Frequency Split Reduction by Directional Lapping of Fused Quartz Micro Wineglass Resonators

Yusheng Wang, Mohammad H. Asadian, and Andrei M. Shkel
MicroSystems Laboratory
Department of Mechanical and Aerospace Engineering
University of California, Irvine, CA, 92697, USA
Email: {yushengw, asadianm, andrei.shkel}@uci.edu

***Abstract*—We present a study on the permanent frequency split reduction of fused quartz micro wineglass resonators by directional lapping. Using the technique, we demonstrated a near 6× reduction of frequency split (n=2 wineglass mode). The process included two steps. First, the orientations of the Principal Axes of Elasticity (PAE) were determined by measuring the mode shapes of the resonator. Then, the directional lapping was performed based on the information about PAE. Three devices were post-processed by directional lapping technique and the frequency split was reduced as predicted, demonstrating feasibility of the technique. The reduction of frequency split is directly correlated to improvements in structural isotropy and the overall performance of dynamic MEMS, such as rate and rate-integrating gyroscopes.**

Keywords*—*frequency split reduction; directional lapping; wineglass resonators; structural asymmetry.

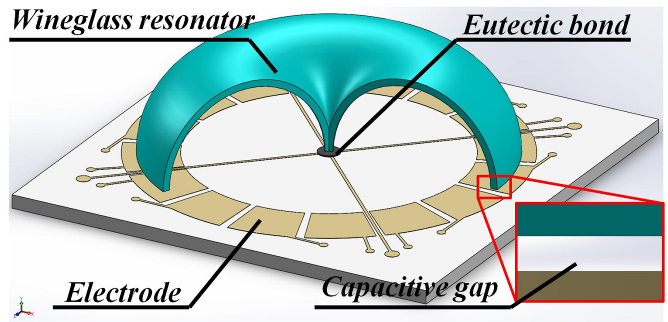

Fig. 1. Schematics of a micro glassblown wineglass resonator with assembled electrodes.

I. Introduction

Macro-scale Hemispherical Resonator Gyroscopes (HRG) have demonstrated high structural symmetry, low energy loss, and remarkable shock resistance [1]–[3], inspiring the development of micro-scale 3D structures for vibratory MEMS gyroscopes. Micro devices fabricated from polycrystalline diamond [4], Bulk Metallic Glass (BMG) [5], and fused quartz [6], [7], showed a potential of micro-scale 3D structures. However, the achievement of high structural symmetry, i.e. low frequency split, remains to be a priority for making progress in precision MEMS devices. Innovative compensation methods are needed to reduce the frequency split to achieve high performance sensors, such as gyroscopes operating in rate-integrating and mode-matched angular rate modes, [8].

There are two main methods to compensate for frequency split of a resonator. The most common method is to apply an electrostatic force to modify the effective stiffness associated with the mode shape. In this method, small initial frequency split of the device is required to tune the device with relatively low tuning voltages. In most cases, however, a permanent modification of the devices is necessary for reducing the large as-fabricated frequency splits.

The mass perturbation method has been widely applied to permanently compensate for the frequency split, where mass-points are added or subtracted from devices to change their overall mass distribution, and therefore reduce the frequency split of the device, [9]. Laser ablation was also applied to single-ring silicon resonators, demonstrating the reduction of the frequency split from 26 Hz to 7 Hz. In these studies, the quality factor was reported to reduce due to damages caused by the laser, [10]. Deposition of localized masses on the spokes of multi-ring resonators was demonstrated to reduce the frequency split from 30 Hz to 80 mHz, without affecting the quality factor, [11]. This method is attractive, but is not currently compatible with 3D shell resonators. Frequency split reduction from 35.5 Hz to 0.35 Hz was demonstrated by ablating coated metal from the tabs at the rim of a diamond hemispherical resonator, [4]. However, the thick metal coating may reduce the overall quality factor of the resonator. So far, no frequency split reduction method has been developed for 3D structures, which would not affect the quality factor. This paper intends to fulfill this gap.

We present a study on the permanent frequency split reduction of fused quartz micro-glassblown wineglass resonators by directional lapping. A near 6× frequency split reduction was demonstrated on n=2 wineglass mode of wineglass shell resonator. This technique has a potential of not affecting the overall quality factor of the resonator since it utilizes the same lapping process as in the structure release step. The orientation of the asymmetry was determined by measuring the mode shapes of the resonator first. Then, the directional lapping was performed based on the information about asymmetry. The reported technique is envisioned as a step in the three-step fabrication sequence, where a precision shell is first fabricated, then directionally lapped, and finally fine-tuned electrostatically.

This material is based upon work supported by DARPA grant W31P4Q-11-1-0006.

II. Asymmetry Identification

Although not a lumped mass-spring system, 3D micro glassblown resonators vibrating in $n = 2$ wineglass modes can be still modeled as a 2 DOF system, if we take the amplitudes of two degenerate modes as variables. In the mode of oscillation, two Principal Axes of Elasticity (PAE) can be identified, where the frequency of vibration will be the lowest if orientation of the mode shape is aligned with one of the PAE and the frequency will be the highest if the mode shape is aligned with the other PAE. Since $n = 2$ wineglass mode is the most commonly used mode in 3D axisymmetric resonator gyroscopes, we only consider the PAE of $n = 2$ mode in this study.

A. Phenomenon Description

Fabrication imperfections will change the mode shape of the resonator as well as induce the frequency mismatch between the two degenerate modes, as shown in Fig. 2. On the left side of Fig. 2, the blue solid line and red dashed line represent the responses of two modes in frequency domain. On the right side of Fig. 2, the lines show the amplitude of motion of modes for different azimuth angles. Note, that the amplitudes for four anti-nodes are not the same due to the structural asymmetry. The orientation of the mode shape that has a lower resonant frequency (blue solid line) is aligned with the direction of asymmetry (y-axis) and the other is separated by 45 degrees. The information about the mode shape can be utilized as an indicator of imperfections.

Many sources of fabrication imperfections will cause a structural asymmetry of glassblown wineglass resonators and a change of the mode shapes of the resonators, including the temperature non-uniformity in the furnace during glassblowing, the misalignment between the device and the lapping plane during release, and thickness variation of the device layer created during the wet etching, [12]. In this paper, we only model the effects of lapping imperfections because the directional lapping compensation can be considered as the reverse step of lapping imperfection. Therefore, the model also helps to understand the compensation mechanism.

Finite element model was developed to study the effects of lapping imperfections on the mode shapes of wineglass resonators. Identical wineglass resonators with different lapping angular errors were modeled by COMSOL MultiPhysics package. In the model, the thickness of the resonators was 100 μm and the outer diameter was 7 mm. Resonators with

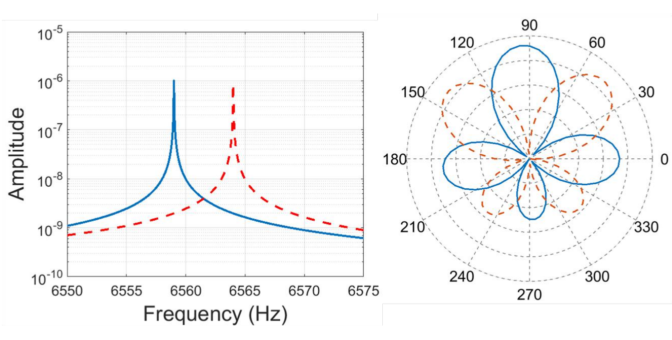

Fig. 2. Effects of fabrication imperfections on the resonant frequency and mode shape of the wineglasss resonator.

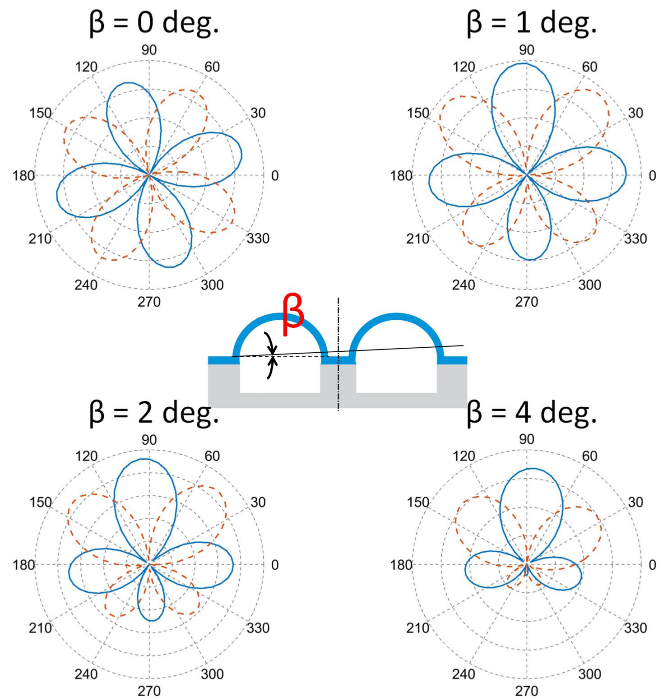

Fig. 3. The effects of lapping angle on the mode shape of the wineglass resonator.

the angular lapping errors of 1 degree, 2 degrees, and 4 degrees were modeled. The results are shown in Fig. 3. When $\beta = 0$, which corresponds to a perfect device, the amplitudes of motion at anti-nodes are the same and the orientations of the mode shapes are random due to axisymmetric nature of the device. As β increases, the mode shapes align with the direction of lapping imperfection, which is the y-axis in this model, and deviate from the case in which the amplitudes at anti-nodes are the same. The ratio between the largest amplitude at the anti-node and the smallest amplitude at the anti-node increases as β increases. The relation between the lapping angle and the ratio of amplitudes (of the mode with lower frequency) is presented in Fig. 4, which shows an exponential relation between the angular lapping error β and the amplitude ratio. This relation allows us to estimate the lapping angle needed to compensate for the structural asymmetry of a wineglass resonator.

B. Experimental Identification of Asymmetry

An experimental setup was developed to determine the orientation of PAE, and it is shown in Fig. 5. The wineglass resonator was temporarily attached to a piezo stack by Field's metal to be able to actuate the device. Then, the device with the piezo stack was attached to a rotary stage controlled by a servo-motor. The device was excited by piezo along the stem of the wineglass resonator and its response to actuation was measured by Laser Doppler Vibrometer (LDV) pointed on the outer edge of the wineglass resonator. The rotary stage was rotated by 10 degrees after each measurement, so that the amplitude at different azimuth angles was measured to obtain the full information about the mode shape. The experiment was conducted in air since the quality factor was not a critical parameter in this study.

The in-plane amplitude of motion along the outer edge of

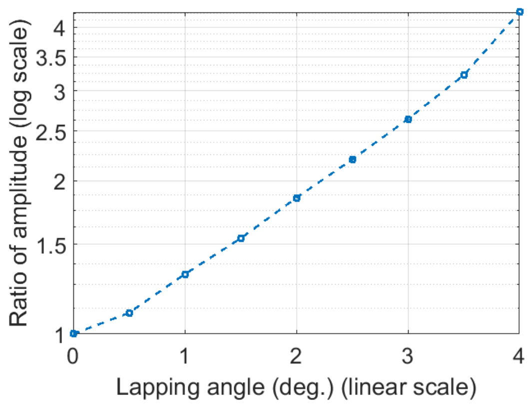

Fig. 4. The relation between the lapping angle and the ratio of amplitude between the largest amplitude at anti-node and smallest amplitude at anti-node for the wineglass resonator.

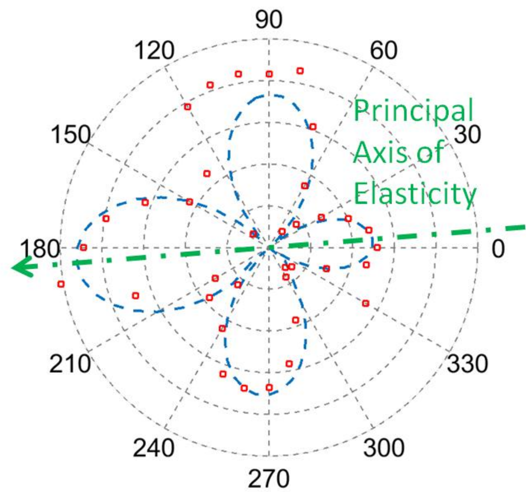

Fig. 6. Experimental result of the mode shape of the wineglass resonator and the identification of PAE.

the device is shown in Fig. 6. Red dots are experimental results and the blue dashed line is the fitted curve. A principal axis of elasticity for $n = 2$ mode was identified according to the mode shape and is shown by a green dashed arrow. The arrow also shows the orientation of the structural asymmetry; therefore, the anticipated directional lapping should be aligned with this direction to compensate for the structural asymmetry.

III. Asymmetry Reduction

In this section, we demonstrate that the directional lapping can be utilized for reduction of asymmetry in wineglass resonators.

A. Directional Lapping Procedure

Special lapping fixtures were designed and 3D printed to perform directional lapping. The lapping fixtures were designed so that 1 degree of the lapping angle was introduced by each lapping. A solid model of the fixture is shown in Fig. 7. The cavity in the middle of the fixture was designed to hold the device and four height references were designed to precisely control the lapping angle. Mounting of the device to the lapping fixture was described in detail in [12]. The vertical resolution of the 3D printer was within 30 μm, corresponding to about 0.1 degree of the lapping angle, and it guaranteed the accurate control of the lapping angle with steps of 1 degree. The directional lapping process was exactly the same as the shell release process, Fig. 7, except that we utilized the specially designed lapping fixture. Therefore, this method has the potential of not reducing the quality factor of the device after the compensation since the same level of surface roughness can be achieved as in the release process.

After the directional lapping, the devices were cleaned by solvent and RCA-1, and characterized in the vacuum chamber by LDV to show the reduction of frequency splits. Then, the identification of asymmetry was conducted again and another directional lapping was applied to the device along the updated direction of PAE to further reduce the frequency split of the device until the frequency split reached its minimum. The goal of the subsequent asymmetry identification was to compensate for any possible errors introduced by the previous directional lapping process, for example the misalignment between the direction of asymmetry and the direction of lapping.

B. Directional Lapping Results

Three devices with initial frequency splits of around 50 Hz were tested in this study. Fig. 8 shows the initial results of directional lapping from the tested devices, illustrating the

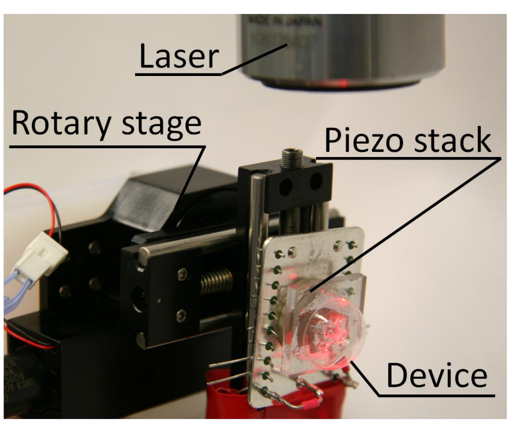

Fig. 5. Experimental setup to determine the orientation of PAE of the wineglass resonator.

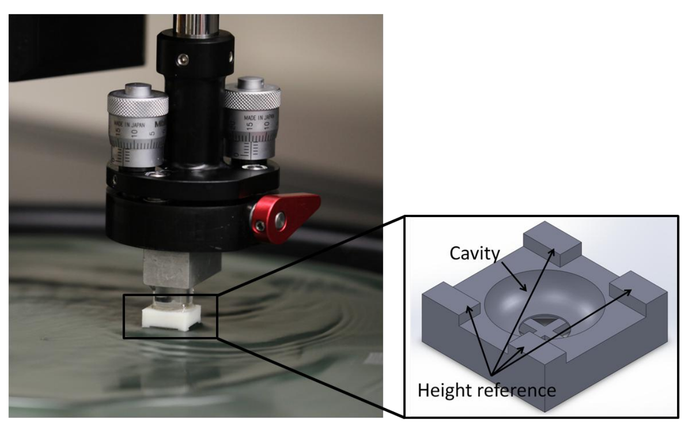

Fig. 7. Experimental setup to conduct the directional lapping of the wineglass resonator and a model of the lapping fixture.

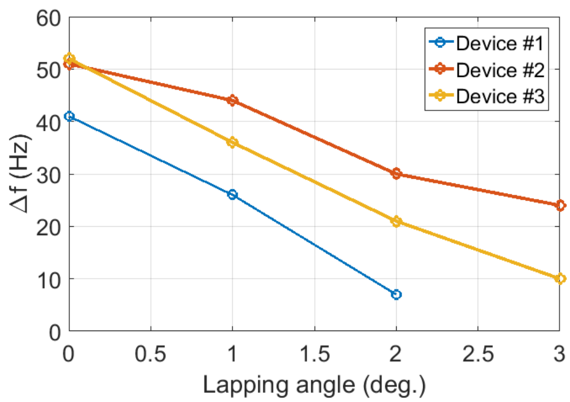

Fig. 8. Experimental results of the directional lapping on three wineglass resonators. The same trend of frequency split reduction showed the feasibility of the method.

same trend of frequency split reduction due to lapping along the PAE, showing feasibility of the method. Our best result was achieved on the device #1. A near 6× frequency split reduction was demonstrated after 2 degrees of directional lapping by reducing the mismatch from 41 Hz to 7 Hz, as presented in Fig. 9. The resonant frequency of the device was also reduced from 5.2 kHz to 4.6 kHz during the process.

Fig. 6 shows the amplitude of motion at the outer edge of the device #1 before compensation. The ratio between the largest amplitude of anti-node of the fitted curve (around 4.5) and the smallest amplitude of anti-node (around 2.5) was 1.8. According to Fig. 4, the ratio of 1.8 corresponds to a lapping angle of about 2 degrees. The experiment also demonstrated that 2 degrees of lapping reduced the frequency split to the minimum. This result verified the relation between the ratio of amplitudes and the lapping angle derived from finite element analysis.

Another advantage of the directional lapping method is that this method is based on the normal mechanical lapping process, and as a result, it is compatible with most materials and no special design of the structure is needed to apply the compensation. Therefore, the directional lapping method can be applied to not only fused quartz wineglass resonators, but to almost all kinds of micro-scale 3D structures.

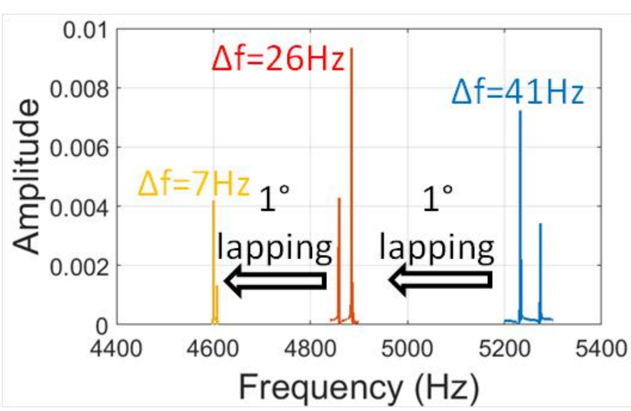

Fig. 9. A near 6× frequency split reduction was demonstrated after 2 degrees of directional lapping by reducing the mismatch from 41 Hz to 7 Hz.

IV. Conclusion

The directional lapping process was developed as a frequency split reduction method in this study. In this process, the structural asymmetry was first identified by measuring the mode shape of a resonator. Then, directional lapping was conducted to reduce the asymmetry, and therefore, the frequency split of the device. This process is envisioned as a step in the three-step fabrication and tuning sequence, where a precision shell is first fabricated, then directionally lapped, and finally electrostatically fine-tuned.

Acknowledgment

Devices were designed and tested in MicroSystems Lab of the University of California, Irvine. Fabrication of the devices was performed in Integrated Nanosystem Research Facility (INRF) of the University of California, Irvine.

References

[1] D. M. Rozelle, "The hemispherical resonator ryro: from wineglass to the planets," *Proc. 19th AAS/AIAA Space Flight Mechanics Meeting*, Savannah, Georgia, USA, February 8-12, 2009.

[2] A. A. Trusov, M. R. Phillips, A. Bettadapura, G. Atikyan, G. H. McCammon, J. M. Pavell, Y. A. Choi, D. K. Sakaida, D. M. Rozelle, and A. D. Meyer, "mHRG: Miniature CVG with beyond navigation grade performance and real time self-calibration," *IEEE International Symposium on Inertial Sensors and Systems*, Laguna Beach, California, USA, February 22-25, 2016.

[3] A. Matthews, and D. A. Bauer, "Hemispherical Resonator Gyro noise reduction for precision spacecraft pointing," *Space Guidance, Control, and Tracking II*, Orlando, Florida, USA, June 12, 1995.

[4] J. J. Bernstein, M. G. Bancu, J. M. Bauer, E. H. Cook, P. Kumar, E. Newton, T. Nyinjee, G. E. Perlin, J. A. Ricker, W. A. Teynor, and M. S. Weinberg, High Q diamond hemispherical resonators: fabrication and energy loss mechanisms, *Journal of Micromechanics and Microengineering*, 25 (8), 2015, pp.085006.

[5] B. Sarac, G. Kumar, T. Hodges, S. Ding, A. Desai, and J. Schroers, "Three-dimensional shell fabrication using blow molding of bulk metallic glass," *IEEE/ASME Journal of Microelectromechanical Systems*, 20 (1), 2011, pp. 28-36.

[6] D. Senkal, M. J. Ahamed, M. H. Asadian, S. Askari, and A. M. Shkel, Demonstration of 1 Million Q-Factor on Microglassblown Wineglass Resonators With Out-of-Plane Electrostatic Transduction, *IEEE/ASME Journal of Microelectromechanical Systems*, 24 (1), 2015, pp. 29-37.

[7] J. Cho, J.-K. Woo, J. Yan, R. L. Peterson, K. Najafi, "Fused Silica Micro Birdbath Resonator Gyroscope," *IEEE/ASME Journal of Microelectromechanical Systems*, 23 (1), 2014, pp. 66-77.

[8] A. M. Shkel, Type I and Type II Micromachined Vibratory Gyroscopes, *IEEE/ION Position, Location, and Navigation Symposium (PLANS)*, San Diego, CA, USA, April 25-27, 2006.

[9] A. K. Rourke, S. McWilliam, and C. H. J. Fox, Multi-mode trimming of imperfect rings, *Journal of Sound and Vibration*, 248 (4), pp. 695-724.

[10] B. J. Gallacher, J. Hedley, J. S. Burdess, A. J. Harris, and M. E. McNie, Multimodal tuning of a vibrating ring using laser ablation, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217 (5), pp. 557-576.

[11] D. M. Schwartz, D. Kim, P. Stupar, J. DeNatale, and R. T. MCloskey, "Modal parameter tuning of an axisymmetric resonator via mass perturbation," *IEEE/ASME Journal of Microelectromechanical Systems*, 24 (3), 2015, pp. 545-555.

[12] Y. Wang, M. H. Asadian, and A. M. Shkel, Predictive Analytical Model of Fundamental Frequency and Imperfections in Glassblown Fused Quartz Hemi-Toroidal 3D Micro Shells, *IEEE Sensors conference*, Orlando, Florida, USA, October 30-November 2, 2016.