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Optical measurement method for mechanical time base characterization

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Abstract
The recent adoption of silicon components by the mechanical watch industry has triggered the search for new time bases to advantageously replace the traditional balance and hairspring oscillator. In particular, flexure-based oscillators manufactured in silicon could be the breakthrough needed to achieve a new level in mechanical watch accuracy. The characterization of these new time bases requires accurate measurements while existing methods suffer from limitations in this context. Indeed, they rely on acoustic signals which make them dependent on the sustaining mechanism and extrapolation to calculate oscillation amplitude. This paper presents a novel technique for the measurement of the instantaneous angular position of a rotational oscillator along with algorithms to extract critical timekeeping characteristics such as quality factor, isochronism defect, and gravity sensitivity. The measuring principle is similar to that of optical encoders: LED light is emitted onto a photodiode through slits etched into the oscillator. This setup has the advantage of using off-the-shelf optical sensors whereas silicon oscillators generally make most optical sensors unusable because of their thinness and reflectivity. This article presents the device and chronometric performance measurements of a watch-scale flexure pivot oscillator silicon prototype. The experimental results are validated by comparison with data from a separate reference sensor.

Optical Encoder, Chronometry, Mechanical Time Base, Flexure Pivot Oscillator, Compliant Mechanism, Silicon Flexures, Quality Factor, Isochronism

1. Introduction

Timekeeping accuracy is the most important performance index for mechanical watches. A variety of norms exist to certify it which typically evaluate the state of the watch once a day and provide the chronometric error in terms of seconds/day.[1] However, when testing the time base performance, it is more practical to measure chronometric error over shorter time intervals. This is done by measuring individual periods of the oscillator. Indeed, this allows to assess oscillator stability when subjected to changes in amplitude, orientation of gravity, temperature, magnetism and shocks, which are the main factors affecting chronometric performance. The measurement method generally used by watchmakers relies on the capture of the acoustic signal produced by shocks between the oscillator and its sustaining mechanism: the escapement [1, 2]. The period of oscillation is derived from the time between successive beat noises. The amplitude of oscillation is extrapolated from the time between the first and third pulses of the beat noise, assuming a purely sinusoidal oscillation and knowing the rotation angle between the two impacts. This angle called *lift angle* is a construction parameter of traditional escapements. This method suffers from two main limitations: it requires the time base to be sustained by a standard escapement with well understood characteristics and extrapolation is prone to introduce inaccuracies.

The recent adoption of silicon components by the mechanical watch industry [3] has initiated the development of promising novel mechanical time bases whose motion is guided by the deformation of flexures instead of the traditional jeweled bearing [4–8]. The resulting reduction in friction leads to significant improvements in quality factor of the time base and energy consumption of the timekeeper. The characterization of these new time bases requires the measurement of their chronometric performance before coupling them to an escapement. This motivated our development of a new method that uses optical instead of acoustic signals. Additional constraints arose from the reflectivity and thinness (0.3 mm) of the silicon wafer from which our prototypes were manufactured (Fig. 1), which made their surfaces unusable as targets for most optical sensors.

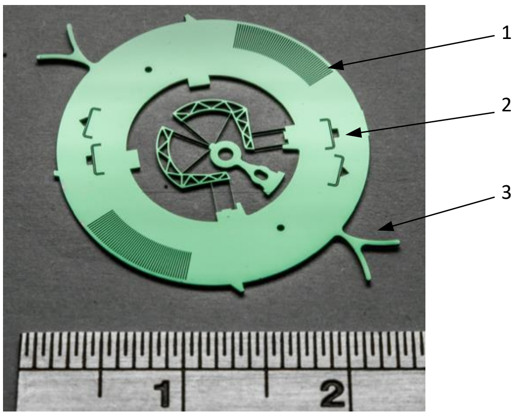


Figure 1. Silicon prototype of co-RCC oscillator [9] with encoder slits (1), clamping features (2) and circle involute targets (3).

In Section 2 we describe our experimental setup and the measurement of the position over time of a silicon "co-RCC" oscillator. This oscillator (Fig. 1) was developed to reach practical mechanical watch specifications such as a planar design within a

[1]The leading norm is the Contrôle Officiel Suisse des Chronomètres (COSC), which certifies millions of watches a year as "chronometers" if their movements have an average daily rate between -4 and +6 s/day in various positions and at different temperatures.

20 mm diameter, a reduced parasitic center shift and a tunable isochronism [8, 9]. Section 3 then presents the algorithm used to extract the frequency and amplitude of the time base. Section 4 validates our method by comparing the results with those obtained with a different sensor and assesses the repeatability of the method. Finally, Section 5 provides examples showing how our new method can be used to measure the quality factor of a prototype, as well as the influence of amplitude and gravity on its frequency. Some of these results were already presented in the first author's Ph.D. thesis [8].

2. Experimental setup

The experimental setup consists of an incremental optical encoder module of type AVAGO HEDS-9730 [10] and a rotational oscillator, in which slits have been cut, acting as "code disk," see Fig. 1. The light sources of the encoder module are aimed at the slits and, as the oscillator rotates, the light reaches a receiver through the slits which alternatively block it (Fig. 2). As the slits all have the same opening width and are arranged periodically, the position of the oscillator with respect to its neutral point can be calculated incrementally. The encoder module has two output signals with a quadrature phase difference between them. This gives the direction of motion in addition to its amplitude and doubles the angular position resolution (0.23 degrees in our case).

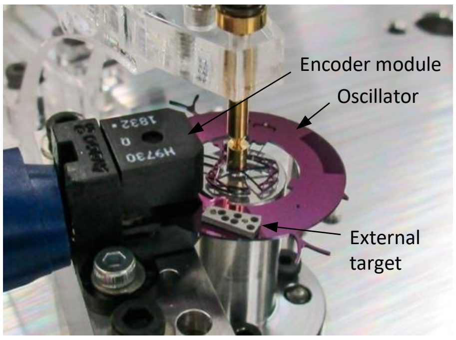


Figure 2. Prototype mounted on test bench.

The encoder signal is sampled at 100 kHz, based on a PXIe-6614 OCXO quartz oscillator with a stability of ± 75 ppb that allows to precisely reconstruct the angular position of the oscillator over time [11]. Since there is no sustaining mechanism, the measurement is performed in free oscillation: the oscillator is offset from its equilibrium position by a given angle and released manually. Figure 3 shows an example of position-time signal obtained by decoding the encoder signal.

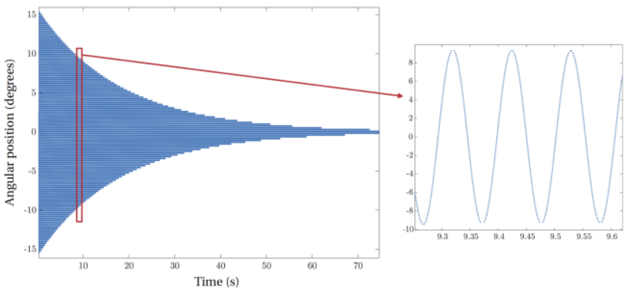


Figure 3. Angular position versus time: signal extracted from the encoder measurement.

3. Algorithm for the frequency and amplitude extraction

Angular position versus time data is processed in subsets by fitting a specified number of samples with a sinusoidal function. The number of samples typically corresponds to 2 to 6 periods of oscillation, such that the amplitude and frequency of the signal are quasi-constant. This window is then swept in steps over the signal, with or without overlap, to process the entire dataset, as depicted in Fig. 4. For our results, we used half-overlapping windows with a width of approximately three periods. For each window n, the algorithm returns a triplet (Θ_n, f_n, t_n) corresponding respectively, to the amplitude and frequency of the sinusoidal function fitted on the window and the mean time of the window. One can then obtain the frequency-amplitude relationship by fitting the (Θ_n, f_n) data points with an even polynomial of order 4 [8, Eq. 5.5].

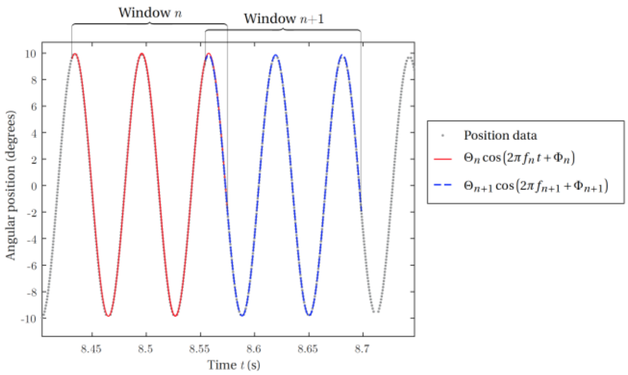


Figure 4. Illustration of the window placing for the frequency and amplitude extraction algorithm.

4. Validation and repeatability of the method

4.1. Validation

In order to validate the method, the results were compared to those obtained with a different sensor. This second method uses a laser distance sensor aimed at external metallic targets (Fig. 2) mounted on the oscillator using the clamping features shown in Fig. 1. These targets have a circle involute shape that has the advantages of having a surface that is always perpendicular to the laser beam as the oscillator rotates and making the distance measured directly proportional to the rotation angle. Note that circle involute targets were also directly integrated into the oscillator for this purpose (Fig. 1) but did not return any sensor readings, probably due to their narrowness and their reflective surface. The frequency versus amplitude curves obtained for one oscillator launch with both methods are displayed in Fig. 5, showing a good match and providing validation for our new method. External targets are used only for validation purposes as these targets affect the inertia, center of mass position and quality factor of the time base.

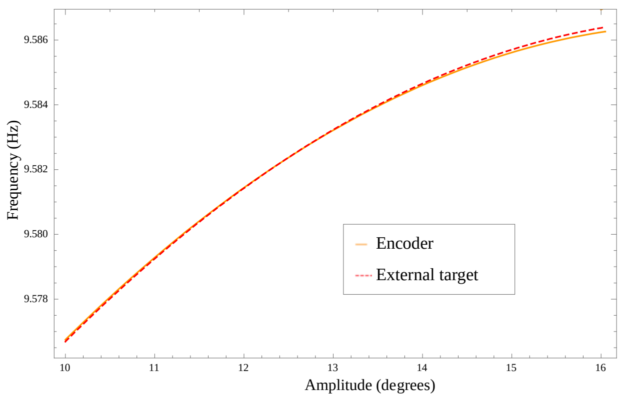


Figure 5. Comparison of frequency versus amplitude measurements obtained with the optical encoder sensor, compared with a laser distance sensor on circular involute target.

4.2. Repeatability

The repeatability of our method was evaluated by performing 10 measurements of the frequency of the same oscillator at an amplitude of 10 degrees by fitting the frequency versus amplitude data between 8 and 12 degrees (Fig. 6). Table 1 shows the results obtained on two different oscillators. In order to relate to watch performance, the range and standard deviation are expressed as daily rate:

$$\rho = 86400\frac{\Delta f}{f_{\text{ref}}} \qquad (1)$$

where Δf is either the range or the standard deviation and f_{ref} is the mean frequency. The daily rate corresponds to the seconds per day gained or lost with respect to a reference frequency f_{ref}. Table 1 shows that the range and standard deviation are well within 1 s/day, which is the order of magnitude we are interested in.[2]

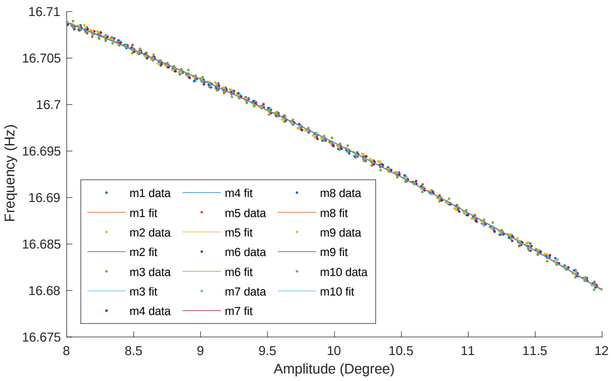


Figure 6. Frequency-amplitude curves for 10 measurements of part V2.

Table 1. Repeatability of the method for 10 measurements.

Part name	Mean freq. (Hz)	Range (s/day)	STDEV (Hz)	STDEV (s/day)
V1	16.7	0.64	$0.45{\cdot}10^{-4}$	0.24
V2	16.7	0.16	$0.11{\cdot}10^{-4}$	0.059

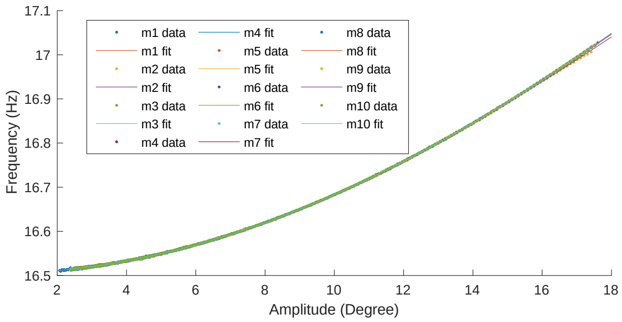
5. Examples of measurements

5.1. Isochronism defect

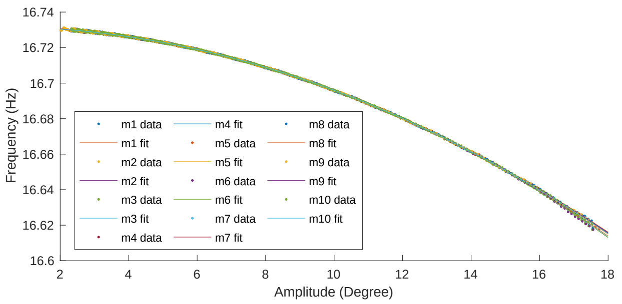
Isochronism, the independence of oscillation period from amplitude, is the basis of accurate timekeeping. The isochronism defect of a time base is given explicitly by its frequency versus amplitude relationship. Figure 7 depicts such curves for two of our prototypes, showing a positive defect for part V1 and a negative defect for part V2. In order to provide numerical isochronism data, we choose a reference amplitude Θ_{ref} with corresponding frequency f_{ref} and express the isochronism defect at amplitude Θ using Eq. (1) with $\Delta f = f(\Theta) - f_{ref}$. Table 2 gives the daily rate ρ for a 10 % amplitude variation from a chosen reference amplitude of 15 degrees, with the two prototypes of Fig. 7.

Table 2. Isochronism defect at 16.5° w.r.t. 10° reference amplitude.

Part name	Mean ρ (s/day)	STDEV (s/day)
V1	383	3.57
V2	-88.9	1.64



a) Prototype V1



a) Prototype V2

Figure 7. Isochronism defect of two different prototypes: frequency versus amplitude curves for 10 measurements.

5.2. Quality factor

The quality factor Q of a time base is important since it affects directly the energy consumption of the time base (hence the autonomy of the timekeeper) and is considered to be an indirect indicator of its potential accuracy [12]. Increasing Q is one of the main drivers for the development of flexure-based oscillators [8]. Since Q describes the amplitude decay of an oscillator, it can be extracted by fitting the amplitude versus time output of the algorithm in Section 3 with $\Theta(t) = \Theta_0\, e^{-C\,t}$, see Fig. 8. The quality factor is then:

$$Q = \pi f_0 / C$$

where f_0 is the limiting frequency as amplitude approaches zero obtained from the frequency versus amplitude relationship. Table 3 shows the values measured on two of our prototypes. Note that the integrated circle involute targets were removed by laser ablation to improve Q. The measurements give Q to be around 775. This value it to be compared to the quality factor of balance and hairspring oscillators of current watches which is typically around 200 [8], i.e., close to a factor 4 lower.

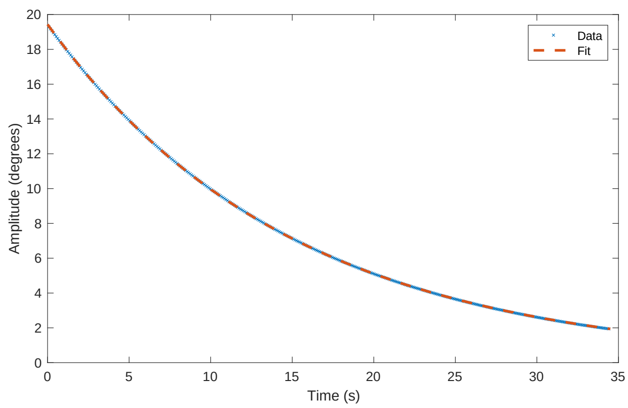


Figure 8. Amplitude versus time data and exponential decay fit for part V1.

[2] Ibid., p.1.

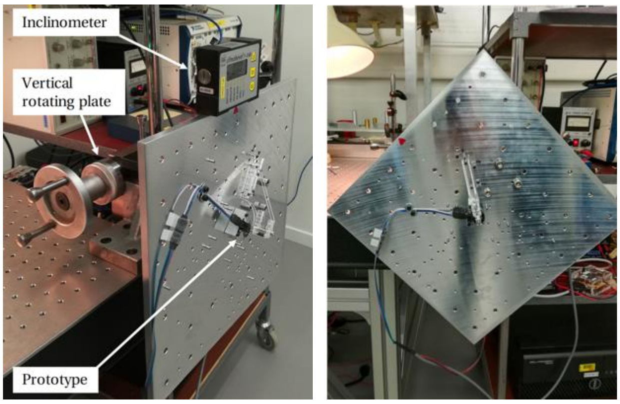
Table 3. Q measurements on 10 launches between 19 and 2 degrees.

Part name	Mean Q	STDEV
V1	776	0.43
V2	775	0.27

5.3. Gravity sensitivity

One of the principle challenges of portable timekeepers is to minimize the influence of the orientation of gravity on their frequency. For this reason, mechanical watches are traditionally tested in different positions with respect to gravity. These tests can be performed with our setup by measuring the frequency versus amplitude relationship of the time base in different positions, for example two horizontal and eight vertical ones. The vertical positions are determined by using an inclinometer, see Fig. 9.

The nominal frequency f_0 of the prototype in each position is determined from the frequency as amplitude reaches zero. The influence of gravity is then expressed in terms of daily rate ρ using Eq. (1) where f_{ref} was arbitrarily chosen as the mean frequency measured in horizontal position facing down (gravity in $z+$ direction) and Δf is the deviation of f_0 from this frequency. An example of result is plotted on Fig. 10 with four measurements per position.



a) $\psi = 0$ degrees b) $\psi = 45$ degrees

Figure 9. Experimental setup for gravity effect measurement.

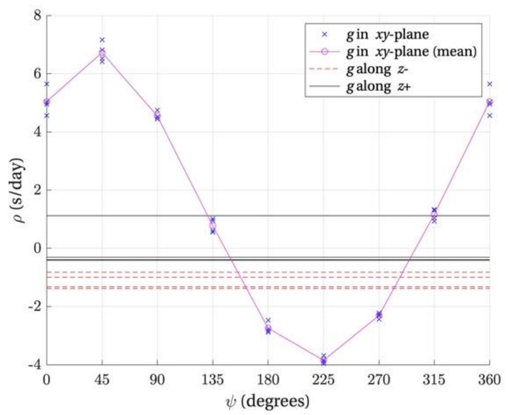


Figure 10. Daily rate $\boldsymbol{\rho}$ measurement on co-RCC prototype for varying angle $\boldsymbol{\psi}$ of gravity in the $\boldsymbol{xy}$-plane (vertical position) and for gravity acting along the $\boldsymbol{z}$ axis (horizontal position).

6. Conclusion

A new experimental method was developed to measure the chronometric performance of rotational mechanical watch oscillators. We showed how it can be used to precisely evaluate the quality factor, isochronism defect and gravity sensitivity of a silicon flexure-based oscillator. The main advantages of our new method are that it does not depend on a sustaining mechanism and is compatible with silicon parts. This makes it a valuable tool for the development of new mechanical time bases and escapements and an important contribution to the search for more accurate mechanical watch time bases. The main limitation of our method is that it requires slits to be cut into the oscillator, which constrains the design. Note, however, that the method is likely to perform well with a smaller angular resolution, which would require less slits. This will be investigated in future work. Another limitation of the method is that it requires an unobstructed optical path to the time base, which makes it incompatible with measurements of movements assembled in their cases. Note, however, that the recent trend towards *skeleton watches*, i.e., mechanical watches whose moving parts are visible through the front and back, makes our method potentially applicable with a sensor that allows more distance from the oscillator. This will also be the topic of future research.

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