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A fluid-structure-thermal model for bump-type foil thrust bearings

Kan Qin [a,*], Peter A. Jacobs [b], Joshua A. Keep [b], Daijin Li [a], Ingo H. Jahn [c]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xian, 710072, China
[b] Queensland Geothermal Centre of Excellence, School of Mechanical and Mining Engineering, The University of Queensland, St Lucia, Brisbane, 4072, Australia
[c] Centre for Hypersonics, School of Mechanical and Mining Engineering, The University of Queensland, St Lucia, Brisbane, 4072, Australia

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ABSTRACT

This paper presents a multi-physics multi-timescale computational framework for the three-dimensional and two-way coupled fluid-structure-thermal simulation of foil thrust bearings. Individual solvers for the transient fluid flow, structural deformation, heat conduction and the coupling strategy are discussed. Next, heat transfer models of the solid structures within foil thrust bearings are also described in detail. The result is a multi-physics computational framework that can predict the steady state and dynamic performance of foil thrust bearings. Numerical simulations of foil thrust bearings with air and CO_2 are then performed. It is found that the centrifugal pumping that naturally occurs in CO_2 bearings due to the high fluid density provides a new and effective cooling mechanism for the CO_2 bearing.

1. Introduction

The supercritical Carbon Dioxide (sCO_2) cycle is considered as a potential alternative to conventional steam power cycle with the advantages of higher efficiency and compact turbomachinery components [1]. However, many challenges have to be overcome before this cycle can be realised, as CO_2 exhibits different behaviours when compared to air or steam. The key components of the supercritical CO_2 cycle have been actively studied in recent years [2–4]. One of the key components to enable sCO_2 turbines and compressors is an efficient bearing solution. The high rotational speeds and thrust loads, especially at small power exceed the capabilities of conventional rolling element bearings. An alternative to these are gas bearings operating with the working fluid. Amongst the foil bearings are a promising solution. Foil bearings (journal and thrust) were tested at Sandia National Laboratories as part of a sCO_2 loop demonstration. This demonstrated that foil bearings are more efficient and have a longer life compared to alternative conventional rolling element bearings. Typical bump-type foil bearings are composed of a top foil and a corrugated bump foil. The top foil is affixed to the bearing housing or a foil block on the upstream side, and on the downstream side, it sits at the height of its bump under structure. This forms a partially ramped profile as indicated in Fig. 1.

The film height (the clearance between rotor and top foil) in the ramp region can be adjusted by implementing a foil block. The use of foil bearings in high-speed turbomachinery systems has various advantages compared to rolling element bearings. The favourable characteristics of foil bearings are improved reliability, elimination of lubricant oil supply system, operation capability at very high and low temperatures, improved dynamic characteristics, tolerance to minor shaft misalignment and external perturbations and the low viscosity of the gas working fluid resulting in lower power losses [5].

Foil bearings have several limitations. At high speeds, high local temperature gradients can cause thermal runaway [6]. This is due to the weak conduction rate of the thin foil structure and low heat capacity of air. The small contact areas between top foil and bump foils and low heat capacity of air cause a progressive warm up of the components that leads to thermal distortion and subsequent failure of the foil bearing. Hence, the temperature distribution within foil bearings has to be carefully considered during design, particularly for bearings operated with high rotational speed or high load [7].

Salehi et al. [8]. performed a first study to model and characterise thermal properties of gas foil journal bearings. The Couette flow approximation for the fluid within foil thrust bearings was implemented to model the temperature distribution. This simplified method had a reasonable agreement with experimental data, but with a maximum over-prediction of 19%. Sim and Kim [9] presented a thermo-hydrodynamic model that accounted for the thermal contact resistance between the top foil, bump foil and bearings housing. The mixing effect between the leading and trailing edges of top foils was also investigated. The suction flow mixing ratio at the groove region was

* Corresponding author.
E-mail addresses: jasonqk@hotmail.com, kan.qin@nwpu.edu.cn (K. Qin).

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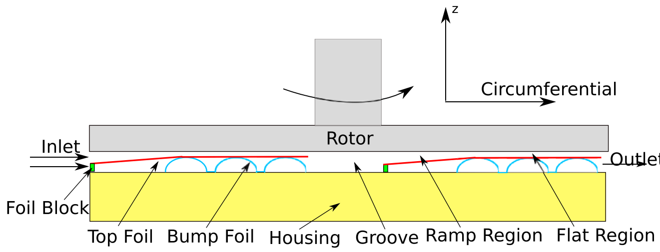

Fig. 1. Side view of foil thrust bearings.

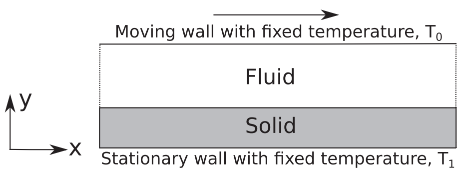

Fig. 2. Schematic diagram for conjugate Couette flow.

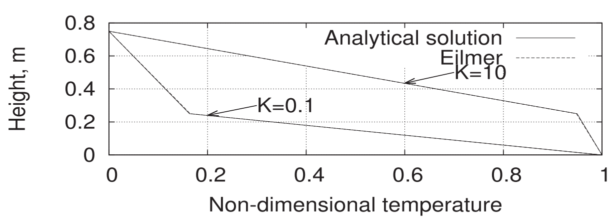

Fig. 3. Comparison of temperature distribution between fluid-thermal simulation and analytical solution.

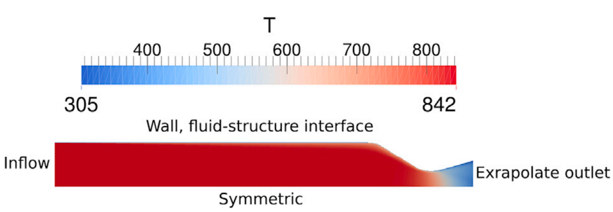

Fig. 4. Boundary conditions for conjugate nozzle flow, coloured by temperature.

obtained and then applied to their model. The detailed mixing model in the groove region is outlined in Ref. [10]. Their proposed cooling strategy is to radially supply flow into the mixing zone. The feasibility of the radial injection cooling was experimentally tested by Shrestha et al. [11]. In addition, the heat conduction behaviour from the top foil to the back plate via the bump foil was experimentally determined in Ref. [12].

The aforementioned work is for the thermo-hydrodynamic modelling of foil journal bearings. Little work has been undertaken to model the temperature field for foil thrust bearings. The Couette flow approximation used by Salehi et al. [8]. was also implemented by Gad and Kaneko [13] to predict the temperature distribution for air foil thrust bearings. Lee and Kim [14] conducted a three-dimensional thermo-hydrodynamic analysis of Raleigh step air foil thrust bearings with forced cooling air flow and the optimum cooling air pressure was found based on the reference simulation condition. For air foil thrust bearings, the influence of temperature rise on the bearing performance is not significant. San Andrés and Ryu [15] conducted isothermal simulations which matched well with the experimental data from Dickman [16].

When considering supercritical CO_2 applications, the operating fluid is far more dense than air, less viscous compared to oil, and highly non-

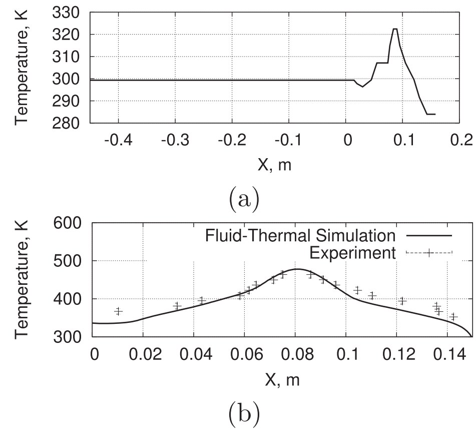

Fig. 5. (a) Temperature distribution along outer wall of nozzle [26], used as the nonuniform temperature boundary condition for numerical simulation, (b) comparison of temperature distribution along inner wall of nozzle between numerical simulation and experiment [26].

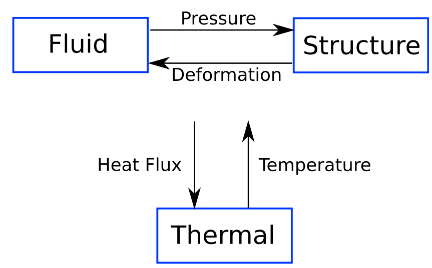

Fig. 6. Schematic diagram for fluid-structure-thermal simulations.

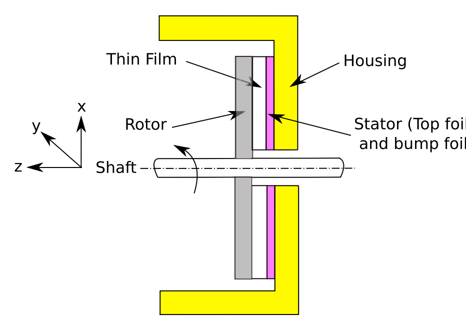

Fig. 7. Schematic diagram for layout of foil thrust bearings.

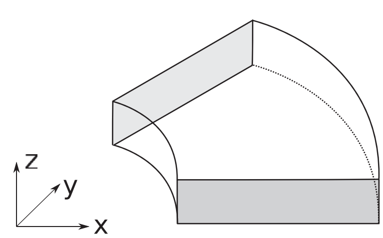

Fig. 8. Computational domain for the rotor.

ideal. These factors present challenges when predicting the performance of foil bearings. This includes the potential for turbulent flow, highly compressible flow, non-linear thermodynamic properties and non-negligible centrifugal inertia force due to high density and high-speed operation. These effects were numerically investigated by Qin et al. [2,