Finite element optimization of flywheel employed in internal combustion engines

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Abstract. The paper researched a flywheel design based on the replacement of typical circular cutouts with longitudinal radial slots which optimizes weight with simultaneous enhancement of the dynamic stress capabilities. A grey cast iron flywheel (FG 200), under conditions representative of its operating conditions, has been modelled using finite element analysis (FEA) in ANSYS and analysed using harmonic, stress analysis and static-equivalent stress analyses. Comparisons of traditional circular cutouts with longitudinal radial slits at the same mass reductions achieved had been done. Slot-based design had less maximum von Mises stress and more evenly spread stress along with smaller resonant amplitudes on the operating band. They will give detailed material properties, boundary condition, meshing and convergence and run sensitivity analysis of slot length, width and end radius to quantify the trade-off between weight reduction and stress. The findings encourage longitudinal radial slot as a viable alternative of reducing inertia and enhancing robustness, so far as slot geometry is optimized and operating speeds would not be resonating.

1 Introduction

Flywheels are necessary elements in stabilizing crankshaft velocity, storing kinetic energy at the non-power strokes and releasing the same where needed. Traditional ways of minimizing flywheel inertia include the use of circular cutouts, which are effective in reducing the weight, but cause high stress concentrations at the edges, and have an adverse effect on fatigue life. Though some past research has investigated lightweight flywheel design, there has been an apparent dearth of systematic and quantitative comparison of conventional circular cutouts versus longitudinal radial slots at the same mass and loading. This is in line with a gap in the literature which is pointed as the potential benefits of slot-type designs in reducing stress consciousness and creating dynamic performance have not been completely considered [1, 2].

This research paper aims at addressing this gap given that it is intended to design a realistic, practical flywheel redesign with longitudinal radial slots located along centrifugal directions of stress. The geometry of the slot is to be reduced to minimize the stress concentration around circular cutouts but achieve the same bulk reduction [3, 4].

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The giving and the improvement of this analysis contain:

1. Proportional test: Coordinated-mass testing of cutouts of circular orifice in comparison to longitudinal radial vacuities under the same load situations.

2. Working: Notified exposure of properties of material, boundary conditions, meshing plans, convergence criteria, and sensitivity investigates.

3. Design perceptions: The engineering evaluation of an internal rectangular rim flywheel topology of six spokes (width/thickness ratio of 2) to concentrate on realistic stress distributions.

4. Practical advice: Numerical relationship between slot structure and dynamic operation, providing practical suggestions to be implemented in model that of slot manufacturability that avoids resonance but maintains stress and energy efficiency.

The principal goal is to rule whether longitudinal radial slots may provide the equal or better dynamic-stress presentation of circle cutouts at the same mass economies and to identify feasible types of slot structure that are robust, formable and resonance free [5-7].

2 Methods

2.1 Geometry and reason:

The flywheel topology involves a rectangular rim (a width/thickness proportion 2) that has 6 spokes that are attached to a central hub and the outer diameter is restricted to 2 m. This design is popular in industry since it offers an excellent trade off between structural rigidity, designability, and weight distribution. The six-spoke design provides adequate circumferential stiffness to provide operating integrity, good modal symmetry to minimize vibration, and does not present a large number of spokes which leads to a lot of stress-concentration or manufacturing complexity. The rim is so made that it supports about 90 percent of the total moment of inertia, to store as much energy as possible per unit mass [8]. There were two flywheels configurations compared:

1. Traditional circular cutouts: Oversized circular holes designed to reduce inertia while preserving cross-sectional area.

2. Longitudinal radial slots: Radially-oriented slots with blunt ends to reduce stress concentration factors, designed to have the same unfilled area as the circular cutouts.

A sensitivity analysis was performed on the slot geometry with the following ranges :

- Length: 0.4 R to 0.7 R
- Width: 0.02 R to 0.06 R.

End radius : 0.5 to 1.5 × slot width.

The research problem that is being investigated is to quantify the trade-off between mass decrease, stress distribution, and dynamic reaction.

2.2 Material properties

Tables 1 and 2 depict the material properties and boundary conditions.

Table 1. Material properties.

Property	Value
Density ρ	7100 kg/m³
Young's modulus E	110–120 GPa (110 GPa used)
Poisson's ratio ν	0.25
Ultimate tensile strength	~200 MPa (cast iron in tension; design uses allowable stress well below UTS)
Allowable working stress (design)	≤ 0.35×UTS, accounting for stress concentrations and fatigue

Table 2. Operating conditions and boundary conditions.

Category	Definition
Speed range	200–220 rpm nominal (210 rpm), and as the harmonic analysis was performed to pick up resonances around 200-1400 Hz response of the elastic structure
Energy fluctuation	30,000 N·m cyclic variation
Peak torque	Both 75,000 N.m (as equivalent loading in the exercise to static-equivalent stress and as input in harmonic excitation)
Constraints	The hub-shaft interface is fixed in all DOFs, spoke-rim and spoke-hub interfaces are bonded.
Damping	Damping ratio modal1–2% (baseline 1.5%)
Mass target	To isolate the effects due to geometry, equal mass was removed in the two designs

2.3 Analyses performed

The rim was represented by 10-node quadricular tetrahedrons and local refinement was used on slots, cutouts and spoke-rim fillets. The model was tested by verifying the energy errors and element quality. Interfaces had been modeled as bonded and not as contact surfaces so artificial loss of stiffness could be avoided. In bulk areas the element size (h) was global (68 mm), and in local areas (cut outs, slots edges, fillets, etc.) it was refined to h = 1.52 mm. The convergence was determined using two criterion, namely, a decrease in von Mises stress of less than 3 percent between mesh refinements, and that variation in the first three natural frequencies of less than 1 percent between successive refinements. A mesh-independence study revealed that only additional mesh refinement could not alter stress and dynamic responses and that reliable numerical results are obtained [8-11].

In order to carry out an ideal analysis on the structural performance of the flywheel, three analyses were carried out. The test was initiated with the analysis of the statical-equivalent

stress to verify the integrity of the structure by the real-life loads, including centrifugal forces caused by rotation and the ultimate operational torque. The stresses in the key regions, including von Mises, radial and tangential stresses, were assessed in order to determine the possible weak points under the most seizing conditions. Then a harmonic analysis was carried out to interpret the vibration behavior of the flywheel [12, 13].

Another experiment that was performed was a frequency sweep between 200 and 1400 Hz, which was applied at the hub, to simulate the changes in torque and was used to identify the resonance points and quantify structural displacement. This test gave an idea of the dynamic stability and vibration sensitivity of the component. Lastly, sensitivity analysis was conducted to investigate the effect of slot dimensions on peak stress and resonance behavior (length, width and corner radius). Pareto diagrams were used to summarise the resulting trade-offs because the connection between the decrease in mass and the increase in stress can be explained visually by using Pareto diagrams. This methodology assisted in the choice of a slot geometry, which would balance the performance, safety and manufacturability factors [14, 15].

3 Results and discussion

3.1 Harmonic response

Figure 1 presents the amplitude of the displacement at various frequencies of three, mass-matched flywheel designs: Model 1 which uses circular cutouts (which is used as the baseline) Model 2 which uses circular cutouts with exponential mass tuning and Model 3 which uses longitudinal radial slots. Although both of the models (Model 1 and Model 2) had their largest amplitude of displacement at approximately 600 Hz, Model 3 had a resonance amplitude shift toward a lower frequency as indicated by the changes in stiffness and mass distribution caused by the radial slots. The highest displacement amplitudes were 0.15 mm with Model 1, 0.13-0.14 mm with Model 2 and 0.08-0.09 mm with Model 3. This large decrease in amplitude in resonance of the slotted design is a sign of better dynamic performance. To reduce the vibration, these findings imply that either the operation speeds should not be found in the resonant frequency ranges or more damping should be applied. Comprehensively, the results highlight the benefit of longitudinal radial slots in optimizing vibration behavior without significant changes in mass reduction, which provides definite practical advice on how to optimize flywheel design.

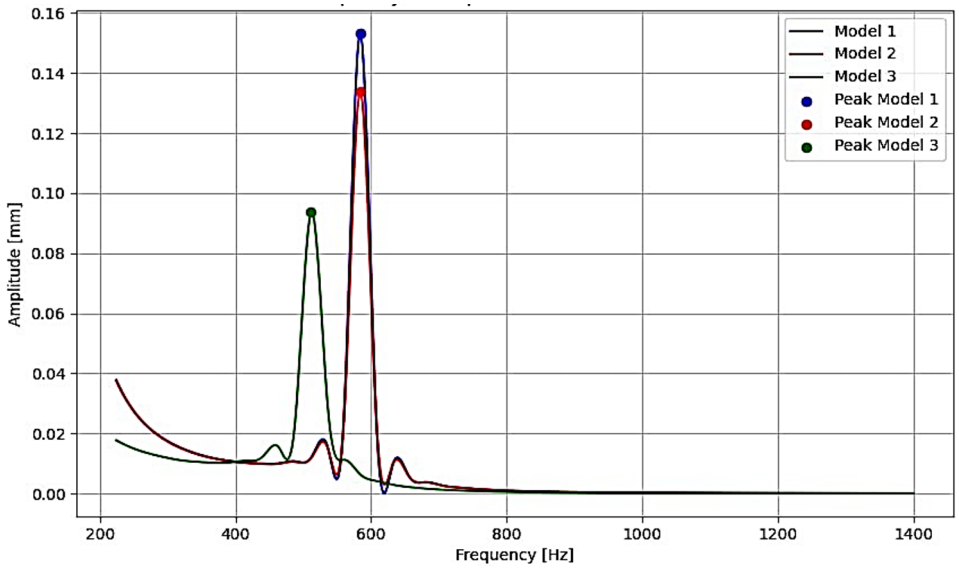

Fig. 1. Frequency versus displacement amplitude for three mass matched.

3.2 Comparison of stresses: circular cut-outs versus longitudinal radial slot

The pattern of stress concentration was very evident in the circular cutout design whereby the greatest von Mises stress concentrated in the edges of the cutout. Conversely, the longitudinal radial slots, which had rounded end radii, essentially reallocated the stresses along the slot boundaries which decreased the maximum values of the stress. The peaks of stresses in the slotted design changed to the edges of the slot and the spokes-rim interfaces, with the higher end radii and slot dimensions helping to reduce the stress levels. Figure 2 shows the correlation between the mass of the rim and the tension in the spokes.

A close linear relationship can be noted: as the rim mass is increased between 200 kg and 750 kg, the maximum stress occurred on the spokes increases between about 0.15 N/mm 2 and 0.65 N/mm 2. Relative mass fractions or design utilization levels are percent values at each data point (30 100). This tendency makes the major trade-off in the design of flywheels apparent: the heavier the rim, the higher the energy storage capacity, the higher the stresses on the spokes. Thus, a good design should strike a balance between the rim mass and structural strength that should enable the highest energy performance and durability. Stress values at different flywheel geometry modifications is shown by Table 3. Longitudinal radial slots have been used to offer a handy way of attaining this balance, consisting of considerable mass-reduction and a reduction in the maximum stress concentrations.

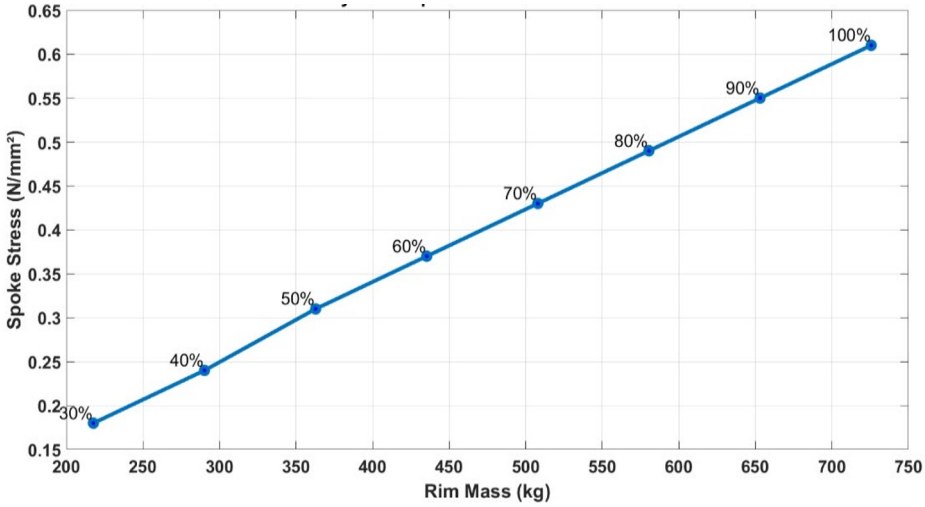

Fig. 2. Von Mises stress—circular cutout.

Table 3. Stress values at different flywheel geometry modification.

Metric	Circular cutouts	Longitudinal radial slots
Max von Mises stress (MPa)	≈ 250	≈ 220
Peak radial stress (MPa)	≈ 120	≈ 105
Peak tangential stress (MPa)	≈ 180	≈ 160
Stress standard deviation (MPa)	≈ 45	≈ 30
Peak location	Cutout edge	Slot inner end/spoke–rim fillet

3.3 Mass–stress and speed–mass relationships

Figure 3 illustrates the existing correlation among flywheel mass, stress and rotational speed, it is worth noting that flywheel mass, stress and rotational speed have a nonlinear relationship that is important in the design of rotational energy storage. The mass required in angular velocity range of 10-30 rad/s reduces considerably which implies that by increasing operating speed by small margins, the flywheel mass can also be reduced accordingly. Above 30 rad/s the curve levels off with less mass being lost by each increase in velocity. This is consistent with the theoretical expression, E=1/2 I ω^2, where EEE is the energy stored, III is the moment of inertia, and O is the angular velocity. Increasing the energy requirement, at a fixed energy requirement, will require a reduction in the moment of inertia and, therefore, mass of the flywheel. Another trade-off in engineering identified in the plot is between rotational speed and structural mass. With this relationship, designers are able to use it to choose high speed, low-mass configurations, which yield the highest material efficiency whilst retaining the desired energy storage capacity. These balances that are necessary in obtaining the best performance and durability in flywheels.

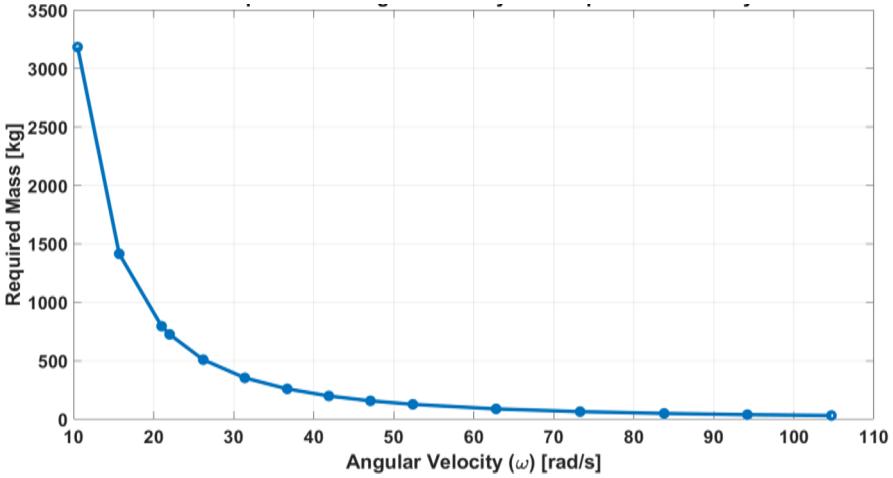

Fig. 3. Angular velocity versus flywheel mass for constant energy.

3.4 Sensitivity and trade-offs slot length:

Make the slots longer will decrease the mass of the flywheel and reduce bending stiffness and move resonances to lower frequencies. An approximate maximum length of slot is 0.6-0.65 R without extra damping. There are wider slots which escalate the stress when end radii are not scaled respectively. To regulate stress concentration factor Kt, it is required to maintain a minimum end radius of slot width. The major stress mitigation parameter is the end radius. Peak von Mises stresses are much lower with an increased end radius without a significant mass penalty. Slots may be machined with CNC or they may be sand cast with cores. Radii are large and uniform fillets reduce the stress concentrations due to machining. In the case of composite rotors, the laminations can be slot-like, but more attention must be paid to the rotor-burst containment at high speeds.

4 Practical guidance operating band:

In order to guarantee good performance of the flywheel, structural resonance detected during the harmonic analysis should be avoided in engine working. In situations where it is not possible to avoid the damping, it is advisable to include more damping. Longitudinal slots are to be designed according to certain targets: the minimum thickness of a slot is to be 1mm, the radius on its end must be bigger than the thickness to strike the balance of mass savings and stress reduction. Both tuning slot length and width are to be optimized in a manner that both reduces the mass and also takes care of resonance frequency changes.

Some of the strengths of the six-spoke topology are the near-spherical symmetry of its stiffness, low axial forces between the rim and the hub, and the ease with which it is cast and machined. Other counts of the spokes (four or eight) may also be tested similarly on account of the packaging limitations. In high-speed rotors at frequencies of more than 10,000 rpm, close attention to material, burst containment, and possibly vacuum working is critical. Whereas the concept of slot design may be used in such condition, it needs to be requalified by stress and modal analysis in order to have safe and effective operation.

5 Conclusions

This paper has shown that longitudinal radial slots are much superior to circular cutouts in minimizing peak von Mises stress and attaining a more uniform stress field at equivalent mass reduction. In addition to this, the analysis of dynamic response reveals that these slot designs lower the amplitude of the peaks of the harmonic response and shift the resonance frequencies to the positive range, thus improving the overall vibration response, but they must be carefully tuned in terms of the operating frequencies to prevent resonant peaks in the structures. The end radius is known to be the most crucial parameter in stress reduction, and slot length and width are convenient ways to manipulate mass, but it is important to note that too much manipulation may have a negative impact on stiffness and resonance properties. Lastly, the research piece supports the fact that slotted flywheel constructions can be fabricated in traditional ways, however, the speedy utilization might require revised material choice, blast safety precautions, and rotor-burst suppressive approaches. These results, jointly, have quantitative and practical implications on how to design flywheel that is lightweight, strong and can be produced.

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