Strain-based vibration measurements using Dragonfly®

Catherine Cadieux, Application Engineer at Wormsensing
www.wormsensing. com | contact@wormsensing.com
Grenoble, France - 2024/04/16

Abstract

Accelerometers have been the most widely used sensors for vibration measurements because of their high sensitivity and ease of use. However, in some cases, such as fatigue analysis, strain can be a more relevant metric as it is closely related to stress. Strain vibration measurements have long remained impossible because of sensor hardware limitations, as the sensitivity of standard resistive strain gauges is way too low for providing accurate signals. Wormsensing Dragonfly® piezoelectric strain sensors have a sensitivity 1000 times higher than standard strain gauges, which enables their use for vibrations measurements at low amplitudes and high frequencies.

In this paper, a tuning fork has been installed on a vibration shaker. Using a sine sweep excitation, we compare the transfer function of a high-end accelerometer, a standard strain gauge, and a Dragonfly® sensor. We also discuss the advantages of directly measuring strain data for stress, fatigue, and modal analysis. The work of Airbus and Insa-Rouen pioneering this work with Dragonfly® are put forward.

Key Words
Vibration testing, Modal analysis, Fatigue, Strain, Piezoelectric sensor

1 Introduction

From aerospace to civil infrastructures, vibration testing became a most recommended step in the design process. It ensures that components and systems can withstand the stresses caused by vibrations during their operational lifetime. By simulating the conditions that a product will face in the real world, manufacturers can identify potential design flaws, guaranty durability, and enhance the safety of their products before they reach the consumer.

Since the 70s, vibration experts have been mainly using piezoelectric accelerometers. Their high sensitivity and ease of use have made them the go-to sensor.

Having strain data in addition to acceleration offers a significant advantage in vibration analysis. Strain is a direct metric of the efforts in the material, whereas acceleration only provides information about the motion of the body. Knowing how much a material stretches or compresses under different conditions is crucial for assessing its structural integrity and durability. Also, strain is proportional to the displacement of the test object, whereas the acceleration must be integrated twice to obtain the displacement, which is often impossible to do because of numerical stability problems during the integration. Strain data has however been difficult to acquire in practice, because of sensor hardware limitations.

1.1 Pre-existing strain sensors

The resolution of standard metallic foil strain gauges is in the best case around 1 µm/m with a full

Wheatstone bridge configuration. This is insufficient for high frequency vibration testing where the amplitude is usually under 0.5 µm/m.

Piezoelectric strain sensors with higher sensitivity have already been commercialized by both PCB Piezotronics and Kistler. They consist of a bulk piezoceramic element placed inside rigid metal casing, around a cm in size. These sensors exhibit very good sensitivity, but their rigid packaging limits their application to perfectly flat surfaces. The packaging also significantly affects the structure on which it is installed by locally stiffening the object, which is redhibitory for thin structures. Furthermore, the maximum strain acceptable by the casing is also very limited (~900 µm/m). The rigidity of these sensors cannot be avoided because of the nature of their sensitive element. Being made of a bulk piezo ceramic, they are thick and fragile.

Flexible sensors made of PVDF have also been commercialized by TE connectivity, Arkema, and others. Their lack of stability over time, sensitivity loss with temperature and omni-directionality make them unsuitable for vibration testing. Here again, the nature of the sensing element itself, a polymer prone to ageing, cannot be overcome.

These limitations and the absence of other sensing solutions have not permitted the development of strain-based vibration testing.

1.2 Dragonfly® flexible piezoelectric strain sensor

Dragonfly® are made of a novel extremely thin crystalline piezoceramic integrated on a flexible PCB. The sensing element being less than 10 µm thick, it is flexible and stretchable like a standard resistive strain gauge, and also has the same form factor.

The whole sensor being flexible, the integration on curved objects is greatly simplified, down to 2 cm of curvature radius. Compared to metallic foil strain gauges, the installation of Dragonfly® sensors is further simplified by the presence of a coaxial connector.

Its crystalline nature results in high durability and a resolution down to the nm/m, making vibration testing possible.

2 Experimental set up

In this paper, a simple tuning fork is placed on a vibration shaker. We compare the transfer functions between an input force cell (FC) and three sensors: a Dragonfly® (DGF), a high-end piezoelectric accelerometer (ACC), and a metallic foil strain gauge (SG).

2.1 Tuning Fork instrumentation

A force cell (PCB Piezotronics 208C02) is installed on the shaker to measure the excitation input. The tuning fork handle is then fixed on it. A Dragonfly® (DGF-UNI-AA20405-10) and a strain gauge (HBM 1-LY16-6/120) are installed at the base of both tuning fork's arms, where the strain will be maximum. A miniature precision accelerometer (PCB Piezotronics tld352a56) is installed at the end of the Dragonfly®-side arm, where acceleration will be the most important. The set up is detailed in Figure 1.

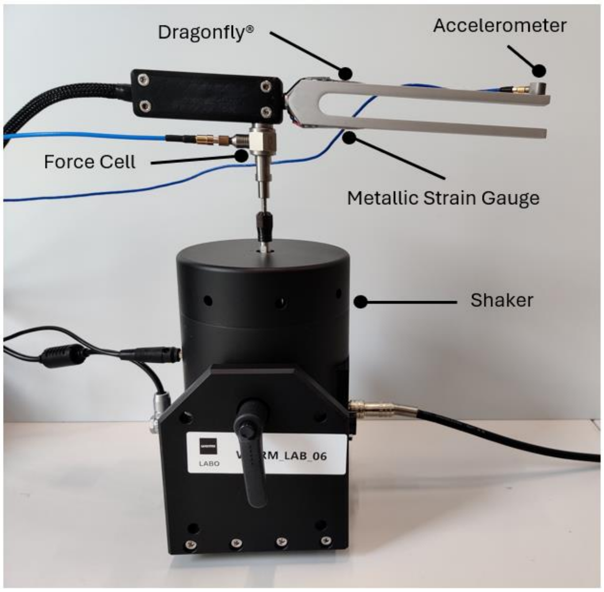

Figure 1: Shaker and sensors set up.

All sensors are connected to a Dewesoft krypton 6-STG acquisition system. The accelerometer and force cell are on a IEPE adaptors (DSI-ACC16). The strain gauge is on a quarter bridge. Dragonfly® is on a charge amplifier adaptor (DSI-CHG).

2.2 Shaker excitation

A sine sweep excitation from 5 to 2 kHz over 0.5 second is generated and looped by a computed and sent to the shaker.

2.3 Signal processing

The signal is acquired for 30 seconds at a 5 kHz sampling rate. With a FFT window length of 2^{14} samples, we have an average of 3 full windows in the recording. We then compute the transfer function using the Welch method as described below. We here use $s(t)$ for the output sensor and $fc(t)$ for the input force cell. First, the Fourier transform ($\mathcal{F}$) of each window is computed.

$$FC(f) = \mathcal{F}\{fc(t)\},$$

$$S(f) = \mathcal{F}\{s(t)\}$$

The auto-power spectral density (P_{FC-FC}) of the input in calculated by averaging the periodogram of each window K.

$$P_{FC-FC}(f) = \frac{1}{K}\sum_{K=1}^{K}|FC(f)|^2$$

The cross-power spectral density (P_{FC-S}) between the input and output is:

$$P_{FC-S}(f) = \frac{1}{K}\sum_{K=1}^{K} FC(f) \cdot S^*(f)$$

We finally obtain the transfer function:

$$H_S(f) = \frac{P_{FC-S}(f)}{P_{FC-FC}(f)}$$

This method has the advantage of lowering the influence of uncorrelated noise by window averaging. Finally, the coherence between the force cell and the sensor is calculated:

$$C_{FC-S}(f) = \frac{|P_{FC-S}|^2}{P_{FC-FC} \cdot P_{S-S}}$$

3 Experimental results

3.1 Temporal signals

Figure 2 presents the temporal signal for all sensors. We observe the sine sweep frequency increasing with time. Little can be said about the strain gauge (SG) temporal signal because of the high noise floor. Compared with the accelerometer (ACC), the Dragonfly® (DGF) signal has proportionally more amplitude at lower frequencies, and less at higher frequencies of the sweep. This is because of the nature of strain and acceleration. Strain is directly proportional to the displacement, whereas acceleration is proportional to its second derivative. Below, we take the Fourier transform ($\mathcal{F}$) of the second derivative of a displacement signal $x\,(t)$:

$$\mathcal{F}\{x(t)\} = X(f)$$

$$\mathcal{F}\left\{\frac{dx(t)}{dt}\right\} = -i\omega X(f)$$

$$\mathcal{F}\left\{\frac{d^2x(t)}{dt^2}\right\} = -\omega^2 X(f)$$

The term ω^2 accounts for this amplification of acceleration at high frequencies, as $\omega = 2\pi f$.

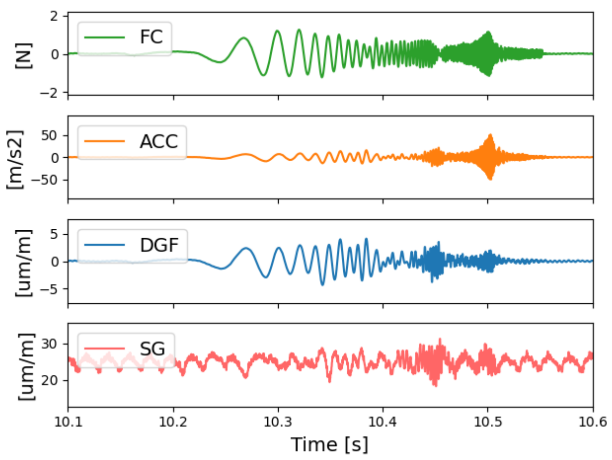

Figure 2: Temporal signals during a single sweep for the input force cell (FC), accelerometer (ACC), Dragonfly® (DGF), and strain gauge (SG).

3.2 Transfer functions: Dragonfly® and accelerometer

We present in Figure 3 the transfer functions between the force cell and both Dragonfly® and the accelerometer. The strain response obtained by the Dragonfly® shows the same resonances as the accelerometer. The coherence is also good on the whole bandwidth as shown on Figure 4. There is an amplitude difference because of the metric different natures (μm/m/N vs m/s²/N) This graph demonstrates that Dragonfly® is capable of identifying vibrational characteristics with the same signal quality as an accelerometer.

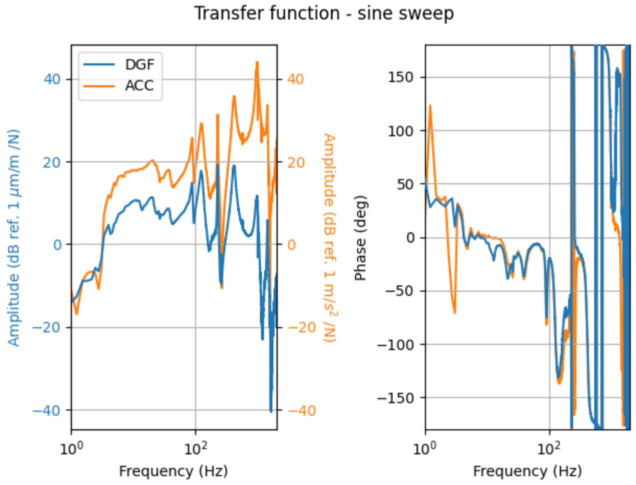

Figure 3: Transfer functions between the input force cell and both accelerometer (ACC), and Dragonfly® (DGF). Amplitude on the left and phase on the right.

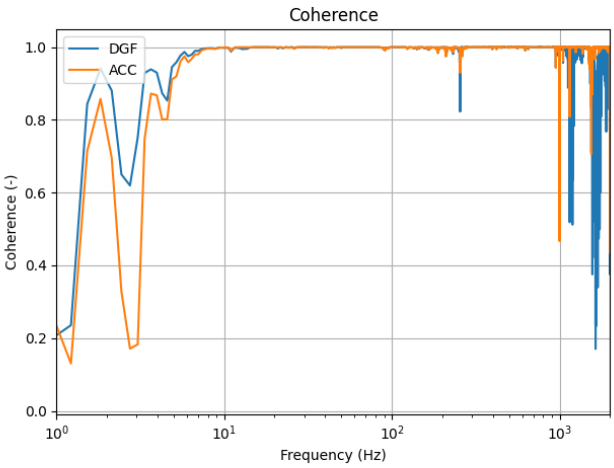

Figure 4: Coherence between the input force cell and both accelerometer (ACC), and Dragonfly® (DGF).

It is worth noting the significant impact of the accelerometer on the structure resonance. The accelerometer used in this study is a high-end miniature model, its mass is negligible compared to the test object. However, its positioning on a single arm of the tuning fork shifts the resonance by 22 Hz, as can be seen on Figure 5, where the Dragonfly® sensor transfer function around the main resonance is zoomed.

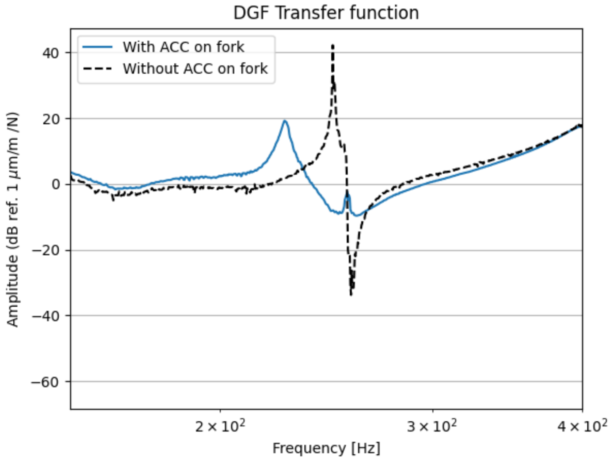

Figure 5: Dragonfly® transfer function with and without the accelerometer (ACC) on the tuning fork. Zoom on the main resonance.

3.3 Transfer functions: Dragonfly® and metallic foil strain gauge

The Dragonfly® and metallic foil strain gauge transfer functions over the force cell are presented below in Figure 6. It shows the resolution improvement Dragonfly® brings to strain-based vibration measurements.

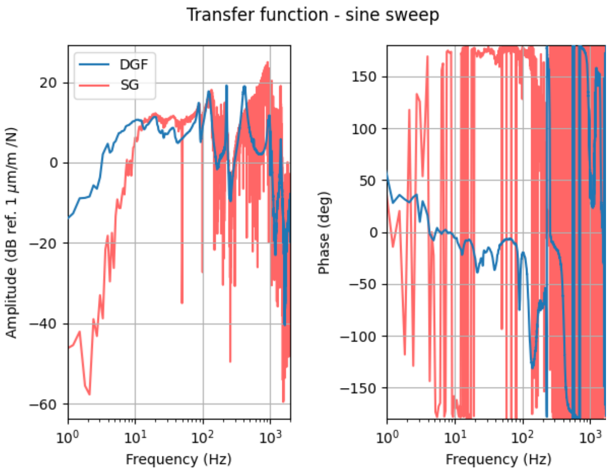

Figure 6: Transfer function amplitude of the strain gauge (SG) and Dragonfly® (DGF) (left). Phase of the respective transfer functions (right).

The coherence presented in Figure 7 confirms that a single strain gauge in this configuration is not adapted as it departs from unity on most of the bandwidth.

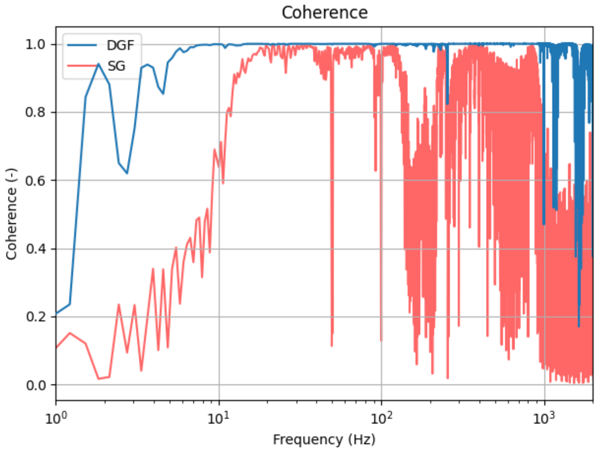

Figure 7: Coherence between the force cell and both the strain gauge (SG) and Dragonfly® (DGF).

4 Application of strain in vibration testing

Measuring strain at higher frequencies has multiple applications for the industry. Here are a few use cases of Dragonfly® sensors in industrial and academic vibration laboratories.

4.1 Critical stress & model validation (Airbus Defense & Space)

Dragonfly® sensors can be placed strategically to gather localized data, helping to characterize specific areas within a structure that are under higher stress. This is particularly useful in complex structures where different components may experience very different stress states. Previously, the stress levels were often not directly measured. They were obtained from a finite element models (FEM) calibrated by acceleration measurements. These models are extensively used in engineering to predict structural behavior under loads.

Accurate strain measurements are key for validating and calibrating FEM of structures. It ensures that the predictions match real-world behaviors.

For example, strain measurements may be used during vibration tests by mounting strain gages at the interface between the adapter and the spacecraft in order to derive interface loads.

In this context, accurate strain measurement is of prime importance as these interface loads is a key acceptance criterion for the launcher authorities.

Mounting such sensors could prevent the installation of complex force measurement device and be thus a time and cost saving factor.

The quality and accuracy of these sensors may also offer the opportunity to notch the input level from a criterion directly based on strain measurement, making it consistent with the space standards and recommendations.

Airbus Defense & Space communicated on the use of Dragonfly® sensors for stress analysis in the aerospace domain at ASTELAB 2024 [6].

4.2 Piloting for fatigue testing (LMN - INSA ROUEN NORMANDIE)

Fatigue testing is very time consuming. It can take more than 70 hours to achieve the typical 10^7 cycles needed for a single point on the S-N curve [1]. Vibration based fatigue testing increases the speed by up to 40 times [2].

Testing close to resonant frequencies requires an excellent control of the excitation to prevent unwanted vibration levels. This control is generally achieved through an accelerometer. However, the acceleration must be correlated with deformation through a simulation. This model can dispart from practice for a number of reasons (e.g., CAD modeling, fixation, materials, …).

The critical metric in fatigue is deformation. However standard strain gauges lack the resolution for vibration-based testing levels as demonstrated in Figure 6. It is now possible to achieve such strain measures, in a convenient sensor format, with the Dragonfly®.

Consult the communication from INSA Rouen on the use of Dragonfly® for strain-controlled fatigue testing at ASTELAB 2024 [7].

4.3 Modal analysis

Modal analysis has been performed mainly using acceleration or displacement sensors to measure mode shapes. Development of strain-based modal analysis has been around since the 80s [3]. It has been shown that using piezoelectric strain gauges like PCB Piezotronics' product, strain modal analysis permits accurate detection of the natural frequencies, displacement mode shapes and damping [5] .

One of the advantages of using strain is the sensor integration. Strain sensor size is smaller and less disturbing for the test object. Strain sensors are typically positioned close to the tests object fixtures for maximum deformation. Like shown in Figure 5, their impact on the structure behavior is thus significantly smaller than accelerometers, which are placed at location of maximum displacement.

However, this technique has not been very popular. The rigid piezoelectric strain gauge is very expensive and impractical for curved surfaces. Standard metallic foil strain gauges lead to many experimental difficulties and low sensitivity [4].

In our whitepaper on the comparison of Dragonfly® and a strain gauge on the tuning fork resonances, we have successfully identified the modes corresponding to the FEM model. We await further developments in this field.

5 Conclusions

The transfer functions between a force cell and three output sensors (a Dragonfly® sensor, an accelerometer and a standard metallic foil strain gauge) have been measured. Obtained from Dragonfly®, the strain signal quality and coherence are on par with the acceleration one. This opens news applicative paths, as the strain signal from the standard metallic gauges is not up to the task. With strain data of such quality, vibrational stress analysis, FEM model validation, shaker piloting and modal analysis have multiple new avenues to be explored.

Let us know which new strain-based vibration application you develop with Dragonfly®.

References

[1] B. D. Hill, B. A. Furman, E. E. German, J. R. Rigby, and R. B. Berke, “Non-contact strain measurement to eliminate strain gages in vibration-based high cycle fatigue testing,” *J. Strain Anal. Eng. Des.*, vol. 58, no. 2, pp. 141–156, Feb. 2023, doi: 10.1177/03093247221076765.

[2] T. J. George, J. Seidt, M.-H. Herman Shen, T. Nicholas, and C. J. Cross, “Development of a novel vibration-based fatigue testing methodology,” *Int. J. Fatigue*, vol. 26, no. 5, pp. 477–486, May 2004, doi: 10.1016/j.ijfatigue.2003.10.012.

[3] L. Y. Yam, T. P. Leung, D. B. Li, and K. Z. Xue, “THEORETICAL AND EXPERIMENTAL STUDY OF MODAL STRAIN ANALYSIS,” *J. Sound Vib.*, vol. 191, no. 2, pp. 251–260, Mar. 1996, doi: 10.1006/jsvi.1996.0119.

[4] F. Marques dos Santos, B. Peeters, J. Lau, W. Desmet, and L. Goes, *An overview of experimental strain-based modal analysis methods*. 2014.

[5] T. Kranjc, J. Slavič, and M. Boltežar, “A comparison of strain and classic experimental modal analysis,” *J. Vib. Control*, vol. 22, no. 2, pp. 371–381, Feb. 2016, doi: 10.1177/1077546314533137.

[6] N. Chauvet, E. Cavro, J.S. Moulet, "Evaluation de jauges piézoélectriques dans le contexte spatial", ASTELAB Conference 25-26th June 2024, Rouen, France

[7] C. Gautrelet, L. Khalij, C. Cadieux, J. Batifoulier, T. Tabata, “Mesures par stéréocorrelation sur un essai vibratoire piloté par une jauge de déformation piezoélectrique”, ASTELAB Conference 25-26th June 2024, Rouen, France