An applied investigation of viscosity–density fluid sensors based on torsional resonators

By

Daniel Brunner

Thesis submitted in fulfilment of
the requirements for the degree of
PHILOSOPHIAE DOCTOR

(PhD)

Faculty of Engineering Science and Technology

UiT The Arctic University of Norway
N-9037 Tromsø

Norway
www.uit.no
©Daniel Brunner
All rights reserved
ISBN: 978-82-7823-221-7

Abstract

Real-time viscosity and density measurements give insight into the status of many chemical and biochemical processes and allow for automated controls. In many applications, sensors that enable the real-time measurements of fluid properties use resonant elements. Such sensors measure induced changes in the element's resonance frequency and damping that can be related to the fluid properties. These sensors have been widely researched, though they are not yet commonly used in industrial processes.

This study investigates two resonant elements to measure the viscosity and density of Newtonian fluids. The first is a probe-style viscosity-density sensor, and the second is a non-intrusive tubular viscosity sensor. These two sensors were investigated using analytical, numerical, and experimental methods. In the analytical method, the sensors' resonance frequencies and bandwidths were predicted based on reduced-order models for both structure and fluid. In the numerical method, the interaction of the resonant element with the fluid was investigated by means of computational fluid dynamics (CFD). Experiments were conducted for validation, to evaluate the sensors' capabilities, and understand cross-sensitivity effects between viscosity and density.

The reduced-order (analytical) method was used to model the resonant elements of the sensors as mass-spring systems, describing their interaction with the fluid. For the probe style viscosity-density sensor, the resonant element was comprised of a two-mass and three-spring system. The tubular viscosity sensor was analyzed by means of a modal analysis by reducing it to a single mass-spring system, where only the first torsional mode was considered. The main advantage of the reduced-order model was that it provided insight into the working principle of the sensors without using complicated and computationally expensive numerical models.

CFD was used to understand the fluid behavior around the resonant element of the probe-style viscosity density sensor. The flow field was solved using CFD because the probe style viscosity-density sensor has a complex geometry, i.e., cylindrical tip with four radial fins where the flow phenomenon is too complex to be described analytically. The solution was validated for independence of discretization, i.e., mesh and numerical methods (finite element method via COMSOL® and finite volume method via ANSYS® CFX). Different boundary conditions, such as by a moving wall and changing the frame of reference, were used to generate similar effects. The resulting fluid forces from the CFD solution were coupled with the reduced-order (analytical) structural model to compute the change in resonance frequency and bandwidth.

A series of experiments were conducted under a range of well-defined conditions to validate the output of the models and test both sensors, namely the probe-style viscosity-density sensor and tubular viscosity sensor. For each condition, the experimentally measured bandwidth and resonance frequency were compared to the predictions of the models. Results from the experiments and models were found to be in good agreement. This led to successfully accounting for cross-sensitivities between viscosity, density, and temperature.

This work successfully modeled and validated the two different torsional resonant element sensors, namely the probe-style viscosity-density sensor and the tubular viscosity sensor against experiments. There are two key output parameters, i.e., resonance frequency and bandwidth. Using these parameters, it is possible to predict fluid viscosity and density. Overall, this work demonstrates the potential of numerical modeling for the development of torsional resonance sensors. These findings directly affect the development of the future generation of fluid viscosity and density sensors.

Keywords: viscosity sensor, density sensor, computational fluid dynamics, fluid–structure interaction, oscillation, resonator, reduced order modelling

Acknowledgments

This study was conducted at the Institute of Computational Physics at the ZHAW in Winterthur from 2017 to 2020 in collaboration with the Arctic University of Norway. This applied research project was done in collaboration with the Rheonics GmbH company. I extend my heartfelt gratitude to my supervisor Dr. Hassan Abbas Khawaja of the Arctic University of Norway who supported me with my writing, planning, and simulations.

I would also like to thank my family members, especially my wife Ashley, who supported me patiently throughout this journey. Dr. Gernot Boiger made this PhD possible by his unwavering support all the way. I thank Dr. Joe Goodbread for supervising all my experimental and design-related work and supporting the designing and building process of the new sensor. The interesting and insightful discussions we had on numerous subjects were very helpful. I am also grateful to Dr. Klaus Häusler, Dr. Sunil Kumar, Dr. Patrick Vogler, and Dr. Vijoya Sa for their support. Last, but not the least, I appreciate my colleagues at the Institute of Computational Physics at ZHAW for their insightful and enlightening discussions over coffee.