Tribology International 104 (2016) 157–165

Contents lists available at ScienceDirect

Tribology International

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

Slip and turbulence phenomena in journal bearings with application to implantable rotary blood pumps

Gordon Paul [a], Amin Rezaienia [a], Xiang Shen [a], Eldad Avital [a], Theodosios Korakianitis [b,*]

[a] School of Engineering and Materials Science, Queen Mary University of London, London, UK
[b] Parks College of Engineering, Aviation and Technology, Saint Louis University, St. Louis, MO, 63103 USA

ARTICLE INFO

Article history:
Received 15 July 2016
Received in revised form
22 August 2016
Accepted 25 August 2016
Available online 28 August 2016

ABSTRACT

This paper describes an investigation into journal bearings with geometries and working fluid similar to centrifugal blood pumps. The aim is to describe the phenomena that cause these journal bearings to deviate from classical predictions. Experimental, analytical and numerical methods are used to investigate the behaviour of a range of bearings with geometries and working fluid similar to blood pumps. It was found that the clearance had a significant effect on the force-eccentricity characteristic of the bearing, with smallest and largest clearances deviating from classical predictions. Experimentally measured pressure distributions show that slip occurs when the clearance is small and that turbulence occurs with the largest clearances. The effects of these phenomena on lubricant pressure and blood compatibility are discussed.

1. Introduction

Cardiovascular disease is the leading cause of death globally, accounting for 31% or 17.3 million deaths worldwide in 2013, a number that is expected to increase to 23.6 million by 2030 [1]. Due to the shortage of heart donors compared with the huge demand, researchers have developed implantable blood pumps to make up for the shortfall. Understanding the behaviour of these pumps and their effect on the blood that passes through them is essential to design pumps that are long lasting and safe.

The first generation of blood pumps were pneumatically driven volume displacement devices. These were effectively chambers which expanded and contracted like the native heart, such as the Thoratec PVAD [2]. It was found that these devices, with several moving parts and membranes, were too susceptible to wear for long term use [3]. The second generation of blood pumps were rotary devices which rotated on mechanical bearings [4], which were typically ceramic. These tended to last longer than their volume displacement predecessors and many of these pumps, such as the Thoratec Heartmate II, are still in use today. However, due to the mechanical contact, there is a risk of flow stagnation and thrombus formation at the bearing site, as well as problems with wear [5]. Consequently the third generation of blood pumps use entirely contactless impellers, which are suspended by hydrodynamic forces [6], passive magnetic suspension [7], active magnetic suspension [8], or combinations of these [9].

In most cases, especially in contactless centrifugal blood pumps, the contactless rotating impellers used in blood pumps have small (< 1 mm) radial clearances and act as journal bearings. Examples include the Thoratec Heartmate III [10], the Cleveland Clinic IVAS [11], and Evaheart [12]. An exhaustive list of such pumps or detailed analysis of each of these is beyond the scope of this paper, however there is a clear journal bearing effect in each of these blood pumps due to the existence of rotating and stationary cylindrical faces with a small clearance. In some cases this is used as part of the suspension mechanism, in others it is considered a side effect. A comprehensive understanding of the behaviour of such bearings will aid the design of the next generation of blood pumps.

Journal bearing systems are composed of a rotating journal inside a sleeve, with a small clearance between the two filled with fluid. They allow a load to be supported without contact due to lubricant pressure generated by the journal's rotation. When the journal is in an eccentric position, the film thickness around the journal circumference is not constant. Where the fluid is pushed into a decreasing gap (nozzle) positive pressure is generated and where the fluid is pushed into an increasing gap (diffuser) negative pressure is generated. At a particular eccentric position or set of eccentric positions the force on the journal due to the lubricant pressure is equal and opposite to the applied load and the journal is in equilibrium. Such a system is useful in blood pumps because it allows partial suspension of a contactless impeller.

In most previous applications, journal bearing systems used oil filled journals, with larger geometries and a much more viscous

* Corresponding author.
E-mail address: korakianitis@alum.mit.edu (T. Korakianitis).

http://dx.doi.org/10.1016/j.triboint.2016.08.032

Nomenclature

c	Clearance (m)
e	Eccentricity (m)
F	Force generated by lubricant pressure (N)
g	Correction factor
L	Journal length (m)
N	Rotational speed (rpm)
P	Pressure (Pa)
r	Journal radius (m)
U	Journal surface velocity (m/s)
z	Axial coordinate (m)
δ	Load angle (degrees)
θ	Azimuthal coordinate (degrees)
μ	Viscosity (Pa.s)

Non-dimensional

$\epsilon = e/c$	Eccentric ratio
$C = 100^*(c/r)$	Clearance ratio
$\Lambda = L/d$	Bearing slenderness ratio

fluid than blood. These were modelled with analytical equations describing the pressure distribution across their surfaces, which generally assume the fluid flow is laminar and use a no-slip boundary condition. Several researchers have described evidence of slip [13,14] and turbulence [15] in journal bearing systems. Since analytical solutions are used for the prediction of blood pump behaviour [23], work is required to verify assumptions in classical theory and allow behaviour prediction for journal bearings in blood pumps, with different geometries and low viscosity working fluid. This paper uses analytical, computational fluid dynamics (CFD) and experimental methods to investigate and describe the behaviour of journal bearings with various geometries and working fluid similar to that found in centrifugal rotary blood pumps.

2. Methods

Three methods are used here to analyse the behaviour of a blood-pump sized journal bearing. These are an analytical method, a CFD method and an experimental method. The journal bearing and its parameters are described in Fig. 1. In this paper, the eccentricity is always in the negative Y direction, θ=180°, and the load angle, δ, is measured from this point. The exact physical dimensions are not disclosed here; the journal radius is fixed at a value between 12.5 and 20 mm and non-dimensional clearance ratio (C) and bearing slenderness ratio (Λ) are used to describe the bearings.

In this paper the region where the film thickness is getting smaller, from 0° to 180°, is described as the nozzle region. The region where the film thickness is increasing, from 180° to 360°, is described as the diffuser region.

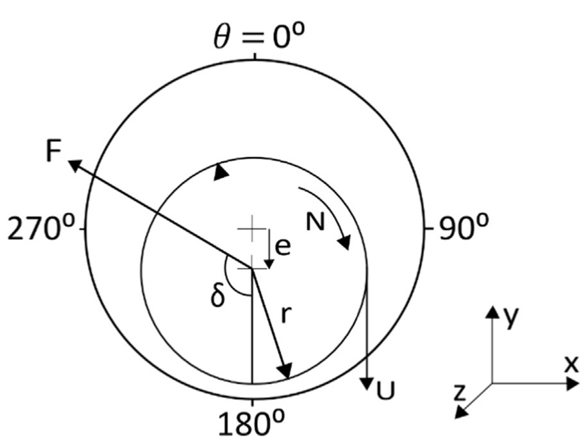

Fig. 1. – A journal bearing of radius r, rotational speed N and journal surface velocity U at eccentricity e, resulting in a force F at angle δ.

2.1. Analytical

An analytical method is used to predict the journal bearing load using infinitely short and infinitely long journal bearing models and correction factors proposed by Hirani et al. [16]. The models for the pressure, P, at a given point on the infinitely short bearing (Ocvirk's solution P_O) [17] and the infinitely long bearing (Sommerfeld's solution, P_S) [18] are given in Eqs. (1) and (2).

$$P_O = \frac{3\mu U L^2}{rC^2}\left[\frac{1}{4} - \left(\frac{z}{L}\right)^2\right]\frac{\epsilon.\ sin\theta}{(1+\epsilon.\ cos\theta)^3} \tag{1}$$

$$P_S = \frac{6\mu U r}{C^2\left(2+\epsilon^2\right)}\left[\frac{\epsilon.\ sin\theta\left(2+\epsilon.\ cos\theta\right)}{(1+\epsilon.\ cos\theta)^2}\right] \tag{2}$$

Where μ is viscosity, L is journal length, r is journal radius, C is clearance ratio and ϵ is eccentricity ratio. Hirani et al. demonstrate the use of correction factors g_O and g_S to combine these models to form an accurate solution for pressure at all bearing coordinates for any bearing slenderness ratio (L/2r), as described in Eqs. (3)–(5).

$$\frac{1}{P} = \frac{g_O}{P_O} + \frac{g_S}{P_S} \tag{3}$$

$$g_O = 1+\epsilon\left(\frac{L}{r}\right)^{1.2}\left[e^{\epsilon^5}-1\right] \tag{4}$$

$$g_S = e^{(1-\epsilon)^3} \tag{5}$$

Where g is the correction factor. A Matlab code is used to calculate the pressure across the bearing according to this solution and sum it to give the force and load angle on the journal for a particular geometry, fluid, speed and eccentricity. The pressure is calculated using Hirani et al.'s solution for 100 radial coordinates across 20 axial coordinates for each case. A full Sommerfeld condition is applied, so the resulting load angle is always 90º.

2.2. Computational fluid dynamics

Computational fluid dynamics is used to simulate the behaviour of the journal bearing in blood. Ansys mesh was used for meshing, and Ansys CFX is used as the solver. A k-ω turbulence model was used because it was considered the most appropriate to describe behaviour of the fluid in small clearances based on work by Fraser et al. [19]. Ansys's documentation states that although a y^+ value of less than 2 is desirable for a k-ω simulation, in most cases it is not achievable given the computational cost. In