Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 16 (2012) 359 – 364

Energy Procedia

2012 International Conference on Future Energy, Environment, and Materials

General Design Method of Flywheel Rotor for Energy Storage System

Yongjie Han[a,*], Zhengyi Ren, Yongxiang Tong

[a]*Engineering training center ,Harbin Engineering University,Harbin Heilongjiang 150001,China*

Abstract

Flywheel rotor design is the key of researching and developing flywheel energy storage system.The geometric parameters of flywheel rotor was affected by much restricted condition.This paper discussed the general design methodology of flywheel rotor base on analyzing these influence,and given a practical method of determing the geometric parameters.The foundation was laid for optimal design and analysis of flywheel rotor in the future.

*Keywords :*Flywheel energy storage system; Flywheel rotor; Rotating disk;Composite rim;Rotordynamics.

---

1. Introduction

Flywheel energy storage system (FESS) mainly consists of a flywheel rotor, magnetic bearings, a motor/generator, a vacuum chamber, and power conversion system. The flywheel rotor was supported by non-contacting magnetic bearings that provide very low frictional losses, It stores energy in a kinetic form,the motor/generator converts mechanical energy to electric form, and vice versa .The flywheel rotor work in a high speed,must be high energy density,high mechanical strength,and dynamics properties. Therefore the flywheel rotor was the key of FESS research and develop.

In the development of the flywheel rotor, current researches have focused on optimum design and stress analysis[1]. However,these work must firstly have the geometric parameters of flywheel rotor.This paper discusses the general design methodology of flywheel rotor base on analyzing these influence,and given a practical method of determing the geometric parameters.The foundation was laid for optimal design and analysis of flywheel rotor in the future.

---

* Corresponding author. Tel.: +86-451-8251-9840; fax: +86-451-8251-9952.
E-mail address:hanyongjie@hrbeu.edu.cn.

doi:10.1016/j.egypro.2012.01.059

2. General design method of flywheel rotor

2.1. Flywheel rotor design process

Fig.1 illustrates flywheel rotor design process and its influence factor.The process included requirements analysis,rotor type option,general design, optimum design, and performance evaluation.Goals of general design is to determinate geometric parameters of flywheel depending upon the limiting factor, a very large number of conditions and factors must be considered,such as general configuration of flywheel energy storage device, the stored energy, operation speed, material behavior, moment of inertia, rotordynamics, flywheel rotor mass, structural manufacturability.

2.2. Maximum outer radius

The primary components of a flywheel rotor are shown on Fig.2 and consist of:metal shaft,flywheel,magnetic bearings rotor and thrust disk,motor/generator rotor. There are two basic classes of flywheels based on the material used in the rotor. The first class of flywheels uses steel as the main structural material. The second class of flywheels uses a metallic hub and composite rim made up of an advanced composite material such as carbon-fiber or graphite. The metal hub of composite flywheels had the same geometrical shape and work condition with the steel flywheels.This section mainly determine their maximum outer radius. The design method is similar in composite rim.

2.2.1. Stress analysis

Fig.2 shows that the metallic hub (or steel flywheel) can be divided into spoke and metal rim.They become of uniform thickness rotating disk. The stress at a point in the disk is three stress states: the radial stress σ_r, tangential stress σ_θ, and axial stess σ_z.Because the surface of the disk is a free surface in the z direction, $\sigma_z=0$. For an isotropic material the radial and tangential stress are expressed by Eq.(1)and(2)[2].

$$\sigma_r = \frac{3+\mu}{8}\rho\omega^2\left(R^2 + r^2 - \frac{R^2 r^2}{r_i^2} - r_i^2\right) \tag{1}$$

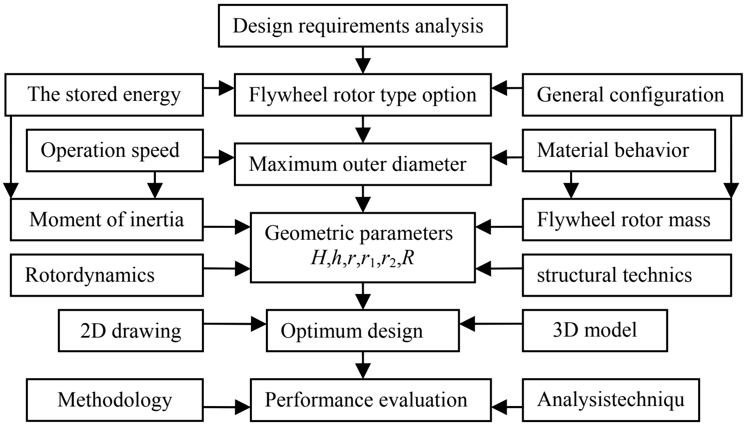

Fig. 1. Flywheel rotor design process and its influence factor

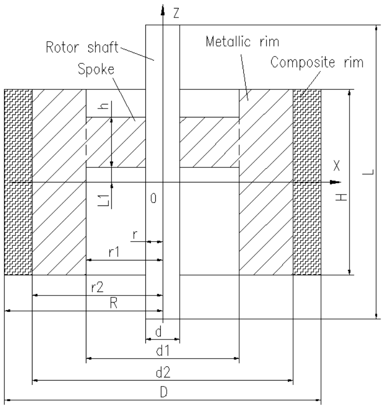

Fig. 2. Flywheel rotor components

$$\sigma_\theta = \frac{3+\mu}{8}\rho\omega^2\left(R^2 + r^2 + \frac{R^2r^2}{r_i^2} - \frac{1+3\mu}{3+\mu}r_i^2\right) \quad (2)$$

where r and R are the inner and outer radius of the disk, μ is the poisson's ratio, ρ is the material density, ω is the angular velocity,and r_i is radius of the *i*th point.

2.2.2. Failure criteria selection

Failure criteria of composite rim are Tsai-Hill, Tsai-Wu, Maximum Failure and Hoffman[3].Failure Criteria of isotropic materials are Tresca, Tresca Stress and Von Mises. Tresca criteria is more conservative than Von Mises, it is also valid for isotropic & ductile materials.The disk is generally made of plastic metal, the tresca stress criterion is used as failure criterion. This states that failure occurs when the maximum shear stress in the component being designed equals the maximum shear stress in a uniaxial tensile test at the yield stress[4],show as Eq.(3).Where σ_1 and σ_3 are the maximum and minimum principal stresses,$[\sigma]$ is the safe yield stress.

$$\sigma_1 - \sigma_3 \le [\sigma] \quad (3)$$

2.2.3. Maximum outer radius calculate

The maximum radial stress is at $r_i=\sqrt{Rr}$ in Eq.(1), the maximum tangential stress is at $r_i=r$, the maximum stress is obtained.

$$\sigma_{r\max} = \frac{3+\mu}{8}\rho\omega^2(R-r)^2 \quad (4)$$

$$\sigma_{\theta\max} = \frac{3+\mu}{4}\rho\omega^2\left(R^2 + \frac{1-\mu}{3+\mu}r^2\right) \quad (5)$$

Comparad tangential stress $\sigma_{\theta i}$ with maximum radial stress $\sigma_{r\max}$ at $r_i=\sqrt{Rr}$ point.

$$\sigma_{\theta i} - \sigma_{r\max} = \frac{3+\mu}{8}\rho\omega^2\left(R^2 + r^2 + \frac{1-\mu}{3+\mu}2Rr\right) - \frac{3+\mu}{8}\rho\omega^2(R-r)^2 > 0 \quad (6)$$

The radial stress is $\sigma_{ri}=0$ when $r_i= r$ and $r_i= R$ in Eq.(1) , the maximum stress is always at the inner radius. From Eq.(5),we obtain

$$\sigma_1 - \sigma_3 = \sigma_{\theta\max} = \frac{3+\mu}{4}\rho\omega^2\left(R^2 + \frac{1-\mu}{3+\mu}r^2\right) < [\sigma] \tag{7}$$

$$R < \sqrt{\frac{1}{3+\mu}\left[\frac{4[\sigma]}{\rho\omega^2} - (1-\mu)r^2\right]} \tag{8}$$

If we define the inner radius of the spoke according to the match of the rotor shaft in overall design project,then the outer radius of the spoke can be calculated from Eq.(8).we define a series of inner radius within the outer radius of the spoke,the homologous outer radius can be obtained with the same method,it is the maximum outer radius depending upon the desired failure condition utilized.For steel flywheel it is the maximum outer radius of the flywheel,it is the maximum outer radius of metallic hub for composite flywheel.

2.3. Geometric parameters of flywheel rotor

The important function of flywheel rotor store kinetic energy,it must have the enough polar moment of inertia.In addition,it also meet the demand, such as mass, dynamics behavior.

2.3.1. The polar moment of inertia

The energy stored by a FESS is calculated by using Eq. (9)[5].

$$\Delta E = \frac{1}{2}J\left(\omega_{\max}^2 - \omega_{\min}^2\right)\eta \tag{9}$$

where $\triangle E$ is the energy stored by the flywheel,$\omega_{\max}$ and $\omega_{\min}$ are the maximum and minimum operation speed of the flywheel, and J is the moment of inertia of the flywheel,i.e.

$$J = \frac{2\Delta E}{\left(\omega_{\max}^2 - \omega_{\min}^2\right)\eta} \tag{10}$$

2.3.2. Distributed moment of inertia

The flywheel rotor are composed of many parts joined together,then its moment of inertia are equal to the sum of moments of inertia of several components.The shaft, magnetic bearings rotor and thrust disk,and motor/generator rotor of moment of inertia J_{ps} can be determined after the overall design of the flywheel energy storage device have be finished,the moment of inertia of flywhell is $J_{\mathrm{pw}}=J_{\mathrm{p}}-J_{\mathrm{ps}}$.The spoke, metallic rim,and composite rim geometry of the flywheel are cylinders. So the cylinders moment of inertia is defined as

$$J_p = \frac{m}{2}\left(r_i^2 + r_o^2\right) = \frac{\pi\rho\, h}{2}\left(r_o^4 - r_i^4\right) \tag{11}$$

$$J_d = \frac{m}{12}\left[3\left(r_{\mathrm{i}}^2 + r_{\mathrm{o}}^2\right) + h^2\right] \tag{12}$$

Where J_{p} is polar moment of inertia , J_{d} is equatorial moment of inertia.The flywheel moment of inertia can be obtained by the sum.

$$J_{pw} = J_{p1} + J_{p2} + J_{p3} = \frac{\pi\rho_2 h}{2}\left(r_1^4 - r^4\right) + \frac{\pi\rho_2 H}{2}\left(r_2^4 - r_1^4\right) + \frac{\pi\rho_3 H}{2}\left(R^4 - r_2^4\right) \tag{13}$$

$$J_{\mathrm{dw}} = J_{d1} + J_{d2} + J_{d3} = \frac{m_1}{12}\left[3\left(r_1^2 + r^2\right) + h^2\right] + \frac{m_2}{12}\left[3\left(r_2^2 + r_1^2\right) + H^2\right] + \frac{m_3}{12}\left[3\left(r_2^2 + R^2\right) + H^2\right] \tag{14}$$

Where J_{p1}, J_{p2}, J_{p3} are respectively the spoke, metallic rim,and composite rim polar moment of inertia, J_{d1}, J_{d2}, J_{d3} are respectively the spoke, metallic rim,and composite rim equatorial moment of inertia for the location of the centroid,m_1,m_2.m_3 are respectively their mass. If they have a distance L_1 between the centroids in Fig.1, the moment of inertia can be computed by the parallel-axis theorem.

2.3.3. Geometric parameters of flywheel

From Eq. (13) we obtain

$$H = \frac{2\left(J_{p2} + J_{P3}\right)}{\pi\left[\rho_2\left(r_2^4 - r_1^4\right) + \rho_3\left(R^4 - r_2^4\right)\right]} = \frac{2\left(J_{pw} - J_{p1}\right)}{\pi\left[\rho_2\left(r_2^4 - r_1^4\right) + \rho_3\left(R^4 - r_2^4\right)\right]} \tag{15}$$

$$m_w = m_1 + m_2 + m_3 = \pi\rho_1 h\left(r_1^2 - r^2\right) + \pi\rho_2 H\left(r_2^2 - r_1^2\right) + \pi\rho_3 H\left(R^2 - r_2^2\right) \tag{16}$$

Where m_w is the mass of the flywheel.The geometric parameters of flywheel included thickness h and inner radius r of the spoke, thickness of flywheel H, the inner radius r_1 and outer radius r_2 of metallic rim,the outer radius R of composite rim ,as shown in Fig.1. A general procedure for determining these parameters is:The first is that r option based on the joined rotor shaft ,h option depend on the stress and stiffness of the materials.The second is that r_2 is selected within the maximum outer radius,then a series of r_1 and R is selected depend on the radial thickness of metallic rim and composite rim,the minimum radial thickness is considered by the structural manufacturability.Thirdly the parameters H,m_w,and J_d/J_p can calculate from Eq. (13), Eq. (14), Eq. (15),and Eq. (16). Finally the general geometric parameters will be obtained,all of which must be simultaneously analysed and optimized.

3. General design method application

3.1. Design requirement

A 600Wh class FESS with the operating speed range of 5,000~15,000rpm, η=90%. Respectively, determine the general geometric parameters of steel flywheel rotor and composite flywheel rotor.

3.2. Select materials and calculate maximum outer radius

The material for the flywheel rotor shaft is 40Cr which is relatively cheap and easy to manufacture.The inner diameter respectively is 300mm,200 mm,and 50 mm,the material respectively is aluminium 7050, carbon steel 45, and alloy steel AISI 4340,the maximum outer diameter can be calculated from Eq.(8),the results are listed in Table 1.The maximum outer diameter decrease as inner diameter are increased,there are the larger outer diameter with better strength and low density materials.So we select that the metallic hub of composite flywheel is made of aluminium 7050 ,and the steel flywheel is made of alloy steel AISI 4340.

3.3. Design result

The density of composite rim is 1800 $\mathrm{kg{\cdot}m^{-3}}$, its thickness is selected from 30mm to 60mm. The geometric parameters of flywheel can be calculated from Eq. (13), Eq. (14), Eq. (15),and Eq. (16). The results are listed in Table 2 for the steel flywheel, and Table 3 for the composite flywheel. The detail design of the flywheel rotor will begin after determinning the general parameters,three dimensional (3D) flywheel rotor is constructed and modified slightly,thus the flywheel rotor design will be finished.

Table 1. Maximum outer diameter and material behavior

Item	Aluminium 7050			Carbon steel 45			Alloy steel AISI 4340		
Density ρ (kg • m^{-3})	2810			7850			7900		
Yield stress [σ] (Pa)	455			355			835		
Poisson's ratio μ	0.33			0.28			0.28		
Inner diameter d_1 (m)	0.05	0.20	0.30	0.05	0.20	0.30	0.05	0.20	0.30
Outer diameter d_2 (m)	0.561	0.554	0.545	0.298	0.284	0.264	0.457	0.447	0.435

Table 2. The geometric parameters of steel flywheel

d (m)	h (m)	d_1 (m)	d_2 (m)	H (m)	m_w (kg)	J_d/J_p
0.07	0.035	0.38	0.42	0.204	79.2	0.66

Table 3. The geometric parameters of composite flywheel

d [m]	h [m]	d_1 [m]	d_2 [m]	D [m]	H [m]	m_w [kg]	J_d/J_p
0.07	0.05	0.30	0.38	0.48	0.227	72.1	0.705

4. Conclusions

This paper discussed the general design methodology of flywheel rotor base on analyzing these influence,and given a practical method of determing the geometric parameters.It was applied to determine flywheel rotor parameters of 600Wh flywheel energy storage system in developing.They have be proved to be a practical method.

The maximum outer radius were calculated by depending upon the tresca stress failure criterion.It suited to the steel flywheel or metallic hub of composite flywheel,which was made of the isotropic & ductile materials.

The maximum stress is always at the inner radius of the flywheel rotor, The maximum outer diameter decrease as inner diameter are increased. The steel flywheel or metallic hub of composite flywheel was made of materials that had the better strength and low density,such as aluminium and Alloy steel.

Acknowledgements

This work was financially supported by the Fundamental Research Funds for the Central Universities (HEUCFZ1024).

References

[1] M.A. Arslan.Materials and Design. 29 (2008): p.514-8.

[2] B. Bolund et al.Renewable and Sustainable Energy Reviews. 11 (2007):p.235–258.

[3] S.M. Arnold et al. Composites: Part B, 33 (2002):p. 433-459.

[4] Yilin Su.Machanics of Materials.Beijing:People's Education Press,1982;p.185(Book One),p.120-3(Book Two);in Chinese.

[5] G.O. Suvire, P.E. Mercado.Electric Power Systems Research .80 (2010) :p.345-353.