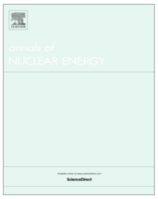
Annals of Nuclear Energy 115 (2018) 220–232

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene



Investigation on the lubrication regimes and dynamic characteristics of hydro-hybrid bearing of two-circuit main loop liquid sodium pump system

Zhongliang Xie, Zhushi Rao *, Na Ta

Laboratory of Vibration, Shock and Noise, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 3 October 2017
Received in revised form 22 January 2018
Accepted 23 January 2018
Available online 2 February 2018

Keywords:
Liquid sodium
Hydro-hybrid bearing
Lubrication performance and mechanism
Dynamic characteristics

ABSTRACT

This manuscript aims to investigate the lubrication performances of the hydro-hybrid bearing which is lubricated by liquid sodium in the fast reactor two-circuit main loop liquid sodium pump system. The liquid sodium lubrication bearing is modeled and analyzed using the advanced rotating mechanical dynamics analysis software. For different initial conditions, lubrication characteristic parameters and dynamic coefficients are studied systematically. Through the analysis, lubrication mechanisms under different operation conditions are revealed, which are completely different from the traditional oil or water lubricated bearing. The investigation lays solid foundation for further study on dynamic analysis of the liquid sodium bearing-nuclear main pump rotor coupled system. Research results have certain directive significance for the special engineering requirement hydro-hybrid bearing.

1. Introduction

Hydro-hybrid bearing with liquid sodium is the important part of two-circuit main loop liquid sodium pump system (Sodium is a chemical element; the chemical symbol is Na). As the key supporting structure of the two circuit main loop rotor system, the fluid film hydrodynamic characteristics and the bearing structure itself will directly affect the dynamic response, the system stability and life, as well as the structural vibration and the noise radiation characteristics of the whole rotor system. Different from the traditional lubricant, the high temperature liquid sodium is kind of liquid metal, and serves as a kind of special lubricating medium with low viscosity. Its absolute viscosity under 310 °C almost equals to that of water at room temperature (Feng, 2003). It has been proved that, compared to traditional lubricating medium (water/oil), high temperature liquid sodium has its certain particularities. At present, there is no established lubrication theory for the hydro-hybrid bearing with liquid sodium, the lubrication mechanism and performance needs further systematic research.

The two-circuit main loop liquid sodium pump system and the hydro-hybrid bearing have special operating requirements, such as: pressure fluctuation of the high temperature liquid sodium, swing of the main rotor system, load shock under extreme conditions (for example earthquake), these circumstances will directly cause the pressure fluctuation, local lubrication insufficient, lubricant starved, and even contact or rub between the rotor and bearing. At the same time, in order to ensure the safe operation of the two-circuit main loop liquid sodium pump system and the normal operation of hydro-hybrid bearing under special conditions (such as earthquake, explosion or other extreme conditions), it is necessary to systematically and deeply investigate the hydrodynamics model and corresponding analysis method for the hydro-hybrid bearing under practical engineering application characteristics.

Through the investigation, the influence of certain coupled factors (such bearing clearance, structure and operating parameters) on the lubrication mechanism, lubrication performance as well as the supporting stiffness of the fluid film will be revealed. Dynamic response and characteristics analysis of the whole fast reactor two-circuit main loop liquid sodium pump system will be further studied. Research fruits will provide solid theoretical foundation and abundant technical reserves for the development and practical application of fast reactor two-circuit main loop liquid sodium pump system.

The aim of this paper is to investigate the hydrodynamic lubrication performances of the hydro-hybrid bearing which is lubricated by liquid sodium in the fast reactor two-circuit main loop liquid sodium pump system. Through the hydrodynamic lubrication theory, the liquid sodium lubrication bearing is modeled and analyzed using the advanced rotating mechanical dynamics

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* Corresponding author.
E-mail address: zsrao@sjtu.edu.cn (Z. Rao).

https://doi.org/10.1016/j.anucene.2018.01.038
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analysis software package. Through the analysis, the manuscript reveals the special characteristics of the lubrication mechanism for the bearing compared to the traditional oil or water lubricated bearing. For different external loads, different rotating speeds and different initial eccentricity ratios, the lubrication characteristic parameters and dynamic characteristics are studied systematically. The investigation lay solid foundation for the further study on dynamic characteristics of the liquid sodium lubrication bearing-nuclear main pump rotor coupled system. Results have certain directive significance for the special engineering hydro-hybrid bearing.

2. Theoretical analysis

2.1. Reynolds equation of unsteady state

Different from the traditional hydrodynamic lubrication plain journal bearing (Zhang et al., 2009; Zhang, 2010), the hybrid lubrication bearing exists hydrodynamic lubrication state and hydrostatic lubrication state at the same time. As can be seen in Fig. 1, for the bearing, directly presents the dimensionless Reynolds equation (Wen et al., 2000):

$$\frac{\partial}{\partial\varphi}\left(\frac{H^3}{\bar{\mu}}\frac{\partial\bar{P}}{\partial\varphi}\right)+\frac{\partial}{\partial\lambda}\left(\frac{H^3}{\bar{\mu}}\frac{\partial\bar{P}}{\partial\lambda}\right)=3\Lambda\frac{\partial H}{\partial\varphi}+6\Lambda(x'\sin\Phi+y'\cos\Phi) \tag{1}$$

where H is the dimensionless fluid film thickness, $\bar{p}$ is the dimensionless fluid pressure, φ,λ is the circumferential and axial coordinate, respectively, Φ is the fluid film attitude angle, ω is the rotating speed of the journal, $\bar{\mu}$ is the dimensionless viscosity of the lubricant.

Let $\bar{p}=p/p_s$, $\Lambda=\frac{2\mu\omega}{p_s\phi^2}$, where p_s is the pressure from external to the static pressure oil chamber or the supply pressure; Boundary condition can be seen from Fig. 1: $\bar{p}|\Gamma_1=\bar{p}|\Gamma_3=\bar{p}_{in}$, $\bar{p}_{in}$ is the dimensionless inlet pressure, $\bar{p}|\Gamma_2=0$, $\bar{p}|\overset{*}{\Gamma}_3=\frac{\partial\bar{p}}{\partial\varphi}\Big|\Gamma_3=0$, $\frac{\partial\bar{p}}{\partial\lambda}\Big|\Gamma_4=0$, $\bar{p}|\Gamma_0=\bar{p}|\Gamma_0=\bar{p}_r$, $\bar{p}_r=\frac{P_r}{P_s}$, where p_r, can be obtained according to the flow rate of the fluid flow in the oil cavity, or the continuity equation in the oil supply orifice. Generally speaking, if the parameters of the oil cavity or the oil supply orifice are regarded as the constraint conditions, then the hybrid bearing can be regarded as one of the special forms of the hydrodynamic lubrication. For the pure hydrostatic bearings, the right term of the Eq. (1) can be set to zero, which can be regarded as one of the special forms of the bearings.

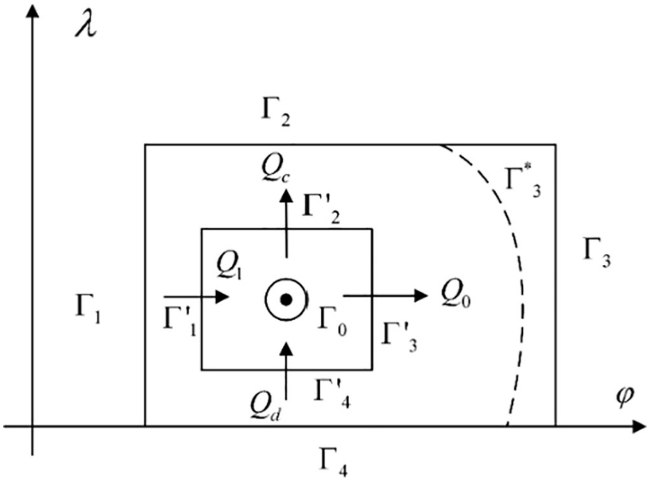

Fig. 1. Expansion Figure of the hybrid bearing with Sodium liquid.

2.2. Calculation of the dynamic parameters

Generally speaking, the stiffness and damping coefficients of the fluid film reflect the changes of the fluid film forces when the rotor system is located near the static equilibrium positions. Therefore, it is necessary to take the Reynolds equation in unsteady motion state as the basis of the calculation and analysis. For the hybrid bearing lubricated with sodium liquid, seek the derivation of Eq. (1) on the perturbation term (hold $\bar{\mu}$ as constant), then we can get (Szeri, 2011; Stachowiak and Batchelor, 2013):

$$\begin{aligned}&\frac{\partial}{\partial\varphi}\left(H^2\frac{\partial\overline{p}_d}{\partial\varphi}\right)+(D/L)^2\frac{\partial}{\partial\lambda}\left(H^3\frac{\partial\overline{p}_d}{\partial\lambda}\right)\\&=3\Lambda\frac{\partial H_d}{\partial\varphi}-3\Lambda\left[\frac{\partial}{\partial\varphi}\left(H^2H_d\frac{\partial\overline{p}}{\partial\varphi}\right)+(D/L)^2\frac{\partial}{\partial\lambda}\left(H^2H_d\frac{\partial\overline{p}}{\partial\lambda}\right)\right]\\&\quad+6\Lambda\frac{\partial}{\partial d}(x'\sin\Phi+y'\cos\Phi)\end{aligned} \tag{2}$$

where d is the perturbation term, $d=\overline{x},\overline{y},x',y',\overline{p}_d=\frac{\partial\overline{p}}{\partial d}$; $H_d=\frac{\partial H}{\partial d}$.

The boundary condition is: $\overline{p}|\overset{*}{\Gamma}_3=\overline{p}_d|\Gamma_1\bigcup\Gamma_2\bigcup\Gamma_3^*$ $(or\ \Gamma_3=0)$, $\overline{p}|\Gamma_0=\frac{\partial p_r}{\partial d},\frac{\partial p_d}{\partial\lambda}\Big|\Gamma_4=0$.

In view of the complex and complicated structure form of the hybrid bearing lubricated by the sodium liquid, when using the finite difference method to solve the Reynolds equation, film thickness is not continuous in the guiding grooves. Therefore, finite element method is exploited to solve the Reynolds equation (Szeri, 2011; Bates et al., 2005). In order to make the static and dynamic properties consistent with the solution, the perturbed Reynolds equation is also solved by the finite element method. The Galerkin variation finite element equation of Eq. (2) is (Shuiguang and Xixuan, 1992):

$$\begin{aligned}&\iint_A H^3\left[\frac{\partial\overline{p_d}}{\partial\varphi}\frac{\partial V}{\partial\varphi}+(D/L)^2\frac{\partial\overline{p_d}}{\partial\lambda}\frac{\partial V}{\partial\lambda}\right]d\varphi d\lambda\\&=3\iint_A\left\{H_d\left[\Lambda\frac{\partial V}{\partial\varphi}-H^2\left(\frac{\partial\overline{p}}{\partial\varphi}\frac{\partial V}{\partial\varphi}\right)+(D/L)^2\frac{\partial\overline{p}}{\partial\lambda}\frac{\partial V}{\partial\lambda}\right]\right.\\&\quad\left.+2\Lambda\frac{\partial(x'\sin\Phi+y'\cos\Phi)}{\partial d}\right\}d\varphi d\lambda\end{aligned} \tag{3}$$

where V is arbitrary function, other symbols and boundary conditions are the same as Eq. (2). The specific solution methods can be find in (Wen et al., 2000).

3. Liquid sodium pump bearing

3.1. Main pump rotor system

According to the design drawings, the three-dimensional structure diagram of the liquid sodium hydro-hybrid bearing-nuclear main pump rotor coupled system is shown in Fig. 2(a). From the figure we can see, hydro-hybrid bearing is the key supporting part of the entire nuclear main pump rotor coupled system, and its lubrication mechanism is different from the traditional bearings. The specific operating circumstances are as follows:

For the initial operating condition, there exists initial pressure p_0 in the liquid supply tank, which makes the rotor of the nuclear main pump in the geometric center of the bearing. When start up the motor, the rotor system begins to operate. Because of the sealing properties and performance of the whole structure, the impeller rotation will drive the steady flow fluid in the stabilizing cover, then the fluid pressure p will press the liquid sodium into the guiding grooves in the hydro-hybrid bearing. With the increase of the rotating speed, the fluid pressure increases sharply. Pressure in the guiding grooves of the bearing also increases, and the hydrodynamic effect enhances.