Vibration Analysis on AC Electric Arc Furnace

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Abstract

A computerized Fast Fourier Transform system has been used to analyse vibration measurements sampled from a 100-ton electric arc furnace. It has been the hypothesis that patterns in the vibration data would correlate to specific events in the electric arc furnace during the melting process. The theory was that the vibration patterns would be most powerful in multiples of 50 Hz, as the electric arcs operate with a frequency of 50 Hz. It was concluded that the multiples of 50 Hz were dominant. Investigation was made regarding how the amount of scrap affects the amplitude in the vibrations after a defined amount of energy input. It was confirmed that the intensity of the vibrations decreased with increasing mass and basket volume. Another discovery was the M-shaped pattern at the beginning of the melting process. This pattern was statistically analysed. It was found that 71% of the 41 charges showed an M-shaped correlation. The appearance of this M-shape was analysed regarding power usage, and steel-type. It was concluded that the steel type affected the appearance of the M-shape. The occurrence of flat-bath was also investigated. The theory was that the vibration data would be fairly constant with the occurrence of flat-bath. It was discovered that the vibration data experienced a somewhat constant behaviour towards the end of the melting process in approximately 57% of the 41 charges. Difficulties were encountered regarding detection of patterns, and correlating them to specific conditions, due to the many parameters that affect the vibration measurements from charge to charge. It was concluded that vibration analysis are unlikely to be used as an absolute way to foresee every event in the electric arc furnace during each charge. But can rather serve as a statistical tool, upon which decisions of how the melting process should be conducted could be based on.
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1. Introduction

1.1. Background
The Swedish energy agency has reserved 85 million SEK for a program named “The iron and steel industries energy consumption - research and development”. The program is conducted in collaboration with Jernkontoret who is coordinating the efforts. The aim of the program is to promote energy-relevant research in iron and steel industry in Sweden, supporting a sustainable energy system[1]. This thesis is a part of a larger project that are conducting research on process control and measurement technique in the electric arc furnace with use of vibration, sound and current harmonic distortion.

1.2. Purpose
The method of analysing vibrations to determine working conditions and wear has been applied in many areas e.g. combustion engines and electric motors[2]. Some articles on vibration analysis on the electric arc furnace (EAF) have been written. Jee Jin Jeong et al. successfully used vibrations to estimate the slag foaming height in the EAF[3]. It has also been found that solid scrap between the arcs and the furnace walls dampen the transmission of sound[4]. Therefore, further research in the area is of interest. This thesis uses vibration measurements sampled from the EAF at Outokumpu ironworks AB, in Avesta. The aim of the thesis are; to investigate the correlation between vibration intensity and scrap volume and mass, to find and investigate dominant frequencies, investigate the existence of repeating patterns around the dominant frequencies, and investigate potential patterns indicating the occurrence of the condition known as flat-bath. This is done by processing the measurements using computerized Fast Fourier Transform. The processed measurements are then analysed by comparing the power output from the EAF to changes in vibration intensity at different frequencies. Different charges are then compared to investigate possible trends between charges in dominant frequencies.

1.3. Electric Arc Furnace
An electric arc furnace consists of a metal-steel shell with water-cooled brick lining. Three graphite electrodes supply the electric energy and the steel scrap is melted by a continuous electrical discharge called electric arc. The arc is struck between the electrodes and the scrap, the area underneath the electrodes are called “hot-spots”[2]. Temperatures around the “hot-spots” arise to approximately 3600-4000 degrees Celsius, and the nearest brick-lining are therefore exposed to more wear than in other places in the EAF. Most of the electric energy supplied by the electrodes is converted into thermal energy which is used for melting the scrap[2]. However some of the electric energy is converted into other forms such as electromagnetic energy or mechanical vibrations[2].
When large components hit the bottom of the furnace, they may cause damage to the brick lining. Therefore smaller pieces are generally charged first[5]. This reduces the impact damage on the brick lining. Thereafter the EAF is filled to the top. The charge-material at the top also consists of smaller pieces. This is beneficial when the graphite electrodes gradually lowers through the material, a process known as bore-in[5]. When all of the scrap has been charged, the roof of the EAF is swung into position over the furnace, and the electrodes are lowered. The power is turned on and the electrodes gradually bore-in through the material.

When the bore-in is completed the graphite electrodes are near the bottom of the furnace. However, most of the scrap are at this point stuck to the walls of the EAF[2]. As the melting process continues, a pool of molten steel is formed as illustrated in Figure 1.1. The scrap stacked along the walls of the furnace begins to fall down and towards the middle of the furnace, increasing heat radiation, and therefore wear on the brick-lining[2].

![Figure 1.1: Schematic image of the melting process in the electric arc furnace](image)

If the scrap falls early, the brick lining are exposed to the heat radiation from the electric arcs during a long period of time. This will increase the damage on the brick-lining[2]. When the scrap melts, there is a volume reduction. Therefore another basket of scrap is added to the EAF as soon as there is room available. Each charge usually contains two baskets. When all of the scrap is melted, a condition known as “flat-bath” occur[2]. When the temperature is correct, the electrodes are lifted out of the furnace, and the molten metal is tapped into a ladle[5].
Today, energy models are used to predict the energy requirements and distribution in the EAF[6]. Unfortunately it is difficult to optimize the melting process as many of the parameters involved in melting scrap vary from charge-to-charge. Some charges melt faster than others and it is difficult to know exactly what and when conditions occur in the EAF. Today the operator has to rely on experience to determine if the steel has melted without opening the furnace. A method to determine the conditions inside the EAF could potentially reduce excessive superheating of the molten metal, and therefore reduce melting-time, excessive wear on the furnace wall, and energy consumption. Investigation regarding real-time measurements during closed furnace is, therefore, of great interest.

1.4. Fast Fourier Transform
Vibration analysis is processed numerically with computers. Fast Fourier Transform (FFT) is an efficient algorithm for performing vibration analysis. The FFT concept is taken from a theory of Jean Baptiste Fourier, which states that all waveforms, no matter how complex, can be expressed as the sum of sine waves with different amplitudes, phases, and frequencies[7]. This method transforms a time-varying signal into components which contain phases, frequencies and amplitudes[8]. A transform is shown in Figure 1.2. The figure illustrates how FFT works, exposing the separation of the vibration time-varying waveform into frequencies.

The FFT computing software contains several adjustable parameters affecting the output data, some of the important parameters are: lines of resolution, frequency-span, averaging type, number of averages, and window type[8].

Lines of resolution is a value that reveals how many lines or bins the frequency spectrum is divided into, however, the more lines of resolution the better accuracy in the data[9].
Every line includes one or more frequencies, depending on the resolution and the frequency-span[8]. The bandwidth is the width of each line and is also related to the lines of resolution. It is calculated by dividing the frequency-span by the lines of resolution[9].

The highest frequency, which can be obtained through the FFT analysis, is stated by the Nyquist sampling theorem. The theorem states that the sampling rate should be larger than two times the maximum frequency in the FFT, this is to ensure that no aliasing will occur[10].

1.5. Window
The FFT assumes that there are an integer number of periods in each time interval[11]. If this would be the case, the transformation would function properly and assign a specific frequency to the analysed waveform. The vibration measurements taken from the EAF is, however, not periodic in character, and have therefore not an integer number of periods in each time interval.

If the data do not have an integer number of periods in a given time interval, it causes leakage into other frequencies on both sides of the main frequency[8]. To reduce this problem a weighting function can be applied. This forces the time-varying signal to be equal to the same value at the beginning and the end of the time interval. This is called applying a window[12]. There are a variety of window-functions to choose between. Some of them provide good frequency resolution, and some provide good amplitude accuracy. Generally, when using a window with better frequency resolution, it is at the expense of amplitude accuracy[12].

One of the window types that are perhaps most widely used is the Hanning window. The reason for this is that it provides a good compromise between frequency resolution and amplitude accuracy. The amplitude error for the Hanning window is approximately 15%[12]. This can seem much in many circumstances, it is, however, acceptable when the main importance is the relative differences between amplitudes in a frequency, and not the exact value of the amplitude itself.
Another window that is similar to the Hanning window is the Hamming window. Although it has a bigger amplitude error, it reduces leakage into adjacent frequencies even more than the Hanning window. This makes it better for separating close frequencies[8]. A comparison between the two is presented in Figure 1.3.

![Hamming Window](image1.png) ![Hanning Window](image2.png)

*Figure 1.3 The FFT of the Hamming window and the Hanning window. As can be seen, the nearest side lobes of the Hamming window are lower, thus reducing leakage into other frequencies more efficiently.*
2. Method

2.1. Retrieving vibrations from the EAF

To gather the vibration data the following equipment were used:

- Kistler Group 8714B500M5 accelerometer with a sample-rate of 25600 measurements of the acceleration g per second.
- National Instruments NI 9234, 4-Channel, 24-Bit Software-Selectable IEPE and AC/DC Analog Input Module.
- National Instruments cDAQ-9184, 4-Slot, Ethernet Chassi.
- Desktop computer running LabVIEW version 14.0.1 64 bit.

To measure the vibration spectrum of the EAF, three accelerometers were attached onto the outside of the furnace wall at different heights. The goal of using three accelerometers at different heights was to examine potential differences in their vibration spectrums. However, the output of the three accelerometers were close to indistinguishable and therefore not further investigated[13].

The analog signal from the accelerometers was sent to the NI 9234 (analog input module) through coaxial cables, which converted the signal from analog to digital. The digital signal was sent through the cDAQ-9184 (ethernet chassi) to the desktop computers LAN port. The desktop computer running LabVIEW received the signal and stored the raw data in a SQL database. The setup of the equipment is described in Figure 2.1 below.

![Figure 2.1: Schematic image of the data gathering setup.](image-url)
2.2. Data Processing
The signal processing was done in LabVIEW. To provide sufficient frequency resolution a frequency span of 0-1000 Hz, and 1001 lines of resolution were chosen, thus providing a bandwidth of 1 Hz. Frequency leakage could, of course, not be removed entirely. However, to reduce the frequency leakage, the Hamming window was chosen, because of its good side-lobe behaviour.

To reduce noise, an average of 80 was chosen. This was considered enough to provide a smoother curve, without removing any relevant information such as large peaks, or relevant changes in amplitude. The averaging type used in the program was root mean square (rms), shown in equation 2.1[14].

\[ g_{rms}^2 = \frac{1}{n} (g_1^2 + g_2^2 + \ldots + g_n^2) \]

Equation 2.1: \( g_{rms}^2 \) for the amplitude were \( n = 80 \)

Figure 2.2 illustrates how quickly the amplitudes decrease as the frequency increase. After initial observation the amplitudes over 1000 Hz was deemed to be too low for any information to be relevant. The information over these frequencies was, therefore, disregarded as noise. The maximum frequency was, consequently, chosen to 1000 Hz, well below the Nyquist frequency determined by the accelerometers sample-rate.

Figure 2.2: The frequency domain from 0-500 Hz of one of the processed charges. As can be seen, the amplitudes are quickly descending to small values compared to those in the 0-350 Hz range.
2.3. Data Analysis

In total there were 41 charges processed, and analysed. The processed data was imported into MATLAB version R2014b. To provide an effective way of analysing the data, a program was made to plot and compare the processed vibrations.

As can be seen in Figure 2.2, the vibrations are dominant in multiples of 50 Hz. The Swedish electrical grid, and therefore the electric arcs, operates with a frequency of 50 Hz. The vibrations in these frequencies are, therefore, most likely originating from the electric arcs. To investigate correlations between the vibration signal and power changes in the electric arcs, the vibration data was plotted in the same graphs as the power output from the EAF or the tap position on the transformer.

To make comparisons between different charges, vertical lines were plotted in the graphs. Each line corresponds to a certain amount of energy. The exact value of the energy were chosen to Y MWh as this information is sensitive to Outokumpu ironworks AB. This made it possible to compare charges when the EAF had used a specific amount of energy, instead of when a specific amount of time had transpired. An example of the vibration data, power output, and the Y MWh lines is shown in Figure 2.3 below.

![Figure 2.3: A typical example of a graph with the vibration data (red), power output (blue) and vertical Y MWh lines. This one shows the 100 Hz vibrations of one of the charges.](image)

After the first basket the power is turned off, it should be noticed that the vibration pattern in the analysed data do not immediately respond to the abrupt change in power. But rather decreases in a slow and controlled way, this effect comes from the smoothing and averaging applied in LabVIEW.
The effects are highly localized and are not deemed to impact the accuracy of the vibration data except in the narrow region after the power is turned off and just after the power has come on.

2.3.1. Investigation of repeating patterns around the multiples of 50 Hz
To investigate if there are patterns present in the vibrations, all multiples of 50 Hz and the four frequencies above and below each multiple, were examined and compared in all the charges chosen. These frequencies were chosen as they derive from the electric arc and therefore carry the most energy. Of these frequencies only the 450 Hz frequency showed potential of having a repeatable pattern over the different charges. The 450 Hz frequency was chosen and the amplitude was plotted in the same graph as the tap position of the EAF shown in Figure 2.4. This was done for all the charges. The tap position is the chosen power output of the electric arc, the different tap positions correlates to different number of turns on the transformers secondary side. A higher number of turns equals a higher voltage in the arc[15].

As the scrap in the different charges differs greatly in volume, weight, density, and alloying components, the power output was normalized against the weight of each charge (kWh / ton).
The normalisation helps with the comparison of the different charges, as the amount of energy required melting metal are proportional to the weight. The charges were compared in two ways, first all the charges were compared without taking the alloy composition into consideration. Secondly the charges were compared according to alloy. As the number of charges was limited to 41, there were only four different types of steel where the number of samples was equal or greater than three. These steels are: 1358 with nine samples, 2323 with four samples, 658919 with three samples and 658924 with five samples. To limit the comparison and exclude potential sources of error, the first basket meltdown was chosen for analysis.

### 2.3.2. Investigation of the amplitude, considering mass and relative basket volume

A possible trend between the amount of scrap and the vibration amplitude was investigated. The amplitudes were studied and plotted against variations in scrap-volume and mass.

The 50 Hz frequency was chosen and studied for all the chosen charges. The investigation continued by comparing charges with similar power output patterns in the beginning of the melting-process, containing the interval from 0 to 2Y MWh. A distinct power output pattern was found, and illustrated in Figure 2.5 for three arbitrary charges. As can be seen, the power output starts to increase with a step-like configuration, followed by more constant maximum values. This pattern will be used as a reference to enable comparisons between the charges.

Values of the amplitudes for all the charges were collected at a total energy input in increments of a defined amount of energy Y, shown as vertical lines in Figure 2.5. The amplitudes are plotted with the mass and the relative basket volume of the scrap. Where the relative basket volume is the percentage of scrap in the basket.

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*Figure 2.5: Shows three selected start-intervals for the first basket in each charge. The red lines show the value of the amplitude ($g_{\text{rms}}$) the blue oscillating lines show the power output and the blue vertical lines show energy.*
2.3.3. Occurrence of flat-bath

There are several different conditions, which could affect the vibration measurements during the process of melting scrap. Many of these could occur during the same period of time. For example, when the bore-in is complete and the electric arcs are in the process of melting the surrounding scrap. When the scrap starts to liquefy there are a lot of scrap movement, and possible cave-ins that could clear a wall of scrap and therefore expose the brick-lining to the heat radiation from the electric arcs. Both the cave-ins and electric arcs could cause vibrations simultaneously, and could therefore be investigated at the same time interval in the vibration data.

The occurrence of flat-bath could, however, be investigated without interference from other conditions. As the name indicates, the presence of flat-bath means that all of the scrap has melted, which results in a pool of molten metal at the bottom of the EAF. One could then hypothesise that all of the vibrations measured would originate from the electric arcs, as there are no other sources of vibrations present in the EAF during a flat-bath.

If this would be the case, the vibration measurements plotted in the graphs should follow the same pattern as the electric arcs i.e. the power output also plotted in the graphs. The period for which this theory was investigated, were in the end of the melting process where the power output was constant, marked out in Figure 2.6. This is the period in which one might expect flat-bath to occur. The electric arcs operate with a frequency of 50 Hz. Therefore 50 Hz and multiples of 50 Hz were investigated. An empirical investigation was then carried out where all the 41 charges were compared in each frequency.

Figure 2.6: Shows the power output during the melting process. The part marked in the graph is in the end of the melting process when the power output is constant. This is the period one might expect flat-bath to occur.
Furthermore an investigation was conducted to why different charges show different patterns in the vibration data, during this period. The energy necessary to melt scrap is proportional to its weight. Therefore a comparison between the charges was made where the total power output was normalized against the total weight of the charge.
3. Results
Four different investigations have been conducted. These include which frequencies that are dominant in the EAF, repeating patterns around multiples of 50 Hz, how the scrap volume and mass affect the vibrations, and when flat-bath has occurred. The results from these investigations will be presented under their separate headlines. Observe that all the values deemed sensitive by Outokumpu ironworks AB have been altered, such as the total energy and weight of the charges.

3.1. Dominant frequencies
The frequency span from one of the charges was plotted to investigate if the dominant frequencies were multiples of 50 Hz. The results are shown in Figure 3.1 below. As can be seen, the expected harmonisations of 50 Hz occur. The harmonisations also seem to be most dominant in the third and fifth multiple of 50 i.e. 150 and 250 Hz. These are marked in the figure.

Figure 3.1: Shows the frequency span of one of the charges. Harmonisations can be seen in multiples of 50 Hz, particularly in the third and fifth multiple.
3.2. Investigation of repeating patterns around the multiples of 50 Hz
The repeating pattern found in the 450 Hz range can be thought of as M-shaped. The vibration intensity increases somewhat linearly to a local maxima. After this point there is a decrease of intensity, followed by a second increase and finally another decrease. A first M-shape can sometimes be found in the beginning of the first basket, and a second M-shape is found towards the end of the first basket. The second M-shape is, usually, more powerful with the distinct M-like shape highlighted in Figure 3.2.

Figure 3.2: Shows a highlight of the second M-shape.
Of the 41 charges tested, 39% contains the lower intensity first M-shape, visible in Figure 3.3 below. The second more powerful M-shape was found in 71% of the charges. 15% of the 41 charges showed a small notch in the increase of the vibration intensity, after which the intensity reached a local maxima and began to decrease also shown in Figure 3.3.

![Figure 3.3](image1.png)

*Figure 3.3: The first black-box shows the first M-shape. The second box displays an example of the notched M-shape.*

In the six remaining charges no clear correlation were visible as parts of the vibration spectra were close to zero, making it impossible to draw any conclusion as illustrated in Figure 3.4.

![Figure 3.4](image2.png)

*Figure 3.4: Shows an example of a charge were the intensity in the vibrations quickly moves to values close to zero.*
As the occurrence of the primary M-shape is of a more random nature and with less intensity, the focus hereafter lies on the second M-shape occurring towards the end of the first basket. To examine the occurrence of the secondary M-shaped pattern in a more statistical approach, the power usage at three points were noted and divided by the weight of the basket for normalization. These three points were: the first maxima, the first minima, and the second maxima of the second M-shape. The data of were the three points of the second M-shape occurs were plotted as boxplots, and a Kruskal–Wallis test were used to establish if the different points of the M-shape originate from the same distributions. The boxplot in Figure 3.5 illustrates in which interval the three critical points of the second M-shape are likely to be found, when considering all the different types of steel. The blue centre portion of the boxplot contains 50% of the values, the red horizontal line corresponds to the mean value of the samples. The dashed whiskers that extends vertically from top and bottom contains 25% of the values each, if a value deviates more than ±2,7σ they are considered outliers and plotted as red crosses.

![Boxplot of all steel types at the three different points of the M-shape.](image)

Figure 3.5: Boxplots of all steels at the three different points of the M-shape.

The Kruskal-Wallis test of the three points of the M-shape for all the charges, determined a statistical significance (p < 0.0005) hence implying that at least one of the points significantly differs from the others. A Two-sample Kolmogorov-Smirnov test determined that the first maxima and the second maxima were significantly different, the first minima showed no statistically differences from the first nor the second maxima.
To compare the effects of the steel types on the interval-width, the boxplot of all steel types were plotted against the boxplots of the steels: 1358, 2323, 658924, and 658919. The results are shown in Figure 3.6-Figure 3.8 below, representing the three different points of the second M-shape.

![First maxima](image1)

*Figure 3.6: Boxplot of all steels compared to four specific steels at the first maxima of the M-shape.*

![First minima](image2)

*Figure 3.7: Boxplot of all steels compared to four specific steels at the first minima of the M-shape.*
3.3. Investigation of the amplitude, considering mass and relative basket volume
It was found that 63% of the 41 investigated charges had the same power output pattern in the beginning of the melting-process. The amplitudes at Y MWh and 2Y MWh were plotted against the weight of the basket in kg shown in Figure 3.9 and also against volume of scrap in percentage, shown in Figure 3.10.
As can be seen, the amplitudes decrease both for increased mass and volume. However, the irregular point-distribution in the figures reveals that the line fitting can merely indicate tendencies.
3.4. Occurrence of flat-bath

The vibration data basically experienced three types of recurring patterns during the end of the melting process where the power output is constant. One pattern where the vibrations are almost completely constant and follow the same pattern as the power output is presented in Figure 3.11. Another pattern where the vibrations are fairly constant except from a few dips is presented in Figure 3.12. A third pattern where the vibrations do not experience some kind of constant behaviour, but rather seem to increase or decrease, even though the power output is constant, and flat-bath should have occurred. An example of this is presented in Figure 3.13.

*Figure 3.11*: Shows an example of when the vibrations follow almost exactly the same constant pattern as the power output from the EAF

*Figure 3.12*: Shows an example of when the vibrations experience a fairly constant behaviour, except from a few dips of approximately 200 g\textsuperscript{rms}.\textsuperscript{2}
The empirical investigation of when the vibration data followed similar patterns as in Figure 3.11, and Figure 3.12 resulted in a statistical analysis. The frequencies 50, 100, 150,..., 900 Hz was examined to investigate how many charges followed similar patterns. The result is shown in Figure 3.14 below.

*Figure 3.13: Shows an example of when the vibrations do not experience some kind of constant behaviour, but rather an increase in amplitude of approximately 20 000 $g_{rms}^2$*

*Figure 3.14: The percentage of the charges that followed similar patterns as in Figure 3.11, and Figure 3.12. As can be seen, there are no distinguishable tendencies throughout the frequency span, and the arithmetic mean of how often similar patterns occur is 57%*
Thereafter an investigation was conducted to why different charges experienced different patterns during the part of the melting process where flat-bath should occur. Here the total power output was normalized against the total weight of the charge. The total weight, total power output, and normalization are shown in Figure 3.15. As can be seen, the normalization is fairly constant with the exception of two “hills” in the graph.

\[\text{Figure 3.15: The total weight, total power output, and the normalization of the 41 charges.}\]
4. Discussion

4.1. Dominant frequencies
As can be seen in Figure 3.1, 50 Hz, and multiples of 50 Hz are clearly dominant. A probable reason for this could be that the electric arcs operate with a frequency of 50 Hz, and that these vibrations therefore originate from the electric arc. One might therefore make the conclusion that these frequencies are of interest when making correlations between vibrations taken from the EAF, and conditions inside the furnace during the melting process.

Harmonisations in the third and fifth multiple of 50 Hz were also visible. Divya Sajeesh and Seema Jadhav have in their article about power quality issues in electric arc furnaces written about the harmonic voltage produced by the EAF[16]. They concluded that the EAF in particular produced a third and fifth harmonic voltage. One could hypothesise that these harmonics are also visible in the frequency spectrum of the mechanical vibrations measured from the wall of the EAF, and that this would therefore be the reason for the harmonisation in the frequency spectrum.

4.2. Investigation of repeating patterns around the multiples of 50 Hz
It is difficult to find clear and undisputable patterns in the vibration data as there are numerous variables constantly changing. The tap position are constantly being adjusted, this affects the electric arc and therefore the vibrations. The increase and decrease in power cause changes in the M-shaped pattern. As the EAF is closed during operation the mechanics of what cause the increases and decreases in vibration intensity of the M-shape remains unknown for now. The second M-shaped pattern could be recognized in 71% of the 41 charges. In 15% of the 41 charges there were a notch, it seems plausible that this notch contains both the first maxima and minima of the second M-shape. The reason for this notch behaviour is unclear, but it seems as the behaviour may be alloy-dependent as three out of four of the 2323 alloy shows this notched M-shape. In the remaining six charges, no clear pattern could be found. Out of these six charges two hardly showed any vibration intensity as seen in Figure 3.4, thus making it impossible to draw any conclusions.

As shown by the boxplot in Figure 3.5, for all of the alloys the span in which the first maxima are expected to be found are 3.8K kWh/ton wide. The centre portion representing 50% of the values are within 1.5K kWh/ton. By only looking at one type of steel, the range in which the points of the M-shape reside decreases. The total span for the steel 1358 is 32% less than for all of the steels and the centre range is 57% smaller. The same pattern seems valid for the rest of the steel types. However, the amount of samples are too low to be statistically certain. As seen in Figure 3.6, the M-shape shifts in position based on the alloy.
This could indicate that the M-shape is indeed coupled to the melting of the scrap, as it is known by studying phase diagrams that the number of components in an alloy affects an alloy's melting point. The shifting effect of the M-shape may also be affected by other physical properties of the scrap in the basket, such as the scrap size distribution or the mass of the scrap in the basket.

The events in the EAF that cause the changes in the vibration pattern observed in the M-shape are unknown. After the first maxima of the M-shape the intensity starts to decrease, a theory is that this decrease is caused by an increasing amount of molten metal at the bottom of the furnace. The vibrations of the remaining scrap may be dampened as more metal melts. The second transition to increasing vibrations after the first minima could be explained by a diminishing scrap-level. As the scrap-level in the furnace decreases there is less material inside the furnace absorbing the vibrations, hence increasing the vibration measured. The final transition to lower intensity after the second maxima is harder to explain, however, this change may be caused by the reduction of power output.

4.3. Investigation of the amplitude, considering mass and relative basket volume

The lines for Y MWh shown in Figure 3.9 and Figure 3.10, exhibits a declining behaviour in the vibrations for an increasing amount of scrap. At this early stage of the process, scrap still protects the furnace walls. This might explain the lower values of the amplitude for a larger amount of scrap.

As can be seen in Figure 3.9 and Figure 3.10 at 2Y MWh, the lines are more constant and has higher amplitude compared to the graphs at Y MWh. This is probably because more scrap has melted, thus increasing the exposure of the EAF walls to the electric arcs, resulting in higher vibrations.

Numerous parameters influence the EAF, and it is difficult to determine which parameters that affect the vibration amplitude. However, this investigation has shown that the volume and mass are affecting the amplitude and greater volume and mass decrease the vibration amplitude.

The only frequency investigated for all charges was 50 Hz. Therefore, multiples of 50 Hz would preferably be investigated to ensure similar behaviour. Furthermore, this investigation only considered 26 charges and has, therefore, certain statistical limitations. Further investigations, including more charges, would produce complementary reliability to the results.
4.4. Occurrence of flat-bath

In the end of the melting process the condition known as flat-bath will occur. The hypothesis has been that as a consequence of flat-bath, all vibrations will then originate from the electric arcs. The existence of three patterns has been observed.

- If the vibrations are constant as in Figure 3.11 one might hypothesise that flat-bath has occurred. If substantial pieces of scrap would be present at that time, one would expect more variations in the vibration data. If there would be pieces of scrap remaining in the EAF, the electric arcs would most probably be affected by this, which would result in changes in the power output. This would also create changes in the vibration measurements, which would deviate from the constant behaviour observed in patterns similar to that in Figure 3.11.

- If large lumps of scrap would be present, one might expect the vibration data to be similar to that of Figure 3.12. The vibrations clearly change amplitude in a random pattern. This could originate from one or a few large lumps of scrap that have not yet melted, causing vibrations similar to the vibration pattern in the figure.

- The pattern in Figure 3.13 is gradually increasing. Opposite patterns have, however, been observed, where the vibration data gradually decreases. It should be mentioned that this kind of pattern have not been a usual one, and approximately 7% out of 41 charges experienced it. One might argue that there still is a large amount scrap in the EAF, and that flat-bath has not yet occurred. A theory is that the scrap gradually melts, which causes the vibrations to increase. One other theory is that foaming slag is formed which causes the vibrations to decrease. However, the gradual increase, or decrease in the vibrations does not originate from changes in power output, as this is constant during this period of the melting process.

Figure 3.14 shows the existence of patterns similar to those in Figure 3.11 and Figure 3.12. It is the theory that these patterns indicate the occurrence of flat-bath. As can be seen, those patterns are fairly regular, and the arithmetic mean of how often they occur is 57% out of 41 charges. However the vibration measurements from charge to charge differ greatly, and because of this it is difficult to observe any general patterns occurring in every charge. Patterns in the vibrations during the end of the melting process have been observed that are not commonly recurring. One pattern that has been observed in some charges is shown in Figure 3.4. As can be seen, the vibration data are quickly moving towards values close to zero. The reason for this could be that one of the accelerometers has malfunctioned. One other reason could be that the formation of slag has dampened the vibrations.

Investigation to why the vibration data differ greatly during the period when the power output is constant was conducted.
The energy required to melt metal is proportional to its weight, and therefore a normalization of the total power output against the total weight of the charge was calculated and shown in Figure 3.15. The normalization is, however, constant, except from two “hills” in the graph. It is, therefore, difficult to derive to any conclusions to why the vibrations differ greatly from charge to charge. One might, however, say that the difference do not only depend on total power to weight ratio. It does rather depend on all the different parameters present during one specific charge.

Some of which are steel-type, steel density, basket fullness, and slag formation. These could all affect how fast the scrap melts, and if there is scrap left that causes vibrations when the process is coming to an end.

It should be mentioned that no confirmations if flat-bath has occurred have been done. The hypothesis has been based on how the vibration patterns may look like if flat-bath would have occurred. Further investigation is necessary to confirm that certain patterns in the vibration data derive from certain conditions inside the EAF. This could be done by opening the roof of the EAF to see if flat-bath have occurred when a specific vibration pattern is visible. Further investigation is also necessary to explain why the vibration data differ greatly from charge to charge. This should include parameters such as steel-type, steel density, basket fullness, and slag formation.
5. Conclusions

5.1. Investigation of repeating patterns around the multiples of 50 Hz
To be able to use the M-shape for controlling the process it is crucial that the interval, in which the critical points reside, can be minimized. If the interval is wide the uncertainties are large as the first point of the second M-shape can be confused with last point of the first M-shape. The span of the M-shape is likely smaller when looking at one specific type of steel, however, the number of samples are too low to be certain.

5.2. Investigation of the amplitude, considering mass and relative basket volume
It was found that the vibration amplitude decreased with increasing amount of scrap and increased with a decreased amount of scrap. This phenomenon considers both mass and relative basket volume. Therefore it is likely that high amplitude is related to high heat exposure on the inside of the EAF.

5.3. Occurrence of flat-bath
Vibration analysis can not predict exactly when flat-bath will occur for every charge. However it can be used as a statistical tool to help show when flat-bath have most likely occurred. In the 41 charges investigated, an arithmetic mean of 57 % showed promising patterns to when flat-bath had occurred.

5.4. Frequencies
- The electric arcs operate with a frequency of 50 Hz. The dominant frequencies in the vibration measurements are multiples of 50 Hz. One might, therefore, make the conclusion that these frequencies originate from the electric arc, and are of interest when making correlations between vibrations taken from the EAF, and conditions inside the furnace during the melting process.
- Harmonisations of 50 Hz occur with integer multiples. The harmonisations are particularly powerful in the third and fifth multiple.

5.5. Data processing parameters
- An average of 80 was enough to reduce noise, but created a delayed response in the vibration data when the power was turned off and on.
- A frequency span of 0-1000 Hz, and 1001 lines of resolutions created a bandwidth of 1 Hz. This resolution was considered high enough for this investigation, and all vibrations over 1000 Hz was low enough to be considered as noise.
- The Hamming window was deemed to be the best alternative to reduce frequency leakage. This resulted in a decline in amplitude accuracy that was considered irrelevant, as the interesting information is the relative changes in amplitude.
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7. References


