Research Article

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Performance optimization of flywheel using experimental design approach

https://doi.org/10.1515/ehs-2022-0007
Received January 25, 2022; accepted June 6, 2022;
published online June 22, 2022

Abstract: The flywheel is the simplest device for mechanical battery that can charge/discharge electricity by converting it into the kinetic energy of a rotating flywheel, and vice versa. The energy storage systems based on flywheel now arousing great interest, since this technology can offer great advantages in durability and lifetime. However, the flywheel performance rotation is limited by the strength of the materials, from which it is constructed, and the geometry. Greater control over those parameters could improve the development of high performance of a flywheel energy storage system (FESS). The main interest of this study is to demonstrate the influence degree of each parameter of geometry by using the mathematical method of design of experiments, in order to be able to optimize the adequate parameters for a high performed shape of the flywheel.

Keywords: design of experiments (DOE); flywheel energy storage system (FESS); optimization; SolidWorks.

Introduction

Flywheels have been used for a long time as mechanical energy storage devices; one of the earliest forms is a potter's wheel. Today, the flywheels are a practical and attractive solution for energy storage technologies. The recent improvements in materials, magnetic bearings, power electronics, and the introduction of high speed electric machines, has re-emerged, the flywheel, as a promising for energy storage applications (Bakay et al. 2010; Bolund, Bernhoff, and Leijon 2007; Conteh and Emmanuel 2016; Erhan and Ozdemir 2021; Haruna et al. 2011; Liu and Jiang 2007; Murakami et al. 2007; Šonský and Tesař 2019). Compared to a chemical battery, the FESS has great advantages in durability and lifetime, especially in hot or cold environments (Takahashi, Amei, and Itoh 1990; Takahashi, Itoh, and Andoh 1989), that makes it an appealing candidate for a wider use in renewable energy systems and become an attractive battery alternative. The storage capacity of flywheel depends on the rotational speed and the moment of inertia; which they are closely related to the form of rotor.

Many research works have been done on flywheel geometry. A study of flywheel geometry by Shinde et al. (2017) showed that flywheel with triangular cross-sectional geometry is more efficient than compared to the rectangular and circular cross-section of geometry. A similar study was done by Pawar et al. (2018); after performing a 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. More recently, a study conducted by Vardaan and Kumar (2022) where they carried out the analysis of the thresher machine flywheel. The authors concluded that the amount of kinetic energy stored by wheel-shaped structure flywheel is greater than any other shape of the flywheel. Therefore, it can be noted that the effect of geometry plays a significant role in flywheel performance.

The purpose of this study is to demonstrate how to find the most efficient geometry in order to increase the performance of the flywheel. A virtual 3D model of the flywheel is designed and analyzed, which provides a database of the design for mathematical modeling and optimization of the flywheel.

Flywheel modelling & simulation

In the present study, among parameters defining the flywheel geometry, three of them were taken under considerations

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Table 1: Geometry parameters of the flywheel.

Geometry parameter	Rim Diameter	Rim Width	Rim Height	Disk Thickness	Hub Diameter	Hub Gap	Hub Height
Designation	Dr	Wr	Hr	Td	Dh	Gh	Hh
Value (mm)	Variable	Variable	Variable	2	20	5	10

which seem to have significant influence on the flywheel performance. As demonstrated elsewhere (Chiriță et al. 2017), the outer diameter, the rim width and the rim height have a remarkable effect on the specific energy accumulated by the flywheel. However, an increasing of the thickness of the disc leads to a decrease in the specific energy. The geometry parameters are given in Table 1 and illustrated in Figure 1.

In order, to optimize the performance of the flywheel, different configurations have been created and analyzed by using SolidWorks software. The flywheel was considered of Titanium alloy material (Ti-3Al-8V-6Cr-4Mo-4Zr) with the mechanical properties as noted in Table 2, rotating at 70,000 rpm, which correspond to an angular velocity of 7330.38 rad/s.

A total of 27 configurations of the flywheel geometry has been created, simulated and optimized. Therefore, using the capabilities of ***Evaluate*** tool in SolidWorks, the flywheel mass (m) and the moment of inertia (I) have been defined. Then, the kinetic energy (E_c) stored in the flywheel (Eq. (1)) and the specific energy (E_{spec}) in Eq. (2), were calculated with the formulas below:

$$E_c = \frac{1}{2} I \omega^2 \tag{1}$$

$$E_{spec} = \frac{E_c}{m} \tag{2}$$

The present study was conducted such that highlights the varying effect of the geometry parameters, on the mechanical stress of the flywheel. SolidWorks Simulation is powerful Finite Element Analysis (FEA) software, that allowed to determine the maximum stresses in the flywheel for each analyzed 3D model configurations.

The geometry parameter values, the mass, the moment of inertia, the kinetic and specific energy and the maximum of Von-Mises stress values are given in Table 3.

Mathematical modelling

In order to investigate the effect of geometry parameters on the flywheel performance under high speed rotation, the modelling by the mathematical method of design of experiments seems adequate. By using the functionalities of MODDE, a software package that is used by scientists, engineers and statisticians alike to help understand complex processes and products (Umetrics™ 2017), the study was conducted using the No-conventional design of experiments, which allow to use the obtained data to establish a mathematical model that makes possible to evaluate the degree of the effect of each parameter separately and their simultaneous interaction, on the accumulated energy and the mechanical stress of the flywheel. Then, according to the desired limit of response, the geometry parameters will be optimized to reach the best possible solution.

Mathematical models

Mathematical modelling by design of experiments is done by a polynomial of a second degree equation (Eq. (3)).

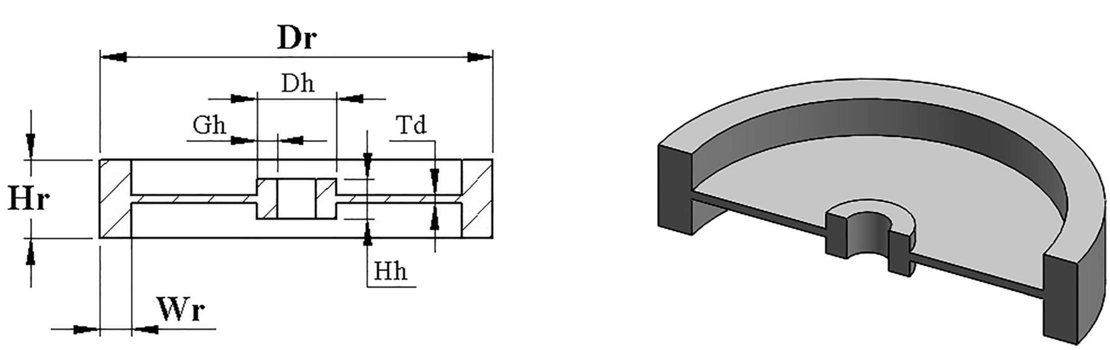

Figure 1: Section view of 3D model of the flywheel.

Table 2: Mechanical proprieties of the flywheel material.

Material	Density (kg m^{-3})	Tensile strength (MPa)	Young's modulus (GPa)	Yield strength (MPa)
Ti-3Al-8V-6Cr-4Mo-4Zr	4820	1220	104	1034.21

$$y_i = a_0 + \sum_{i=1}^{k} a_i x_i + \sum_{i=1}^{k} a_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} a_{ij} x_i x_j \quad (3)$$

After estimating the coefficients, using the capabilities of *Edit Model* tool in MODDE (Umetrics™ 2017), the mathematical models of the specific energy response (Eq. (4)) and Von-Mises stress response (Eq. (5)) are established.

$$y_{\text{Espec}} = 58478.6 + 10638.7x_1 + 1105.69x_2 + 5203.31x_3 + 447.17x_1x_2 + 996.47x_1x_3 - 615.186x_2x_3 \quad (4)$$

$$y_{\text{VMs}} = 743.445 + 124.934x_1 + 76.899x_2 + 117.953x_3 + 11.447x_1x_2 + 25.945x_1x_3 + 25.832x_2x_3 \quad (5)$$

- x_1: represent the coefficient of rim diameter;
- x_2: represent the coefficient of rim width;
- x_3: represent the coefficient of rim height;
- y_{Espec}: represent the response of specific energy;
- y_{VMs}: represent the response of Von-Mises stress;

It is important to note that the model validity (R2) and reproducibility (Q2) qualities of coefficients estimated above are acceptable (Table 4), which ensure the validation of the mathematical models to be exploited in further studies.

The effect of geometry parameters

Figure 2 is a graphical presentation of the estimated coefficients of the mathematical models. From the vertical bars of the diagram results that, in general, the effects of parameters separately appear to have a positive act on the increase of the specific energy. The rim diameter (Dr) and rim height (Hr) presents a relatively large effect compared to that of width rim (Wr). Although, the effects of parameters separately might increase the maximum value of

Table 3: Configurations & Calculated parameters of flywheel.

N°	Dr (mm)	Wr (mm)	Hr (mm)	Mass (Kg)	Inertia (Kg mm^{-2})	Kinetic Energy (J)	Specific Energy (J/Kg)	Von-Mises Stress (MPa)
01	100	4	10	0.13	202.561	5442.259	41863.527	465.584
02	100	4	20	0.188	336.765	9047.952	48127.404	577.373
03	100	4	30	0.246	470.968	12653.619	51437.474	593.85
04	100	6	10	0.152	246.738	6629.173	43612.983	515.318
05	100	6	20	0.237	436.164	11718.530	49445.276	657.958
06	100	6	30	0.323	625.589	16807.861	52036.721	728.424
07	100	8	10	0.173	285.285	7664.826	44305.350	560.011
08	100	8	20	0.284	522.894	14048.728	49467.351	706.261
09	100	8	30	0.396	760.502	20432.603	51597.482	771.789
10	110	4	10	0.151	283.606	7619.715	50461.692	558.905
11	110	4	20	0.215	464.212	12472.103	58009.783	699.461
12	110	4	30	0.279	644.818	17324.491	62094.951	742.946
13	110	6	10	0.175	344.2	9247.710	52844.057	600.194
14	110	6	20	0.27	600.549	16135.105	59759.647	768.725
15	110	6	30	0.364	856.898	23022.499	63248.624	855.202
16	110	8	10	0.198	397.812	10688.117	53980.391	659.851
17	110	8	20	0.322	721.175	19375.994	60173.896	859.464
18	110	8	30	0.445	1044.538	28063.871	63064.879	926.309
19	120	4	10	0.173	386.116	10373.87798	59964.61262	652.607
20	120	4	20	0.243	622.755	16731.71892	68854.81038	797.407
21	120	4	30	0.314	859.395	23089.58673	73533.71569	856.655
22	120	6	10	0.2	466.761	12540.58796	62702.9398	715.09
23	120	6	20	0.303	804.207	21606.83652	71309.69149	930.909
24	120	6	30	0.407	1141.653	30673.08508	75363.84542	1027.426
25	120	8	10	0.225	538.926	14479.4636	64353.17154	751.406
26	120	8	20	0.361	966.579	25969.32685	71937.19349	994.369
27	120	8	30	0.497	1394.232	37459.19011	75370.60384	1099.517

Table 4: Summary of coefficient qualities list.

	Specific energy	Von-Mises stress
Model validity (R2)	0.990816	0.968959
Reproducibility (Q2)	0.983968	0.939926

Von-Mises stress. The rim diameter shows the highest effect, followed by rim height and relatively less important effect of width rim.

On the other hand, the interaction effect of Dr*Wr and Dr*Hr. leads to an increasing of the specific energy. However, the simultaneous increase of Wr*Hr, may negatively affect on this last and even on Von-Mises stress by increasing its maximum value. The highest and lowest interaction effect on Von-Mises stress are shown successively by Dr*Hr and Dr*Wr interaction of parameters.

Optimization of parameters

The aim of this part is to design a flywheel with a high energy storage density and supporting high speed. By observing the effect of Wr and Hr separately, which is positive on the specific energy and their interaction (Wr * Hr) which seems has a negative effect; for this reason, care has to be taken in manipulating the values of design parameters. Therefore, it is appropriate to apply the optimization of geometry parameters in the design of flywheel; by using the capabilities of ***Optimizer*** tool on MODDE, which helps on how to find the optimal conditions or best compromise as a set point and alternatively the most robust set point.

Table 5: Optimization.

Parameters	Objective	Optimized value
Specific energy (J/Kg)	Maximize	73533.715
Von-Mises stress (MPa)	>Yield strength	856.655
Rim diameter (mm)	Free	**120**
Rim width (mm)	Free	**4**
Rim height (mm)	Free	**30**

The bold values represent the optimized values calculated by the software "MODDE".

In general, flywheel designs are subject to size constraints in addition to stress constraints. Actually, the load on the flywheel is mainly centrifugal force. Therefore, the objective of optimization is based on a combination of reducing the stress constrains applied to the flywheel and reaching the highest level of energy storage density (Table 5).

Table 5, shows the optimized values of geometry parameters, with the goal of maximizing the specific energy while minimizing Von-Mises stress, such a way that the high value of the stress constraints, shall be less than the yield strength of the flywheel material. The table exposed the design parameter values which allow to obtain the highest possible value of specific energy under minimum values of applied stress constraints and without exceeding

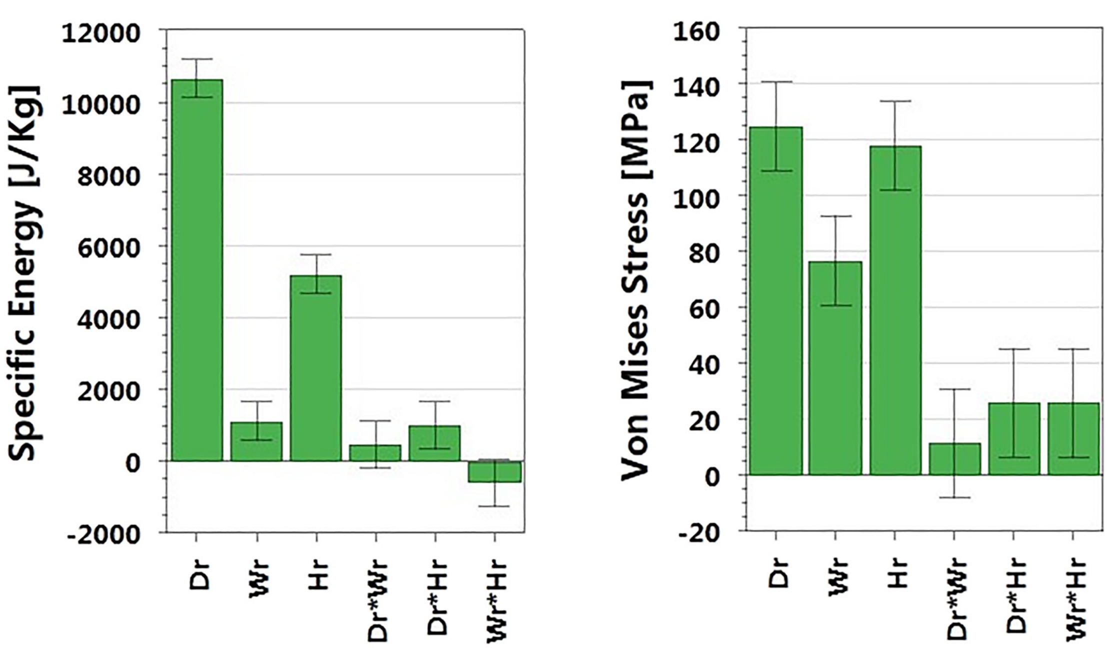

Figure 2: Diagram representation of the parameters effects.

the Yield strength. It is noted that the optimized values of rim diameter and rim height, reached their maximum levels, however, it reached its lowest level for the rim width. As demonstrated previously, the simultaneous increase of geometry parameters can have a negative effect on responses.

The optimized values of design parameters of the flywheel, at constant rim diameter values of 105 and 115 mm, are shown in Table 6. The specific energy exhibited a high value for the configuration M_{115}, about 16% more than for M_{105}. This result was achieved with a relatively little decrease of the rest of the parameters. A remarkable increase of von-mises stress value is noted for M_{115}, without certainly exceeding the yield strength.

In Table 7, the optimized values of design parameters of the flywheel are obtained at constant rim width values of 5 and 7 mm. From the table, it is noted that the high value of the specific energy was recorded by the configuration M5. However, the rise in the constant value of rim width, leads to a relative decline in response of specific energy, in M7. For the rest of parameters, no change was noted of the rim diameter, and a considerable decrease in rim height. On the other hand, the maximum stress value of both configurations, do not show a significant difference.

Table 6: Optimization at a constant rim diameter (Dr = Cst).

Parameters Configuration	Objective	Optimized value M_{105}	Optimized value M_{115}
Specific energy (J/Kg)	Maximize	58131.2	69928.7
Von-mises stress (MPa)	Minimize	882.967	1002.18
Rim diameter (mm)	**Constant**	**105**	**115**
Rim width (mm)	Free	8	7.20
Rim height (mm)	Free	30	29.99

The bold values represent the optimized values calculated by the software "MODDE".

Table 7: Optimization at a constant rim width (Wr = Cst).

Parameters Configuration	Objective	Optimized value M_5	Optimized value M_7
Specific energy (J/Kg)	Maximize	74,848.2	72,250.6
Von-mises stress (MPa)	Minimize	955.189	975.28
Rim diameter (mm)	Free	120	120
Rim width (mm)	**Constant**	**5**	**7**
Rim height (mm)	Free	30	24

The bold values represent the optimized values calculated by the software "MODDE".

Table 8: Optimization at a constant rim height (Hr = Cst).

Parameters Configuration	Objective	Optimized value M_{15}	Optimized value M_{25}
Specific energy (J/Kg)	Maximize	67877.9	73044.3
Von-mises stress (MPa)	>Yield strength	871.861	1007.63
Rim diameter (mm)	Free	120	120
Rim width (mm)	Free	8	7.33
Rim height (mm)	**Constant**	**15**	**25**

The bold values represent the optimized values calculated by the software "MODDE".

In Table 8, the optimizing was carried out at constant rim height values of 15 and 25 mm. The optimized values of design parameters of the flywheel show a high value of specific energy in the configuration M_{25}. Compared to M_{15}, only the rim width was readjusted to 7.33 mm, with the change of the constant value of rim height from 15 to 25 mm, however, the rim diameter remains similar. As for Von-Mises stress, it was relatively highest in M_{25}.

Conclusions

Flywheel mechanism can effectively improve the mechanical performance of the system, and the flywheel's energy storage density can be significantly improved by highlights the degree of the effect of the design geometry parameters. This paper presents a mathematical method for optimization of geometry parameters of the flywheel which offer many possibilities to optimize according to the desired limit of response.

The results obtained in the present study can be summarized by the following conclusions:

- The 3D model configurations were created and simulated using the modeling capabilities and powerful Finite Element Analysis (FEA) of SolidWorks software, which reveal a great efficiency in the study of different design cases.
- The outstanding modeling capabilities of MODDE based on the Design of Experiments (DoE) approach, allow to establish a mathematical model of the response, which easily explains the degree of the effect of the design parameters separately and their simultaneous effect.
- The analysis of mathematical models of the responses of specific energy and Von-Mises stress, has demonstrated that the rim diameter presents a high influence

on the accumulated energy by the flywheel; followed by the rim height and the rim width. However, their interaction may adversely affect the responses.

– The use of the capabilities of *Optimizer* tool on MODDE, can be very helpful on how to find the optimal values of design parameters based on a combination of primarily reaching the highest level of energy storage density and reducing the stress constrains exercised centrifugal force and by applied to the flywheel.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.
Research funding: There is no funding source.
Conflict of interest statement: The authors declare that they have no conflict of interest.
Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.
Informed consent: Informed consent was obtained from all individual participants included in the study.

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