# IPRO 331:
# Machine Vibration Monitoring and Control Solutions for A. Finkl & Sons

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Final Report

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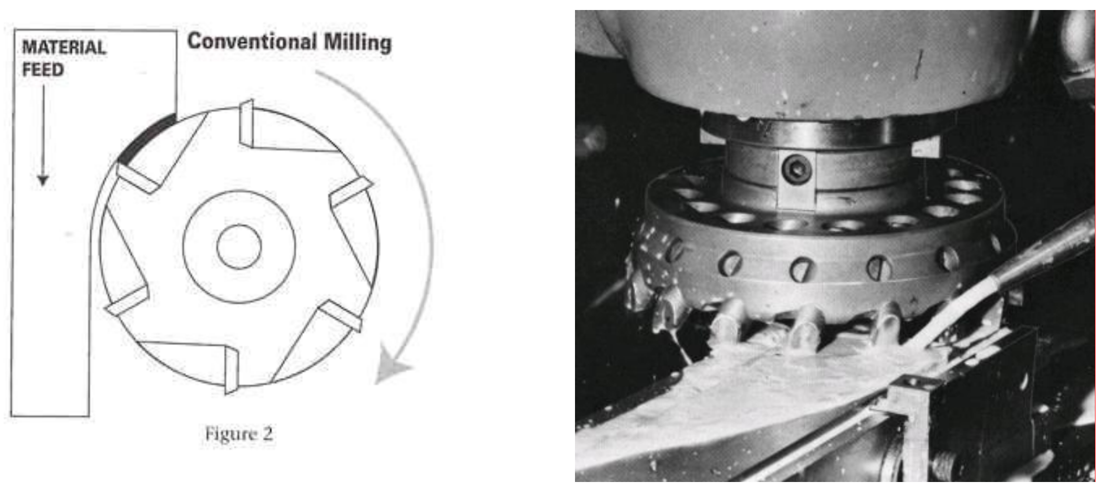
**Introduction:**

The purpose of IPRO 331 is to develop a system to automatically detect an irregularity with a mill at A. Finkl & Sons Co. A.Finkl & Sons is the world's leading supplier of forging die steels, plastic mold steels, die casting tool steels and custom open-die forgings. Finkl open die forgings are produced at its fully integrated production facility in the vicinity of Lincoln Park in Chicago, IL. Finkl steels are distributed domestically and to over 18 countries around the world

**Background:**

Milling is the process of cutting away material by feeding a workpiece past a rotating multiple tooth cutter. The particular machine that is subject of this project is a face milling machine, in which the cutter is mounted on a spindle having an axis of rotation perpendicular to the workpiece surface, as seen in Figure 1. The milled surface results from the action of cutting edges located on the periphery and face of the cutter. Mills typically use interrupted cutting, which means each pass overlaps the previous one, and the cutting teeth are never all contacting the material at one time.




(a) (b)

Figure 1: (a) Diagram and (b) picture of a mill

The mill has tungsten carbide tooth inserts that do the actual cutting. Although this material is very hard, it is also quite brittle and is prone to chipping and fracture. A chipped or broken tooth results in an increase in the cutting force and, accordingly, the temperature seen by the remaining teeth and an increase in the power drawn by the machine. It also results in a poorer surface finish on the piece. When a tooth breaks, or is severely chipped, the machine must be shut down and the tooth insert replaced. Therefore, the machine requires constant monitoring while running. This comes at the cost of a significant number of perhaps superfluous man-hours, which can be partially eliminated if the wear on the tool can be monitored remotely and machine shut down in the event of a tooth breakage can be automated.

Tool monitoring used to be performed by skilled machinists who could hear the cutter as it wore out, or who could look at chips and determine if the machine was operating at optimal levels. However, automated, shielded machining and chip recycling procedures have isolated machinists from the process, making it hard for the machinist to determine if something is wrong. In addition, it is somewhat wasteful to hire a person to sit and listen to the mill at all times. Therefore, tool monitoring setups are becoming more and more necessary to prevent damage to machines and work pieces. Tool monitoring detects a collision or a broken, worn, or missing tool in order to prevent damage to the tool itself, the machine as a whole, and the workpiece being machined. The sooner a problem is detected, the less likely permanent damage will result. In addition, the decreased surface finish quality resulting from a problem will be minimized. Furthermore, tool monitoring has two major benefits. One is a reduction in tool costs due to the extension of the useful cutting life of a tool, and another is an increase in a machine's productivity, since tool monitoring provides an increased confidence in running it at optimal speeds and feeds.

Tool monitoring involves two main components. The first is a sensor or sensors that collect data from different components of a machine. The data is then somehow transmitted to the second component, a data analyzer of some sort. The analyzer is then responsible for figuring out what occurs during the cutting process and making decisions based on the data.

Tool monitoring systems and the sensors they utilize must be tailored to individual applications depending on specific machining conditions. In general, that tool monitoring greatly benefits high volume manufacturers since it has the potential to increase productivity, while reducing costs. It can also benefit low-volume high cost manufacturers since tool monitoring can reduce the risks of damage to a workpiece by a dull or broken tool.

Several methods of monitoring mills are currently in use. Sensors are used to monitor power consumption, force, noise, and vibration. Power sensors measure the amount of power a machine motor is using to rotate a tool. Such a sensor can measure the differences in power usage of a machine that has a dull or broken tool and that with a sharp one. Force sensors measure the force required to move the tool through a workpiece. They are very sensitive and are usually considered the best components for a tool monitoring system. A loud "pop" occurs when a tooth breaks. A simple microphone can be used to detect the "pop". Vibration sensors measure the acceleration or velocity of a machine tool structure. Once a normal condition is established by running the machine with a proper operating tool, this device can sense any deviations from it, signaling a damaged tool, and proper steps can be taken.

In addition to monitoring the power consumption of the mill itself, tool wear rate can be monitored by monitoring the feed motor current. The feed motor is the motor that drives the bed, which the workpiece is mounted on. The motor current is algebraically related to the force required to move the bed. Monitoring the feed motor current, it can be determined when the tool wear rate is accelerating and therefore, when the tool needs replacing. The time to replace the tool is characterized by the abnormal or catastrophic wear at the end of the life of a cutting tool which will be reflected in the readings for tool wear rate. Various related parameters whose characteristics change at this point are found and are used along with the feed motor current in an algorithm that is used for monitoring the tool condition. This method can be limited by light cuts where the useful signal is too hard and small to separate from the total current.

Another method of tool monitoring is Acoustic Emission (AE), which detects the acoustical energy released when a tool breakage occurs. This type of sensor is commonly used for monitoring small tools. AE can be broken into two types. One type, continuous AE, is the result of the plastic deformation of the cutting piece and work piece during the cutting process. The second type, burst AE, is a result of chips breaking off, chip impact and chip tangling.

Fibre optic interferometery is a method used to detect Acoustic emission (AE) at frequencies above normal machine vibration. The Michelson interferometer developed for the experiment was used in conjunction with active phase modulation techniques which resulted in the ability to detect ultra-sonic vibrations in real time over unlimited time scales, where the limiting factor in resolution is the noise of the work piece that the interferometer detects and photoelectric detection, and not the signal processing. The interferometer is designed to have two signals, one that actually detects vibrations and one that is used as a reference to account for low frequency machine vibrations as well as other error factors. Results of testing compared to piezoelectric transducers showed that the interferometer was more responsive than the transducer, the interferometer actually seeing the rebound of an impact wave from the boundaries of the work piece. The interferometer also had less of a ‘ringing’ effect than the piezoelectric transducer. This method of detecting AE is promising, but the results have not yet been compared to tool condition for validation.

**Purpose:**

The purpose of IPRO 331 is to develop a system to automatically detect an irregularity with a mill at A. Finkl & Sons Co. The system will either turn the mill off or warn the operator when a tooth breaks, or some other irregularity occurs. This system will involve measuring vibration, sound, and power consumption, or some combination of these variables. This system will replace the current setup, which involves an operator remaining in close proximity to the mill at all times in order to turn it off when an irregularity occurs.

**Research Methodology:**

IPRO 331 focused on monitoring vibration, noise, and power consumption. Two systems were used to monitor vibration. The first is a system A. Finkl & Sons had purchased prior to this IPRO, and had a maximum sampling rate of 1 Hz. The vibration data is acquired with SpecView software and stored on a PLC. The second is a system from Illinois Institute of Technology, which was used at a sampling rate of 10 kHz.

A web camera was purchased and set up at A. Finkl & Sons. This way the mill can be monitored remotely by the students in IPRO 331, and they can keep track of when the operator changes a tooth, or turns off the machine because of a problem. The web camera is necessary in order to know when an irregularity occurs, so the data at that point can be analyzed. The information from the web camera is used to determine which data represents healthy teeth and which represents the point when a broken tooth occurs.

A Behringer ECM8000 Microphone was purchased to monitor noise. The microphone will be used to record the particular noise, a 'pop', which occurs when a tooth breaks. It will be plugged into the microphone jack on the web-cam. The analysis for a graph of amplitude versus time is not reliable because of the effect of the environmental noise in the factory. Therefore, a FFT frequency analysis is required to reveal the difference between when the milling machine works normally and when the tooth breaks. First, the noise will be recorded under normal operating conditions, and then when a tooth breaks. An FFT analysis will be performed on each set of data, and the amplitudes of the different frequencies will be compared to determine the difference between the two. The microphone specifications are summarized in Table 1.

| | |
|---|---|
| Type | omni electret condenser |
| Impedance | 600 ohms |
| Sensitivity | -60dB |
| Linear Frequency Response | 15Hz-20kHz |
| Connector | gold-plated XLR |
| Phantom power | 15-48V |
| Weight | 4 oz. |
| Phantom powered | +15V to +48V |

Table 1: Behringer ECM8000 Specifications

A Brunel PTM-3 Power Meter was purchased to monitor the power consumption of the mill. As the teeth on the mill wear down and eventually break, the cutting forces increase and the power drawn by the machine increases accordingly. With this device, this increase in drawn power can be used to signal the operator or shut down the machine automatically. It can interface with either a PC or a PLC, and the device can be monitored remotely via a PC. Data is collected with a high sampling rate and can be logged for review at a later date.

**Assignments:**

<u>Power Meter Research</u>
Leland Barnard
Vitaliy Kunin
Craig Cahan

Microphone Research
Kyoung-min Min
Sung Song
Daniel Sanchez

General Mill Monitoring Research
All team members

Data acquisition and analysis
Mark Schreckengost
Jose Contreras Vega

Website
Matthew Matute

Finkl Contact
Christopher Lee

**Obstacles:**

Cooperating with an outside company presented several challenges and impeded the progress of IPRO 331. For the first month of the semester, the mill was not operational. There were also times when our inquiries went unanswered for several weeks. They also said they would set up their existing vibration monitoring system and obtain data. After several weeks, two members of the IPRO obtained permission to set it up themselves. In addition, it took several weeks to obtain approval to buy the new equipment, such as the web camera, microphone and power meter. To date, the power meter and microphone have still not been installed at A. Finkl & Sons.

**Results:**

Preliminary data was obtained on a mill at Illinois Institute of Technology (IIT), using a vibration monitoring system from IIT. The sampling rate was 10 kHz. A peak occurs when a tooth over the previous path impacts the uncut material of the new path. When a tooth is missing, the peak that would have occurred is absent, as seen in Figure 2.

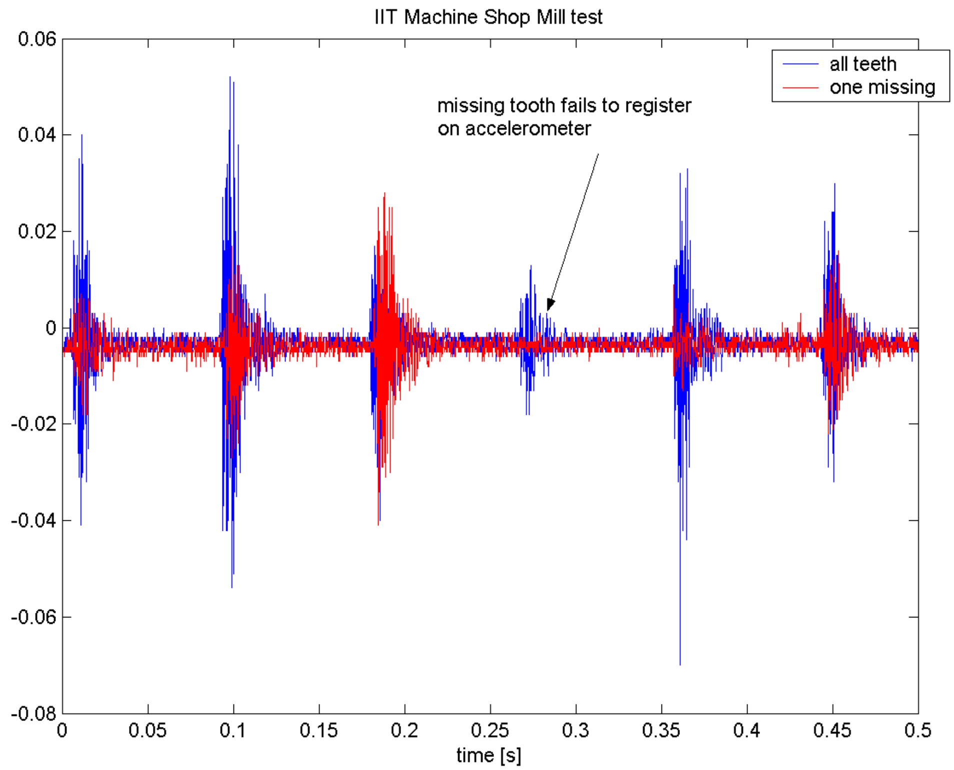



Figure 2: Data from the Mill at IIT taken at 10 kHz

Next, data was obtained at A. Finkl & Sons using a system they purchased prior to the creation of IPRO 331. This system samples at a frequency of 1 Hz, which is too slow to be useful. This data is shown in Figure 3.

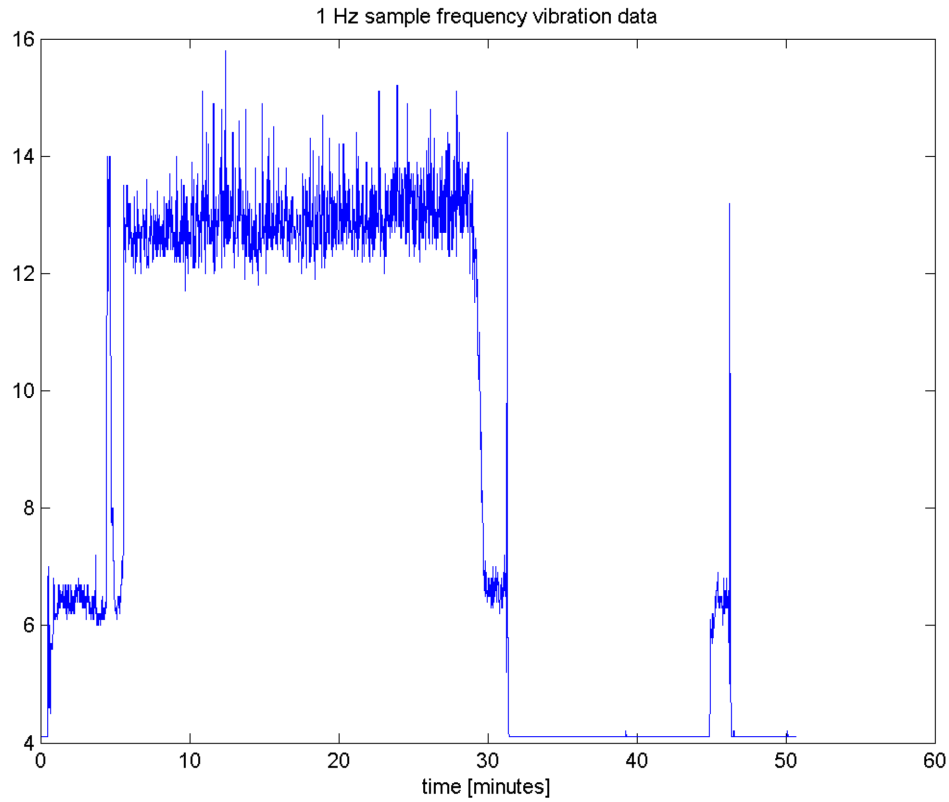



Figure 3:  Data from the Mill at A. Finkl & Sons at 1 Hz

The data provided taken by the existing system is only capable of a 1 Hz sampling rate. To better examine the behavior of the mill under certain conditions IPRO 331 sent the data acquisition system from IIT to A. Finkl & Sons to take data at a sample rate of 10 kHz.  Data was taken in sections of 256 samples and a Fourier Transform was performed on each section.  This gave us a maximum viewable frequency of 5 kHz with a spectral resolution of 20 Hz, and is shown in Figure 4.

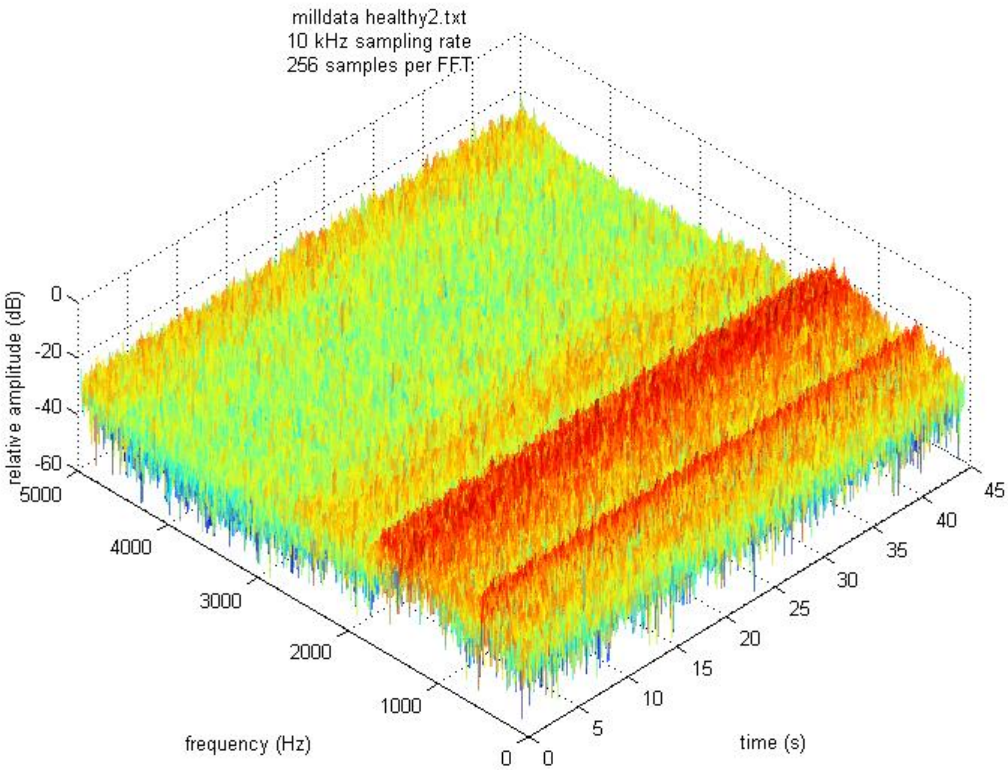



Figure 4: Data from the Mill at A. Finkl & Sons at 10 kHz

Two frequency bands have higher amplitudes. In fact, after approximately 1800 Hz there is little spectral content at an average of about –40 dB. Since there is nothing to alias past 1800 Hz it is possible to sample at a much lower rate of 3.6 kHz and still having minimal aliasing.

Before stripping the data down to the lower sampling rate, we examined the difference between the data from the healthy mill and the broken one. In general, it was determined that, of the two active bands, the broken mill vibrated with more intensity in the lower frequencies. Therefore, it is probably possible to measure the power in a given frequency band and use it as a criterion to determine the status of the mill. Figures 5 and 6 show the 10 kHz data for a mill with a broken tooth, and a healthy mill, respectively.

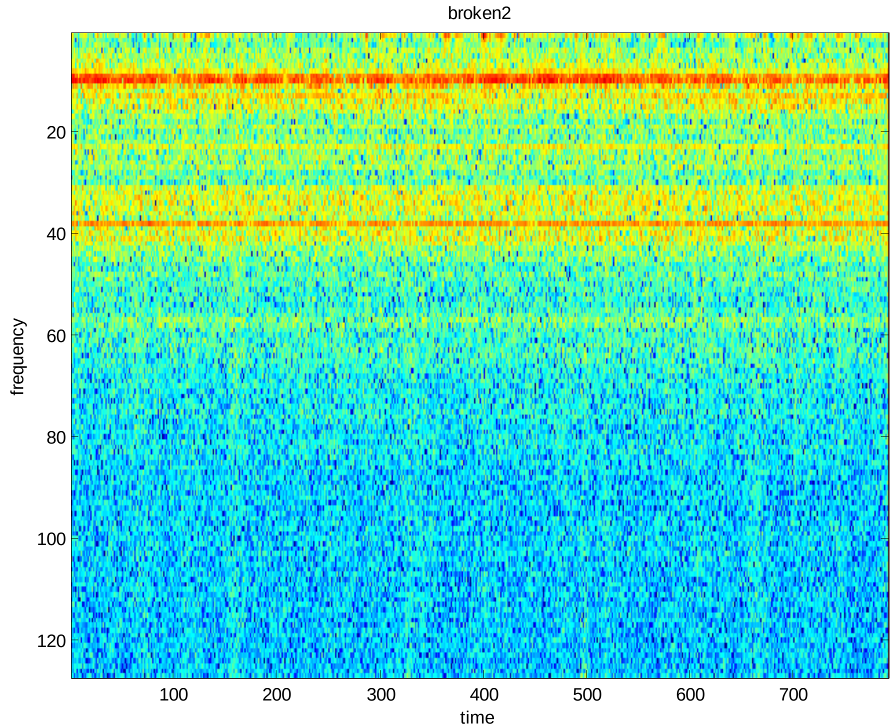



Figure 5: Data from the Mill at A. Finkl & Sons at 10 kHz

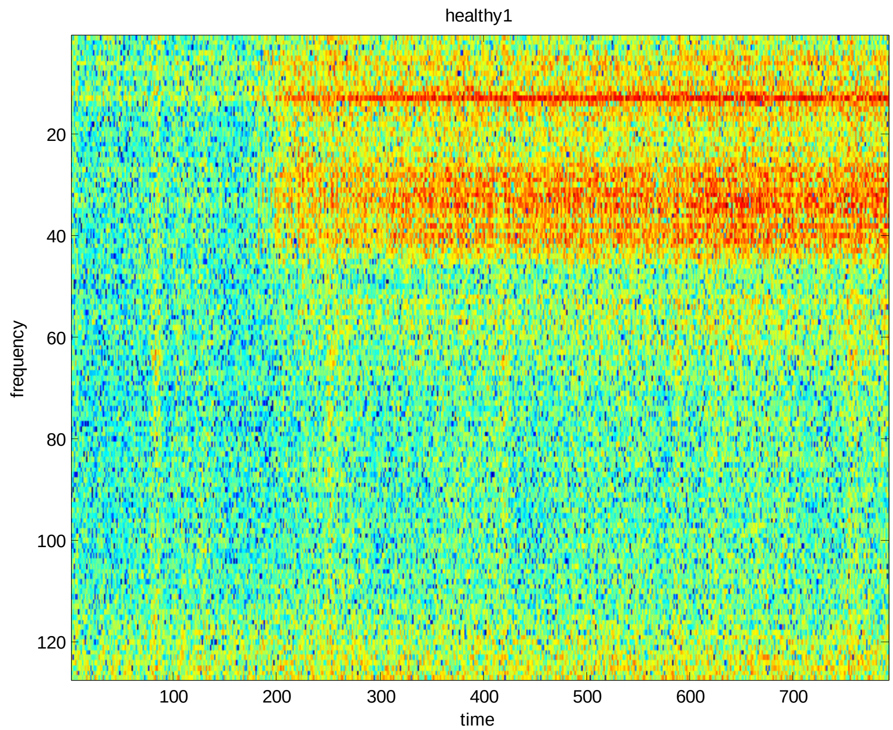



Figure 6: Data from the Mill at A. Finkl & Sons at 10 kHz

A sampling rate of 10 kHz is undesirable in practice since it often fills the buffer in lab view on our laptop and is uses excessive computer resources.  Therefore, a majority of the samples were removed to simulate taking data in real time at 3.6 kHz.  It is still possible to discern the interesting frequencies with a lower number of samples per transform.  This allows use to drop from 256 to 128 samples, again lessening computation intensity and increasing speed.  Data for a broken and health mill are shown in Figures 7 and 8, respectively.

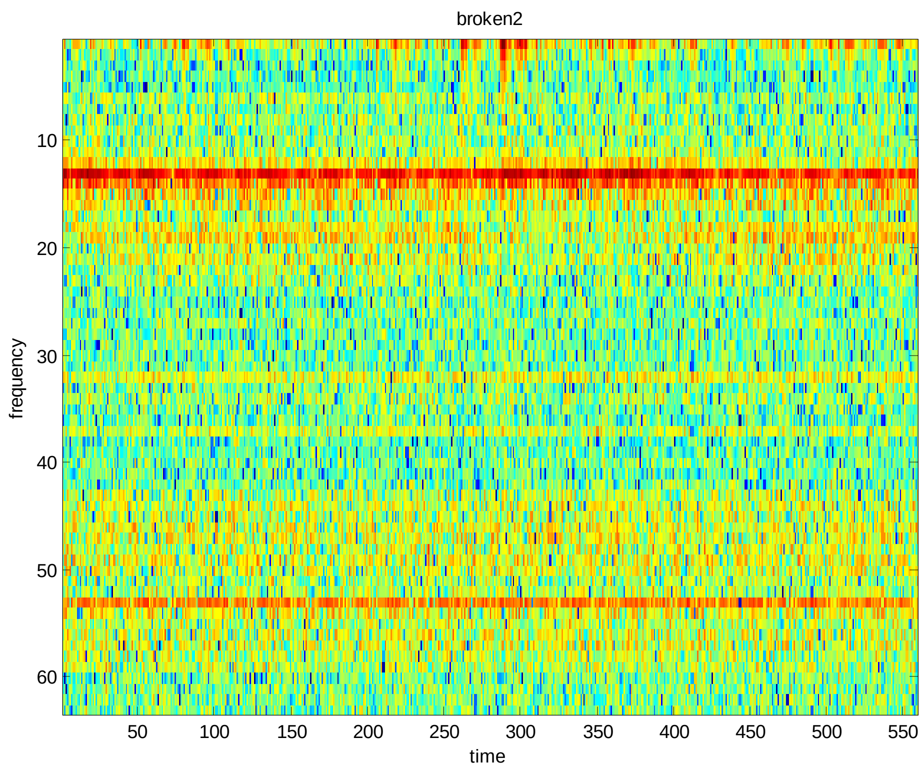



Figure 7: Data from the Mill at A. Finkl & Sons taken at 3.6 kHz

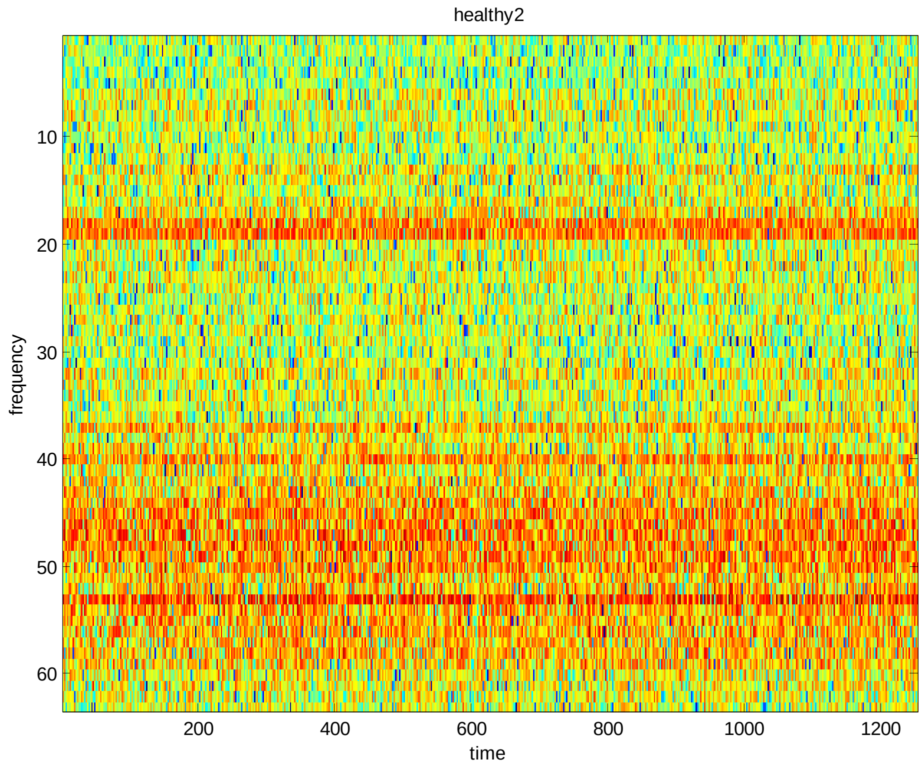



Figure 8: Data from the Mill at A. Finkl & Sons taken at 3.6 kHz

The bands of interest are apparent from the preceding two figures. With conversion for sample rate and the shift from the FFT we identified the meaningful band to be between 182 and 288 Hz.

Next the amplitude of the frequency band of interest was graphed over several examples of good and bad data. There is great fluctuation in the broken power values but they are all above the maximum value of the healthy data. This is shown in Figure 9. Setting a threshold will be a statistical problem that will require more data.

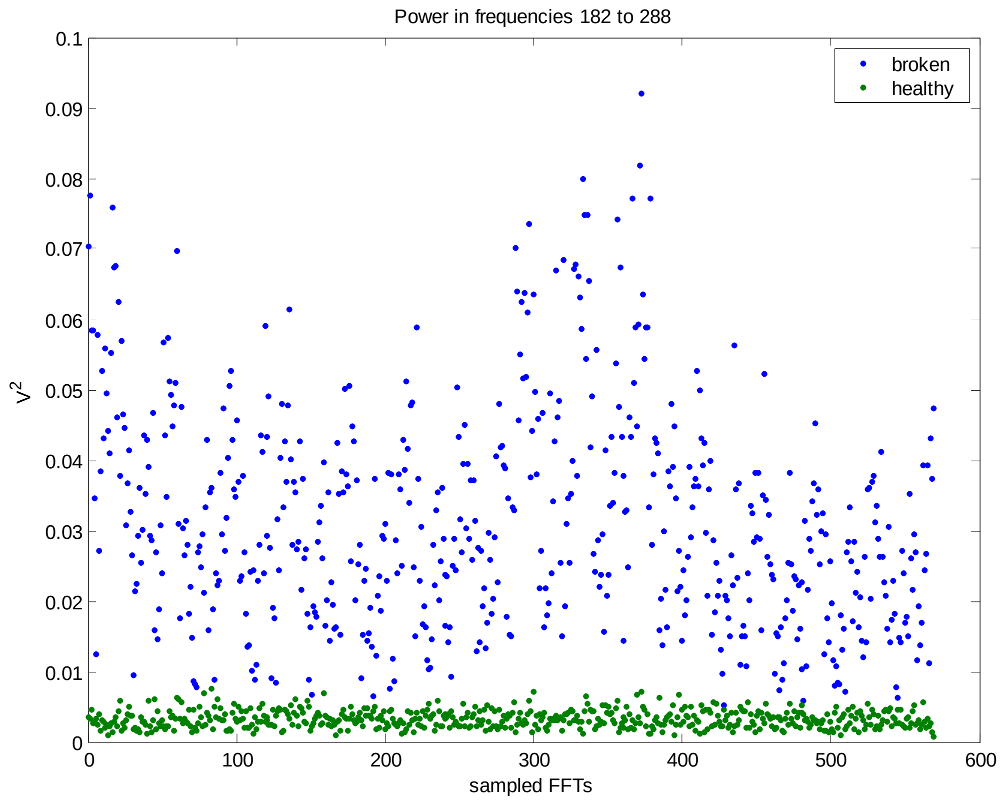



Figure 9:  Amplitude of Broken and Healthy Data

The data in Figure 9 is rearranged to create a graph of the probability that the mill has a problem, as seen in Figure 10.

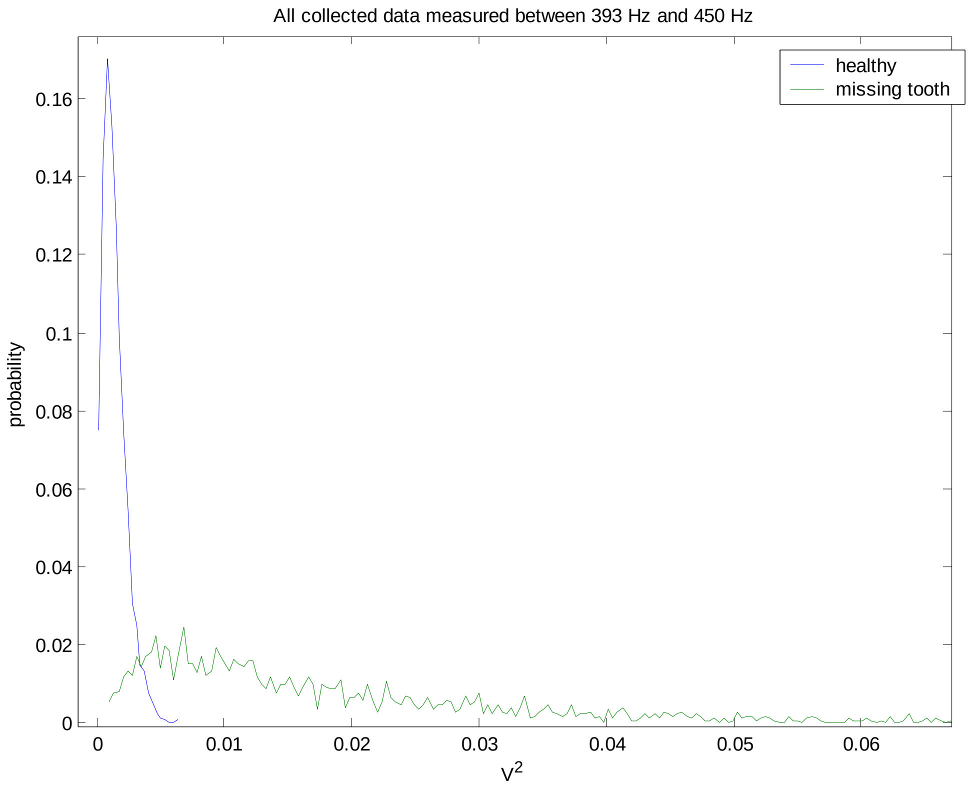



Figure 10: Probability of a Broken Tooth

**Summary of Results:**

Preliminary data from the mill at Illinois Institute of Technology shows a clear difference between a mill with all healthy teeth, and one with a broken or missing tooth. However, the 1 Hz data from the mill at A. Finkl Steel is not useful because the sampling rate is too slow. The 10 kHz sampling rate data reveals a significant increase in vibration when a failed tooth is present, particulary at a frequency of 210 Hz. Additional data analysis reveals 3.6 kHz is an acceptable sampling rate, and a 128 sample FFT is able to resolve the frequencies of interest. This technique appears promising but will require testing and adjustment before it can perform autonomously.

**Recommendations:**

An initial sampling frequency of 3.6 kHz appears acceptable; however, the ideal sampling frequency for vibration monitoring must still be determined. If the frequency is too low the signal will not be detected, but if it's too high the system will require a large amount of memory. In addition, a large amount of data and further data analysis is required to determine a threshold. Once the microphone and power meter are installed, data must be collected and analyzed. After data analysis is complete, the results will determine which method or methods to implement. Once the monitoring system is in place, it will need to be validated. This will be accomplished by creating a system to sound an alarm when the mill is out of normal operating parameters for validation. Once validated, another system will be implemented to automatically turn off the mill.

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