Tuning Fork: A Comparison Between Dragonfly® Sensor and Strain Gauge

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Abstract
Worms Dragonfly® sensors are high sensitivity flexible strain sensors that enable the measurement of very small strain, in the nano-deformation range. From aerospace design to industrial monitoring, conventional metal foil strain gauges are widely used for mechanical testing and force sensing. Dragonfly® sensors sensitivity permits the observation of phenomena that would previously have gone unseen. In this paper, we demonstrate this improvement on a tuning fork equipped with a Dragonfly® sensor and a metal strain gauge. Quantitative low-frequency strain measurement, and high-frequency modal analysis is achieved with a single Dragonfly® sensor.

Key Words
Piezoelectric, Strain gauge, Deformation, Tuning fork, Modal analysis

1 Introduction

1.1 Metal foil strain gauges

Since its conception in the early 20th century, metal foil strain gauges (SG) have been the reference sensors to measure strain. Whether it is to design new plane wings or to monitor a high-rise building, SGs are used to measure the deformation of materials.

The SG design has remained the same for a dozen of years, even though it implies a few limitations:

- A Wheatstone bridge is needed to measure the sensor.
- SGs are very sensitive to ambient electromagnetic radiations. A multi-sensor Wheatstone bridge configuration can compensate this effect, but it increases the installation cost.
- Sensitivity is limited to ~10 µdef in the best circumstances.

1.2 Piezoelectricity for strain sensing

Several types of piezoelectric materials have been developed in recent years for strain measurement. Although piezoelectric sensors are not adapted for static measurement, their high sensitivity has triggered a high interest for their development.

Polyvinylidene fluoride or polyvinylidene difluoride (PVDF) is a piezoelectric polymer that has failed to reach the industrial market due to poor repeatability and durability. Lead zirconate titanate (PZT) or quartz sensors reached industrial maturity. However, their bulky and brittle nature limits them to low strain amplitudes (<900 µdef)[1] on flat objects. The price and difficulty of integration in real life non-flat context have been adoption blockers.

Dragonfly® sensors (Dragonfly®) are made of a novel extremely thin crystalline piezoceramic. The sensing element being less than 10 µm thick, it gains the flexibility and stretchability of a 2D material. The whole sensor being flexible, the integration on objects is greatly simplified. Its crystalline nature results in high durability and signal quality.

For performance comparison, a tuning fork with a resonance at 246 Hz was equipped with a SG and a Dragonfly® at the base of each resonating arm (Figure 1).

Figure 1: Tuning Fork equipped with a strain gauge and a Dragonfly®.

The piezoelectric sensor equivalent electrical schematic is shown below. This type of sensors are dynamic by nature because neither the sensor intrinsic resistance (R_p), nor the acquisition system resistance (R_{acq}), are infinite. The charges generated by deformation will always decrease over time. This means that they won't measure completely static strain. However, the lowest measurable frequency depends on the type of acquisition system used for the measurement. Piezoelectric sensors can be measured in both voltage mode and in charge mode configurations.

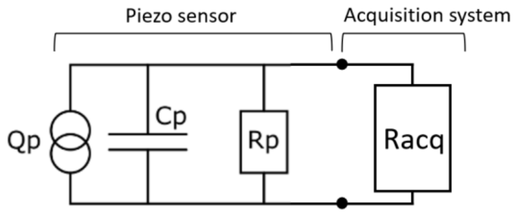

Figure 2: Electrical schematic of a piezoelectric sensor.

In voltage mode, the lower cut-off frequency (f_{LC}) is a couple between the sensor electrical properties (R_p and C_p) and the acquisition system input impedance (R_{aq}).

$$R_{eq} = (R_p * R_{aq})/(R_p + R_{aq})$$

$$f_{LC} = \frac{1}{2\pi C_p R_{eq}}$$

When operated in charge mode (using a charge amplifier), the cut-off frequency is determined by the charge amplifier itself and can be very low (<0.01 Hz) with a dedicated design. Stable measurements over several minutes are possible with a limited drift (<1%).

2 Demonstration set up

The SG installed on the tuning fork is a 120 Ohm gauge with a gauge factor of 2.18. The gauge is covered with HBM SG250 protective coating. It is measured in quarter bridge configuration.

A Dragonfly® passive sensor is installed with the same adhesive and protective coating as the SG. It is measured through a charge amplifier with a 0.07 Hz lower cut-off frequency. Both sensors are measured on a Dewesoft IOLITE 6-STG system.

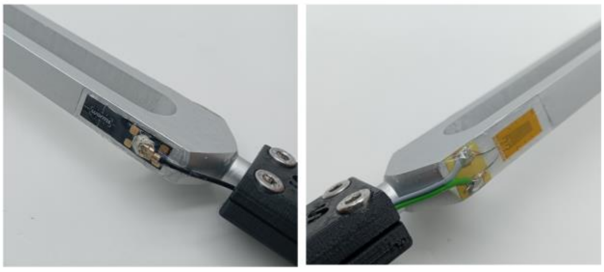

Figure 3: Dragonfly® sensor (left), Strain Gauge (right).

3 Signal processing

For comparative value, no signal processing is done on neither the strain gauge nor the Dragonfly®. It highlights the fact that Dragonfly® is a shielded sensor and is therefore immune to ambient electromagnetic radiation. The Dragonfly® sensitivity used is 16.4 pC/(µm/m), as per the specification sheet.

4 Results

At rest, the ambient noise level is much higher for the SG. There are two reasons. First, strain gauges are unshielded sensors and subject to ambient radiation [2]. Second, the resolution is limited by the conditioning Wheatstone bridge circuitry ability to reject power supply noise [3]. As shown in Figure 4, 0.1 µdef peak-to-peak noise level is achieved with the Dragonfly®.

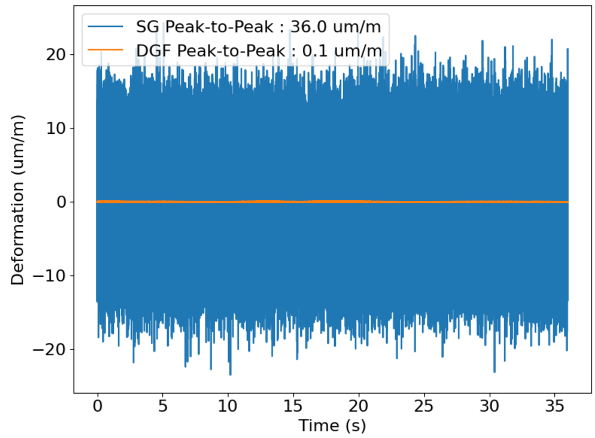

Figure 4: Background noise for both SG and Dragonfly® (DGF).

4.1 Fork bending

<u>Large deformation (>10µdef):</u> When a large force is applied with the fingers on each end of the tuning fork, the same strain amplitude can be seen on both SG and Dragonfly®. On Dragonfly®, the small offset in-between pushes is due the charge amplifier return to zero.

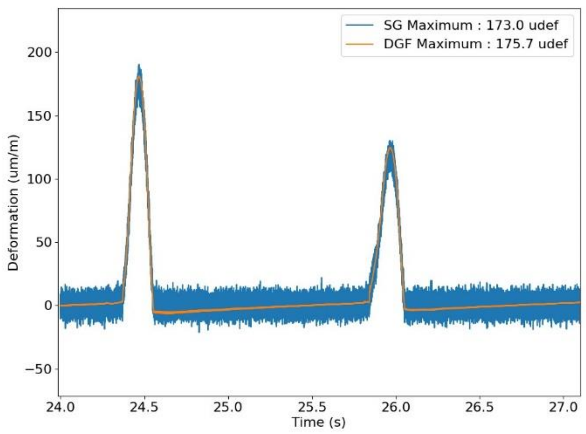

Figure 5: Large amplitude deformation for both SG and Dragonfly® (DGF).

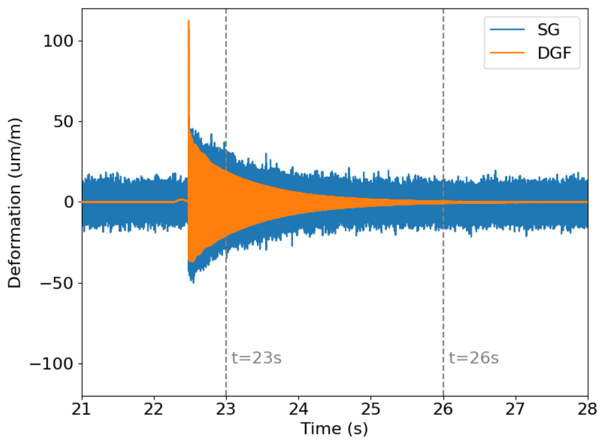

Figure 7: Tuning fork resonance temporal signal for both SG and Dragonfly® (DGF). The grey lines are the times around which the PSD of Figure 8 and Figure 10 are based.

Small deformation (<10μdef): In order to reduce significantly the bending amplitude, the tuning fork is simply shaken in the air. As only inertia is used to bend the tuning fork arms, the resulting strain is much lower. The measured strain is well below the SG noise level, but can be easily quantified with the Dragonfly®.

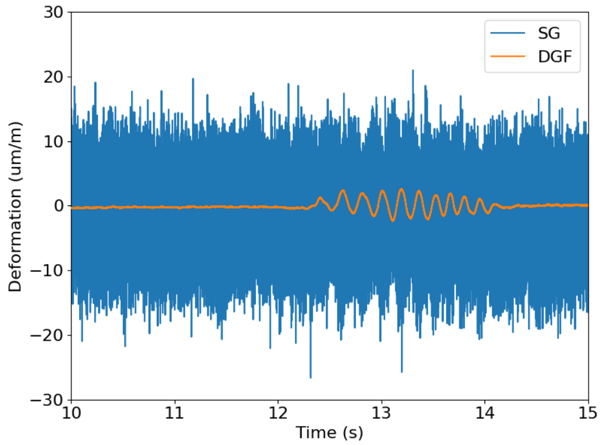

Figure 6: Small amplitude deformation for both SG and Dragonfly® (DGF).

4.2 Fork Resonance

The tuning fork is lightly hit on the table to excite its resonances. Both temporal and frequency domain signal are presented in the figures below. Right after the impact, both sensors capture the 245 Hz main resonance, but further modes can be observed on the Dragonfly® signal. On Figure 8, secondary modes are identified at 734 and 1531 Hz with a black line. Also, it can be seen that the noise floor is 1000X lower on the Dragonfly® at higher frequencies.

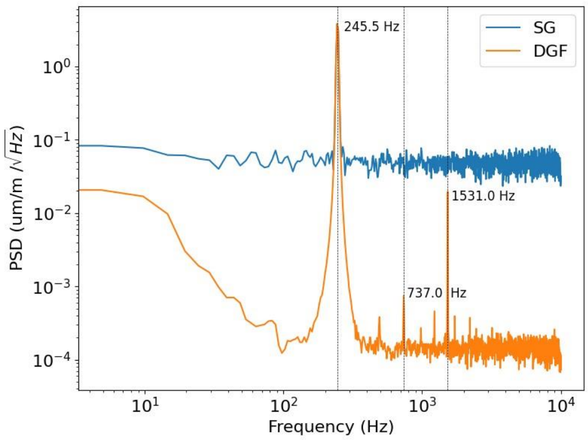

Figure 8: PSD right after tuning fork impact, at t=23s.

Using 3D finite element model, we made a modal analysis simulation. The modes obtained are presented in Table 1. Modes 1 and 4 clearly correspond to the peaks identified on Figure 8. Mode 3 also corresponds to the 737 Hz peak. The experimental difference can be explained by a slight design difference with the model.

Table 1: Modes obtained from simulation.

Modal simulation	Frequency (Hz)
Mode 1	249
Mode 2	733
Mode 3	1007
Mode 4	1544

Simulated mode shapes for modes 1 and 4 is presented in Figure 9. The color scale is normalized.

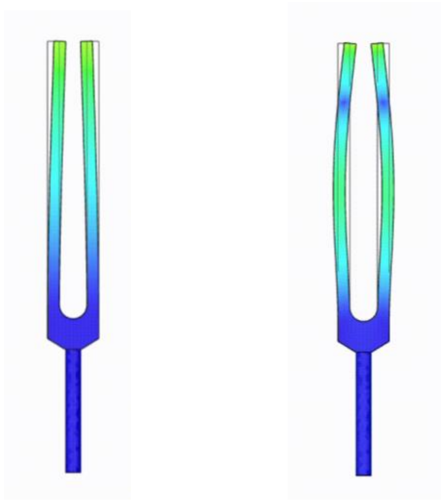

Figure 9: Simulation of resonance modes. Mode 1 at 249 Hz (left), mode 4 at 1544 Hz (right).

After just a few seconds, the resonance amplitude is well below the SG noise floor on Figure 10.

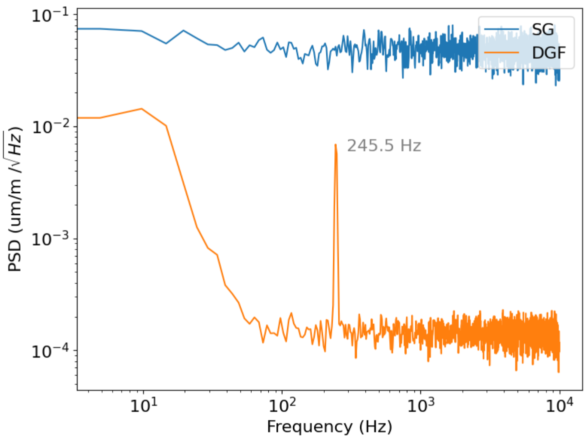

Figure 10: PSD further after tuning fork impact, based at t=26s. The principal resonance mode is still clearly visible on Dragonfly® (DGF)

4.3 Live Demo

A video demonstrating the real-time operation of the tuning fork is available on YouTube. SG and Dragonfly® signals can be directly compared for various manipulations of the fork.

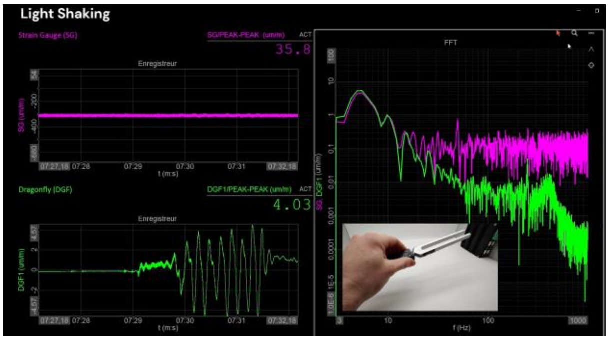

Figure 11: YouTube video demonstrating the real-time operation of the tuning fork.

https://www.youtube.com/watch?v=9X44KGK4Wk0

5 Conclusion

A tuning fork has been used to demonstrate the difference in sensitivity between a metal foil strain gauge and the piezoelectric Dragonfly® sensor. At large deformation amplitude, values are in good agreement. However, the low noise level and high sensitivity of the Dragonfly® enables the observation of strains a thousand times smaller at high frequencies. A modal simulation allowed us to identify the higher vibration modes observed with the Dragonfly®. Being at higher frequencies, the displacement generated by these modes is too small to be detected with a standard strain gauge. Accelerometer have historically been used in this case.

The Dragonfly® bridges the measurement worlds of strain and vibration in a single sensor.

References

[1]https://www.pcb.com/Contentstore/mktgcontent/LinkedDocuments/Aerospace/AD-Series-740_Lowres.pdf

[2] Vishay Precision Group, “Noise Control in strain Gauges”, Tech Note TN-501-2.

[3] Boujamaa, El Mehdi . « Rejection of Power Supply Noise in Wheatstone Bridges: Application to Piezoresistive MEMS ». In *2008 Symposium on Design, Test, Integration and Packaging of MEMS/MOEMS*, 96-99. Nice, France: IEEE, 2008.