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Whole-Angle MEMS Gyroscopes

Challenges and Opportunities

Doruk Senkal | Andrei M. Shkel

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List of Abbreviations

Table 1 Control system abbreviations.

Symbol	Description
Quadrature	Unwanted component of oscillation that interferes with estimation of the pattern angle, manifests as a result of structural imperfections
AGC	Amplitude Gain Control, closed-loop control of drive amplitude
PLL	Phase Locked Loop, closed-loop control system that generates an AC signal with a predetermined phase offset from the resonator
FTR	Force-to-rebalance, closed-loop control system that actively drives the pattern angle to a setpoint
Quadrature null	Closed-loop control system that actively suppresses the effects of structural imperfections within the gyroscope

Table 2 Mechanical parameters of the resonator.

Symbol	Description
f	Mean frequency of the two primary modes of the resonator
τ	Mean energy decay time constant of the resonator
Q-factor	Ratio of stored energy to energy loss per vibration cycle ($Q = \tau\pi f$)
Δf	Frequency split between primary modes in Hz ($\Delta f = f_x - f_y$)
$\Delta\omega$	Frequency split between primary modes in rad/s ($\Delta\omega = \omega_x - \omega_y$)
$\Delta\tau^{-1}$	Measure of anisodamping within the gyroscope ($\Delta\tau^{-1} = \mid \tau_x^{-1} - \tau_y^{-1} \mid$)
θ_ω	Angle defining the orientation of actual versus intended axes of elasticity
θ_τ	Angle defining the orientation of actual versus intended axes of damping
(x, y, z)	Coordinate frame oriented along intended axes of symmetry x and y
$n = 2$ mode	A 4-node degenerate mode pair of a wineglass or ring/disk system
$n = 3$ mode	A 6-node degenerate mode pair of a wineglass or ring/disk system
Precession pattern	Vibration pattern formed by superposition of x and y vibratory modes, which is capable of changing its orientation (precesses) when subjected to Coriolis forces or an external forcing function
Pattern angle (θ)	Orientation of the precession pattern in degrees, which is a measure of angular rotation in a Rate Integrating Gyroscope

Preface

Coriolis Vibratory Gyroscopes (CVGs) can be divided into two broad categories based on the gyroscope's mechanical element: degenerate mode gyroscopes (type 1), which have x–y symmetry, and nondegenerate mode gyroscopes (type 2), which are designed intentionally to be asymmetric in x and y modes.

Currently, nondegenerate mode gyroscopes fulfill the needs of a variety of commercial applications, such as tilt detection, activity tracking, and gaming. However, when it comes to inertial navigation, where sensitivity and stability of the sensors are very important, commercially available MEMS sensors fall short by three orders of magnitude. Degenerate mode gyroscopes, on the other hand, offer a number of unique advantages compared to nondegenerate vibratory rate gyroscopes, including higher rate sensitivity, ability to implement whole-angle mechanization with mechanically unlimited dynamic range, exceptional scale factor stability, and a potential for self-calibration. For this reason, as the MEMS gyroscope development is reaching maturity, the Research and Development focus is shifting from high-volume production of low-cost nondegenerate mode gyroscopes to high performance degenerate mode gyroscopes. This paradigm shift in MEMS gyroscope research and development creates a need for a reference book to serve both as a guide and an entry point to the field of degenerate mode gyroscopes.

Despite the growing interest in this field, the available information is scattered across a disparate group of conference proceedings and journal papers. For the aspiring scientist/engineer, the scarcity of information forms a large barrier to entry into the field of degenerate mode gyroscopes. This book aims to lower the barrier to entry by providing the reader with a solid understanding of the fundamentals of degenerate mode gyroscopes and its control strategies, as well as providing the necessary know-how and technical jargon needed to interpret future publications in the field.

The book is intended to be a reference material for researchers, scientists, engineers, and college/graduate students who are interested in inertial sensors.

The book may also be of interest to control systems engineers, electrical and electronics engineers, as well as semiconductor engineers who work with inertial sensors. Finally, materials scientists and MEMS production engineers may find the section regarding various fabrication technologies and fabrication defects/energy loss mechanisms interesting.

Doruk Senkal
Andrei M. Shkel

About the Authors

Doruk Senkal

Dr. Senkal has been working on the development of Inertial Navigation Technologies for Augmented and Virtual Reality applications at Facebook since 2018. Before joining Facebook, he was working as a MEMS designer at TDK Invensense, developing MEMS Inertial Sensors for mobile devices.

He received his PhD degree (2015) in Mechanical and Aerospace Engineering from the University of California, Irvine, with a focus on MEMS Coriolis Vibratory Gyroscopes, received his MSc degree (2009) in Mechanical Engineering from Washington State University with a focus on robotics, and received his BSc degree (2007) in Mechanical Engineering from Middle East Technical University.

His research interests, represented in over 20 international conference papers, 9 peer-reviewed journal papers, and 16 patent applications, encompass all aspects of MEMS inertial sensor development, including sensor design, device fabrication, algorithms, and control.

Andrei M. Shkel

Prof. Shkel has been on faculty at the University of California, Irvine, since 2000. From 2009 to 2013, he was on leave from academia serving as a Program Manager in the Microsystems Technology Office of DARPA, where he initiated and managed over $200M investment portfolio in technology development. His research interests are reflected in over 250 publications, 40 patents, and 3 books. Dr. Shkel has been on a number of editorial boards, most recently as Editor of IEEE JMEMS and the founding chair of the IEEE Inertial Sensors (INERTIAL). He has been awarded in 2013 the Office of the Secretary of Defense Medal for Exceptional Public Service, 2020 Innovator of the Year Award, 2009 IEEE Sensors Council Technical Achievement Award, 2008 Researcher of the Year Award, and the 2005 NSF CAREER award. He received his Diploma with excellence (1991) in Mechanics and Mathematics from Moscow State University, PhD degree (1997) in Mechanical Engineering from the University of Wisconsin at Madison, and completed his postdoc (1999) at UC Berkeley. Dr. Shkel is the 2020–2022 President of the IEEE Sensors Council and the IEEE Fellow.

Part I

Fundamentals of Whole-Angle Gyroscopes