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

(Continuation)

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Introduction and Background

Annular seals restrict secondary leakage between stages in compressors and centrifugal pumps. Typical annular seals are balance piston, wear ring, 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. The goal of this project is to develop *industry-ready tools to prevent the potentially bad consequences of inadvertently operating a pump's balance piston seal in transition regime, namely lurching into unstable asynchronous whirl.*

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]. 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, as shown in Fig. 1. The discrepancy between experiments and the model was attributed to the laminar-to-turbulent transition.

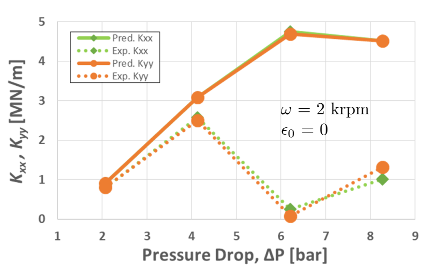


Figure 1: Direct stiffness vs. pressure drop [CB21].

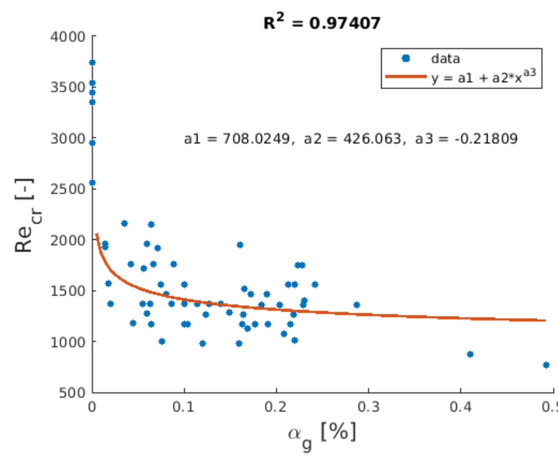


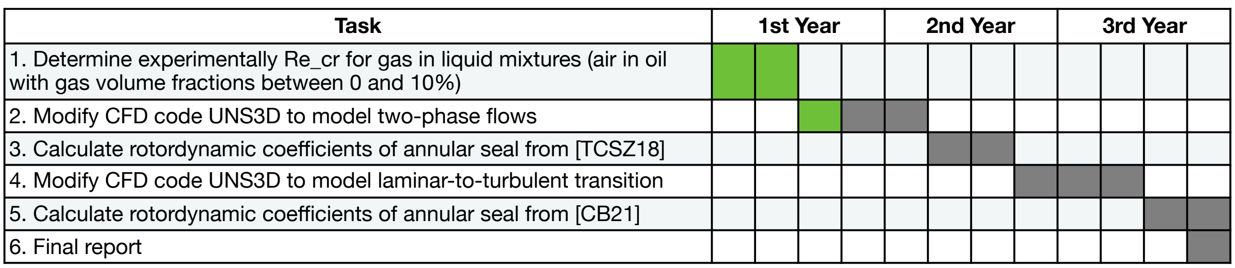
Figure 2: Critical Reynolds number vs. gas void fraction.

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 (GVF), 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 approach 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 three objectives. The first objective, the experimental determination of the critical Reynolds number for two-phase flows (gas in liquid) as a function of the gas volume fraction values, has been completed. Figure 2 shows the variation of critical Reynolds number with gas void fraction. The second objective, the modification of the in-house TRC-UNS3D CFD code to model the two-phase flow, has started. Progress has also been made on the third objective, the modeling of two-phase flow effects on the laminar-to-turbulent transition, as shown in the progress report.

Schedule



Deliverables 2022-2023

1. Complete the update of CFD code TRC-UNS3D to model two-phase flows;
2. Calculate rotordynamic coefficients of annular seal from [TCSZ18].

Budget 2022-2023

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.

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