Analysis of dynamic deformation and disturbing torque of superconducting spinning sphere rotor

Chunyan Cui, Xinning Hu, Hui Wang, Lankai Li, Hao Wang, Qiuliang Wang, Member IEEE

Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing 100190, China

Phone: 86-10-8254-7262 , Fax: 86-10-8254-7161, E-mail: ccyan@mail.iee.ac.cn

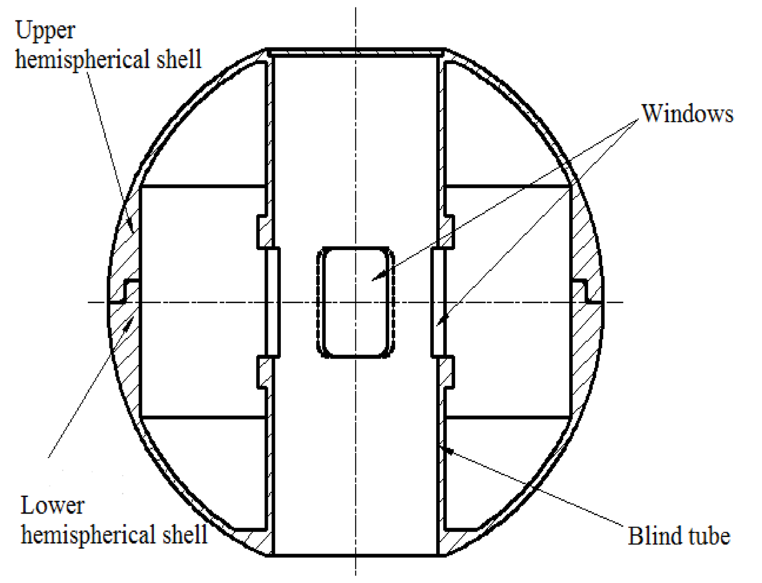
Introduction

- Superconducting magnetic suspension is widely applied in high precision instruments such as superconducting gravimeter, superconducting gradiometer and inertial instruments etc.
- The suspension system is based on the Meissner effect. During the rotation of the superconducting rotor, the rotor deformation will generate disturbing torque on the rotor which is harmful to the rotational stability and drift accuracy.
- The rotor deformation includes static deformation and dynamic deformation. The static deformation is mainly caused by the manufacture error. The dynamic deformation is mainly caused by the centrifugal force due to high rotation velocity which is difficult to be measured accurately.
- In this paper the rotor dynamic deformation is calculated by the analytical method and simulated by finite element method.
- A spherical-like rotor structure is presented to compensate the influence of the centrifugal deformation.

Structure of superconducting rotor

The superconducting rotor is designed with a hollow thin-walled structure to reduce the quality.

- the upper hemispherical shell
- the lower hemispherical shell
- the central blind tube
- four symmetrical windows spaced 90 degrees apart



- As the core component of the suspension system, the rotor material must be with higher critical temperature, critical magnetic field, rigidity and stability. In our laboratory the superconducting rotor was made of niobium with a purity of 99.999% which has a high transition temperature 9.2 K.
- The upper critical magnetic field of niobium is 1922 Gs, the density is 8.57 g/cm3, modulus of elasticity is 106.9 GPa and Poisson ratio is 0.38.

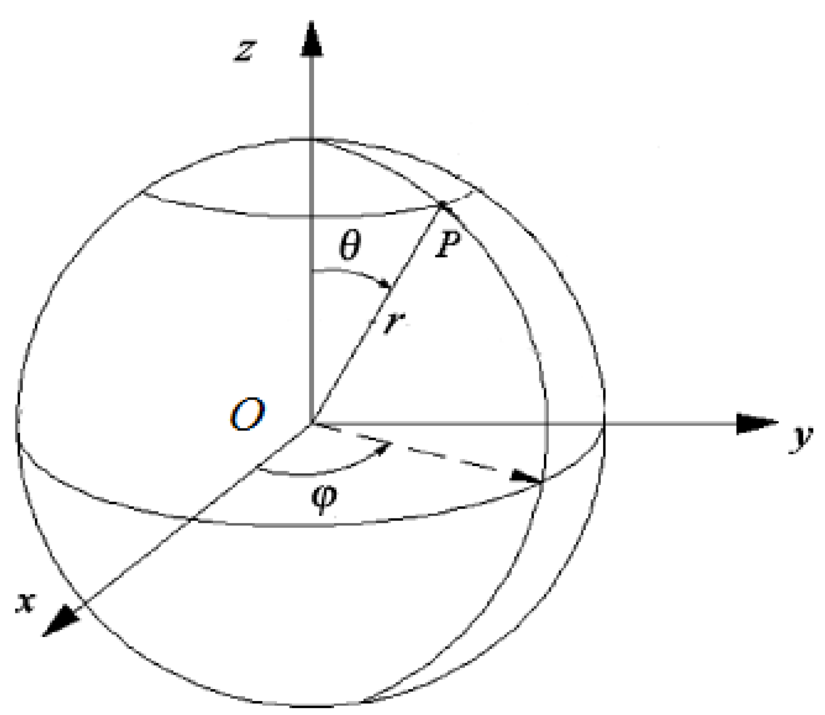
Analytical calculation of dynamic deformation

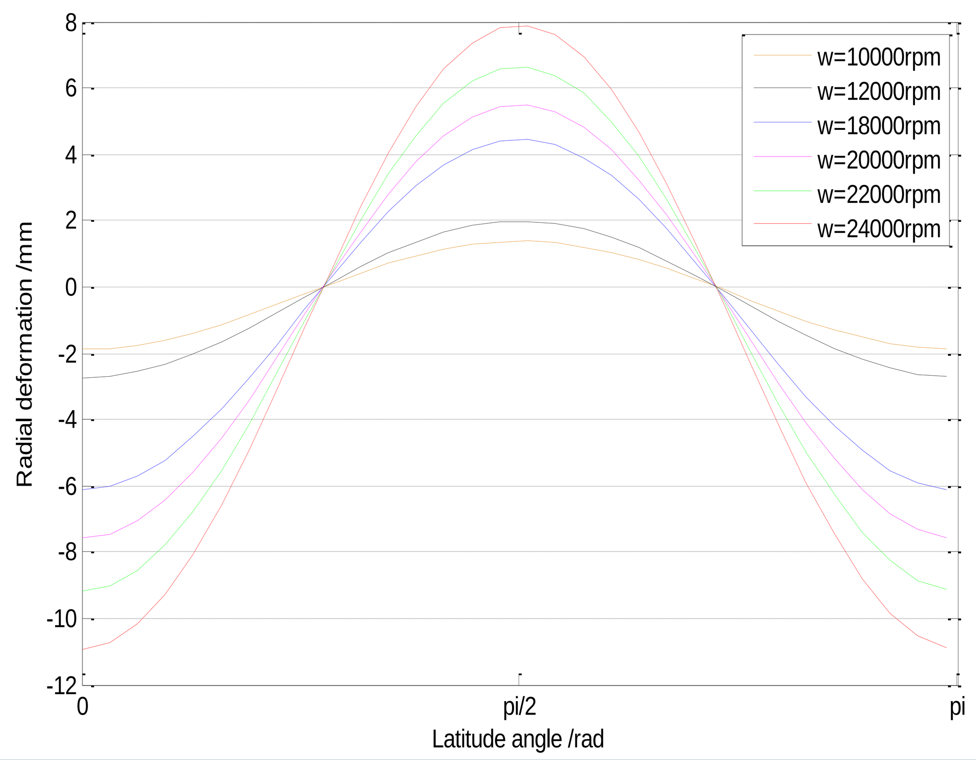
To simplify analysis, some assumptions are made as following:

- The superconducting rotor is homogeneous and isotropic elastic body;
- The outer surface of the rotor is ideal spherical shape before distortion;
- The thickness of the thin shell varies symmetrically with respect to the polar and equatorial planes;
- There is only direct stress on the positive section of the shell, and there is no bending moment and shear stress.

The radial deformation of the rotor

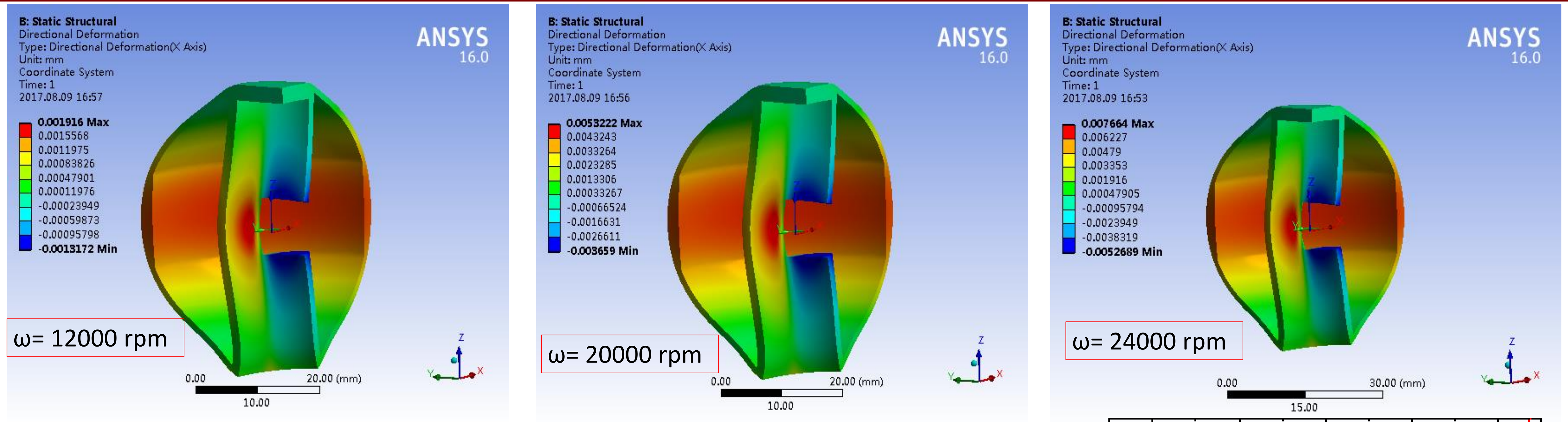
$$\Delta r(\theta) = r(\theta) - r_0 = -\frac{\rho \omega^2 r_0^3}{2E}\left(v + (2+v)\cos 2\theta\right)$$



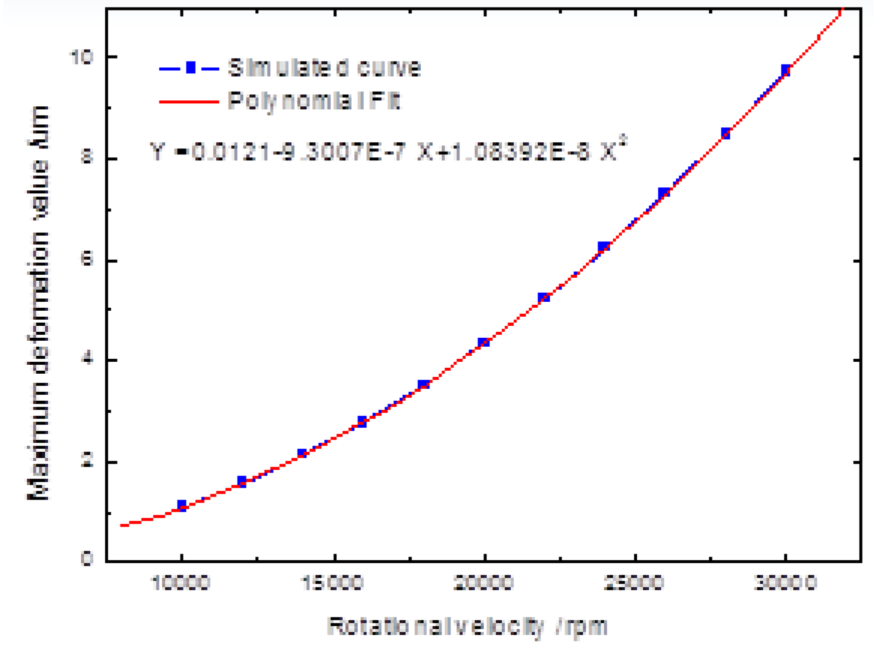


- The maximum positive deformation occurs at the equator (θ=π/2).
- The maximum negative deformation is at the poles (θ=0,π).
- The higher the rotational angular velocity is, the greater the radial displacement deformation is.

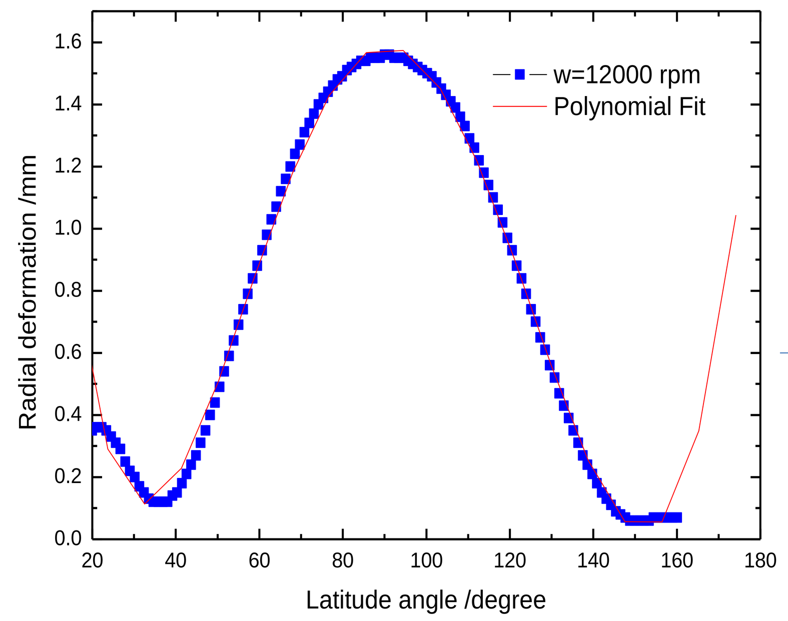
FEM analysis of dynamic deformation



- The outer surface of the rotor is no longer an ideal sphere, but a spherical-like rotor with a long equator and short poles.
- The equator and the two poles of the rotor all expand outward under the centrifugal force.
- The maximum radial deformation of rotor outer surface is located on the equator which is 1.56 μm, 4.33 μm and 6.23 μm at 12000 rpm, 20000 rpm and 24000 rpm respectively.
- Considering the special structure of the superconducting rotor, that is, there is a blind tube which is opened at one end and closed at the other end, the deformation value is positive unlike the ideal sphere.



Design of spherical-like superconducting rotor



Simulated deformation at ω=12000 rpm

- The overall trends of the simulated and theoretical deformation are approximately the same
- It is distinguished at the poles due to the structural constraints of the central blind tube.
- The range of the simulated radial deformation of the rotor is less than that of the theoretical curve.
- The equator and the two poles are all expand outward.
- The deformation value at the equator is larger than that of two poles.
- Near the poles, the value of the rotor deformation is decreasing first and then increasing.

Design principle: a prolate ellipsoid at static condition with a short equtor and long poles

$$\begin{aligned} r'(\theta) &= r_0 - \Delta r(\theta) \\ &= r_0 + 1.75\times10^{-10}\theta^5 - 2\times10^{-7}\theta^4 + 5.77\times10^{-5}\theta^3 \\ &\quad - 0.006\theta^2 + 0.250\theta - 3.46 \end{aligned}$$

Conclusion

- The relationship between the centrifugal deformation and the rotational velocity of the rotor is obtained by FEM software.
- The higher the rotational velocity, the greater the centrifugal deformation.
- The superconducting rotor is designed to be a prolate ellipsoid under static condition which can compensate the deformation and reduce the disturbing torque.

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