Monitoring milling machines using Dragonfly®

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Abstract
Wormsensing Dragonfly® is a class of dynamic strain sensors surpassing traditional strain gauges in terms of sensitivity by a factor of 1000, while maintaining the same form factor (less than 150μm-thick flexible PCB). The wide bandwidth of Dragonfly® (from 0.02Hz to more than 100kHz) enables simultaneous assessment of the quasi-static forces acting on structural components, and of conventional vibration metrics of rotating machines such as the amplitudes of harmonics of the rotation frequency. To illustrate its practical utility, the spindle of an industrial milling machine is instrumented with both Dragonfly® and a standard accelerometer. Comparative analysis shows that Dragonfly® can detect abnormal efforts causing early wear of the spindle, and at the same time deliver the standard vibration metrics (such as friction and shock) traditionally obtained from the accelerometer signal. The ability to measure forces on the spindle enables active control of the tool, and especially automatic stopping in case of abnormal use.

Key Words
Milling, Machine monitoring, Piezoelectric strain sensor

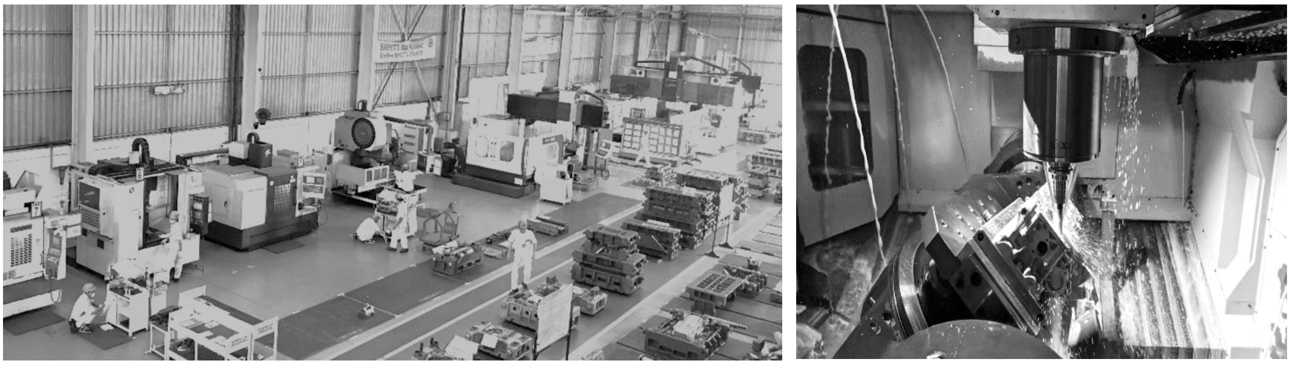

Figure 1: Typical industrial milling machine instrumented in this study. (left) Machine and facilities overview. (right) Close view of a typical milling chamber.

1 Introduction

Thanks to the recent wide scale availability of automatic machine monitoring equipment, the industry is today experiencing the so-called new 4.0 industrial revolution. The monitoring systems can now acquire vibration signals, process the data in real time and send to the cloud relevant metrics. Many common industrial machines among which milling, drilling, and cutting tools are equipped with sensors to detect early signs of wear, excessive efforts, unsuitable operation, to stop the machine and proceed to maintenance before any damage occurs. The ability to immediately stop the machine in case of excessive effort is a game-changer compared to manual checks, as the machine can be stopped before the effort damages it. The ultimate goal is to reduce machine downtime, which directly results in reduced production and added costs for the machine owner.

Historically, the most widely used sensors for machine monitoring are accelerometers, as prescribed in the ISO 20816 standard. It defines the various methods for vibration monitoring, and the related metrics which are mostly derived from acceleration measurements.

In the field of milling process monitoring, several physical quantities have been suggested to monitor the tool condition [1]:

- The cutting force has been estimated by adding strain gauges or piezoelectric PVDF films inside the spindle or in the working table. This is the metric which is the most directly linked to the tool condition.
- The tool vibrations have been measured by accelerometers located at different positions [2], on the spindle, on the CNC table, or on the workpiece. The installation of accelerometers is generally straightforward, so they have been widely used for this purpose. However, the analysis of acceleration signals is more complex as the measured quantity is less closely related to the tool condition than the cutting force.
- Other metrics have been monitored, such as the motor power or temperature, but they do not provide an such a precise insight on the tool condition as acceleration or cutting force measurements.

Usually, the industrial milling machines have not been designed to integrate a sensor to monitor the cutting force, and there is thus a crucial installation challenge: the sensor must be installed quickly in a constrained geometrical context, without modifying the structural parts of the machine.

The first option is to use traditional resistive strain gauges [3], but these sensors have a low sensitivity, and cannot measure accurately small deformations (below 10µdef). The structural parts of milling tools are designed to be very rigid to deform little during the process. Thus, the measured deformations are close to the noise floor of the resistive strain gauges, especially at high frequencies. The measured signal is thus noisy and difficult to analyze.

The second option relies on piezoelectric strain sensors which are more sensitive. Two options currently exist on the market:

- Thin film PVDF strain sensors, made of a polymer material. These are low cost, flexible and easy to integrate, but their piezoelectric properties tend to degrade with time and temperature, making them unsuitable for reliable machine monitoring.
- Piezoelectric extensometers made of a piezoelectric crystal embedded in a metal casing. These sensors are stable over time but are hard to integrate in existing machines, as a flat and hard surface at the right location must be available.

The Dragonfly® strain sensor produced by Wormsensing bridges the gap between these two technologies: it embeds a thin piezoelectric high-quality crystal film into a flexible PCB, resulting in a very sensitive, robust and easy to handle strain sensor, which is straightforward to integrate in constrained geometries. It is compatible with all IEPE acquisition systems, which is an industry wide standard nowadays.

In this study we analyze the application of the Dragonfly® sensor to monitor an industrial milling tool by instrumenting the spindle casing. The measurements are compared to an industrial accelerometer (see Figure 2). The instrumented machine is a production asset of a major manufacturer in the aerospace industry.

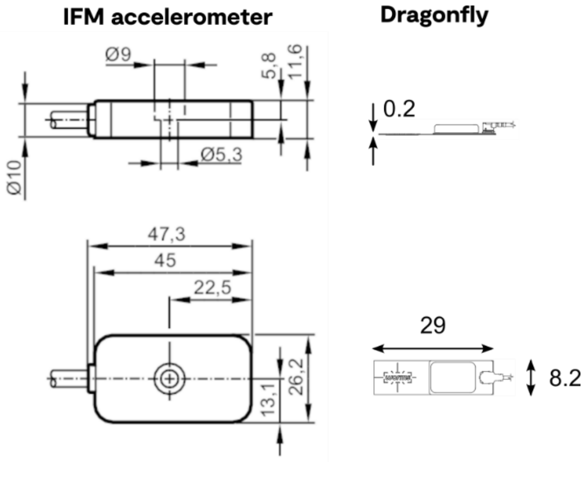

Figure 2: Schematics and dimensions in mm of the industrial accelerometer installed on the milling tool, and of the Dragonfly® sensor.

2 Industrial use case

2.1 Goals

The equipment studied in this section belongs to a big manufacturer of the aerospace industry. It typically operates 24 hours a day to mill aluminum pieces. The part of interest here is the spindle: the mechanical part containing the bearings which connect the milling tool to the motor.

The spindle manufacturer claims that the spindle is designed to withstand 10 000 hours of milling, but in practice it needs to be changed every 4 000 hours. In an attempt to determine the causes of the early wear, the milling equipment was first instrumented with a 3-axis accelerometer positioned on the frame holding the spindle. However, not all problems could be identified.

Indeed, the efforts passing through the spindle cannot be measured by the accelerometer, and adding a force cell in the equipment is not possible as it must be placed on the force path which would require a modification of the structural parts. The high sensitivity of the Dragonfly® sensor allows to measure the small strains created in the spindle structure due to the efforts applied by the milling tool. Thus, it appears to be the ideal sensor to monitor abnormal use of the spindle creating dangerous efforts in it.

2.2 Setup

A picture of the monitored tool is shown in Figure 3.

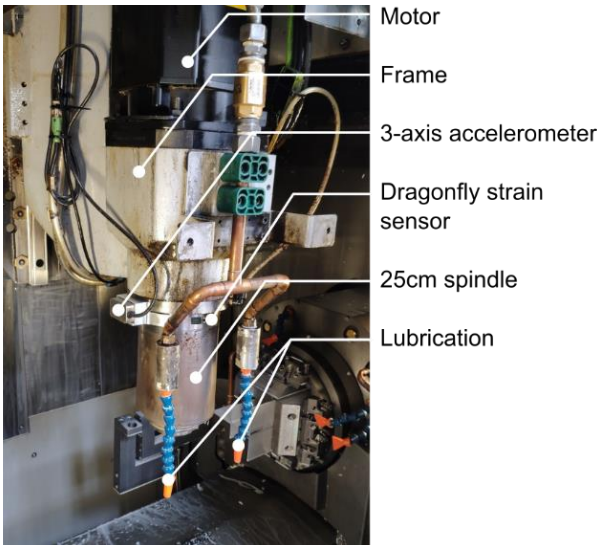

Figure 3: Picture of the monitored milling tool. The accelerometer is fixed on the frame, and the Dragonfly® strain sensor on the spindle.

The milling cutter is not shown in the picture but will be installed inside the spindle. The spindle itself contains bearings to withstand the strong forces applied by the tool on the processed material.

The spindle is equipped with two sensors:

- A typical industrial MEMS accelerometer, manufactured by IFM, from the VSM line. A custom metal holder was designed specifically for this application to be able to fix the accelerometer to the spindle at the right position.
- A Dragonfly® unidirectional strain sensor manufactured by Wormsensing, glued at the top of the spindle, close to its clamping area. The installation of the Dragonfly® sensor took 20 minutes, including the surface cleaning and cabling. The sensor contains an IEPE charge amplifier, which makes it compatible with most acquisition devices.

The technical drawings of the installed sensors are shown in Figure 2.

Both sensors are connected to an industrial 16-bits acquisition and monitoring system, also from IFM, which is set up to record the signals at a sampling rate of 50kHz, with an analog anti-aliasing filter cutting at 12kHz.

3 Results

3.1 Analysis of a milling session

The time data and spectrogram of Dragonfly® during a typical milling session are plotted in Figure 4. The various events, such as machine start and milling start are indicated on the plots. They can be clearly identified from the signal. It is also possible to locate the two steps of a milling phase, when the tool first moves vertically, and then horizontally to widen the hole.

When the machine head reaches the tool around t=10s, there is a large peak which is clearly visible in the time signal, indicating that a strong force is applied on the spindle. When the machine operator discovered this information, he checked the coordinates of the tool position and found an error which caused this excessive effort.

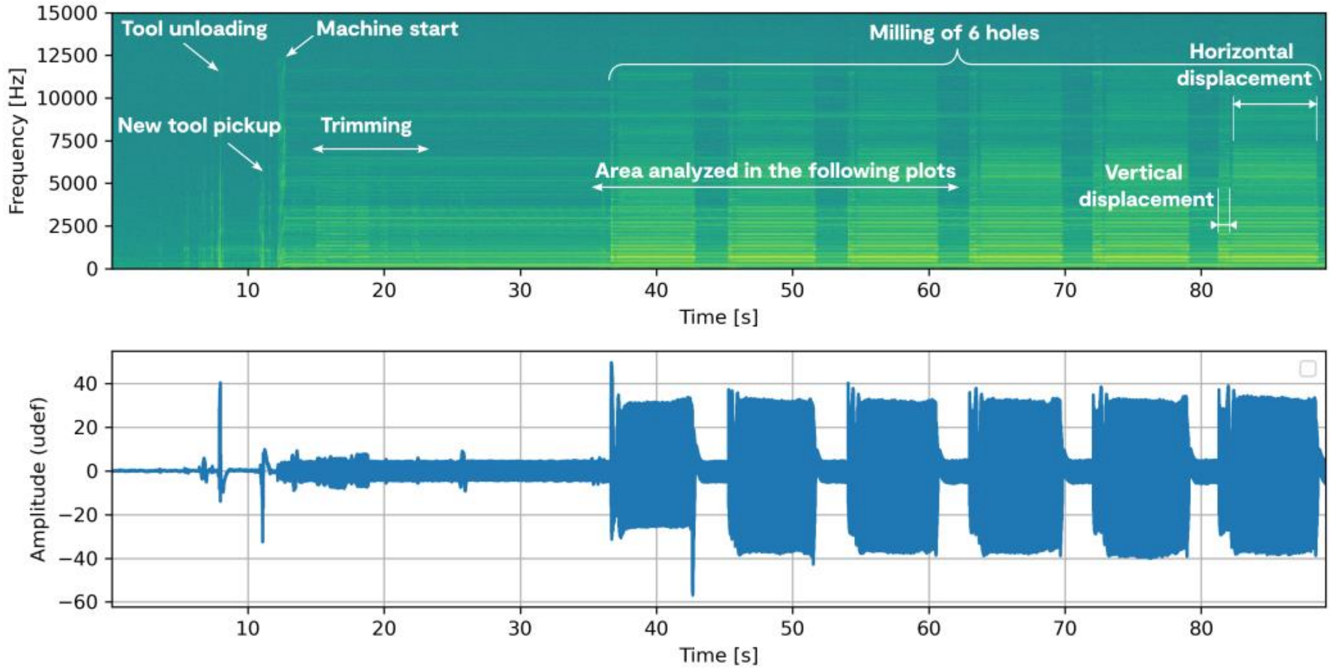

Figure 4: Time data and spectrogram of Dragonfly® during a milling session, and description of the different phases.

3.2 Comparative study between Dragonfly® and an accelerometer

Only one sensor could be recorded at a time, so two similar milling sessions were performed, and recorded once with the accelerometer and once with the Dragonfly® strain sensor. The recorded data is plotted in Figure 6, in which the raw time-data, the spectrograms over the whole frequency range and at low frequencies are shown. The sensor signals are also filtered and post-processed to compute various metrics over 300ms time windows which can be useful for machine monitoring:

- The peak-to-peak amplitude at low frequencies (0-50Hz)
- The peak-to-peak amplitude at medium frequencies (50-1000hz)
- The peak-to-peak amplitude at high frequencies (1-15kHz)

The milling sessions consists of several phases during which the tool is in contact with the raw material, during approximately 3s.

3.2.1 Spectrogram

Figure 6 shows that both the accelerometer and Dragonfly® can measure all the harmonics of the rotation frequency of the tool. Dragonfly® has a wider frequency-range, and captures the harmonics above 5kHz, which seems to be the resonance frequency of the accelerometer. Moreover, Dragonfly® shows a better signal to noise ratio (SNR) at low frequencies. Indeed, it measures strain, which is proportional to the displacement of the spindle, and not acceleration which is obtained by differentiating twice the displacement with respect to time, thus reducing the SNR at low frequencies.

3.2.2 Spectrum

The Power Spectral Density (PSD) of the two signals during a single milling phase is plotted in Figure 5.

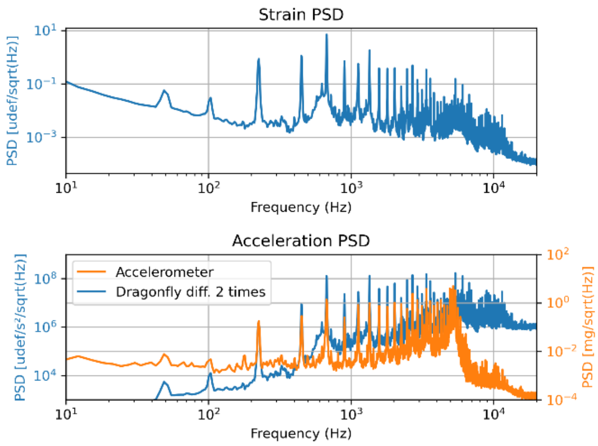

Figure 5: PSD of the sensor signals during a milling phase.

The first plot of Figure 5 shows the PSD of the raw Dragonfly® signal, whose unit is strain. To compare the PSD of the Dragonfly® to the PSD of the accelerometer, the Dragonfly® signal is differentiated twice with respect to time, in order to exhibit the same temporal dependence as the acceleration. The acceleration PSD and the differentiated strain PSD are shown in the second plot of Figure 5. This comparison shows that the same peaks are identified in both PSDs, both at high and low frequencies. Moreover, the relative amplitudes of the various peaks are similar in both PSD. This means that the vibration analysis methods

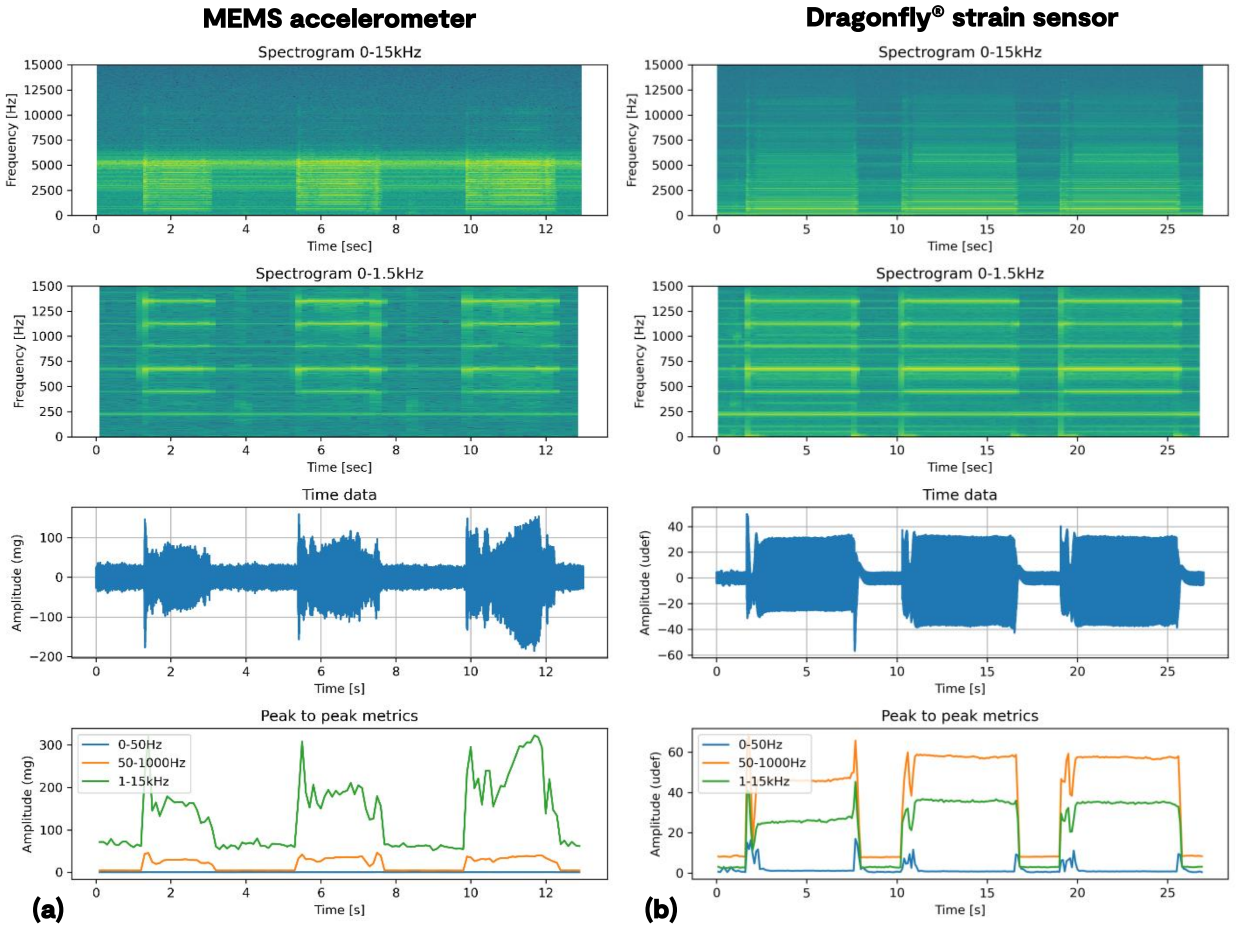

Figure 6: Spectrograms, time data and frequency and indicators measured during a milling session, which includes three milling steps. (a) MEMS accelerometer fixed on the driving head. (b) Wormsensing Dragonfly® strain sensor glued on the spindle. The data from the two sensors are not synchronous and come from two similar milling sessions.

developed for acceleration signals to perform predictive maintenance can be directly applied to Dragonfly® signals.

3.2.3 Time data

The raw time data of the Dragonfly® sensor contains much more information at low frequencies than the accelerometer. This is typically visible at the beginning and at the end of each milling phase, when the tool gets in contact with the workpiece, and applies a constant effort on the spindle. A zoom of the time signals at the beginning of a milling phase is shown in Figure 7.

Figure 7 shows clearly that the accelerometer signal does not contain any information below 50Hz. On the other hand, Dragonfly® captures a rise in the mean level at 63.7s approximately, when the tool contacts the process material. The amplitude of the low-passed signal is representative of the force applied by the tool on the workpiece and can be monitored to check if the contact is too violent.

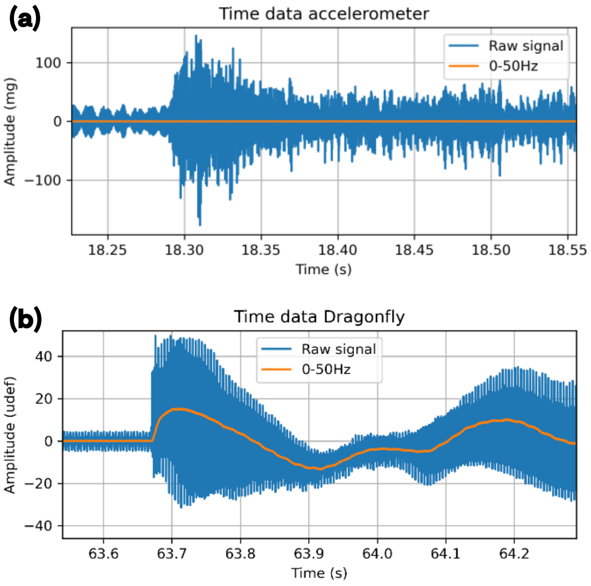

Figure 7: Time data at the beginning of a milling phase. (a) Accelerometer. (b) Dragonfly®. Blue line: raw signal, orange line: smoothed data using a low-pass filter at 50Hz.

During the test session, the analysis of the low frequency Dragonfly® signal revealed that the coordinates of the tool where badly calibrated in some configurations, resulting in excessive effort in the spindle, which could explain its early wear.

Moreover, the acquisition system used to acquire the Dragonfly® signal was locked at a low high-pass cutting frequency and filtered out any information below 2Hz. The Dragonfly® sensor itself has a cutting frequency of 0.02Hz, meaning that its raw signal contains even more low-frequency data than shown in the plots above.

3.2.4 Metrics

In the last plot of Figure 6, key metrics computed over sliding windows of 0.3s are plotted.

As explained in the preceding paragraph, the peak-to-peak amplitude at low frequencies (0-50Hz) may be used to monitor the contact force and prevent shocks which may damage the spindle. This metric typically increases at the beginning and at the end of the milling phases, when the effort applied by the tool on the workpiece varies (either from zero to some value, or from some value to zero). As Dragonfly® is a piezo-electric sensor, it is adapted to measure dynamic forces. The sensor signal will drop to zero in a timescale of seconds due to charge leakage in the IEPE amplifier as soon as the force does not vary. The accelerometer provides no information on the force applied on the spindle.

The two other indicators (the peak-to-peak amplitude at mid and high frequencies) are typically used to monitor shocks and friction and are equally well computed using the two sensors.

4 Conclusions

By installing a Dragonfly® strain sensor on the spindle of an industrial milling machine, we showed that this sensor provides all the information contained in the signal from an industrial accelerometer, and additionally gives access to valuable information. It is possible to estimate the forces applied by the tool on the workpiece, and thus develop additional indicators which correlate more directly to the wear of the spindle. The knowledge of the efforts applied on the spindle also allows the implementation of automatic stopping of the machine to prevent permanent damage.

For information on another use-case where Dragonfly® is used to estimate the forces in industrial machines, check our whitepaper Seamless integration of force sensing and position monitoring on robot arms with Dragonfly® strain sensors.

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