Acoustic Emission in Alarm Applications

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Abstract

This thesis, issued by Securitas Direct, investigates the possibility of using acoustic emission as a basis for an intrusion alarm application. Piezoelectric elements were used to detect and characterise fractures in glass, metal and wooden materials. As a comparative study, the functionality and possibilities of using an existing glass break detector, GlassAlert$^{\mathrm{TM}}$, on wooden materials were investigated. The work was performed on selected specimens of wood and glass in a laboratory environment. The results conclude that, possibly with some software modifications, GlassAlert$^{\mathrm{TM}}$could be used as a reliable glass break detector but even with hardware changes it could prove difficult detecting fractures in wood. It is on the other hand most possible to use the piezoelectric element on different materials by implementing different software in the detector structure. However, the work with piezoelectric element should be further examined before concluding that it can really be a product suited for the market.

Preface

A traditional intrusion alarm system usually involves magnetic contact and triggers an alarm when a door or window frame is opened, severing the magnetic connection. This method often gives an intruder much time before security arrives.

Recently, specific transducers to detect glass break has gained some popularity, but by using the principle of a microphone and analysing sound in its environment, they are associated with problems concerning falsely triggered alarms. As a result, Securitas Direct, Europe's leading supplier of security systems for businesses and home owners [1], wishes to examine a different approach involving acoustic emission.

During crack formation in materials, energy is released in the form of a mechanical wave. By detecting and analysing these signals it is desired to be able to trigger an alarm at the first sign of breakage.

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Chapter 1

Introduction

This report is a result of the master thesis issued by Securitas Direct Sverige AB and performed during the summer and autumn of 2011. The report should make a good start for future work on this subject, and may hopefully act as the base for a later actual product.

The original aim of this thesis was to determine if an existing sensor designed for glass break detection could be mounted on door or window frames and used to detect fractures in wood and/or metal. However, this proved difficult due to the low output of the sensing element and high dampening effect of wooden materials compared to glass. Thus, the piezoelectric elements were added as a complementary study, and the focus of the thesis was somewhat changed.

The existing sensor in mind was the GlassAlert^{TM}from a company called Covial Device, and was developed during a couple of years until certification by SP Technical Research Institute of Sweden in 2007 [2]. This sensor uses a different construction than similar products on the market, and claims it have some benefits over the existing techniques. However it uses the same phenomenon as several other techniques, namely Acoustic Emission (AE). AE is the emergence of mechanical elastic waves due to fast, high energy deformation in a material, e.g. micro cracks tied up with fractures. AE is also used in this thesis, where a wood and glass fracture detector was created using a piezoelectric ceramic element.

There are quite a few studies that have already been done in the domain of acoustic emission. However, most of these do not have the pretension to be able to distinguish acoustic emission from acoustic noise in such an extent as in this application. For example, it is highly unwanted to trigger an alarm on non destructive signals while the alarm is turned on, e.g. if there would be someone knocking on the door, small objects that by mistake hits the door, keys jingling by the lock and similar. Therefore this application is a more complex issue, and the standard ways of measuring AE could not always be applied.

However, if the interested reader would like to dig deeper on AE applications some work that has a connection to this field is presented. Starting out with quite large scale applications in bridges, most studies consider only the number of AE events, e.g. [3], [4]. There are also some studies done in small scale monitoring systems, e.g. in the application of termite infestation detection, where a different approach is used and a ratio for the response between two frequency intervals is calculated [5].

The work started out with the use of a piezoelectric ceramic as a sensor element, and the secondary goal, to construct an algorithm for determination and separation of fracture signals got more prioritised. The sensor from Covial Device was examined later in the project.

The report consists of several parts, where the first chapter after this introduction is a gathering of the theory behind the work, and is supposed to give the reader an introduction to the subjects discussed in the thesis, and how the method works in real applications. The following chapter discusses the methods used in this thesis and also what is measured and the equipment used. It also describes the algorithms used to determine whether to classify a signal as an alarm signal or not. After these describing chapters, the report will focus on the results, the acquired signals and how they are processed and why. The discussion chapter will cover problems during this thesis and compare the GlassAlert$^{\text{TM}}$with use of a piezoelectric sensing element. The last chapter will conclude the thesis work, and also address things that could be done in future work and if something could be done differently.

Chapter 2

Theory

2.1 Acoustics

2.1.1 Mechanical Waves

When a force is applied to a material the atoms can be forced to vibrate around their equilibrium. Because atoms in a solid are elastically bound to one another this may affect neighbouring atoms and in turn create a mechanical wave. These mechanical waves can propagate through the medium in the form of a variety of waves where some of the most commonly discussed waves are called longitudinal- and shear-waves. As the name suggests longitudinal waves oscillates in the longitudinal direction and these oscillations are parallel to the propagation direction of the wave. The particles in a shear wave on the other hand oscillate perpendicular to the wave propagation. The movement of the waves is illustrated in Fig. 2.1.

2.1.2 Reflection and Attenuation

The acoustic impedance of a medium affects how the mechanical wave propagates through the object and can best be described as *the opposition to passage of sound waves, being the product of the density of a substance and the velocity of sound in it* [6]. When

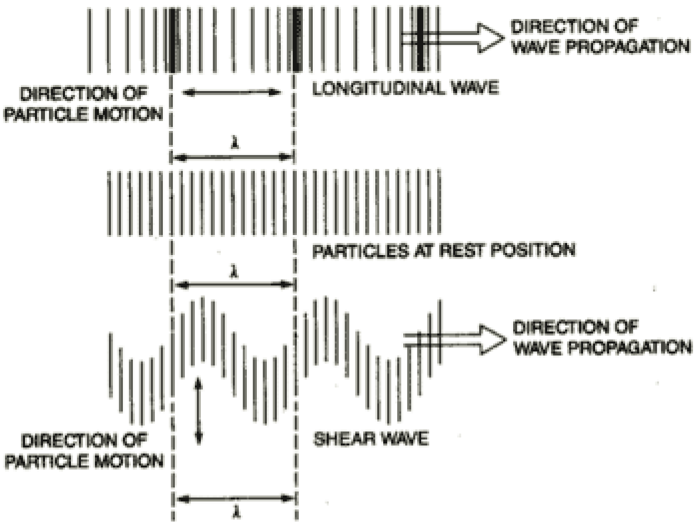


Figure 2.1: An illustration of a longitudinal- and a shear-wave [7]

a mechanical wave propagates through a medium, solid or liquid, and encounters a boundary to another medium with a mismatch in acoustic impedance, part of the energy will be reflected and some transmitted. This is something to consider when choosing coupling agent between the transducer and sample when studying AE. Irregularities in materials have a scattering effect on a travelling wave, where some of the energy is refracted, which causes a change in direction. This together with the dampening effect, energy losses associated with e.g. heat development, is described as the attenuation of the material. The attenuation can be expressed in relation to its attenuation coefficient and increases with frequency, meaning that higher frequencies will be more efficiently attenuated [8]. Due to the large amount of irregularities found in wood, for example knots and growth rings, the attenuation is greater in a wooden material than e.g. glass or metal and attenuation between 30 dB/m up to 200 dB/m [9] can be recorded. This results in difficulties measuring AE on large distances and the transducer should always, if possible, be kept close to the source of activity.

Growth rings in wood are formed by the uneven growth rate trees undergo during the seasons. During spring and early summer the growth rate increases, forming light coloured material with lower density [8] and thus lower acoustic impedance compared to the dark coloured, denser cell types, formed during the slower growth season in the late summer and fall. The wave velocity parallel to the grain, L direction in Fig. 2.2, can vary from 4000 to 6000 m/s and up to 50% [9] lower when travelling perpendicular to the grain formations. Because the wave velocity is connected with the acoustic impedance and consequently its attenuation the dampening effect varies depending on propagation direction. Most affected are the longitudinal waves, which experience the highest attenuation perpendicular to the grain while no significant change can be seen for the transverse waves [8].

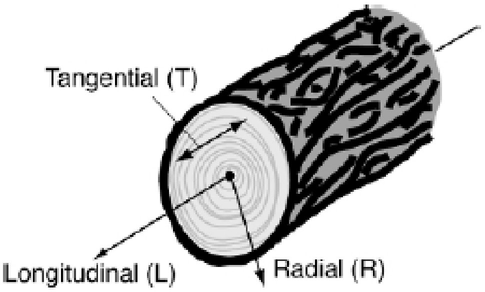


Figure 2.2: Propagation directions in wood [9]

Glass and metal have a more organised structure and a lower amount of irregularities, meaning less scattering, and a higher density, which results in a lower attenuation. This leads to a larger response in the higher frequency regions than e.g. wood.

2.2 Piezoelectric Effect

The piezoelectric effect can be used for many purposes. Some of them are implementations of measurement devices for pressure, acceleration, strain and acoustic emission, where the last mentioned is the application that is the subject of this thesis. The main advantage of using piezoelectric elements for measuring is that they have, depending on which dimensions the elements are, a very broad linear bandwidth, usually stretching from DC to several GHz [10].

As a very brief introduction to the piezoelectric effect, it can be said that a mechanical force that deforms a piezoelectric element gives rise to a proportional change in the charge over the element. This is called the direct piezoelectric effect. There is also a converse piezoelectric effect, which means that placing an electrical field over the element makes the element deform proportional to the difference in electric potential. See Fig. 2.3 for an illustration of these effects. By using the direct effect it is possible to translate a mechanical motion, such as a sound wave, into a voltage that can be detected, compared and processed by using an oscilloscope, DAC-card (data acquisition card) or micro controller. First to come is a section about the theory of the piezoelectric materials.

2.2.1 Ceramic Elements

There are many materials that are expressing piezoelectric characteristics. However, not many of these materials have the sufficient level of piezoelectricity for practical use in technical applications. The materials that show the most piezoelectric effect are crystals and certain ceramics. The material most often used, which is also used in the ceramic element during this thesis, is a compound named PZT, lead zirconate titanate. This compound

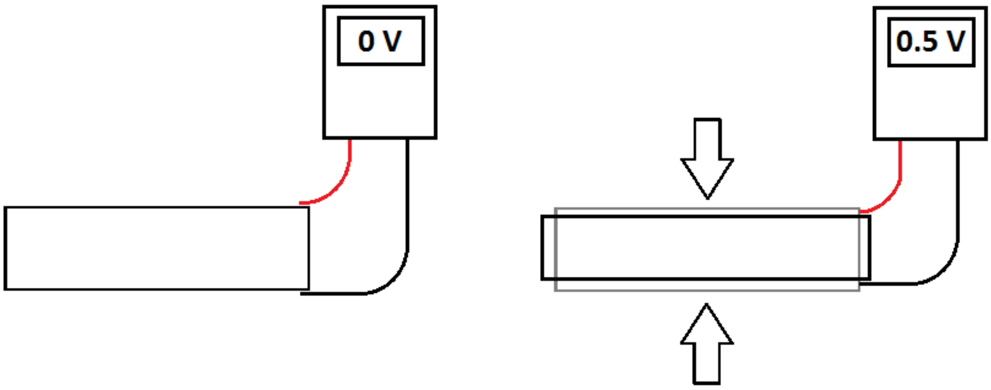


Figure 2.3: A deformation of the element gives rise to a voltage.

was developed in the 1950's and has been used widely since [11].

The main idea behind piezoelectricity is, as stated earlier, that when a force is applied to the surface of the piezoelectric material, a change in charge level rises across the material.

In order to make a piezoelectric ceramic element one would of course need a suitable material, for example a PZT material. Initially, the ceramic doesn't have any overall polarisation, the dipoles are randomly organised in the material with no remarkable structure. A strong direct current electric field is applied over the material, called the polarisation, which will cause the dipoles to be arranged in a certain pattern with positive ends facing one direction and negative ends facing the opposite direction. When the electric field is removed, the dipoles remain in basically the same position as during the polarisation, and that polarisation becomes permanent. This process is illustrated in Fig. 2.4

When a force, i.e. compression or tension, is applied along the same axis as the polarisation, the dipole moment changes and thus creates a measurable voltage [12].

Piezoelectric ceramics are available in many different shapes

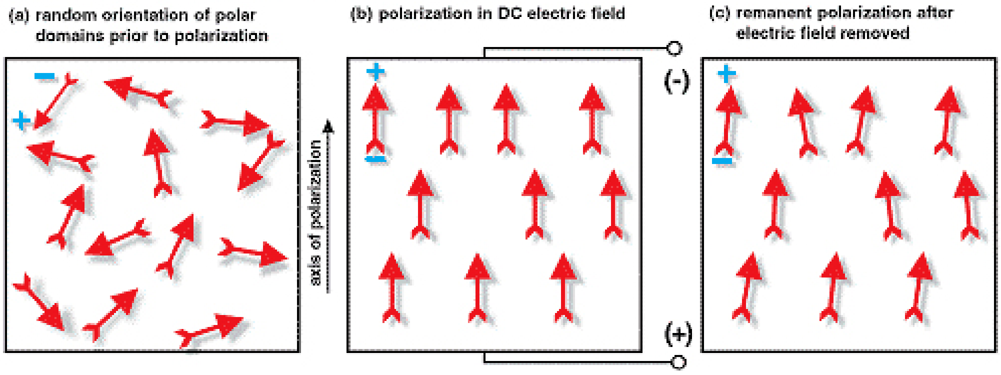


Figure 2.4: Polarisation process. [12]

and configurations. The ceramic usually has one or more resonance frequencies, depending on the dimensions. This can be a drawback since the frequency response can differ between types of ceramic elements and as a result of this the relative frequency response should be treated with respect to the elements resonance frequency. However, if the intention is comparing signals in a particular frequency region with just one sensor, as in this thesis, this effect does not have any significance.

2.2.2 Plastic Films

Plastic films have been studied since the late 1960's [13], but are not as widely used as piezoelectric ceramics. This was due to the slow development of plastic materials, but in the last twenty years it has been advancing on the market. Though it is functioning the same way as a ceramic piezoelectric element, it has several benefits over the more traditional alternative. One of these is lower acoustic impedance; it is in fact close to the acoustic impedance of water and organic tissues [14]. This means that signals are more easily transferred when measuring on soft materials like mentioned above, in water and human tissue. Other benefits compared to ceramics are e.g. higher output voltage for the same force, more durable to strong electric fields and having a linear response in broad areas, stretching from near DC to ca. 2 GHz [15]. There is although a few drawbacks, which sometimes makes the ceramic a better candidate, including but not limited to a poor performance as a transmitter, especially in lower frequencies, and it can also be more sensitive to electromagnetic radiation i.e. noise [14].

2.3 Sensor from Covial Device

The glass break detector GlassAlert$^{\text{TM}}$, shown in Fig. 2.5, was part of the reason why this master thesis started. The sensor is a compact and neat product, suited for stand-alone use or with a central unit, also provided by Covial Device, which handle alarms and can monitor several GlassAlert$^{\text{TM}}$'s simultaneously. The sensor is to be glued directly on the glass. It operates on the principle of acoustic emission, although with a different approach using a non-standard technique with an amorphous thin metal film reacting to a mechanical stress by creating a magnetic field. An amorphous material is defined as a material with lack of an ordered atomic structure, such as glass.

There is not much information available about the theory behind the sensor as it is patented and not widely used in the industry. Since the goal of the thesis was to find out if it was possible to use the present sensor for different applications, not much time was spent on trying to find out more about its internal design, as it was not needed.

Figure 2.5: The GlassAlert$^{\text{TM}}$. [16]

2.4 Acoustic Emission

The common description of AE is that when an event occurs that makes a material crack, micro cracks as well as macro cracks, this causes the material to emit energy in the form of transient elastic waves, that propagates trough the material and can be registered using different sensors. The properties of AE is usually a frequency of approximately 10 kHz to over 1 MHz and with an amplitude in the order of nm [17].

The main use of AE is non-destructive testing, which means that a material can be tested or monitored without cutting, drilling or in any other way harm or affect the specimen. The use of AE as a testing method is considered to be passive, since it will only register cracks as they happen. Active methods could be those methods that also emit sound waves to check how the response, echo, have changed, such as ultra sound testing. This chapter will for starters give an introduction to acoustic emission, followed by a section describing the structure of a typical AE application, and also a brief introduction to what AE can be capable of in different applications.

2.4.1 Background

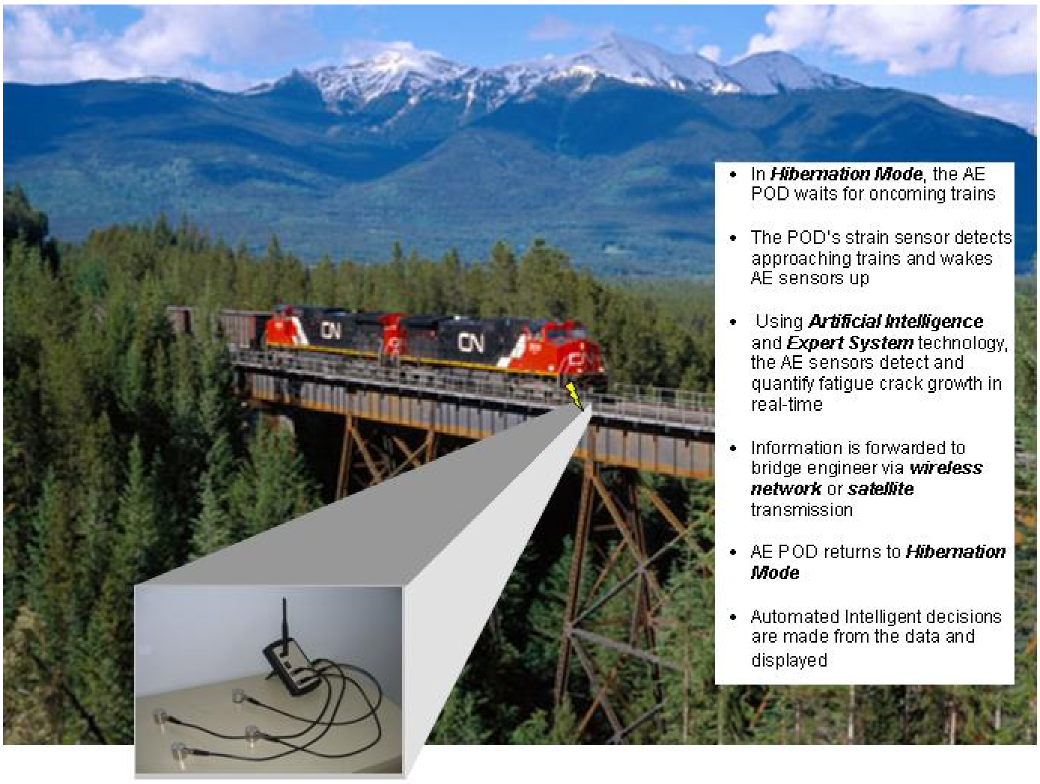
Although acoustic emission can appear a bit foreign to most people, the phenomenon has been known for a very long time. Every time a crack is heard, acoustic emission is involved. This simple fact has been used by humans as well as animals to detect for example if a tree is about to fall, a bridge about to collapse, or craftsmanship techniques to decide if a clay pot was defective, or the notice that tin 'cries' when being plastically bent. All these examples are of the same origin, acoustic emission. AE can also be compared to seismology, although in a much smaller scale, where earthquakes give rise to elastic waves that can be felt from a very far distance. More scientific and modern approaches with acoustic emission emerged in the 1930's, but would not be defined as AE until the 1950's, with the work of J. Kaiser, and B.H. Schofield in 1961 [18]. Since then, the technique has been developed and is now in practical use worldwide in many different applications.

2.4.2 Applications

Due to the fact that more or less every material can carry mechanical waves (in different levels of course), the AE method is suitable for any application where general material failure needs to be monitored. It can be in the range from monitoring very small specimens for material control, to large scale monitoring of concrete bridges for heavy traffic. There are also many companies that are specialised in AE and have complete sensors ready for measuring and monitoring. According to some of these companies, some of the most applied uses are:

- Material research [19]. Determining different materials or specimens maximum load during different stresses or strains, damage evolution after initial breakage and similar.

- Detecting high pressure leaks in pipes, or monitoring flow in pipes for detection of unwanted contaminants [20].
- General monitoring of pressure vessels [21].
- Structural health monitoring, which according to Vallen Systeme GmbH. is *the only cost efficient method to monitor structures 24 hours a day, 7 days a week.* [22]. Fig. 2.6 shows a good example of this use.



- In ***Hibernation Mode***, the AE POD waits for oncoming trains
- The POD's strain sensor detects approaching trains and wakes AE sensors up
- Using ***Artificial Intelligence*** and ***Expert System*** technology, the AE sensors detect and quantify fatigue crack growth in real-time
- Information is forwarded to bridge engineer via ***wireless network*** or ***satellite*** transmission
- AE POD returns to ***Hibernation Mode***
- Automated Intelligent decisions are made from the data and displayed

Figure 2.6: Application of AE in a train bridge monitoring system [23].

2.4.3 Typical AE Measurement

The typical AE monitoring/measuring system is built up of different devices. Such a system is shown in Fig. 2.7. There are some different sensors but in general, and almost always, a piezoelectric sensor is used. The signal from the sensor can be very low, which means that some amplification is necessary. Sometimes both a pre-amplifier and a higher gain amplifier is used. The pre-amplifier should be located near the sensing element to amplify the small signal before noise or other interference affects the signal. By using a pre-amplifier, the signal-to-noise ratio improves, meaning that the output of the main amplifier will be cleaner. When a strong signal is achieved after the amplification it will, if the aim is to examine the AE signal, be captured and stored, often with a DAC-card or an oscilloscope. The signal can be transferred to a computer or micro controller, and may be the subject to eventual signal processing algorithms, for example filtering or transforming into the frequency plane. The signal is then at last displayed.

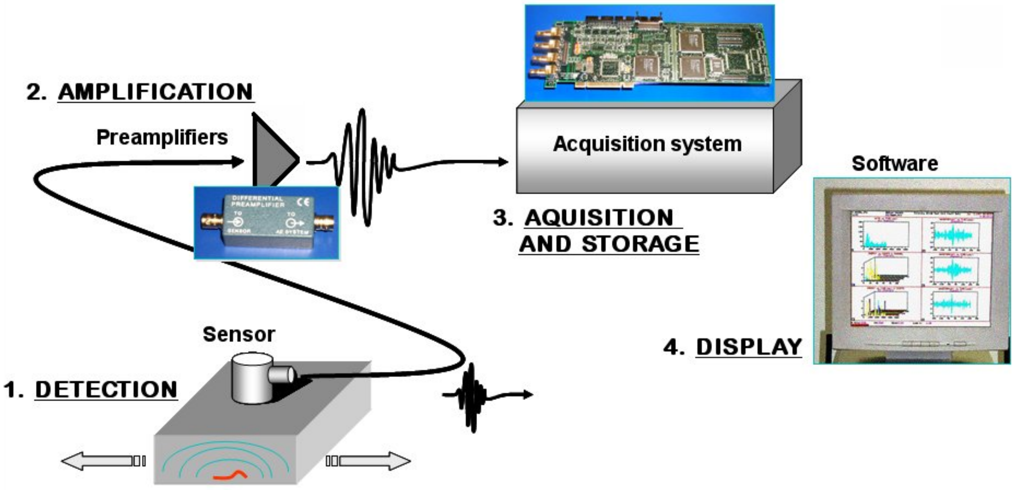


Figure 2.7: A typical AE measurement set-up. [24]

Chapter 3

Methods

The focus in this thesis has been AE in wooden materials, detected with piezoelectric elements. As a comparative study, collaboration with Covial Device and their glass break-detector, GlassAlert$^{\mathrm{TM}}$, were introduced and thus testing on glass was examined as well.

A piezoelectric ceramic, consisting of PZT and with a diameter of 12 mm, was mounted on the material. Some research was made to see if the market had an adhesive that matched the materials acoustic impedance, to maximise the transmission of the sound wave. This is generally not something that glue manufacturers test and specify in the data sheet, so the choice fell on a standard epoxy glue, Casco 2805, because it is supposed to be quite hard when it stiffens, gaining the most similarities with the specimen. There were several elements all attached to the different materials, as shown in Fig. 3.1. Pictures of the different measuring situations are shown in Fig. 3.2 and Fig. 3.3 to illustrate how the measuring was performed. Testing one material at a time, the sensor was coupled via a standard oscilloscope probe to a GaGe CompuScope CS1250 DAC-card and LabVIEW V.10 for processing and analysis. Because of the relatively small distances between the activity and transducer, no amplification that traditionally is needed in AE measurements, had to be used. The oscilloscope software supplied from the GaGe DAC-card was modified, allowing storage of the waveform for further analysis. The signals was stored in a length of 100 ms and with a sample rate of 10 MHz, making sure it was possible to study high frequencies. The amplitude measurement interval varied between 5 volts in the glass measurements down to 2 volts in the more attenuated wood measurements.

The study consisted of in-depth analysis, searching for similarities and differences between the signals that were collected in the database. An overview of the different test cases are shown in Table 3.1.

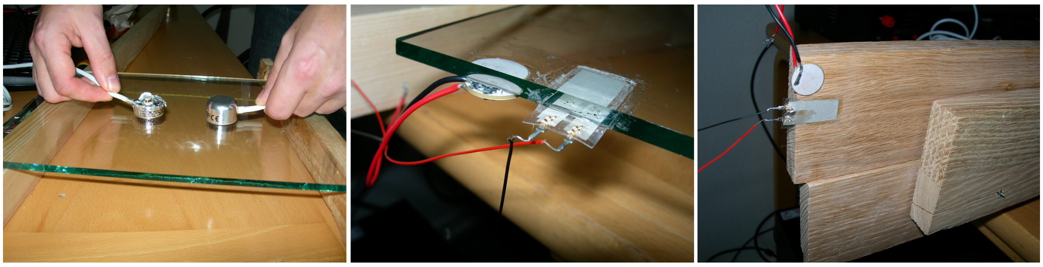


Figure 3.1: The mounting of the elements and sensor. The GlassAlert$^{\text{TM}}$'s to the left, the piezoelectric ceramic and plastic film mounted on glass in the middle, and on wood to the right.

Test case	Applicable on:	How:	Why?
Hand-knock	Wood, glass	Knocking with a hand	Common signal
Knock with tool	Wood, glass	Knocking with a metal tool	Common signal
Hammer strike	Wood, metal	Striking with a hammer	Ev. break-in attempt
Keydrop	All	Dropping keys	Common signal
Coin snap	All	Snapping with coin	Common test
Cut	Glass	Using a glass cutter	Break-in attempt
Bend	Metal	Using a plier	Break-in attempt
Crush	Glass	Breaking with a plier	Break-in attempt
Break	Wood	Using a crowbar	Break-in attempt
Saw	Wood, metal	Using a saw or angle grinder	Break-in attempt

Table 3.1: An overview of the different test cases.

3.1 Measurements and Measuring Set-up

3.1.1 Wood

Due to the variety in structures and characteristics of wood, two materials, oak and pine were chosen to undergo testing. Both materials are commonly used in doors and window frames but as oak is a more dense material than pine, some differences in signal propagation were expected. For the actual breakage a chisel was used as can be seen on the right in Fig. 3.2. Signals originating a couple of centimetres and up to 2 m from the transducer were recorded.

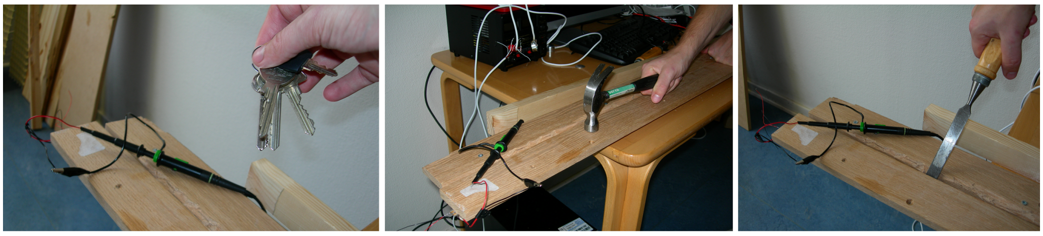


Figure 3.2: Some of the wood measurements. Keydrop to the left, hammer strike in the middle, and break with a chisel to the right.

3.1.2 Glass

Similar to the wood testing a piezoelectric ceramic transducer was mounted on the glass. Canola oil was first tried as an acoustic couplant but due to the lack of casing and difficulties mounting the transducer, epoxy glue was chosen. There was however no other drawback with the canola oil, its acoustic properties was sufficient in these tests.

In accordance with the tests on wood, knocks with metal tools, keys dropped and snapping with a coin was chosen as comparative signals. For the destructive signals a glasscutter was used as well as a plier for actually breaking the glass. Some of these measurements are clarified in Fig. 3.3.

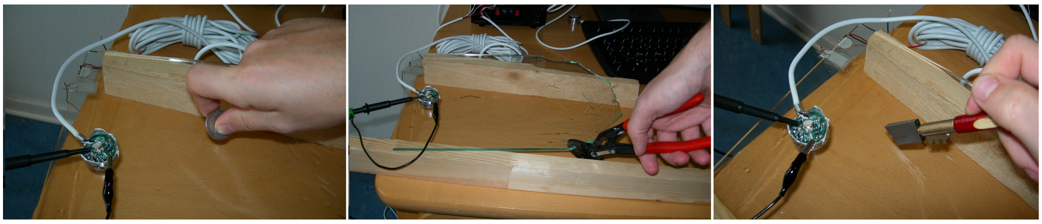


Figure 3.3: Some of the glass measurements. Coin snap to the left, the crush using a plier in the middle, and glass cutting to the right.

3.1.3 GlassAlert™

The GlassAlert™sensor was mounted on the glass and wood in accordance with Fig. 3.1 and canola oil was used as an acoustic couplant. As instructed the sensor was powered by 12 V DC from a standard power supply and a LED on the sensor indicated if an alarm was triggered.

The casing was removed as shown to the left in Fig. 3.1 and probes were mounted on soldered connection cables, with intention to measure the analogue signal before filtering and amplification was introduced. This proved difficult because of the low output from the active element, in the range of a few mV, and thus amplification was needed.

Simulations with LTspice, a SPICE (Simulation Program with Integrated Circuit Emphasis) from Linear Technology, over the existing circuit in the sensor revealed a small amount of filtration in the lower frequencies, and a linear amplification of 112 dB in the region 1 kHz to 400 kHz, usually associated with AE, shown in Fig. 3.4. Thus the signal was measured and analysed before it was passed on to the PIC-processor.

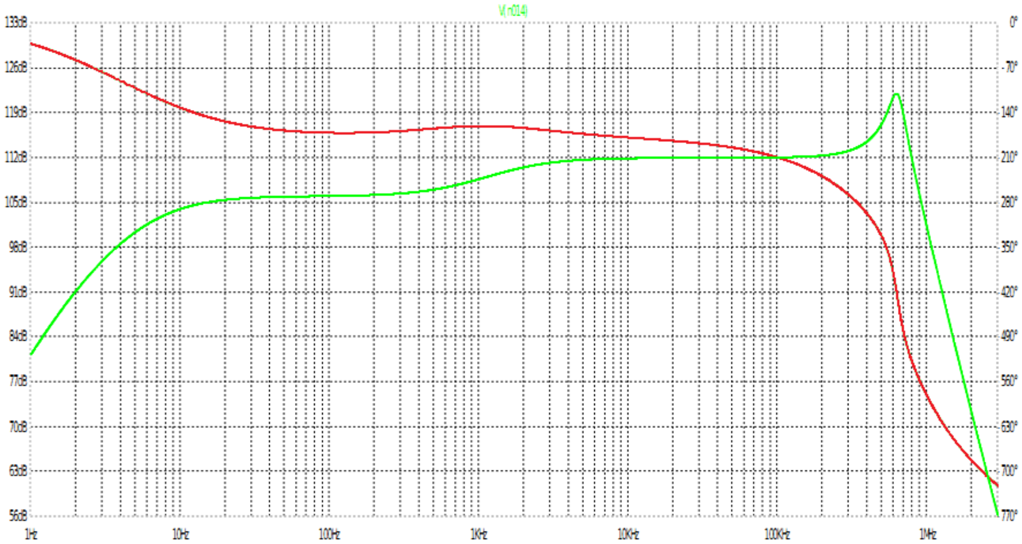


Figure 3.4: The frequency response from the GlassAlert^{TM}. Amplification is displayed in green and the phase in red.

3.1.4 Metal

As a complimentary comparison, some measurements on metal were also performed. A piezoelectric element was mounted with epoxy glue on a metal plate and similar tests as in glass and wood were performed and illustrated in Fig. 3.5. A plier was used to bend the plate and an angle grinder to cut the metal.

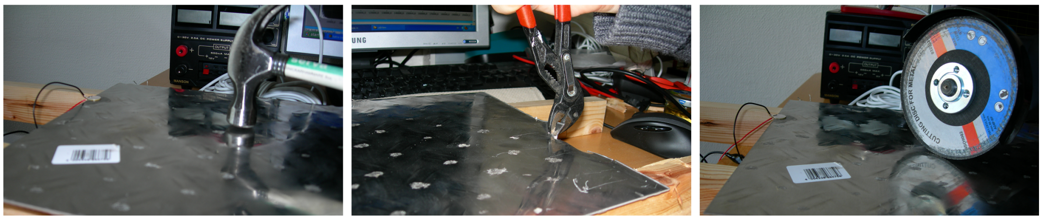


Figure 3.5: Some of the metal measurements. Hammer strike to the left, bending using a plier in the middle, and cutting with an angle grinder to the right.

3.1.5 Noise

A small study was also made to see if there was any significant noise that could interfere with the detected AE signal when measuring with the piezoelectric element. The measurements were made with a piezoelectric element mounted on a pine material. A trigger was forced on the DAC-card, and the signal achieved was analysed.

3.2 Signal Processing

To distinguish critical signals from other signals, i.e. signals not associated with fractures, different methods and algorithms were used. They are listed and described briefly below, and a more comprehensive description can be seen in section 4.2.

When studying algorithms and software in different applications it is evident that there is no general standard for processing and separating AE signals, but each system is developed and suited for its specific material and measurement situation. Some systems only rely on the frequency content [5] in the acquired signals and other study the time signal e.g. amplitude, pulse duration [25] or rise time [26], calculated as the duration from passing a pre-set value to reaching its maximum peak amplitude.

Because of this our algorithms consider a combination of methods were both the time signal and frequency spectrum is analysed.

In the power spectrum:

- Counting number of detected peaks.
- Calculating area
- Performing the above when different band-pass filters are applied.

In the time signal:

- Calculating the mean value of a number of the largest peaks.
- Peak detection
- Performing the above when different band-pass filters are applied.

The reason why these algorithms made it possible to distinguish fractures from other signals are due to the difference in appearance and characteristics. All signals can be categorised by certain parameters and this will be described more in detail in the Detector Structure section, 4.2.

Chapter 4

Results

The result of this thesis is mainly the constructed detector, and it was constructed after analysis of the signals acquired from the measurements.

4.1 Acquired Signals

At least ten of each signal in all materials was recorded and analysed thoroughly. The analysis showed that there were similarities and differences between the signals that made it possible to distinguish them from each other. Below, the signals acquired in different materials are discussed.

Due to the low output of the GlassAlert$^{\text{TM}}$and the high dampening effect in wooden materials, these measurements were inconclusive, and discussed further in the next chapter.

4.1.1 Wood

When studying the frequency spectrum, AE signals associated with crack formation generally have larger response in the higher regions. Crack formation in oak is associated with a strong frequency response from 25 kHz to ca 60 kHz, while in pine which is a softer material and thus more efficient in dampening higher frequencies, this corresponding region is instead seen from 15 kHz to 40-45 kHz. Exception can be made for some of the 'key-drops' and all the coin snaps, and as a result two more distinctions were made. Responses associated with cracks also contain a small, yet calculable, frequency response in the region 100-300 kHz for both pine and oak and a larger amount of detected frequencies compared to the coin snap. A flowchart of the algorithms used to detect crack formations can be seen in Fig. B.1. A few other test are also performed to introduce a threshold for allowed amplitudes and a study of the time-signal to faster detect clearly suspicious signals by counting the number of peaks.

4.1.2 Glass with GlassAlert$^{\text{TM}}$

The same tests were performed on GlassAlert$^{\text{TM}}$and results on the tool-knock and keydrop can be shown in Appendix Fig. A.39 to A.42. These tests triggered no alarm. Alarm was indicated, as expected, when actual destruction of the material was performed with a glasscutter and a plier, see Appendix Fig. A.45 to A.48, but also during the coin snap, Appendix Fig. A.43 to A.44. The GlassAlert$^{\text{TM}}$is supposed to withstand the coin snap [27] and thus this was categorised as false alarm. When performing a fast fourier transform, FFT, on the acquired signal from the GlassAlert$^{\text{TM}}$it clearly can be shown that destructive signals generate a larger response at 350 kHz than tool-knock, key drop and coin snap. The GlassAlert$^{\text{TM}}$is a tested and certified product on the market, however, in our test cases it was concluded there had to be a problem in the software of the sensor.

4.1.3 Glass with Piezoelectric Element

The signals acquired in glass are displayed in Appendix Fig. A.29 to A.38. As expected, and mentioned earlier, the signals acquired in glass had much higher frequency content than the corresponding signals in wood. Also since the attenuation is much lower, more details in the power spectrum could be observed, which led to the fact that the algorithm only analyses the frequency domain.

The non destructive signals had large response up to ca. 50 kHz, with exception for the coin snap that generally had significant frequency content up to 160 kHz. This made it easy to distinguish suspected fractures, since the signals from the glass cutter had frequencies up to over 200 kHz, which was also the case with the glass breakage although small and not easily seen in Appendix Fig. A.38. Some of the signals from snapping with a coin and dropping keys also had similarly high frequencies, but when filtering the signal 10 kHz to 500 kHz and using a combination of peak detection in the power spectrum and area calculation between 150-500 kHz, they could be separated from the fractures. A flowchart showing the detector of glass fractures can be seen in Appendix Fig. B.2.

4.1.4 Metal

Because of the ductile structure, unlike the brittle glass and wood, no significant AE could be detected when bending the plate. However the use of an angle grinder resulted in a very large frequency response, compared to the non destructive tests as can be seen in Fig. A.49 to A.56.

4.1.5 Noise

The noise generally had a very low amplitude, up to 20 mV, which is lower than the detected AE signals. With no filtering, the only significant frequency was the 50 Hz from the power grid. If an order fifteen bandpass-filter was applied, with cut-off frequencies 100 Hz and 500 kHz, some dominating frequencies could be seen in the lower frequency region, i.e. around 450 Hz and 1.3 kHz. Since these frequencies had an insignificant amplitude compared to the detected AE signals, the noise was concluded as minimal. However, disturbances could possibly be detected in further studies, and considering electrical crosstalk, a casing in a future prototype is strongly advised.

4.2 Detector Structure

With the results obtained above, and by analysing the characteristics of the obtained signals it was possible to estimate different parameters to define a fracture signal and construct a detector which could be used for real time testing. Though its execution time is not as fast as it could be due to unnecessary fast sample rate, it shows a good accuracy. The detector was written in LabVIEW, and run on a personal computer, coupled with a DAC-card. The detector consists of different tests, designed to disregard non destructive signals and pass forward suspicious signals that might be associated with fractures, for further analysis. This way the largest number of non destructive signals will be discarded in the detector, and if a fracture is detected it will pass through all test before setting a LED to indicate alarm. The less 'alarm-like' the signal is, the earlier it will be discarded, making the detector avoid execution of unnecessary tests.

Since the signals in glass and wood differ, there are two different structures in the detector and these are presented below. When there are filters applied, if nothing else is stated, a digital band-pass filter of order fifteen, to make the cut-off frequencies steep is used. Flowcharts of the detectors can be seen in Appendix Fig. B.1 to Appendix Fig. B.2.

As the same program handles all the test cases, it starts with letting the user define what kind of material the current measurements are performed on. With respect to this, the software sets the variables used in the algorithms. The variables were chosen with respect to the acquired data during this thesis, but could easily be changed if needed.

Some detectors rely on the principle of counting number of AE events detected [3], [4]. Using the detector described in this section, depending on the application, a system could be designed to not trigger an alarm until a certain number of AE events have occurred in a given timeframe. The signal recorded and analysed with these algorithms are 100 ms but, with the introduction of a buffer memory, once the system is triggered a longer signal could be recorded and analyzed in intervals of 100 ms.

4.2.1 Wood Detector

Although the tests are the same for all wooden materials, because of the different characteristics of dense and softer wood, different parameters are set for oak and pine. A mean value for a number of the maximal peaks in the time signal is calculated. Even if a signal is not associated with a crack formation it might be desired to trigger an alarm if the amplitude is high, resulting from e.g. a hammer strike or similar. This threshold could be changed or completely disregarded depending on the application. Fracture signals can in most cases be separated from other disturbances, e.g. hand-knocks that probably is the most common signal to be analysed in a door application, merely by considering the time signal. By analysing the time signal under 30 kHz and calculating the number of peaks, most disturbances are disregarded and some of the fractures are detected without performing a more complex and time-consuming FFT. The signal is disregarded and considered a non-fracture if the calculated number of peaks falls under the first threshold. If the number of calculated peaks is more than the second threshold it is considered a fracture and immediately triggers an alarm. If the calculated peaks are greater than the first threshold but lower than the second it is considered a possible fracture and an FFT is performed with a band-pass filter in the range 300 Hz to 100 kHz to further study the frequency content associated with AE. If the area of the frequency spectrum, in the range 20-100 kHz, and the number of detected frequencies are above the threshold the signal is considered a fracture. A flowchart over the test can be seen in Appendix Fig. B.1

4.2.2 Glass Detector

A flowchart of the detector used in glass can be seen in Appendix Fig. B.2. Due to the lower signal attenuation in glass, more details of the signals could be observed and this made it possible to have fewer tests than in the wood detector. As in the wood detector, the parameters are obtained from start, when the material is chosen.

There are some minor tests made in the first steps of the detector to see if the signal is strong enough to possibly be a suspicious signal. This was added to disregard very small signals obtained with scratching on the glass with different tools, making no actual harm to the material. However, these signals characteristics reminded of a suspicious signal except for its amplitude. These minor tests are not illustrated in the flow chart, and are voluntary to include in the algorithm. It may be a better alternative to simply increase the trigger level, however this proved difficult due to some limitations in the trigger setting of the GaGe DAC-card.

The signal is filtered with a band-pass filter with cut-off frequencies 100 Hz and 500 kHz. This is basically the whole signal content with exceptions of very high and low frequencies with no significance to the tests. Then a power spectrum is performed, and the area is calculated from 60 to 100 kHz. This is due to the high frequency content obtained in glass material failure. If the area calculated is below a specific threshold, the detector indicates no alarm, but if the area is sufficient, it is treated as a suspicious signal and further testing is performed. Before the second test the signal is filtered with the same type of band-pass filter, but with the cut-off frequencies 10 to 500 kHz. Peak detection is performed on the power spectrum to calculate the number of detected frequencies and if the number is below a specific threshold, again no alarm is indicated. If the threshold is exceeded, a final test is done to make sure it is really a fracture signal. The area of the power spectrum between 150 and 500 kHz is calculated, and if the threshold for this is exceeded, alarm is indicated.

Chapter 5

Discussion

There were a few concerns that arose during this thesis, and together with their possible solutions they will be discussed in this chapter.

5.1 Data Acquisition

The DAC-card and its software were not entirely easy to cooperate with. Some time was spent just trying to understand how the software oscilloscope worked, and how it could be modified to suit our purposes. Since there was not enough time to understand all of its features, we often settled with good enough properties and attributes, and this was the case with the sample frequency. The detector runs with a sample rate of 10 MHz, and that makes the program execution time approximately ten times slower than actually needed, since the highest frequency studied is 500 kHz in the glass measurements. By following the Nyquist Theorem [28], which is strongly advised, no higher sampling rate than 1 MHz is needed to detect the frequency content, and in the wood measurements no higher frequency than 300 kHz was studied, lowering the minimum sample rate to 600 kHz. With the 10 MHz sample rate, the execution time was in worst case scenario approximately fifteen seconds, and with a major decrease to 1 MHz the execution time would theoretically drop to a maximum of two seconds, because there will be much less data to consider in the peak detector and FFT calculations.

5.2 Piezoelectric Element

The software used with the piezoelectric ceramic sensor could possibly be more optimised if some more time was spent on development. However, it is actually very flexible, since all the tests are depending on parameters to define if the signal is to be considered as a fracture. This also means that the sensors sensitivity can be configured according to the application. This in turn means it could not just be used as a fracture sensor, but also as a general sensor for detecting events.

A design consisting of the piezoelectric element also exhibits one or more resonance frequencies, determined by the shape and diameter, but not as dominant which makes it a more flexible system, and able to study several regions in the frequency spectrum. Because there is no need for amplification with a piezoelectric ceramic, considering short distances, the hardware design could potentially be minimal. But unlike the GlassAlert$^{\text{TM}}$, it would consist of more software, putting higher demands on the memory and processor of the micro controller. Since the focus of this thesis was not the sensing element itself, not very much effort was made to characterise the piezoelectric ceramic in terms of resonance frequencies, frequency response, linearity and similar properties. Additional approaches could be made possible by further analysis of these properties.

Most of the challenges in a piezoelectric sensor consist of its software, but its broad bandwidth makes it possible to use the same sensor on different materials simply by configuring the software.

5.3 GlassAlert$^{\text{TM}}$

GlassAlert$^{\text{TM}}$is designed to work on glass and the sensing element clearly has a strong resonance frequency at 350 kHz, which makes it difficult to study frequencies in other areas. This could potentially be problematic if a source of disturbance or another case similar to the coin snap is discovered which is difficult to separate from the destructive signals.

Since the software of the GlassAlert$^{\text{TM}}$is not entirely known, we can not for sure tell how the acquired signal is processed, and AE separated from other signals. However it actually worked quite well when triggering real alarms, like breaking glass and onset with the glasscutter. The problem was snapping with a coin on the glass, which consistently triggered an alarm on our test rig.

5.4 GlassAlert$^{\text{TM}}$on Wood

GlassAlert$^{\text{TM}}$is designed to work on glass and the resonance frequency has to be altered to study AE associated with wooden materials. Because wooden materials differ in structure and properties, which results in different frequencies associated with AE, it could prove difficult to study only one frequency region, connected with the resonance frequency of the sensor, to detect fractures in both dense and light wooden materials. If this would be the case, one might have to use different sensors on different wooden materials, which would be both expensive and impractical. Another aspect that has to be considered is the amplification. GlassAlert$^{\text{TM}}$already has a strong amplification of 112 dB, and to study wood that is highly attenuated compared to glass, this amplification probably has to be increased even further. This creates challenges in the hardware, not to amplify unwanted signals and not to create additional disturbances.

5.5 Glass

According to this early investigation both the piezoelectric element and GlassAlert^{TM}, with some adjustments in software, can be used to detect glass fractures associated with an intrusion. However, with the current software of the GlassAlert^{TM}, the piezoelectric element with proper software would be a more reliable alternative.

5.6 Metal

In the quick tests performed on metal no significant AE could be detected when bending the metal plate. The piezoelectric element could however possibly be used in situations where larger destructive signals, like the electric grinder, is expected e.g. on a metal container.

Chapter 6

Conclusions and Future Work

The results achieved from this thesis suggest that it is indeed possible to separate a destructive signal from other disturbances, with quite simple techniques. By using the piezoelectric ceramic, a very flexible sensor can be constructed which could possibly even be used on different materials. The 'difficulty' in using the same sensor on different materials is that the parameters needed for determination of signal characteristics differ.

As mentioned earlier, a future prototype could have a much decreased sample rate, allowing for faster execution time. Also, some optimization of the code and algorithms could possibly be done to increase the performance.

Due to the fact that GlassAlert$^{\mathrm{TM}}$is an already developed product this could, possibly with some modification of the software, be used as a reliable glass break application. Depending on rules and regulations in an already certified product, it could be a quick and cost efficient solution to simply change the software of the GlassAlert$^{\mathrm{TM}}$, compared to the piezoelectric element which require more testing in 'realistic' environments such as on mounted doors and window frames. As a long term solution the piezoelectric element could prove to be a more cost efficient system, using the same sensor on glass, wood and possibly metal only by modifying the software.

Before the sensor with a piezoelectric ceramic could be considered as an alternative there are some practical issues that must be taken care of. Since the ceramic used in this thesis is very simple, the connections are placed one on each side of the element. This makes it impractical to mount on the surface anywhere but the edge as displayed in Fig. 6.1. However there are elements that have the connectors 'wrapped around' the same side, hence called wrap-around piezoelectric element, which could be more practical. An illustration of this could be seen in Fig. 6.2. But since there will be a change of elements, the characteristics will change and thus the parameters have to be reconfigured, but the structure of the detector could probably be kept.

Since the algorithm constructed with the piezoelectric sensing element would need more software to handle different signals, maybe a more advanced micro controller is needed than the simple PIC controller used in the GlassAlert$^{\text{TM}}$. Micro controllers such as the ARM have become quite powerful and have grown in popularity during recent years, due to low cost and very low power consumption. Although it is more advanced than the PIC, the ARM is considered to be the major processor architecture in use today, making it cheap and well documented. [29] This altogether suggests that it probably will not be a problem implementing the algorithms on a micro controller.

Figure 6.1: Piezoelectric element mounted on the edge of a specimen to the left, and on the surface to the right. The later creates a distance between the surfaces, which causes a poor contact.

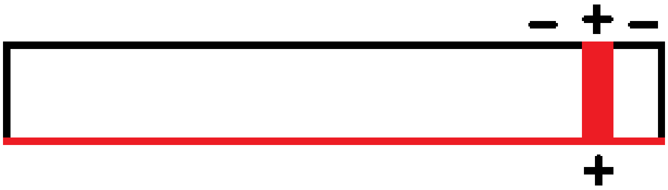


Figure 6.2: A piezoelectric ceramic element with wrap-around connector, which allows for direct contact on one side of the element.

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Dear John at GaGe Instruments Dynamic Signals LLC, for interesting mail conversations.

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Appendix A

Acquired Signals

Since too many signals were recorded to be displayed, this Appendix shows one representative signal for each measurement and material. The first signals are from oak, with the piezoelectric ceramic, followed by signals from pine with the same sensor. After that is glass with the piezoelectric ceramic, followed by glass with the GlassAlert$^{\text{TM}}$sensing element, and finally metal measurements with the piezoelectric ceramic. All signals are filtered with a digital band-pass filter between 100 Hz and 500 000 Hz, to show only the relevant frequency content. Please note that the frequency scale of the power spectrum differ from wood to glass. This is due to the fact that glass have larger frequency response in higher regions, and there is none or insignificant content outside the displayed region.

A.1 Oak

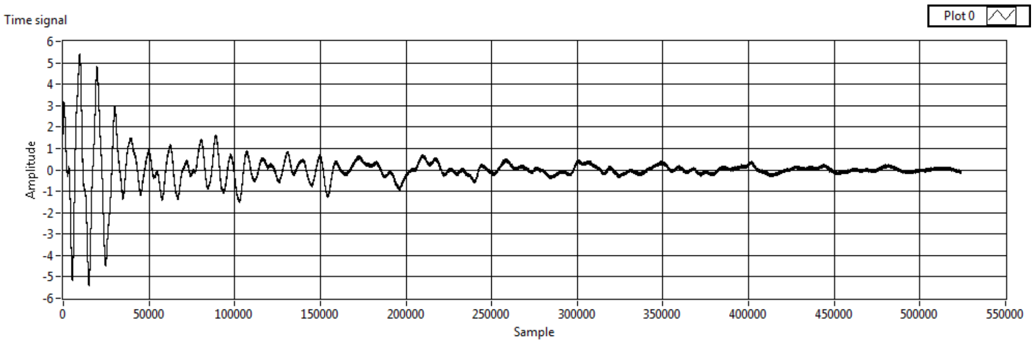

Figure A.1: Hand-knock Time Signal

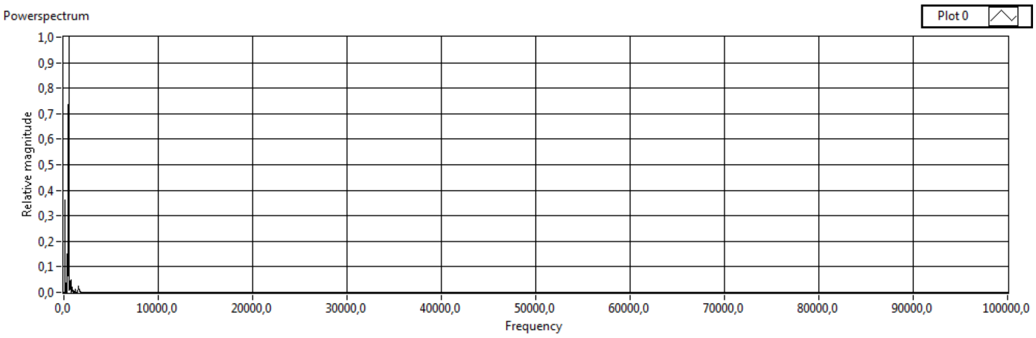

Figure A.2: Hand-knock Power Spectrum

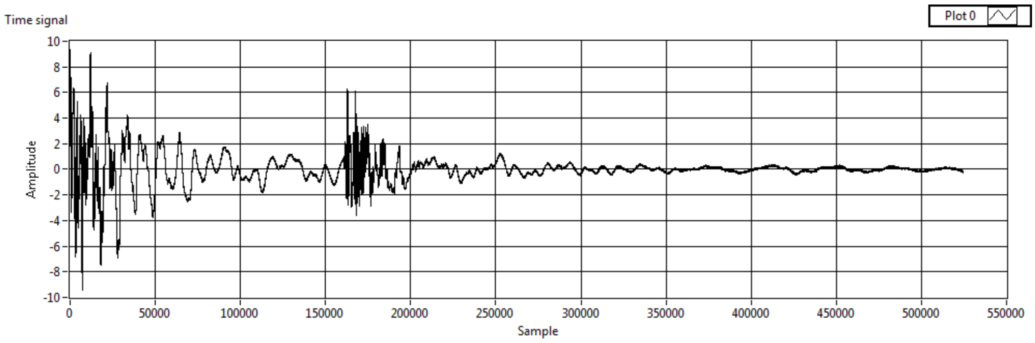

Figure A.3: Tool-knock Time Signal

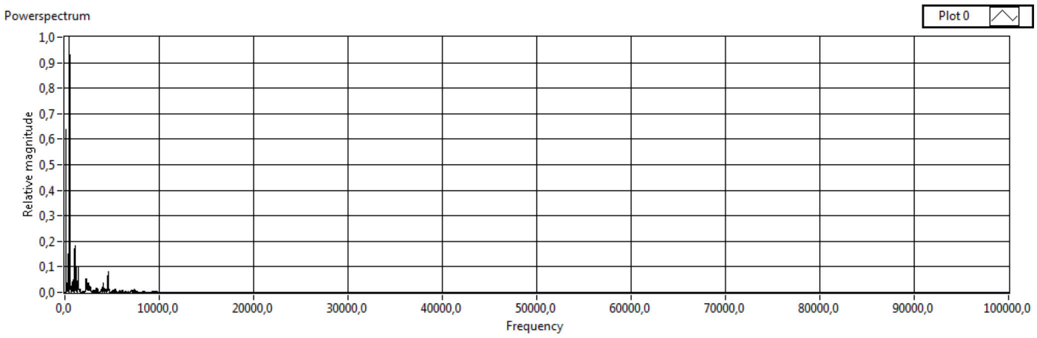

Figure A.4: Tool-knock Power Spectrum

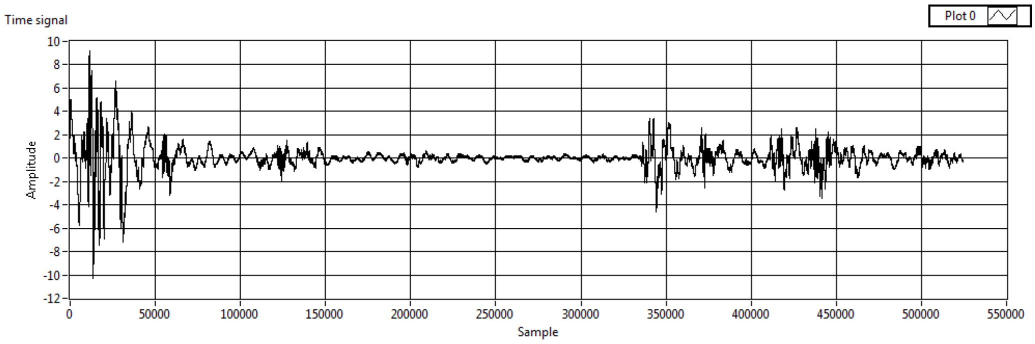

Figure A.5: Keydrop Time Signal

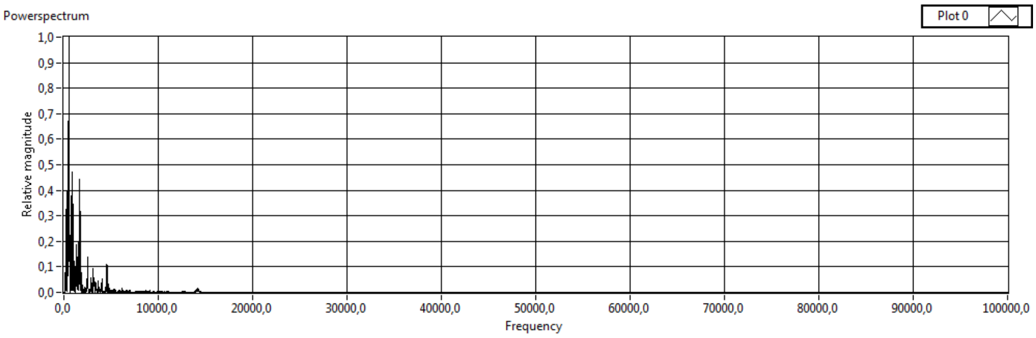

Figure A.6: Keydrop Power Spectrum

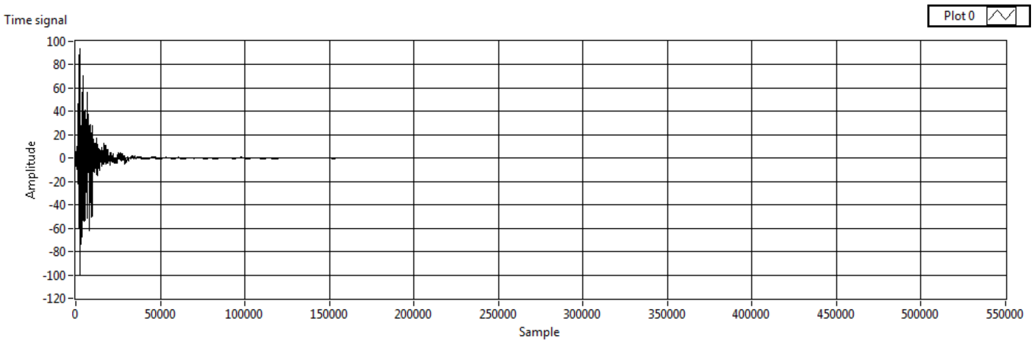

Figure A.7: Coin Snap Time Signal

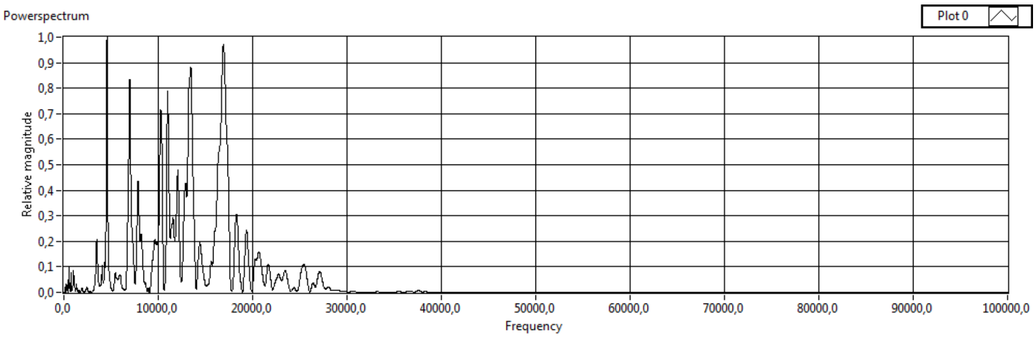

Figure A.8: Coin Snap Power Spectrum

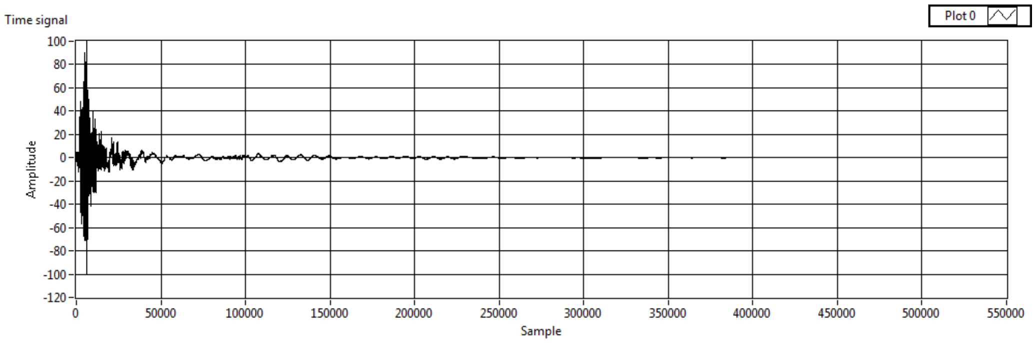

Figure A.9: Hammer Strike Time Signal

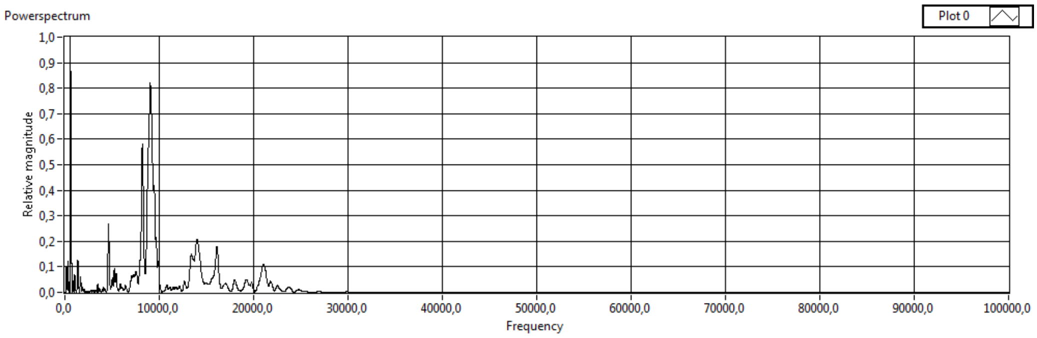

Figure A.10: Hammer Strike Power Spectrum

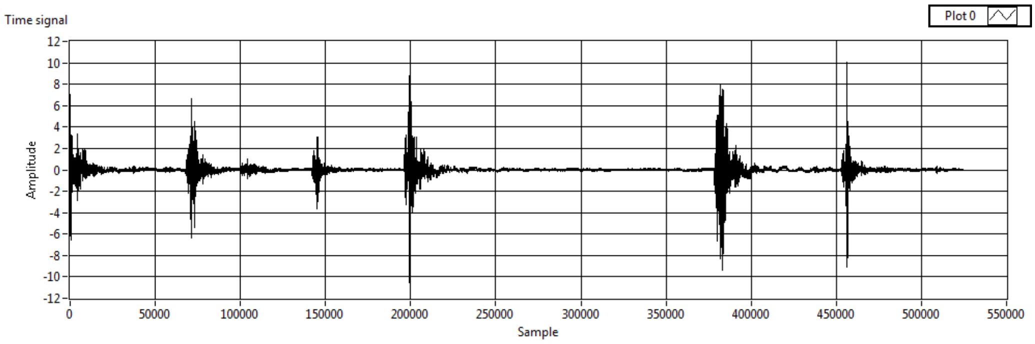

Figure A.11: Break Time Signal

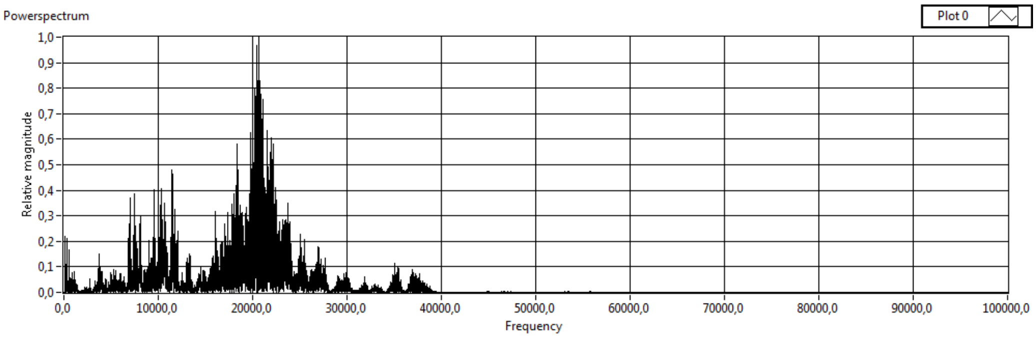

Figure A.12: Break Power Spectrum

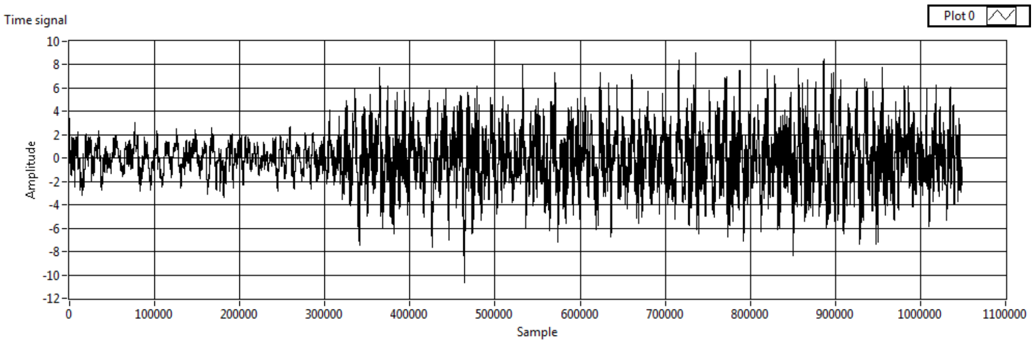

Figure A.13: Saw Time Signal

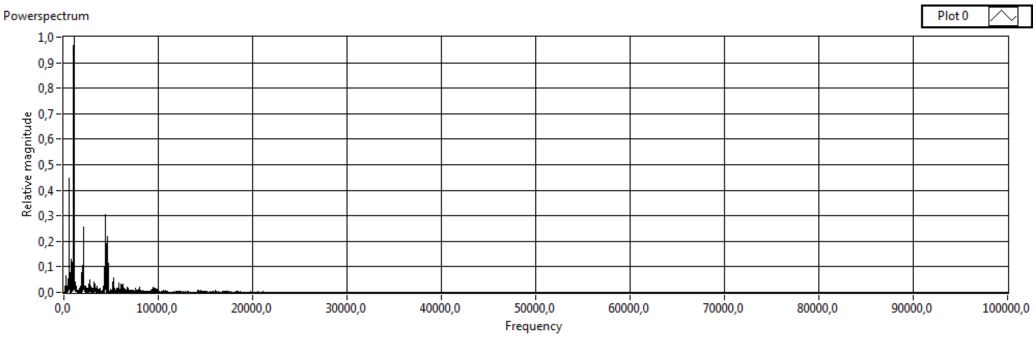

Figure A.14: Saw Power Spectrum

A.2 Pine

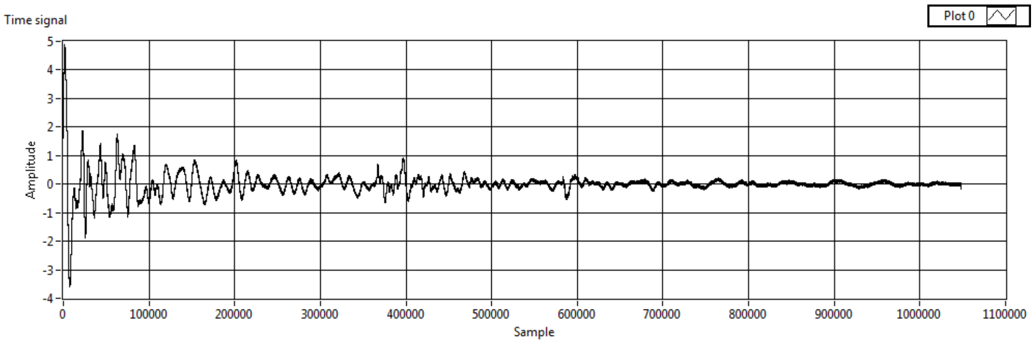

Figure A.15: Hand-knock Time Signal

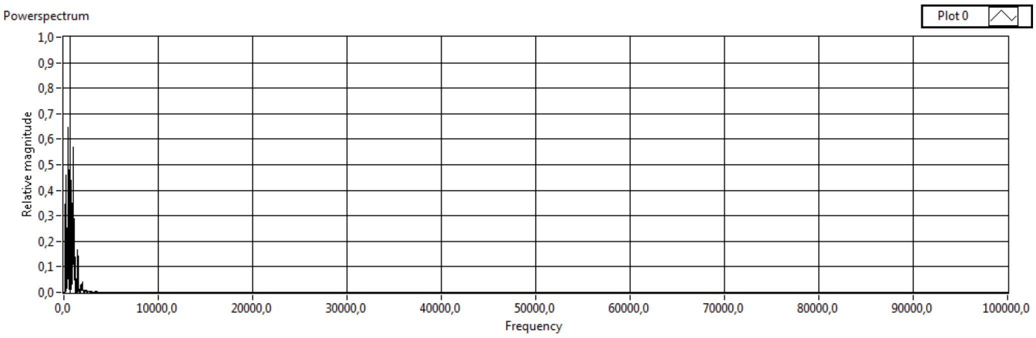

Figure A.16: Hand-knock Power Spectrum

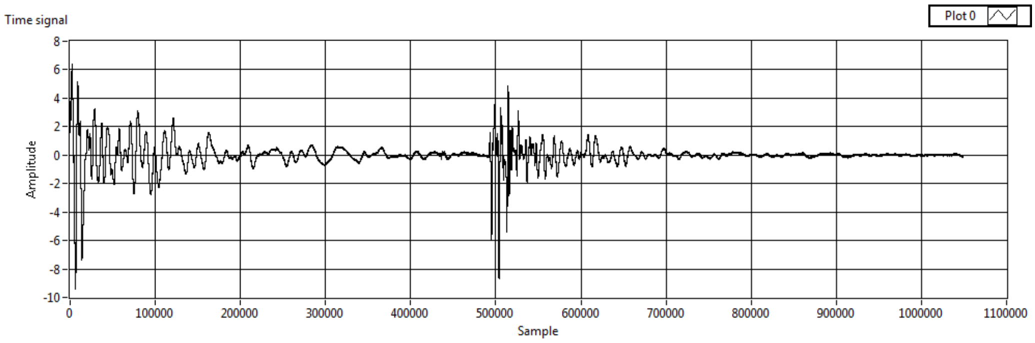

Figure A.17: Tool-knock Time Signal

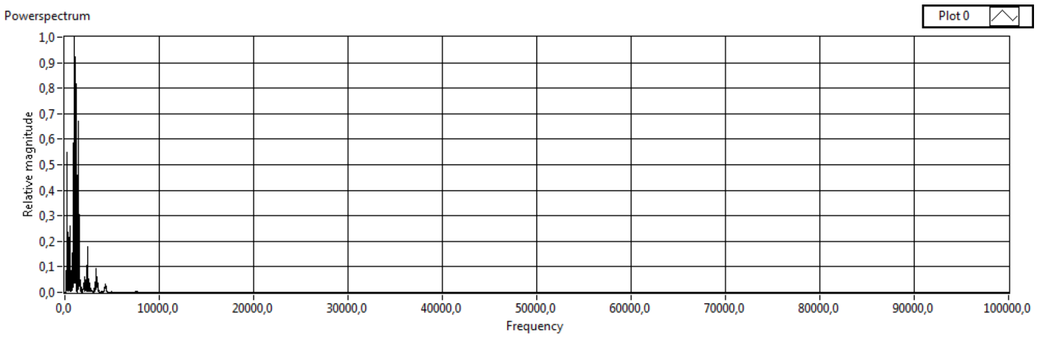

Figure A.18: Tool-knock Power Spectrum

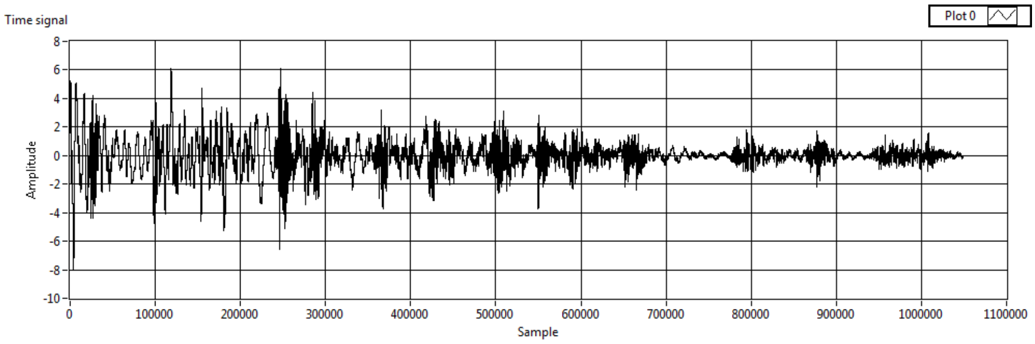

Figure A.19: Keydrop Time Signal

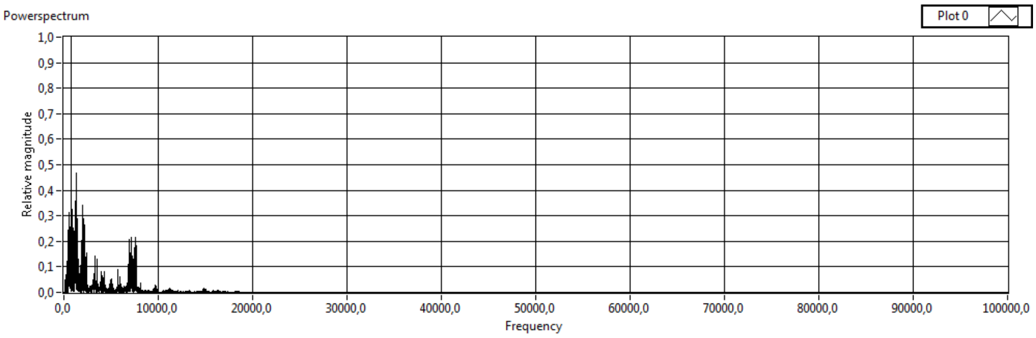

Figure A.20: Keydrop Power Spectrum

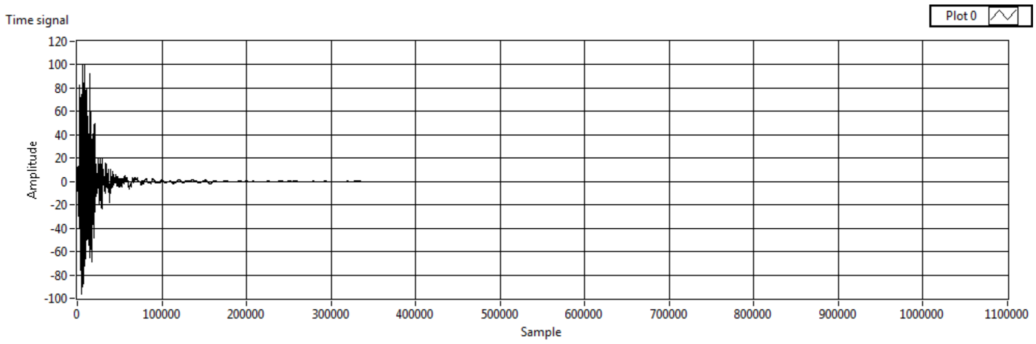

Figure A.21: Coin Snap Time Signal

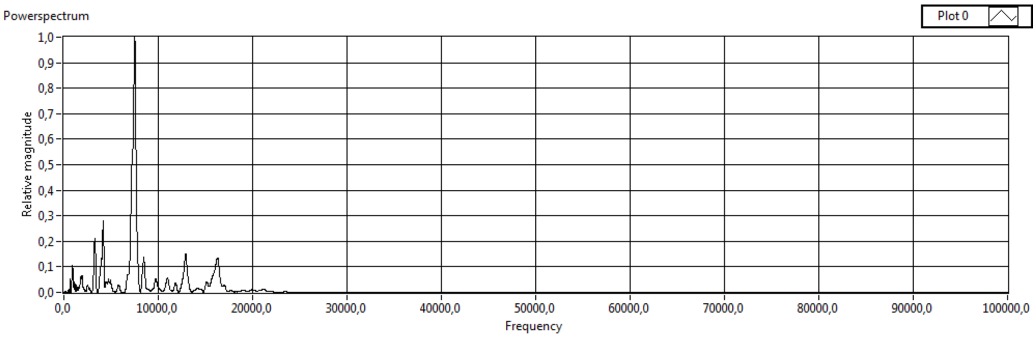

Figure A.22: Coin Snap Power Spectrum

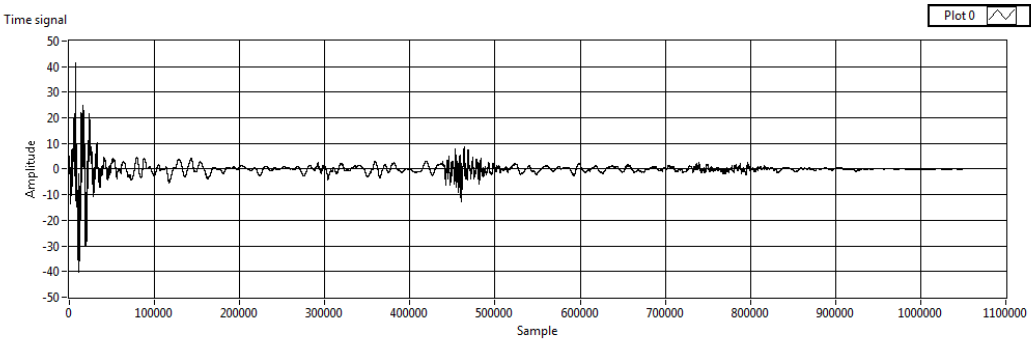

Figure A.23: Hammer Strike Time Signal

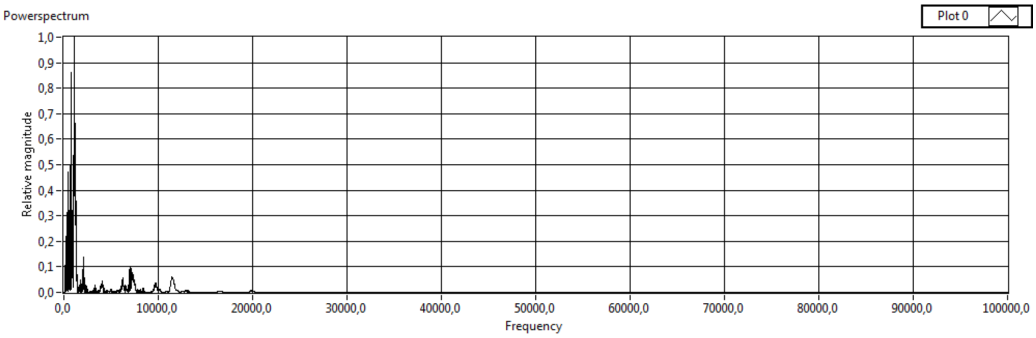

Figure A.24: Hammer Strike Power Spectrum

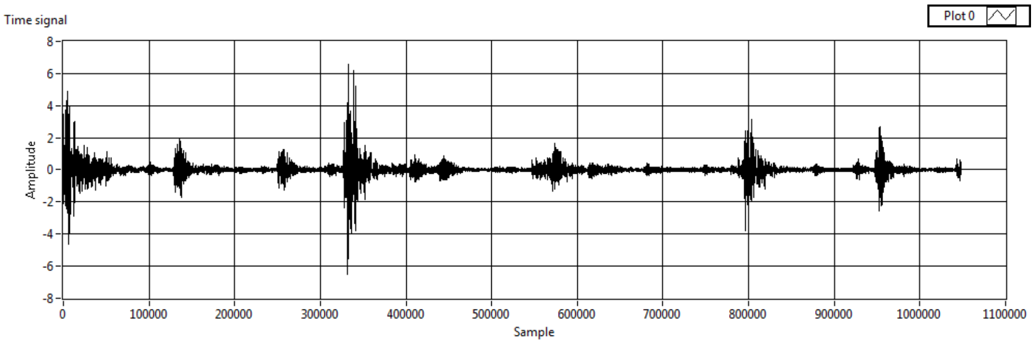

Figure A.25: Break Time Signal

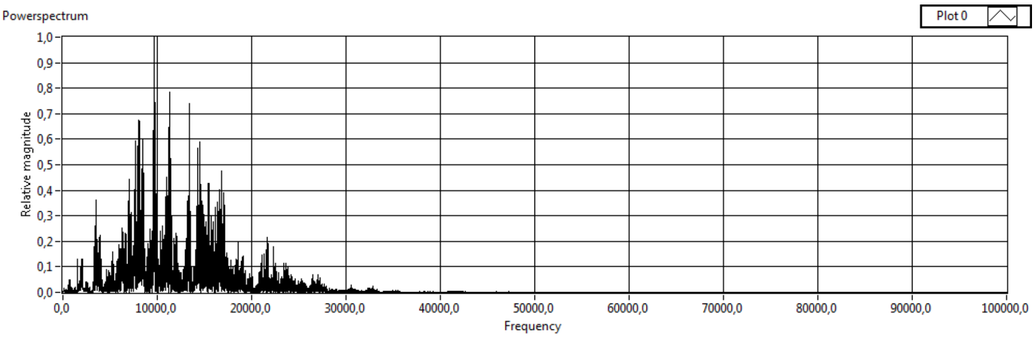

Figure A.26: Break Power Spectrum

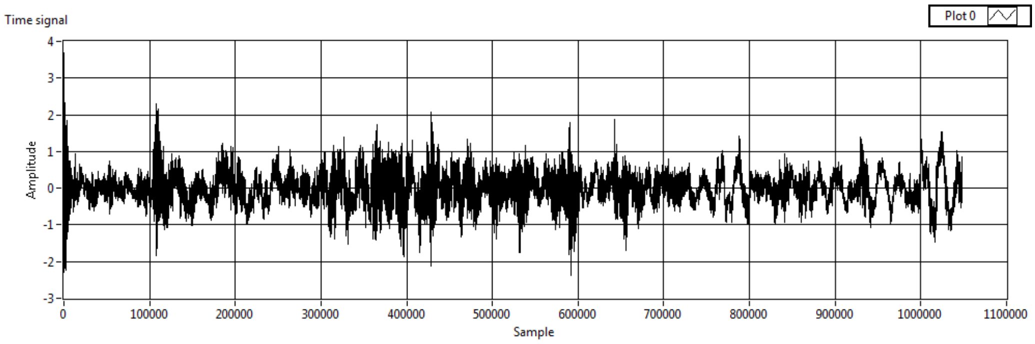

Figure A.27: Saw Time Signal

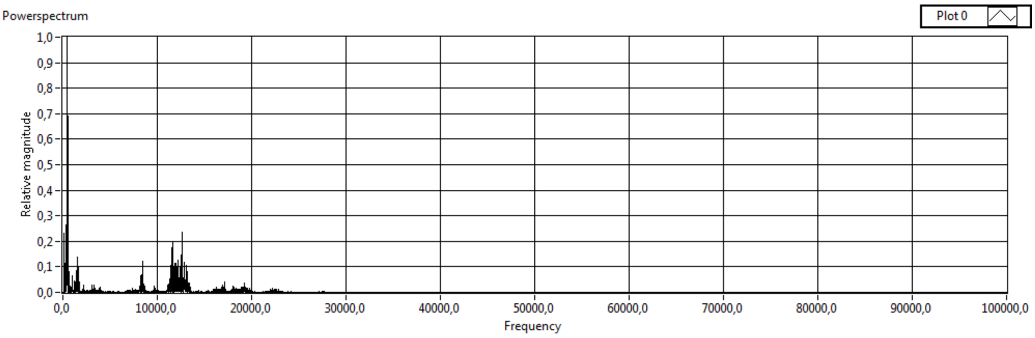

Figure A.28: Saw Power Spectrum

A.3 Glass

A.3.1 Piezoelectric Element

Please note, that for displaying purposes, the magnitude of the power spectrums in this section is scaled 10:1.

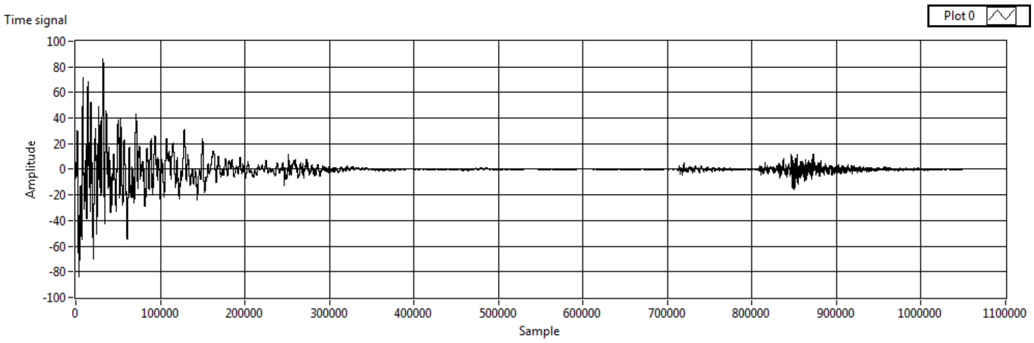

Figure A.29: Tool-knock Time Signal

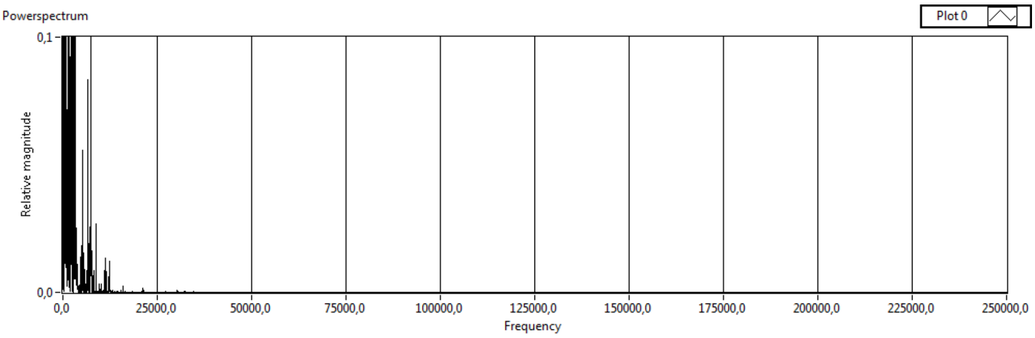

Figure A.30: Tool-knock Power Spectrum

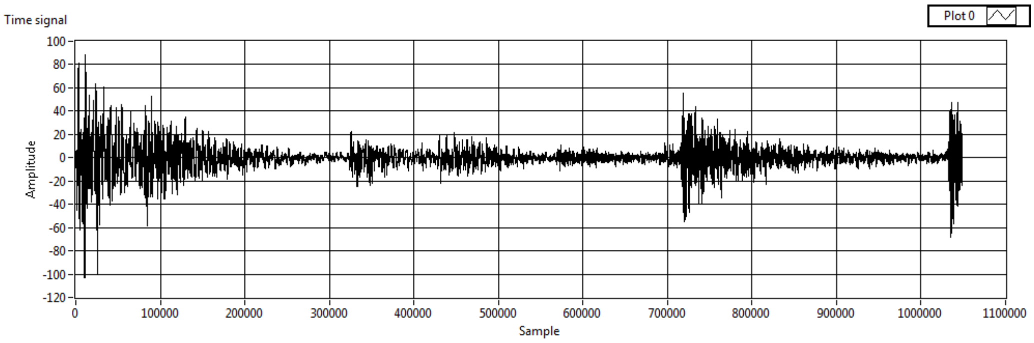

Figure A.31: Keydrop Time Signal

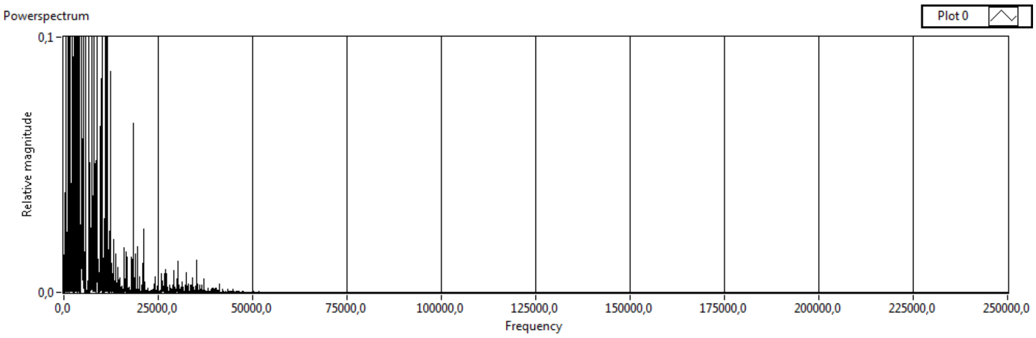

Figure A.32: Keydrop Power Spectrum

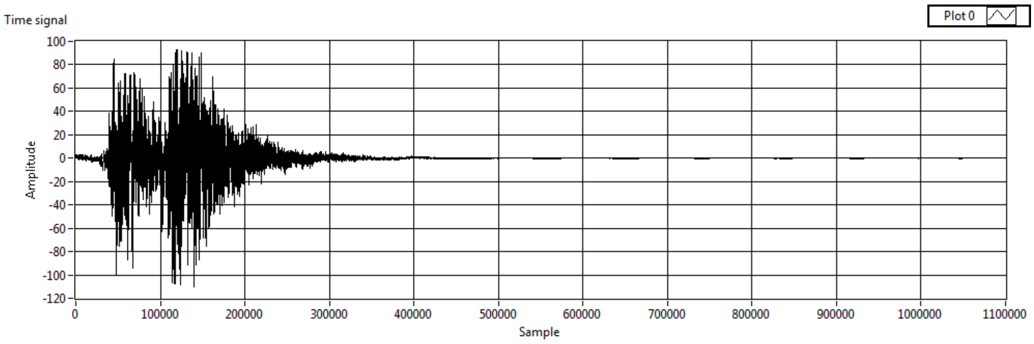

Figure A.33: Coin Snap Time Signal

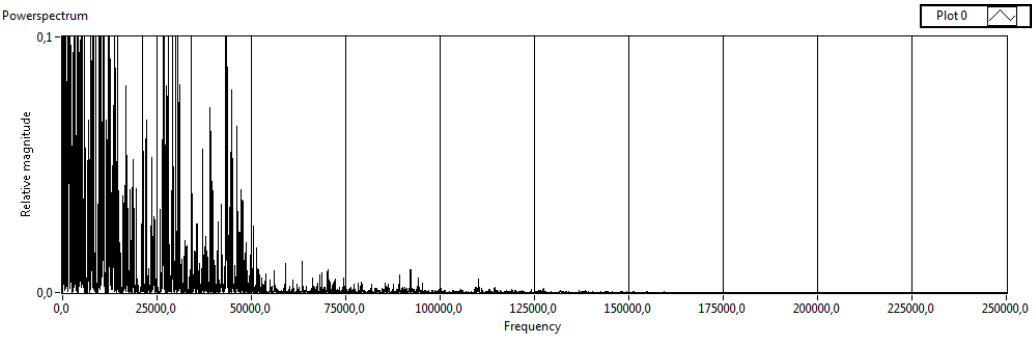

Figure A.34: Coin Snap Power Spectrum

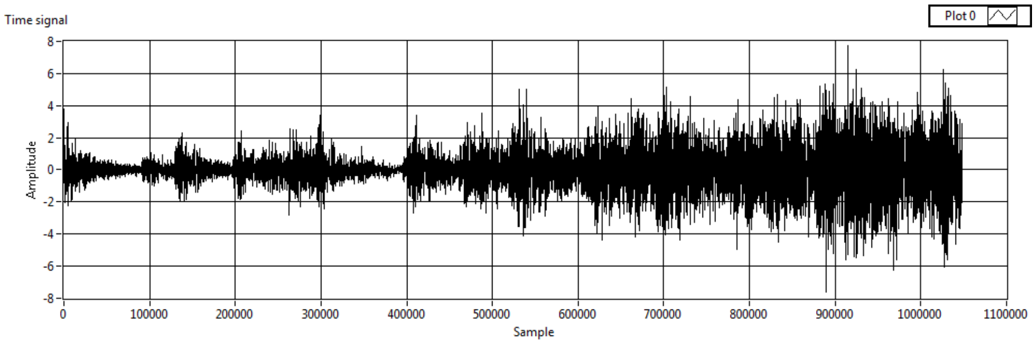

Figure A.35: Glass Cutting Time Signal

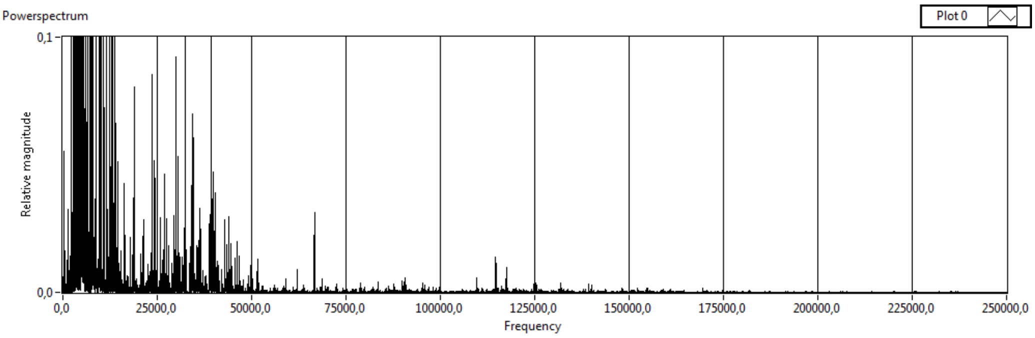

Figure A.36: Glass Cutting Power Spectrum

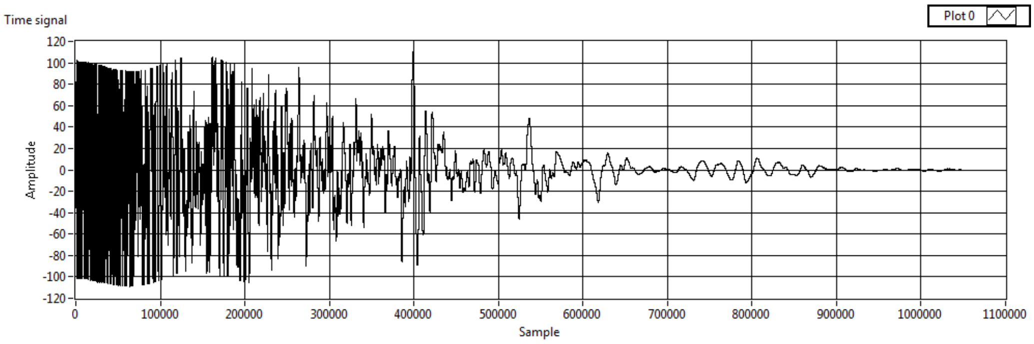

Figure A.37: Glass Breaking Time Signal

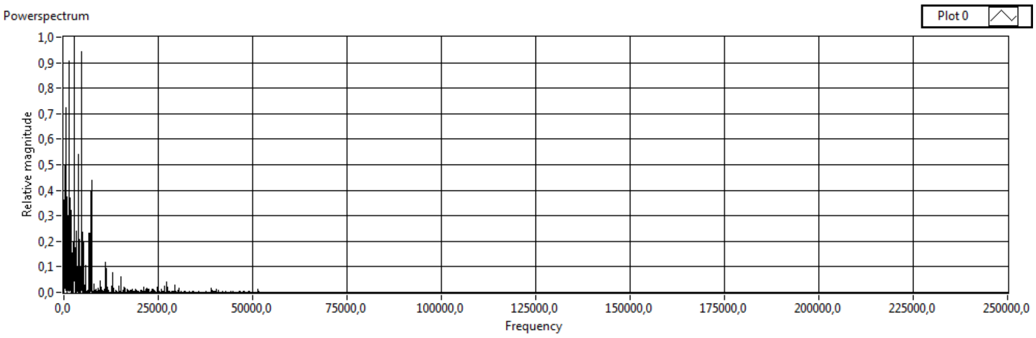

Figure A.38: Glass Breaking Power Spectrum

A.3.2 GlassAlert^{TM}

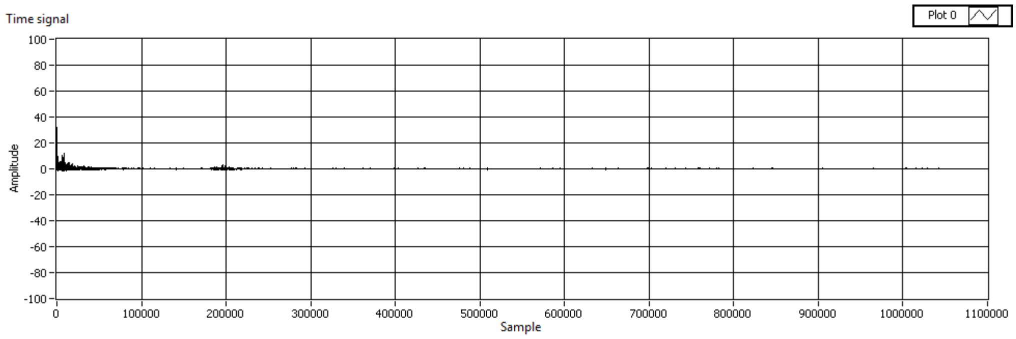

Figure A.39: Tool-knock Time Signal

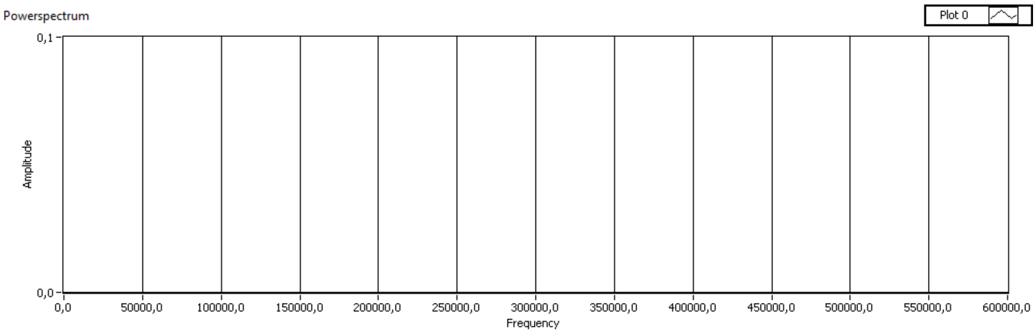

Figure A.40: Tool-knock Power Spectrum

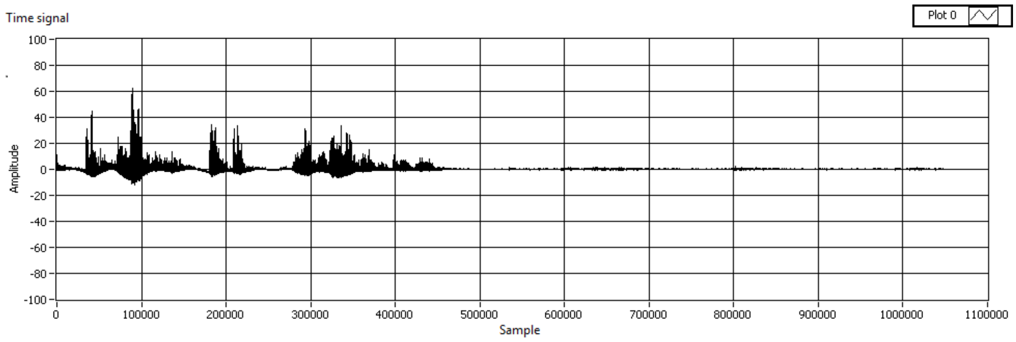

Figure A.41: Keydrop Time Signal

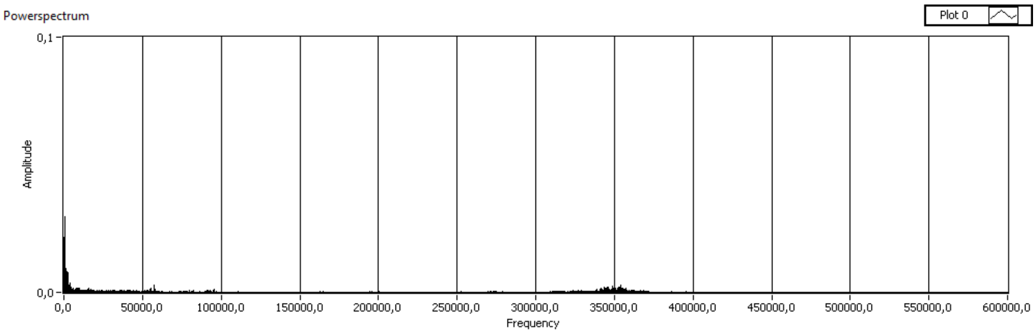

Figure A.42: Keydrop Power Spectrum

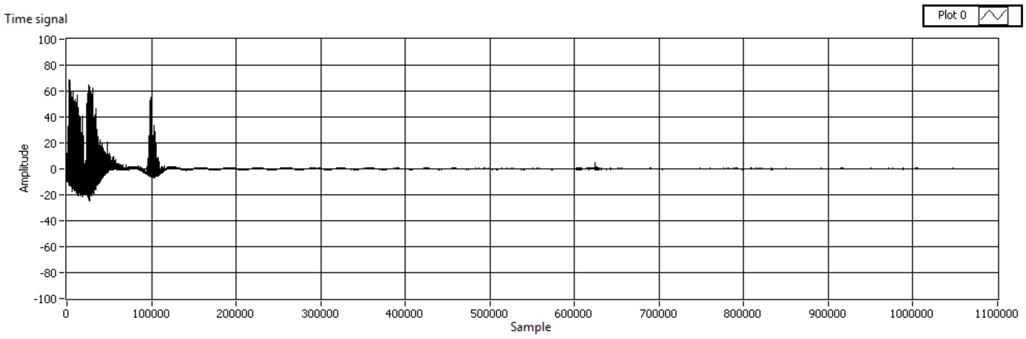

Figure A.43: Coin Snap Time Signal

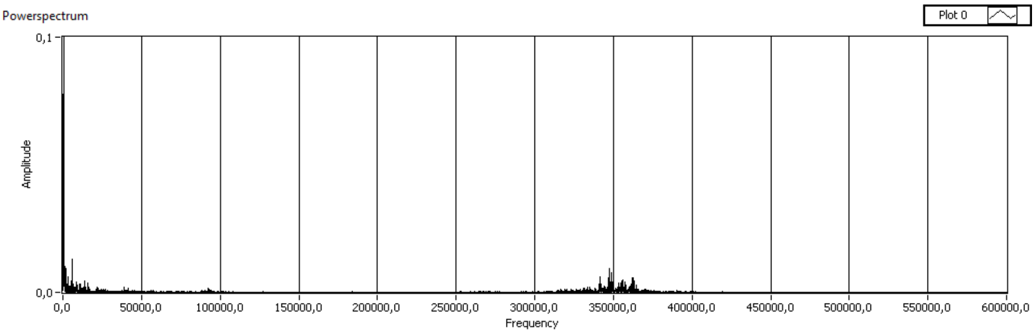

Figure A.44: Coin Snap Power Spectrum

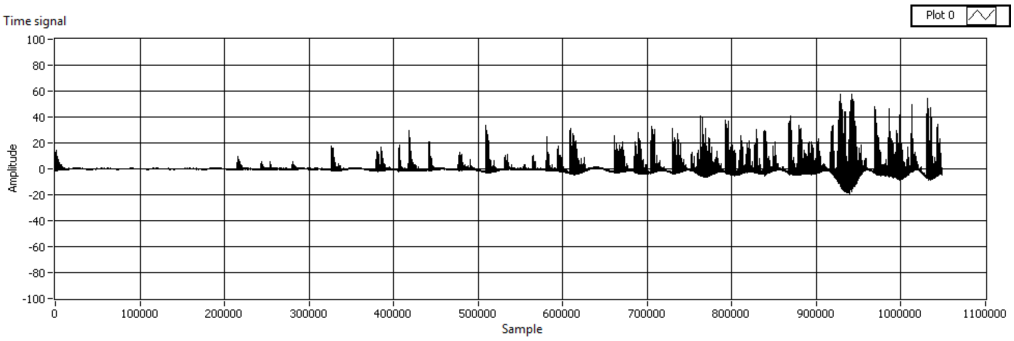

Figure A.45: Glass Cutting Time Signal

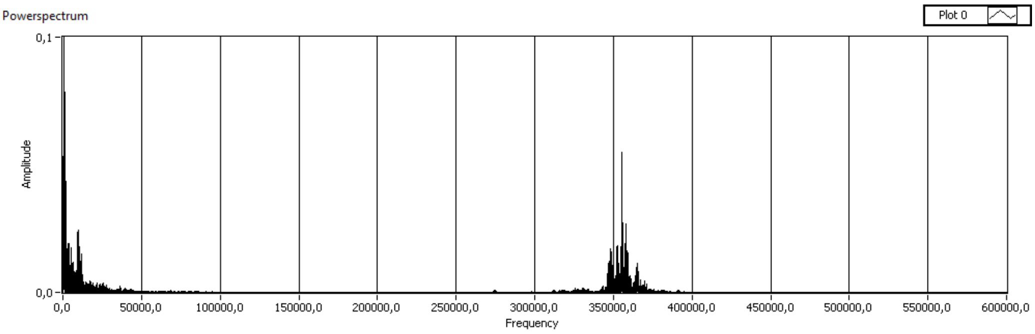

Figure A.46: Glass Cutting Power Spectrum

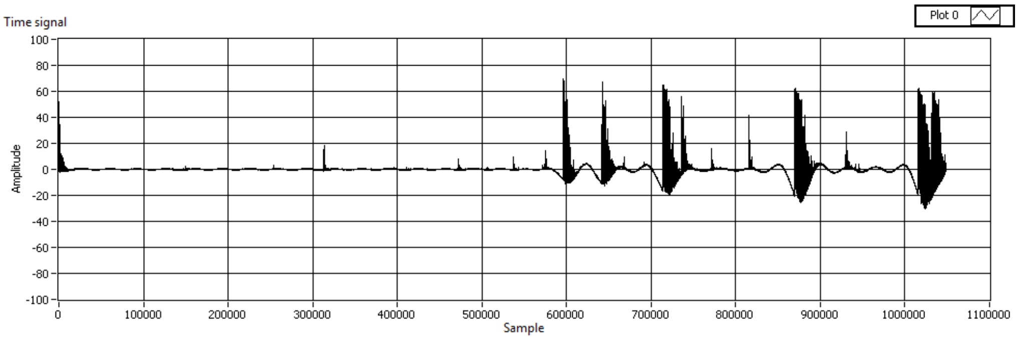

Figure A.47: Glass Breaking Time Signal

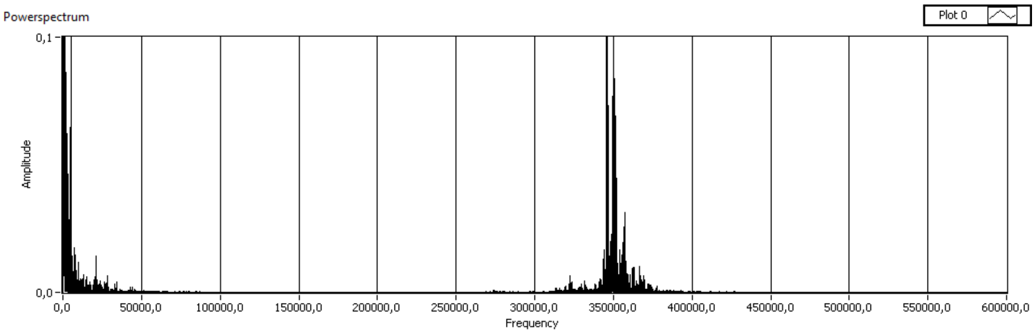

Figure A.48: Glass Breaking Power Spectrum

A.4 Metal

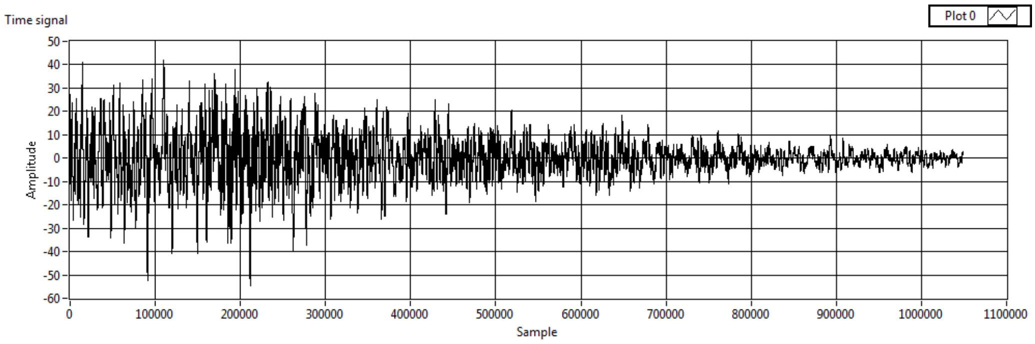

Figure A.49: Keydrop Time Signal

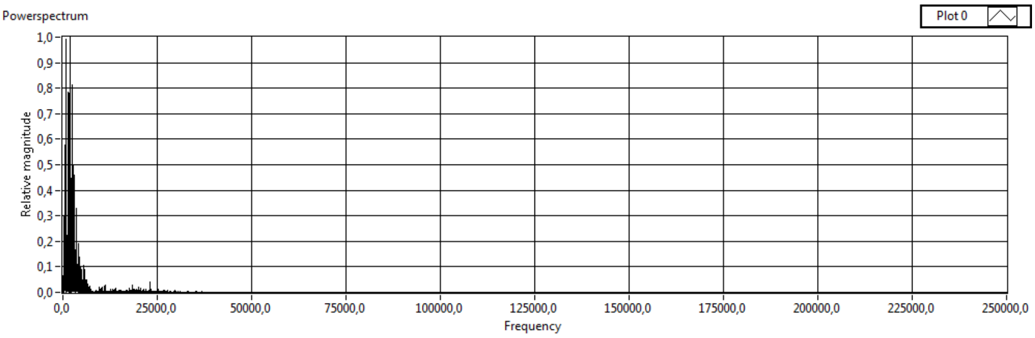

Figure A.50: Keydrop Power Spectrum

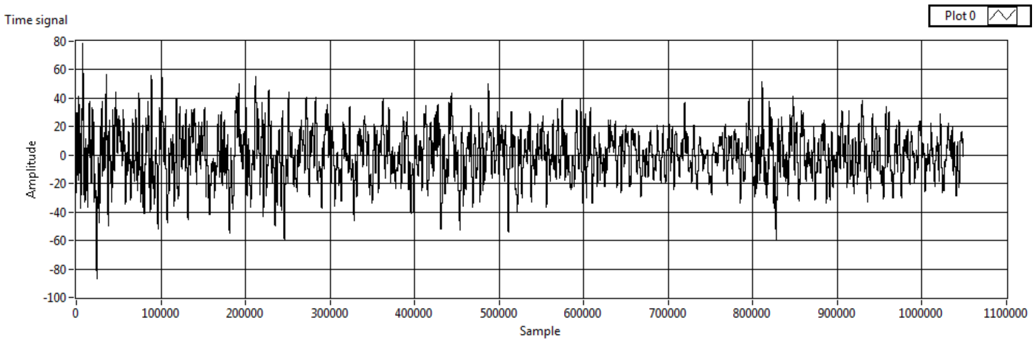

Figure A.51: Hammer Strike Time Signal

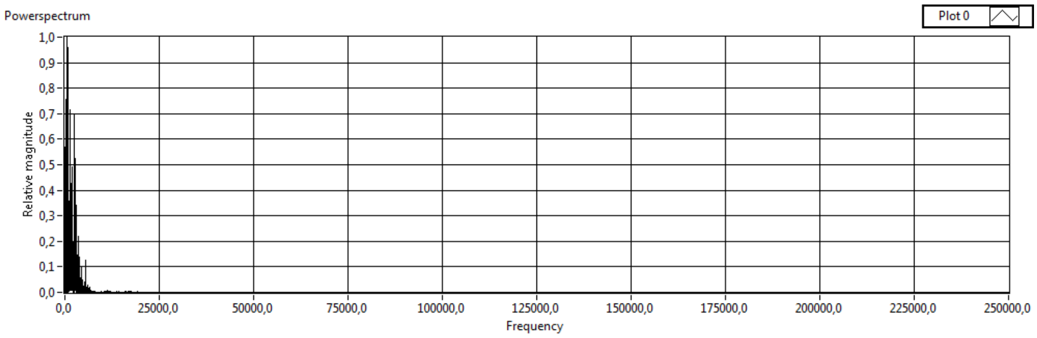

Figure A.52: Hammer Strike Power Spectrum

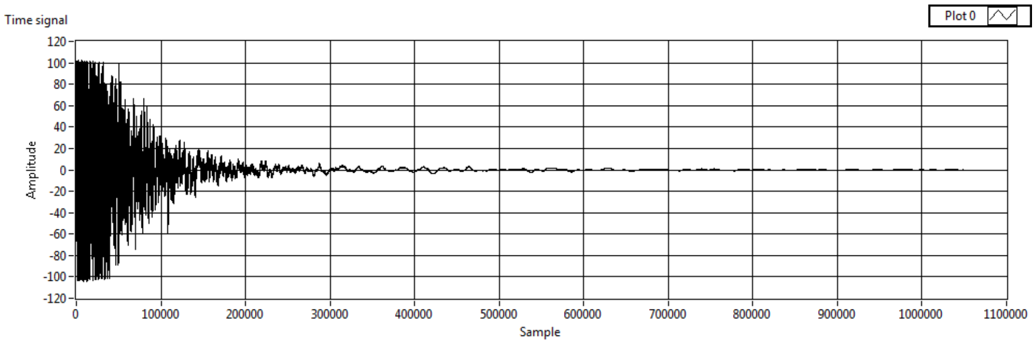

Figure A.53: Coin Snap Time Signal

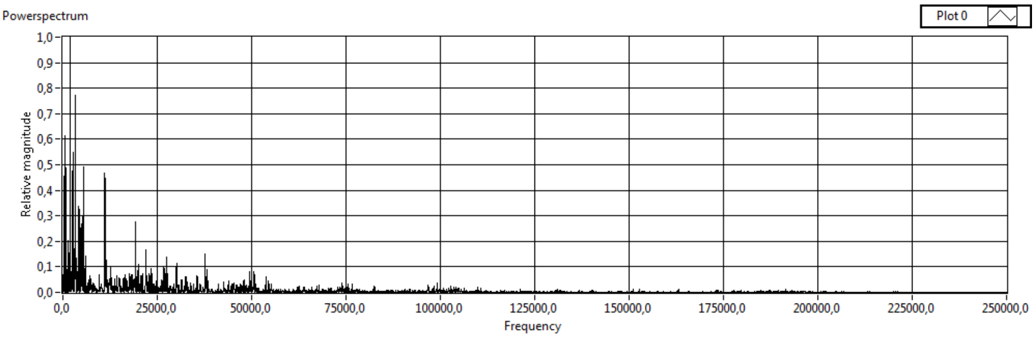

Figure A.54: Coin Snap Power Spectrum

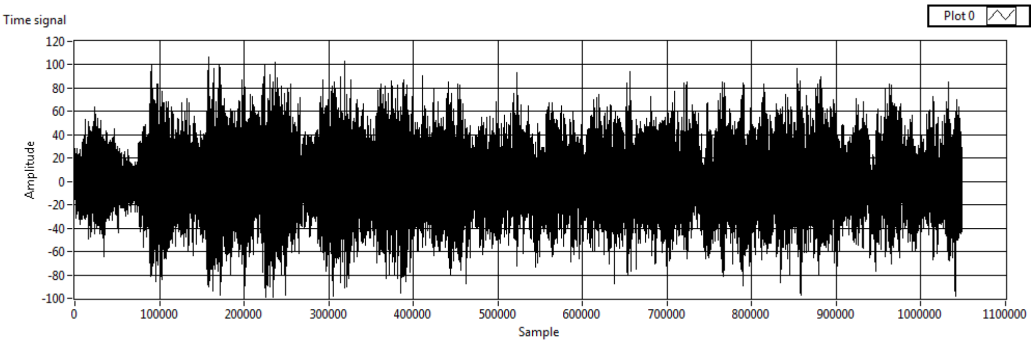

Figure A.55: Angle Grinder Time Signal

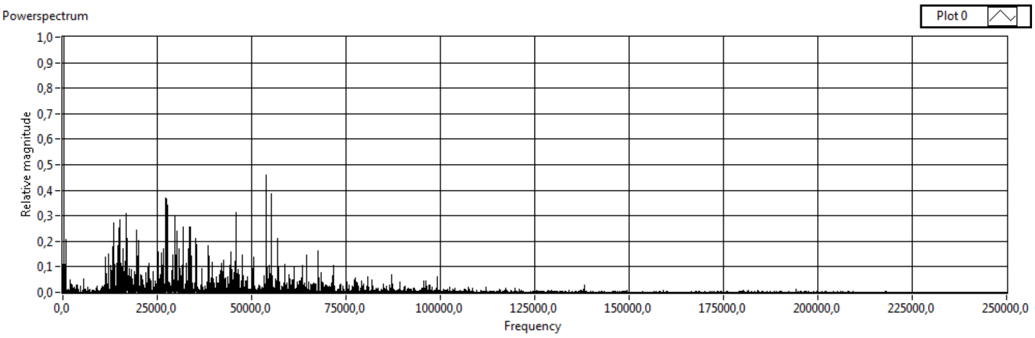

Figure A.56: Angle Grinder Power Spectrum

Appendix B

Flow Charts

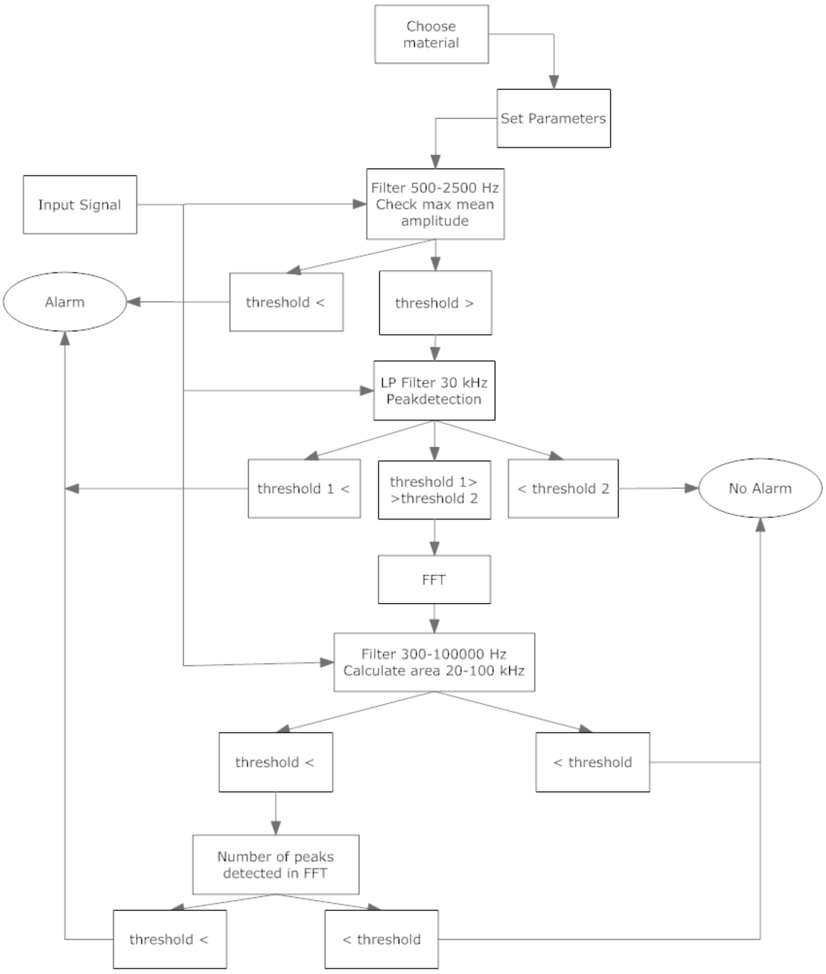

Figure B.1: Flow chart of the wood detector

Figure B.2: Flow chart of the glass detector