Impact of Synchronization in Micromechanical Gyroscopes

In this paper, we study the occurrence of synchronization between the two degenerate resonance modes of a microdisk resonator gyroscope. Recently, schemes involving the simultaneous actuation of the two vibration modes of the gyroscope have been implemented as a promising new method to increase their performance. However, this strategy might result in synchronization between the two modes, which would maintain frequency mode-matching but also may produce problems, such as degrading stability and sensitivity. Here, we demonstrate for the first time synchronization between the degenerate modes of a microgyroscope and show that synchronization arising from mutual coupling dramatically reduces frequency instability at the cost of increased amplitude instability. We present an alternative synchronization scheme that suppresses this drawback while still taking advantage of a passive frequency mode-match operation. [DOI: 10.1115/1.4036397]

1 Introduction

Synchronization describes the tendency of weakly coupled oscillators to track each other’s frequency. This phenomenon has been observed for centuries in various fields in science, describing human’s internal clock modulated by daylight periodicity [1], the behavior of grasshoppers singing in harmony [2], or fireflies’ flashes emitted at once and with the same period [3]. Nowadays, synchronization is implemented in technologies, providing beat stability in dysfunctional hearts thanks to pacemakers [4] and enhancing telecommunication systems [5].

With the development of microtechnologies, synchronization has also been studied in microelectromechanical systems (MEMS), locking the micro-oscillator’s frequency to an external generator [6] or to another MEMS [7] in order to reduce phase noise [8], one of the main sources of fluctuations in microsensors. More specifically in MEMS gyroscopes, frequency fluctuations are intensively investigated, since they directly affect the stability of the gyroscope [9]. Different methods have been suggested in order to reduce these fluctuations [10], but most of them rely on active feedback [11,12] whereas synchronization passively fixes the resonance frequency.

This paper focuses on the implementation of synchronization in a disk resonator gyroscope (DRG) and the resulting outcomes of this technique. In the first part, we describe the device and the gyroscopes’ working regime. We then explain the synchronization implementation between one mode of the gyroscope and an external oscillator. In the following part, we present the implementation of mutual synchronization between the two modes of the gyroscope. Next, we discuss on the performance of the gyroscope operated with these techniques. In the last part, we present an alternative scheme and demonstrate it improves synchronization implementation for gyroscopes’ applications.

2 The Disk Resonator Gyroscope

The microgyroscope is a silicon disk with a diameter of 600 μm and a thickness of 40 μm (Fig. 1), first time presented in Ref. [13], made through the episeal process [14]. The disk, consisting in interconnected concentric rings, is anchored at its center and released at its edge. It is surrounded by 16 parallel plate electrodes spaced by a gap of 1.5 μm from the device, enabling a large control of the gyroscope parameters. As we apply a voltage difference between the electrodes and the device, we can drive the resonant modes of the disk, tune their resonance frequency [13]. control

Fig. 1 Schematic of the DRG and shape of the two modes X and Y used to probe Coriolis force and study the synchronization process
their nonlinearity [15], and adjust their coupling [16]. We detect differentially each of the gyroscope’s modes electrostatically, the amplitude being readout by a lock-in amplifier (LIA) (Zurich Instruments, HF2LI). In our disk, the gyroscope operation is based on the actuation of the two in-plane 20 wineglass modes (described in the following as X and Y modes), the dynamics of which are described by the following equations:

\[
\dot{X}_\text{AX} + \Delta \omega_X A_X + \omega_X^2 X_\text{AX} + q_X A_X^2 + \frac{8 \omega_X}{3} X_\text{AX}^3 = F_X - 2 \Omega \dot{X} \tag{1}
\]

\[
\dot{X}_\text{AY} + \Delta \omega_Y A_Y + \omega_Y^2 X_\text{AY} + q_Y A_Y^2 + \frac{8 \omega_Y}{3} Y_\text{AY}^3 = F_Y - 2 \Omega \dot{X} \tag{2}
\]

where \(X_{AX}, \Delta \omega_X, \omega_X, q_X, X_{AY}, \Delta \omega_Y, \omega_Y, q_Y, k, \) and \(F_X, F_Y\) represent the amplitude, bandwidth, resonance frequency, stiffness (or quadrature) coupling coefficient, Duffing coefficient, Coriolis coupling coefficient (or angular gain), and force applied for, respectively, the X and Y modes (normalized to their mass, which are assumed to be equal). Due to both the fabrication process and the symmetry of the device, the two modes present very similar parameters, especially bandwidth \(\Delta \omega = \Delta \omega / 2\pi\), natural resonance frequency \(f_0 = \omega_0 / 2\pi\), and Duffing coefficient \(\Delta \omega\) of, respectively, 3 Hz, 250 kHz, and \(-180 \text{ Hz/ \mu m}^2\). However, as fabrication may induce imperfection in the structure, the resonance frequency difference between X and Y may be adjusted electrostatically to correct any asymmetry.

The coupling coefficient \(q_{XY}\), often introduced as quadrature, describes the linear coupling of one mode on the other and can be controlled by electrostatic means [16]. The Duffing coefficient \(\Delta \omega\) affects the nonlinearity of the system and mainly transforms the resonance frequency into an amplitude-dependent parameter [15]. The analytical solution for the coupled mode gyroscopic equations was at the core of decades of investigations on gyroscopes’ performance [10,11,17,18]. In this paper, we focus on the contribution of coupling and nonlinearity as part of the synchronization phenomenon, which affects the performance of the gyroscope.

When the device is operated as a gyroscope, one mode is driven as an oscillator (the drive mode, \(X\)), while \(F_Y = 0\). As a rotation \(\Omega\) is applied to the device, energy is transferred to the second mode (the sense mode, \(Y\)) due to Coriolis coupling through the angular gain \(k\). This energy transfer takes place at the resonance frequency of the driven mode, and in the simplest case where nonlinearity and mode coupling are negligible, and the resonance frequencies of the two modes are near matching, the amplitude of the sense mode is described by

\[
A_Y = \frac{k F_X}{\omega_0} \frac{1}{\omega_Y - \omega_0 + i \Delta \omega/2} \tag{3}
\]

The amplitude of the sense mode directly provides a measurement of the rate \(\Omega\) applied to the gyroscope, and maximum sensitivity is obtained when the two modes’ resonance frequencies match (\(\omega_Y = \omega_0\)), a condition known as mode-matching. This mode of operation will be referred in the following as the standard gyroscopic operation.

Neglecting electrical or circuit related noises, there are mainly three noise sources in such gyroscope, emerging from Eq. (3), which distort the measurement of the rate \(\Omega\). First, there are the fluctuations arising from the drive mode’s amplitude \(F_X / (\omega_0 A_0)\), which are usually canceled through a feedback loop, limiting the X mode to a fixed amplitude. A second source of noise comes from the bandwidth of the Y mode, which fluctuates with temperature usually between 0.1%/°C and 1%/°C, described by the temperature coefficient of quality factor (TCQ). For a mode-matched gyroscope, this parameter induces then a variation of the gyroscope output of the same quantity. Finally, stiffness also is altered by temperature variations, resulting in a temperature coefficient of frequency (TCF) for both modes of the gyroscope. In silicon MEMS oscillator, TCF usually ranges from 10 ppm/°C to 30 ppm/°C. However, because the amplitude of \(Y\) depends on the frequency difference between the two modes, only the TCF difference between \(X\) and \(Y\) contributes to the fluctuations of gyroscope output. Due to the symmetry of the system, this residual TCF is generally small and of the order of 1 ppm/°C. In the presented D RG, we measured the TCF of \(X\) and \(Y\) to be, respectively, 14.9 ppm/°C and 15.5 ppm/°C; this asymmetry of 0.6 ppm/°C leads to a frequency shift between \(X\) and \(Y\) of 0.15 Hz/°C. According to Eq. (3), this variation results in amplitude fluctuations of \(Y\) of 5%/°C for mode-matched operation. Fluctuations in the frequency difference between \(X\) and \(Y\) are therefore the leading source of noise in the presented gyroscope, resulting from its high quality factor. In the followings, we present how the implementation of synchronization affects this frequency difference and the resulting amplitude fluctuations of the gyroscope.

### 3 Synchronization to an External Source

In nowadays electronic, it is common to track the frequency of an incoming signal. To do so, a well-known technique consists in mixing the incoming signal with the one of an internal low phase noise oscillator, which resonance frequency can be controlled (such as a voltage controlled oscillator (VCO)) and adjusted to the one of the signal to track. The internal oscillator may be described as synchronized to the incoming signal. This active technique where the oscillator’s frequency is locked to a second signal through a third controlled subsystem should not be confused with the passive synchronization phenomenon described in the following.

When an oscillator experiences a perturbation at a frequency close enough to its resonance frequency, the oscillator will naturally tend to match its own frequency to that of the perturbation, without additional interaction with the system [1], which is also defined as a synchronization process and is what we will refer to from now on. Investigating this phenomenon in our gyroscope requires a specific setup, presented in Fig. 2 for the synchronization of \(X\). In this section, the Y mode’s resonance frequency has been tuned far from the X mode, such that there is no coupling between them, in order to study X as an independent oscillator.

First, the resonance (here of the X mode) needs to be driven as an oscillator, which is performed thanks to a phase-locked loop (PLL), maintaining the oscillation at the resonance frequency \(f_X\). Note that the natural frequency \(f_0\) of \(X\) does not always coincide with the resonance frequency \(f_X\), a fact which will be at the core of the following parts.

In a second step, we send an external tone to the system at the frequency \(f_e\), provided by a temperature-stabilized quartz oscillator, inducing an additional force \(F_e\) applied to the mode. As we sweep the frequency of the external tone within few bandwidths from the natural frequency of the X mode, we observe a region where synchronization takes place (Fig. 3), in which the mode tracks the frequency of the external tone.

The range of this synchronization regime \(\delta f_X\) is described by

\[
\delta f_X = \frac{f_e}{F_e} \sqrt{\Delta \omega^2 + 16 \omega_0^2 A_X^4} \tag{4}
\]

Once synchronized, as long as the external tone’s frequency \(f_e\) is not further than \(\delta f_X/2\) from the natural frequency \(f_0\) of the oscillator, the oscillator’s frequency \(f_X\) is locked to \(f_e\). Because of

![Fig. 2 Setup for implementation of synchronization between the X mode and an external tone](image-url)

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temperature variations, the natural frequency of the oscillator is fluctuating as well, such that steady synchronization can only occur for a synchronization range larger than the frequency fluctuations. In the linear regime, we see from Eq. (4) that the synchronization range depends only on the force ratio between the external tone and the drive, the bandwidth being fixed by the oscillator properties. Because the external tone should be a perturbation compared to the initial drive, the synchronization range in the linear regime can only be a fraction of the bandwidth of the oscillator. Considering the DRG’s TCF and the typical $\pm 0.2 \, ^\circ\text{C}$ temperature stabilization of the system, $f_{ox}$ fluctuates by $\pm 0.75$ Hz, making a steady synchronization in the linear regime difficult to maintain.

On the other hand, entering in the nonlinear regime allows a larger synchronization range which increases with the Duffing frequency shift $\alpha A_1^2$ (inset of Fig. 3 shows ranges up to five bandwidths). In this regime, we could maintain synchronization even without temperature controller (our room temperature fluctuating over 4 $^\circ\text{C}$ during the day).

For a fixed frequency $f_e$, the synchronized oscillator’s frequency $f_s$ remains fixed and is locked to $f_e$ even in the presence of fluctuations of the DRG’s natural frequency $f_{ox}$. In order to quantitatively observe the improvement of the frequency stability in the synchronization regime, we present in Fig. 4 the Allan deviation of the resonance frequency of the oscillator with and without the implementation of synchronization. The Allan deviation describes the precision of a parameter (here the resonance frequency) as we average it over time. Due to temperature fluctuations, the Allan deviation of the unsynchronized DRG’s oscillation frequency increases for averaging times greater than 0.1 s. On the other hand, in the synchronization regime, the DRG’s frequency stability is determined by the stability of the external temperature-stabilized quartz oscillator.

While the fluctuating parameters altering the natural frequency $f_{ox}$ are effectively removed from the frequency response of the oscillator $f_s$, the synchronization phenomenon does not affect the properties of the structure to induce this stabilization. To highlight this important concept, in addition to the synchronization setup presented in Fig. 2, we actuated another mode of the same structure at a higher frequency. This higher mode (referred to as HM from now on) is likely to be a 50 wineglass mode vibrating at a resonance frequency of 484 kHz. The TCF of this HM is very similar to the one of $X$, measured at 14.4 ppm/°C, belonging to the same mode shape family (nθ wineglass modes). Therefore, when synchronization is switched off, HM and $X$’s resonance frequencies behave with a similar trend, since frequency fluctuations are mostly due to TCF in this device. As we turn off and on the external tone reference, $X$’s frequency response is dictated by its natural frequency or the reference signal, respectively (see Fig. 5). However, we observe in the process that the HM’s resonance frequency changes due to TCF even when synchronization is switched on, suggesting the mechanism at the origin of these frequency fluctuations still alters the properties of the device and thus the $X$ mode. The synchronization phenomenon enslaves the frequency response to the external reference, but as the mechanical properties of the resonator vary its natural frequency is still inclined to drift, and for a shift larger than $\delta_0/2$ synchronization will be lost.

In a complex system wherein each parameter needs to be stable, synchronization enables to solve separately the frequency fluctuations’ issue. However, to improve the performance of a mode-matched gyroscope, one needs to reduce the fluctuations of the frequency difference between the drive and the sense modes, involving a more complex implementation of synchronization.
4 Mutual Synchronization in the Disk Resonator Gyroscope

Starting from Sec. 3, one possible way to synchronize both modes of the gyroscope would be to duplicate the setup presented in Fig. 2 for both the X and Y modes. In such a scenario, each mode’s frequency would be locked to the same external tone’s frequency, providing mode-matching at $f_x$. However, this technique would require an external frequency reference, increasing the complexity for gyroscopic applications. A less demanding implementation of synchronization can be performed, keeping the vibrating mode in the linear regime while enabling a passive frequency mode-match between the two modes that rejects temperature variations.

As discussed previously, synchronization only occurs with oscillators; thus, both the X and Y modes need to be driven with separate PLLs (see Fig. 6). Then, instead of implementing an external tone to which the modes would be synchronized, we exploit the coupling (quadrature) existing between the two modes to induce synchronization.

In gyroscopes, this coupling is canceled out by electrostatic means [16] to reduce bias and bias instability. However, a residual coupling usually remains, of a few percents of the mode’s amplitude. Due to this coupling, the actuation of one mode affects the other one, which induces a perturbation acting like the external tone in Sec. 3. As we drive both X and Y, each mode locks its frequency to the other one, entering in mutual synchronization. Thus, as one mode’s frequency drifts, the other one follows, as long as the difference between their natural frequencies is sufficiently small. To first approximation, the maximum difference is determined by

$$|f_{0x} - f_{0y}| \leq \sqrt{\frac{\Delta \omega}{2}^2 + \frac{2g_x A_y}{F_X} + \frac{2g_y A_x}{F_Y} + \frac{4g_x A_y A_x^n}{F_X A_y^n + F_Y A_x^n} + \frac{4g_y A_x A_y^n}{F_Y A_x^n + F_X A_y^n}}$$

(5)

Note that Eq. (5) is equivalent to Eq. (4) if one of the mode’s coupling $g$ is negligible compared to the other one, in which case the synchronization acts only in one way. On the other hand, if both modes are operated at the same amplitude with the same coupling, the linear terms in Eq. (5) cancel and synchronization occurs solely due to nonlinearity (right part of the square root).

As discussed previously, tuning the nonlinearity enables a larger synchronization range than a linear coupling. However, in this particular scheme, the fluctuations that must be handled to perform synchronization are much smaller than in the case with only one mode. Because the TCFs of the two modes are closely matched, the frequency difference between the two modes remains small when subject to temperature variations even though the absolute frequency of each mode shifts by 3.7 Hz/°C. Thus, the linear coupling by itself could handle small temperature variations. Considering Eq. (5), only the first term of the square root remains in the linear regime, which vanishes for a perfectly symmetric system. However, due to imperfections in both the geometrical structure of the gyroscope and its coupling with the surrounding electrodes, quadratic cancelation usually leads to an asymmetric residual coupling between X and Y. For the purpose of this experiment, a residual coupling of about 5% of the modes’ amplitude remains (with X and Y driven at the same amplitude for simplicity) with an asymmetry of a few percents between the two coupling. While we measure such asymmetry after this partial quadratic cancelation, it is difficult to distinguish for such small residual the part due to internal mode coupling from the one arising from the asymmetry in the detection of X and Y (irregularity in the gap size between the device and the electrode). However, due to the small TCF difference between the two modes, we measure that the mode coupling asymmetry part is enough to perform steady mutual synchronization.

In this configuration, the Allan deviation of the resonance frequencies’ difference (see Fig. 7) shows a stability similar as in Fig. 4, demonstrating mode-matched operation at long integration time. According to Eq. (3), this mutual synchronization phenomenon enables to suppress gyroscope output noise arising from frequency fluctuations between X and Y, being initially the primary source of noise in our system.

5 Amplitude Stability and Zero Rate Output

By using the asymmetric linear coupling between the two modes, the gyroscope is operated in a perfect frequency mode-matched regime, the frequency fluctuations being canceled through the synchronization process. As a constant rate is applied to the gyroscope in mutual synchronization operation, we see that the scale factor (the energy transfer from one mode to the other) is the same to that of a standard gyroscope: the synchronization process does not change the output form of the gyroscope (see Fig. 8).

However, a closer look at the amplitude in the synchronized case suggests larger amplitude fluctuations than the nonsynchronized regime, which mainly comes from two different phenomena. First, as X and Y are mutually synchronized, the system becomes highly sensitive to electronic connectors’ imperfection that induces phase delay between the two modes. This is measured in particular when rate is applied, but can be avoided as the system becomes fully integrated. Second and more importantly, the synchronization regime inherently converts the natural frequency fluctuations of the synchronized oscillator into amplitude fluctuations (Fig. 9), the magnitude of which is directly related to the synchronization parameters. The coupling needed to compensate frequency fluctuations will induce amplitude fluctuations in the

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Fig. 6 Setup for the mutual synchronization of the X and Y modes through natural mode coupling (curved arrows)

Fig. 7 Allan deviation of the frequency difference between X and Y ($f_x - f_y$) in the mutual synchronization regime. Inset: fluctuations of the resonance frequencies of X and Y in the time domain.
synchronization regime: as synchronization is induced, frequency fluctuations of up to 10% may be induced. We present in Fig. 10 the phase spaces for amplitude and frequency fluctuations summarizing the outcomes of the synchronization regime: as synchronization is induced, frequency fluctuations are reduced at the cost of amplitude fluctuations.

When operating the device as a gyroscope, an important test enabling to quantitatively measure its performance lies in the zero rate output (ZRO). In this operating mode, one of the two modes is usually driven (the drive mode) while the other one is not (the sense mode), and no rate is applied. By measuring the fluctuations at the output of the sense mode, one has access to the stability of the gyroscope without rate and therefore its sensitivity to rate. In the synchronization regime, both X and Y should be driven as oscillators and both will be affected by the Coriolis force; therefore, in the setup presented in Fig. 6, the notion of drive and sense mode vanishes. However, driving both modes of a gyroscope has already been used to perform different operating scheme [18] or reveal new information of the system [11]. In the current operation mode, because X and Y are synchronized to each other, both modes suffer from (opposites) amplitude fluctuations. Because synchronization-induced amplitude fluctuations are in phase with the Coriolis force, combining X and Y amplitudes to suppress these fluctuations would cancel the rate to measure as well. Therefore, because of these induced amplitude fluctuations, the gyroscope performance decreases in the synchronization regime with the current configuration (see Fig. 11).

This result is generic to any gyroscope, wherein: (1) the modes are operated in a frequency mode-matched regime, (2) the modes are coupled to each other (which are induced at least by the Coriolis force), and (3) the modes are driven simultaneously as separate oscillators.

In parallel, recent work has shown promising results by driving both modes of a gyroscope simultaneously [11, 18]. The results presented here suggest that in such a configuration, care should be taken to avoid accidental synchronization, which could decrease gyroscope performance. To prevent synchronization, the mode-matched regime can be avoided, a phase difference may be fixed between the two modes [18] (which are no longer separate oscillators), only one PLL may be used for the two modes [11] (which are no longer driven as oscillators), or by any means which violate one of the three statements of the previous paragraph.

6 One-Way Synchronization for Gyroscope Applications

In a standard amplitude modulated gyroscope, the noise of the drive mode is usually compensated using a closed-loop such as a proportional–integral–derivative (PID) controller to prevent its fluctuations to be transferred to the sense mode through the Coriolis force. In the case of the mutually synchronized gyroscope, the amplitude fluctuations that both modes experience arise from the fluctuations of their frequency difference, such that controlling the amplitude of one mode will not stabilize the other one, and controlling both will prevent any rate measurement. However, mutual synchronization is not the only synchronization scheme enabling perfect passive frequency mode-match between X and Y.

Fig. 8 Y response upon applied constant rate with and without synchronization. Top: rate of 20 deg/s for 9 s. Bottom: rate of 40 deg/s for 4.5 s. Note that for the synchronization case, the constant driving amplitude has been subtracted.

Fig. 9 Amplitude and frequency response as a function of time, as synchronization is turned on (dashed area) and off. When X is synchronized to the external oscillator, its amplitude (top) fluctuates with the same trend as the frequency of HM (bottom). The transitions between the two regimes (typically 1 s) have been removed for clarity. Inset: cosmol simulation of X and HM.

same proportion. Typically, if 10% coupling is the lower limit to enable synchronization, amplitude fluctuations of up to 10% may be induced. We present in Fig. 10 the phase spaces for amplitude and frequency fluctuations summarizing the outcomes of the synchronization regime: as synchronization is induced, frequency fluctuations are reduced at the cost of amplitude fluctuations.

Fig. 10 Typical phase spaces resulting from the two synchronization setups presented (left: X synchronized with an external tone in the nonlinear regime and right: synchronization between X and Y in the linear limit, both graphs using the same scales) and compared with the nonsynchronized scenario. These plots reveal that the frequency fluctuations vanish in the synchronization regime at the cost of greater amplitude noise.

Fig. 11 Allan deviation of the zero rate output of the gyroscope with and without mutual synchronization. As the frequency fluctuations are converted into amplitude fluctuations, the performance of the gyroscope decreases.
As discussed previously, from Eq. (5), if the coupling is completely asymmetric, only one of the two modes is synchronized to the other and we recover the synchronization regime described in Sec. 3. In this regime, the synchronized mode tracks the frequency of the other—free—oscillator, enabling frequency matching as well as in the mutually synchronized scenario. However, in this configuration, the free oscillator does not experience any additional fluctuations arising from the synchronization regime.

To perform this strong asymmetry in our gyroscope, we implement an additional drive to the system (see Fig. 12) which frequency is dictated by the one of the mode Y. Note that this could also be performed directly on the printed circuit board without the need of an external oscillator by using an amplifier and sending part of the signal coming from Y into X. In our setup, we fix the additional signal amplitude to 10% of the one of X (remaining in the small perturbation limit). In this configuration, we thoroughly cancel the initial quadrature, such that we neglect any coupling between X and Y compared to the 10% between Y and X induced with the external oscillator. This way, Y is a free oscillator and can be used as the sense mode of the gyroscope, and X becomes the drive mode.

In the absence of rate, Y amplitude is not affected by the synchronization process anymore, but as rate is applied the fluctuations that X experiences are transferred through the Coriolis force to Y. To prevent this issue, we implement a PID in the driving loop fixing the amplitude of the mode X. In such configuration, the two modes of the DRG are synchronized, enabling passive frequency mode-match, while the gyro’s output does not suffer from the synchronization-induced amplitude fluctuations. Using this one-way synchronization scheme, we present in Fig. 13 that the ZRO is indeed more stable than in the mutual synchronization case.

While temperature variations usually degrade microgyroscope sensitivity through TCF, it also contributes to quality factor fluctuations (TCQ) by reducing the bandwidth stability of MEMS oscillators. This issue affects in particular frequency mode-matched gyroscopes where both modes are supposed to be on resonance, with the amplitude proportional to the mode’s quality factor. In a standard gyroscope operation, the sense mode is usually not driven, reducing the effect of TCQ. The ZRO is then limited by the circuit noise and the quadrature between the two modes. However, as rate is applied, the sense mode becomes driven by the Coriolis force, and its TCQ adds up to the initial noise sources. In the case of the one-way synchronization scheme, the sense mode needs to be driven, here to an amplitude similar to the one of the drive mode, such that fluctuations due to TCQ are predominant even for ZRO measurements and are the ideal limiting noise floor of this scheme. This explains the discrepancy between the ZRO of a standard gyroscope operation presented in Fig. 11 and the one of the one-way synchronization presented in Fig. 13. Note in the latter that the ZRO measured is close to the limit imposed by the fluctuations due to its TCQ, demonstrating the strong asymmetry of the coupling between the two synchronized modes.

As the gyroscope experiences rate in the synchronization regime, the sense mode is TCQ limited just as a standard gyroscope operation. However, in the synchronization case, TCQ is induced both by the Coriolis force and the initial drive, leading to a gyroscope generally less stable than in a mode-matched standard operation. On the other hand, a gyroscope with no control on its frequency matching will suffer from larger fluctuations as temperature drifts [11]. Maintaining both modes on resonance is therefore crucial for amplitude modulated mode-matched gyroscopes and usually involves active feedback loops adjusting the frequency of the modes [11,12]. The synchronization regime gives a passive solution, where the frequencies are adjusted due to the nature of the phenomenon itself.

7 Conclusion

We demonstrated that the synchronization of a mechanical oscillator enables stabilization of its resonance frequency in the presence of temperature variations. By driving both modes of a DRG, we used the coupling between the modes to perform mutual synchronization, wherein each mode tracks the other one’s frequency. This configuration enables a perfect passive frequency mode-match between the two modes, robust over temperature variation. However, we demonstrated that this technique converts the frequency fluctuations into amplitude fluctuations, which decreases the gyroscope performance. We presented an alternative regime where the induced coupling is asymmetric, enabling frequency mode-matching without synchronization-induced amplitude fluctuations at the output of the gyroscope. Because this scheme requires both modes to be driven, the gyroscope stability becomes limited by the intrinsic fluctuations of the driven sense mode.

This work highlights the outcome that might result from gyroscopes wherein both modes are driven simultaneously, igniting their synchronization and inducing amplitude instability if performed without a careful control.

Acknowledgment

The authors would like to thank Professor Thomas Kenny and his research group at Stanford University for device fabrication. This project was funded by the members of Berkeley Sensor and Actuator Center.

References


