A Two-Phase Flow CFD Model for Predicting Rotordynamic Performance of Annular Seals During Laminar-to-Turbulent Transition

(New Proposal)

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Introduction and Background

Annular seals restrict secondary leakage between stages in compressors and centrifugal pumps. Typical annular seals are balance-pistons, wear rings, and interstage seals. Rotordynamic forces on annular seals can be the primary contributor to the overall vibration characteristics of rotating machinery. Recent pump failures can be attributed to inadequate modeling of annular seals in the laminar-to-turbulent transition regime, possibly operating with a two-phase flow working fluid.

Annular seals are typically designed to operate with either a gas, as in the case of a compressor, or a liquid, as in the case of a pump. Annular seals are rarely designed to operate with a gas/liquid mixture. It is not unusual, however, that these seals operate with mixtures. This is the case with pumps in deep sea reservoirs, which work with gas in liquids; and gas compression systems, which work with liquids in gas mixtures.

In a set of experiments done at the Turbomachinery Laboratory [CB21], the rotordynamic performance of a smooth annular seal was measured and compared against a prediction using Zirkelback and San Andres' model [ZA96]. This seal was similar to an annular seal used in electric submersible pumps that "have shown remarkable balance piston flow mechanisms affecting both rotordynamic behavior and step-changes in volumetric efficiency for the pump assembly" [EBK+18]. The seal had a length-to-diameter ratio, $L/D = 0.5$, a diameter, $D = 51$ mm, and a nominal radial clearance, $C_r = 0.2$ mm. Tests were conducted for angular shaft speeds between 2 and 8 krpm, axial pressure drops between 2.1 and 8.27 bars, eccentricity ratios $\epsilon_0 = e_0/C_r$ (e_0 is the static eccentricity) between 0 and 0.8, using ISO VG 2 oil. The measured and predicted results were generally consistent with expectations, except for the direct stiffness coefficients K_{xx} and K_{yy} at 2 krpm. The discrepancy between experiments and the model was attributed to the laminar-to-turbulent transition. As the pressure drop increased, transition occurred at a vector Reynolds number Re = 1700, as opposed to the 1000 value used in the Zirkelback and San Andres model. In addition, the flow became fully turbulent at Re = 2500 instead of 3000 used in [ZA96]. Furthermore, the direct virtual mass coefficients were approximately 2 to 3 times larger than predicted.

Another experimental investigation done at the Turbomachinery Laboratory measured the rotordynamic coefficients and mass leakage rates of a long, smooth annular seal tested with a mixture of silicone oil and air [TCSZ18]. The seal had a length-to-diameter ratio, $L/D = 0.75$, a diameter, $D = 114.7$ mm, and a nominal radial clearance, $C_r = 0.2$ mm. The experiment tested three inlet preswirl inserts, four pressure drops (between 20.7 and 41.4 bars), and six inlet gas volume fractions (between 0% and 10%) [TCSZ18]. The experimental results were compared against the predictions of a two-phase, homogeneous-mixture, bulk-flow model [SA12]. The predicted mass leakage rate was smaller than the measured value. The measured leakage remained constant or slightly increased with increasing gas volume fraction, while the predicted leakage decreased. The model predicted a drop of direct stiffness as the gas volume fraction increased, but the measured values dropped much more rapidly than predicted. In addition, the model did not predict the strong tendency of direct stiffness to drop when preswirl increased. The authors of the experiment concluded that the measured drop in direct stiffness was not explained by either (1) a reverse Lomakin effect from operating in the laminar-to-turbulent transition flow regime, or (2) the predicted drop in direct stiffness at higher gas volume fractions from the model. The authors claimed that "a separate and

as yet unidentified two-phase flow phenomenon probably causes the observed result" [TCSZ18].

Proposed Work

The goal of this project is to improve the prediction of rotordynamic coefficients by supplementing the bulk-flow model with a computational fluid dynamics (CFD) model. The project has two objectives: (1) improve prediction of rotordynamic coefficients during laminar-to-turbulent transition by modeling the growth of the turbulent perturbations, the kinetic energy of turbulent perturbations, and the turbulent dissipation, and (2) improve modeling of two-phase flow by solving the mass, momentum, and energy balance equations. This project will also have an experimental component to determine the critical Reynolds number, Re_{cr}, for two-phase flows (gas in liquid) as a function of the gas volume fraction values. The project will be completed in three years, as shown in the schedule.

Schedule

Task	1st Year				2nd Year				3rd Year			
1. Determine experimentally Re_cr for gas in liquid mixtures (air in oil with gas volume fractions between 0 and 10%)	▓	▓										
2. Modify CFD code UNS3D to model two-phase flows			▓	▓								
3. Calculate rotordynamic coefficients of annular seal from [TCSZ18]					▓	▓						
4. Modify CFD code UNS3D to model laminar-to-turbulent transition							▓	▓	▓			
5. Calculate rotordynamic coefficients of annular seal from [CB21]										▓	▓	
6. Final report												▓

Deliverables 2021-2022

1. Experimentally determined Re_{cr} for oil with gas (air) volume fractions between 0 and 10%;

2. Updated in-house CFD code UNS3D that models two-phase flows.

Budget 2021-2022

Support for graduate student (20 hours/week)	$26,400
Fringe benefits and insurance	$3,127
Tuition and fees	$17,186
Hardware and instrumentation	$3,287
Total	$50,000

References

[CB21] D. W. Childs and J. Bullock. Rotordynamic performance of smooth liquid annular seals in the laminar, transition, and turbulent regimes over a range of imposed pre-swirl ratios. manuscript, 2021.

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[SA12] L. San Andres. Rotordynamic force coefficients of bubbly mixture annular pressure seals. *Journal of Engineering for Gas Turbines and Power*, 134:022503–1–8, February 2012.

[TCSZ18] D. L. Tran, D. W. Childs, H. Shrestha, and M. Zhang. Preswirl and mixed-flow (mainly-liquid) effects on rotordynamic performance of a long (l/d = 0.75) smooth seal. In *47th Turbomachinery & 34th Pump Symposia*, pages 1–22, Houston, Texas, 2018. Turbomachinery Laboratory, Texas A&M Engineering Experiment Station.

[ZA96] N. Zirkelback and L. San Andres. Bulk-flow model for the transition to turbulence regime in annular pressure seals. *Tribology Transactions*, 39(4):835–842, Oct. 1996.