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Design and Structural Simulation Analysis of Flywheel Rotor

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Abstract. Flywheel mechanism can effectively improve the mechanical performance of the system, and the flywheel's energy storage density can be significantly improved by optimizing the design. According to the optimal control design theory, the 3D model of the flywheel is established, and the structural analysis is carried out by with the Workbench. In order to improve the flywheel rotor, the influence of the size of the weight reduction hole on the stress distribution and energy storage density of the flywheel was studied. Through the simulation of finite element analysis, the important data for the design and optimization of flywheel has been obtained.

Introduction

The flywheel play an important role in mechanical dynamic system is huge, which can effectively improve the smooth operation of mechanical power system [1]. At the same time, modern technology on energy storage technology requirements are increasingly high and the application of magnetic levitation technology also has made high-speed flywheel energy storage be widespread concern and research. The rotational inertia and speed of the flywheel rotor determine the storage capacity of the flywheel, where the moment of inertia is closely related to the shape and quality of the rotor. The speed is limited because of the yield limit of the material [2]. Therefore, the shape of the flywheel can be optimized to improve the performance of the flywheel. In this paper, a virtual flywheel model is designed and analyzed, which provides data support for the design and optimization of flywheel.

Flywheel shape design

Influence factor of flywheel energy storage. The energy stored in the flywheel is the kinetic energy of the flywheel at high speed [3]. So the storage energy of the flywheel is expressed as:

$$E = \frac{1}{2} I w^2 \tag{1}$$

In this formula: Energy storage density ---- e, Flywheel shape factor (Depending on the shape and stress distribution of the flywheel) ---- K_s, Flywheel material factor(Determined by material properties)--- K_m, Density ----- ρ, Material tensile strength----- σ_b .Thus, the performance of flywheel rotor can be improved from two aspects: (1) increase the quality of flywheel rim, (2) to improve the speed. Excessive rim quality can cause the system to be less flexible. And because of the characteristics of the material, flywheel speed can’t be too high. Therefore, the shape optimization of the flywheel can effectively increase the flywheel's energy storage density under the same conditions.

Typical flywheel shape. Typical composite flywheel rotors are flat rotors, tapered rotors and other shapes of rotors. Specific shapes are thin rings, thick rings and discs. At the same time, flywheel shape includes single-layer cylindrical, multi-layer cylindrical, spindle-shaped, umbrella-shaped, solid disc, belt inertia and wheel and so on.

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Flywheel shapes are complex and diverse, and are suitable for different materials, but the flywheel design materials are distributed evenly along the radial direction and the load on the flywheel material is non-uniformly distributed [4]. In order to make good use of the material, the problem can be solved to a certain extent by optimizing the flywheel shape

Flywheel shape optimization

Solid flywheel shape optimization design. The purpose of this paper is to design a flywheel with a high energy storage density at low speed. In general, flywheel rotors are subject to size constraints in addition to stress constraints:

$$h_{\min} \le h(d) \le h_{\max} \tag{2}$$

In the formula： $h_{\min}$ -- Minimum axial thickness of the rotor, $h_{\max}$ -- Maximum axial thickness of the rotor. According to the optimal control theory, the optimal shape of the solid flywheel rotor is shown in Fig.1.

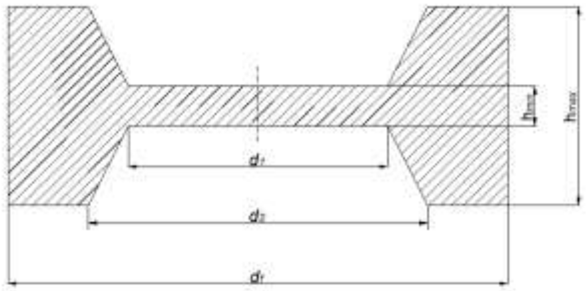

Figure 1. Optimal shape of solid flywheel

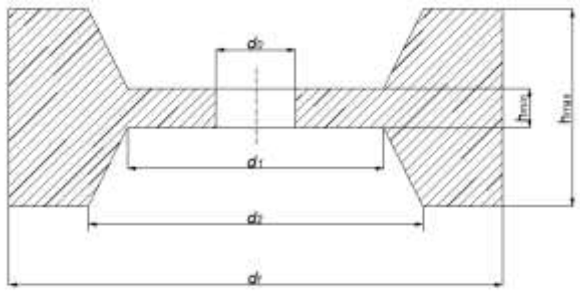

Figure 2. Optimal shape of hollow flywheel rotor

$$h(d) = \begin{cases} h_{\min} & 0 \le d \le d_1 \\ \dfrac{1}{2}\delta_0 (d - d_1) + h_{\min} & d_1 \le d \le d_2 \\ h_{\max} & d_2 \le d \le d_f \end{cases} \tag{3}$$

This is available: $d_2 = d_1 + 2(h_{\max} - h_{\min}) / \delta_0$

Depending on the actual installation requirements, the solid flywheel needs to be designed as a hollow flywheel. Thus, the optimal shape of the hollow flywheel rotor is shown in Fig. 2, and hollow rotor and rotor has the same shape, in addition to the diameter of center hole.

Flywheel topology optimization design. Actually, the load on the flywheel is mainly centrifugal force. Therefore, the actual engineering applications, usually to design the same size of the round hole along the direction of the flywheel, reducing the quality of the flywheel, in order to enlarge flywheel's energy storage density [5].

Through the topology optimization can theoretically design the optimal distribution of the weight loss hole, but in order to reduce the production cost, generally choose a relatively simple optimization model, such as round weight reduction hole. In this paper, the finite element structure simulation method is used to study the relationship between the size of hole and the energy storage density [6].

Flywheel rotor structure analysis

Flywheel stress analysis. During the high-speed rotation, the flywheel is mainly subjected to the centrifugal force. Assuming that the axial thickness of the rotor is smaller than the radius, the stress of the rotor can be analyzed by the plane stress theory [7]. From the equilibrium conditions:

$$h(r)r\frac{d\sigma_r}{dr}+r\frac{h(r)}{dr}\sigma_r+h(r)(\sigma_r-\sigma_\theta)+h(r)\rho w^2 r^2=0 \tag{4}$$

Among them: σ_r ---- Radial stress, σ_θ ----- Ring stress, ρ ---- Rotor material density.

The stress coordination equation:

$$\frac{d\sigma_\theta}{dr}-\mu\frac{d\sigma_r}{dr}+\frac{1+\mu}{r}(\sigma_\theta-\sigma_r)=0 \tag{5}$$

Among them: μ --- The Poisson ratio of the material.

By connecting the above two formulas corresponding to the displacement or stress boundary solution conditions, that is, to find the distribution of the rotor.

Under the centrifugal action, the radial stress and the circumferential stress of the rotor in the plane stress are tensile stress. Using the largest stress criterion:

$$\begin{cases}\sigma_\theta \le [\sigma] \\ \sigma_r \le [\sigma]\end{cases} \tag{6}$$

$[\sigma]$----Permissible stress of rotor material

Modeling of flywheel rotor. Flywheel design parameters: density ρ=2700 kg/m^3, Poisson's ratio 0.3, Elastic Modulus $E=70GPa$, Allowable stress $[\sigma]=500MPa$, Rotor diamete $d_f=600mm$, Minimum thickness $h_{min}=20mm$, Maximum thickness $h_{max}=90mm$.So, $d_1=476.4mm$ and the d1 of the hollow rotor remains unchanged.

Finite element analysis of hollow flywheel rotor. As the design of the model is relatively simple, the use of Workbench on the flywheel for structural analysis, grid division using hexahedral-oriented meshing, grid size is set to 10mm.

The equivalent stress map and displacement map are shown in Fig.3 and Fig.4. The results show that when the flywheel speed is 500 rad / s, the maximum stress is 62.87MPa and the maximum displacement is 0.8967mm.The maximum stress is mainly concentrated at the edge of the middle hole. The maximum deformation occurs at the rim.

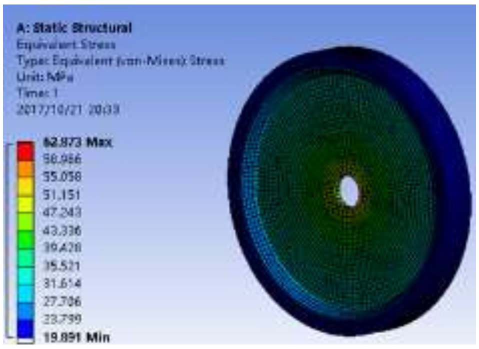

Figure 3. 500rad / s stress distribution

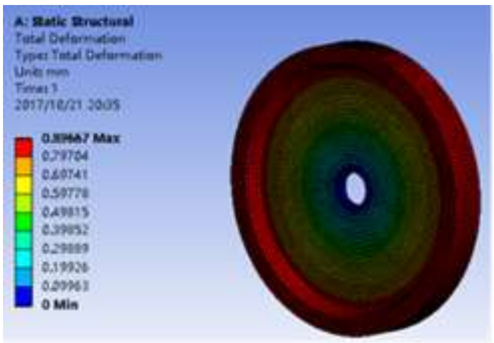

Figure 4. 500 rad/s displacement map

The maximum stress and maximum deformation of the flywheel are shown in Table 1 at different speeds. With the increase in speed, maximum stress and maximum displacement deformation increase speed faster. When the speed is set at 500rad / s, the stress and deformation are very small, meeting the requirements.

Table 1 Flywheel stress and displacement with the speed of change

Rotating speed rad/s	100	200	300	400	500	600	700	800	900
Maximum stress MPa	0.51	10.06	22.63	40.24	62.87	90.54	123.23	160.96	203.71
Deformation displacementmm	0.0359	0.1435	0.3228	0.5739	0.8967	1.2912	1.7575	2.2955	2.9062

In order to simplify the analysis process, the six circular holes are directly distributed on the circumference of 140 mm from the center of the rotor. In the finite element software for its calculation, when the diameter of the hole is 60mm, flywheel speed of 500rad / s when the distribution and deformation should be shown in Figure 5 and Figure 6, the maximum stress of 90.459MPa, the maximum displacement of 1.035 mm. The maximum stress concentration hole resembles the hole in the radial direction.

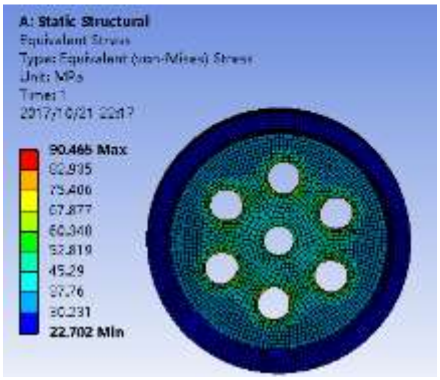

Figure 5. Stress distribution

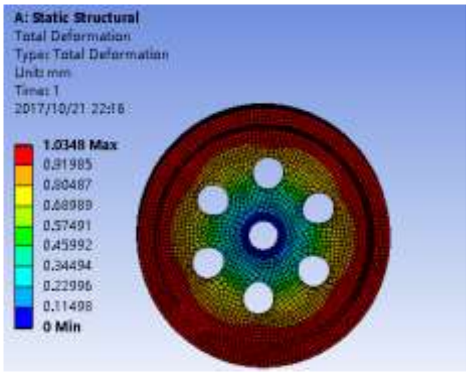

Figure 6. Displacement deformation diagram

Table 2 500rad/s Different weight reduction hole diameter

Diameter/mm	50	60	70	80	90	100
Max-stress/MPa	88.464	90.459	92.926	96.916	101.95	108.72
Max-deformation/mm	0.993	1.035	1.084	1.1387	1.2034	1.2081
Inertia/ KG`m2	1.928	1.931	1.9152	1.9171	1.8981	1.8876
Quality/KG	31.25	30.971	30.64	30.258	29.852	29.342
Energy storage density	7712	7793	7813	7919	7947	8041

From table 2, it is found that increasing the diameter of the hole can effectively increase the energy density of the flywheel rotor.

Conclusions

Flywheel system is a mechanical system to maintain a smooth and effective adjustment mechanism, flywheel rotor as the core of energy storage parts, to optimize the design of its significant research value. In this paper, the flywheel model is designed with the optimal flywheel shape and the actual case. The results show that the maximum stress of the hollow flywheel is concentrated at the edge of the hole when the speed is 500 rad / s. In order to further improve the energy storage density of the flywheel, the influence of the diameter of the hole on the energy storage density of the flywheel is studied. With the increase of the diameter of the reducing hole, the energy storage density of the flywheel increases, but the corresponding stress and displacement also increase. After the weight loss design of the flywheel, the maximum stress concentrated in the weight hole. Improve the stress distribution of the structure or material properties, can significantly enhance the performance of the flywheel.

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