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Sensorische Spannpalette zur Rattererkennung

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Sensoric clamping pallet for chatter detection

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Vienna, 29th October, 2019

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Kurzfassung

Rattern ist ein Vibrationsphänomen, welches bei Bearbeitungsvorgängen, wie dem Fräsen, auftritt. Dies kann zu Werkzeugschäden, Spindelschäden, Oberflächenrauheiten und allgemein zu Qualitätsmängeln der hergestellten Teile führen. Rattern kann kaum vorhergesagt werden und wird normalerweise durch Einstellen der Bearbeitungsparameter während des Bearbeitungsvorganges behoben. Dies erfordert die Messung von Vibrationen während des Bearbeitungsvorganges. Die Überprüfung, ob diese Vibrationen einen bestimmten Schwellwert überschreiten, wird als Rattererkennung bezeichnet. In dieser Arbeit wird beschrieben, warum es zum Rattern kommt, welche Arten es gibt und wie es erkannt und reduziert werden kann. Mehrere Komponenten, welche zur Rattererkennung benötigt werden, werden bewertet und miteinander verglichen. Es hat sich gezeigt, dass piezoelektrische und kapazitive Beschleunigungsmesser für diese Anwendung gut geeignet sind. Darüber hinaus ist ein Prototyp für ein solches Rattererkennungssystem entwickelt worden. Dieser Prototyp wurde gebaut und auf seine Funktionalität getestet.

Abstract

Chatter is a vibrational phenomenon arising in machining operations, such as milling. It can cause tool damage, spindle damage, surface roughness and, in general, poor quality of the produced parts. Chatter can hardly be predicted and is typically addressed by adjusting machining parameters "online". This requires measuring vibrations during the milling process and checking if they exceed a certain threshold, which is called chatter detection. In this thesis, it is described why chatter occurs, which types exist, how it can be detected and reduced. Multiple components for chatter detection are evaluated and compared against each other. It is shown that piezoelectric and capacitive accelerometers are well suited for this application. Furthermore, a prototype for a chatter detection system is developed. This prototype is built and tested for its functionality.

Contents

CHAPTER 1

Introduction

Chatter is a self-excited vibration that still causes trouble for productive environments, by damaging tools and workpieces in cutting and milling processes. This problem was already researched very early, with the conclusion that it can be avoided by adjusting cutting parameters [1]. Today there are already different methods developed to detect and reduce chatter [2] [3] [4]. Chatter detection still revolts mostly around calculating a threshold value and then checking if this limit was exceeded.

1.1 Motivation

Chatter in milling processes is a problem that affects the quality of the machined workpieces, the tool integrity and limits the maximum achievable material removal [3]. This limits productions and slows down manufacturing. By integrating automatic chatter reduction methods, there is less responsibility and dependability from humans necessary.

1.2 Problem statement

Chatter can be reduced by either knowing stable cutting parameters for processes in advance or by adjusting the parameters while the cutting is in progress. Since the environment, tools, and materials can vary, knowing stable cutting parameters can be a challenging task. Therefore, for adjusting the parameters while the cutting is in progress it is crucial to know when chatter is happening. Chatter detection is also not a trivial task since it comes with its own problems such as clear classification of chatter, selection of sensors, sending feedback to processing machine quick enough, etc.

1.3 Aim of the work

It shall be shown an efficient method of measuring vibrations in a sampling speed/frequency band where chatter can be found. Therefore, an evaluation and comparison of appropriate sensors and System on a Chips (SoCs) shall be conducted. Additionally, a prototype of a measuring system shall serve as proof of concept.

1.4 Approach

The measuring system is in-cooperated in a custom Printed Circuit Board (PCB), by using a capacitive accelerometer and a Linux SoC, connected through an Analog Digital Converter (ADC). The measured acceleration data are saved in a database and visualized via a webserver on the system.

1.5 Structure of the work

In Chapter 2, it is described why chatter occurs, how to reduce it and different detection methods are shown. In Chapter 3, different kinds of accelerometers are evaluated and compared to which fit chatter detection the best with their respective properties. Chapter 4 compares and evaluates different Linux compatible SoCs. Chapter 5 shows the selection of the accelerometer and Linux SoC for being the best fit for a small chatter detection system and how they are connected together. Chapter 6 shows the functionality of the measuring system by experimental tests. The conclusions are given in Chapter 7.

CHAPTER 2

Chatter in machining processes

Cutting and milling in machining processes may have a tendency to produce chatter, which is a self-excited vibrational phenomenon. Chatter can cause many troubles in manufacturing where milling machines are used. This includes, but is not limited to, abnormal tool wear or tool breakage, damage of both the tooling structure and the spindle bearings, poor surface roughness and poor dimensional accuracy of the workpiece [5]. Figure 2.1 shows the effects of chatter on a workpiece.

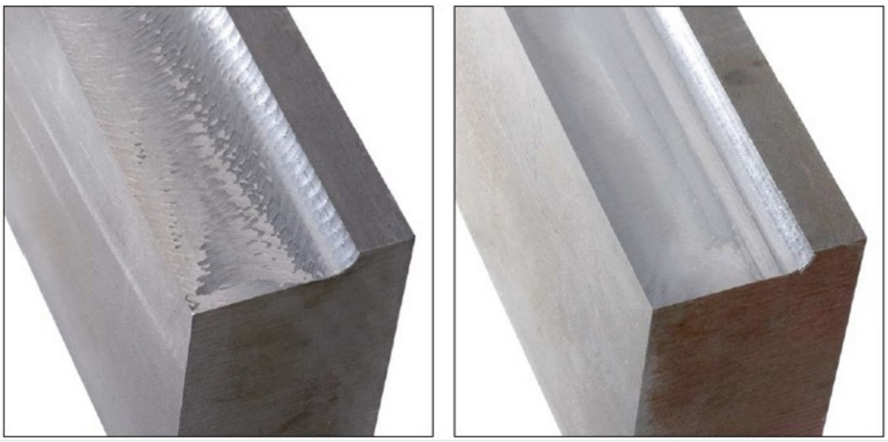


Figure 2.1: The image above, taken from [6], shows a workpiece with chatter on the left and one without on the right.

Chatter is a mostly regenerative effect, which makes it hard to find the main cause. There are various forms of chatter such as frictional chatter, thermo-mechanical chatter, mode coupling chatter and regenerative chatter, depending on the self-excitation mechanism that causes the vibration [2]. Regenerative chatter is the most common one of these. It can occur in most metal cutting operations, which involve overlapping cuts, which can be the source of vibration amplification [2]. This is because when the vibrations while milling leave a wavy surface, the next tooth that cuts into the wavy surface, will also generate a new wavy surface. This phenomenon can become dominant and build up chatter. This type of chatter was found to be characterized by large amplitude oscillations, unstable, chaotic movements of the tool and strong variances in cutting forces.

The most common causes of chatter are the following:

- too fast or too slow feed rate
- badly clamped work piece
- wrong clamping length of the tool
- malformed cutter
- too much cutting depth

In stability lobe diagrams, it can be shown, with empirically collected data, when chatter happens. These diagrams are good to find chatter-free zones, while still ensuring beneficial cutting depth and spindle speeds, for specific combinations of milling parameters. An example is shown in Figure 2.2.

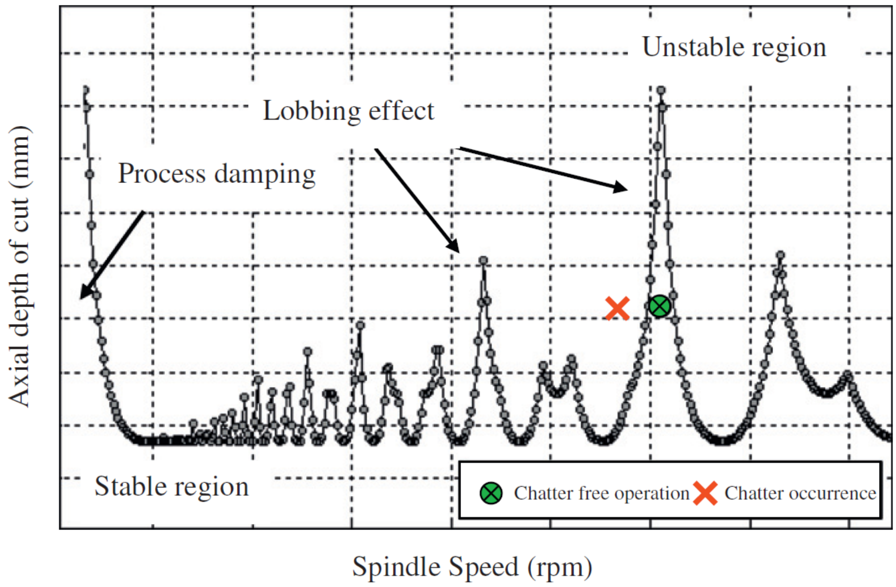


Figure 2.2: The image above, taken from [2], shows a stability lobe diagram.

2.1 Methods of chatter detection

There are several ways to identify chatter in milling processes. The most commonly used sensors are plate dynamometers, microphones, displacement and acceleration sensors [5].

The use of microphones for chatter detection has been found to give a better sensitivity than the other options. Microphones on the other hand are limited by directional considerations, low-frequency response, and environmental sensitivity, which makes environmental noise suppression mandatory. Rotating dynamometers can be difficult to apply since they reduce the stiffness of a system and limit the selection of cutting parameters. Furthermore, the frequency bandwidth only reaches up to 1 kHz. Accelerometers have a wide enough frequency bandwidth for chatter detection, although the placement of the sensors can be difficult, since it requires knowledge of the dynamic behaviour of the machine tool [5].

To give accurate results, the location of the sensor and the frequency bandwidth are important. The closer the sensor is to the source of the vibration is, the better. Also, the sensor should be able to measure frequencies down to 100 Hz and up to 5 kHz to 10 kHz [5] [7].

To properly identify vibrations as chatter, indicators in the range from zero (stable) to one (extremely unstable) are used. These indicators are either taken in the frequency domain, which are based on the energy distribution in the signal spectrum, or in the time domain, for example by using once-per-revolution sampling. As already mentioned, the indicators are always relative to the milling parameters, where the spindle speed is the most important one for the calculation [5]. There are already new methods developed which are not that inflexible, but still make use of the indicators in one form or another. A method is before calculating the indicator, that order tracking and synchronous averaging methods are applied for pre-processing the vibrational signals and the data coming from the spindle encoder [3]. Another option is by using machine learning with Topological Data Analysis to train a computer model in detecting chatter [4].

2.2 Methods of chatter reduction

In order to ensure stable cutting in machining processes, chatter can be classified into two main groups, which provide approaches for this problem. One way is by choosing cutting parameters in a way such that the operation is in a stability lobe in an appropriate stability lobe diagram, like the green marker in Figure 2.2. To distinguish further, this can either be done with an in-process or out-of-process method. In the out-of-process method the cutting parameters are selected before the milling process. Therefore, the stability frontier has to be known before the milling operation. In the in-process method, the cutting parameters are adjusted while manufacturing, when the need to migrate to a stable zone in the stability lobe diagram arises. Hereby it is necessary to identify chatter occurrences while the milling is in progress [2].

Another way is by changing the system behaviour and modifying the stability frontier to prevent chatter. This can either be achieved in a passive or active fashion. The behaviour of the system can be passively changed by modifying the machine tool, the cutting tool or the tool holder. The stability frontier can be raised by actively modulating the quantity of work provided, absorbing or supplying energy to certain elements [2]. The various strategies are summarized in Figure 2.3 for an easier overview. Often these strategies are combined to achieve better results.

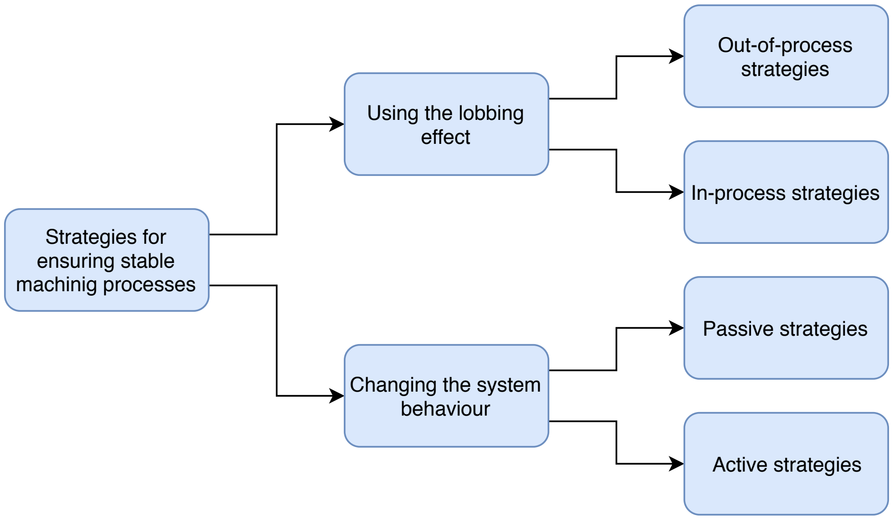


Figure 2.3: The image above, created from [2], shows a classification of chatter prevention methods.

CHAPTER 3

Accelerometer

An accelerometer is a device that measures the acceleration of the device itself. This can be done in a single, two or in three axis. Accelerometers can be often seen as mass-spring-damper systems as when the force is applied to the mass, the displacement over the time from the initial position is measured and therefore giving the acceleration [8].

Accelerometer are divided into two categories: 1. AC-Response accelerometers 2. DC-Response accelerometers. AC accelerometers can only measure dynamic changes. DC accelerometers can measure dynamic and static acceleration, such as gravity [9]. As stated in [9], a problem of AC accelerometers is that they have deviations at slow moving accelerations (<2 Hz) because of the intrinsic limitation imposed by their RC time constant. Because most often velocity and displacement are needed for calculations and can be derived from the acceleration by integration or double integration, the previous mentioned deviations can get larger over time. A DC coupled accelerometer does not have this issue. AC accelerometer can still be relevant because of their wide frequency response range and high signal-to-noise ratio, which makes them good for vibration measurements [10].

With the use of an 3 axis accelerometer, it is possible to determine the orientation of a device by using the static acceleration of 1 g caused by earth's gravity. On the other hand, dynamic acceleration can be useful for detecting the way a device is moving [11].

3.1 Important characteristics of accelerometers

There are a number of different types of accelerometers. They differ by the following properties:

- Interface: The interface of accelerometers can be either analog or digital. Analog accelerometers output a continuous voltage signal which is proportional to the measured acceleration. Digital accelerometers output a square wave in a Pulse Width Modulation (PWM) form at certain frequency, where the time of the high-level determines the acceleration[11]. In addition, digital output accelerometers must have a resolution due to quantization. This does not have to affect the overall result when considering noise, as shown in an example in [10].

- Response type: As stated in the previous section, accelerometers can either have a AC- or a DC-Response. AC-Response types can not give a statement about static acceleration (0 Hz).

- Frequency Response or Bandwidth: The bandwidth, or frequency response, of an accelerometer specifies the frequency range in which an accelerometer can measure [10]. This tells the user how low or high the frequency of a moving object can be, to still give accurate results. It should be noted that all accelerometers have a resonance frequency determined by the natural resonance of the mechanical structure of the accelerometer. The resonance frequency can be roughly seen as upper limit of the frequency response. An output of the sensor near the resonance frequency will be highly amplified, resulting in unusable data. Therefore, the user has to make sure not use an accelerometer near its resonance frequency. Piezoelectric accelerometers cover the largest frequency response which is about 1 Hz - 20 kHz.

- Measurement range: The measure range restricts an accelerometer how much force can be measured. The measure range is typically given in the unit g. Accelerometer often have symmetrical measurement ranges and only a small portion of sensors have a further restricted lower bound [8]. As shown in Figure 3.1, the measurement range is not entirely dependent on the sensor type, but also on how it is manufactured. Piezoelectric accelerometers have the highest measure range with more than 10^4 g in both directions.

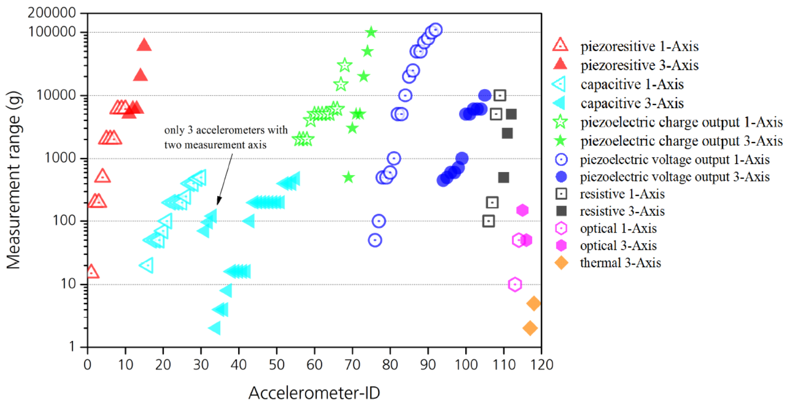


Figure 3.1: The image above, taken from [8], shows the upper measurement range of different accelerometers

- Shock limit: The shock limit defines how much acceleration the device can take before it is damaged. The shock limit is especially important in application such as drop-testing, automotive crash-testing, and pyroshock simulation [12]. Most accelerometers have a shock limit in the range of 10^4 g [8].

- Power consumption: The power consumption defines how much electrical energy has to be supplied to operate. Accelerometers commonly have an upper power consumption limit of about 1 watt. Capacitive accelerometers and piezoelectric accelerometers with voltage output have the lowest power consumption in general. Also, the measure range does not effect the power consumption of the sensor [8].

- Sensitivity: Another criterion of accelerometers is sensitivity which specifies the rate in which the mechanical energy is converted to an electrical signal. The higher this number is, the better is the signal-to-noise ratio. The sensitivity is often given as millivolts per g or picocoulombs per g and is usually about 1 - 100 mV/g for accelerometers. For small vibrations, a higher sensitivity may be necessary to provide a higher signal-to-noise ratio [10].

- Temperature sensitivity: Some accelerometers types are more temperature sensitive than others. A drift in temperature may alter the sensitivity of the sensor and need some sort of temperature compensation to ensure valid measurement results [10].

- Sampling rate: If the sampling rate is too low, aliasing can happen. This can be corrected by either increasing the sampling rate or filtering with a low pass filter [10].

- Cost: The manufacturing costs of different types of accelerometers vary a lot. For example, capacitive accelerometers are in general cheaper than piezoelectric accelerometers. Additionally, for sensors with analogue output, an ADC could be needed if the values should be stored on a digital system.

3.2 Types of accelerometers

The characteristics of accelerometers are mostly defined by the sensors type. Therefore, an overview of the most common types of accelerometers is given in the following.

3.2.1 Piezoelectric accelerometers

Piezoelectric accelerometers consist of a mass in conjugation with a piezoelectric material like a natural quartz. When the sensor accelerates, mass is dislocated and puts stress on the connected piezoelectric crystal. This causes the piezoelectric effect, which creates a charge in the crystal. The amplitude of the charge can be used as a reference of the acceleration. Since the accelerometer does not give a steady voltage but pulses, the piezoelectric accelerometer is considered in charge mode. To actually convert the charges in acceleration, it is still required to convert them in a voltage signal first. The principle of operation is shown in Figure 3.2 [8].

By adding a charge amplifier to the device and then converting the charge to a voltage signal, the piezoelectric accelerometer is then in voltage mode. In voltage mode, these sensors can eiter be connected in a 3-wire way (Signal, Ground, Power) or in a 2-wire way (Signal/Power, Ground), which is also called Integral Electronics PiezoElectric (IEPE). IEPE accelerometers can also be called ICP, CCLD, Isotron, Deltatron, Piezotron and others [13]. The drawback of the integrated electrical amplifier is that accelerometers in voltage mode have a maximum temperature resistance of 175 °C, while charge mode accelerometers can be used at 640 °C and beyond [9]. To counter any DC signal, a capacitor is used to block it [9]. Piezoelectric accelerometers are AC-Response devices. Piezoelectric accelerometers are often used for vehicle crash testing and high-frequency vibration measurements such as gear noise analysis or turbine monitoring because of their high measurement range and frequency response.

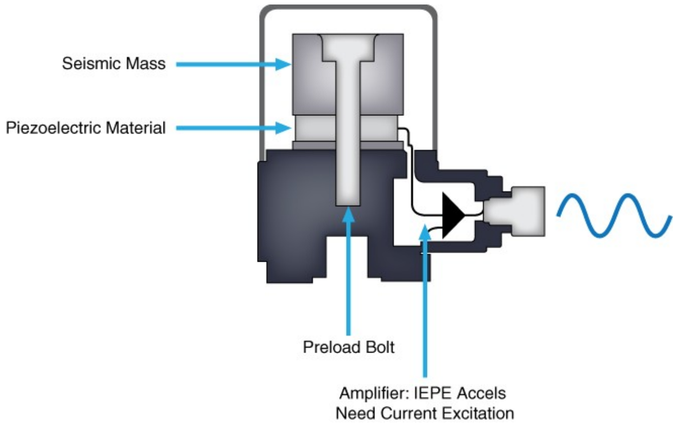


Figure 3.2: The image above, taken from [14], shows the operation principle of a IEPE accelerometer

3.2.2 Piezoresistive accelerometers

By applying acceleration to a piezoresistive accelerometer, a mass is straining a suspension beam. This can then be measured by a piezoresistive element, which is most commonly made of semiconductor materials, at the end of the beam [15]. The piezoresistive material changes its electrical resistance according to the applied pressure on the beam [16]. The principle of operation is shown in Figure 3.3. Piezoresistive accelerometers change the electrical resistance according to the currently applied pressure on them, which makes them DC-Response devices. The design of piezoresistive accelerometers makes them highly durable, which is why they are widely used in automobile safety testing including impact-testing, safety air-bags as well as in general high-g applications and seismic measurements [15]. It should be noted, that piezoresistive accelerometers could theoretically compete with piezoelectric accelerometers in terms of high-frequency vibration measurement, but have often a bad sensitivity, which is why they are rarely used in this sector.

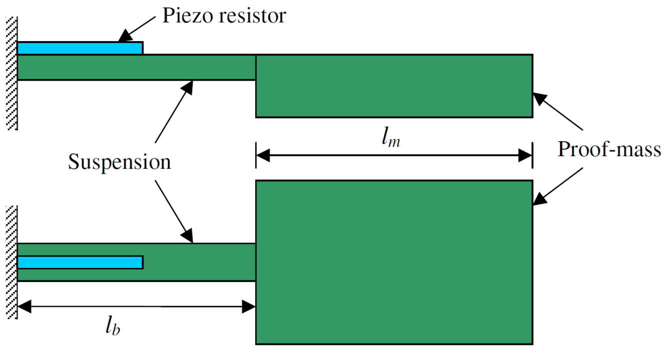


Figure 3.3: The image above, taken from [15], shows the operation principle of a piezoresistive accelerometer

3.2.3 Capacitive accelerometers

Capacitive accelerometers measure the capacity changes between two plates. While one plate is fixed, the other one is mounted on a mass with a suspension which can be displaced through acceleration. The capacity change is then either invoked by a change in the gap of the plates or the overlapping surface of the plates [15]. This makes them vulnerable to a surrounding electrical field, which can falsify the measurement of the sensor [15]. The principle of operation is shown in Figure 3.4. Capacitive accelerometers are DC-Response devices [8], since static acceleration causes a static change in capacity. The bandwidth of capacitive accelerometers is often limited. It should be noted that parasitic capacitance and electromagnetic interference can alter the result of the sensor. These types of accelerometer have a low price to manufacture, because they mainly consist of electrical components [9] [10]. This makes them good for applications like orientation determination and suspension testing in cars. They are also used for internal navigation and micro-gravity detection.

3.2.4 Optical accelerometers

Optical accelerometers typically consist of a cantilever attached to a Fiber Bragg Grating (FBG). A FBG is a reflector, which only reflects a certain range of wavelengths. When acceleration is applied to the cantilever, the strain is then transferred to the FBG. The strain then causes a wavelength shift in the FBG, which is a direct relation to the acceleration. For maximum sensitivity, the cantilever is attached to the tip of the FBG [17]. The principle of operation is shown in Figure 3.5. Similar approaches exist with measuring the intensity of a LED on a moving membrane, polarisation or diffraction [15], but measuring the wavelength seems to be the most common approach. Optical accelerometers are DC-Response devices [8]. Optical sensors are, like capacitive

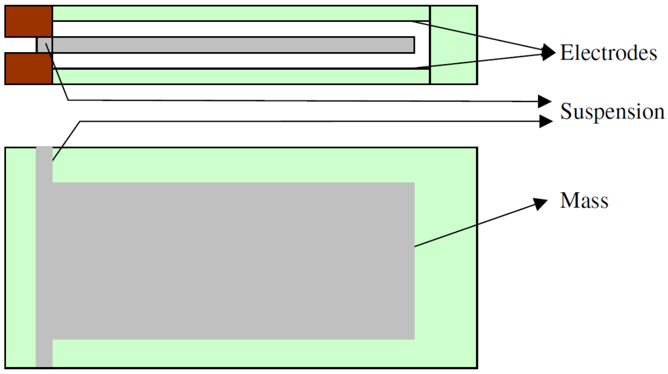


Figure 3.4: The image above, taken from [15], shows the operation principle of a capacitive accelerometer

sensors, used for internal navigation and detecting small vibrations, but can operate in places with electromagnetic fields and other hostile environments without being affected [15].

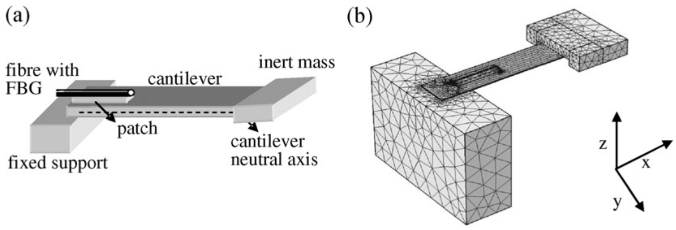
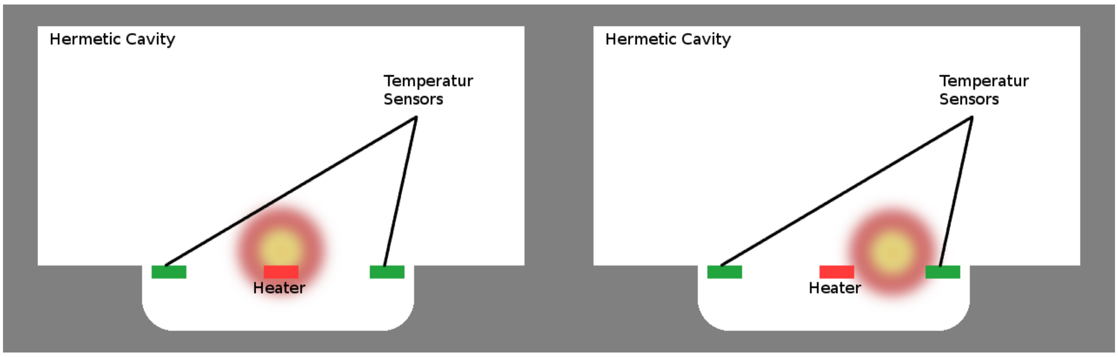


Figure 3.5: The image above, taken from [17], shows the operation principle of a optical FBG accelerometer

3.2.5 Thermal accelerometers

Thermal accelerometers have no moving parts. Instead they consist of a resistive heating element which is enclosed in a gas. The temperature can then be measured with temperature sensors, e.g. thermocouples, on each side of the gas. When acceleration is applied to the sensor, the less dense air molecules of the gas move in the direction of the acceleration. As a result, the denser and cooler molecules move in the opposite direction. This creates a temperature difference which can be measured and is direct proportional to the applied acceleration. The principle of operation is shown in Figure 3.6. [18]

Since, as already mentioned, thermal accelerometers have no moving parts, they have a high overload shock resistance [8]. Also thermal accelerometers seem to be cheaper than capacitive ones [18]. Although the frequency response is the lowest of all accelerometer types, with extension circuits frequency's above 100Hz can be reached [8] [18]. Thermal accelerometers are DC-Response devices [8]. They are used for inclination sensing, low-g



(a) No applied acceleration (b) With applied acceleration

Figure 3.6: The images above, created from [18], shows the operation principle of a thermal accelerometer with and without applied acceleration

and low-frequency vibration measurement and motion measurement [12]. Because of this they often find use in the automotive and gaming sector [18].

3.3 Comparison of accelerometer types

Different types of applications require different types of accelerometers. Therefore, the characteristics of the accelerometer types are summarized in Table 3.1. Additionally, in Table 3.2 a few common use cases are given in respect to which accelerometer could be suitable for them.

	Piezoelectric	Piezoresisitive	Capacitive	Optical	Thermal
Response Type	AC	DC	DC	DC	DC
Frequency Response	1-20kHz	5kHz	1kHz	1,2kHz	100Hz
Measurement Range	$>10^4$g	$>10^4$g	500g	100g	10g
Shock limit	$\leq 2 \text{x} 10^5$g	$\leq 10^5$g	$\leq 10^4$g	$\leq$ 1100g	~5x10^4g
Power consumption	10^{-4}W - 1W	0.1W - 1W	10^{-4}W - 1W	/	10^{-2}W
Sensitivity	high	low	high	high	very high
Temperature sensitivity	large	large	moderate	small	moderate
Cost	high	moderate	low	high	very low

Table 3.1: Comparison of accelerometer types

	Piezoelectric	Piezoresisitve	Capacitive	Optical	Thermal
Static Acceleration		✓	✓	✓	✓
Extreme Shock	✓	✓			
Low Frequency Vibration (<5Hz, <25g)		✓	✓	✓	✓
General Vibration (5-500Hz, <25g)	✓		✓	✓	✓
High Frequency Vibration (>500Hz, <25g)	✓				
Micro-G Vibration	✓		✓		

Table 3.2: Common use cases of accelerometer per type

CHAPTER 4

Linux System on a Chip

A SoC is a microchip which includes all necessary circuitry for a required computing system on a single chip. These systems contain the same major components as a regular computer but are much smaller. This often includes a CPU, a memory, a secondary-memory and General Purpose Input/Output (GPIO)'s. SoC devices are often used as embedded systems and in the Internet of Things (IoT). Typically, SoCs are applied in automotive, communication and multimedia [19]. They are generally very cost efficient and have a low power consumption.

Like normal microcontrollers, which are also commonly integrated in SoCs, a SoC does not necessary need an Operating System (OS) to be used, but can be programmed directly. This can have a direct impact on the SoCs performance, since it will only run tailored code for a specific application. However, an OS in a SoC provides abstractions, hardware initialisations, housekeeping, task management, resource management, interprocess communication and concurrency control. Using an OS reduces time spent, developing code for a given SoC, while also making applications easier and less error prone. Another option to program a SoC is using a microkernel. This sacrifices a bit of abstraction from the OS to have more control over the system. A microkernel also allows for a more direct access to the SoCs components, which may result in better performance in a given application.

For an OS to be useful in an SoC, the OS has to fulfil the following requirements [19]:

- The OS has to be modular like the modular nature of the SoC. It also must be possible to adapt the OS when the SoC is changed, without redefining the application layer.
- The abstraction, brought from the OS, must not be too great to prevent application specific functionality. This might negate the benefits of why the SoC was used in the first place.

- The OS has to provide protection and concurrency control, to ensure that interrupt handlers, drivers, application code, etc. do not interfere with each other.
- The OS and application code should be portable to other platforms.

An OS can be either a traditional embedded OS or Real-Time Operating System (RTOS). RTOS are designed for embedded systems. These are often lightweight, scalable and provide support for real-time applications [19].

4.1 Structure of a Linux SoC

A SoC has a modular design and often consist of typical computer components. These components can include, but are not limited to:

- Processor cores, which a SoC must have at least one. Today, such chips often include multicore processors.
- Memories, which include registers, caches, RAM and data storage.
- Interfaces, which are used to communicate with peripherals or other systems, like GPIOs, USB, RS232, Ethernet, etc.
- On-Chip-communication, which connects the modules on the chip together and is typically provided by a network or bus system.

SoC designs often integrate multiple semiconductor Intellectual Property COREs (IP cores), which are reusable units of logic, such as USB. These components on a SoC can be designed with a high-level programming language, which can then be converted in a Hardware Description Language (HDL). Some components can remain exclusively software, which can be embedded in soft-core processors on the SoC as IP core. To verify a design before putting the real product together, a Field-Programmable Gate Array (FPGA) can be used. An FPGA is reprogrammable and can be used to save time and money while prototyping.

4.2 Comparison of Linux SoCs

By the limitation imposed by the problem statement (cf. Section 5.1), that the embedded system may only have a maximum height of 1 cm, only boards which can actually satisfy this restriction are taken into account. As an exception, boards where the RJ-45 connector can be de-soldered to fit the restriction, are also considered. Also each board has to be able to run a Linux system as OS. The technical information of the different SoCs is shown in the comparison Table 4.1 [20].

	Raspberry Zero W	BeagleBone Black Wireless	Cloudbit	Odroid-C0	pc-Duino8
Price($)	10-29	69	60	30	49
Processor	Broadcom BCM2835	TI Sitara AM3358	Freescale i.MX233	Amlogic S805	Allwinner H8
Cores	1x A8 @ 1GHz	1x A8 @ 1GHz	1x ARM9 @ 454MHz	4x A5 @ 1.5GHz	8x A7 @ 2GHz
MCU	no	PRU	no	no	no
RAM	512MB	512MB	64MB	1GB	1GB
Dimensions(mm)	65 x 30 x 5	86.36 x 53.34 x 4.76	15 x 10 x 5	58 x 56 x 11	96 x 56 x 20
Power consumption when idle	120mA	300mA	280mA	500mA	<2000mA
On-board ADC	no	yes	no	yes	no

Table 4.1: SoC comparison

CHAPTER 5

Methodology

The aim was to measure vibrations in a milling machine and detect when chatter occurs. In future work, this shall happen in real-time which allows for in-process chatter reduction.

To measure chatter, a prototype of a measuring system was built. This prototype is supposed to be installed in a pallet which can be mounted on a machine table in a milling machine by using a zero-point clamping system. The vibration is measured with an accelerometer and afterwards evaluated in a Linux SoC. To ensure fast enough speeds, the C++ language was used to create a program, which takes the samples, creates Fast Fourier Transform (FFT) analysis and stores the data in a database. For an easy and fast way to display the gathered data, a webserver is used to show plots on an remote host. For an easier understanding this is also shown in Figure 5.1.

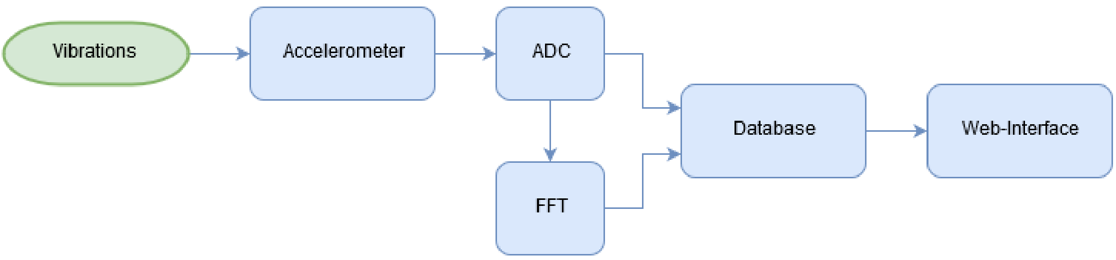


Figure 5.1: The image above shows the data processing chain.

5.1 Requirments/Limitations

Since the measuring system shall be in-cased in a pallet inside a milling machine, several requirements have to be fulfilled. This means the measuring system is only allowed to have the height of 1 cm. Also the length and width have to fit inside the pallet, which is about 15x15 cm^2. As stated in Section 2.1, the sensor has to be able to measure signals with at least 5 kHz. This corresponds to a sampling rate of more than 10.000 samples per second, by applying the Shannon theorem. Also the components of the system should have a low power consumption, since the system has to be powered by a battery pack, which shall also be in-cased in the pallet, and still be able to operate for at least 8 hours. Furthermore, with regard to using a Time-Sensitive Network, ath9k_htc has to be supported on the system. By using a Linux distribution on the system, an already developed driver can be used.

5.2 Accelerometer selection

Chatter is a regenerative effect causing an infinite phase space [21]. This makes it hard to find a sensor with appropriate frequency response, since real sensors always have an upper limit.

In [15], it is shown that a measurement range up to 10^3 g and a frequency response up to 5 kHz is needed for machine vibration measurement. These bounds will be used to select an accelerometer. By the sampling theorem of Shannon, to be able to reconstruct a signal perfectly, the sampling frequency has to be at least the highest doubled frequency measured. Therefore, the selected sensor should at least have a frequency response of 10 kHz. While this upper bound of 10 kHz would normally only leave piezoelectric accelerometers, there are special capacitive accelerometers from Analog Devices which have a frequency response up to 21 kHz.

A high sensitivity is necessary for vibration measurement to provide a higher signal-to-noise ratio. Since piezoresisitve accelerometer have less than 1 mV/g, they are not an optimal choice [10].

The temperature sensitivity is ignored in this comparison, because the insides of a milling machine is not a hostile environment in terms of temperature. Furthermore, the sensor should be enclosed in a palette, which also protects it for temperature variations.

As of the requirement of having less than 1 cm height in the pallet of the milling machine in which the sensor is going to be mounted, an optical sensor can not be used [8].

Overload shock is not an issue for selecting an accelerometer in the application. As stated in [8], most accelerometers have an overload shock limit of 10^4 g. The table of a milling machine should not accelerate above this bound in normal operation.

The only downsides of using a triaxial accelerometer is that the frequency response and measuring range are lower in comparison to a uniaxial one [8]. Nevertheless, there also is not a real gain by using a triaxial instead of a uniaxial one, since vibrations spread in all three axes. If a triaxial accelerometer should be needed for any given case, it is also possible to just use three uniaxial accelerometers and mount them in the right directions.

Since the accelerometer is supposed to be mounted in a pallet, the sensor should not consume too much power. While the upper bound of all accelerometers is already only

1W, capacitive and piezoelectric accelerometers with voltage output show the lowest power consumption [8].

Considering the above statements it becomes clear, that a piezoelectric and capacitive accelerometers are the best choice for vibration measurement in milling processes, by giving enough measure and frequency range while still being comparably small and having low power consumption. In this case the capacitive accelerometer, the ADXL1002 from Analog Devices, is chosen because of being cheaper than piezoelectric accelerometers.

5.3 Linux SoC selection

In addition to the technical details to compare the boards, the quality, versatility, the ease of use, maturity and completeness of the available OS must also taken into account. This makes it impossible to designate an overall best SoC. However, in respect to the problem statement, a comparison is possible. The following points are the most curial parameters to compare from:

- Power Consumption: All before-mentioned SoCs have a low power consumption. There are only small differences between the boards. Furthermore, the values are often not well documented and inaccurate.
- ADC: While the BeagleBone Black Wireless has an onboard microcontroller with an ADC, it also has a RJ-45 female connector, which has to be de-soldered to fit the 1 cm restriction. Also a missing ADC is not that big of a problem, since an external ADC can be connected to a SoC via Serial Peripheral Interface (SPI) or Inter Integrated Circuit (I2C).
- Size: To fit the SoC in the palette of the milling machine, a smaller size is preferable. Therefore, the pcDuino8 and Odroid-C0 are not well suited.
- Ease of Use: A dedicated OS and its widespread use make the Rasperry Pi the best choice in terms of usability.

For this prototype, the Raspberry Pi Zero W is chosen. Since this SoC has no onboard ADC, an external ADC is used. For this prototype, the AD4000 from Analog Devices is used.

5.4 Assembly

The measuring system to detect the chatter and fulfil the requirements of Section 5.1 was soldered onto a single custom PCB[1], as shown in Figure 5.2. As stated in previous sections a Raspberry Pi Zero W is used in addition to an ADXL1002 accelerometer. For

[1] `git.auto.tuwien.ac.at/thesis/sensorische-spannpalette`

easier manufacturing instead of directly soldering the accelerometer onto the PCB, an evaluation board, which already had the accelerometer pre-soldered is mounted onto the custom PCB. This evaluation board already comes with a second-order RC low-pass filter with a cutoff frequency at 10 kHz. Since the accelerometer only has an analog output, an external ADC, an AD4000, is used to digitize the signal. A 4-wire SPI is used by the Raspberry Pi Zero W to read from the ADC. In Figure 5.3, the connection between each component is shown.

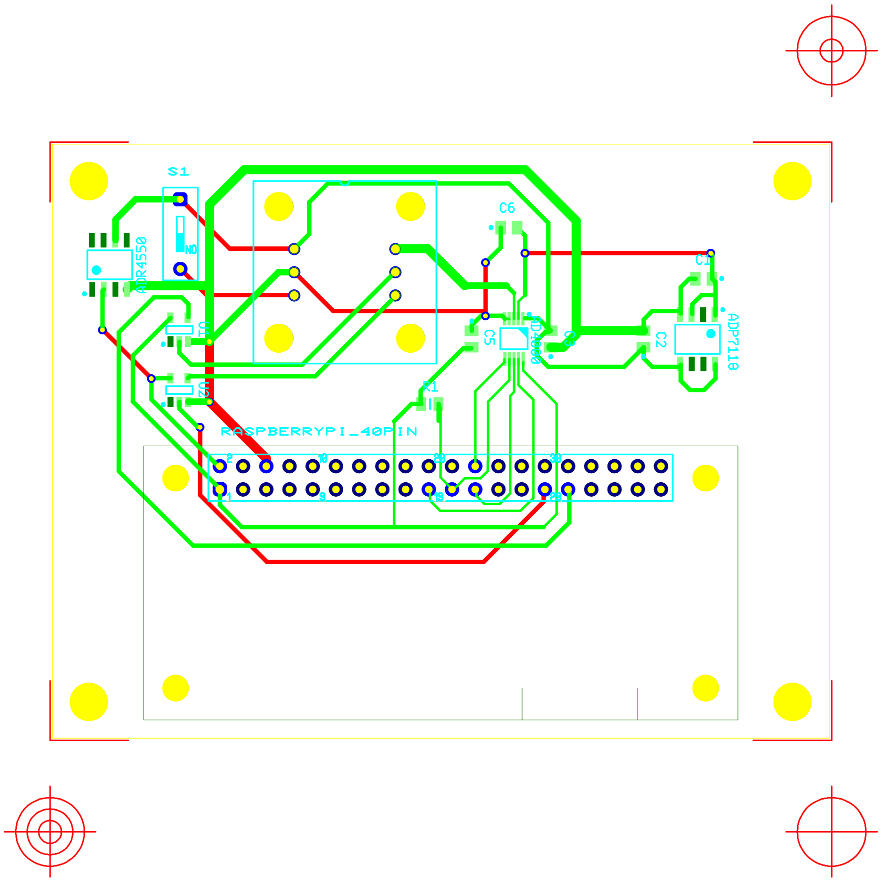


Figure 5.2: The image above shows PCB design of the circuit.

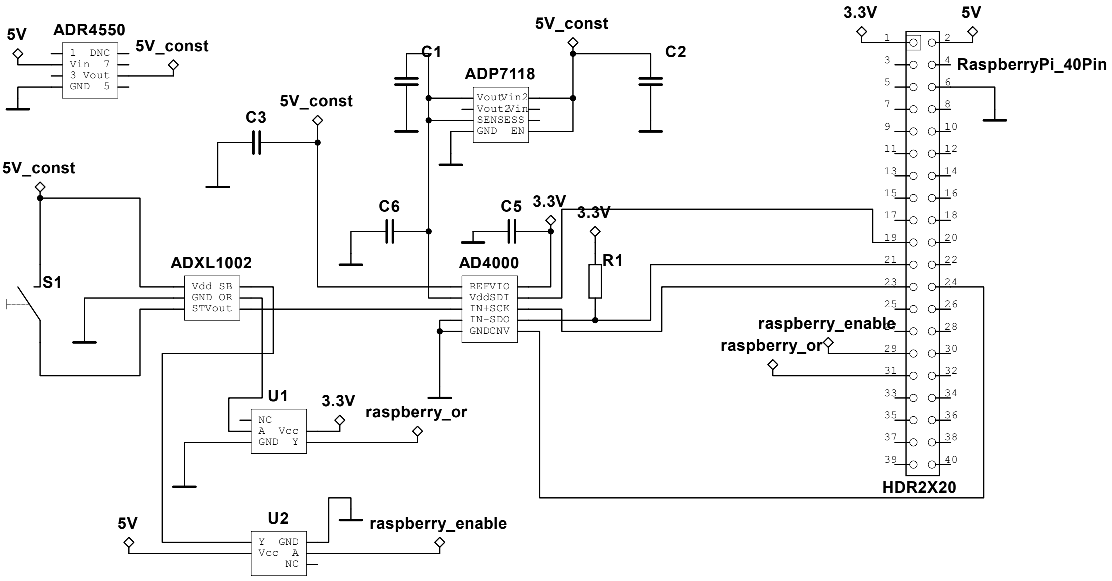


Figure 5.3: The image above shows the schematic design of the circuit.

CHAPTER 6

Evaluation

The program which is responsible for collecting the data[1] is written in C++. The data is sampled with a constant sample time of 100 μs, to achieve a resolution of 10 kHz. With this adjustment, it is possible to reconstruct signals with a frequency smaller than 5 kHz, as by the Shannon theorem. It is preferable that the sample number is a power of two, because this enables for a faster FFT analysis. The time and frequency data are stored in an InfluxDB database. The collected data is plotted via a webserver on the Raspberry Pi Zero W with a JavaScript framework.

The idle power consumption of the PCB is dominated by the Raspberry Pi Zero W and measured at around 120 mA. While the measurement is in progress, the PCB draws 180 mA. At 5 V voltage the power comes to 0.6 W while idle and 0.9W while measuring.

For the tests of the measuring system in the time and frequency domain, the PCB is mounted onto a speaker with beeswax, as shown in Figure 6.1. The vibrations are conveyed to the case of the speaker on which the system is mounted.

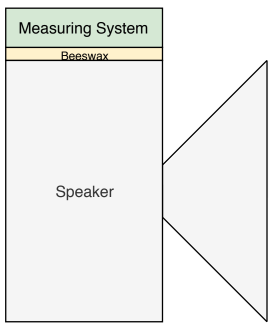


Figure 6.1: The image above shows schematic setup for the tests.

[1] git.auto.tuwien.ac.at/thesis/sensorische-spannpalette

6.1 Test for time domain

A quick and easy way to check a DC coupled accelerometer for functionality is by not moving the sensor and taking samples. If the accelerometer is held in or against the direction of the earth gravity it should display plus or minus 1 g respectively. To test the functionality in the time domain further, the speaker, on which the measuring system is mounted, is playing metronome sounds. This should and does result in distinctive g spikes in the time domain as shown in Figure 6.2.

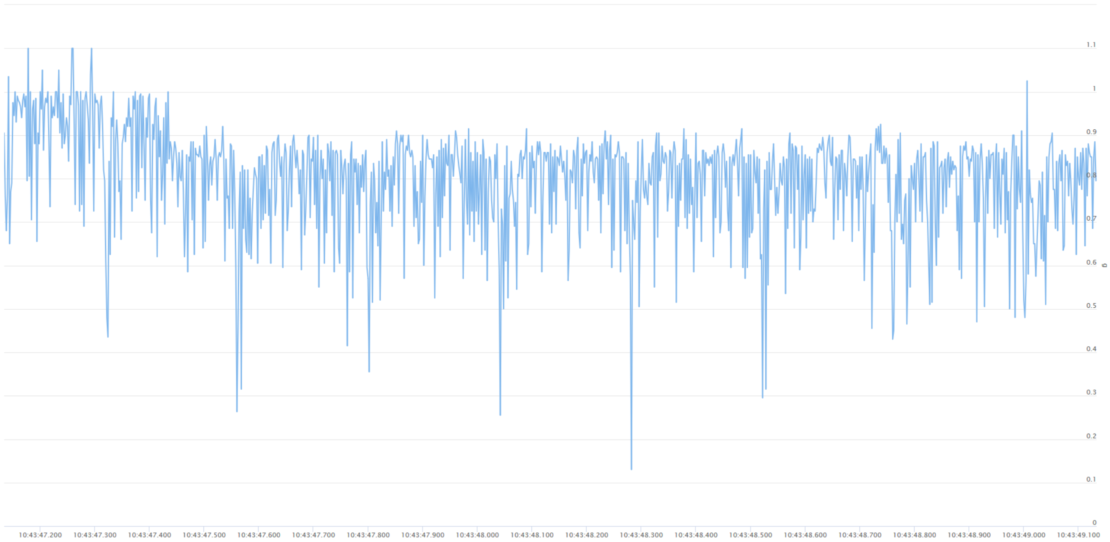


Figure 6.2: The image above shows the acceleration in the time domain under 250 bpm.

6.2 Test for frequency domain

To test the measuring system in the frequency domain, the speaker should then play a sine signal at a certain frequency (in this case at 200 Hz and 3 kHz). If the system works correctly a spike at the given frequency should be seen in the frequency spectrum. This is shown for 200 Hz in Figure 6.3 and for 3 kHz in Figure 6.4. For a better visualisation, the steady component is set to zero. It should be noted that in the 3 kHz test, in Figure 6.4, there is a spike at the desired 3 kHz as well as a smaller spike at 2 kHz. It is suspected that this is due to the speaker vibrating to a harmonic of the 3 kHz. The smaller bars in both figures are generated from noise of the sensor and small vibrations which do not come from the generated sine tone. For a resolution of the FFT down to as low as approximately one Hertz, 8192 samples at a 100 μs sample time are taken. This calculates as the following:

$$\frac{0.0001^{-1}s}{8192} = 1.220703125Hz$$

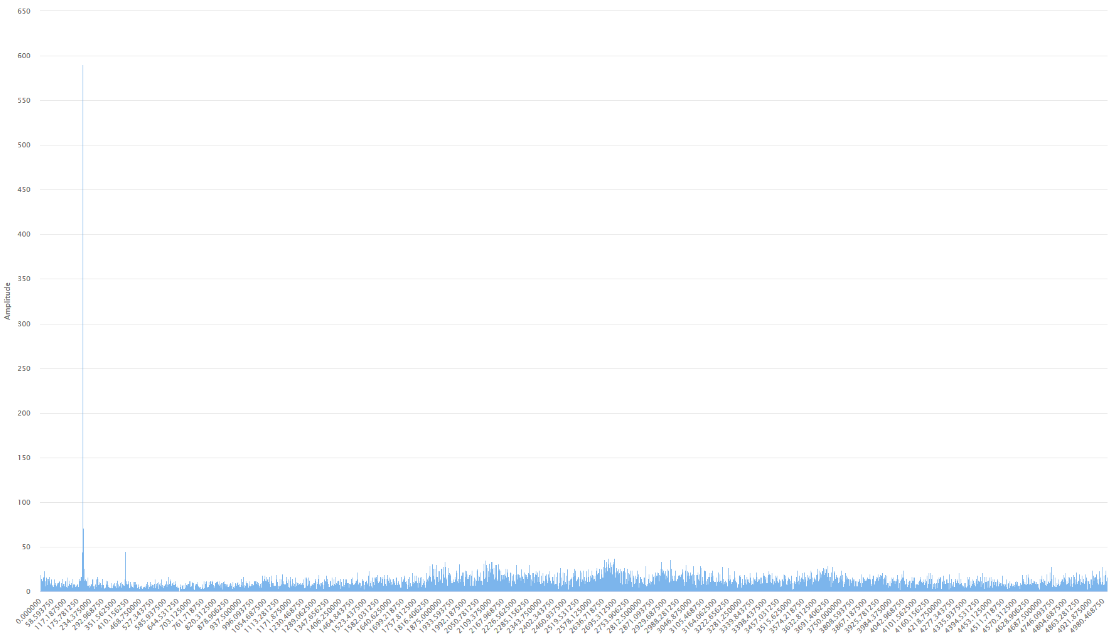


Figure 6.3: The image above shows the frequency spectrum while playing a sine at 200 Hz.

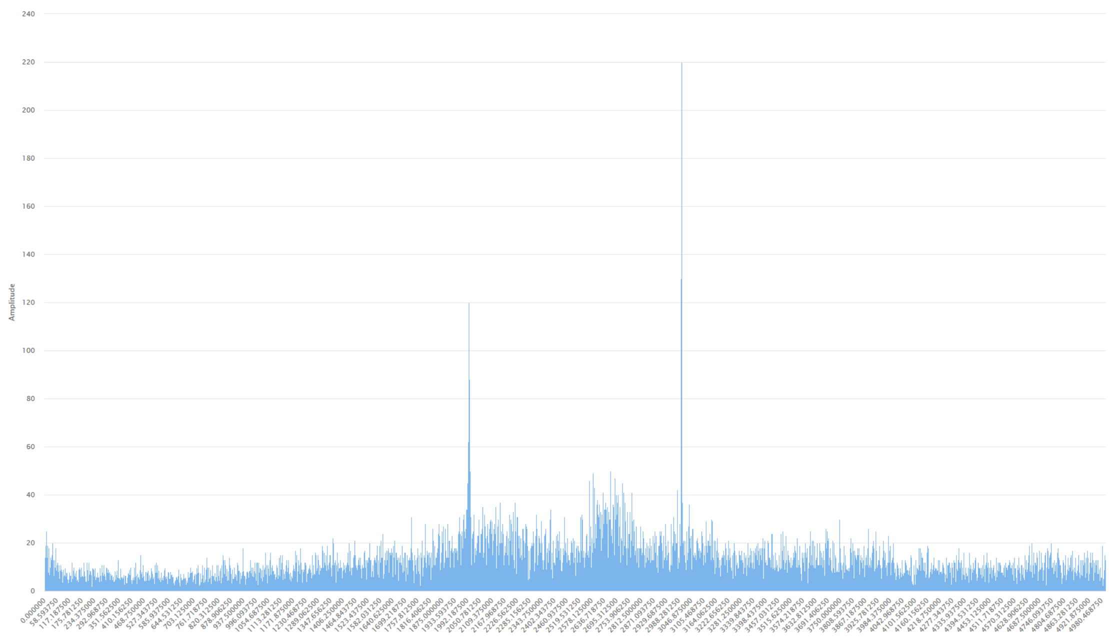


Figure 6.4: The image above shows the frequency spectrum while playing a sine at 3 kHz.

CHAPTER 7

Conclusion and future work

It was demonstrated that a small chatter detection system can be built, while satisfying the requirements mentioned in Section 5.1. The system was tested to work in time and frequency domain. It was also shown that a capacitive accelerometers with a high frequency response are currently the cheapest while still being able to detect chatter in milling processes. Furthermore, by using a SoC, the power consumption and height requirement becomes less of an issue, while still maintaining high customizability to fit different applications. Still choosing among different SoCs may come down to personal preference and which fits the application in mind the most, since there is no best SoC.

Although the measuring system was tested for functionality, it is left to see how well chatter can be detected by installing the system into a milling machine. Furthermore, a concept for the power supply has to be considered to supply the measuring system and an ath9k-WLAN stick for Time-Sensitive Networking. Runtime tests shall then be carried out, to see if the requirement for an uptime of at least 8 hours is met.

By the introduction of capacitive accelerometers with a high frequency bandwidth, which are more cost efficient than piezoelectric accelerometers, it seems probable that these sensors will have an upward trend of usage in productive environments. By connecting a chatter detection system to a Time-Sensitive Network, which can give fast and reliable feedback to a milling machine, in-process chatter reduction may find appliance in manufacturing.

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Acronyms

ADC Analog Digital Converter. 2, 9, 17, 21, 22

FBG Fiber Bragg Grating. 11, 12, 31

FFT Fast Fourier Transform. 19, 25, 26

FPGA Field-Programmable Gate Array. 16

GPIO General Purpose Input/Output. 15, 16

HDL Hardware Description Language. 16

I2C Inter Integrated Circuit. 21

IEPE Integral Electronics PiezoElectric. 10, 31

IoT Internet of Things. 15

IP core semiconductor Intellectual Property CORE. 16

OS Operating System. 15, 16, 21

PCB Printed Circuit Board. 2, 21, 22, 25, 31

PWM Pulse Width Modulation. 8

RTOS Real-Time Operating System. 16

SoC System on a Chip. 2, 15, 16, 19, 21, 29

SPI Serial Peripheral Interface. 21, 22

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