condition was applied (23), and outputs were taken as shown in Figure 6. The dynamic stress and output velocity and acceleration values for both materials were obtained to find energy storing capacity and output torque for the corresponding input velocity. Rotating input velocity = 52rad/sec. (500rpm) and time control 0.001 sec.

Results and Discussion

This study conducted static, vibration, torque and dynamic using FEA method and following results were observed. In this static and torque analysis, for both the materials were conducted and the results show that CFRP exhibits enhanced performance for the applications of flywheel.

Figure 3 shows static analysis of the flywheel under load due to the gravitational force that is

applied to the flywheel. It could be seen that the maximum stress occurs at the corner of the hub portion. This is due to the hub portion holding the total weight of the flywheel, and it is connected to the bearing for rotating purposes. It is also observed that the stress is eventually distributed up to the middle portion of the flywheel (6-hole portion), and the minimum stress occurs at the outer portion of the inner cylinder and the rim portion. The equivalent stress, circumferential stress, and radial stress of the flywheel are taken into account.

Figure 4 shows torque analysis of the flywheel under torque loading conditions. Here, it could be seen that the maximum stress occurs at the inner surface of the hub portion, and the stress is eventually distributed up to the middle portion of the flywheel (6 holes portion). It is also observed that above this middle portion and rim section, there has been very low stress due to torque load, and deformation due to the torque is also high at the middle portion of the flywheel. In this part, torque characteristics are identified only at the 0° angle, but not at the different angle. If the torsional angle increases, the overall stiffness is enhanced and continuously variable. When the torsional angle decreases, the stiffness is basically unchanged (22).

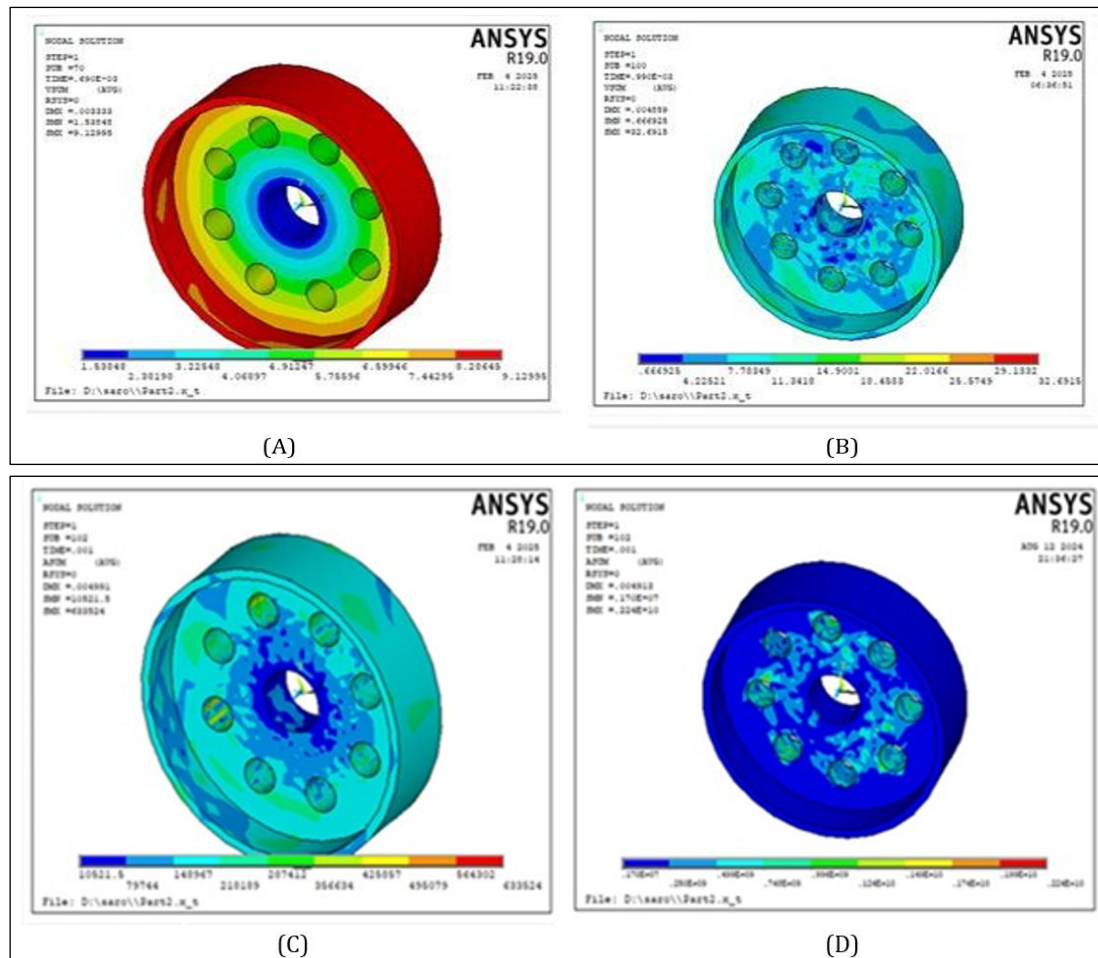


Figure 6: Dynamic Analysis: (A) Output Velocity (0.00069sec) - Steel, (B) Output Velocity (0.00099sec) - CFRP, (C) Acceleration (0.001sec) - Steel, (D) Acceleration (0.001sec) - CFRP

A torque stress of a flywheel involves the stresses induced within the flywheel due to rotational inertia and applied torque load, which can lead to potential failure if the induced stresses exceed the material's tensile strength. Figure 7 shows the

stress for the torque load up to 15000 Nm. The CFRP material exhibits very low when compared to its ultimate tensile strength (Table 1). Thus, it is under a safer region for maximum torque loading conditions.

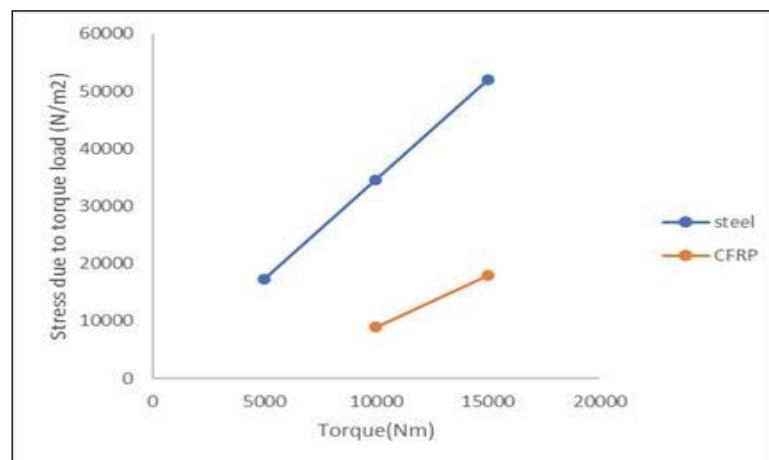


Figure 7: Torque Stress for Both the Materials

The result obtained from Figure 5 is the frequency values from the 1st mode to the 10th mode for both

materials were taken. It is observed that CFRP material exhibits very low frequency when

compared to steel. Table 2 shows that frequency ranges for steel and CFRP. In this study, the mode shape and frequency range influence vibration fatigue damage. For the steel, because of its isotropic nature and homogeneity of the material, fatigue damage can be described by frequency range and deformation due to vibration (8).

Moreover, because the specific strength and specific rigidity of CFRP are higher than that of steel and the density of CFRP is much lower than that of steel alloy, the natural frequency characteristics of the CFRP flywheel are obviously better than those of the steel flywheel when the size is the same.

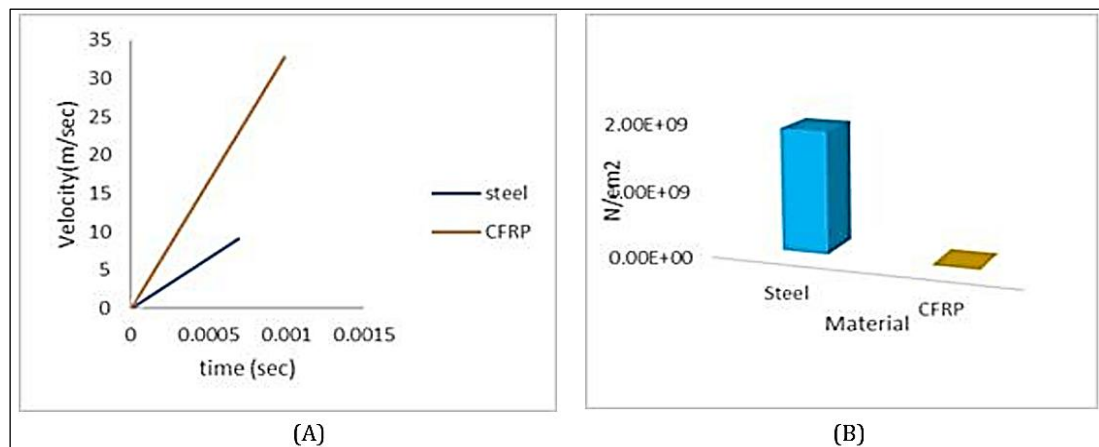
Table 2: Frequency of Steel and CFRP

Mode.no	Frequency (Hz)- Steel	Frequency (Hz)- CFRP
1	2093.5	0.12128
2	2093.5	0.14650
3	2525.0	0.16491
4	2542.5	0.14741
5	2750.8	0.15901
6	2832.7	0.20785
7	5154.4	0.29810
8	5201.4	0.30061
9	5883.8	0.32580
10	5902.3	0.34321

In Figure 5, it could be seen that the deformation due to vibration occurs at the rim portion and, also, it is very at the hub portion. This is due to the rim is being located at some offset distance from the hub portion (restrained portion). It is like a cantilever beam; the deformation due to vibration is maximum at the free and very low at the fixed end. In order to improve better performance under vibration conditions, the thickness of the rim portion is higher than that of the inner of the cylinder as it is designed in Figure 2.

Figure 8 shows the dynamic characteristics of steel and CFRP flywheels. The angular velocity of CFRP is better than steel for the given input angular velocity (52 rad/sec). Figure 8 shows that time

taken for reaching maximum velocity for both the materials. It could be seen that the time taken to reach maximum velocity for steel is less than CFRP. However, the maximum velocity for CFRP is 4 times higher than steel. The dynamic stress for CFRP is very low when compared to steel. In Figure 8, it is observed that the acceleration for CFRP is much higher than steel. In addition to this work, incorporating resonance analysis, damping considerations, and critical speed evaluation is essential to prevent failures, reduce maintenance requirements, and ensure the optimal performance of flywheel systems under dynamic operating conditions. However, this analysis is not included in the present study.



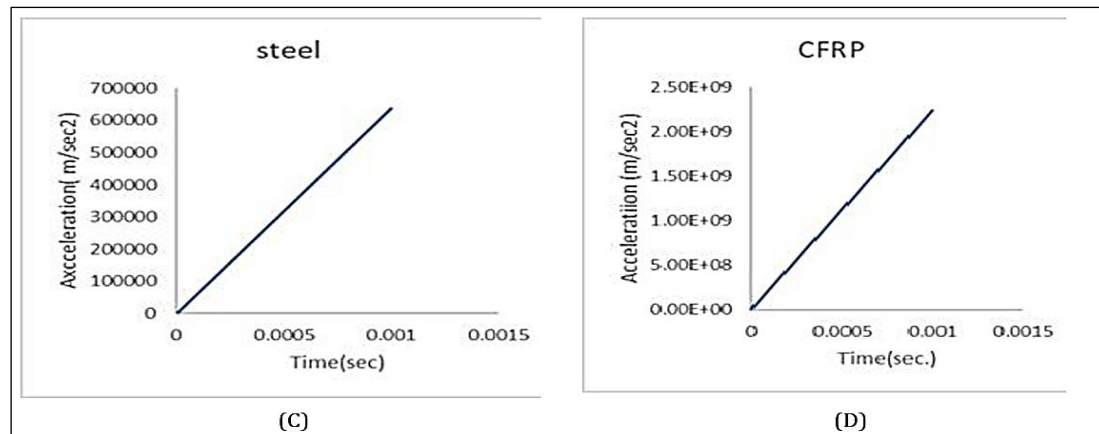


Figure 8: Dynamics of Flywheel, (A) Output Angular Velocity, (B) Stress- Dynamics, (C) Steel- Acceleration, (D) CFRP- Acceleration

In this section, it could be seen that the maximum velocity is obtained at the rim of the flywheel, and it is low at the hub portion. This is due to maximum energy stored at the rim portion of the flywheel. Thus, optimization and increasing in dimension are very important for improving the energy-storing capacity of the flywheel. This result revealed that less dense materials (CFRP) provide high velocity (Figure 8) and acceleration (Figure 8). Moreover, enhanced mechanical properties with less dense materials provide better energy-storing capacity with weight reduction. The performance criterion, the CFRP material is better than the steel, The reason is the average energy stored by composite flywheel is 1.5 times better than steel flywheel (12).

Conclusion

The static, vibration, model, and dynamic performance of an energy storage system was successfully evaluated. The numerical results demonstrated the mode shapes, output torque, angular velocity, and acceleration of flywheels. This was further confirmed by determining the characteristics of maximum torque and high speed.

The following conclusions are made based on analytical and FEA results:

- CFRP exhibits better performance than steel under static loading conditions
- In torque analysis, CFRP exhibits low stress when compared to steel. Moreover, it is in a safer region under high torque loading conditions.
- Vibration characteristics of CFRP are superior to steel due to its significantly higher strength-to-weight ratio than steel. Also, it provides lighter and stronger flywheels.

During dynamic analysis, CFRP provides better velocity, more acceleration, stores more kinetic energy per unit weight, and less rotational stress, enabling faster charging and discharging of energy when compared to steel.

CFRP flywheel provides 2.864 more energy-storing capacity with 4.48 times mass reduction.

The focus of this contribution is for CFRP to be compared with steel for flywheel application. In future work, an experimental work will be carried out for finding this, which draws out the major issues for composite materials flywheels.

However, this study has several limitations, such as the use of simplified geometry in the FEA, a fixed input torque of 10,000 Nm, a maximum rotational speed of 52 rad/s (500 rpm), the neglect of 3D stress effects, the omission of temperature effects, and the extraction of only the first five modes for the flywheel's target application. Therefore, strong conclusions cannot be drawn from the present study. Furthermore, the overall efficiency of the flywheel energy storage system (FESS), including the effects of other components, was not considered. Thus, the findings may only be directly applicable to automotive flywheel designs of similar size and specification.

Abbreviations

CFRP: Carbon Fiber Reinforced Polymer, FEA: Finite Element Analysis, FEM: Finite Element Method, FESS: Flywheel Energy Storage System.

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Author Contributions

Saravanan Annamalai: Material preparation, Data collection, Manuscript preparation, subsequent revisions Jagannathan Sundarababu: Study's conception and design, Statistical analysis, Praveen SR Konduri: Testing and analysis, Muthu Gunalan: Review and editing. All the authors have read and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare no use of Artificial intelligence (AI) for the write-up of the manuscript.

Ethics Approval

Not applicable.

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Appendix A

Were,	ω for CFRP = 32.69 rad/sec. [Figure 8(A)]
ω = Angular velocity of the flywheel,	E- energy storage in flywheel
σ = Specific strength of a material,	For steel, $m_{\text{steel}} = 75360$ kg
ρ = Density of the material (Table 1)	For CFRP, mass of $m_{\text{CFRP}} = 16800$ kg
$E = 1/2 I \omega^2$ ----[9]	Mass ratio $m_R = m_{\text{steel}} / m_{\text{CFRP}} = 4.485$
m- mass of flywheel	Energy ratio: $E_{\text{steel}} = 8.317 \times 10^{10}$
I – mass moment of inertia	Energy ratio: $E_{\text{CFRP}} = 2.4 \times 10^{11}$
ω for steel = 9.12 rad/sec. (Figure 8(a))	Energy ratio: $E_R = E_{\text{steel}} / E_{\text{CFRP}} = 3.6$

Appendix B

The value of the stored kinetic energy per unit weight (specific energy) of a flywheel is proportional to the ratio of ultimate tensile strength and density. Now, Eqn. (1) becomes,	Let us assume, K is unique:
$K.E/\text{unit weight} = K * (U / \rho)$	$K.E_{\text{steel}} = 745/7850 = 0.099$
Were, U- ultimate tensile strength	$K.E_{\text{cfrrp}} = 2741/1750 = 1.566$
ρ – Density	Kinetic energy/ unit weight ratio:
K- shape factor (depends on geometry)	$K.E_r = K.E_{\text{cfrrp}} / K.E_{\text{steel}} \quad \text{----} [10]$
	$= 1.566 / 0.0949 = 16.5$
	Eqn. (10) show specific energy of CFRP is 16.5 times better than the steel.

Appendix C

Based on vibration of flywheel,	$M\ddot{u} + C\dot{u} + Ku = 0; (U=0) \quad \text{---} [12]$
The motion differential equation for multi degrees of freedom is,	Condition (ii), if there is no damping effect, the equation [12] becomes,
$M\ddot{u} + C\dot{u} + Ku = U \quad \text{----}[11]$	$M\ddot{u} + Ku = 0; (U=0) \quad \text{---} [13]$
Were,	From the eqn. [13], mass inversely proportional to mode shapes and mode vectors and the results revealed that less mass with high stiffness (Table1-CFRP has high UTS) material produces low vibration on flywheel.
M- Mass matrix; C- damping matrix	
K- stiffness matrix	
Condition(i), if there is no external excitation, the equation [11] becomes,	

Appendix D

Torque analysis, $T = I \alpha$ ----[14]	α for CFRP = $2.24 \times 10^9 \text{ rad/sec}^2$ (Figure 8(d))
T- Torque on flywheel	$T_{\text{CFRP}} / T_{\text{steel}} = 3.58 \quad \text{---} [15]$
I – mass moment of inertia	Eqn. [15] show that torque performance CFRP is 3.58 times better than the steel.
α - acceleration of flywheel	
α for steel = 636524 rad/sec^2 . (Figure 8(c))	