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2017

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VIABILITY STUDY OF ACOUSTIC EMISSIONS FOR PRODUCTION TESTING OF A UPS ASSEMBLY

Examiners: Prof. Pertti Silventoinen, Dr. Tommi J. Kärkkäinen

Abstract

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34 pages, 14 figures
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Supervisor: Dr. Tommi J. Kärkkäinen
Keywords: acoustic emission, production testing, non-destructive testing

Acoustic emission testing has been used for health monitoring of bearings and large structures like bridges. Recent studies examined the acoustic emissions of insulated gate bipolar transistors and ceramic capacitors. In both studies damaged components could be told apart from the pristine ones with the acoustic emission testing. This thesis takes the acoustic emission testing to a bigger scale: The viability of using acoustic emissions for production testing of a fully assembled UPS is studied. The UPS used in the study is Eaton 93PS 10 kW.

In this thesis the acoustic emissions are studied outside the UPS enclosure. Detection of simple defect, a removed screw, is attempted with two experiments. The first experiment uses an external impact from a pendulum construction as the source of the acoustic emissions. On the second experiment the UPS unit is the source of the acoustic emissions as it's running idle and a 6kW load. The measurement setup consists of acoustic emission sensor, preamplifier and oscilloscope. The recorded data is analyzed using spectral density estimates and spectrograms.

It was found that the UPS emits acoustic emissions when in operation and they can be told apart from the electromagnetic interference. With the first experiment it was verified that it is possible to detect a missing screw with acoustic emissions. On the the second experiment it was found that the acoustic emissions emitted by the UPS vary considerably within the same measurement conditions and so the missing screws were not detected. With these findings using acoustic emissions for production testing outside of the fully assembled device is not found viable. It is recommended that such acoustic emission testing would take place closer to the source of the emissions, inside the UPS units enclosure.

Tiivistelmä

Lappeenranta University of Technology
LUT School of Energy Systems
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Juuso Rautio
Soveltuvuustutkimus akustisten emissioiden käytöstä UPS:n tuotantotestauksessa
Diplomityö
2017

Tarkastajat: Prof. Pertti Silventoinen, TkT Tommi J. Kärkkäinen
Ohjaaja: TkT Tommi J. Kärkkäinen
34 sivua, 14 kuvaa
Hakusanat: akustinen emissio, tuotetestaus

Akustisiin emissioihin perustuvia mittauksia on käytetty perinteisesti erilaisten laakereiden ja suurten rakennelmien, kuten siltojen, kunnon monitoroimiseen. Viimeaikoina on tutkittu elektronisten komponenttien, keraamisten kondensaattoreiden ja eristehilabipolaaritransistorien akustisia emissioita. Molemmissa tapauksissa viallisia komponentteja on tunnistettu niiden akustisten emissioiden perusteella. Tutkimuksessa arvioidaan akustisten emissioiden käyttöä täysin kootun UPS laitteen tuotantotestauksessa. Tutkittu laite on Eaton 93PS 10 kW.

Tässä diplomityössä akustisia emissioita tutkitaan laitteen peltikuoren ulkopuolelta käsin. Tutkimus koostuu kahdesta kokeesta, joissa akustisten emissioiden lähteenä käytetään ulkopuolista heiluria sekä itse UPS laitetta sen toimiessa tyhjäkäynnillä ja kuormitettuna 6 kW:lla. Molemmissa kokeissa yritetään tunnistaa kotelosta irroitettu ruuvi mittausten perusteella. Mittausjärjestelmä koostuu akustisten emissioiden anturista, esivahvistimesta ja oskilloskoopista. Mittauksia analysoidaan spektrogrammeina ja tehospektreinä.

Mittausten perusteella UPS tuottaa akustisia emissioita ollessaan toiminnassa ja nämä emissiot voidaan erottaa sähkömagneettisista häiriöistä. Heilurikokeen perusteella irroitettu ruuvi on mahdollista tunnistaa mittauksista. Toisessa kokeessa irroitettuja ruuveja ei voitu tunnistaa. Samojen mittausryhmien sisällä huomattiin merkittäviä eroavaisuuksia ja siten eroja ruuvillisten ja ruuvittomien mittausten välillä ei voitu tunnistaa. Näiden kokeiden tulosten perusteella akustisten emissioiden käyttöä valmiin UPS:n tuotantotestauksessa ei suositella. Mittauksia suositellaan tehtävän lähempänä akustisten emissioiden lähdettä laitteen sisällä.

Acknowledgements

First of all I want to thank my supervisor Dr. Tommi J. Kärkkäinen and all the other guys at the Laboratory of Applied Electronics for helping me conduct this research. Thank you Pertti for examining the thesis and reeling me in for the doctoral studies.

I also want to thank the guys at Eaton for providing the subject for this thesis. The research has proved to be a rewarding learning experience. I hope the results of the study are of use to you.

Juuso Rautio
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Lappeenranta, Finland

Contents

Abbreviations

AE - Acoustic emissions

EMI - Electromagnetic interference

NDT - Non-destructive testing

UPS - Uninterruptible power supply

1 Introduction

The objective of this research is to investigate if acoustic emissions (AE) can be used as a way of production testing on the Eaton 93PS series uninterruptible power supply (UPS). In this thesis production testing means the quality assurance of for example the assembled UPS unit. What phonomena can be verified using AE method is evaluated. The focus on the research is on studying the acoustics of the UPS unit from the simplest phenomenon up.

Uninterruptible power supplies provide emergency power in case of its input power source failing for example during a blackout. They store energy in batteries, supercapacitors or flywheels. The internal energy storage capacity is not high, in case of the Eaton 93PS the batteries can run nominal load for around 10 minutes depending on which battery option is installed. UPS runs the load through short power cuts or in case of a longer blackout it acts as a buffer before a backup generator is started. Another function of a UPS is power conditioning and so protecting its load from anomalies in the mains voltage.

Today the amount of energy demand is expected to rise significantly. More and more electricity generation is done with wind and solar power plants (IEA, 2016). A case study by Su et al. (2016) shows that a large percent of wind turbine failures in China are related to electrical component failure, for one control group the percent is higher than that of mechanical failures. The failure modes caused by electrical components failing were also severe, meaning imminent disruption of wind power generation (Arabian-Hoseynabadi et al., 2010). Production testing of components and final products can make failures less possible if defects, that lead to failures, are detected early on. The success of such testing depends on how precise the testing method is and how well the source of the failure is known.

Non-destructive testing (NDT) is an examination performed on a test object without changing the object itself to determine conditions that may have an effect on the usefulness of the said object. NDT is a part of every major industry: Individual parts and ready build products are tested in the assembly and before they are shipped to the customer, especially if a product failure can result in accidents (Hellier, 2012). The more commonplace term for NDT in the industry is production testing. Production testing is a form of quality control and it offers financial savings due to less faulty or soon-to-be broken units reaching the consumer.

Acoustic emission testing is considered unique among the non-destructive testing methods as it is usually applied during loading. Most other methods are applied before or after the loading. Acoustic emission can be used to detect the emerging failure before the structure fails, which makes it very useful for system health monitoring in addition to production testing (Grosse et al., 2008). The test setup used in acoustic emission testing is simple compared to most other methods. It consists of a acoustic emission sensor, preamplifier, AD converter and data analysis tools. This makes implementing the setup easy and cheap which makes using acoustic emissions for production testing very desirable. The phrase ”Acoustic emission” is misleading since most of the acoustic emissions in these tests are not audible to humans. The emissions are usually in the 20 kHz - 2 MHz ultrasonic frequency range.

The general idea behing all acoustic emission related testing, production testing included is that a defect causes noticeable differences to the acoustic emissions due to changing the acoustics of the system. Acoustic emission waves moving through the material will lose their energy. They will also reflect, at least partly, at the interfaces of the structure (Müller, 2007) (Nazarchuk et al., 2017). Reflections can be generated also within discontinuities in the material itself (Burrascano et al., 2015). The possible reflections and attenuation can be detected and used to identify a defect that caused it.

The use of acoustic emissions in non-destructive testing is not a new venture. It was originally developed for health monitoring of static structures and later on extended for rotating machines and bearings. (Mba, 2003) Recently using acoustic emission NDT for power electronic components such as insulated gate bipolar transistors (Kärkkäinen et al., 2014a) and ceramic capacitors (Levikari et al., 2017) has been studied. It was found that the switching transient in a power semiconductor module causes an acoustic emission (Kärkkäinen et al., 2014a,b). Levikari et al. (2017) found that cracks in ceramic capacitors cause changes to the capacitor acoustic response. A correlation between acoustic emissions and semiconductor power module health state has also been found (Müller et al., 2016). Therefore it might be possible to observe these acoustic emissions on a larger scale where the device under test is not a single component but instead a complete assembled device. These emissions may also be used to detect faults in either the components or the assembly. Production testing on the UPS unit is meaningful as a UPS usually provides power in emergency situations and its operation is critical in preserving system functionality. For example a malfunction of the backup power system in a hospital environment would cause danger to human life. Of course more accurate and cheaper production testing will also save money.

1.1 Course of the research

The research question to be answered is: Can acoustic emission testing be used to find defects in fully assembled uninterruptible power supply?
To answer the research question, it needs to be determined if changes in the assembly of the 93PS UPS unit can be detected from its acoustic emissions. As this research is first of a kind to be conducted on this type of device the progression is started from a very basic level. As a first step the changes in assembly are easily reproduced and simple, a missing screw on the outer enclosure. At first an external force is used to produce the acoustic emissions. On the second experiment the UPS unit is in operation and its power electronics are the source of acoustic emissions. Conclusions and the answer to the research question are drawn from the experiment results.

2 Eaton 93PS

This section introduces the device under study and some of the measurement conditions. In this research a 10 kW variant of the Eaton 93PS UPS is used. This unit is part of the standard frame chassis product line where the power options range from 8 to 20 kW. Eaton also offers the same power variants on a smaller C-model frame and bigger units on which the output power ranges from 8 to 40 kW (Eaton, 2016). The unit used in the research has a battery installed.

Inside the metal outern shell of the UPS are multiple subsections reserved for different electrical components. For example lookin at the unit from the front there is a rectangular slot that houses a modular power module. This module comes in its own aluminium housing. There are also other vertical and horizontal panels that divide the insides of the main UPS shell into different partitions. The electrical operation is divided to multiple circuit boards mounted around on the dividing walls.

The unit is fed from a 400 V three phase mains power into its rectifier input. The unit also has a bypass input that is left without connections. During the measurements the UPS will run on double conversion mode. On double conversion mode the three phase mains power is first converted into DC and then back to AC for the output. The current path during double conversion mode is presented on figure 2.1 highlighted in bold black. The double conversion mode will also charge the connected batteries when they are not fully charged.

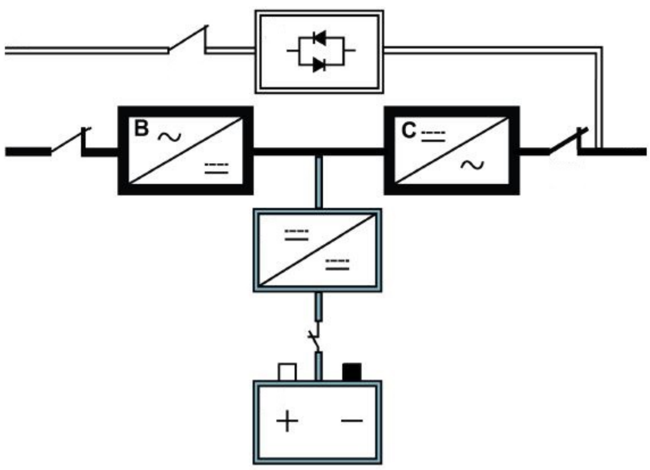


Figure 2.1: Current path through the UPS in double conversion mode, highlighted in black. Block B is AC to DC conversion and block C DC to AC conversion. (Eaton, 2016)

The three phase outputs are connected to a resistive load that consists of a 6 kW sauna heater. The heater is connected in wye configuration where it will draw the nominal 6 kW from the feeding UPS. Thermostat circuit on the sauna heater is bypassed so it acts as a constant 6 kW load and does not turn on and off by itself. This makes taking measurements easier as the load is kept constant. A block diagram of the heaters connected to the UPS can be seen on figure 2.2.

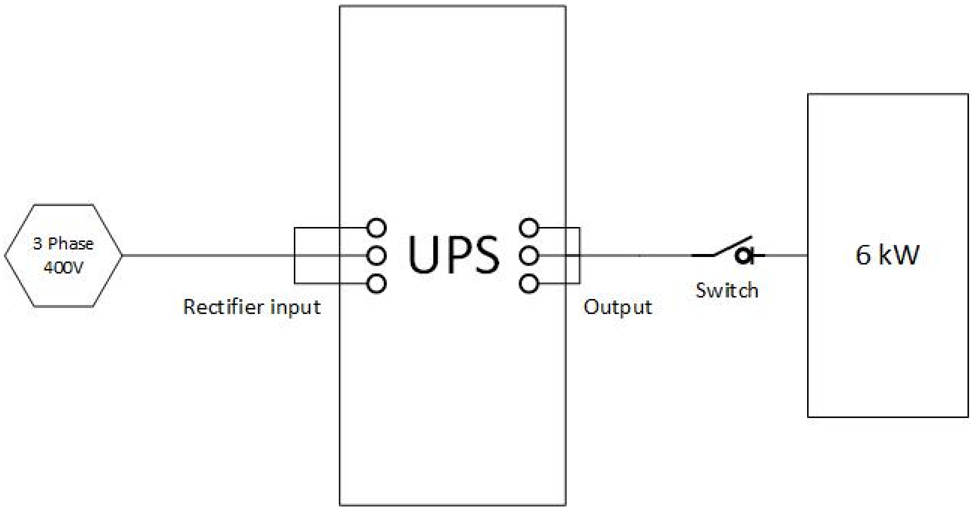


Figure 2.2: A block diagram of UPS rectifier input fed by three phase power and the heater connected as load to the UPS unit. The heater is connected to three phases with wye configuration.

In the measurements where the unit is operational either idle load or 6 kW load is used. As seen on the figure 2.2 the load is controlled with a switch.

3 Acoustic emission measurements

When performing acoustic emissions measurements the sensor placement is crusial due to attenuation and reflections of the acoustic emissions (Müller, 2007) (Nazarchuk et al., 2017). Attenuation and reflections become more probable as the distance and structures between the emission source and the sensor increase. This makes the sensor placement even more crusial when measurements are done on a large and mechanically complicated structures such as the UPS enclosure. With some placements certain frequencies of acoustic emissions may be undetected due to attenuation because all of the emission sources are not located near each other. In the study this was taken into account by taking measurements with multiple sensor placements.

The body of the UPS unit is made out of metal alloys. These alloys are not homogenous materials. The amount of acoustic emission generated by a material is highly dependent upon parameters like grain size, composition, impurity content and even its prior stress history (Mullin and Mehan, 1973). While this is applicable to stress testing of an item the same paremeters apply to the UPS as it is the medium for the waves to travel on. In addition the metal pieces of which the main body is made of are not geometrically uniform between individual units due to the accuracy of the manufacturing processes. The differences in materials and constructions are hard to estimate and they are likely to vary between different units. Without further research the micro scale differences in heterogeneous materials are assumed to be of smaller significance than the macro scale phenomena that are studied. Determining how significant unit to unit differences are to the acoustics of the system needs to be addressed in possible future research.

The measurement setup used on the research consists of acoustic emission sensor, preamplifier and oscilloscope. The sensors used are Kistler Piezotron 8152B111 piezoelectric type sensor and Mistras R15D. The sensors are rated for 50-400 kHz $\pm$ 10 dB for Kistler and 50-400 kHz for Mistras. Used preamplifiers are Kistler Piezotron Coupler type 5125B and Mistras 2/4/6. The oscilloscope used in the research is Agilent Technologies DSO6104A.

The two possible ways to approach the acoustic emission analysis are signal-based quantative and parameter-based classical analysis (Grosse et al., 2008). On classical analysis the full signal is not recorded and parameters like event count and count rate are tracked instead (Grosse et al., 2008) (Roberts and Talebzadeh, 2003). One example of such event is when a threshold voltage is crossed. This type of analysis works the best when the studied phenomenon is well-known. It is also useful in saving computational power. Due to the first observations nature of this research the signal-based analysis is more fitting as all of the data is available for analyzing. The analysis is not done in real time so constraints are not dictated by computational power. The most used tools in this research are spectral density estimates and spectrograms. Spectral density analysis showcases possible resonance peaks and it gives a general view on the frequency content of the acoustic emissions. Spectrogram analysis is an extension of the spectral density estimation as it shows time domain information in addition to the frequency content of the signal.

The objective of the first experiment is to investigate if it's possible to detect simple changes in the enclosure with an external stimulus. On the second experiment the UPS unit is powered and it will drive various loads. This will act as an internal stimulus for acoustic emissions. A screw that is removed from the UPS enclosure is used as a defect to be identified on both of the experiments. A screw will be removed from multiple locations on the enclosure and its effect on the acoustic emission signature is studied.

4 External stimulus

For the first experiment a repeatable external stimulus was needed. A pendulum structure was created to be a source of repeatable external stimulus. The pendulum proved to be the best at being repeatable with other options being a plastic hammer and a magnet. The pendulum consist of a fishing sinker and wire hanging from the roof. The surface of the sinker is not completely smooth which adds uncertainty to the impact with the UPS back panel due to possibility of different sized impact areas. A large bearing ball is a better alternative but attaching it to the wire is hard and such large bearing balls were not available for use. A functional drawing of the external stimulus measurement setup is presented on figure 4.1.

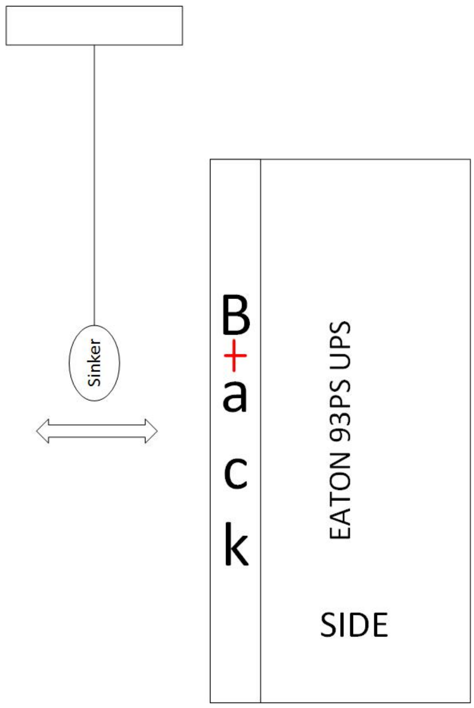


Figure 4.1: The pendulum construction used for the external stimulus used to generate acoustic emissions by swinging the sinker against the impact point symboled by red cross on the back panel of the UPS unit.

On the experiment the pendulum is taken to a designated position on which it is then released. The sinker hits a fixed position on the back panel of the UPS, creating elastic waves into the UPS enclosure. The generated emissions are recorded with acoustic emission sensor connected to a preamplifier and oscilloscope. The sensor placements and impact point can be seen on figure 4.2 and 4.3.

Figure 4.2: On the left the front view of UPS unit. On the right the sensor location on the front panel with a screw to be removed highlighted with blue circle. The screw is labeled A for identification.

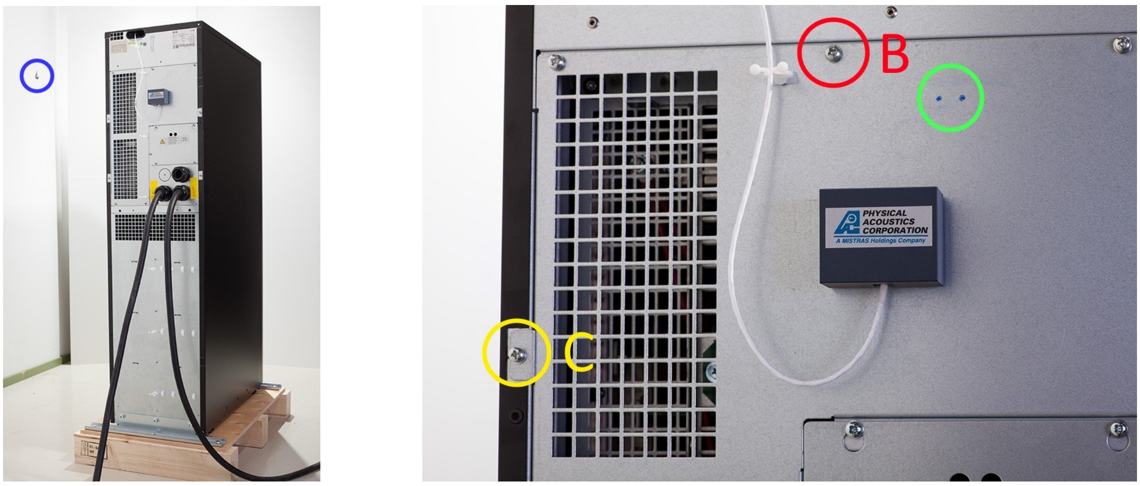


Figure 4.3: On the left the back side of the UPS with the pendulum sinker circled in blue. On the right the impact area marked with a marker (green), sensor location and the screws that are removed for the matching measurements (red and yellow). The removed screws are labeled B (red) and C (yellow) for identification.

The point of impact is located on the back panel of the UPS unit while the AE sensor is located on the front panel. This way the elastic waves travel through the whole unit before reaching the sensor. The Kistler sensor is attached to a screwhole on the power module. An original screw on the panel was replaced with a longer one to fasten the sensor to the surface. It is to be noted that the longer distance the elastic waves travel the more they are attenuated. Higher frequency components attenuate faster than low frequency ones (Grosse et al., 2008). This leaves the sensor placement another variable in the acoustics of the system.

The impact point was chosen for it generated a strong signal. The impact area is limited to be 1.1 cm wide by marking it. With every measurement the impact area is monitored by watching where the sinker makes contact with the UPS unit. After that the waveform is checked for anomalies. Within this area measurements had consistent waveforms on the oscilloscope screen. Any impact outside of the area or one that had a noticeably different waveform was discarded. An example of a discarded result is a double hit due to the uneven surface of the pendulum. These double hits were rare and they were easy to tell apart from the accepted cases. The release point of the pendulum was controlled by releasing it from approximately the same height and distance. The way the pendulum is released from the measurers hand has an effect on the rotation and speed of the pendulum. This adds uncertainty. As an example two sets of 6 measurements are plotted on figure 4.4. The plots represent the root mean square value of the signals voltage at the time specified on the x-scale. The red plot is for all screws fastened and black plot for when screw B was removed from the back panel.

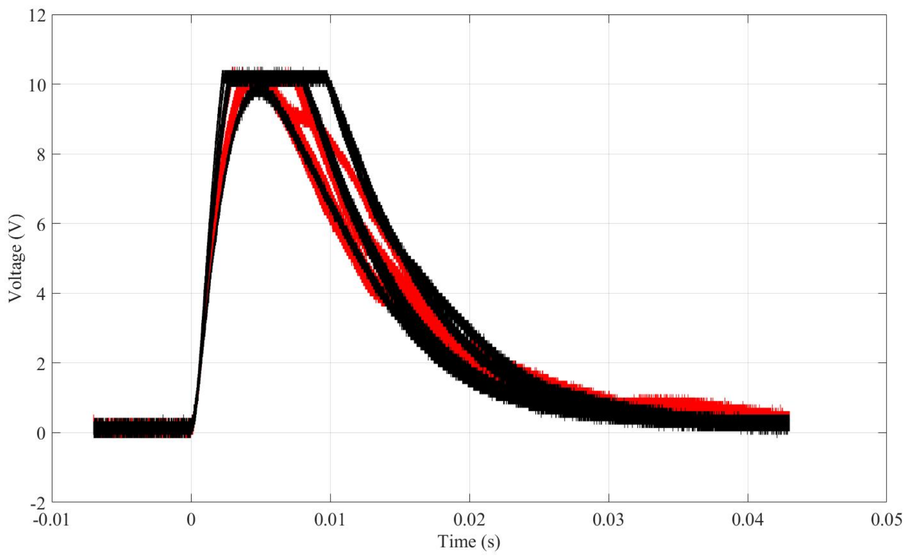


Figure 4.4: Root mean square plots of 6 measurements for each case: all screws fastened in red and screw B removed from the back panel in black.

It is seen that the waveform is close to uniform and the differences are on the amplitude. Some of the measurements were discarded later because the RMS plot showed clipping.

The clipping happens because of the preamplifiers limited voltage output. As seen on the figure 4.4 the different cases have similar RMS waveforms and they could not be reliably told apart from each other.

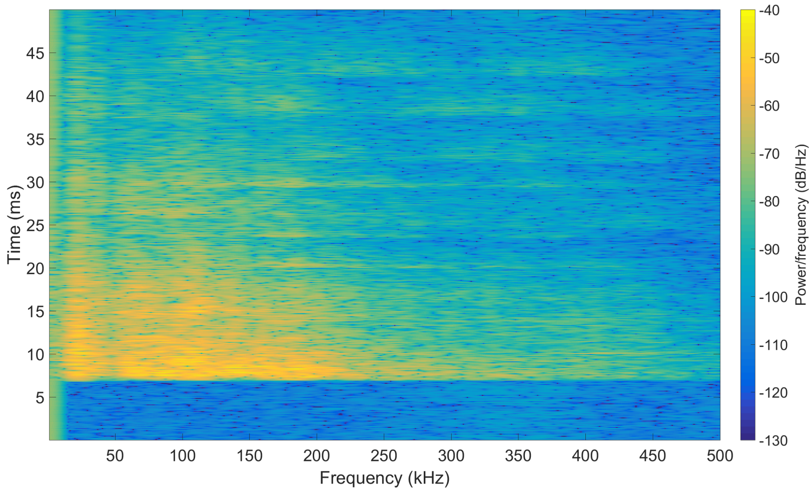
4.1 External stimulus results

10 measurements were taken for each case: All screws fastened, a screw from back panel removed and a screw from front panel removed. The sensor or the screws were not touched between measurements. The following spectrograms are generated in Matlab using the spectrogram function. The value of 20000 is used for the window parameter, dividing the spectrogram plot into 20000 segments which are then windowed with a Hamming window. For the number of overlapped samples the value of 10 is used. Each individual measurement contains eight million data points.

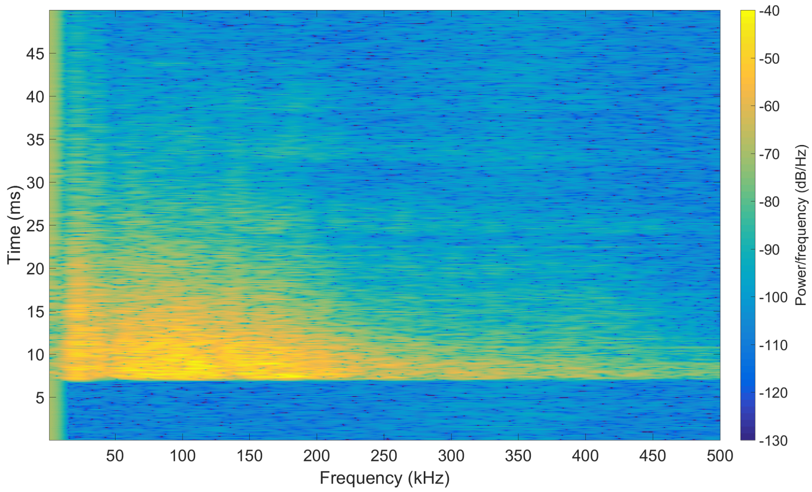
Figure 4.5a shows a spectrogram plot when all of the screws on the UPS body are intact. It can be seen that there is a echo-like behavior in the form of horizontal lines across the 100 kHz - 350 kHz frequencies. The emissions that form the lines are of short duration which makes the lines very thin and easy to identify visually. These echoes remain until 45 milliseconds on the graph. When screw B is removed from the back panel of the UPS unit and other measurement conditions are kept the same it can be seen from the figure 4.5b that the echoing energy is attenuated earlier. Particularly the energy from 200 kHz and up is attenuated. There are still horizontal lines that are repeated but they are not as numerous as when all the screws are fastened. There are two thicker areas of energy around 25 and 35 ms marks. These areas are also present on the figure 4.5a but there are also thinner areas of energy in between.

This behavior is consistent within the 10 measurements that share the same conditions. There is variance between individual measurements as seen on the figure 4.5c, but the differences to the figure 4.5a are still noticeable: The continuous horizontal lines are attenuated after 35 ms mark and particularly energy in the frequencies over 300 kHz is attenuated compared to the measurements with all screws intact. It is to be noted that the differences are not caused by a weaker initial signal getting to the sensor. As seen on figures 4.5b and 4.5c the initial impact energy is similar to the figure 4.5a. The looser connection of the back panel to the UPS main body does not reduce initial energy transferred all the way to the front panel where the sensor is attached.

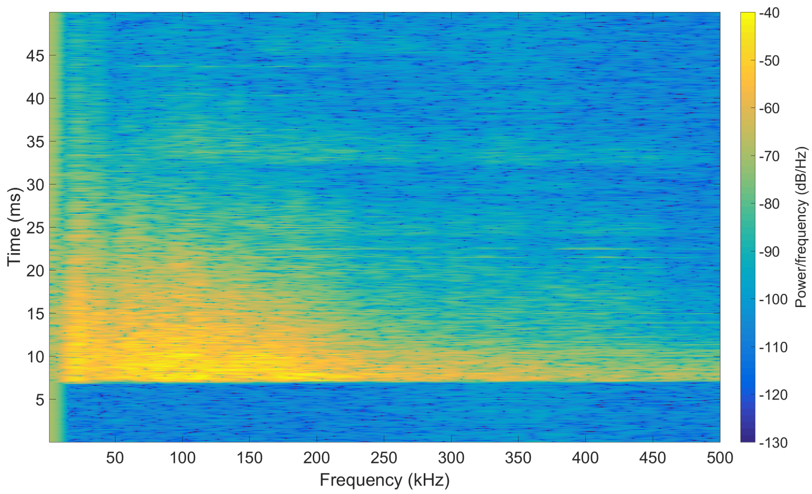
These results were verified using the other sensor: Mistras R15D with the appropriate preamplifier. A set of 10 measurements was taken. Figure 4.6a shows that energy around 150 kHz and 250 kHz is continuous and it persists over the 40 ms mark. Differences between measurements done with Kistler and Mistras sensors are apparent. Even though the specified frequency ranges are the same, 50 - 400 kHz, the Mistras spectrograms don't show significant energy above 250 kHz.



(a)

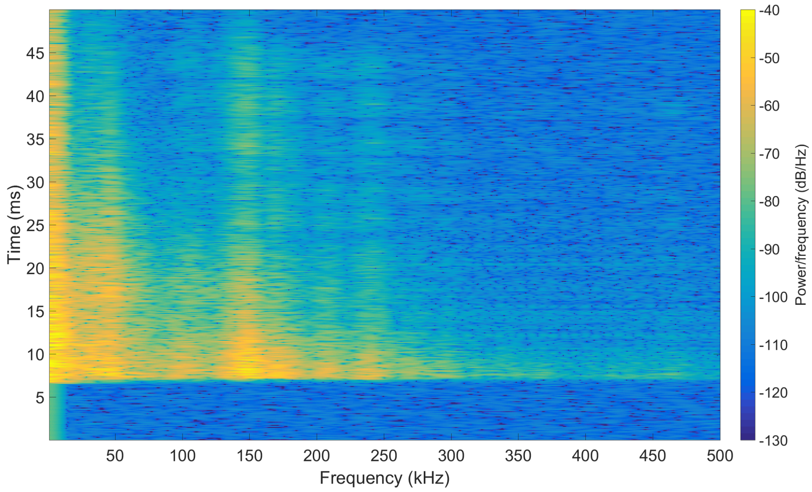


(b)

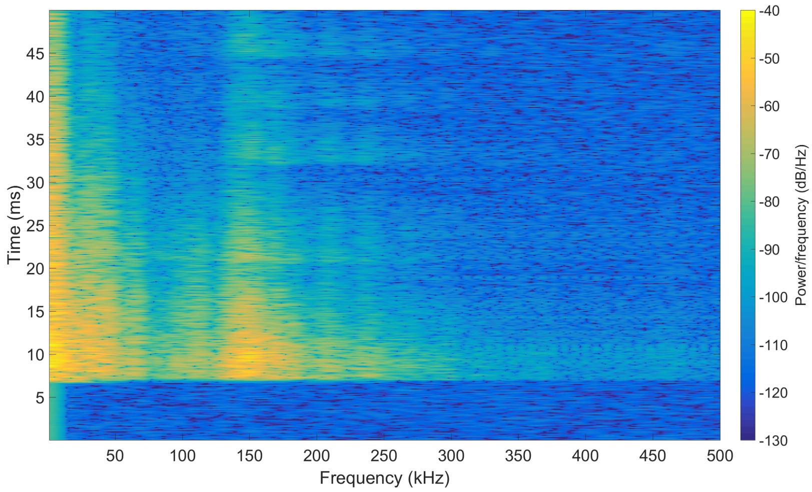


(c)

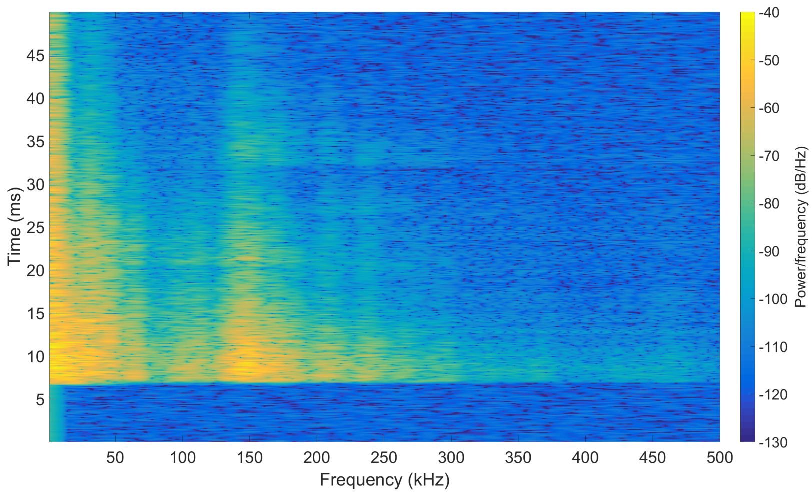
Figure 4.5: Spectrograms when using external stimulus with Kistler sensor, a) All screws fastened. b) and c) Screw B removed from the back panel marked with red on figure 4.3.



(a)



(b)



(c)

Figure 4.6: Spectrograms when using external stimulus with Mistras sensor. a) All screws fastened. b) and c) Screw B removed from the back panel marked with red on figure 4.3.

The same screw was removed from the back panel of the UPS unit and another set of 10 measurements was taken. Figure 4.6b shows the individual measurement that was hardest to tell apart from the measurements where no screws are removed.

It can be seen that there are pulsating areas of energy in the 150-250 kHz frequency range. The energy is not continuous, as it was when no screws were removed: There are dark blue gaps in the spectrogram. This individual measurement is the only one out of 10 samples where the energy between 200 and 250 kHz lasts to the 45 ms mark. On the other measurements the removed screw could be told apart with looking at the 200 - 250 kHz energy. Figure 4.6c shows more common behaviour where the 200-250 kHz energy is attenuated before 45 ms mark. These differences are most likely due to different kind of impacts. It is concluded that the measurement setup enables variance between individual measurements. The removed screw B could be detected from single spectrogram plots even with variance in the stimulus.

When a screw was removed from the front of the power module on the front panel of the unit the measurements yielded similar results to when no screws were removed. As seen from figure 4.7 the echoes and 300-350 kHz energy that remains to 40 ms are similar to the measurements where no screws were removed.

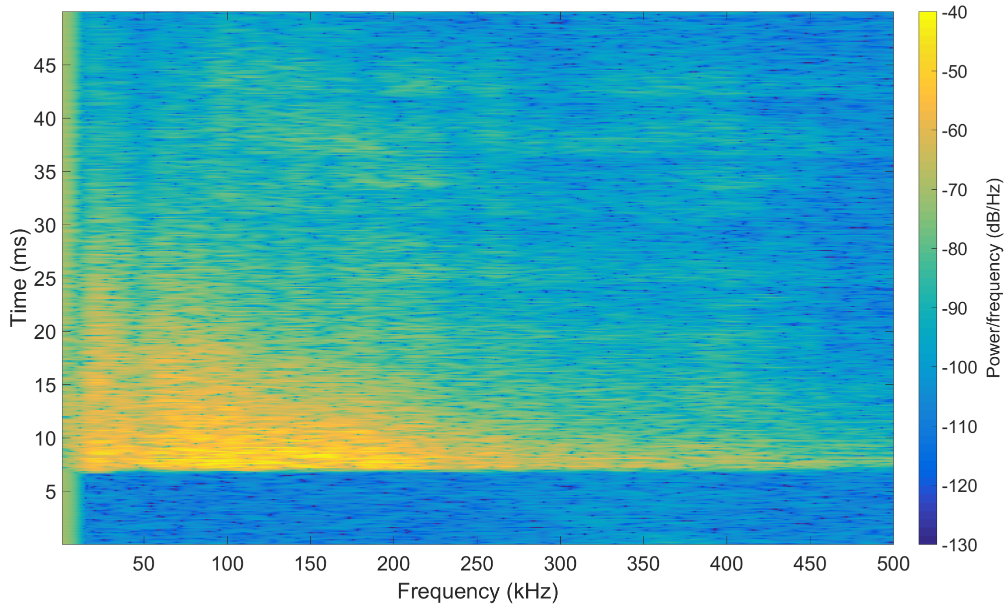


Figure 4.7: Spectrogram when Screw A is removed from the power module on the front panel of the UPS.

Looking at the spectrograms these two conditions are not consistently distinguishable from each other. The horizontal lines are similar and there is no attenuation of high frequency energy. As on the other measurements there is some variance between individual measurements. The thickness and number of the horizontal lines vary between individual measurements and so comparing the lines can't be used to distinguish the different measurement conditions.

It can be concluded that not every missing screw can be verified with these measurements. There are structural differences between the back panel and the power module on the front panel: The power module material is thicker and is more rigid. Removing a screw from it does not seem to make the connection to the main body weaker. On the other hand the thinner back panel when hit will ring for some time and removing a screw seems to make the connection to the main body less sturdy.

To determine if other missing screws can be verified from spectrograms more experiments were carried out. Just like on the first experiment a screw was removed, now screw C marked on the figure 4.3 with yellow circle. A set of 10 measurements was taken and compared to the control set where all screws are fastened.

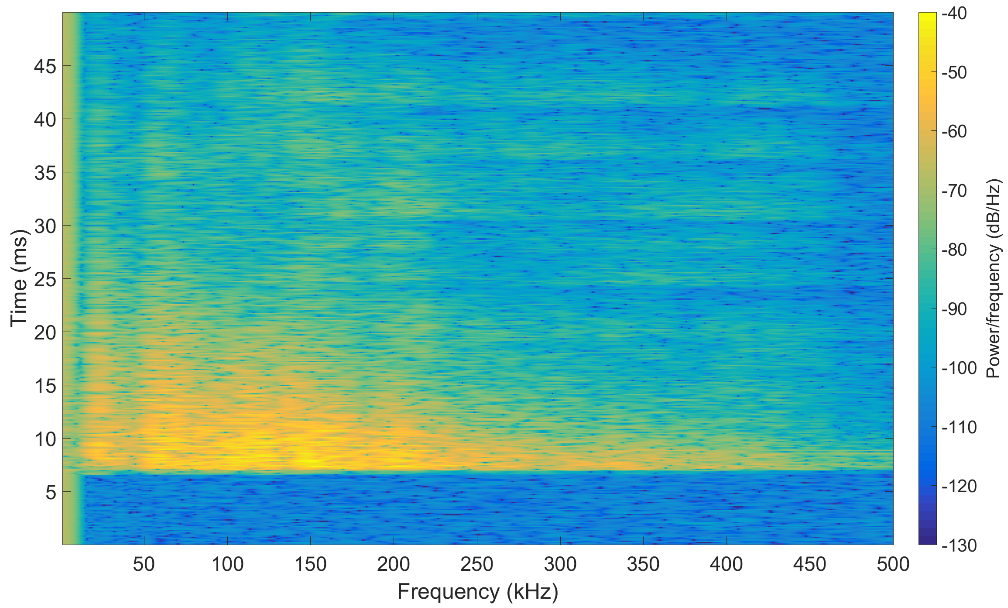


Figure 4.8: Spectrogram when Screw C is removed from the back panel of the UPS.

It can be seen that the spectrogram on figure 4.8 resembles the measurements where no screws are removed from the chassis. These cases can not be distinguished from each other. The hypothesis is that because the impact area is further away from the missing screw, the effect on the elastic waves that reach the sensor are too small to be noticeable. This is because the testing method is close to a through-transmission ultrasonic testing technique where the elastic waves propagate through the tested unit from a transmitter to a receiver (Burrascano et al., 2015). If the defect is not between the transmitter and the receiver, in this case the pendulum sinker and the sensor, it's effect on the elastic wave characteristics may become harder or even impossible to identify.

5 Internal stimulus

In this section the acoustic emissions generated by the UPS in operation are studied. The UPS is connected to 3 phase 400 V mains voltage and it runs in double conversion mode. The loads used in the measurements are idle and one 6 kW sauna heater. The switching transients and rotating fans among other operation related electrical and mechanical phenomena are the source for the acoustic emissions. Both the Kistler and the Mistras sensors are used to study the emissions.

The measurement process starts with powering up the UPS and attaching the sensors to their dedicated placements. With idle measurements the UPS output is turned on and left on until all measurements are taken. The mechanical switch controlling the load heater is turned off making the effective load 0 kW.

When taking 6 kW loaded measurements the sauna heater was warmed up before taking the measurements to keep the measurement conditions more stable. The load was turned off with the switch in between the measurements for the time that the oscilloscope was saving the data. This was to avoid triggering the fire alarm due to excess heat emitted by the heater. Taking and saving each measurement took around the same amount of time, so the heater was turned on and off for similar amounts of time in between the measurements. To make the measurement conditions exactly the same the heater would have to be on constantly and its temperature would have to be monitored.

Like on the external stimulus measurements the same spectrogram function in Matlab is used to generate the spectrograms from the internal stimulus experiment data. The parameter values are kept the same from the external stimulus measurements: Number of windows is 20000, Hanning windowing is used and the number of overlapping samples is 10.

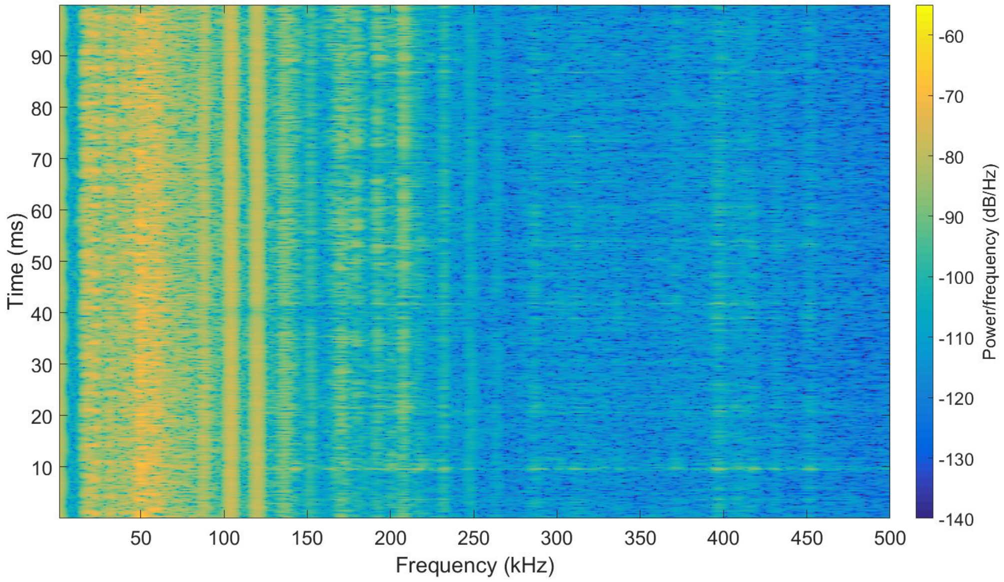
5.1 Electromagnetic interference

When the UPS unit is switching high power it will inevitably cause electromagnetic interference (EMI). The interference may be picked up by the acoustic emission sensors and they might be mistaken for acoustic emissions. Because of this it was meaningful to determine the amount of noise, caused by electromagnetic interference, in the measured signal. Estimating noise from the surrounding area excluding the UPS, background noise, is not necessary as the interference from the electrical contact and close vicinity to the UPS exceeds the background noise of the used laboratory room. The background noise is also inevitably included in the noise measurements.

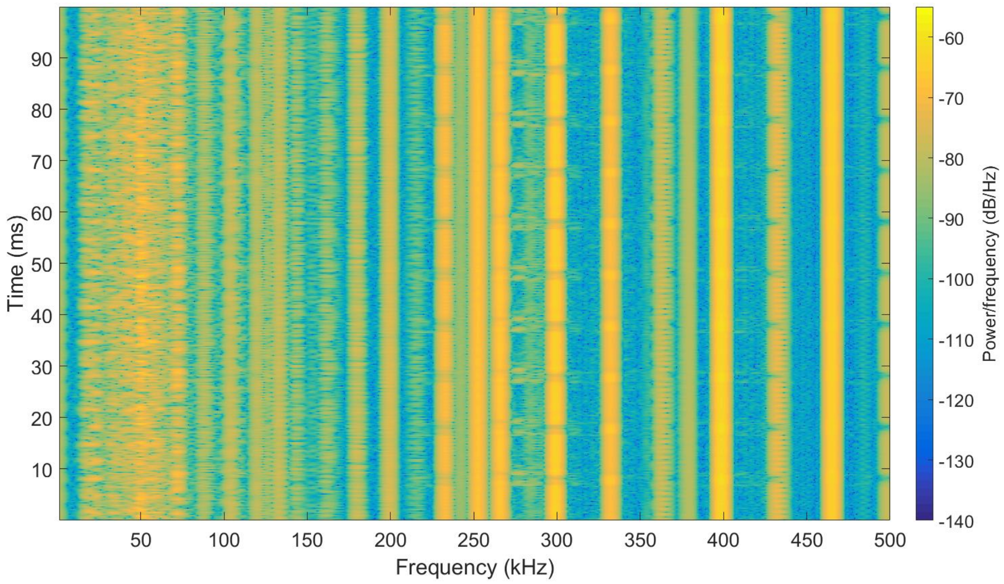
A set of 10 measurements was taken for idle and 6 kW loads. On these measurements the body of the sensor was in electrical contact with the UPS unit's metal enclosure. This was achieved by holding a corner of the sensor's metal outern shell against the UPS front panel. The acoustic coupling was also hindered with this action. It was found that EMI picked up by the Kistler sensor did not increase with increasing the load. The worst case interference found was on a idle load measurement and it is highlighted on figure 5.1a. The maximum frequency analyzed is limited to 500 kHz because the sensor is specified for 50 - 400 kHz. It can be seen that most of the interference is below 200 kHz. Figure 5.1b shows a spectrogram of an actual idle load acoustic emission measurement.

Comparing the AE measurement with the EMI one it is clear that below 150 kHz the acoustic emissions are hard to tell apart from the EMI. On higher frequencies the noise is of much smaller magnitude than the acoustic emissions.

Figure 5.1b shows that there are several stronger acoustic emission frequencies. These emissions are between 250 - 475 kHz. This is valuable information for further research as other sensors that operate in this frequency range can be used to verify these results. These results were also verified using the Mistras sensor.



(a)

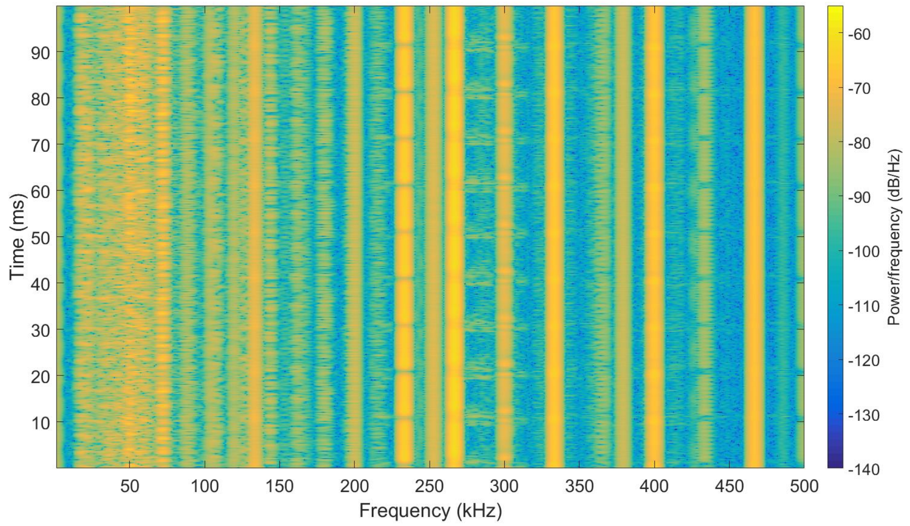


(b)

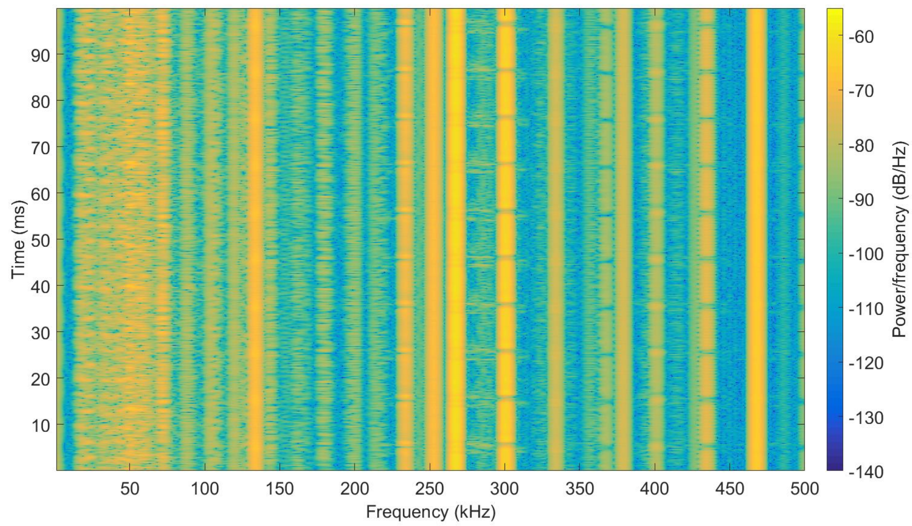
Figure 5.1: a) Electromagnetic interference b) Acoustic emissions. Kistler sensor with idle loading.

5.2 Internal stimulus results

Two sets of 10 measurements were taken where the UPS was loaded with 6 kW and the Kistler sensor placed on the front panel. Figures 5.2a and 5.2b show spectrograms of individual acoustic emission measurements, on (a) all screws on the enclosure are fastened and on (b) the screw B that was detectable with external stimulus was removed from the back panel.



(a)



(b)

Figure 5.2: Acoustic emissions with 6 kW loading when a) all screws are fastened b) Screw B was removed from the back panel. Kistler sensor on the front panel.

Looking at the two measurements the notable differences are on 235, 300, 335 and 400 kHz frequencies. However it was found that none of the differences were consistent between the measurement conditions: There are differences between individual measurements but no constant behavior that applies to all samples. Any variance found would either be absent in more than one of the 10 samples or it would exist in both groups of measurements, screw removed and not removed.

The sources of the acoustic emissions are presumably mostly inside the power module. The structural differences in the back panel of the unit may be masked by the continuous acoustic emissions coming from closer to the sensor. With the continuous stimulus the echoes can not be detected as they were with the external hit stimulus as the attenuating acoustics emissions are masked by stronger fresh ones. As stated by Grosse et al. (2008) acoustic emission testing is better suited for burst type signals instead of continuous one. The Mistras sensor, which can be freely placed anywhere on the UPS body because of it's magnetic attachment, was used to study if the missing screw could be detected with another sensor placement. The sensor was attached to the back panel as seen on figure 4.3.

A set of 5 measurements for each case was taken and there were noticeable differences between the different measurement conditions at 400 kHz. Another set of 10 measurements per condition was taken to confirm the results. However it was found that the differences exist within the same measurement conditions and for that reason it is not an indicator of a removed screw. From this finding it can be said that with the internal stimulus there are variable acoustic emissions on the 400 kHz frequency. These differences can be discarded in possible further research as they do not indicate the phenomenon under study.

The magnitude of the differences within the same measurement conditions is highlighted on figure 5.3. The time window on these measurements was increased to 1 second to study if the differences with individual measurements are of short duration. As seen on the spectrograms the power hardly changes within the 1 second time window so it can be assumed that the differences are of rather long duration and they are not related to the missing screw. The highlighted measurements are consecutive and taken within 3 minutes of each other.

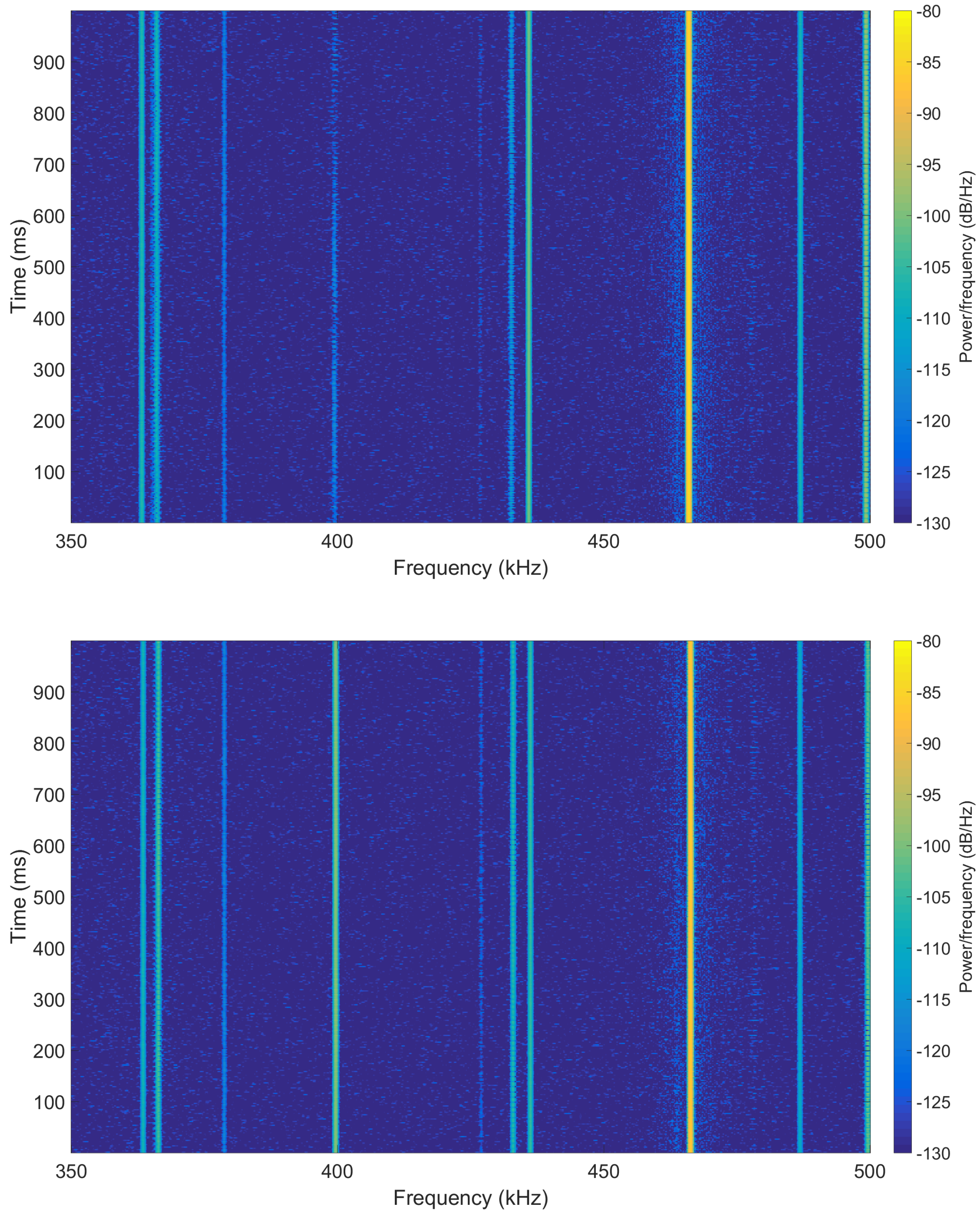


Figure 5.3: Two acoustic emission measurements from the back panel using Mistras sensor. Same measurement conditions, screw B removed, and 1 second time window. 400 kHz power varies by 15-20 dB.

It can be seen that on the top spectrogram of figure 5.3 the power at 400 kHz is close to -120 dB. On bottom spectrogram the same frequency has power of over -100 dB. Another frequency on which the power can vary up to 20 dB with the same measurement conditions is 468 kHz. The changes in the power also shift the frequency by a few kHz. This is highlighted on the figure 5.4. Here the difference in power is 10 dB. 200 kHz is another frequency of acoustic emissions which repeats the same type of behavior. On one pair of measurements the difference in power is 22 dB and the measurement with more power shifts the frequency to 202 kHz. The shift direction is not dependent on the power: The frequency shift direction does not dictate higher or lower power.

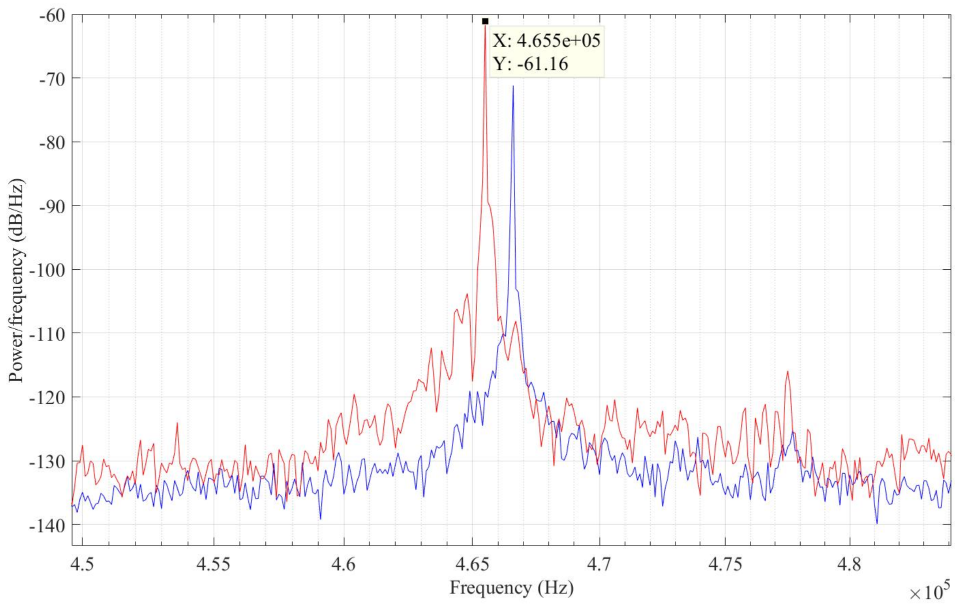


Figure 5.4: Two measurements with same measurement conditions with variable spectral density power and frequency. 6 kW load, Kistler sensor on the front panel.

The power electronics in the UPS are controlled by a control system. The control system works in the background and it could not be controlled in this study. It is most likely that the differences within same mesurement groups are due to differences in power electronics operation caused by the internal control. The UPS also has a computer controlling the user interface in addition to computing the input and output measurement data. The acoustic emissions generated by the computer should by all means be of much smaller magnitude than the electronics handling high power. The acoustic emission measurement window is short and it can't be timed to avoid unwanted behavior by the UPS since there is no indication on the control operation.

6 Discussion

On external stimulus experiment the Mistras sensor and preamplifier were used to verify the results found with the Kistler sensor. The measurements done with Mistras sensor show that the acoustic emissions over 300 kHz attenuate faster than with the Kistler sensor. This might be due to the grease used with the Mistras sensor: the sensor contact was covered with lube as adviced by the manufacturer. The Kistler sensor was used without any grease between it and the UPS enclosure surface. A more refined grease may have an effect on the results but in the premise of this study it did not matter. The removed screw that was detected with the Kistler sensor was also detected with the Mistras sensor.

The external stimulus, an impact, produces a burst of energy and as it was found the removed screw was detectable by the acoustic emission decay characteristics. As it was found there are problems with measuring continuous acoustic emissions when the UPS is in operation. If a frequency sweep stimulus, for example a sine chirp, was used the decay characteristics would be available for analysis. Another option is to generate fast pulses of single frequencies and examine the their decay characteristics. A pulse chirp signal has been used to study acoustic emissions in ceramic capacitors by Levikari et al. (2017). Such stimulus proved to be useful in finding cracks in the capacitors. Making the UPS drive a controlled test signal would also keep the power electronics operation repeatable throughout the measurements. However in the premise of this study such stimuli was not available to be outputted into the load.

A testbench on which the unwanted variation in the UPS unit operation could be removed is adviced for possible further research. Keeping the measurement conditions the same makes it possible to pinpoint small differences from the measurement data. Another possibility is to try and keep the load and input conditions more static. This would require a precisely temperature controlled resistive load and UPS temperature resulting in more static operation. Instead of this method the above discussed test signal approach is recommended. When the signal outputted by the UPS is kept the same the load temperature control becomes less demanding and hard to achieve. This is because the sweep or pulse type signal is of short duration and so is not likely to have a big effect on the load temperature. This way the only temperature dependent variables are the power electronic components, the source of the acoustic emissions. Controlling them to a set temperature, for example one that reflects it's normal operation, is still adviced.

Further acoustic emission research that takes place outside of the ready assembled UPS unit enclosure is not adviced. One possible future research subject could be heatsink integrity on power electronic components. By observing the results of this research to study this from outside of the UPS case seems very hard or impossible. The power electronic components are located around the dividing inside walls so there are multiple sources for acoustic emissions. In addition the physical structure of the unit is complicated, consisting of many interfaces of different structure blocks. In order to first learn about the acoustic emissions related to a spesific phenomenon it would be beneficial to monitor the emissions closer to their source. After studying if the phenomenon can be detected the sensor could be moved further away and the measurements would be repeated. This way the farthest point on which the phenomenon is still reliably detectable can be found.

7 Conclusions

It was found that small changes to the acoustics of the UPS enclosure, namely a screw removed from the back panel, could be detected with using an external stimulus to create elastic waves. However another more distant screw that was removed from the back panel could not be detected with the same impact and sensor location. It was also found that removing a screw from the front panel could not be detected with the same methods. With these findings it's safe to say that the impact placement and the removed screw placement will affect the detection of the removed screw greatly. If for example heatsink integrity were to be studied the sensor should be moved closer to the defect to avoid attenuation of the acoustic emissions due to excess distance between the sensor and the defect.

With the internal stimulus experiment it can be concluded that the UPS unit generates acoustic emissions of various frequencies when in operation. Below 150 kHz the measured emissions are hard to tell apart from the electromagnetic interference. Above 200 kHz there are several frequency bands where the acoustic emissions were 20 dB more powerful than the measured electromagnetic interference. Multiple notable acoustic emission frequencies were found in 200 - 475 kHz range. The used sensors are specified from 50 kHz to 400 kHz but looking at their frequency responses they can pick up signals of greater frequencies. With internal stimulus removing screws could not be detected with spectral power estimates or spectrograms. Individual measurements showed notable variation within the same measurement conditions. This is most likely due to variation in the UPS operation: The power electronics are controlled by a control system that could not be made to operate in a static manner which leads to differences in power electronics operation.

By the results of this research using acoustic emissions for final production testing of the studied Eaton 93PS is not found viable. Trying to study the defects in power electronics located inside the enclosure from outside is not considered worthwhile before more specific studies that would happen closer to the defects are performed. Chirp and pulse type signals are recommended for future research in addition to the sine signal the UPS outputs normally. Different output signals require a testbench software but they make it possible to study the decay characteristics of the acoustic emissions.

The results can be applied for other similar sized uninterruptible power supplies and the general advice mentioned in the discussion section holds: First the phenomenons effect on the acoustic emissions should be studied close to its origin with different type of output signals. After the acoustic emission behavior related to the defects is well-known the next step is to move away from the source of the emissions and attempt to detect the same behavior. This way if the defects are detectable at any level the production testing methods may be optimized to work around the limitations of the method.

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