Minimal Realization of Dynamically Balanced Lumped Mass WA Gyroscope: Dual Foucault Pendulum

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***Abstract*—We report a new type of MEMS rate integrating gyroscope. The Dual Foucault Pendulum (DFP) gyroscope consists of two dynamically equivalent, mechanically coupled proof masses, oscillating in anti-phase motion, creating a dynamically balanced resonator with x-y symmetry in frequency and damping. Phase synchronization is established by mechanical coupling of the two proof masses, whereas quadrature suppression is achieved by four differential shuttle pairs placed in-between. Dual axis tuning fork behavior provides vibration immunity and anchor loss mitigation, resulting in a Q-factor over 100,000 on both modes at a center frequency of 2.7 kHz. Whole angle mechanization is demonstrated by FPGA-based closed loop control of the gyroscope, showing a scale factor variation of 22 ppm RMS over 2 hours of measurement. We believe Dual Foucault Pendulum is the minimal realization of a dynamically balanced lumped mass whole angle (WA) gyroscope.**

Keywords*—Rate integrating MEMS gyroscope, whole angle mechanization, closed loop control, tuning fork behaviour.

I. Introduction

Tuning fork architectures are widely used in high performance gyroscopes, due to high-Q drive modes, low power consumption, and vibration immunity. For example, a tactical grade tuning fork gyro was demonstrated in [1]. A matched mode tuning fork gyro was reported in [2]. Two tuning forks were combined via lever mechanisms in [3] to achieve degenerate mode operation. With the exception of [3], these devices are not suitable for whole angle mechanization due to lack of x-y symmetry. In this work, we are exploring a new gyro architecture that combines dynamic balance of tuning fork gyros (anti-phase motion) with high rate sensitivity and rate integrating capability of degenerate mode gyroscopes (x-y symmetry) in a minimal configuration (two-mass system).

II. Design

Core of the Dual Foucault Pendulum (DFP) Gyroscope is two mechanically coupled and dynamically equivalent proof masses, oscillating in anti-phase motion, Fig 1(a). Each proof mass is free to swing in any direction on the x-y plane, analogous to a Foucault Pendulum. Unlike a conventional tuning fork gyroscope, center of masses of the two proof masses are aligned, Fig 1(b). This creates force and moment balance for both x and y modes, providing immunity to vibration and shock as well as anchor loss mitigation. As a result, high-Q and and frequency symmetry can be achieved along both x and y modes. In addition, cross-axis coupling can be mitigated by four differential shuttle pairs located in between the two proof masses, which also house the electrodes, Fig 2.

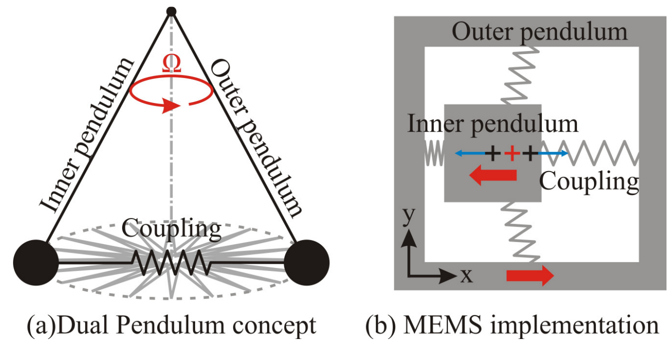

Fig 1. Dual Foucault Pendulum (DFP) gyroscope consists of two mechanically coupled Foucault Pendulums, oscillating in anti-phase motion.

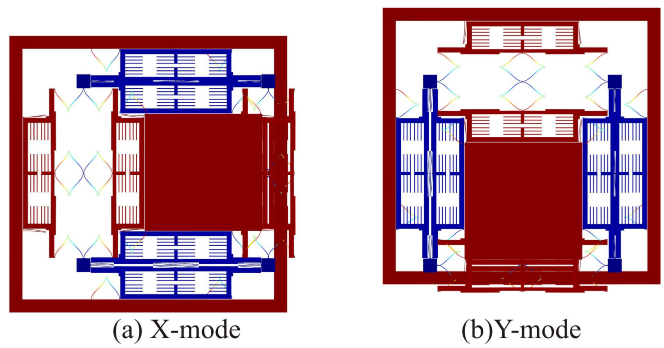

Fig 2. FEA showing x-y symmetric anti-phase operation. Differential shuttle pairs provide quadrature cancellation.

Device was fabricated on a 100 µm SOI process, with a footprint of 6700 µm x 6700 µm, Fig 3. Electrostatic transduction is provided by arrays of parallel plates located on the shuttle assemblies. In order to achieve large displacements necessary for low noise operation, 8 µm capacitive gaps are used on the parallel plates, resulting in 12.5 pF total capacitance (dC/dx = 1.5 µF/m). A high-vacuum test-bed with a non-evaporable getter pump was used for continuous 360 degrees rotation at sustained vacuum levels of < 10 µTorr. Ring-down characterization of the mechanical element revealed an energy decay time constant (τ) of 11.9 seconds at 2.7 kHz, which corresponds to Q-factor over 100,000 on both modes. An as-fabricated frequency split (Δf) of 18 Hz was observed and electrostatically tuned to < 0.5 Hz using 16 V DC.

III. Experimental Results

After electrostatic tuning, closed loop control of the gyroscope was implemented on Kintex 7 FPGA board, Fig 4. Virtual carouseling experiments were performed to identify the pattern angle dependence of Phase Locked Loop (PLL), Amplitude Gain Control (AGC), AC quadrature null, and

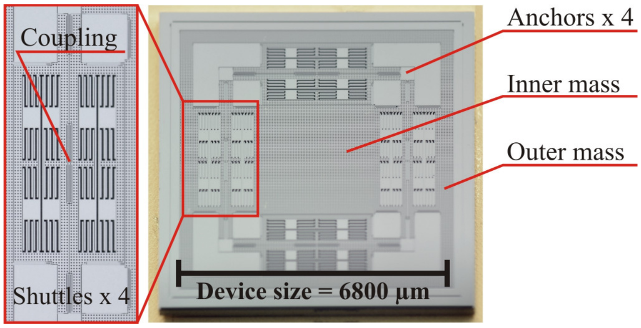

Fig 3. Image showing fabricated gyroscope with a close-up on mechanical coupling between pendulums. Four main anchors are shared by the two masses.

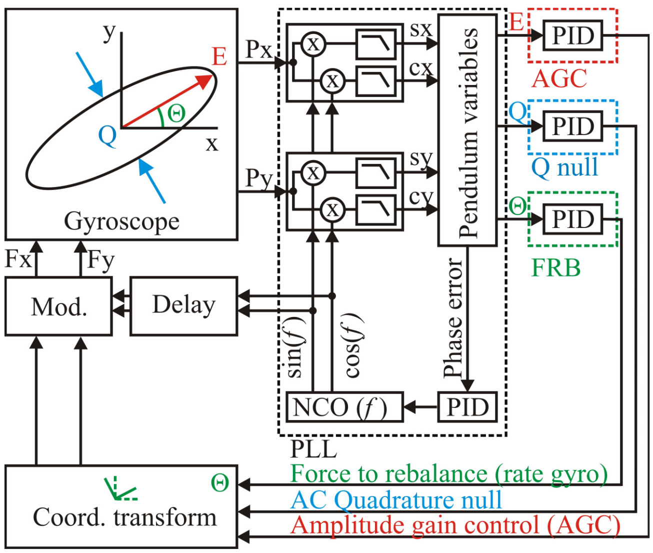

Fig 4. Rate integrating gyro control implemented on a Kintex 7 FPGA running at 500 kHz, provides closed loop control of PLL, AGC, quad. null, and FRB.

force-to-rebalance loops (FRB), Fig. 5 [4]. Frequency mismatch of Δf < 0.1 Hz was observed on x and y geometric axes, whereas a stiffening up to 0.5 Hz was observed at 45° pattern angle. A nominal drive voltage of 1 mV was used for amplitude control. Maximum variation in quadrature null command signal was < 25 mV, whereas the variation on force-to-rebalance command signal was < 5 mV. Uncompensated quadrature null and force-to-rebalance loops showed 2θ and 4θ dependence on pattern angle, Fig. 5.

In order to permit precession of the vibration pattern the force-to-rebalance loop was disabled. Rate integrating gyroscope operation was demonstrated by applying a continuous rate input of 180 deg/s over 2 hours duration on a rate table, Fig. 5. A linear fit to the experimental data revealed an angular gain factor of ~0.8. Local perturbations of > 5° were observed in the uncompensated gyro output due to pattern angle dependent bias (angular error and pattern drift). Despite these perturbations, RMS error of a linear fit to the 10 Hz data was found to be 29° over 2 hours duration (1,296,000° of rotation), showing a scale factor variation of 22 ppm RMS.

IV. Conclusions

A new type of MEMS rate integrating gyroscope is presented. Dual Foucault Pendulum (DFP) Gyroscope aims to combine dynamic balance of tuning fork gyroscopes with high rate sensitivity and rate integrating capability of high-Q degenerate mode gyroscopes in a minimal (two-mass) configuration. Rate integrating operation of the gyroscope is experimentally demonstrated via FPGA-based closed loop control. An angular gain factor of ~0.8 and scale factor variation of 22 ppm RMS was measured over 2 hours of rate integrating operation. We believe, Dual Foucault Pendulum (DFP) is the minimal realization of a dynamically balanced lumped mass gyroscope. Further improvement in frequency and damping symmetry may lead to high performance rate integrating gyroscope operation in a compact architecture.

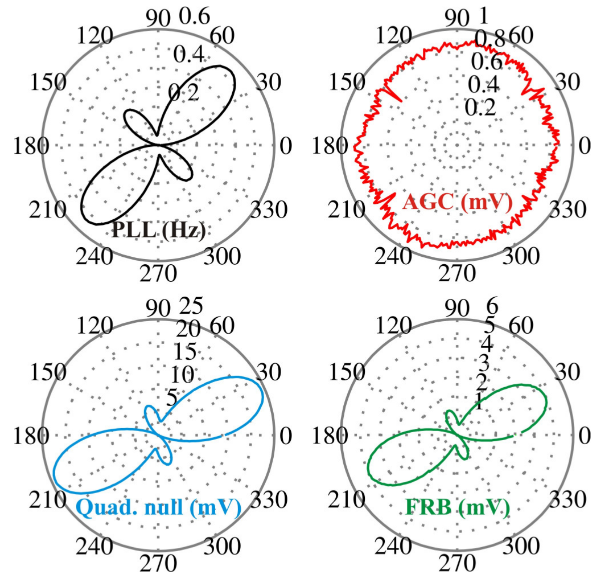

Fig 5. Polar plots showing the pattern angle dependence of four main closed loops. 2θ and 4θ dependence indicate freq. mismatch and forcer misalignment.

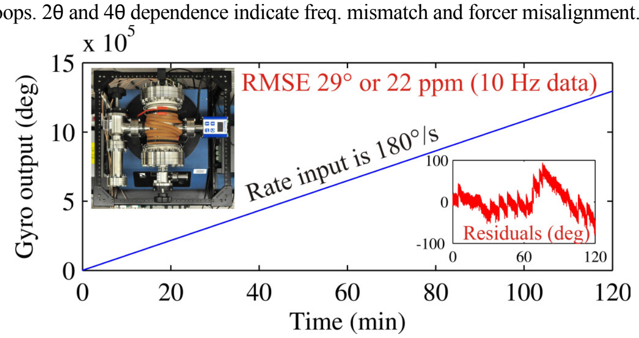

Fig 6. Spooling of the rate integrating gyro output over 2 hours of continuous rotation. Linear fit shows angular gain factor of ~0.8 and RMSE of 22 ppm.

References

[1] J. Bernstein, S. Cho, A. T. King, P. Kourepenis, P. Maciel, and M. Wienberg, "A micromachined comb-drive tuning fork rate gyroscope," IEEE MEMS, pp. 143–148, 1993.

[2] M. F. Zaman, A. Sharma, and F. Ayazi, "High performance matched-mode tuning fork gyroscope," IEEE MEMS, pp. 66–69, 2006.

[3] I. P. Prikhodko, A. A. Trusov, and A. M. Shkel, "Achieving long-term bias stability in high-Q inertial mems by temperature self-sensing with a 0.5 millicelcius precision," Hilton Head Workshop, pp. 287-290, 2012.

[4] D. D. Lynch, "Vibratory gyro analysis by the method of averaging," in Proc. 2nd St. Petersburg Conf. on Gyroscopic Technology and Navigation, pp. 26-34, 1995.