Disk brake monitoring using Dragonfly® sensors

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Abstract Brake system monitoring could predict maintenance needs, prevent brake failure, and improve the overall safety and performance of the system. However, the limitations of standard sensors do not provide a complete representation and monitoring of the wear and failure of the mechanism. For the first time, Wormsensing Dragonfly® sensors demonstrated a complete and quantitative measurement of the failure and degradation mechanism in braking systems. These breakthrough results are achieved using Dragonfly® sensors high sensitivity, and flexible integrability. They enable the simultaneous monitoring of both quasi-static deformations, and high frequency vibrations.

Here, Dragonfly® is used to monitor breaking torque and vibration on a scooter wheel. Braking torque amplitude of each braking event is measured and classified for life-time estimation. A comparison with a MEMS accelerometer is also presented and illustrates the relevance of measuring local strain over global acceleration in this use case.

Key Words
Piezoelectric, Strain gauge, Deformation, Brake monitoring, Brake pad
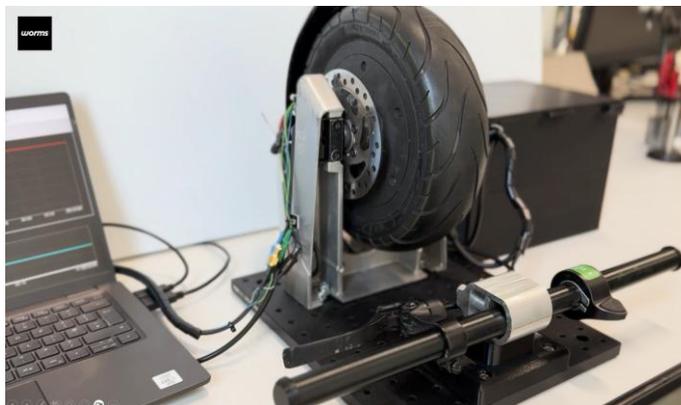

Figure 1: Scooter wheel with internal motor. Brake and motor control on the handlebar.

1 Introduction

In our ever-accelerating world, being able to decelerate when needed is crucial. Most of the transportation industry—trucks, cars, trains, bicycles, and more—relies on disk brakes to achieve this.

Despite their critical role, pads and disks monitoring has not yet been adopted in the industry. The usual pad wear check is usually done through visual inspection, or end-of-life acoustic / electronic indicators. These methods do not account for pad hot spots, pad partial cracks, misalignments, and disk issues. Predicting the lifetime of braking systems remains a challenge up to this day [1] .

System response to braking is a complex process that involves both high-frequency vibrations and quasi-static loads. Until now, there have been no single sensors capable of effectively combining and addressing these requirements.

1.1 Challenges of brake monitoring

Transport brake systems operate in high vibration environments. The vibration levels can be affected by multiple factors, such as vehicle acceleration, road surface conditions, and the mechanical maintenance state of the vehicle.

In recent years, accelerometers have become the most widely used sensors for online process monitoring [2]. However, the factors mentioned above often introduce parasitic noise, which can interfere with accurate measurements. In summary, acceleration is not directly related to the effort passing through the braking system but also includes exogenous data.

An alternative solution to this issue is to measure the internal forces in the brake's mechanical components. However, conventional force cells need to be installed in-line with the force, which is impossible in such a robust and safety-critical system. The last conventional sensor option is to install strain gauge on the mechanical parts. Unfortunately, the strain gauge resolution is insufficient for such rigid structures.

1.2 Dragonfly® for disk brake monitoring

Dragonfly® sensors are dynamic strain gauges based on an extremely thin crystalline piezoceramic sensitive element. This 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.

2 Demonstration set up

A scooter rear-wheel with an internal electrical motor is presented in Figure 1. The handlebar in the front carries the brake lever and the motor actuator. The brake caliper is equipped with a Dragonfly® sensor on the wheel-side part (Figure 2 and Figure 4). A state-of-the-art MEMS accelerometer (Analog Devices ADXL356) is installed on the wheel frame. The acquisition is done on a Dewesoft Dewe43 system.
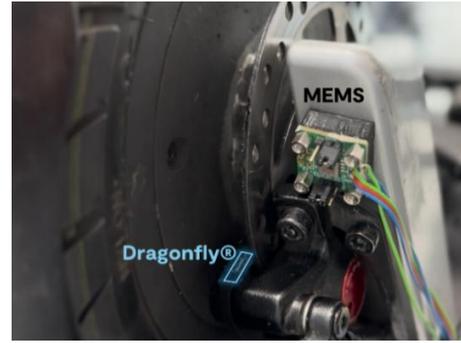

Figure 2: Close up on the brake sensor installation.

2.1 Measuring torque through strain

Dragonfly® measures the deformation (strain) of the brake caliper. The following section describes strain relation to torque. Braking torque (T_b) is dependent on the friction force and the effective radius ($r_{\text{}}$).

$$T_b = F_{friction}\, r_{eff}$$

The friction itself is related to the clamping force F_c of both pads (Figure 3 and Figure 4), where μ is the friction coefficient.

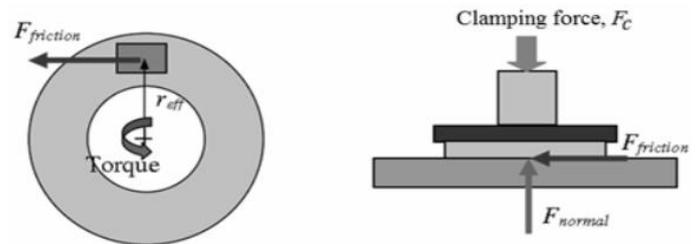$$F_{friction} = 2\mu F_c$$

Figure 3: Schematic of the disk torque and pad friction (left) and relation to the brake clamping force (right, in-plane view) [3].

This force is proportional to caliper deformation.

$$F_c = \alpha \times strain$$

Where α is related to the shape and material properties of the caliper. The torque is then obtained as:

$$T_b = 2\,\mu\, r_{eff}\, \alpha \times strain = \beta \times strain$$

Where the parameter β is estimated during the calibration step. The calibration only needs to be performed once to find the β parameter.
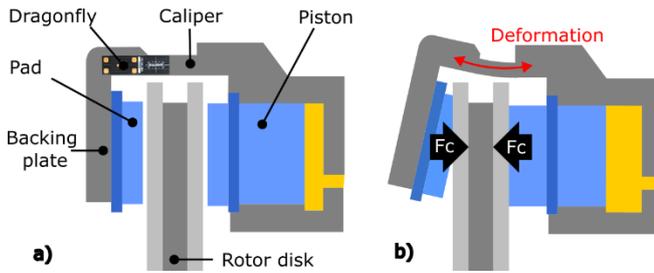
Figure 4: Schematic of the caliper (a), clamping force and caliper deformation while braking (b) [4].

2.2 Calibration of torque measure through Dragonfly®

To find this β parameter, we applied a known torque through a force cell. Figure 5 shows the calibration set up.
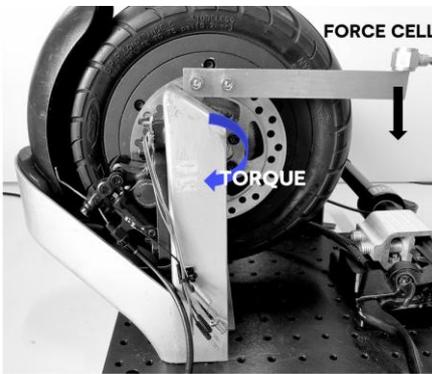

Figure 5: Braking torque calibration with a force cell.

3 Results

3.1 Comparing Dragonfly® and acceleration

Figure 6 shows the signal for the MEMS acceleration and the torque from the Dragonfly sensor. Three break periods are easily identified on the Dragonfly signal. The transition step amplitude is the breaking torque. Being a dynamic sensor, we can observe the signal discharge between the break lever pull and release for each braking event.
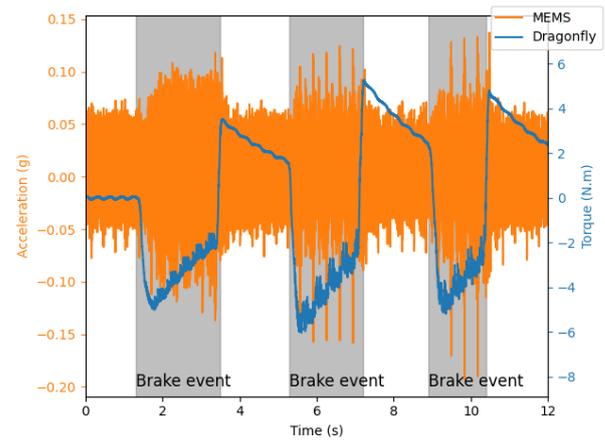

Figure 6: MEMS acceleration and Dragonfly® deformation during 3 braking events.

The Dragonfly® high-frequency signal can also be analyzed in a similar way to the accelerometer. Figure 7 show the Dragonfly® signal after a high-pass filter. The signal-to-noise ratio (SNR) is much improved on the strain-related signal of Dragonfly®.
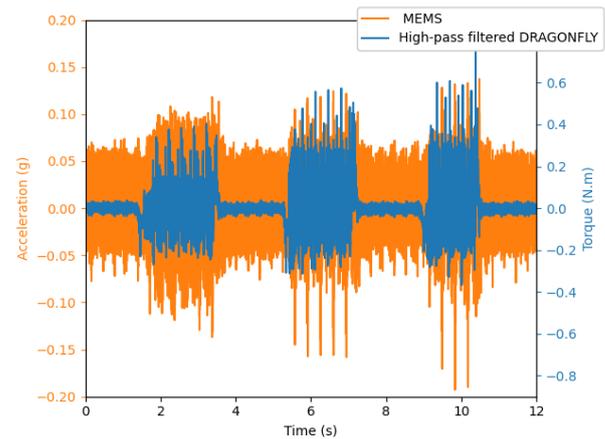

Figure 7: Same signal with a high-pass filter on Dragonfly®.

This is explained by the strain being directly related to the braking event torque. The strain signal at higher frequency is less polluted by the environment than with acceleration data. Figure 8 and Figure 9 show the spectrograms of the same measurement for Dragonfly® and the MEMS accelerometer respectively. The rotation frequency decreases during the breaking events on both spectrograms. Electromagnetic noise at 50 and 100 Hz is very visible on the MEMS as it is not shielded.
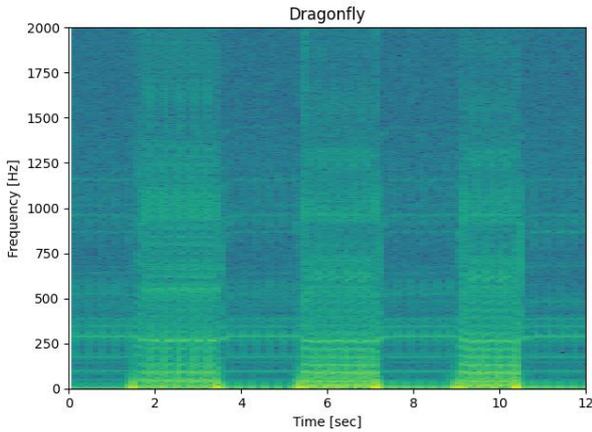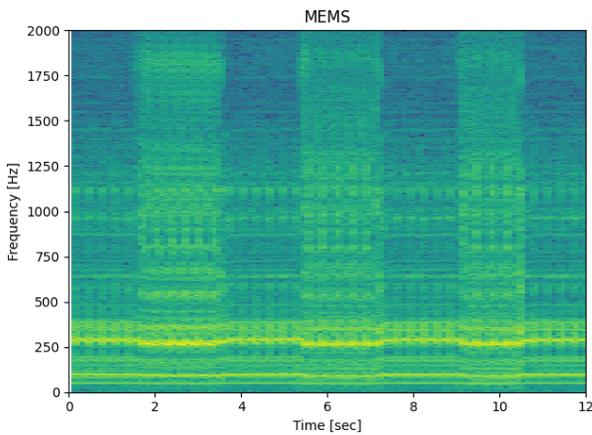
Figure 8: Spectrogram of the Dragonfly® sensor.

Figure 9: Spectrogram of the MEMS accelerometer.

3.2   Measuring the break lifetime

Using the Dragonfly calibrated torque signal, we can identify the torque amplitude at each brake event beginning and ending. Figure 10 shows the Dragonfly signal over multiple braking events. Figure 11 plots the signal variance. When the variance peaks up, the signal peak–to–peak (braking step associated with the lever actuation) is measured. In Figure 12, these data are stored in a table and classified according to amplitude. This enables fatigue estimation according to Miner's rule.
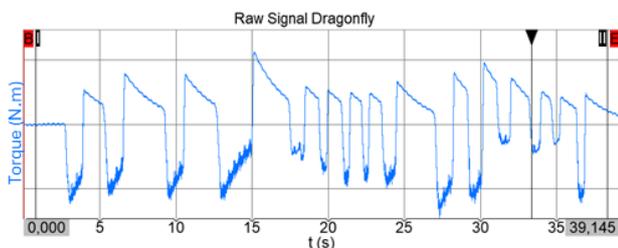

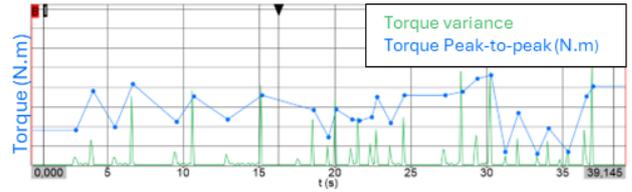Figure 10: Raw Dragonfly signal over multiple braking events.

Figure 11: Signal Variance and threshold for braking beginning and ending torque amplitude of Figure 10 signal.
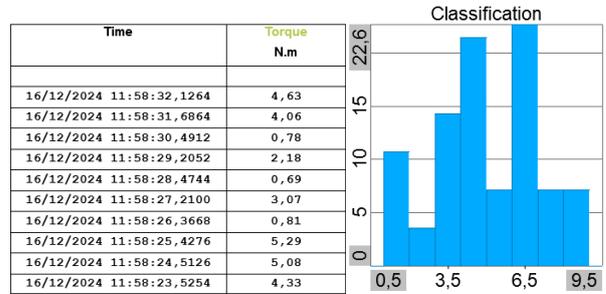
Time	Torque N.m
16/12/2024 11:58:32,1264	4,63
16/12/2024 11:58:31,6864	4,06
16/12/2024 11:58:30,4912	0,78
16/12/2024 11:58:29,2052	2,18
16/12/2024 11:58:28,4744	0,69
16/12/2024 11:58:27,2100	3,07
16/12/2024 11:58:26,3668	0,81
16/12/2024 11:58:25,4276	5,29
16/12/2024 11:58:24,5126	5,08
16/12/2024 11:58:23,5254	4,33

Figure 12: Table of torque peaks history. Classification in bins of 1 N.m interval.

Miner's amplitude classification is very common for material fatigue. However, in this case the wear also comes from the duration of the friction forces. Measuring brake events beginning and ending, we can easily calculate the duration of each event. Figure 13 shows the total break time accumulation during Figure 10 measurement. A combination of the brake duration weighted by the torque amplitude should result in the most accurate damage estimation. An estimate of remaining useful life can then be calculated in real time.
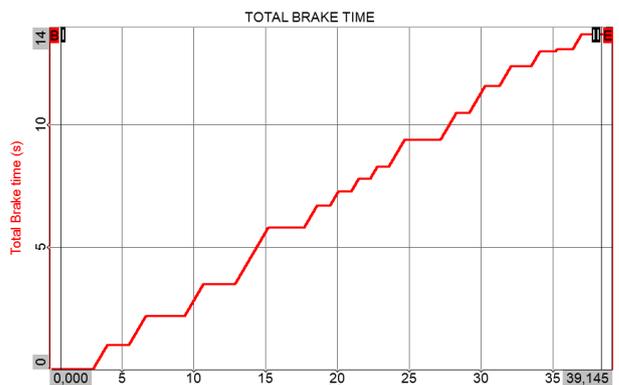

Figure 13: Braking time compatibilization.

4   Conclusion

A disk brake system has been instrumented with a Dragonfly® dynamic strain sensor and a MEMS accelerometer. Measuring deformation, which is proportional to the braking torque, enables a measurement of the forces endured by the system and responsible for wear. Also, strain being a local phenomenon, the signal is a lot less polluted by surrounding noise sources than the acceleration

which can be caused by remote phenomena. This robust signal can be used to launch corrective actions and improve user safety.

Dynamic strain is the ideal candidate for monitoring friction related wear in rigid structures and high vibration environments.

References

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