Optimization design of the reactor coolant pump flywheel comprised of multi-ring packing heavy metal alloy

L Jiang1,2,3, C W Wu2, X J Shao1, Y Zhang1 and M D Yu1

1 National Key Laboratory of Science and Technology on Reactor System Design Technology, Nuclear Power Institute of China, Chengdu 610041, China
2 State Key Laboratory of Structural Analysis for Industrial Equipment, Dalian University of Technology, Dalian 116024, China

E-mail: npic_lujiang@163.com

Abstract. To improve energy storage performance of the multi-ring RCP flywheel comprised of inner hub, tungsten alloy ring and outer retainer, optimization design process for the radial thicknesses of components and interference fit assembly is demonstrated. Radial thicknesses of these components and magnitude of interference fit are set as design parameters to construct parametric analysis model. Design of experiments (DOE) technique is adopted to generate design matrix for sensitive analysis. Subsequently, radial basis function (RBF) approximation is employed to search for the optimal design considering structural integrity requirement. Finally, a proper range of the magnitude of interference fit is obtained which can not only prevent neither slippage nor separation between the inner hub and tungsten alloy ring but also ensure the safety of structural strength. In addition, it is found that to ensure a high moment of inertia and energy density, a reasonable large radial thickness of tungsten alloy ring and a reasonable small radial thickness of outer retainer are required.

Nomenclature

\( r_1 \): Inner radius of inner hub [mm]
\( r_2 \): Outer radius of inner hub [mm]
\( r_3 \): Outer radius of tungsten alloy layer [mm]
\( r_c \): Outer radius of outer retainer [mm]
\( t_1 \): radial thickness of inner hub [mm]
\( t_2 \): radial thickness of tungsten alloy [mm]
\( t_3 \): radial thickness of outer retainer [mm]
\( \delta \): magnitude of interference fit [mm]
\( E \): Elastic modulus of material [GPa]
\( m \): Mass [kg]
\( \nu \): Poisson’s ratio
\( \rho \): Mass density [kg/m\(^3\)]
\( \alpha \): Thermal expansion coefficient [1/°F]
\( \sigma \): Yield stress [MPa]
\( \sigma_{max} \): Maximum structural stress [MPa]
\( P_{max} \): Maximum contact pressure [MPa]
\( I \): Moment of inertia [kg-m\(^2\)]
\( e \): Energy density [J/kg]
\( R_e \): Increase ratio of energy density
$R_i$: Increase ratio of inertia

1. Introduction

In nuclear power plant, to prevent the fuel assembly damage due to a sudden power loss of the reactor coolant pump (RCP)[1,2], an energy storage flywheel is designed to ensure a slow decrease of coolant flow through the nuclear reactor core[3]. This RCP flywheel works with a high speed rotating rotor storing large enough kinetic energy under normal working condition and releases this high energy when encountering power outage. Generally, the capacity of the kinetic energy stored in the flywheel is proportional to the moment of inertia (hereinafter referred to as inertia) of the rotor and the square of rotation speed \[4,5\]. But practically, the rotation speed of flywheel is specified by RCP system. Therefore, to ensure storing a sufficient kinetic energy, designing a rotor with a high inertia is one of the key design requirements for RCP flywheels.

For a flywheel with a given rotation speed, the inertia is determined by the rotor mass and the square of its radius. Clearly, increasing the rotor mass is an available way to improve the inertia. However, the RCP flywheel is usually sealed inside a pressure vessel which leads to a small design space for the rotor size. Therefore, in order to design a large rotating mass, high-density material should be selected to design this flywheel rotor. On the other hand, a high-density material frequently results in a large rotor mass and exceeds the carrying capacities of the thrust bearing supporting the shaft of RCP system. Therefore, the energy density (the energy stored per unit mass) also should be considered during the design process [6,7]. In one word, to obtain both sufficient inertia and high energy density become a critical design technique for RCP flywheels.

Curtiss-Wright Electro-Mechanical Corporation proposed a flywheel design comprised of inner hub, tungsten alloy ring and outer retainer for the RCP system in 2013[8]. Compared with solid steel disk, this type of flywheel can provide a much higher inertia and shows a high energy density as well. This configuration, here called multi-ring flywheel packing heavy metal alloy, has provided a novel design concept for the RCP flywheels. However, to date, very few publications can be found on studying the structural design technique of this RCP flywheel configuration. Ozturk [9] studied the stress distribution of a two-disc shrink fit assembly respectively considering a hollow and solid shaft. By analytical modeling, Antoni [10] made efforts to obtain critical separation and failure rotation speeds for a shrink-fit assembly flywheel. Park et al [11] studied the structural integrity evaluation of a RCP flywheel consisting of a disc and an intermediate bush. Fawazi et al [12] use finite element analysis to predict equivalent stress of flywheel under different rotational speed and then optimize the flywheel stress and mass at high speed. Based on our previous study [13], the present paper is dedicated to exploring the optimization design technique for on this multi-ring RCP flywheel. Specifically, satisfying the structural integrity requirement, optimization design with the objective to improve the inertia and energy density is investigated. The optimization design method performed and results obtained in this paper could provide potential value guiding for engineering design of RCP flywheels.

2. Problem formulation

To carry out optimization modelling for the RCP flywheel, structural configuration and the design objectives and considerations of the multi-ring flywheel packing tungsten alloy are introduced.

2.1. The RCP flywheel configuration

As shown in Figure 1, for the structural configuration of multi-ring flywheel, the rotor consists of three rings: inner hub, heavy metal alloy and outer retainer. The heavy metal alloy, also called middle ring, is composed of 12 tungsten alloy segments which are evenly distributed along the circumference to keep the balance of system. The flywheel rotor is supported by shaft and thrust bearings. A spline connection is adopted between the shaft and inner hub to transfer the torque between the shaft and rotor. The outer retainer is heated to high temperature and assembled outside the tungsten alloy ring to form interference fit assembly. Prestress by this interference fit assembly is used to keep the tungsten
alloy segments clamped to the inner hub so as to prevent neither interface slippage nor separation under working condition.

**Figure 1.** Assembly schematic of the multi-ring flywheel packing tungsten alloy.

In accordance with the RCP flywheel configuration, the inner hub generally is made from stainless steel, the middle ring is made of tungsten based alloy with high density and the outer retainer is made of high strength steel so as to withstand the high stress due to high rotation speed and the interference fit assembly between tungsten alloy ring and outer retainer. As a matter of fact, owing to the high density (more than twice the density of steel) and long radial distance to the shaft, the tungsten alloy ring certainly can contribute to a much higher inertia than traditional solid steel disk under the same size. Therefore, for this RCP flywheel configuration, the middle ring can take full use of its characteristic of high density to ensure a high inertia rotor for storing kinetic energy. Undoubtedly, among the three rings, tungsten alloy ring is the key component of flywheel rotor as it provides the major inertia.

2.2. **Design objectives and requirements**

As illustrated in Figure 2, $r_1$ and $r_4$ represent respectively the outer radiuses of shaft and rotor. It is in this design space ($r_4-r_1$) that the inner hub, tungsten alloy ring and outer retainer are designed. Within this design space, it should be recognized that the radial thickness of the tungsten alloy ring ($r_3-r_2$) has a great impact on the inertia of the flywheel. Specifically, increasing the radial thickness ($r_3-r_2$) and its distance to the shaft ($r_2$), i.e., increase the mass and the distance to shaft of the high-density tungsten alloy ring, are both beneficial to improve the inertia of rotor. Additionally, different radial thickness designs will lead to different centrifugal forces and different stress distributions\[14\]. However to date, no publication has addressed how to optimally allocate the radial thicknesses of the tungsten alloy ring for this kind of RCP flywheel. Therefore, with the goal to design a rotor with sufficient inertia and high energy density for RCP flywheel, optimization design for the radial thickness of the middle ring appears to be indispensable.

**Figure 2.** Dimension of the RCP flywheel configuration: $r_1$, $r_2$, $r_3$ and $r_4$ represent the outer radiuses of shaft, inner hub, tungsten alloy ring and outer retainer respectively.
On the other hand, in order to prevent failure of RCP flywheel system, structural integrity requirement must be considered during the optimization design process. Firstly, the tungsten alloy segments are clamped to the inner hub and neither slippage nor separation is permitted between the inner hub and tungsten alloy ring under working condition. Therefore, to ensure a closed status, a proper magnitude of interference fit between the tungsten alloy ring and outer retainer is required. Secondly, from the perspective of structural strength safety, stresses in inner hub, tungsten alloy ring, and outer retainer must be kept less than the allowable stresses. According to the structural integrity requirement of RCP flywheel, the maximum structural stress cannot exceed 1/3 of the yield stress of material under normal working condition. Therefore, to ensure the safety of structural strength, the maximum structural stresses in each component must be kept in safety ranges.

3. Methodology

3.1. FEA model of the RCP flywheel

For optimization design, finite element analysis (FEA) model is first established. The loads for the RCP flywheel mainly include the gravity force, centrifugal force, thermal stress and prestress by interference fit assembly. The gravity force is ignored due to its small effect on structural stress and thus the flywheel can be simplified into plane stress model. Moreover, owing to the structural periodic symmetry, flywheel model can be further simplified to a basic structure (1/12 of the whole model, see Figure 3a) with a periodic boundary condition. Interference fit is built between the tungsten alloy ring and the outer retainer. In addition, three contact pairs are established between the shaft, inner hub and tungsten alloy segments. Considering the high temperature under working condition, the friction coefficients of these contact pairs are set as 0.2. The FEA modeling process is accomplished using Abaqus python script.

As illustrated in Figure 3b, the radial thickness of tungsten alloy ring, $t_2$, radial thickness of outer retainer, $t_{3}$, and the magnitude of interference fit between tungsten alloy ring and outer retainer, $\delta$, are what we will study. The outer radiuses of shaft and rotor, $r_1$ and $r_4$, are generally specified by RCP system, and therefore, the radial thickness of inner hub, $t_1$, is determined by relationship: $t_1=r_4-r_1-t_2-t_3$. In fact, design spaces for these parameters depend on the scale and output power of RCP system and therefore the specific sizes cannot be disclosed due to the security consideration. To get access to the stress distribution, the outer radiuses of shaft and rotor are respectively given as $r_1=150$ mm and $r_4=500$ mm as an example. The radial thicknesses of three rings are defined as $t_2=130$ mm, $t_3=70$ mm, $t_1=150$ mm, and the magnitude of interference fit is set as 1.0 mm for initial size definition[15]. Material properties of the RCP flywheel are listed in Table 1. Under normal working condition, the rotation speed of RCP flywheel is 1800 rpm and the temperature is 400 °F[16].

![Figure 3. RCP flywheel model: (a) basic structure, (b) dimension illustration.](image)
Table 1. Material properties of the RCP flywheel[16].

| Components          | Elastic modulus $(E)/$GPa | Density $(\rho)/$kg$\cdot$m$^{-3}$ | Thermal expansion coefficient $(\alpha)/(1/°F)$ | Yield stress $(\sigma)/$MPa |
|---------------------|---------------------------|-----------------------------------|---------------------------------------------|----------------------------|
| Shaft, inner hub    | 198                       | 7850                              | $6.2\times10^{-6}$                          | 275                        |
| Tungsten alloy      | 325                       | 17500                             | $2.5\times10^{-6}$                          | 520                        |
| Outer retainer      | 198                       | 7850                              | $6.2\times10^{-6}$                          | 1700                       |

Figure 4 shows the stress distributions of the RCP flywheel and Figure 5 shows Mises stress and radial stress distributions along radius under normal working condition. The radial path selected is a rotor radius passing through the center of single tungsten alloy segment. From Figure 4a and Figure 5a, it can be seen that both the inner hub and tungsten alloy segment show very low stress levels meeting the requirement of structural strength safety. However, the outer retainer expresses a much higher stress level and the maximum structural stress occurs basically in the inner surface of outer retainer. According to Ozturk’s study[9], the interference fit assembly of two disks will give rise to a high circumferential stress at the contact interface. Therefore, to ensure the structural strength safety in the outer retainer, an upper limit for the magnitude of interference fit is determined.

Figure 4. Stress distribution of the RCP flywheel.

Figure 5. Stress distribution along the radius of rotor: (a) Mises stress, (b) Radial stress.

On the other hand, from Figure 4b and Figure 5b, it can be seen that all the components are in compression along radius due to the prestress by interference fit assembly. Actually, under working condition, a part of this prestress is released by the centrifugal force induced from the high rotation speed. Clearly, a lower limit for the magnitude of interference fit is also required to guarantee a closed status between the inner hub and tungsten alloy ring. In summary, the design concept in this paper can be described as to obtain a proper range for the magnitude of interference fit to satisfy the structural
integrity requirement and then seek reasonable radial thickness design for the components with the aim to improve the inertia and energy density of rotor.

3.2. DOE model and RBF approximation

Instead of obtaining a simple optimal solution for the radial thicknesses of the components, DOE design technique[17] and radial basis functions (RBF) approximation[18],[19] is adopted in this paper to demonstrate optimization design method for this type of RCP flywheel. Optimization modeling process is carried out using Abaqus and Isight commercial software. The design process can be simply divided into three steps as demonstrated in Figure 6. Firstly, to build the DOE model in ISIGHT, design parameters are defined as factors and the output parameters are defined as responses. Then, design space of each factor will be divided into different levels and using level combination method sample design points are generated to create a DOE design matrix. To optimize this combination, using optimal Latin hypercube design (Opt LHD) space filling method[20], each factor will be divided uniformly to create the matrix in which the design points are spread evenly within the design space. Secondly, by DOE design technique, those sample design points will be executed to investigate the effects of factors on responses. Thirdly, basing on the sample design data obtained by DOE, the RBF approximation model is established to gain insight to the relationship between the factors and responses so as to search for appropriate decisions.

![Figure 6. Schematic diagram of the optimization design process.](image)

As shown in Table 2, the magnitude of interference fit, \( \delta \), radial thicknesses of tungsten alloy ring, \( t_2 \), and outer retainer, \( t_3 \), are set as design parameters. Design space of each parameter is given around the initial size design. Since practical design space is not limited to the scope given above, the design space here is set as example used to demonstrate the optimization design process for RCP flywheels. To ensure fitting accuracy between the factors and responses, three factors are divided into 21 levels. Accordingly, full design space will be filled by 9261 possible combinations. To reduce design cost, Opt LHD space filling method is adopted to create the design matrix which is filled with 21 design points evenly covering the design space. Energy density, mass, inertia moment and the maximum structural stress, \( \sigma_{\text{max}} \), in the outer retainer of flywheel are observed and defined as responses. Considering the non-uniform contact pressure between inner hub and tungsten alloy ring, the maximum contact pressure, \( P_{\text{max}} \), is monitored to measure the contact status.

Since the maximum structural stress, \( \sigma_{\text{max}} \), and contact pressure, \( P_{\text{max}} \), are also influenced by the radial thicknesses of tungsten alloy ring, \( t_2 \), and outer retainer, \( t_3 \), the effects by them must be taken into consideration in the decision process. To achieve this goal, RBF approximation model is adopted to assess the relationships between the factors and responses within the design space. The average approximation error of maximum structural stress is 2.32%, and average approximation error of maximum contact pressure is 2.27%.
Table 2. DOE model for the RCP flywheel.

| Factors | Responses |
|---------|-----------|
| Magnitude of interference fit, $\delta$ (0.5–1.5 mm) | Mass, $m$ |
| Radial thickness of tungsten alloy ring, $t_2$ (65–195 mm) | Moment of inertia, $I$ |
| Radial thickness of outer retainer, $t_3$ (35–105 mm) | Energy density, $e$ |
| | Maximum structural stress in outer retainer, $\sigma_{\text{max}}$ |
| | Maximum contact pressure between inner hub and tungsten alloy ring, $P_{\text{max}}$ |

4. Results and discussions

Based on RBF approximation model, the maximum structural stress in outer retainer and contact pressure between inner hub and tungsten alloy ring are used to determine a proper range for the magnitude of interference fit with given design space in Table 2. Then, with the objectives of maximizing the energy density and inertia respectively, searching for optimal thickness design for the tungsten alloy ring and outer retainer is studied.

4.1. Magnitude of interference fit

First, we make efforts to seek the upper limit for the magnitude of interference fit considering the effects by the radial thicknesses of tungsten alloy ring and outer retainer on maximum structural stress. The 3D contour graph of maximum structural stress, $\sigma_{\text{max}}$, versus magnitude of interference fit, $\delta$, and radial thickness of outer retainer, $t_3$, using RBF approximation is illustrated in Figure 7a. According to structural integrity requirement, the maximum structural stress cannot exceed 1/3 of the yield stress of material if the yield safety coefficient is taken as 3. Thus with an allowable stress of $[\sigma] = 567.0$ MPa, an upper limit of 1.35 mm for the magnitude of interference fit can be determined from the 2D contour graph in Figure 7b. In the same way, the contour graph of maximum structural stress versus magnitude of interference fit and radial thickness of tungsten alloy ring is illustrated in Figure 8. From Figure 8b we can get another upper limit of 1.25 mm for the magnitude of interference fit. Based on these two limits, we can obtain the upper limit of 1.25 mm for the magnitude of interference fit between the tungsten alloy ring and outer retainer to satisfy the requirement of structural strength safety.

Figure 7. Contour graph of maximum structural stress, $\sigma_{\text{max}}$, versus magnitude of interference fit, $\delta$, and radial thickness of outer retainer, $t_3$, using RBF approximation: (a) 3D graph, (b) 2D graph.
Figure 8. Contour graph of maximum structural stress, $\sigma_{\text{max}}$, versus magnitude of interference fit, $\delta$, and radial thickness of tungsten alloy ring, $t_2$, using RBF approximation: (a) 3D graph, (b) 2D graph.

Similarly, we can search for the lower limit for the magnitude of interference fit which is used to guarantee effective contact pressure between inner hub and tungsten alloy ring. Contour graphs of the maximum contact pressure versus magnitude of interference fit, radial thicknesses of outer retainer and tungsten alloy ring are shown in Figure 9 and 10. Clearly, to keep the effective contact status, lower limits of 0.85 mm and 0.50 mm for the magnitude of interference fit can be determined respectively in Figure 9b and Figure 10b. Based on these two limits, we can obtain the lower limit of 0.85 mm for the magnitude of interference fit between the tungsten alloy and outer retainer to satisfy the requirement of effective contact pressure between inner hub and tungsten alloy ring. Finally, using RBF approximation model, a proper range of 0.85~1.25 mm for the magnitude of interference fit is obtained. In other words, this range of magnitude of interference fit is able to prevent neither interface slippage nor separation between the inner hub and tungsten alloy and also ensure the safety of structural strength within the design space given in Table 2.

Figure 9. Contour graph of maximum contact pressure, $P_{\text{max}}$, versus magnitude of interference fit, $\delta$, and radial thickness of outer retainer, $t_3$: (a) 3D graph, (b) 2D graph.

Figure 10. Contour graph of maximum contact pressure, $P_{\text{max}}$, versus magnitude of interference fit, $\delta$, and radial thickness of tungsten alloy ring, $t_2$: (a) 3D graph, (b) 2D graph.
4.2. Radial thicknesses

After proper range for the magnitude of interference fit is determined, we can design the radial thicknesses of the tungsten alloy ring and outer retainer components. Due to the little effect on energy density and inertia of the magnitude, we only need to consider the effects of the two radial thicknesses on design objectives. Using RBF approximation, the contour graph of the increase ratio of energy density, $R_e$, versus the radial thicknesses of tungsten alloy ring, $t_2$, and outer retainer, $t_3$, is shown in Figure 11. The increase ratio is defined as the ratio of energy density of the multi-ring flywheel to solid disk rotor made from steel under the same size. From Figure 11b, it can be found that reducing the radial thicknesses of either tungsten alloy ring, $t_2$, or outer retainer, $t_3$, both can improve the energy density. Generally, increasing the radial thickness of tungsten alloy ring actually will significantly increase the rotor mass due to the high-density characteristic of tungsten alloy, and increasing the radial thickness of outer retainer will shorten the radial distance of the high-density tungsten alloy ring to the shaft. As a result, they both lead to the decrease of the energy density. In addition to this, it can be seen that reducing the radial thickness of outer retainer, $t_3$, shows a larger efficiency on improving the energy density than reducing the radial thickness of tungsten alloy ring, $t_2$. The reason for this is that reducing the radial thickness of outer retainer can directly increase the radial distance of the high-density tungsten alloy ring to the shaft. This reminds us that with the aim to increase the inertia, we should give priority to design a radius as large as possible. Within the given design space, radial thickness design of 100 mm and 35 mm respectively for the tungsten alloy ring and outer retainer can increase the energy density by 11.6% compared with solid steel rotor.

![Figure 11. Contour graph of increase ratio of energy density versus radial thicknesses of tungsten alloy, $t_2$, and outer retainer, $t_3$: (a) 3D graph, (b) 2D graph.](image)

On the other hand, to store enough kinetic energy, a high inertia is required. Therefore, with the objective to maximize the inertia, optimal design for the two radial thicknesses is studied. Using RBF approximation, the increase ratio of inertia, $R_i$, versus the radial thicknesses of tungsten alloy ring, $t_2$, and outer retainer, $t_3$, is illustrated in Figure 12. Similarly, this increase ratio is defined as the ratio of inertia of the multi-ring flywheel to the solid disk rotor made from steel under the same size. Firstly, from Figure 12b it is easily found that this kind of RCP flywheel can provide a much higher inertia than the solid steel rotor with the maximum increase ratio of 80.8%. Clearly, this can be attributed to the middle ring comprised of high-density tungsten alloy. Secondly, increasing the radial thickness of tungsten alloy ring, $t_2$, can remarkably improve the inertia, but increasing the radial thickness of outer retainer, $t_3$, will reduce the inertia. Just as mentioned above, due to the high-density characteristic, increasing the radial thickness of tungsten alloy ring, $t_2$, will significantly increase the rotor mass and hence improve the inertia. By contrast, a small radial thickness of outer retainer, $t_3$, not only can spare radial space but also lengthen the radial distance to the shaft for the high-density tungsten alloy ring. Within the design space, it is known that the maximum increase ratio of 80.8% can be achieved with radial thickness design of 195 mm and 35 mm respectively for the tungsten alloy ring and outer retainer.
Figure 12. Contour graph of increase ratio of moment of inertia versus radial thicknesses of tungsten alloy, $t_2$, and outer retainer, $t_3$: (a) 3D graph, (b) 2D graph.

In summary, a large radial thickness of tungsten alloy, $t_2$, can be used to ensure a high enough inertia for storing kinetic energy, but too large a thickness will result in a large mass and a low energy density of rotor. Additionally, combined with Figure 11b and Figure 12b, it is found that a small radial thickness of outer retainer, $t_3$, not only can guarantee a high energy density but also can contribute to a high inertia of rotor.

5. Conclusions
In this paper, with aim to improve the moment of inertia and energy density of the multi-ring flywheel, DOE design technique and RBF approximation model are adopted to optimize the radial thicknesses of rotor components and interference fit assembly. The optimization design method demonstrated in this paper can provide valuable guidance for structural design of the multi-ring RCP flywheel comprised of heavy metal alloy. The conclusions can be summarized as follows:

1) To satisfy the structural integrity requirement of RCP flywheel, through the presented optimization design process, an optimal range for the magnitude of interference fit between tungsten alloy ring and outer retainer can be obtained.

2) For the multi-ring RCP flywheel, a large radial thickness of tungsten alloy ring can be designed to provide high enough inertia so as to store sufficient kinetic energy, but too large a thickness will lead to a low energy density.

3) As for a small radial thickness design of the outer retainer, it can contribute to not only a high energy density but also a high moment of inertia for the rotor.

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Conflict of Interest
The authors declare that they have no conflict of interest.

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