ACHIEVING LONG-TERM BIAS STABILITY IN HIGH-Q INERTIAL MEMS BY TEMPERATURE SELF-SENSING WITH A 0.5 MILLICELCIUS PRECISION

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ABSTRACT

We present long-term bias drift compensation in high-quality (*Q*) factor MEMS gyroscopes using real-time temperature self-sensing. The approach takes advantage of linear temperature dependence of the drive-mode resonant frequency for self-compensation of temperature-induced sense-mode drifts. The approach was validated by a vacuum packaged silicon quadruple mass gyroscope, with signal-to-noise ratio (SNR) enhanced by isotopic *Q*-factors of 1.2 million. Owing to high *Q*-factors, a measured frequency stability of 0.01 ppm provided a temperature self-sensing precision of 0.0004 °C, on par with the state-of-the-art MEMS resonant thermometers. Real-time self-compensation yielded a total bias error of 0.5 °/hr and total scale-factor error of 700 ppm over temperature variations. This enabled repeatable long-term rate measurements required for MEMS gyrocompassing with a milliradian azimuth precision.

INTRODUCTION

In recent years several groups have reported silicon MEMS gyroscopes with sub-degree per hour Allan deviation of bias [1-3]. However, long-term bias and scale-factor drifts limit their potential in real-world missions. The drift source for most MEMS is their inherent sensitivity to temperature variations. An uncompensated bias sensitivity of 500 (°/hr)/°C is typical for MEMS gyroscopes [4]. Whereas, quartz and silicon MEMS resonators used in timing applications exhibit orders of magnitude higher long-term stability, due to more advanced compensation techniques. For instance, high-stability dual-mode oscillators use the secondary mode as a thermometer for the compensation of primary mode drifts [5]. In contrast, conventional approaches for gyroscope's calibration rely on third-order thermal models and external temperature sensors, which suffer from such effects as thermal lag and temperature-induced hysteresis. These limitations motivate the development of new real-time self-calibration methods for inertial MEMS.

Fused quartz hemispherical resonator gyroscope utilizes a temperature compensation technique which uses the resonant frequency as a measure of gyroscope temperature [6]. Successful implementation of this self-sensing technique relies on two main factors. The first is linearity of the temperature-frequency dependence of the resonator material, and the second is high frequency stability, brought forth by a high *Q*-factor. Recently, we introduced a MEMS quadruple mass gyroscope (QMG) [2,3,7], which satisfies these requirements with *Q*-factor above 1 million, and linear temperature coefficient of frequency (TCF), thanks to the single crystalline silicon resonator body, Fig. 1 inset.

Frequency-based measurements of temperature also provides inherently better stability then amplitude-based (voltage) readings commonly employed in temperature sensors (1 ppm stability and repeatability is easy in frequency domain, but almost impossible in analog signal domain). These make high-resolution self-sensing potentially possible in silicon MEMS technology. In this paper, we demonstrate that the resonant temperature self-sensing can be used in real-time for high-*Q* MEMS gyroscopes (Fig. 2) to yield a sub-degree per hour total bias error over temperature variations. We also demonstrate that the long-term stability provided by the self-compensation approach allows for repeatable measurements of small angular rates, required for gyrocompassing applications.

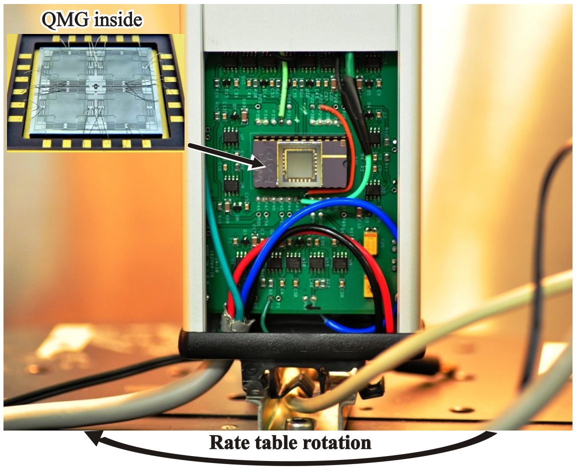

Figure 1: Photo of the experimental setup, showing the vacuum packaged QMG rate sensor, PCB electronics, and a rate table.

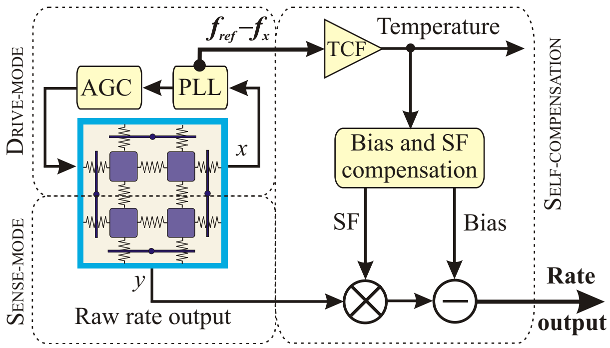

Figure 2: Signal processing using drive-mode frequency for self-compensation of temperature-induced bias and scale-factor drifts.

TEMPERATURE SENSITIVITY ANALYSIS

Here we analyze temperature-induced drift sources in high-*Q* gyroscopes and show the importance of temperature compensation.

Temperature-Induced Drifts

Operation of vibratory *z*-axis angular rate gyroscopes is based on energy transfer between two vibratory modes, Fig. 2. The drive-mode is continuously excited at resonance, and the sense-mode is used for the rate detection. The amplitude (y) of the sense-mode is proportional to the rate (Ω_z), with scale-factor (SF) and bias (B):

$$y = SF \times (\Omega_z + B). \tag{1}$$

Assuming a worst-case scenario, the sense-mode is open-loop, and thus more susceptible to temperature variations. Scale-factor and bias are functions of the angular gain ($k \leq 1$), the sense-mode natural frequency ω_y, and the drive amplitude (x) [8]:

$$SF = 2kQ_{eff}\, x \big/ \omega_y\,, \quad B = \Delta(1/\tau)\sin(2\theta_\tau)\big/2\,. \tag{2}$$

Here, $\Delta(1/\tau)$ is the damping mismatch between vibratory modes, θ_τ is the principal axis of damping, and Q_{eff} is the effective Q-factor:

$$Q_{eff} = Q_y \Big/ \sqrt{1 + 4Q_y^2(\Delta\omega/\omega_y)^2}\,, \tag{3}$$

which reaches maximum Q_y at zero frequency mismatch ($\Delta\omega = 0$).

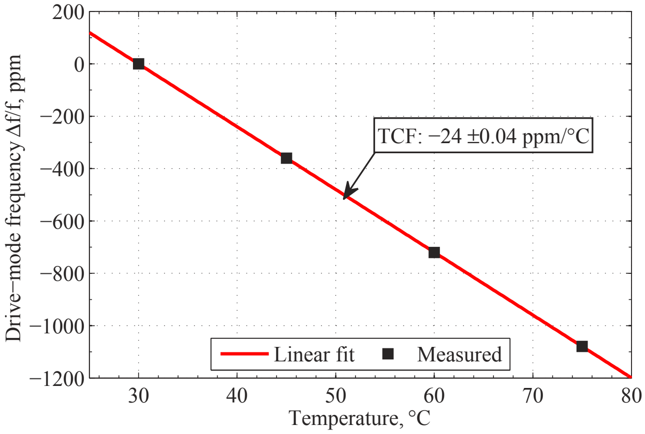

Figure 3: Linear frequency-temperature dependence, revealing a −24 ±0.04 ppm/°C TCF over temperature range of 30 °C to 75 °C.

It follows from (2) and (3) that the mode-matched condition over wide temperature range, i.e. $\Delta\omega = 0$ and $\Delta(1/\tau) = 0$, is desired to ensure stability of scale-factor and bias. While these requirements can be satisfied by a symmetric transducer design, the temperature dependence of the rest of the parameters in (1)-(3) still reduce the overall accuracy and repeatability of rate measurements. The only parameters with negligible sensitivities are the drive amplitude x, stabilized by an automatic gain control (AGC), and the angular-gain factor, k, with a sub-ppm/°C stability over temperature [6].

Thus, the parameter with the highest sensitivity is either the sense-mode frequency, ω_y, or the sense-mode quality factor, Q_y. Typical temperature sensitivity of a resonant frequency for silicon MEMS is only −31 ppm/°C near room temperature. Whereas, the sensitivity of Q-factor depends on the dominant energy loss mechanism. For the thermo-elastic dissipation, with the associated strong $1/T^3$ temperature dependence [2], the Q-factor sensitivity is the primary factor that contributes to the scale-factor fluctuations.

Scale-Factor and Bias Sensitivities

The relationship between the scale-factor (as well as bias) and temperature is non-linear; however, for limited temperature range, we can consider the change to be linear. Quantitatively, we can estimate the effect of the Q-factor on scale-factor by taking the derivative of the expression (2) with respect to temperature. The result is divided by the nominal scale-factor to find the relative change (assuming $\Delta\omega = 0$):

$$\frac{1}{SF}\frac{dSF}{dT} = \frac{1}{Q_y}\frac{dQ_y}{dT}. \tag{4}$$

Previously we reported experimental temperature characterization of the Q-factor for the vacuum sealed QMG, which confirmed that the dominant energy loss mechanism is thermoelastic dissipation [2]. Linear fit to the $Q(T)$ data [2] reveals dQ_y/dT of 12,000 °C^{-1}, yielding a scale-factor sensitivity of 10,000 ppm/°C near room temperature. Calculation of the derivatives dQ_y/dT at different temperature shows that the sensitivity varies from 5,000 ppm/°C to 20,000 ppm/°C over wider temperature range of −40 °C to 120 °C.

In a similar manner, analysis of the bias sensitivity shows that even for a symmetric design with constant $\Delta(1/\tau)$ over temperature, drifts can be caused by variations of the principal axis of damping, θ_τ. In principle, the effect can be minimized by applying the drive force at the angle $\theta = \theta_\tau$, but temperature variations can still shift the angle θ_τ. This analysis suggests that high-Q gyroscopes require temperature compensation for repeatable rate measurements.

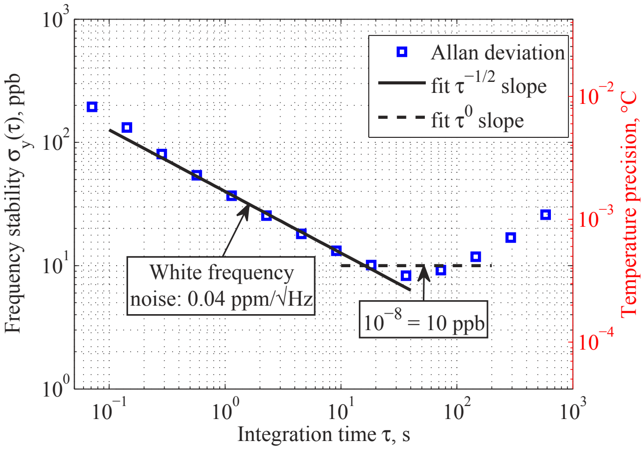

Figure 4: Experimental demonstration of 10^{-8} frequency stability, which translates to $4{\cdot}10^{-4}$ °C precision of temperature self-sensing.

TEMPERATURE SELF-SENSING

In this section we describe the temperature compensation method and demonstrate its accuracy and precision using QMG.

Frequency-Based Temperature Sensing

While the gyroscope drive-mode is controlled by a phase-locked loop (PLL) and AGC loop, Fig. 2, the open-loop sense-mode mode is susceptible to temperature variations, as shown in the previous section. To compensate for temperature-induced scale-factor and bias drifts, we propose to use the drive-mode frequency as a built-in thermometer, which is free from any spatial or temporal thermal lag. The silicon resonator frequency changes linearly with the temperature, so by monitoring this change, on-chip gyroscope temperature can be measured directly.

Scale-factor and bias drifts are obtained using the temperature sensitivity coefficients, which are measured experimentally in a calibration run. Fig. 2 shows the real-time self-compensation signal processing. The instantaneous frequency change is first converted to the temperature using the measured TCF. Once the temperature is obtained, it is converted to the scale-factor and bias drifts. Finally, the raw gyroscope output is corrected by multiplying it with the scale-factor change, followed by subtraction of bias drifts.

Self-Sensing Accuracy and Precision

The QMG transducer [2,3,7] was chosen for the evaluation of the approach due to its symmetric high-Q design and isotropy of both frequency and damping. Stand-alone QMGs were fabricated using an SOI process with a 100 μm thick device layer. Singulated devices were vacuum sealed using getters inside a ceramic package, providing sub-mTorr vacuum sustainable over many years. Characterization of the packaged QMGs showed drive- and sense-mode Q-factors of 1.17 million at 25 °C and 0.7 million at 100 °C, with $\Delta Q/Q$ symmetry of 1 %, or $\Delta(1/\tau)$ of 10 °/hr [2]. Frequency symmetry $\Delta\omega$ over temperature range of 30 °C to 75 °C was also confirmed with a 0.2 ppm/°C uncertainty. High Q-factor is expected to provide a sub-ppm frequency stability, required for high-precision frequency-based temperature sensing.

The signal processing for temperature self-sensing takes advantage of high Q-factors and linear TCF of the silicon QMG. As shown in Fig. 2, a PLL monitors the resonant frequency change relative to a high-stability frequency reference, which is then converted to temperature. Accuracy of the frequency-to-temperature conversion thus relies on accuracy and linearity of the TCF value. The TCF was measured over a temperature range of 30 °C to 75 °C

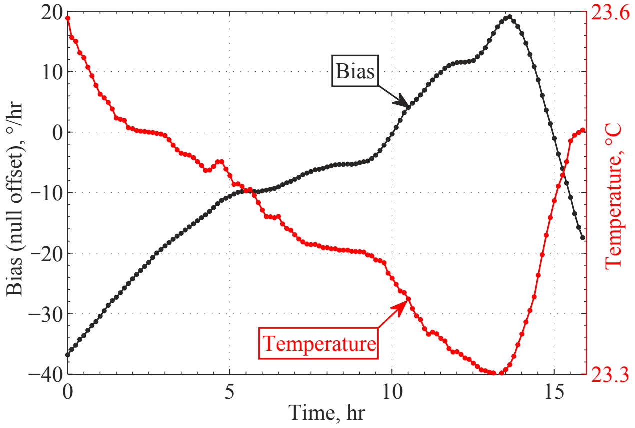

Figure 5: Experimentally measured 99 % temperature correlation of a gyroscope bias during a 16 hr run (uncompensated data).

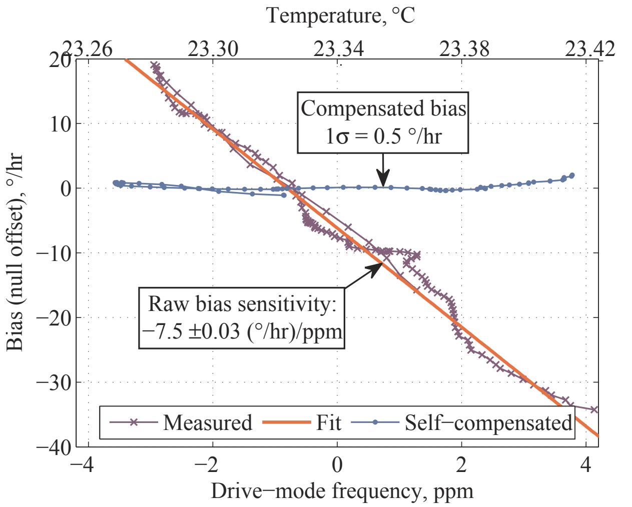

Figure 6: Self-compensated gyroscope bias, revealing a 1-σ bias total error of 0.5 °/hr over temperature during 16 hour run.

using a thermistor from GEC Instruments with accuracy and precision of 10^{-4} °C. The TCF of –24 ppm/°C was calculated from a linear fit to the frequency-temperature data with an accuracy of 0.04 ppm/°C, Fig. 3.

The precision of the frequency-based temperature sensing depends on the resonant frequency stability of the anti-phase drive-mode of the gyroscope. Owing to high-*Q* factor, we demonstrated a 40 ppb/√Hz white frequency noise, resulting in 10 ppb frequency stability at 30 s for the QMG (near room temperature) [7], Fig. 4. Using the TCF of −24 ppm/°C, the measured frequency stability translates to temperature self-sensing precision of 0.002 °C at 1 s averaging time 0.0004 °C at 30 s averaging time (with an accuracy of 0.002 °C), on par with the state-of-the-art MEMS resonant thermometers [9]. Next, we demonstrate the self-compensation of QMG drifts using the high-resolution frequency thermometer.

DEMONSTRATION OF SELF-COMPENSATION

Here we demonstrate self-compensation of QMG output drifts. As discussed earlier, the frequency and damping symmetry of the QMG significanlty reduce scale-factor and bias temperature sensitivities. Nevertheless, imperfections in fabrication, packaging, and electronic component drifts contribute to sensor's temperature sensitivity. To experimentally measure output drifts, we mounted the QMG with its input axis horizontal on a rotary platform and separated scale-factor from sensor's bias by virtue of continuous rotation in a horizontal plane. The method is similar to carouseling technique used for continuous modulation of constant rotation rate of the Earth [3]. The gyroscope control (Fig. 2) was implemented in HF2 Zurich Instruments (ZI) hardware. From the measurements a strong correlation between the gyroscope bias and temperature was observed during a 16 hr run, Fig. 5. The measured 99 % correlation confirmed environmental changes to be the primary drift source.

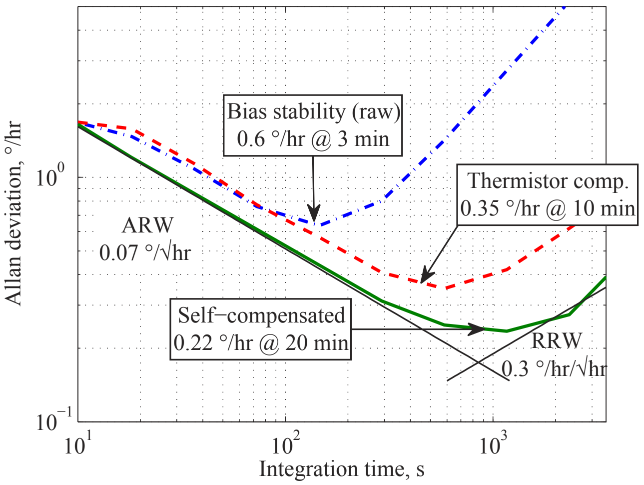

Figure 7: Allan deviation of gyroscope outputs over temperature variations, showing a 0.2 °/hr self-compensated bias instability.

Self-Compensation of Bias and Scale-Factor Drifts

As expected, a linear relationship is observed for bias (null offset) as a function of the on-chip gyroscope temperature, Fig. 6. The direct gyroscope temperature was self-sensed by monitoring its resonant frequency. The temperature sensitivity coefficient of −7.5 ±0.03 (°/hr)/ppm was found by linear least squares fitting, which translates to the bias coefficient of −180 ±0.8 (°/hr)/°C. This sensitivity coefficient was used to perform self-compensation of temperature-induced bias drifts near the room temperature. Self-compensation removed the linear trend and enabled a total 1-σ bias error of 0.5 °/hr over day/night temperature variations, Fig. 6.

The scale-factor sensitivity was characterized over a wider temperature range of 24 °C to 60 °C using a custom-built package-level heater for separation of transducer drifts from interface electronics drifts. Temperature change of 36 °C resulted in 30 % drop of the scale factor, yielding a temperature coefficient of 9,460 °C ppm/°C, in a fairly good agreement with the theoretical value of 10,000 ppm/°C. The measured sensitivity coefficient was used for self-compensation of scale-factor changes, yielding a total 1-σ scale-factor error of 700 ppm over temperature variations, confirming the feasibility of the approach.

Long-Term Stability Analysis

Allan deviation analysis allows determination of noise processes present in a gyroscope output. As discussed earlier, the advantage of the proposed method is absence of thermal lag. Fig. 7 compares the compensation accomplished by using self-sensing vs. using a high-precision external thermistor from GEC Instruments. For long-term stability assessment we compared rate random walk (RRW) values, Fig. 7. Allan deviation of the raw data (from Fig. 5) revealed the bias instability of 0.6 °/hr after 3 min integration time. For longer integration times the output was dominated by the temperature ramp with a τ^{+1} slope.

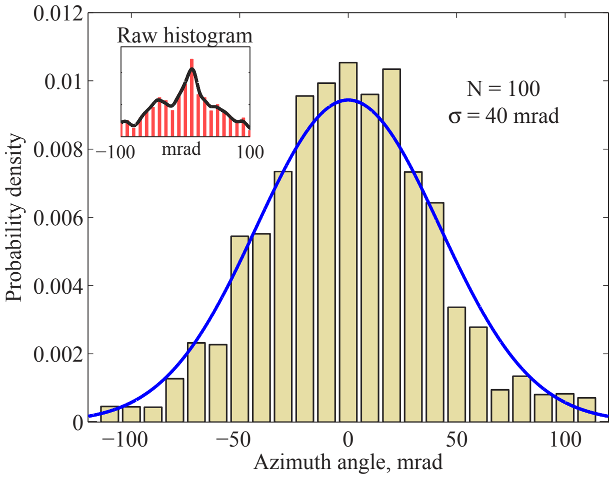

Figure 8: Distribution of gyrocompassing errors, showing normal distribution after self-compensation. Inset: distribution of raw data

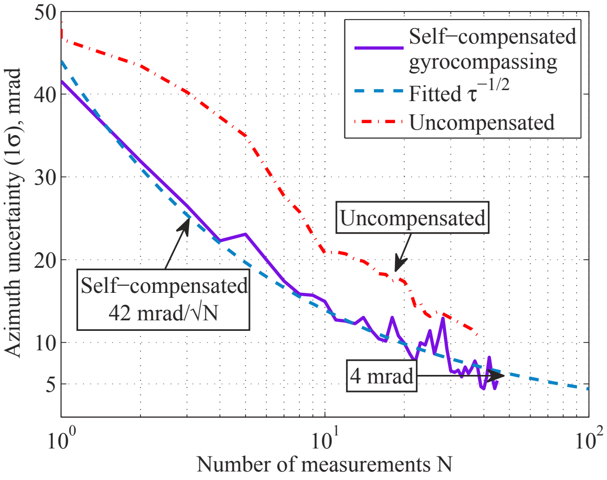

Figure 9: Azimuth precision as a function of number of averages. Self-compensated azimuth precision is 4 mrad after averaging.

Bias drift compensation using the external thermistor resolved RRW process of 1 °/hr/√hr, showing that the output was no longer affected by temperature variations. Despite an excellent thermistor accuracy, conventional compensation did not significantly improve the bias instability due to apparent thermal lag. In contrast, self-compensation resulted in a threefold improvement of the bias instability, providing a 0.2 °/hr value at 20 min. Most importantly, the RRW improved down to 0.3 °/hr/√hr, indicating long-term stability. Next, we use gyrocompassing application to illustrate the benefits of self-compensation for improving repeatability.

Self-Compensation for Gyrocompassing

Frequency-based temperature self-sensing can be applied to various applications. One of the demanding inertial applications that require long-term stability is gyrocompassing, – non-magnetic north-finding using a gyroscope. While north-finding is discussed in [3], here we highlight effects of temperature-induced drifts.

The gyrocompassing requires constant bias over temperature for repeatable measurements. In practice, however, bias was time-varying, which resulted in a non-stationary random distribution of azimuth measurement errors, Fig. 8 inset. The detailed analysis confirmed temperature variations to be the primary drift source. Temperature self-compensation using the gyroscope frequency as a thermometer resulted in normal distribution of errors, Fig. 8. The uncertainty of 100 repeated azimuth measurements was 0.04 rad. Filtering of the data produced azimuth estimation with uncertainty diminishing as the square root of the number of measurements, reaching a 4 milliradian precision after averaging, Fig. 9.

CONCLUSIONS

We demonstrated self-compensation of gyroscope drifts by utilizing its resonant frequency as an embedded thermometer. The approach relied on linear frequency-temperature dependence in the silicon quadruple mass gyroscope, with SNR enhanced by high *Q*-factor. The measured frequency stability of 0.01 ppm provided a temperature self-sensing precision of 0.0004 °C, on par with the state-of-the-art MEMS resonant thermometers. Self-compensation removed the sense-mode temperature sensitivity and improved the Allan deviation of bias from 0.6 to 0.2 °/hr. Most importantly, this method enabled a total bias error of 0.5 °/hr and a total scale-factor error of 700 ppm over temperature variations. When applied to gyrocompassing, self-compensation enabled normal distribution of azimuth measurements, yielding a 4 milliradian precision after averaging. The demonstrated self-compensation method may provide a path for inertial-grade silicon MEMS gyroscopes with proven long-term bias and scale-factor stability.

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