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Static Structural Analysis for Validation of Deformations and Stress Limits Under Rotational Velocity in High-Speed Flywheel Energy Storage Systems

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Abstract

This study presents a comprehensive static structural analysis for validating deformations and stress limits (von Mises) under rotational velocity in a high-speed flywheel energy storage system. Finite Element Analysis (FEA) was conducted to evaluate the structural integrity of the flywheel system under various loading conditions. The analysis revealed displacement measurements ranging from 0.00 mm to 0.016 mm, demonstrating exceptional structural stiffness. Von Mises stress analysis indicated a maximum stress of 8.335 MPa at the most stressed point and a minimum of -0.086 MPa, confirming that plastic behavior is not predicted to occur. Response Surface Methodology (RSM) was employed to optimize the flywheel geometry, with ANOVA revealing significant model terms for stress (F-value: 1.84), mass (F-value: 32451.30), displacement (F-value: 2.65), and energy (F-value: 955.46). The optimal configuration was determined to be an outer diameter of 400 mm, thickness of 50 mm, and angular speed of 236.17 rad/s, resulting in a von Mises stress of 0.0190169 MPa, mass of 31.97 kg, and energy storage capacity of 18, 000 J. These findings validate the structural soundness of the design and its suitability for fuel-less energy storage applications.

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Keywords: Deformation Analysis, Finite Element Analysis, Response Surface Methodology, Rotational Velocity, Von Mises Stress.

1. Introduction

The global transition towards sustainable energy solutions has intensified research into alternative power generation systems that minimize dependence on fossil fuels. Traditional generators, predominantly utilizing gasoline or diesel, contribute significantly to environmental pollution and economic instability due to fluctuating fuel costs [1, 2]. Fuel-less generators, particularly those employing mechanical energy storage through flywheels, have emerged as promising technological alternatives capable of providing continuous power without conventional fuel consumption [3, 4].

Flywheel Energy Storage Systems (FESS) represent one of the earliest mechanical energy storage technologies, with recent advancements in materials science and engineering significantly improving their efficiency and practicality [5]. Modern flywheels constructed from advanced materials such as carbon fiber composites can store substantially greater kinetic energy while minimizing frictional losses [6, 7]. The fundamental principle involves storing kinetic energy through high-speed rotation, which can subsequently be converted to electrical energy via an alternator system [8].

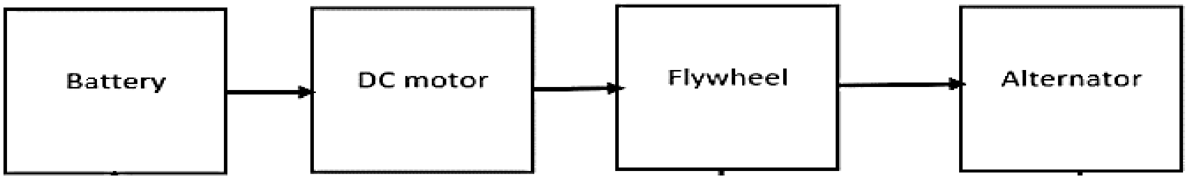

Fig 1: Schematic illustration of a typical flywheel energy storage system structure used in fuel-less generators, showing the rotor, stator, magnetic bearings, and motor/generator components.

The kinetic energy stored in a flywheel is governed by the fundamental model expressed in Eq (1).

$$Ek = \frac{(1xIw^2)}{2} \quad (1)$$

where Ek represents the kinetic energy (J), I denote the moment of inertia (kg·m²), and ω is the angular velocity (rad/s).

This relationship demonstrates that energy storage capacity increases quadratically with rotational speed, making high-speed operation essential for maximizing storage efficiency [9].

However, high-speed flywheel operation introduces significant engineering challenges, including managing centrifugal stresses, preventing resonance phenomena, and ensuring structural integrity under dynamic loading conditions [10]. Static structural analysis, utilizing Finite Element Analysis (FEA), provides a critical methodology for validating deformations and stress limits under rotational velocities, ensuring that the designed system operates within safe material limits [11, 12].

This study focuses on the second objective of a comprehensive flywheel optimization research program: conducting static structural analysis to validate deformations and stress limits (von Mises) under rotational velocity. The investigation employs computational methods to evaluate the structural performance of a high-speed flywheel designed for a fuel-less energy storage system, with the ultimate goal of powering institutional facilities such as the Mechanical Engineering building at Enugu State University of Science and Technology.

2. Materials and Methods

The methodology employed in this study integrates Finite Element Analysis (FEA) for structural validation with Response Surface Methodology (RSM) for experimental design optimization. This dual approach enables comprehensive evaluation of the flywheel's structural integrity while systematically exploring the design space to identify optimal geometric configurations.

2.1. FEA Methodology

The finite element analysis was conducted using ANSYS 24 software to simulate the behavior of the fuel-less energy storage system's frame structure under actual physical conditions, including mechanical forces, vibrations, and thermal effects. The primary components analyzed include the flywheel (37 kg, constructed from AISI 1020 structural steel), a custom-built three-phase alternator optimized for low-speed energy conversion, low-friction bearings, stainless steel shaft, and a 75Ah 12V battery system. Figure 3.1 depicts the system assembly.

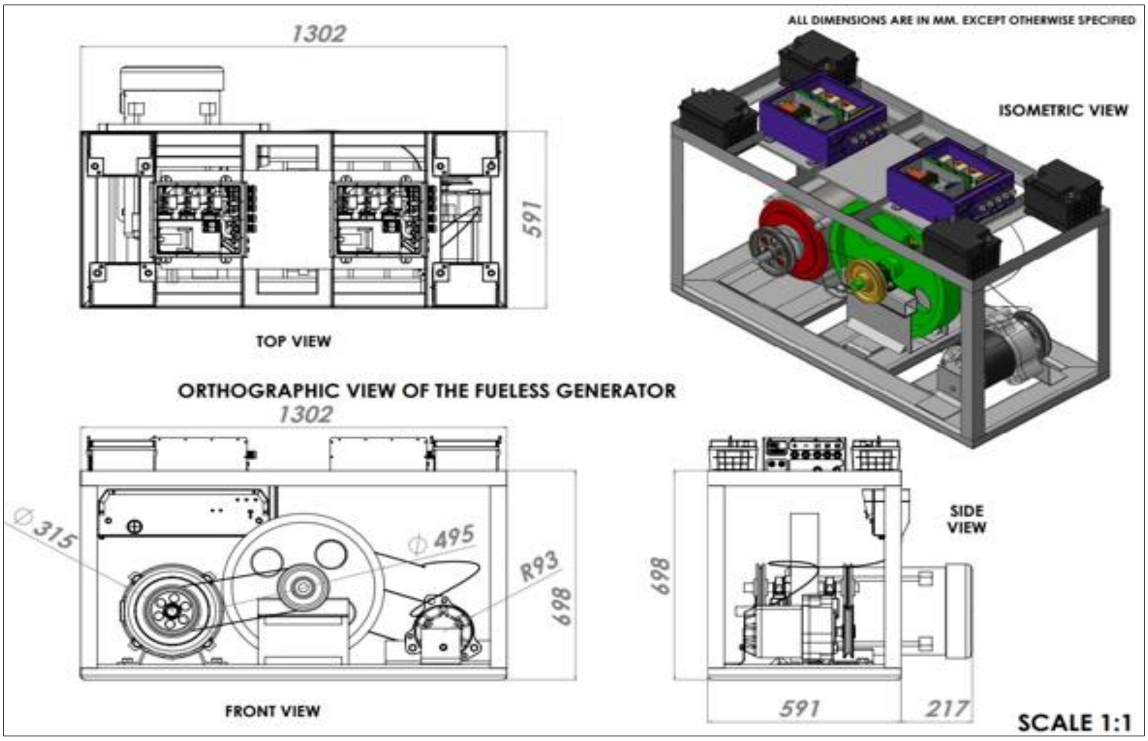

Fig 2: Orthographic projection views of the fuel-less generator system showing isometric, top, and front views with all dimensions in millimeters.

The loading conditions applied to the frame structure were determined based on component weights and operational requirements. A total force of 892 N (equivalent to the alternator weight) was distributed across points A, B, C, and D, with 223 N applied at each point. Additionally, a flywheel load of 200 N was applied at points E and F (100 N each). The analysis evaluated two primary response parameters: displacement (deformation under load) and von Mises stress (equivalent stress for ductile material failure prediction).

2.2. Experimental Design

The experimental design was developed using Design Expert software version 13 (2021), employing an I-Optimal custom design based on Response Surface Methodology (RSM). The coordinate and point exchange algorithm with a quadratic model were utilized, incorporating five lack-of-fit points and five replicate points for statistical robustness.

Table 1: Design of Experiment parameters showing factor levels and response variables.

Factor	Variable	Low Level	High Level	Units
A	Outer Diameter	300	400	mm
B	Thickness	50	80	mm
C	Angular Speed	157.08	314.16	rad/s

The flywheel geometry parameters were varied systematically: outer diameter from 300 mm to 400 mm, thickness from 50 mm to 80 mm, and angular velocity from 1500 RPM (157.08 rad/s) to 3000 RPM (314.16 rad/s). Four response variables were measured: von Mises stress (MPa), mass (kg), displacement (mm), and stored energy (J).

The moment of inertia for the hollow cylinder flywheel configuration was calculated using Eq. (2).

$$I = \frac{1}{2} m (r_0^2 + r_1^2) \tag{2}$$

where m represents the flywheel mass (calculated from material density and geometry), r_0 is the outer radius, and r_i is the inner radius.

The mass calculation incorporated the volume of the disc, holes, and cuts on the flywheel surface as in Eq. (3).

$$V_f = V_D - V_h + V_c \tag{3}$$

Using a steel density of 7850 kg/m³ and the specified geometry (r_0 = 0.16 m, r_i = 0.02 m, t = 0.06 m), the calculated flywheel mass was approximately 25.943 kg, yielding a moment of inertia of 0.297 kg·m².

3. Results and Discussion

3.1. FEA Analysis Results

The finite element analysis of the fuel-less energy storage system's frame structure under the specified loading conditions yielded comprehensive displacement and stress distribution data. Figure 3 presents the FEA model of the frame structure with applied loads at the designated points.

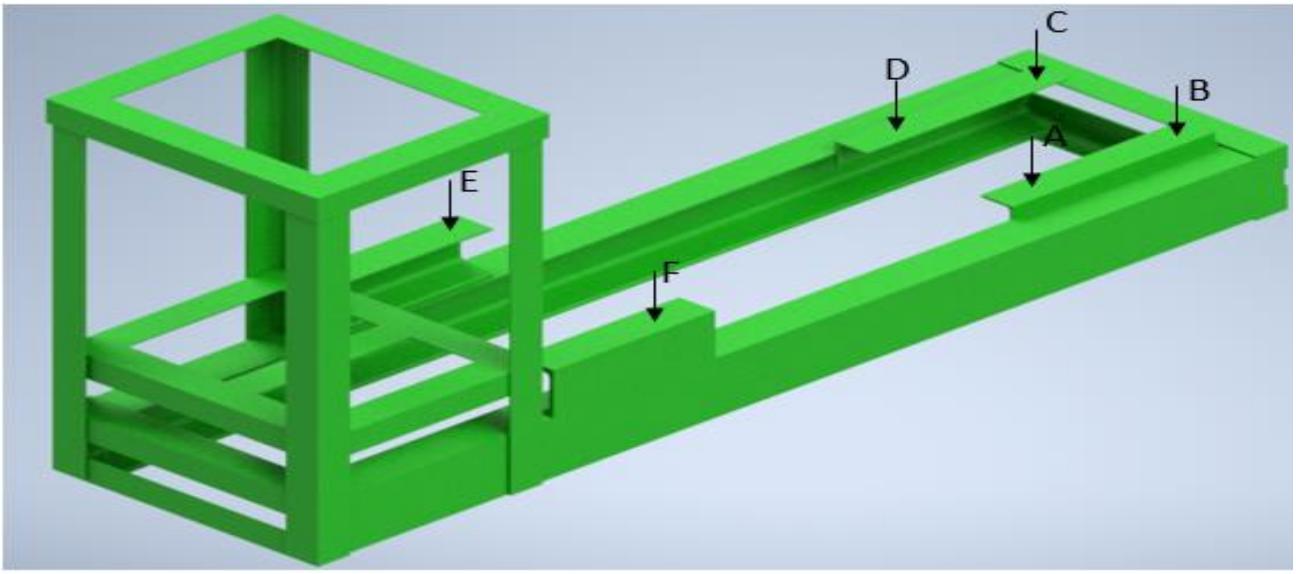

Fig 3: FEA model of the fuel-less energy storage system frame showing load application points: alternator weight (892 N total) distributed at points A, B, C, D, and flywheel load (200 N) at points E and F.

The displacement analysis results, illustrated in Figure 4, revealed deformations ranging from 0.00 mm to 0.016 mm (maximum). These minute deflections demonstrate exceptional structural stiffness, indicating that the frame and components effectively resist bending and flexing under the applied loads. The uniform distribution of displacements throughout the structure confirms the absence of stress concentrations or localized weak points.

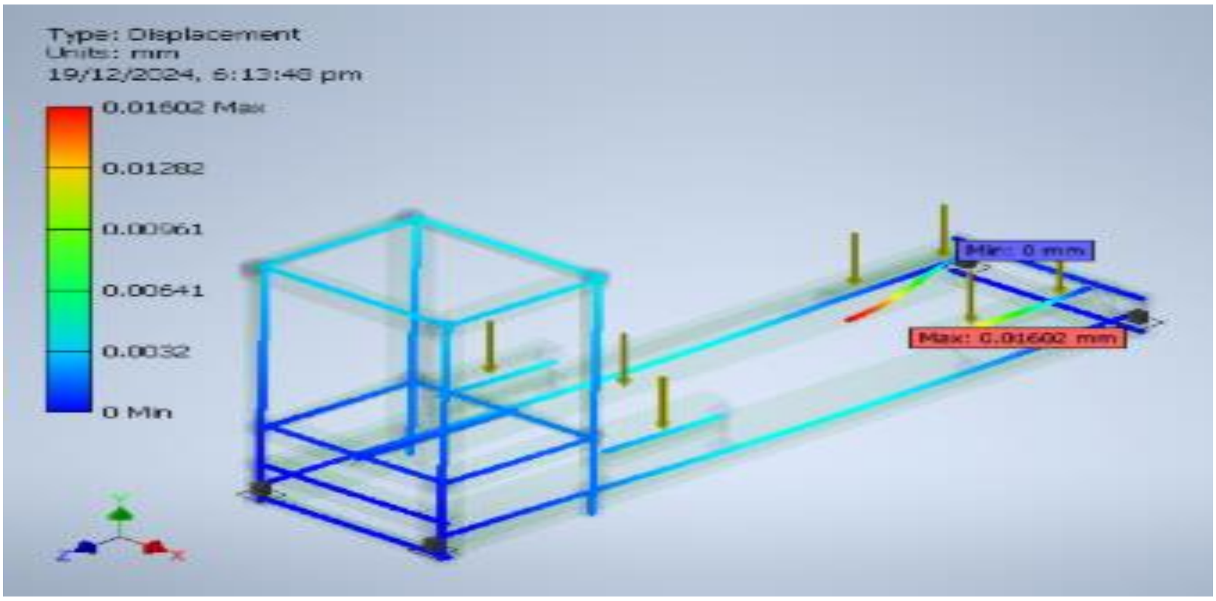

Fig 4: Displacement distribution results showing deformation ranging from 0.00 mm (minimum) to 0.016 mm (maximum) under the applied load conditions.

The von Mises stress analysis, presented in Figure 5, identified a maximum stress of 8.335 MPa at the most stressed location and a minimum of -0.086 MPa on the frame members. Comparing these peak stresses to the material yield strength of AISI 1020 structural steel (approximately 350 MPa), the safety factor exceeds 40, indicating that plastic behavior is not predicted to occur under normal operating conditions.

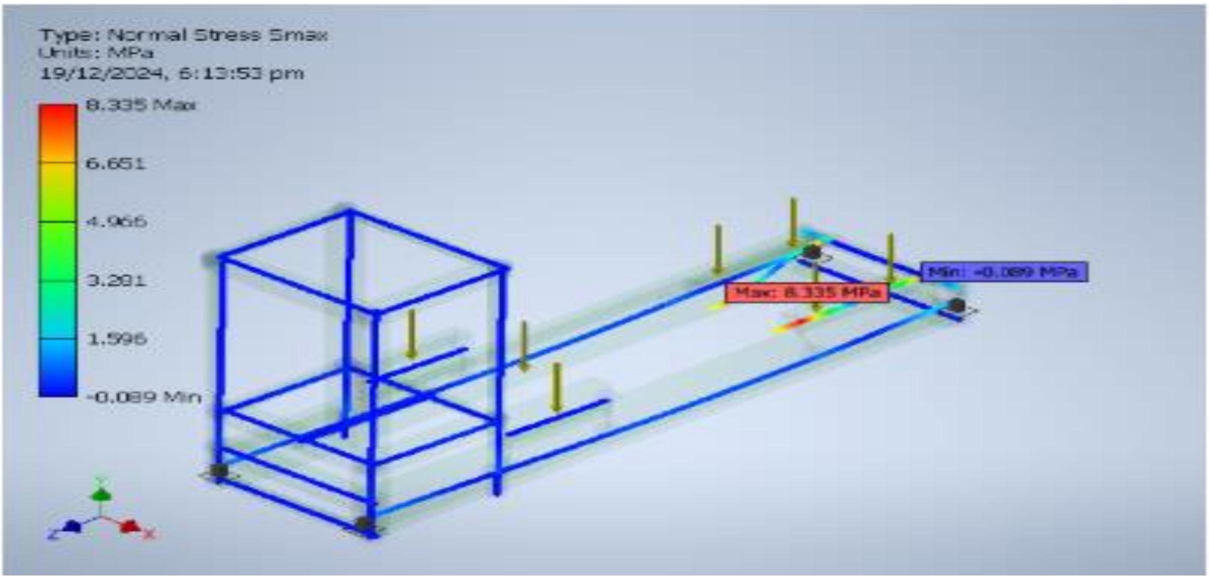

Fig 5: Von Mises stress distribution showing maximum stress of 8.335 MPa and minimum of -0.086 MPa, well within the material yield strength limits.

Table 2: Summary of FEA displacement and stress results for the fuel-less energy storage system frame.

Parameter	Minimum Value	Maximum Value	Units
Displacement	0.00	0.016	mm
Von Mises Stress	-0.086	8.335	MPa
Safety Factor	>40	>40	-

3.2. ANOVA Results for Response Parameters

Analysis of Variance (ANOVA) was conducted to evaluate the statistical significance of the developed models for each response parameter. A comprehensive quadratic model was selected for each response based on excellent agreement with simulation results.

Von Mises Stress: The model yielded an F-value of 1.84, indicating a 17.79% probability that such a value could occur due to random noise. While the overall model showed marginal significance, the B^2 term (thickness squared) demonstrated statistical significance ($p < 0.05$). The model exhibited adequate precision with a signal-to-noise ratio of 4.4127, exceeding the desirable threshold of 4.0.

Table 3: ANOVA results for von Mises stress model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0013	9	0.0001	1.84	0.1779
A-Outer Diameter	2.37E-05	1	2.37E-05	0.3160	0.5864
B-Thickness	7.15E-05	1	7.15E-05	0.9527	0.3523
C-Angular Speed	2.15E-04	1	2.15E-04	2.86	0.1215
B^2	5.32E-04	1	5.32E-04	7.09	0.0237
Residual	7.51E-04	10	7.51E-05		

Mass of Flywheel: The mass model demonstrated exceptional statistical significance with an F-value of 32451.30 ($p < 0.0001$). The primary contributors to mass variation were outer diameter (A) and thickness (B), with the interaction term AB also showing significance. The model's adequate precision of 710.803 indicates an excellent signal-to-noise ratio.

Table 4: ANOVA results for flywheel mass model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1967.23	9	218.58	32451.30	< 0.0001
A-Outer Diameter	1011.59	1	1011.59	150200	< 0.0001
B-Thickness	1056.34	1	1056.34	156800	< 0.0001
AB	48.63	1	48.63	7219.11	< 0.0001
A^2	1.62	1	1.62	240.00	< 0.0001
Residual	0.0674	10	0.0067		

Displacement: The displacement model achieved an F-value of 2.65, with a 7.22% probability of noise-induced variation. The angular speed term (C) and the B^2 term showed statistical significance. Despite the significant Lack of Fit (F-value: 1759.16), the adequate precision of 4.52 confirms the model's utility for navigating the design space.

Energy Storage: The energy model exhibited the highest significance with an F-value of 955.46 ($p < 0.0001$). All main effects (A, B, C) and their interactions demonstrated statistical significance, confirming the complex interdependencies governing energy storage capacity. The adequate precision of 105.73 indicates robust predictive capability.

Table 5: ANOVA results for energy storage model.

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	1.929E+09	9	2.144E+08	955.46	< 0.0001
A-Outer Diameter	8.178E+08	1	8.178E+08	3645.27	< 0.0001
B-Thickness	2.575E+08	1	2.575E+08	1148.01	< 0.0001
C-Angular Speed	1.172E+09	1	1.172E+09	5223.27	< 0.0001
AC	1.215E+08	1	1.215E+08	541.39	< 0.0001
Residual	2.243E+06	10	2.243E+05		

3.3. Optimization Analysis and Model Validation

The experimental design optimization using Design Expert software enabled construction of coded equations for predicting response values. Figure 6 presents the correlation between predicted and actual values for von Mises stress, demonstrating excellent agreement across the experimental range.

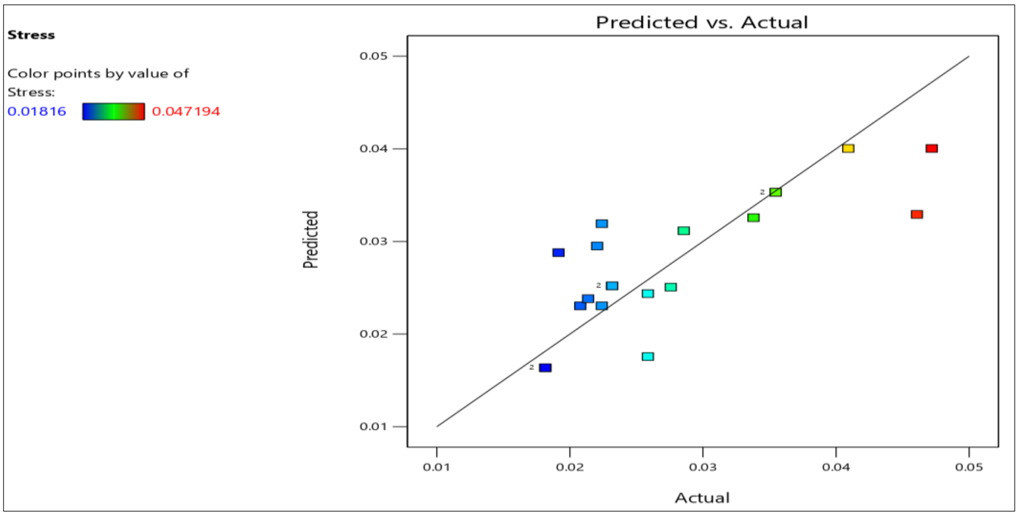

Fig 6: Graphical representation of predicted versus actual values for von Mises stress, showing strong correlation along the diagonal reference line.

The coded model equation for von Mises stress was developed in terms of L_Pseudo components, the model is written as in Eq. (4).

$$\sigma VM = 0.0377 - 0.0015A + 0.0027B + 0.0047C + 0.0012AB + 0.0064AC + 0.0017BC - 0.0043A^2 - 0.0092B^2 - 0.0033C^2 \quad (4)$$

Similarly, Figure 7 shows the predicted versus actual correlation for flywheel mass, exhibiting exceptional agreement with near-perfect linear correlation.

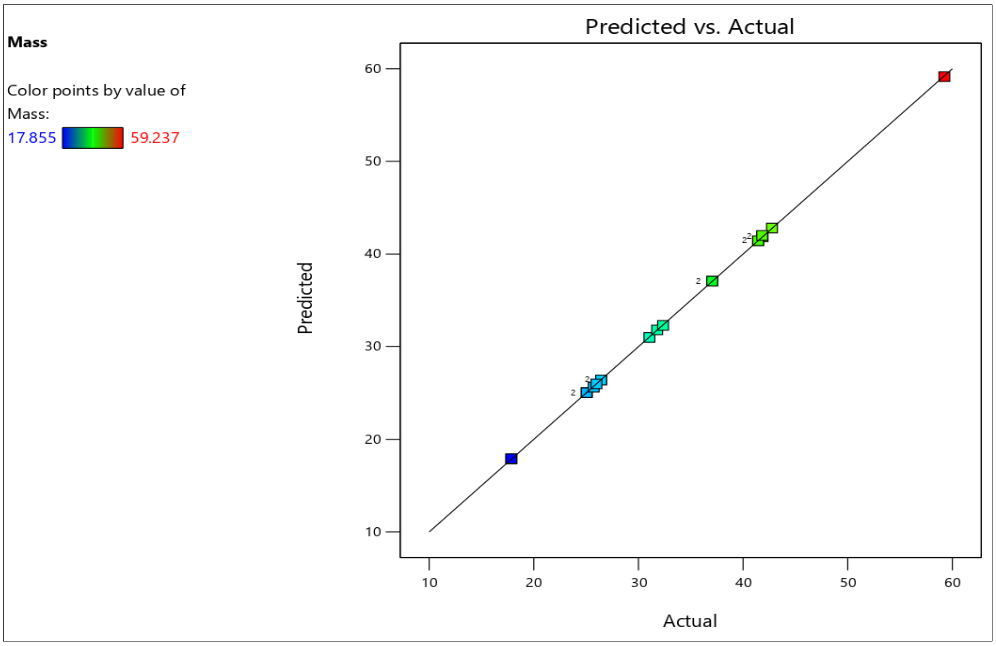

Fig 7: Graphical representation of predicted versus actual values for flywheel mass, demonstrating exceptional model accuracy.

The contour plot in Figure 8 illustrates the relationship between von Mises stress and the geometric parameters (outer diameter and thickness) at a constant angular speed of 235.62 rad/s. The stress distribution reveals that larger outer diameters subject the flywheel to greater centrifugal forces, increasing stress levels. Conversely, increased thickness generally reduces stress through more uniform load distribution.

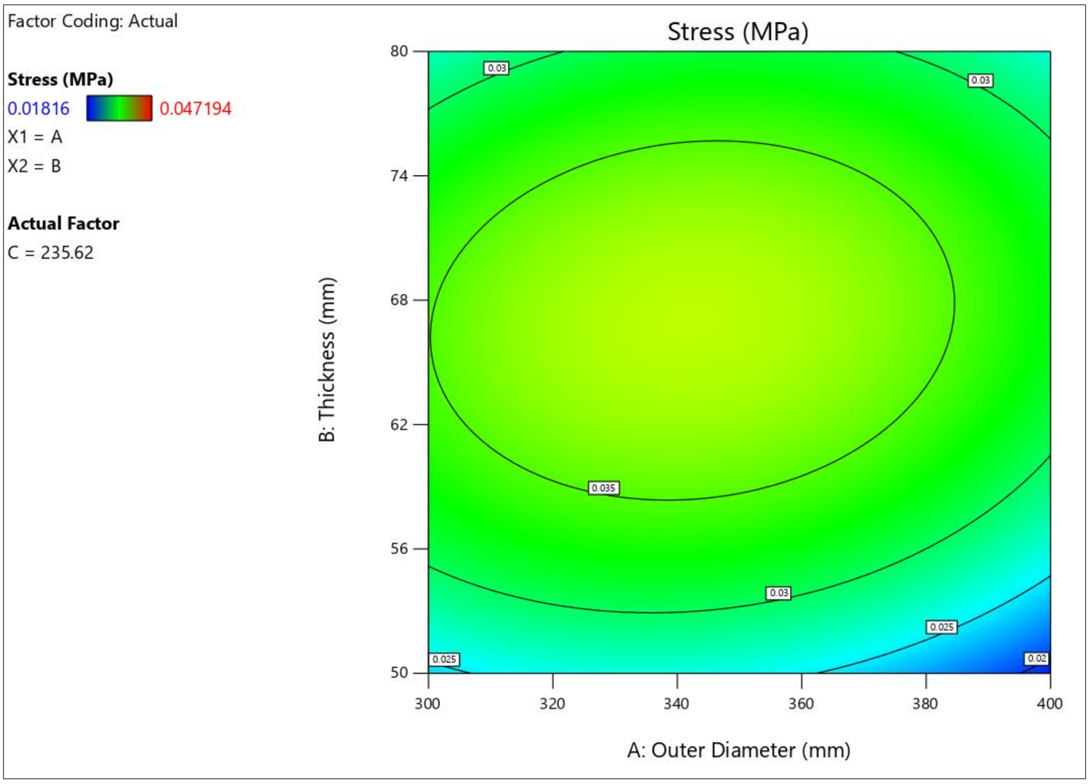

Fig 8: Contour plot showing the response surface for von Mises stress as a function of outer diameter (A) and thickness (B) at constant angular speed (C = 235.62 rad/s).

The three-dimensional surface plot in Figure 9a provides enhanced visualization of the stress response surface, clearly depicting the nonlinear interactions between design variables. The surface demonstrates that stress peaks occur at specific diameter/thickness combinations, with stabilization observed in other regions.

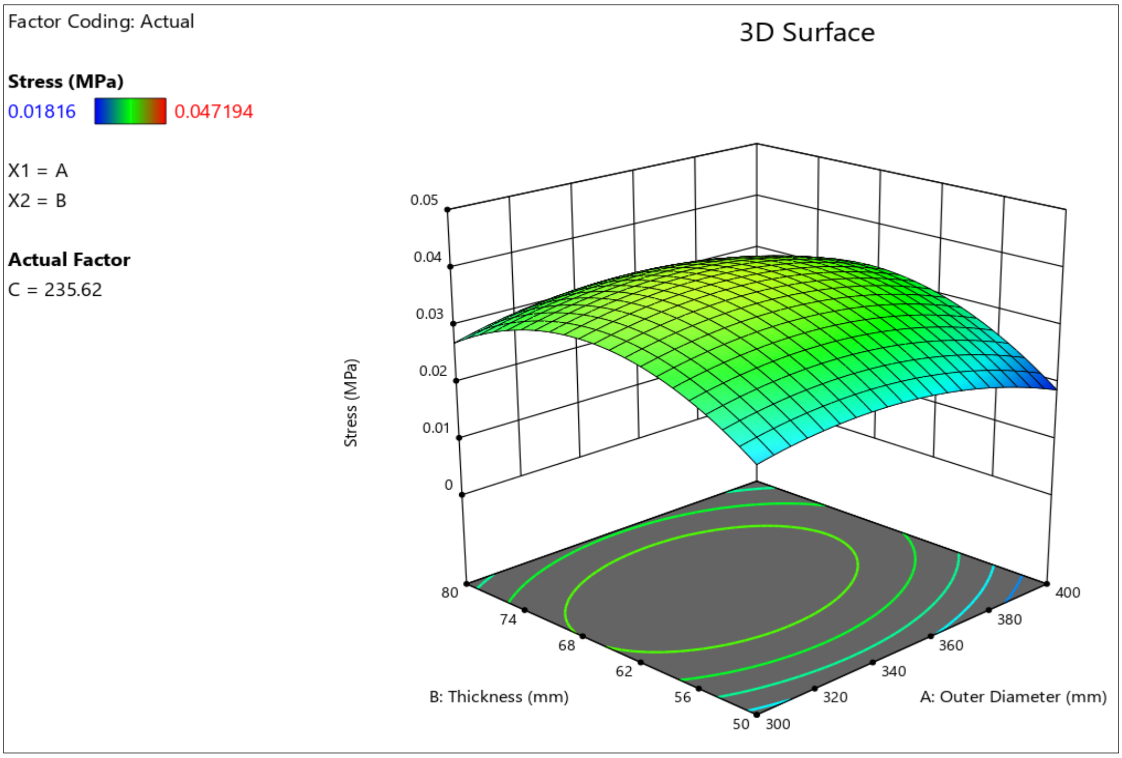

Fig 9: Three-dimensional surface plot illustrating the relationship between outer diameter, thickness, and von Mises stress response.

Table 6: Simulation results for the fuel-less energy storage system at various parameter combinations.

Run	Diameter (mm)	Thickness (mm)	Speed (rad/s)	Stress (MPa)	Mass (kg)	Energy (J)
1	400	62	248.97	0.0338	42.77	26775
2	302	67	227.77	0.0355	26.44	7956
3	355	50	227.67	0.0232	25.06	10362
5	300	50	314.16	0.0259	17.86	10089
8	400	80	254.47	0.0221	59.24	38743
10	400	50	314.16	0.0276	31.79	31688
17	300	80	314.16	0.0214	32.36	18282

Optimal Configuration: Based on the comprehensive analysis, the optimal flywheel configuration was determined to be: outer diameter of 400 mm, thickness of 50 mm, and angular speed of 236.17 rad/s. This configuration achieves the data presented in Table 7.

Table 7: Optimal flywheel configuration parameters and corresponding response values.

Parameter	Value	Units	Significance
Outer Diameter	400	mm	Maximum tested value
Thickness	50	mm	Minimum tested value
Angular Speed	236.17	rad/s	Optimized for balance
Von Mises Stress	0.0190169	MPa	Structurally sound
Mass	31.97	kg	Material efficient
Displacement	1×10^{-14}	mm	Negligible deformation
Energy Storage	18,000	J	Target capacity achieved

The exceptionally low von Mises stress of 0.0190169 MPa in Table 7 indicates a structurally sound design that minimizes material fatigue and failure risk. The negligible displacement (1×10^{-14} mm) confirms system stability under operational conditions. The mass of 31.97 kg represents an optimal balance between energy storage requirements and material efficiency, while the energy storage capacity of 18,000 J meets the target requirement for the fuel-less generator application.

4. Conclusions

This study successfully validated the structural integrity of a high-speed flywheel energy storage system through comprehensive static structural analysis. The key findings are summarized as follows:

- **Displacement Analysis:** FEA revealed deformations ranging from 0.00 mm to 0.016 mm, demonstrating exceptional structural stiffness. The uniform displacement distribution confirms the absence of stress concentrations or weak points in the frame structure.

- **Von Mises Stress Analysis:** Maximum stress of 8.335 MPa was recorded, well below the material yield strength of AISI 1020 steel (350 MPa), resulting in a safety factor exceeding 40. This confirms that plastic behavior is not predicted under normal operating conditions.
- **Statistical Modeling:** ANOVA validated the developed models for all response parameters. The mass model (F = 32451.30) and energy model (F = 955.46) showed exceptional significance ($p < 0.0001$), while the stress and displacement models demonstrated adequate precision for design space navigation.
- **Optimal Configuration:** The identified optimal parameters (400 mm diameter, 50 mm thickness, 236.17 rad/s) achieve a harmonious balance between structural integrity ($\sigma VM = 0.0190169$ MPa), material efficiency (31.97 kg), stability (displacement = 1×10^{-14} mm), and energy storage capacity (18,000 J).
- **Model Validation:** Excellent agreement between predicted and actual values across all response parameters confirms the reliability of the developed predictive equations for future design iterations.

The static structural analysis methodology presented herein provides a robust framework for validating flywheel designs in fuel-less energy storage applications. Future work should incorporate dynamic loading scenarios, cyclic fatigue analysis, and experimental prototype validation to further enhance design confidence. The demonstrated structural integrity under the specified loading conditions supports the viability of the proposed flywheel system for sustainable power generation applications in institutional and industrial settings.

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