

MEMS Reference Shelf

Cenk Acar
Andrei Shkel

MEMS Vibratory Gyroscopes

Structural Approaches to
Improve Robustness

 Springer

Mems Vibratory Gyroscopes Structural Approaches To Improve Robustness Mems Reference Shelf

Ridha Almikhlafi



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MEMS Vibratory Gyroscopes Cenk Acar, Andrei Shkel, 2008-12-16 MEMS Vibratory Gyroscopes provides a solid foundation in the theory and fundamental operational principles of micromachined vibratory rate gyroscopes and introduces structural designs that provide inherent robustness against structural and environmental variations In the first part the dynamics of the vibratory gyroscope sensing element is developed common micro fabrication processes and methods commonly used in inertial sensor production are summarized design of mechanical structures for both linear and torsional gyroscopes are presented and electrical actuation and detection methods are discussed along with details on experimental characterization of MEMS gyroscopes In the second part design concepts that improve robustness of the micromachined sensing element are introduced supported by constructive computational examples and experimental results illustrating the material MEMS Vibratory Gyroscopes Cenk Acar, 2008

Sensors for Automotive and Aerospace Applications

Shantanu Bhattacharya, Avinash Kumar Agarwal, Om Prakash, Shailendra Singh, 2018-11-01 This volume covers the various sensors related to automotive and aerospace sectors discussing their properties as well as how they are realized calibrated and deployed Written by experts in the field it provides a ready reference to product developers researchers and students working on sensor design and fabrication and provides perspective on both current and future research

Integrated Microsystems Krzysztof Iniewski, 2017-12-19 As rapid technological developments occur in electronics photonics mechanics chemistry and biology the demand for portable lightweight integrated microsystems is relentless These devices are getting exponentially smaller increasingly used in everything from video games hearing aids and pacemakers to more intricate biomedical engineering and military applications Edited by Kris Iniewski a revolutionary in the field of advanced semiconductor materials Integrated Microsystems Electronics Photonics and Biotechnology focuses on techniques for optimized design and fabrication of these intelligent miniaturized devices and systems Composed of contributions from experts in academia and industry around the world this reference covers processes compatible with CMOS integrated circuits which combine computation communications sensing and actuation capabilities Light on math and physics with a greater emphasis on microsystem design and configuration and electrical engineering this book is organized in three sections Microelectronics and Biosystems Photonics and Imaging and Biotechnology and MEMs It addresses key topics including physical and chemical sensing imaging smart actuation and data fusion and management Using tables figures and equations to help illustrate concepts contributors examine and explain the potential of emerging applications for areas including biology nanotechnology micro electromechanical systems MEMS microfluidics and photonics Photonic Microsystems Olav Solgaard, 2009-04-05 This book describes Microelectromechanical systems MEMS technology and demonstrates how MEMS allow miniaturization parallel fabrication and efficient packaging of optics as well as integration of optics and electronics The book shows how the characteristics of MEMS enable practical implementations of a variety of applications

including projection displays fiber switches interferometers and spectrometers The authors conclude with an up to date discussion of the need for the combination of MEMS and Photonic crystals

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The British National Bibliography Arthur James Wells, 2009

Differentiable Periodic Maps P. E. Conner, 2006-11-15 MEMS Vibratory Gyroscopes provides a solid foundation in the theory and fundamental operational principles of micromachined vibratory rate gyroscopes and introduces structural designs that provide inherent robustness against structural and environmental variations In part one the dynamics of the vibratory gyroscope sensing element is developed common micro fabrication processes and methods commonly used in inertial sensor production are summarized design of mechanical structures for both linear and torsional gyroscopes are presented and electrical actuation and detection methods are discussed along with details on experimental characterization of MEMS gyroscopes In part two design concepts that improve robustness of the micromachined sensing element are introduced supported by constructive computational examples and experimental results illustrating the material

MEMS Vibratory Gyroscopes is a must have book for engineers in both industry and academia who specialize in the design and manufacture of gyroscopes Readers will find A unique balance between theory and practical design issues Comprehensive and detailed information outlining the mathematical models of the mechanical structure and system level sensor design Solid background Information on mechanical and electrical design fabrication packaging testing and characterization About The MEMs Reference Shelf The MEMs Reference Shelf is a series devoted to Micro Electro Mechanical Systems MEMs which combine mechanical electrical optical or fluidic elements on a common microfabricated substrate to create sensors actuators and microsystems The series authored by leading MEMs practitioners strives to provide a framework where basic principles known methodologies and new applications are integrated in a coherent and consistent manner

STEPHEN D SENTURIA Massachusetts Institute of Technology Professor of Electrical Engineering Emeritus

Mechanical Design, Dynamics, and Control of Micro Vibratory Gyroscopes Seyed Parsa Taheri Tehrani, 2017

Micro machined vibratory gyroscopes are very small devices up to a few millimeters in dimension that work based on Coriolis force coupling between two resonance modes The small size low power consumption and cheap price make these sensors

popular in automotive gaming smart phones and robotics industries These sensors referred to as MEMS microelectromechanical system gyroscopes are currently not used for navigation applications because due to their miniature size and imperfections in fabrication methods they do not have enough accuracy In this thesis we present methods in design and control algorithms for MEMS vibratory gyroscopes to cancel the effect of imperfections in fabrication and improve gyroscopes performance First chapter of this thesis is an introduction on MEMS vibratory gyroscopes and their principles and standard operations modes The second chapter presents the structural design and analysis of a single structure 3 axis MEMS gyroscope The gyroscope has four resonant modes of interest and uses a decoupling mechanism whereby auxiliary masses are used to actuate the drive mode of the gyroscope in order to reduce drive force coupling to sense modes motion one of the sources of errors in MEMS gyroscopes The use of auxiliary masses results in a two degree of freedom DOF mechanism of the drive mode To compare the effectiveness of using auxiliary masses two gyroscope types has been design one actuated from auxiliary masses type A and one actuated from major masses type B The two designs are simulated analytically to study the displacement of each mass in each design while comparing the force required to achieve that displacement for drive mode Experimental data from fabricated devices show how using auxiliary masses will decrease drive force coupling and as a result improve the gyroscope s performance Third chapter describes the operation of a high quality factor gyroscope in various regimes where electromechanical nonlinearities introduce different forms of amplitude frequency A f dependence Experiments are conducted using an epitaxially encapsulated 2 x 2 mm² quad mass gyroscope QMG with a quality factor of 85 000 The device exhibits third order Duffing nonlinearity at low bias voltages 15 V due to the mechanical nonlinearity in the flexures and at high bias voltages 35 V due to third order electrostatic nonlinearity At intermediate voltages 26 V these third order nonlinearities cancel and the amplitude frequency dependence is greatly reduced A model is developed to demonstrate the connection between the electromechanical nonlinearities and the amplitude frequency dependence also known as the backbone curve Gyroscope operation is demonstrated in each nonlinear operating regime and the key performance measures of the gyroscope s performance angle random walk ARW and bias instability are measured as a function of drive mode vibration amplitude While the bias instability is nearly independent of the drive mode s nonlinearity we find that ARW increases when the third order nonlinearities are minimized and the decrease in ARW due to increase of amplitude is independent of drive mode s type of nonlinearity In the fourth chapter we present a direct angle measurement method in gyroscopes Towards the objective of direct angle measurement using a rate integrating gyroscope RIG without a minimum rate threshold and performance limited only by electrical and mechanical thermal noise in this chapter we present the implementation of a generalized electronic feedback method for the compensation of MEMS gyroscope damping asymmetry anisodamping and stiffness asymmetry anisoelasticity on a stand alone digital signal processing DSP platform Using the new method the precession angle dependent bias error and minimum rate threshold two issues identified by Lynch

for a MEMS RIG due to anisodamping are overcome To minimize angle dependent bias we augment the electronic feedback force of the amplitude regulator with a non unity gain output distribution matrix selected to correct for anisodamping Using this method we have decreased the angle dependent bias error by a factor of 30 resulting a minimum rate threshold of 2.5 dps To further improve RIG performance an electronically induced self precession rate is incorporated and successfully demonstrated to lower the rate threshold

MEMS Vibratory Gyroscopes Cenk Acar, Andrei Shkel, 2008-12-16 MEMS Vibratory Gyroscopes provides a solid foundation in the theory and fundamental operational principles of micromachined vibratory rate gyroscopes and introduces structural designs that provide inherent robustness against structural and environmental variations In the first part the dynamics of the vibratory gyroscope sensing element is developed common micro fabrication processes and methods commonly used in inertial sensor production are summarized design of mechanical structures for both linear and torsional gyroscopes are presented and electrical actuation and detection methods are discussed along with details on experimental characterization of MEMS gyroscopes In the second part design concepts that improve robustness of the micromachined sensing element are introduced supported by constructive computational examples and experimental results illustrating the material

Analysis and Modeling of Capacitive MEMS Gyroscopes with Feedback Control Wei Cui, 2010 **Adaptive sliding mode control of a Mems vibratory gyroscope** Juntao Fei, 2008

Fabrication, Testing and Characterization of MEMS Gyroscope Ridha Almikhlafi, 2017 This thesis presents the design fabrication and characterization of two Micro Electro Mechanical Systems MEMS vibratory gyroscopes fabricated using the Silicon On Insulator Multi User MEMS Process SOIMUMPs and Polysilicon Multi User MEMS Process Poly MUMPs Firstly relevant literature and background on static and dynamic analysis of MEMS gyroscopes are described Secondly the gyroscope analytical model is presented and numerically solved using Mathematica software The lumped mass model was used to analytically design the gyroscope and predict their performance Finite element analysis was carried out on the gyroscopes to verify the proposed designs Thirdly gyroscope fabrication using MEMSCAP s SOIMUMPs and PolyMUMPs processes is described For the former post processing was carried out at the Quantum Nanofab Center QNC on a die level in order to create the vibratory structural elements cantilever beam Following this the PolyMUMPs gyroscopes are characterized optically by measuring their resonance frequencies and quality factor using a Laser Doppler Vibrometer LDV The drive resonance frequency was measured at 40 kHz and the quality factor as Q 1 For the sense mode the resonance frequency was measured at 55 kHz and the unity quality factor as Q 1 The characterization results show large drive direction motions of 100 $\mu\text{m/s}$ in response to a voltage pulse of 10 V The drive pull in voltage was measured at 19 V Finally the ratio of the measured drive to sense mode velocities in response to a voltage pulse of 10 V was calculated at 1.375

Modelling of MEMS Vibratory Gyroscopes Utilizing Phase Detection Antonie Christoffel Dreyer, 2008 **Advanced Control Design of MEMS Vibratory Gyroscopes** Juntao Fei, 2011-10 MEMS Micro Electro Mechanical Systems technologies were

developed by applying semiconductor microfabrication technologies to make three dimensional microstructures and mechanical systems MEMS technologies offer the advantages of batch fabrication of numbers of devices as well as an ability to integrate multiple functional units in a small area which is important for developing smart and sophisticated devices Gyroscopes are commonly used sensors for measuring angular velocity in many areas of applications such as navigation homing and control stabilisation Fabrication imperfections and thermal mechanical noise may hinder the measurement of angular velocity of MEMS gyroscope This book presents a comprehensive treatment of the analysis and advanced control design of MEMS gyroscope for the problem of angular velocity measurement and minimisation of the cross coupling between two axes **Mode Ordering in Anti-phase Driven Mems Gyroscopes and Accelerometers** Brenton Ross Simon,2014

Inertial sensors have a wide spectrum of applications ranging from consumer electronics to precision navigation As these devices continue to maximize performance while minimizing Size Weight and Power SWaP requirements these opportunities will only continue to expand Vibratory Micro Electro Mechanical System MEMS inertial sensors are uniquely positioned in this landscape due to their low SWaP metrics and high potential for enhanced performance In this dissertation the fundamental challenges behind the further advancement of these devices are explored with a number of potential solutions proposed For vibratory gyroscopes one of these fundamental challenges is the tradeoff between rate and acceleration sensitivity both of which are enhanced by low frequencies of operation Anti phase resonances are typically employed to decouple this influence however when conventional flexures are used the anti phase vibratory mode is forced to a higher frequency reducing rate sensitivity For this reason a novel coupling structure has been designed analyzed modeled fabricated and tested This structure is experimentally shown to selectively stiffen in phase vibration creating a high degree of modal separation in excess of 120% a value that is believed to be the highest in published literature along with reducing acceleration sensitivity by over 20 fold Theoretical analysis shows that the observed frequency separation can continue to be expanded with this technique which is only limited by fabrication constraints This type of structure was also applied to a new frequency modulated accelerometer and shown to enhance the mechanical scale factor by over 20 times Resonator quality factor is another critical element that can be maximized to enhance the performance of some inertial sensors By identifying the primary energy loss mechanisms within the frequency range of interest each mechanism was modeled and minimized through design and fabrication The result of this work was a resonator with quality factor of 2 34 million and decay constant of 1300 s both of which are also believed to be the highest in published literature for microfabricated structures In addition to these highlights investigations also include an in run scale factor calibration method through the use of an integrated torsional rate stage as well as packaging considerations for enhanced temperature robustness Vibratory Gyroscopes Based on Micro-Electro-Mechanical and Non-Micro-Electro-Mechanical Systems Valeri V. Chikovani,2023-12 This book provides a unified approach for the two versions of Coriolis vibratory gyroscopes Micro Electro Mechanical System MEMS

and non MEMS It describes a new differential mode of operation analyzing the new triple mode gyro rate rate integrating and differential The latter provides the gyro with an increased versatility by providing the maximum possible accuracy under changeable motion parameters and environmental conditions The book also presents computer simulation experiments and test results on the rejection of external disturbances and considers the fabrication processes of MEMS metallic and quartz resonators It will interest researchers scientists engineers and students specializing in the field of inertial sensors as well as engineers of digital control systems and inertial sensors test engineers It can also be used as a reference book when designing vibratory gyros

Toward Inertial-Navigation-on-Chip Haoran Wen, 2019-09-14 This thesis develops next generation multi degree of freedom gyroscopes and inertial measurement units IMU using micro electromechanical systems MEMS technology It covers both a comprehensive study of the physics of resonator gyroscopes and novel micro nano fabrication solutions to key performance limits in MEMS resonator gyroscopes Firstly theoretical and experimental studies of physical phenomena including mode localization nonlinear behavior and energy dissipation provide new insights into challenges like quadrature errors and flicker noise in resonator gyroscope systems Secondly advanced designs and micro nano fabrication methods developed in this work demonstrate valuable applications to a wide range of MEMS NEMS devices In particular the HARPSS process platform established in this thesis features a novel slanted nano gap transducer which enabled the first wafer level packaged single chip IMU prototype with co fabricated high frequency resonant triaxial gyroscopes and high bandwidth triaxial micro gravity accelerometers This prototype demonstrates performance amongst the highest to date with unmatched robustness and potential for flexible substrate integration and ultra low power operation This thesis shows a path toward future low power IMU based applications including wearable inertial sensors health informatics and personal inertial navigation

Dual-Mass Linear Vibration Silicon-Based MEMS Gyroscope Huiliang Cao, 2023-05-04 This book introduces the key technologies in the manufacture of double mass line vibrating silicon micromechanical gyroscope respectively The design of gyrostructure detection technology orthogonal correction technology the influence of temperature and the design of measurement and control system framework are introduced in detail with illustrations for easy understanding It presents the principle structure and related technology of silicon based MEMS gyroscope The content enlightens the researchers of silicon based MEMS gyroscopes and gives readers a new understanding of the structural design of silicon based gyroscopes and the design of dual mass gyroscopes

Toward Navigational Grade MEMS Gyros Design, Control, and Error Mitigation of MEMS Gyroscopes Howard Haoquan Ge, 2018 Coriolis Vibratory Gyroscope CVG is considered the most critical component in a strap down inertial navigation unit It measures the rate of rotation through the Coriolis coupling or exchange of angular momentum between a pair of resonance modes with very close resonance frequency often referred to as a degenerate mode pair The measurement error however is closely related to how close the degenerate mode pair match in frequencies Further the errors also drifts over time making precise

calibration nearly impossible There is a particular class of CVGs with radial symmetry in their geometric design Such symmetry permits the simultaneous actuation and measurement of multiple Coriolis mode pairs Such design opens up the possibility of operating more than one pair of degenerate modes on the same resonator The UCLA resonator URES was designed to exploit the benefits of this possibility The first challenge to overcome is the simultaneous modal frequency match of two Coriolis mode pairs The two mode pairs of interest are the $n=2$ mode which is elliptical in shape and the $n=3$ mode which is trilobal in shape The as etched resonator typically exhibit frequency mismatch on the order of 10Hz for both mode pairs A technique using mass perturbation has been developed to simultaneously reduce the frequency mismatch of both mode pairs to within 0.1 Hz Once tuned a system identification procedure is performed to determine the modal properties of both mode pairs from which the drive and sense electrodes and the peripheral electronics can be optimally configured to maximize signal to noise ratio and reduce quadrature error ii A new control architecture is then implemented to simultaneously operate both mode pairs on the tuned resonator as two independent Coriolis sensors thus allowing the extraction of two independent rate measurements from the same resonator The noise and long term stability performance of both mode pairs are characterized Angle random walk ARW bias stability and scale factor for each mode pair are first characterized with the other mode pair turned off The performance parameters are subsequently compared to those when the two mode pairs are simultaneously operated Degradation in the noise performance due to nonlinearity in the electronics was analyzed and an effective mitigation using frequency domain filtering was implemented Correlation between the $n=2$ and $n=3$ bias drift was observed and studied in detail in this research Further a blending filter architecture is introduced to optimally combine the two rate measurements to yield a single superior rate measurement in terms of both the sensors noise characteristics and its long term bias stability Lastly a novel in situ technique is introduced to adaptively identify a finite impulse response FIR model for the parasitic feedthrough signal between the input port and the output port of a microelectromechanical MEMS resonator The identified FIR model is then used as a filter to cancel the parasitic signal leaving a clean resonance peak Experiments conducted on multiple two input two output resonator devices show that the filters can adapt to different devices without precise knowledge of the devices parameters The filters also track the changes in the parasitic feedthrough over time providing consistent cancellationSuppressions of more than 30 dB on the parasitic feedthrough signals are obtained on all tested devices

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