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Vibrations during Resonance Frequency Analysis of Dental Implant Stability

Master of Science Thesis

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Abstract

Titanium implants are being used increasingly to support replacement of missing teeth with implant prostheses. A fixture needs to be unloaded for a period of up to 6 months after being placed into the bone, to promote the healing process. During this period it is valuable to monitor the healing process non-invasively. There are some existing methods for measuring implant stability where pictures from radiography are the most common. Osstell AB is a company who develops and market products for measuring of dental implants, and they have a product, called OsstellTM Mentor. The principle for this product is to measure the resonance frequencies from a small metal rod, which is attached into the implant. Both the excitation of the small rod and the receiving of the signal are made by using magnet field. On top of the rod there is a small magnet and in the probe there is a coil.

All implants have different stabilities in different directions and the number of resonance frequencies is in most cases two. Sometimes the OsstellTM Mentor registers more than two resonances and in this thesis the phenomenon of more than two resonance frequencies has been analyzed by studying the hardware, physiological causes, management and outer circumstances.

In management and outer circumstances the affect of different mechanical disturbances was analyzed by disturbing the contact surface between the metal rod, called SmartpegTM, and the implant with different types of mechanical errors. The tests showed that mechanical disturbances could affect the resonance frequencies by reducing the resonance frequency in one direction but no more than two resonances were detected.

Physiological causes were studied by measuring on implants, both placed into a jaw model made of plastic and in different types of plastic cylinders. In some cases in these measurements the phenomenon of more than two resonance frequencies was found. The cause to the phenomenon was assumed to depend on two things. The first thing was an insufficient signal processing and the other was that in some cases it seems to occur additional resonances in the models.

To analyze the hardware, a second independent measuring system was used. This measuring equipment is based on a laser vibrometer which measures vibrations by using Doppler Effect. The laser vibrometer has been used in almost all the tests in this thesis and the OsstellTM Mentor has been used as a complement to receive a basis for comparison. The analysis was made for the same frequency spectrum from both measuring systems and the comparison resulted in a suggestion for a new signal processing procedure.

One simple test was also made for testing the protection of disturbances from electrical sources. This test showed that disturbances are registered in the OsstellTM Mentor frequency spectrum but the disturbances did not lead to any errors in the calculations of the resonance frequencies in the signal processing.

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1. Introduction and Problem Presentation

Titanium implants are used increasingly to support replacement of missing teeth with implant prostheses. There is good histological evidence that the bone forms in intimate contact with the implant fixture. Currently, fixtures are left unloaded for a period of 3-6 months to promote the healing process. During this time it is valuable to monitor the healing process non-invasively to determine more exactly when it is safe to load the dental implant. [1]

Today there are several companies on the dental implant market and they are selling many different models. Osstell AB develops and market products for stability measuring of dental implants. The products are based on a patented solution and they are sold under the product name OsstellTM Mentor. [2] The principle of the method is to measure resonance frequencies from an excited sensor element, called SmartpegTM, which is fastened into an implant. All implants have different stability in different directions and the resonance frequencies are in most cases two, perpendicular to each other. Sometimes the OsstellTM Mentor system registers more than two frequencies and the phenomenon behind these extra frequencies is not known. The target with this thesis was to find out from where the different vibrations modes originate. In a second step the target was to find a way to filter them from the real modes. [3] It was suspected that the extra frequencies are a result of coupled resonances and the real modes is not.

The strategy for solving this problem was to divide the problem into three main areas, which are presented below. There was also one overall target: to find out if the measured signal was reliable by comparing the frequency spectrum from OsstellTM Mentor with a laser vibrometer. By comparing the frequency spectra and interpreting the differences, the knowledge about how the OsstellTM Mentor works was increased. The laser system was used in the three areas in this report and a description of the laser method is presented in chapter 4.1.

The first main area, presented in chapter 5.1, was called “Hardware” and in this part the SmartpegTM was measured when being put into ideal cases. There were also measurements made with the OsstellTM Mentor system in order to get knowledge about its function.

The second area was to study “physiological causes” by measuring on a plastic model of a jaw and on different plastic cylinders. The purpose was to find out what realistic signals look like in the frequency spectrum. The work was made with both the OsstellTM Mentor and the laser method and is presented in chapter 5.2.

The third area, “Management and physiological circumstances”, is presented in chapter 5.3. In this chapter measurements were made when some different errors were applied to the measuring system. The different applied errors were worn out threads and deformations made of both soft material and of metal. The errors were placed in the contact surface between SmartpegTM and implant.

This thesis starts with a short description of the theory behind measuring dental implant stability, which is presented in chapter 2, followed by a function description of the OsstellTM Mentor in chapter 3 and a description of the method in chapter 4. After the main chapter 5, where all measurements are analyzed, the conclusions are presented in chapter 7. In chapter 6 there are some proposals for future work based on the results from this thesis. Figures from all the measurements are to be found in the Appendix and in the Appendix 1 there is an instrument list of the equipment used in the laser vibrometer measurements.

2. Theory behind Measurement of Dental Implant Stability

Pictures from radiography are a common non-invasive method for studying stability of dental implants. One disadvantage with radiography is the difficulties to obtain reproducible pictures of high accuracy. Attempts have been made to measure the condition between implant and bone by striking the tooth with a mass of metal, which is accelerated by an electromagnet, and measure the contact duration with an accelerometer. The contact duration is related to stiffness of the body being struck but there is little evidence for this method as a sensitive and reproducible way for monitoring bone formation during healing process between implant and tissue. Another method for dental stability measuring is to screw a small rod in the implant and measure resonance frequencies in the system. The resonance frequencies depend partly on the fixture and partly on stiffness in implant/bone interface. [1]

The technique in OsstellTM Mentor is based on the last example. Factors that influence resonance frequency analysis are [4]:

Constants

- Implant length
- Implant diameter
- Implant geometry (Implant system)
- Implant surface characteristics
- Placement position
- Abutment length

Variables

- Bone quality
- Bone quantity
- Damping effect of marginal mucosa
- Bone implant contact, BIC (3- dimensional)
- Effective implant length, EIL
- Connection of transducer

It has been shown in clinical tests with resonance frequency analysis technique that a relevant parameter is measured. The parameter correlates with the clinical performance of the implant. The technique can serve as an important tool to measure implant stability and document the clinical outcome of implant treatments. It gives the possibility to assure that sufficient stability has been reached before the prosthetic treatment starts. [5]

The location of the implant affects the stability values. In general there are lower stability values in softer bone (maxilla) and higher stability values in denser bone (mandible). If there is a large sudden decrease of the stability value, it is important to know if the reason is due to for example loss of marginal bone, or demineralization. In these cases it is important to follow up the decreased stability value with radiography. [5]

Most of the implants have two different stability values. The highest value is normally in the mesio-distal direction and the low value in the bucco-lingual direction. Both values reflect the stability situation and it could therefore be useful to follow both values. Osstell AB recommends the users to do measurements in both these directions. [6] Figure 1 shows measurements in bucco-lingual and mesio-distal directions.

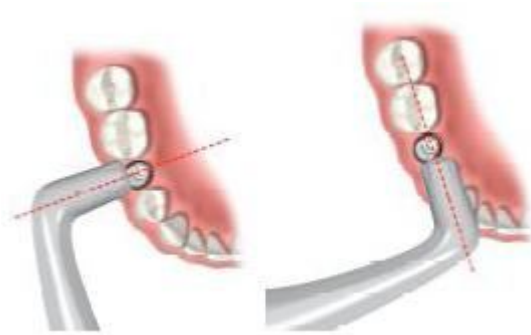


Figure 1. Left jaw: Measurement in bucco-lingual direction. Right jaw: Measurement in mesio-distal direction. [6]

The OsstellTM Mentor measures the stability of an implant at one particular moment. It is possible to see the effect of osseointegration if the stability value increases between the surgery and some time later by repeated measurements. [6]

3. Function Description of Osstell™ Mentor

The Osstell™ Mentor is a development of a measuring system, using resonance frequency analysis, RFA, for stability measurement. The earlier version is only described briefly in this chapter and the new version is described more detailed.

3.1. Earlier Version of the Measuring Equipment

The forerunner to Osstell™ Mentor was different mainly considering the measure sensor in the dental implant. A picture of the old measure sensor is shown in figure 2.



Figure 2. Earlier measure sensor. [7]

The earlier sensor was measuring stability in one direction and to receive values from many directions the sensor had to be moved between the measurements. Excitation of the sensor was made by a piezoelectric element placed on one side of the rod and the resonance frequency was measured by another piezoelectric element on the opposite side of the rod. [1]

The measuring sensor of this model had a wire connection to the instrument. [8]

3.2. Smartpeg™ and Probe

The new version of measuring sensor, called Smartpeg™, is also measuring resonance frequencies but with a different technique compared to the older version. In figure 3, one Smartpeg™ is shown.



Figure 3. Smartpeg™. [9]

Instead of exciting the system by a piezoelectric element, the Smartpeg™ is excited electromagnetically. A small magnet on top of the rod is excited by a magnet field from a coil in the probe. Figure 4 shows a Smartpeg™ which is excited by the probe. [8]



Figure 4. Smartpeg™ and probe. [10]

When the probe has sent a magnetic impulse, the apparatus switches automatically to a mode for detection of resonance frequencies from the Smartpeg™. Some advantages with the new system is partly the easier way of measuring where the sensor does not need to be moved between the measurements and partly that the sensor is smaller and is working without cables. [8]

3.3. Function Description of the Instrument

Figure 5 shows the instrument and the probe.



Figure 5. Instrument and probe. [11]

When Osstell™ Mentor is turned on, the instrument measures automatically without any activation from the user. [6] Signals are transmitted and received continuously, and during one measurement cycle with Osstell™ Mentor there are 4 different pulse frequencies transmitted in an interval of approximately 2-8 kHz. The center frequencies of the 4 pulses are 3 kHz, 4,4 kHz, 5,8 kHz and 7,2 kHz and their amplitudes are different from each other. The reason to the difference in amplitude is that Osstell™ Mentor can not deliver as high amplitudes for high frequencies as for lower frequencies. Osstell™ Mentor is designed to deliver as high amplitude as possible for every frequency. Each pulse is transmitted 4 times, which means that totally 16 pulses are transmitted during one measuring cycle, and from the received spectra a mean value is calculated for each frequency area. [8] In figure 6 the transmitted signals in the frequency spectrum are shown.

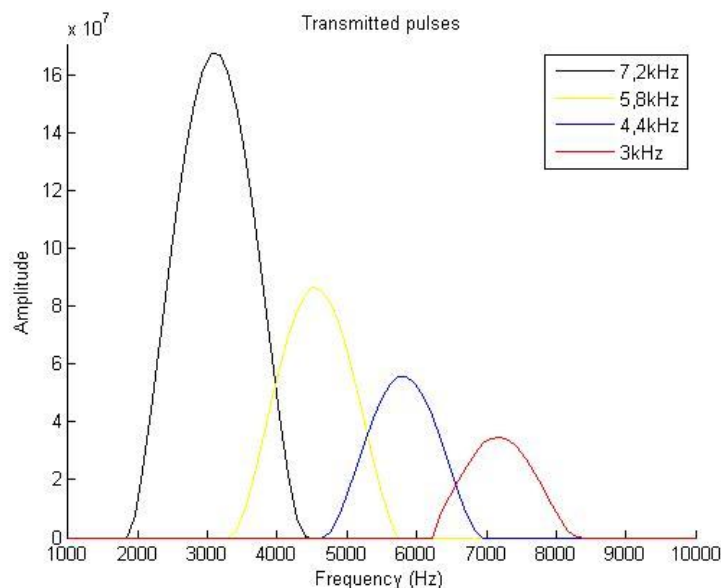


Figure 6. Transmitted signals from Osstell™ Mentor. [12]

In the time domain each of all the transmitted frequency pulses corresponds to a 1.2 ms long signal. An example of one transmitted pulse, measured by the probe, is presented in time domain in figure 7 below.

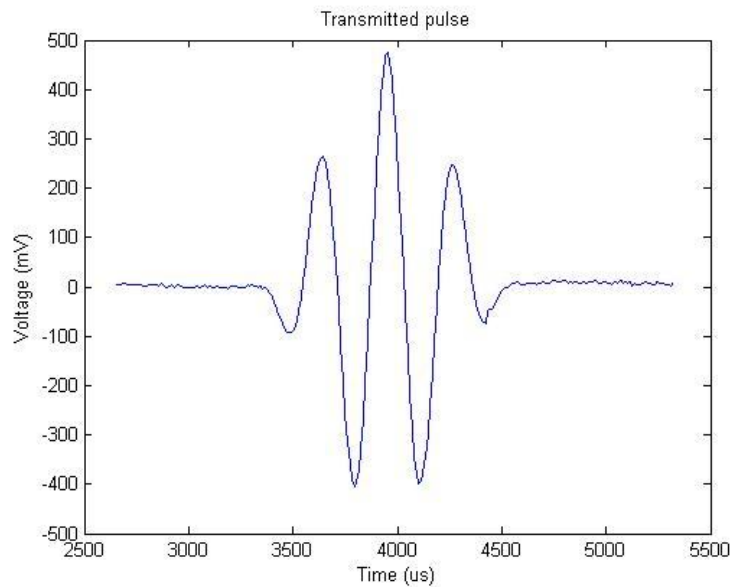


Figure 7. Measured transmitted pulse from the probe. [12]

The probe is connected to a data manager where the signals are stored and processed. In the signal processing there is a peak detection of the spectrum that finds the resonance frequencies and a quality value of each resonance is calculated. The peak detection of the spectrum is made in 4 frequency spans, corresponding to the 4 transmitted frequency spans. The two resonance frequencies with the highest quality value from the peak detection are extracted and each is converted into a value called ISQ, which is a scale developed by the OsstellTM company for making the presentation of resonance frequencies easier. ISQ is scaled from 0 to 100 where 0 presents the lowest stability of the implant and ISQ 100 presents the maximum stability. Sometimes there is only one resonance frequency with sufficient quality and then the data manager only presents one ISQ value in the display. Otherwise there are two ISQ values presented in the display. [13] The translation from frequencies into ISQ is presented in figure 8. The figure is also presented in Appendix 2.

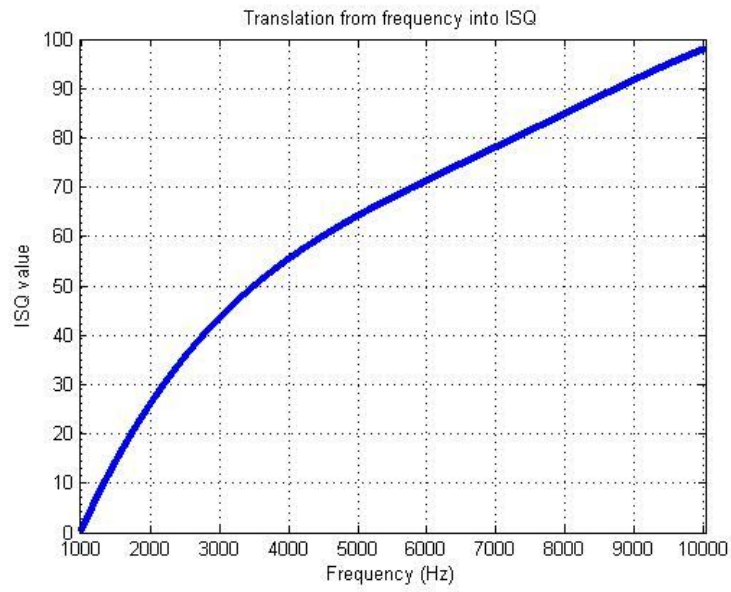


Figure 8. Translation from frequency into ISQ. [13]

The two calculated ISQ values are then shown on the display of the instrument and by using a docking station it is possible to receive the whole measured data file into a PC. In this thesis, the measurements were loaded into a PC in order to be analyzed in MATLAB.

4. Methods of Solving the Problem

For localizing from where the different modes originate, the problem was divided into three main subject areas: “Hardware”, “Physiological causes” and “Management and outer circumstances”. The strategy was to get knowledge about how Osstell™ Mentor system works in the “Hardware” chapter, to get an understanding for the signal environment of a realistic environment by studying plastic models in the chapter “Physiological causes”, and to measure the Smartpeg™ and an implant when they were affected of convincible mechanical errors in the chapter “Management and outer circumstances”. One overall target in the whole thesis was to compare the received signals from the Osstell™ Mentor with measurements from the Laser Doppler system. In the thesis the Laser Doppler system was mainly used in the measurements, and Osstell™ Mentor was used parallel in the chapters “Physiological causes” and “Management and outer circumstances”, to get a basis of measurements for the analysis of the hardware.

4.1. Laser Vibrometer

The chosen measuring system, for comparison of the frequency spectrum from Osstell™ Mentor, was based on a laser vibrometer which measures vibrations with Doppler Effect. By using the laser equipment and one spectrum analyzer, the frequency response of the system, containing the Smartpeg™ and probe, could be measured. [14] It was also necessary to use a signal amplifier to drive the probe, whose resistance was measured to be 4.4 ohm. A list of the equipment is to be found in Appendix 1.

In the laser equipment the measured frequency shift is:

$$\Delta f = f_B + f_D$$

where f_B is a fixed frequency in the interferometer and f_D is the Doppler frequency:

$$f_D = 2 \frac{v}{\lambda}$$

In the Doppler frequency f_D , λ is the wavelength of the light and v is the velocity of the measure object. Δf is transmitted to the decoder for the laser signal, and from the decoder the vibration frequency of the object is transmitted. [15] This transmitted signal was connected to a frequency analyzer and the whole setup of the measuring system is presented in figure 9.

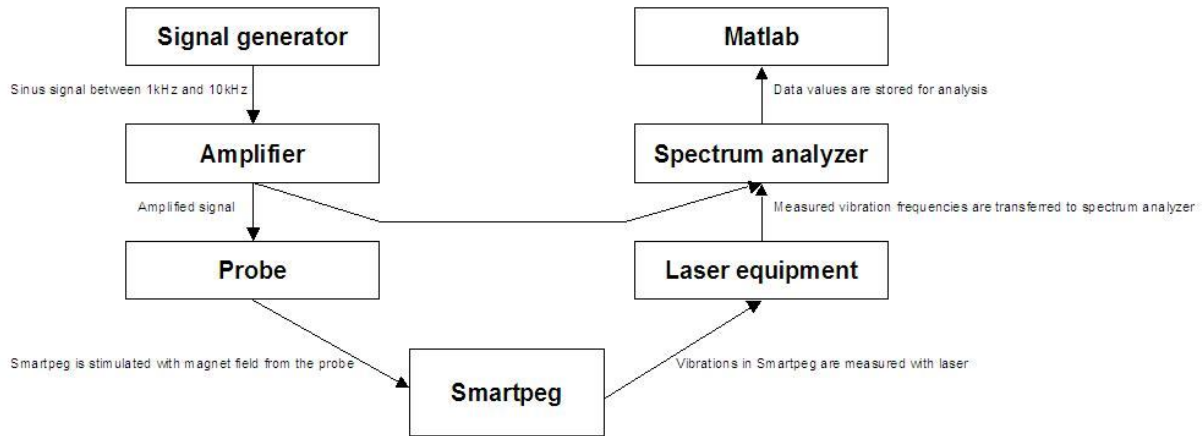


Figure 9. Setup of measuring equipment for measuring frequency response.

For verifying that the measured frequency was the same as the vibration frequency, a test was made where a SmartpegTM was stimulated with a 3 V peak sinus signal. Then the measured frequency, displayed in the spectrum analyzer, was the same as the frequency by which the SmartpegTM was stimulated.

While OsstellTM Mentor measures 256 points in the frequency span 1-10 kHz, or ISQ 1-100, the laser frequency response was measured with the same conditions. There was however a difference in the way of measuring resonance frequencies with the laser equipment compared to OsstellTM Mentor. The laser equipment in one moment stimulates the SmartpegTM with one frequency and measures the resonance response at that frequency [14]. The OsstellTM Mentor on the other hand, stimulates the SmartpegTM with 4 frequencies in the interval 2-8 kHz and measures the frequency response in the whole frequency band, 1-10 kHz, simultaneously with each of the transmitted signals.

4.2. Differences between OsstellTM Mentor and Laser Equipment

There was one important difference between measuring with OsstellTM Mentor and the laser equipment. The laser was only measuring the vibration frequency in one direction while the coil in the probe was registering all variations in the magnet field, including magnet field variations from different directions. The probe is designed to be sensing mainly in the axial direction but other directions are also detected. The way of stimulating the SmartpegTM was also different in the two methods of measuring. When using the laser equipment the transmitted probe signal was 256 sinus signals in the interval 1-10 kHz. OsstellTM Mentor on the other hand transmitted 4 pulses in the interval of approximately 2-8 kHz, and received in 1-10 kHz.

4.3. Defining Measurement Directions

In test measurements it was seen that the directions opposite to each other, had almost identical frequency spectra when measuring the frequency response. Because of that, measurements were only necessary to be done in 180 degrees. In this thesis measurements were mostly made from 4 directions equally divided on 180 degrees. In some tests more than 4 measurements were made and therefore the 360 degrees were divided into 16 directions. Figure 10 shows how the measuring directions were defined in this thesis. The directions followed the jaw, which means that direction 2 and 4 always were in the direction where the bone mass was small, in the bucco-lingual direction.

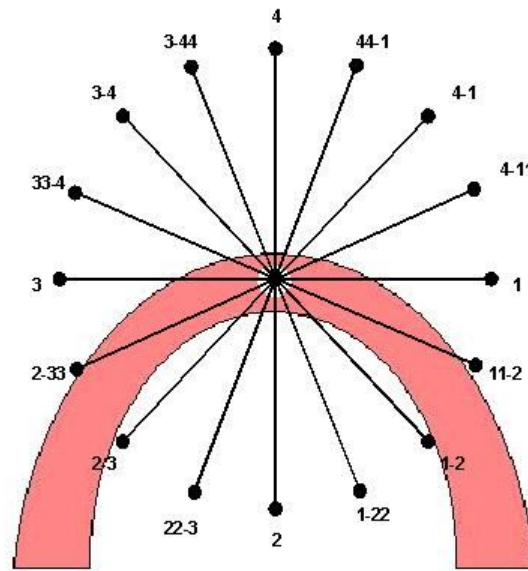


Figure 10. Defined directions for measuring on a plastic mandible seen from above.

4.4. Method for the Comparing Measurements

The first step in a measurement for comparison was to receive a frequency response from OsstellTM Mentor and after that to receive a response with the laser equipment. Switching between the two measurements was made by changing the cable connection. The probe was attached to a stand and was not moved during the switching from OsstellTM Mentor to the laser equipment. When a new direction was measured the object had to be moved which led to a different distance between the SmartpegTM and the probe in different directions. This meant that the amplitudes were possible to be compared between the laser equipment and OsstellTM Mentor in the same direction, but comparisons of the amplitudes between different directions were more insecure. In all measurements the SmartpegTM was fastened into the implant with a torque driver which was adjusted to 5 Ncm.

5. Results from measurements

All the measurements in the thesis are presented in this chapter. The measurements are divided in the chapters “Hardware”, “Physiological causes” and “Management and outer circumstances”. There is also one finishing chapter called “Summary of the results”, where all the results from the measurements are summarized. Spectra from all measurements are to be found in the Appendix. In some of the spectra in the Appendix there is no legend in the figures from the Osstell™ Mentor measurements. In these cases the legend is leaved out with purpose to make more space for the signals in the spectra. The legend is however the same in all the measurements with Osstell™ Mentor, and the legend could be found for example in figure 6.

5.1. Hardware

The “Hardware” chapter contains measurements made on the Smartpeg™ with the Laser Doppler system, and also measurements made with the Osstell™ Mentor system.

5.1.1. Self Resonance of Smartpeg™ and an Implant

In order to increase the knowledge about how the Smartpeg™ works, the self resonance of the Smartpeg™ when screwed with high torque into an implant was measured. In the first measurement the self resonance of the Smartpeg™ and implant when being in free space was measured. Figure 11 shows that measurement.

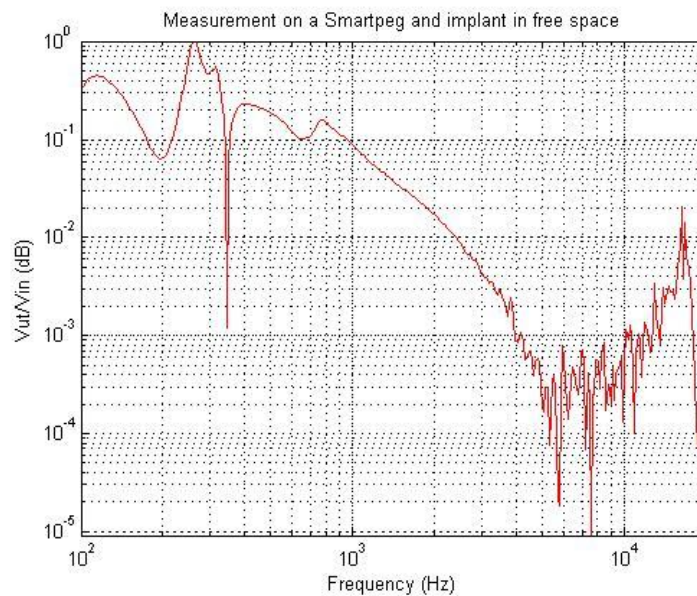


Figure 11. Measurement of Smartpeg™ and implant in free space.

In the low frequency spectrum, up to 1000 Hz, there were several resonances. At about 16.5 kHz there was another weak resonance frequency. One assumption of the resonances in the low frequency area was that the whole piece of metal was moving when the frequency was low. The resonance at 16.5 kHz is assumed to be the self resonance of either only the Smartpeg™ or most likely the system of both the Smartpeg™ and the implant.

In the next step the piece of metal was fastened into a vice, close to the top of the implant. The frequency spectrum from the measurement is presented figure 12.

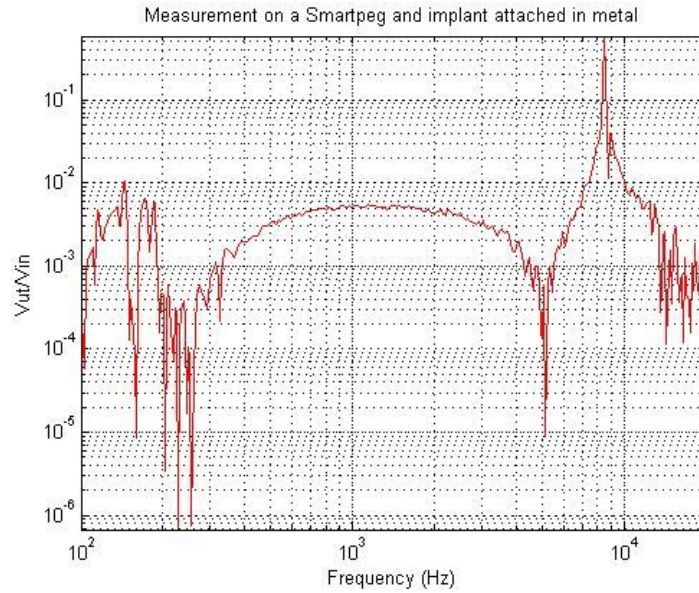


Figure 12. Measurement of Smartpeg™ and implant in a vice.

There was one resonance frequency at 8487 Hz which is assumed to be the self resonance frequency of the Smartpeg™. The

One new measurement was made when the Smartpeg™ and the implant were screwed into a vice. This time the piece was fastened at the top of the implant. The result of the measurement is presented in the figure 13.

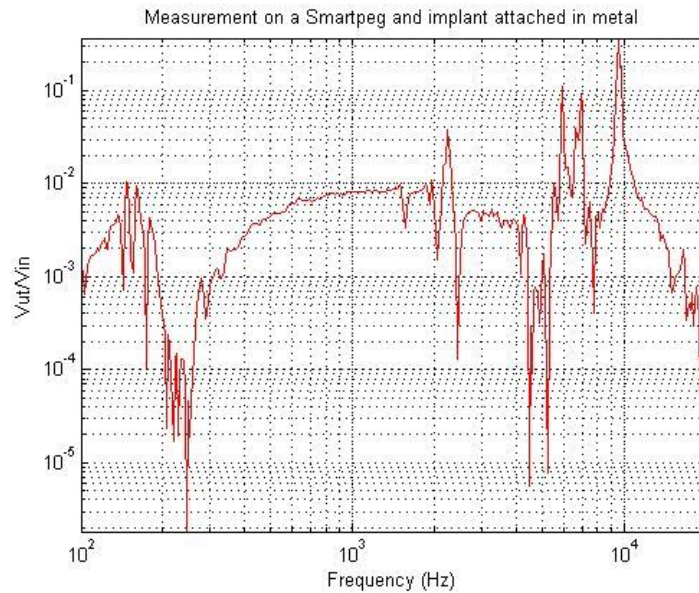


Figure 13. Measurement of Smartpeg™ and implant in a vice.

In this measurement there were several resonance frequencies. The resonance frequency of the Smartpeg™ is assumed to be the strongest peak at about 9511 Hz.

5.1.2. Ideal Cases Considering Frequency Response

To get knowledge about how the Osstell™ Mentor works in the high and the low frequency range respectively, two types of measurements were made. For low frequencies the

SmartpegTM was held with high pressure between two fingers while the OsstellTM Mentor was registering the ISQ- value. For high frequencies the SmartpegTM was fastened in a metal cylinder.

The frequency response of the first measurement is shown in figure 14.

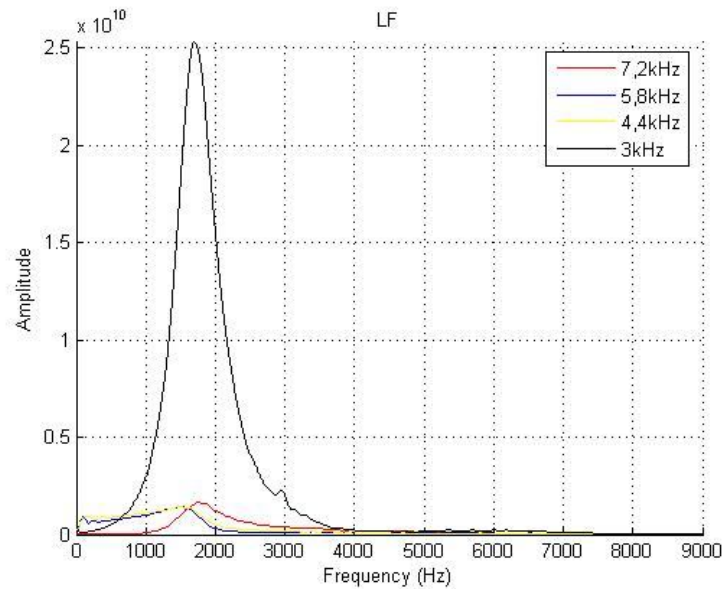


Figure 14. Measurement in the low frequency area.

In the first measurement the resonance frequency was registered by the 3 kHz pulse. The three other pulses were also registering the resonance frequency but the response of the 3 kHz pulse was much stronger.

In the next measurement the SmartpegTM was held with less pressure than in the previous measurement and the result is shown in figure 15.

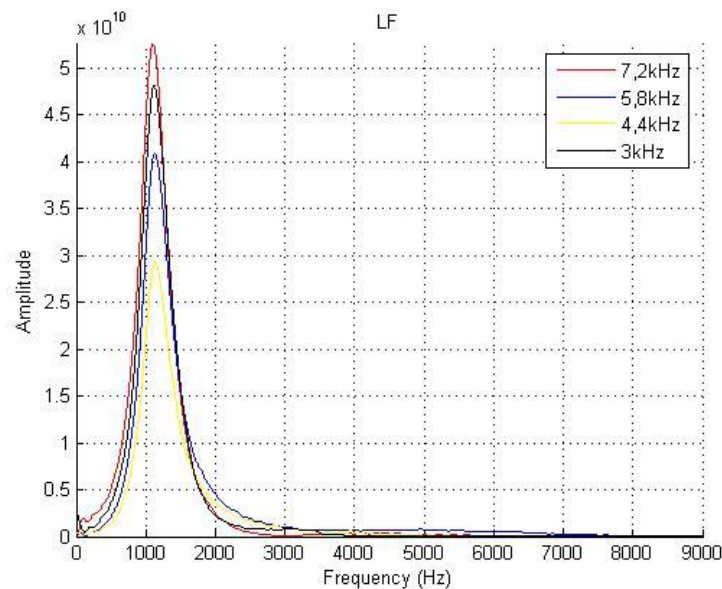


Figure 15. Measurement in the low frequency area.

In the second measurement the strongest frequency response was registered with the 7.2 kHz pulse. The closest pulse to the frequency response was the 3 kHz but from figure 15 it was noted that the frequency response was outside the transmitted frequency area. OsstellTM

Mentor has filters for filtering signals less than 1 kHz and the figure above may visualize an example where the resonance frequency actually were close to or below 1 kHz and that all the measured signals were affected by the filter.

One possible explanation to why a transmitting pulse of higher frequency also registered a lower frequency response is that the OsstellTM Mentor system is in a receiving mode during the SmartpegTM's whole vibration process. If the SmartpegTM starts to vibrate with a frequency of for example 7.2 kHz then it will decrease in vibration frequency until the vibration has stopped completely. If the OsstellTM Mentor receives during the whole vibration process, from 7.2 kHz to 0 kHz, then it is possible for higher transmitted pulses to register resonance frequencies outside the transmitted area. In the signal processing algorithm a pulse peak in each area is calculated from the corresponding transmitted pulse. Therefore this phenomenon does not result in any errors. It could however be possible to increase the measuring speed if the OsstellTM Mentor was calibrated for receiving in only the transmitted area.

The other ideal case was when the SmartpegTM was vibrating in the high frequency area. This was made by screwing a SmartpegTM in a metal cylinder. The first of the two measurements are presented in figure 16.

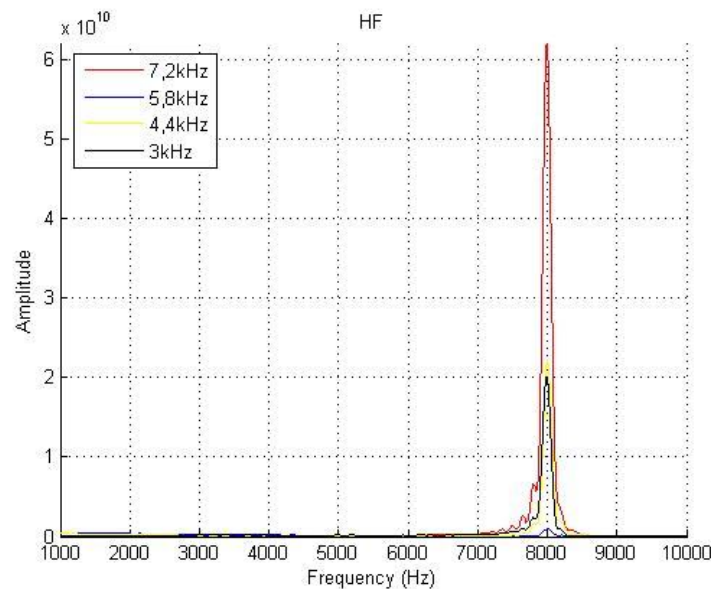


Figure 16. Measurement in the high frequency area.

In the first high frequency measurement all transmitted pulses resulted in a resonance frequency at the same frequency. This phenomenon looks very similar to the low frequency measurements but in this case the explanation cannot be the same. One explanation could be that the SmartpegTM vibrates with overtones to the lower transmitted pulses but while the SmartpegTM is similar to a tuning fork, and an ideal tuning fork does not have any overtones, there is another more possible explanation [16]. In non-linear amplifier, distortion could lead to overtones of second, third etc. frequency of normal mode [17]. If the low frequency pulses from OsstellTM Mentor have some energy of 8 kHz and the system responds many times more efficient at the resonance frequency, then the response at 8 kHz can be dominant.

In the next high frequency measurement the SmartpegTM was fastened even harder into the metal cylinder. The result of the measurement is shown in figure 17.

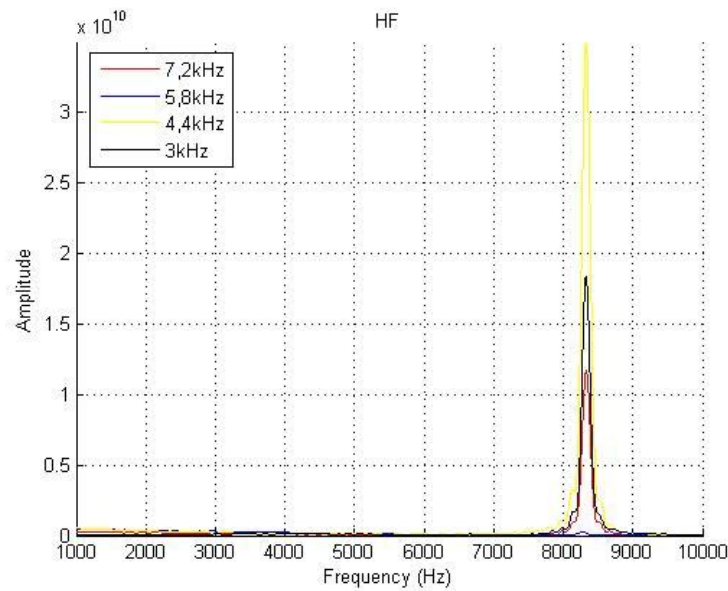


Figure 17. Measurement in the high frequency area.

This time the resonance frequency was higher than the transmitted range and the closest transmitted frequency peak was only the third strongest pulse. Both the resonance peaks from the “4.4 kHz” and the “3 kHz” pulses were stronger. The “5.8 kHz” pulse does not result in a resonance frequency. This verifies the theory of overtones, either mechanical overtones in the Smartpeg™ or electrical overtones in the transmitted signals. The “3 kHz” pulse has a frequency span of approximately 2 kHz to 4 kHz. In this span it could be assumed that the resonance frequency was the result of the third overtone. In the “4.4 kHz” case the span is approximately 3.5 kHz to 5.5 kHz. This could be the result of a second overtone at the resonance frequency. In figure 17 the “4.4 kHz” pulse leads to a higher frequency peak the “3 kHz” pulse, which means that the second overtone is stronger than the third. The pulse absolute levels are higher at the lower frequency pulses, see figure 6, which also affects the result.

5.1.3. Measurement on a Smartpeg™ from Different Directions

In figure 18, from Appendix 3.1, one measurement is presented where the Smartpeg™ was stimulated from one direction and the laser vibrometer was measured from three different directions.

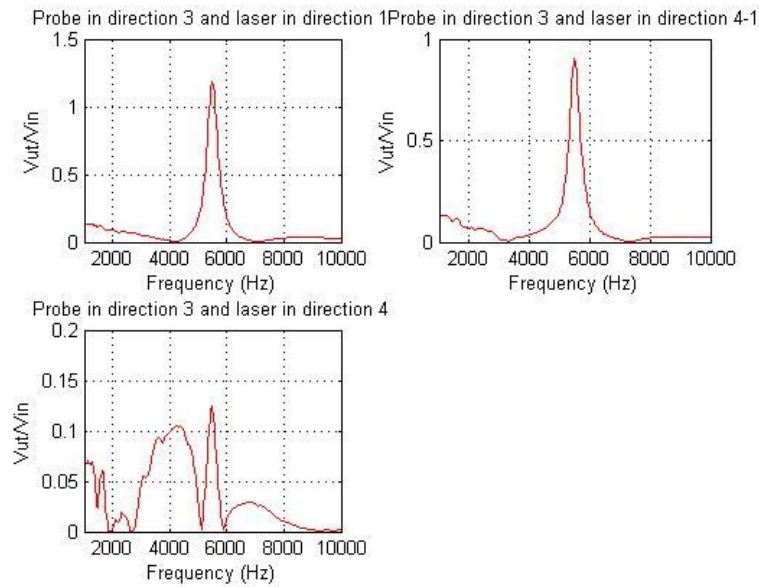


Figure 18. Probe in direction 3 and laser in different directions.

From the measurements there were two resonance frequencies registered. This figure shows that the Smartpeg™, when being stimulated from one direction, starts to vibrate in other directions where resonances occur. There is also a resonance phenomenon at 1 kHz. In figure 19, from Appendix 3.2, there are measurements on the same implant but the probe was placed in direction 2 instead.

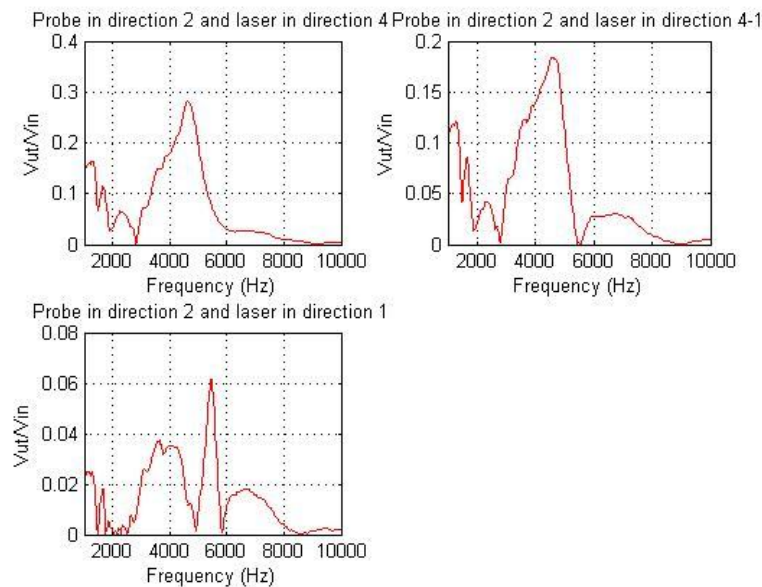


Figure 19. Probe in direction 2 and laser in different directions.

The figure shows that the same two resonance frequencies as in the earlier figure were found and that the Smartpeg™ was vibrating in mainly two directions when being stimulated from one direction. A resonance at 1 kHz is also to be found in this measurement.

In Appendix 3.3-3.6 similar measurements are presented but the laser spot measures on other places on the Smartpeg™ than on top as in figure 18 and 19.

5.2. Physiological Causes

In this chapter it was studied how the signal environment looked like in more realistic cases. The first measurements were made on a plastic model of a jaw and the last measurements were made on two different types of plastic cylinders. The measurements in this chapter were both made with the laser vibrometer and the Osstell™ Mentor. The purpose was to get an understanding of how the measured signals looked like in more realistic environment, and also to receive a basis of measurements to be able to analyze the difference in measured signal between the laser vibrometer and the Osstell™ Mentor in the frequency spectrum. Another purpose was to analyze which ISQ-values the Osstell™ Mentor registered to be able to analyze how well the Osstell™ Mentor registered the two expected resonance frequencies when using the two recommended measurements with an angle of 90 degree [6]. The last purpose was to measure on the jaw with the laser equipment and to study if there were any resonance frequencies originating from the jaw.

5.2.1. Measurements on a Jaw Made of Plastic

For a high accuracy the number of measurements on the Smartpeg™ was 16, symmetrically divided in the way described in chapter 4.1.3. The measurements were made on two different implants in the jaw, called implant number 3 and 4. Figure 20 shows the placement of the implants in the jaw.

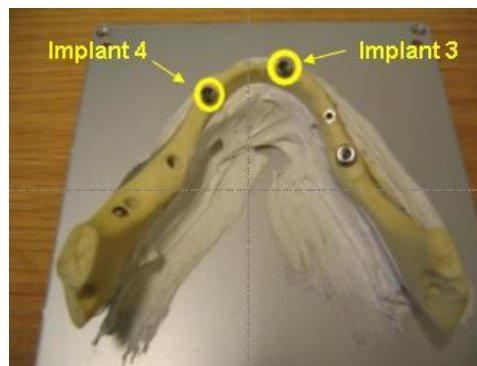


Figure 20. Placement of implant 3 and 4.

The results of these measurements are presented in Appendix 4.1-4.4 and 5.1-5.4. In the direction 2 the measurements on the jaw were made without moving the Smartpeg™. Only the laser was moved to different spots on the system. One spot was on the part of Smartpeg™ closest to the implant. Another spot were on the implant and the two last spots were on the top of the jaw and on the middle of the jaw. These measurements are presented in Appendix 4.5 and 5.5.

On implant number 3 there were only two resonance frequencies detected with both the laser and the Osstell™ Mentor in their frequency spectrum. Despite that, Osstell™ Mentor registered 3 different ISQ values. The two most common values in all the 16 measurements were at about ISQ 58 and 70. The registered values 57, 59 and 71 were assumed to belong to 58 and 70. The third ISQ value was 37, which was registered in direction 2. ISQ 37 should correspond to a resonance at about 2850 Hz. In figure 21 the measurement of direction 2 is showed and in figure 22 the frequency spectrum of interest is zoomed.

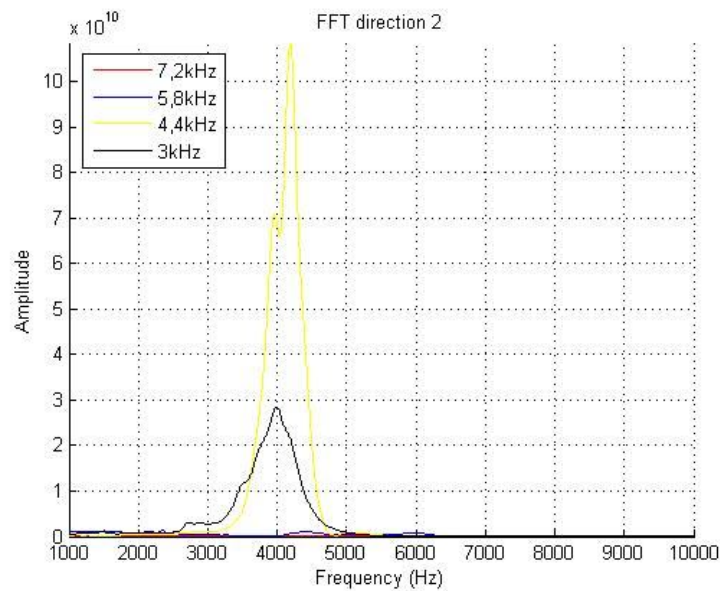


Figure 21. Direction 2.

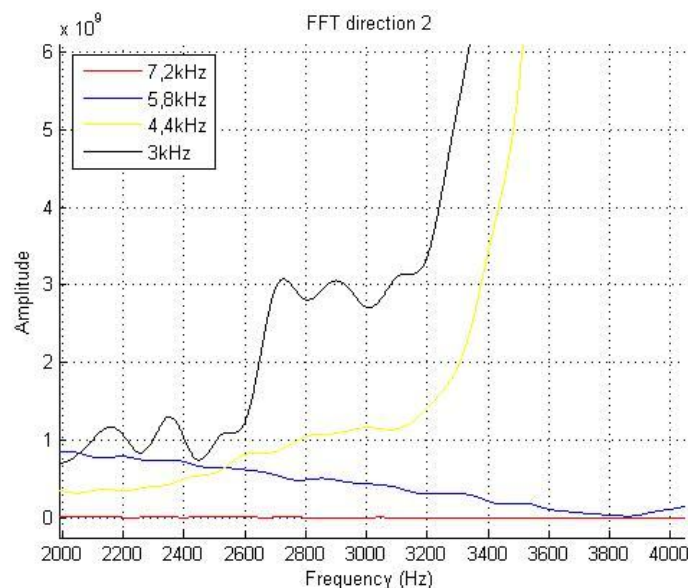


Figure 22. Zoomed area of direction 2.

In the area around 2850 Hz there was a higher level of the measured signal but there was no real resonance frequency. The higher level was in the lower area of the resonance frequency at about 4 kHz which corresponds to the ISQ value of 57. The detection of the third ISQ value of 37 was accordingly not a resonance which is shown in the frequency spectrum with both the laser vibrometer and the OsstellTM Mentor. There was not any new frequency detected in Appendix 4.5 either. The ISQ value of 37 was instead probably a result of an incomplete signal processing algorithm. The real resonance frequency was almost 10 times greater than the third ISQ of 37. In this case the ISQ value 37 should be avoided with a higher requirement of the third resonance frequency amplitude.

The measurements on implant number 4 had distinguished frequency spectrums compared to the spectrums from the measurements on implant 3. The measurements closest to direction 1 and 3 had strong and clear resonance frequencies. In directions closest to 2 and 4 there are

more diffuse frequency spectrums. The registered ISQ values were 44, 46, 59, 60 and 68. From a study of the frequency spectrum the assumption was that 44 and 46 are originating from the same resonance phenomenon and likewise did 59 and 60 originate from the same resonance phenomenon. In for example direction 2 and 22-3 there were three resonance phenomenon in the frequency spectrum but in the opposite laser vibrometer measurement, there was only one resonance frequency. There was accordingly a difference between the laser vibrometer and the Osstell™ Mentor measurement.

In Appendix 5.5 there are measurements in direction 2 on other places than on top of the Smartpeg™. The measurements on the bottom of the Smartpeg™ and on top of the jaw were similar to the measurement on the top of the Smartpeg™ in Appendix 5.2. On the other hand, the resonance frequency at 4597 Hz was weaker on top of the jaw and on the jaw. The strongest frequency on the jaw was at 2985 Hz. This could be equivalent to the registered resonance frequency at 44 ISQ with the Osstell™ Mentor. In all the ordinary laser vibrometer measurements there were only two registered resonance frequencies, at 4597 Hz and 5432 Hz. These two frequencies corresponded to the ISQ values at about 60 and 68. If it is supposed that these two frequencies were the two expected frequencies from the implant/bone interface, then the frequency peak at ISQ 44 was originating from another phenomenon that was not detected in the laser ordinary measurements on top of the jaw. There was however a resonance frequency registered in the laser measurement on the jaw. This means that the ISQ 44 value, in opposite to the measurement on implant 3, originated from a physical phenomenon.

One important parameter was that the implant number 4 was screwed on a place where there were very little bone, or plastic, mass surrounding the implant in direction 2 and 4. This was maybe resulting to vibrations in the bone, which was registered with the laser measurements in Appendix 5.5. A reason to why the phenomenon was to be seen in the frequency spectrum with the Osstell™ Mentor but not with the laser vibrometer on top of the Smartpeg™, may be explained with that the strongest transmitted signal from Osstell™ Mentor was at 3 kHz, which was studied in chapter 3. Maybe the bone resonance was increased when the stimulating pulse was as strongest at the same frequency as the resonance frequency.

To sum up, one of the results from the measurement with the plastic jaw was that an incomplete signal processing resulted in false ISQ values. Another result was that a third vibration mode did come up in a direction where the bone mass was small. In these cases it was possible that the bone resonance was magnified because the transmitted pulses had different amplitudes. This may convey that the calculated ISQ value originated from the bone resonance.

5.2.2. Different Spring Constants

When an implant is screwed into bone, the bone is exposed for compression. The so called second stability, in the cancellous bone, is decreasing during four weeks after implant placement and after that, the stability increases again [4].

In this chapter the spring constant of the bone is studied. Three Straumann implants were screwed into two plastic cylinders made of different kind of material. The cylinders were of same size but the first cylinder was made of a heavier material than the second cylinder and the first cylinder was loaded with two implants. Figure 23 shows the plastic cylinders.

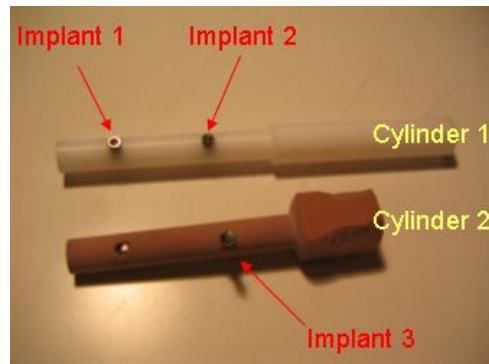


Figure 23. Plastic cylinders.

The second implant in the first cylinder was applied in a drill hole of larger diameter compared to the first implant in the same cylinder. The way of measuring was first to make 4 measurements on an implant when the cylinder was resting on damping material. In the next step the cylinder was placed into a vice and then set out for high pressure from direction 2 and 4.

The first two measurements were made on the first implant in the heavier cylinder. These measurements are presented in Appendix 6.1 and 6.2. In the case without pressure on the cylinder there were three resonance frequencies at 2512 Hz, 7456 Hz and 7674 Hz. The Osstell™ Mentor presented two corresponding ISQ values of the two lowest frequencies, 35 and 81. When the cylinder was exposed to pressure, the frequency spectrum turned diffuse. The strongest resonance in direction 1 was measured to 6722 Hz with the laser vibrometer and Osstell™ Mentor measured both a similar spectrum and a corresponding ISQ value of 75. There was also a resonance frequency at 6095 Hz which was also registered with Osstell™ Mentor as ISQ 72. There was also a diffuse high frequency area at 7674 Hz which was also registered in the frequency spectrum from Osstell™ Mentor. This frequency should correspond to a value of 83 with Osstell™ Mentor if it was not less prioritized. In direction 1-2 the laser vibrometer registered one resonance at 6531 Hz. The Osstell™ Mentor calculated a corresponding ISQ value of 75 but in the frequency spectrum the Osstell™ Mentor has more than one frequency in the spectrum. The lower frequency was not calculated as an ISQ value. In direction 2 the laser equipment measured one resonance phenomenon at 6531 Hz. The Osstell™ Mentor calculated a corresponding value of 75 but in Osstell™ Mentors frequency spectrum there was one more peak which was calculated to ISQ 70. In direction 2-3 there were two frequency peaks at 6201 Hz and 6530 Hz and they were also to be seen in the spectrum from Osstell™ Mentor. There was also, in similarity to direction 1, an area with higher amplitude at about 7330 Hz. The Osstell™ Mentor presents the ISQ value of 72 from the corresponding peak at 6201 Hz. A value of ISQ value 62 was also presented which originates from a small peak in the Osstell™ Mentor frequency spectrum.

In this test there was a complicated signal environment and the laser equipment, total in the four directions, had three strong detected frequencies and one high amplitude area close to each other. Osstell™ Mentor calculated the ISQ values 72 and 75 from direction 1, 1-2 and 2. One more ISQ value of 70 was also presented. This value originated from a weak signal in the frequency spectrum from Osstell™ Mentor and in the spectrum from the laser there was no such frequency in any direction. Maybe this value was a resonance in vertical direction which would explain why only Osstell™ Mentor detects the signal. A different signal processing in Osstell™ Mentor should not present this as a value. With the same discussion the ISQ value of 62 in direction 2-3 should not be presented. The peak at 6201 Hz in direction 2-3 is probably originating from same phenomenon as the peak at 6095 Hz in direction 1. Maybe,

the frequencies at 6722 Hz and 6531 Hz also originate from the same phenomenon. Then the correct presentation of stability values should be 72 and 75 and perhaps a presentation of the higher area at 7674 Hz.

In Appendix 6.3 and 6.4 measurements on the second implant in the same cylinder is presented. The measurements without pressure on the cylinder resulted in simple signal environment with two frequency peaks. The measurements with laser vibrometer and Osstell™ Mentor are similar to each other. The difference when the cylinder is exposed to pressure was that the lowest resonance frequency turned higher. This was assumed to be due to the fact that the stability in direction 2 was increased because it was in the same direction as with the applied pressure. The registered ISQ values in the first measurements are 63 and 68 which seemed to be correct when studying the frequency spectrums. In the measurements with applied force the ISQ values were calculated to 59, 64, 65 and 68. The values of 64 and 65 are assumed to depend on same resonance phenomenon. Both 65 and 68 were originating from clear resonance frequencies in the spectrums. The value of 59 on the other hand corresponded to a frequency of about 4500 Hz. There was no peak to be seen at that frequency in the spectrum in figure 23 and figure 24 presents the area around 4500 Hz zoomed.

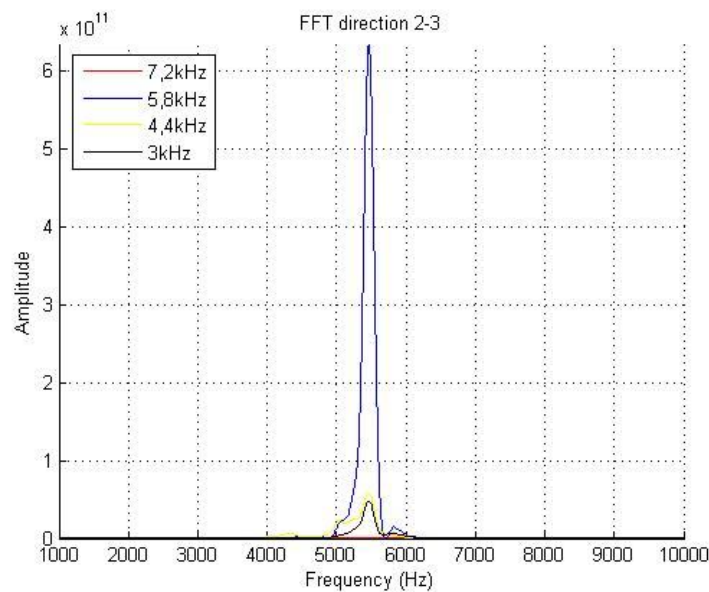


Figure 24. Direction 2-3.

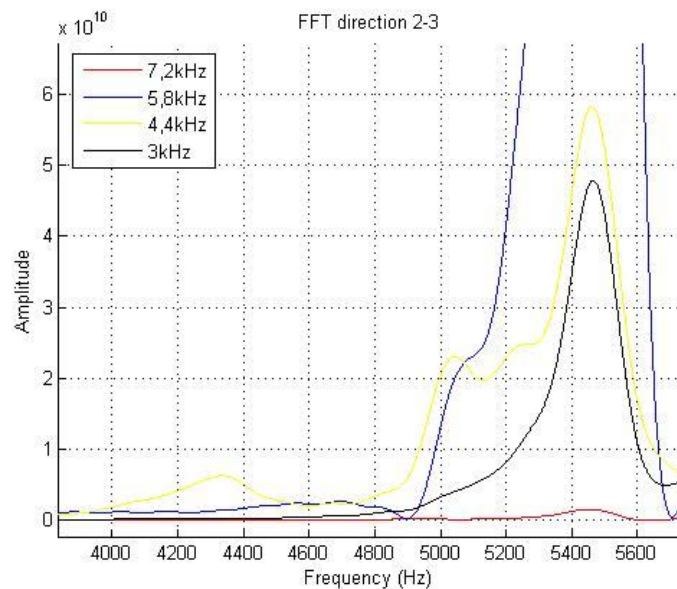


Figure 25. Zoomed area of direction 2-3.

The zoomed figure shows that there was one small peak at 4338 Hz. In the opposite laser measurement there was also one small peak at 4390 Hz. This resonance frequency was very weak in both the laser and the Osstell™ Mentor measurement. A different signal processing should avoid presenting this peak as an ISQ value.

In Appendix 6.5 and 6.6 the measurements on the third implant, in the lighter cylinder, are presented. In 6.5 there is to be seen that the received signal resulted in simple frequency environments with both measure methods. There were two resonance frequencies in the measurements and the Osstell™ Mentor calculated two corresponding ISQ values. In 6.6 the frequency spectrum became more disturbed. Like the measurements on implant nr 2 the lower frequency in direction 2 from 6.5 has become a higher frequency. Once again it is assumed to depend on that the stability was increased in that direction when the vice applied pressure from that direction. From direction 1 and 1-2 in 6.6 the calculated ISQ value was 73. From direction 2 the calculated ISQ value 70 corresponded to the frequency peak at the highest frequency at about 5600 Hz. Both the laser and the Osstell™ Mentor measured a peak at a lower frequency but this was not calculated as an ISQ value. In direction 2-3 there was one strong peak at a frequency corresponding to the ISQ value 74. This value is assumed to originate from the same phenomenon as the value 73 in direction 1 and 1-2. In the direction 2-3 there was also a calculated ISQ value of 65 from the small peak which is registered with both the laser equipment and the Osstell™ Mentor in their frequency spectrum. The value 65 was a resonance frequency that was seen in direction 2 and in that direction it was the strongest peak with the Osstell™ Mentor. In the laser measurements this peak is very small and perhaps Osstell™ Mentor would have registered this as a small peak to if the transmitted signal was different. A different signal processing should not calculate the small peak in direction 2-3 to a stability value.

5.3. Management and outer Circumstances

In this chapter the affect of different physical disturbances in the implant/ Smartpeg™ interface is analyzed. To receive a simple and clean frequency environment in the frequency spectrum, the measured Straumann implants were cast into 20 gram of plaster. Next after that, a Smartpeg™ was screwed into one of the implants with a force of 5 Ncm, and the

measurements were preceded. Figure 26 shows the plaster model with two implants applied. There is a SmartpegTM in the left implant.



Figure 26. Two implants cast into 20 gram of plaster. A SmartpegTM is placed in the left implant.

The resulted resonance frequencies from the measurements were at about the same frequency as the measured self resonance of the SmartpegTM and implant screwed into a vice, which was presented in chapter 4. Hence it is possible that the measured frequencies in these measurements are self resonance of the SmartpegTM and not the implant/plaster interface. The measurements are still interesting to study if new resonance frequencies can occur when the implant/ SmartpegTM interface is disturbed.

In the tests on plaster the main measuring equipment was the laser vibrometer. The purpose with the test was in the first place to study the SmartpegTM /implant interface. Sometimes the OsstellTM Mentor was used to complement the laser measurements. Since the resonance frequencies were outside the transmitted frequency span of the OsstellTM Mentor, these measurements were not aimed to be used for comparison between OsstellTM Mentor and the laser vibrometer with purpose to find eventual errors with OsstellTM Mentor. The OsstellTM Mentor measurements were instead aimed to be used as a second method for verifying the cause of events when different physical errors were applied on the SmartpegTM. In some cases it was not possible to receive a value with the OsstellTM Mentor because the received signal was too strong. This was indicated with a beep in the OsstellTM Mentor.

5.3.1. Rough Surface on the Bottom Side of the SmartpegTM

A rough surface can occur when for example coagulated blood gets stuck between the SmartpegTM and the implant. A rough surface can also be caused of metal dust from wear of the SmartpegTM or may be from the manufacturing. Below two test series are presented where one of them was a test of a rough surface caused by a soft error and the other was a test of a rough surface caused by an error made of metal. One interesting discover was made during a microscope study of the implant before the measurements. In the opposite place in the implant where the ledge of the SmartpegTM gets contact with the implant there was a punch from the manufacturer. This punch could be one convincing source for errors made of metal.

Soft Error Made of a Straw Hair

In this test a soft error was created by a straw of hair fastened with glue on the surface of SmartpegTM where contact between SmartpegTM and implant occurs. A series of measurements was made with the following order:

- Normal Case
- One Error Applied
- Error Removed
- A New Error Applied
- Error Removed Again

All tests in the series were repeated two times, with the SmartpegTM screwed out and into the implant again between the measurements, in order to obtain a better basis for analysis.

The two normal cases are to be found in Appendix 7.1 and 7.2. The frequency responses were similar to each other. In 7.2 both peaks were at higher frequency peaks than the opposite frequency peaks in 7.1. The difference was assumed to be due to the fact that the SmartpegTM was fastened harder into the implant in measurement 2 than in measurement 1, even if a torque driver was used. The difference between the two peaks was about 250 Hz in 7.2 compared to about 400 Hz in 7.1. Besides that, the two measurements were similar to each other.

There were two resonances in 7.1 and 7.2 and in systems with two modes there may occur antiresonance. In for example direction 1 in 7.1 the result of antiresonance is to be seen in the region direct above the resonance frequency. The magnitude in the frequency response was suddenly reduced when the second mode was subtracted from the first. [18]

The affect of antiresonance was also seen in some of the following measurements.

In the next step one error was made by a straw of hair which was fastened with glue. As before two measurements were made where the SmartpegTM was screwed out and into the implant again. This time measurements with OsstellTM Mentor were also made. The result of the measurement is presented in Appendix 7.3 and 7.4. In these measurements there was a double peak in direction 1 and 2 but single peaks in direction 1-2 and 2-3 which was contrary to the normal cases. The divergence between the double peaks has become larger than in the normal case. With an error applied the divergence was about 500-700 Hz compared to about 250-400 Hz in the normal case. One thing to note is that the laser equipment usually registers the same two frequencies in all directions, which do not usually differ in registered frequency response. However the lower frequency peak in direction 1, 7.3, is at 7807 Hz but in direction 2 the lower frequency is at 7852 Hz. The difference of approximately 40 Hz depends on the resolution in the laser vibrometer measurements. The frequency span is 9000 Hz divided into 256 points, which means approximately 35 Hz per point. The high frequency peak was registered at 8318 Hz in all directions. A conclusion is that even if the lower frequency differs between direction 1 and 2 the two frequencies originated from the same phenomenon. In direction 2-3, 7.4, there was also a similar difference to the other lower frequencies in other directions compared to 7.3.

Before the next measurements the straw of hair was removed and two new “normal cases” were measured. The measurements are to be found in Appendix 7.5 and Appendix 7.6. This time the measurements reverted to be similar to the first normal case in Appendix 7.1 and

Appendix 7.2 considering which directions the double peaks were registered. The diversion between the peaks this time was about 500 Hz.

When the measurements of the Smartpeg™ with a removed straw of hair were made, a new straw of hair was applied to the Smartpeg™ and two new measurements were made. These new measurements are presented in Appendix 7.7 and Appendix 7.8. This time one of the peaks became as low as 6273 Hz and the diversion between the peaks was about 1600-1900 Hz which is much more than in the earlier measurements. As in the first error case there are three registered frequency peaks at 6722 Hz, 8366 Hz and 8414 Hz. The two last frequencies are assumed to belong to the same resonance mode. With a soft error applied it is assumed that the Smartpeg™ was sloping which could be the reason to the larger difference between the frequency peaks compared to the normal cases.

The second error was then removed and two new measurements were made, presented in Appendix 7.9 and Appendix 7.10. This time the diversion between the peaks was reduced to about 450-600 Hz but the frequency response was not as similar to the first normal case in Appendix 7.1 and Appendix 7.2 as the second normal compared to the first normal case.

A conclusion from the measurements with an applied error made by a straw of hair is that the frequency response is affected by an applied error in such a way that the divergence between peaks becomes different and the number of peaks in one direction. In all measurements made by the laser equipment there were only registered peaks at maximum two frequencies in each measurement. There has been a third frequency in both the cases when an error was applied but because two of the frequencies were so close to each other, the conclusion is that they originate from the same resonance phenomenon and no new modes are discovered as a result of applying a soft error.

Hard Error Made of Metal and Glue

In this test a hard error was made by a thin piece of metal thread fastened with glue on the same surface as in the case with the soft error but on a new Smartpeg™. The series of measurements followed the same structure as in the case with the soft error.

The results from the normal cases can be studied in Appendix 8.1 and 8.2. The resonances were at higher frequencies in 8.2 than in 8.1, which is similar to the normal cases in the measurements with a soft error. In the same way the assumption is that the difference depends on difference in screwed force. The difference between the resonance frequencies was about 150-200 Hz.

In the next measurements an error made of thin metal thread was fastened in the way described before. The differences between the resonance frequencies were about 250-500 Hz. The larger difference in 8.3 was due to the fact that the lower frequency response became lower which, in a similar manner as in the case with soft error, is assumed to be owing to that the Smartpeg™ was sloping when the metal error was applied. In 8.4 the difference between the frequency responses was about 250 Hz, which was smaller than in 8.3. This may be a result of wear on the glue or the metal error when the Smartpeg™ was screwed into the implant for a second time. This led to a smaller slope which resembled the normal cases.

In Appendix 8.5 and 8.6 the metal error was removed. The difference between the frequency responses was about 200 Hz which was similar to the two first normal cases.

The measurements with a new error applied are presented in Appendix 8.7 and 8.8. In both measurements the lower resonance frequency became lower compared to the normal cases but this result was clearer in 8.7 than in 8.8. The difference between the frequencies responses was about 400-1250 Hz.

The two last normal measurements in this series are presented in 8.9 and 8.10. The separation between the resonance frequencies was about 500 Hz.

The metal error measurements showed the same thing that was shown in the soft error measurements: The errors made the SmartpegTM lean which led to a larger separation between the resonance frequencies compared to normal cases. In the tests no new resonance frequencies were found. A possibility to the very similar result in the soft error measurements and the hard error measurement could be that the glue affected the metal error measurements to become a soft error problem. To be able to exclude the influence from glue a new metal error was made, where the contact surface became rough caused of welding instead.

Error Made by Welding

The first two measurements were on a new SmartpegTM and can be studied in Appendix 9.1 and 9.2. The separation of the resonance frequencies in the measurements was about 300-400 Hz.

In the next two measurements, Appendix 9.3 and 9.4, there was simulated wear on threads on the SmartpegTM by welding on three spots on the contact surface. The tool for welding was a conductor which discharged on the SmartpegTM. The three welding spots were symmetrically placed over the circular surface. The separation of resonance frequencies was about 150-250 Hz and no new frequency peaks were registered.

The two following measurements, Appendix 9.5 and 9.6, were on the SmartpegTM when the number of welding spots was increased to 8 symmetrically placed spots. The measurements were similar to the case with 3 spots and no new resonance frequency was found. The separation between the peaks was 300-400 Hz.

After the case with 8 spots the whole ledge surface was covered with welding spots. The frequency spectrums were still similar to the earlier tests and they are presented in Appendix 9.7 and 9.8. The peak separation was about 300-350 Hz.

On the SmartpegTM, the bottom side has no contact with the implant but in the next two measurements, the whole bottom side was covered with welding spots with purpose to exclude the affect of a rough bottom surface. The measurements are presented in Appendix 9.9 and 9.10. The frequency spectrums are similar to the earlier and the separation between the peaks was about 300-500 Hz.

In the two last measurements, the whole 45 degree surface was covered with welding spots and the result of the measurements is presented in Appendix 9.11 and 9.12. The separation between the peaks this time was reduced to about 150 Hz.

The result of the two measurement series for metal error was that no new resonance frequency was discovered. The placement of the peaks in the frequency spectrum was affected when a piece of metal or glue was attached. It is assumed that the different attached errors made the SmartpegTM to a rake, which affects the resonances.

5.3.2. Wear on Threads

Wear on threads can occur for example when one Smartpeg™ is used several times. To simulate wear, the threads in one test series were destroyed by physical force from metal tools in an ascending way with measurements between the new errors. With this way of creating errors some chips of metal also came up.

In Appendix 10.1 and 10.2 there are two measurements for normal cases presented. The distinction between the resonance frequencies was about 150-300 Hz in the measurements.

After the normal cases one third of the thread, closest to the main body of the Smartpeg™, was destroyed and two measurements were made. They are presented in Appendix 10.3 and 10.4. The divergences between the peaks were about 550-650 Hz. The larger disparity was due to that the lower frequency became lower compared to the normal cases. This was maybe a result of the wear on the threads.

In Appendix 10.5 and 10.6 the same thread is destroyed but this time even more. The frequency responses were comparable to the measurements in Appendix 10.3 and 10.4.

The next step was to involve the thread closest to the end of the Smartpeg™ by placing a similar destruction as in the case with only the first thread. This means that one third of two threads were destroyed and the result is presented in Appendix 10.7 and 10.8. The difference between the peaks was about 500 Hz.

In Appendix 10.9 and 10.10 there are measurements when all threads were destroyed. The separations between the peaks were about 450-600 Hz.

In the last measurements the screw threads were destroyed completely after pressuring with a tong around the threads. When the Smartpeg™ was screwed into the implant the metal mass from the ledges was still on the Smartpeg™ but divided as a smooth area. The measurements are presented in Appendix 10.11 and 10.12. The separation between the resonance frequencies was about 1250-1700 Hz

In similarity to the measurements in chapter 4.3.1 the result of destroyed threads was a separation of the resonance frequencies. This phenomenon is assumed to be due to the fact that when the threads were destroyed, the Smartpeg™ leaned which resulted in different resonance frequencies. Another result is that no new resonance frequency has been registered, neither with the laser vibrometer, nor the Osstell™ Mentor.

Although no new frequency was found in the measurements with applied errors and wear on threads, the results shows that to get accurate ISQ- values, new Smartpeg™'s and clean threads should be used.

5.3.3. Disturbance Caused by Electromagnetic Sources

Electromagnetic sources may disturb other electric sources while in use and in this test the Osstell™ Mentor was exposed to a disturbance of a constant sinus wave. Osstell™ Mentor has a protection for disturbances that will warn the user by beeping when the level of disturbances is too high. However, it was interesting to measure how well the disturbance protection was working.

Around the cable, which connects the probe with the instrument, an unshielded signal cable was twisted and a sinus signal was transmitted in the unshielded cable. The amplitude of the sinus signal was maximized to be at a voltage level close below the level where the OsstellTM Mentor is warning. At different frequencies there were different voltage levels. When the disturbance was maximized one measurement on a SmartpegTM screwed into a metal cylinder was made. In Appendix 10.1-10.10 the result of the measurements are presented.

In the cases with disturbances at 3-10 kHz, the disturbing signal was to be seen in the frequency spectrum, but the amplitude of the disturbing signal was not enough to affect the OsstellTM Mentor to present the disturbance as an ISQ- value.

5.4. Summary of Results

The self resonance of the SmartpegTM screwed into an implant in free space was measured to approximately 16.5 kHz and the self resonance of the SmartpegTM, when screwed into an implant which was screwed into a vice, was measured to be 8487 Hz.

Measurements showed that all the transmitted pulses from the OsstellTM Mentor registered the resonance frequencies at lower frequencies than the transmitted pulse, since the SmartpegTM starts to vibrate at the same frequency as the transmitted signal and stop to vibrate before next pulse is transmitted. During the vibration all the resonance frequencies are registered.

OsstellTM Mentor registered signals of frequencies higher than the transmitted signals. The strongest measured signal originated from the transmitted pulse which had half the frequency of the resonance frequency. The second strongest signal was in a similar way from the signal of one third of the frequency. This phenomenon possibly depends on either that the SmartpegTM vibrates with overtones of the transmitted signal frequency or that distortion in the transmitted signal was amplified by the system at the resonance frequency.

In measurements on a jaw model made of plastic, more than two ISQ values were registered. In the frequency spectrum from both measurements with the laser vibrometer and the OsstellTM Mentor, no significant resonance phenomenon was found. This indicates an insufficient signal processing.

From measurements on the same jaw model but on another implant, three unique resonance frequencies were detected with the OsstellTM Mentor but only two of them with the laser vibrometer when measuring on top of the SmartpegTM. The third frequency was detected with the laser vibrometer when measuring on a spot on the jaw. The bone mass in the measured direction was small, which may indicate that the third frequency was a bone vibration. The third resonance frequency was approximately 3 kHz.

An overall look at the measurements on the jaw model and the plastic cylinders shows that there seems to be a connection between the measured resonance frequency and the quantity of surrounding mass. A small quantity results in a low resonance frequency and a large quantity results in a higher resonance frequency.

The influence of attached SmartpegTM errors made by soft material and metal was that one of the registered resonance frequencies had got lower frequency compared to the normal cases which led to a higher separation between the two measured resonance frequencies. No new resonance frequency was detected.

The results from the measurements on a SmartpegTM with destroyed threads resembled the case with attached errors on the SmartpegTM. The separation between the peaks was increased and no new resonance frequency was detected.

Disturbance from electrical source was registered in the frequency spectrum from measurements with OsstellTM Mentor. The disturbances did not result in any calculated ISQ value on the OsstellTM Mentor.

6. Proposals for Improvement

The upcoming development work of OsstellTM Mentor should start with a look at the result of the measurements on the jaw made of plastic where the problem with more than two resonance frequencies has been found. The reason to more than two detected resonance frequencies was in this thesis found to depend on two things:

1. An insufficient algorithm for signal processing and peak detection.
2. In some cases it seems to be more than two resonance phenomena.

6.1. Signal Processing

In the measurements on the jaw made of plastic, on implant nr 3, there were only two main peaks in the frequency spectrums from both OsstellTM Mentor and the laser vibrometer. Despite that, the OsstellTM Mentor presented an ISQ value of 37 from a very weak resonance frequency in Appendix 4.2, apart from the two main resonance frequencies. Similar occurrences were detected in the measurements on the plastic cylinder in Appendix 6.4 and 6.6. This problem should be avoided with a different signal processing.

The measurements on implant number 4 in the same jaw model, showed a problem which is probably not only a result of an incomplete signal processing. In Appendix 5.1-5.4, three resonance phenomena were detected in the frequency spectrum from the OsstellTM Mentor, while only two frequencies were detected with the laser equipment. The two resonance frequencies from the laser vibrometer measurements were corresponding to two of the three registered resonance frequencies from the OsstellTM Mentor measurements. The third frequency was however detected with the laser vibrometer when the laser spot was moved to the jaw instead of the top of the SmartpegTM. This could mean that the third resonance frequency was a bone vibration which the OsstellTM Mentor registered. In this case the eventual bone frequency had the lowest frequency and here it would be interesting to analyze why the OsstellTM Mentor measures the bone resonance but the laser vibrometer do not.

The laser vibrometer did not detect the third frequency when it measured on the top of the SmartpegTM while the OsstellTM Mentor did. This difference is assumed to depend on either the way of measuring or the way of transmitting the excitation signals. OsstellTM Mentor transmits signals of lower frequencies with a higher power level than signals of higher frequencies; it should mean that the SmartpegTM vibrates stronger at lower frequencies. This means that in this case where the bone frequency has a lower frequency than the two other resonances phenomenon, the bone resonance gets the strongest excitation signal. This influence, from the transmitted signals, is assumed to be the most probable reason to the strong bone resonance even if differences in measure methods can not be neglected.

The laser equipment transmits 256 different sinus signals of the same amplitude in the interval of 1000 to 10000 Hz while OsstellTM Mentor only transmits 4 pulses designed to cover the same interval. The 4 OsstellTM Mentor pulses have different amplitudes. It would be desirable to make the transmitted signal more similar to the laser measurements.

A proposition is to design one OsstellTM Mentor to transmit a larger number of pulses to cover the frequency span. The amplitude of the transmitted signals should also be changed to be at the same levels at all the transmitted frequencies. Then it could be possible to add all received signals into one frequency spectrum because the signals would become more comparable. The peak detection would then be made on the whole frequency span and not in the corresponding

area to the transmitted pulses, which is the case today. This change in Osstell™ Mentor should probably avoid both the problem with the signal processes in implant number 3 and the problem with bone resonance in implant number 4.

6.2. Bone Vibrations

The changes on the Osstell™ Mentor would result in a better received signal and a better peak detection. However, it is still important to analyze the bone resonances more. In the case with bone resonance on the implant number 4, the bone resonance occurred at lower frequency than the stability resonances and had actually smaller vibration power, even if Osstell™ Mentor received a strong signal. It is important to get more knowledge about the phenomenon with the eventually bone resonances. One thing is to analyze at what frequencies the bone vibrates. Another thing is to analyze how strong the bone resonances are in comparison to the stability values. It could be possible that bone resonances in some cases are stronger, or have higher frequencies, than the stability resonances. The case in Appendix 6.1 and 6.2 has three vibration frequencies and maybe is one of the resonances originating from bone vibrations. In this case it was not measured on the cylinder and it was therefore difficult to see which of the frequencies that was originating from the bone/plastic resonance.

The measurements in chapter 4.1.7 showed a resonance at approximately 1 kHz in the direction where the bone/plastic mass was small. This resonance could eventually indicate a bone resonance.

An example on a test for measuring bone vibrations is to drill a large hole in a piece of bone which has one direction with large bone mass and one with a small bone mass. The implant should then be cast with materials of different stiffness, or maybe one material whose stiffness could be changed by changing the temperature. By using materials in a range, from softer than the bone material to much stiffer, it could be possible to analyze the bone resonances which should occur in the cases with the most stiff materials.

In an overall look at the measurements on the jaw model and the plastic cylinders, the connection between the measured frequency and the measured direction is found. In directions where the bone/plastic mass was small the resonance frequencies were at lower frequencies than in directions with more bone/plastic mass. This phenomenon could be examined further with more measurements. It could be interesting to quantify how the stability value depends on the surrounding bone mass.

6.3. Remaining Propositions

One remaining suggestion is to change the spring constant of the Smartpeg™ to get the resonance frequency, when being fastened in for example a vice, to become higher than the measured area up to ISQ 100.

It is also recommended to protect the equipment better against disturbances from electrical sources.

The proposition for a better signal processing was based on a development on the technology used today in the Osstell™ Mentor product. Another convincing development is that the stimulation of the Smartpeg™ would still be made with magnet field from a coil but the receiving will be made acoustic with a microphone. In the laser measurements, it was possible to hear the vibration frequency of the Smartpeg™. The advantage with acoustic measurements could be that measurements would possibly be faster than today, while it

would be possible to measure constantly without switching between transmit mode and receive mode. In that case it could also be possible to increase the resolution by increasing the number of transmitted signals.

Another thought is to develop the probe to be able to measure in more than one direction by using two coils. It could then be possible to compare signals from more than one direction, which could lead to a higher accuracy.

7. Conclusions

The most interesting results in this thesis were made from the measurements on the jaw model and also from the measurements on the plastic cylinders. The measurements with different mechanical disturbances between implant and SmartpegTM have been useful to be able to exclude mechanical disturbances in the measurements on the plastic jaw. There was found that mechanical disturbances affect the resonance frequencies but in this thesis they did not result in new resonance frequencies. However, the affect of mechanical disturbances did show that it is important to use new and clean SmartpegTM's in measurements.

The problem with more than two resonance frequencies has been found to depend on more than one thing where the first cause was found to be an incomplete signal processing. In some cases there were found, in 16 directions on one implant, two main resonances in the frequency spectrum, but in one of the single measurements the OsstellTM Mentor calculates a weak resonance to an ISQ value. This phenomenon is assumed to be due to the fact that the OsstellTM Mentor calculates peaks in 4 frequency spans, and values the frequency spans differently because the transmitted signal has different power in different spans. The problem could be avoided with a different signal processing. In the chapter "Proposals for Improvement", there was one suggestion to transmit more than 4 pulses to cover the frequency span and to make the transmitted signals to have the same amplitudes. This would render to a possibility to make a better peak detection in the whole frequency span, and not in 4 different spans.

The second cause to more than two resonance frequencies was found to be owing to that in some cases there seemed to come up bone vibrations. It is recommended to make more measurements to get a better knowledge about these vibrations. In one of the jaw measurements, an eventual bone resonance was found. In that case, the resonance frequency is assumed to be possible to be avoided with the suggested change of the signal processing. However, it is important to get more knowledge about the eventual bone resonances, for example about how much power the bone vibrations have compared to the other resonance frequencies and also at which frequencies they occur.

In an overall look at the measurements on the jaw model and the plastic cylinders, there seemed to be a connection between the quantities of the surrounding bone mass in the measured direction and the received resonance frequencies. A small mass resulted in a lower resonance frequency while a large mass resulted in a higher resonance frequency. This phenomenon could be interesting to quantify with more measurements.

The self resonance of the SmartpegTM screwed into an implant has been found to be at a frequency of 8487 Hz. This was close to the upper frequency span for the OsstellTM Mentor and it is recommended to change the design of the SmartpegTM to get a self resonance above 10 kHz.

In the thesis, a simple test was made to investigate the protection against disturbances from electrical sources on the OsstellTM Mentor. In this test it was shown that disturbances were detected in the frequency spectrum but they did not result in any calculated ISQ value. It is still recommended to work more with the electric disturbance protection.

The measurement data in this thesis could be used for signal processing developments in the future.

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Appendix 1: List of Instruments

SPECTRUM ANALYSER

Agilent, 35670A Dynamic signal analyser.

AMPLIFIER

Rotel, RB-976 MK-II, Six channel power amplifier.

LASER

Polytec, HLV1000, Hearing Laser Vibrometer.

Polytec, HLV700.

OSCILLOSCOPE

Tektronix, 2245A, 100 Hz Oscilloscope.

SIGNAL GENERATOR

GFG-8216A

Agilent, 35670A Dynamic signal analyser.

Appendix 2: Translation from Frequency into ISQ

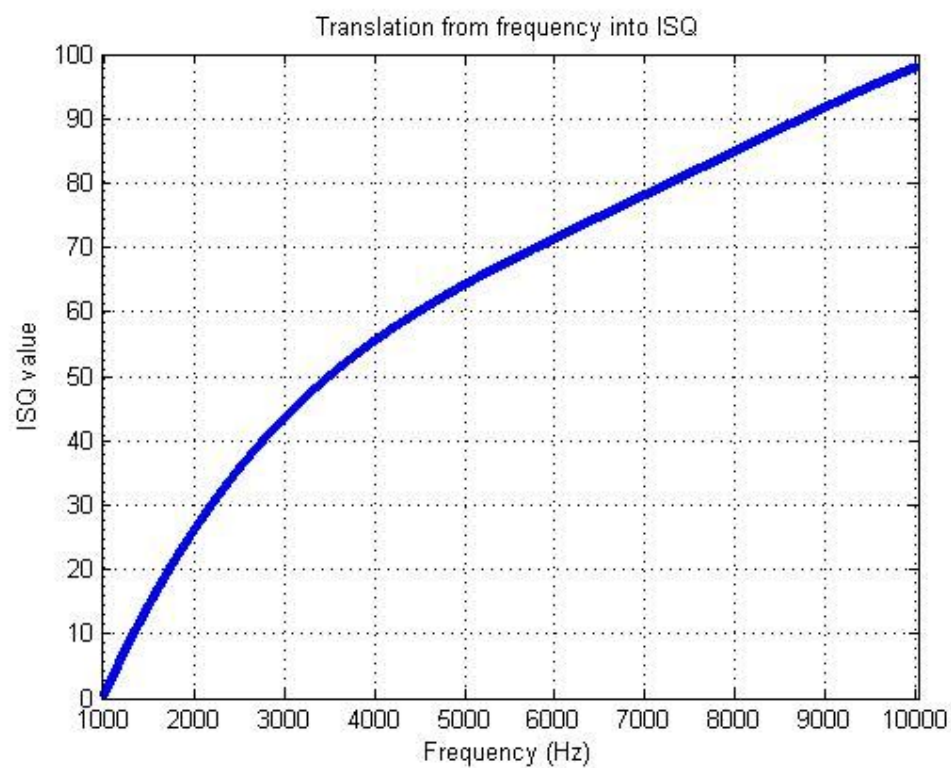


Figure 27. Translation from frequency into ISQ. [13]

Appendix 3.1: Probe Direction 3, Different Laser Directions

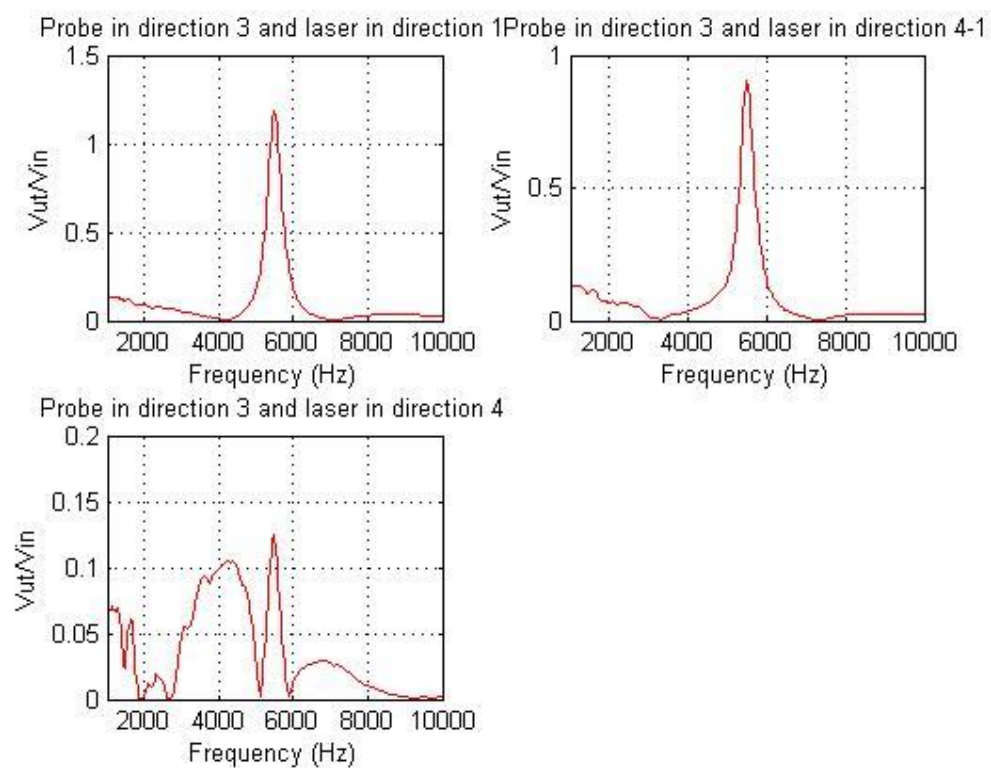


Figure 28. Probe in direction 3 and laser in different directions.

Appendix 3.2: Probe Direction 2, Different Laser Directions

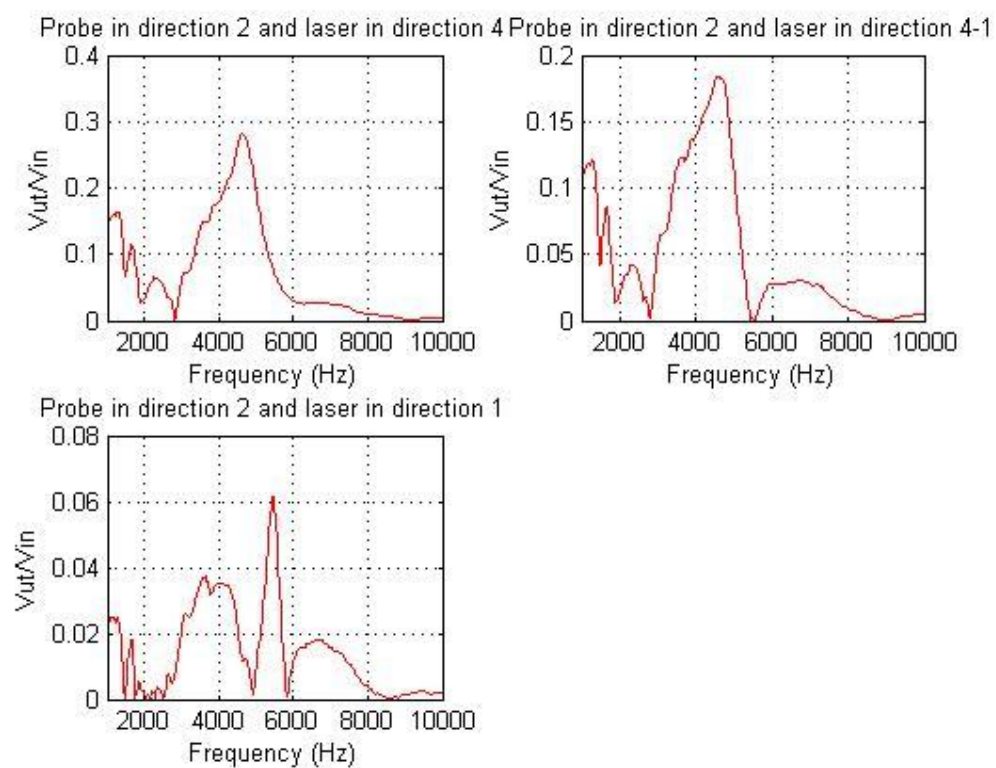


Figure 29. Probe in direction 2 and laser in different directions.

Appendix 3.3: Probe Direction 3, Different Laser Directions, Middle Part of Smartpeg™

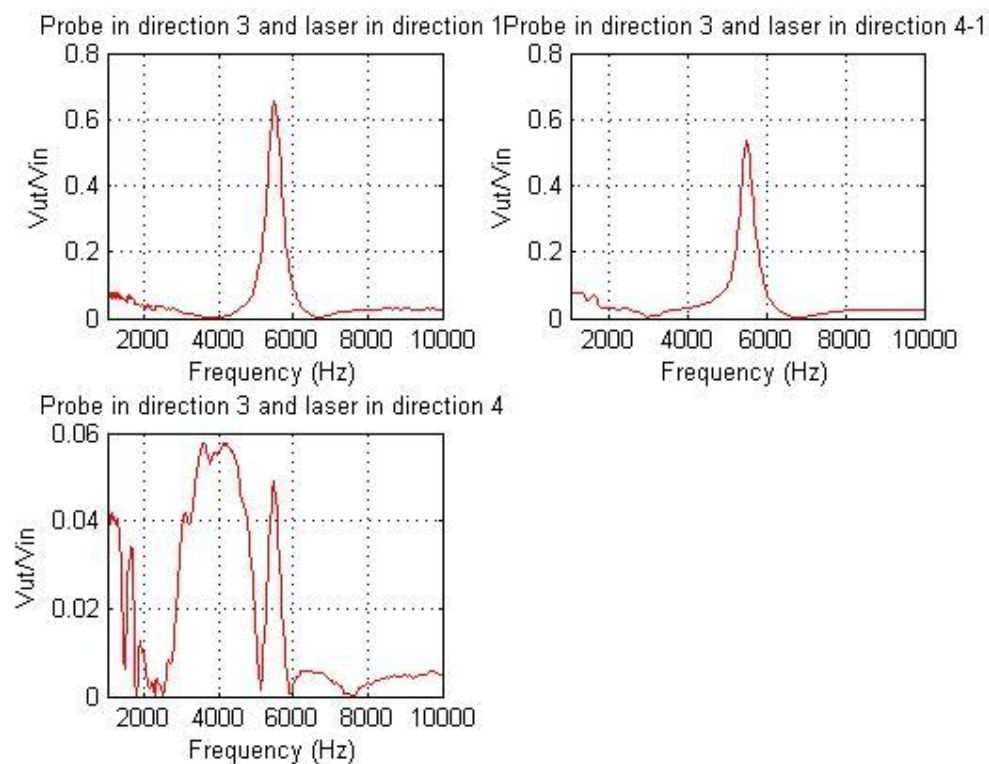


Figure 30. Probe in direction 3 and laser in different directions on middle part of Smartpeg™.

Appendix 3.4: Probe Direction 2, Different Laser Directions, Middle Part of Smartpeg™

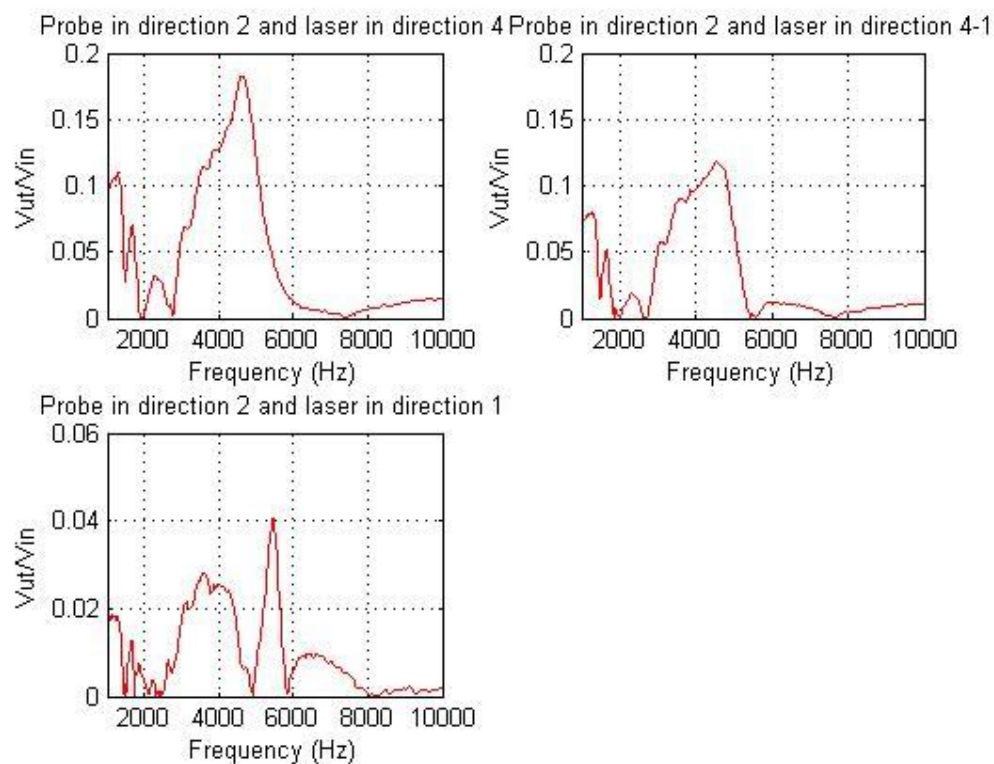


Figure 31. Probe in direction 2 and laser in different directions on middle part of Smartpeg™.

Appendix 3.5: Probe Direction 3, Different Laser Directions, Bottom Part of Smartpeg™

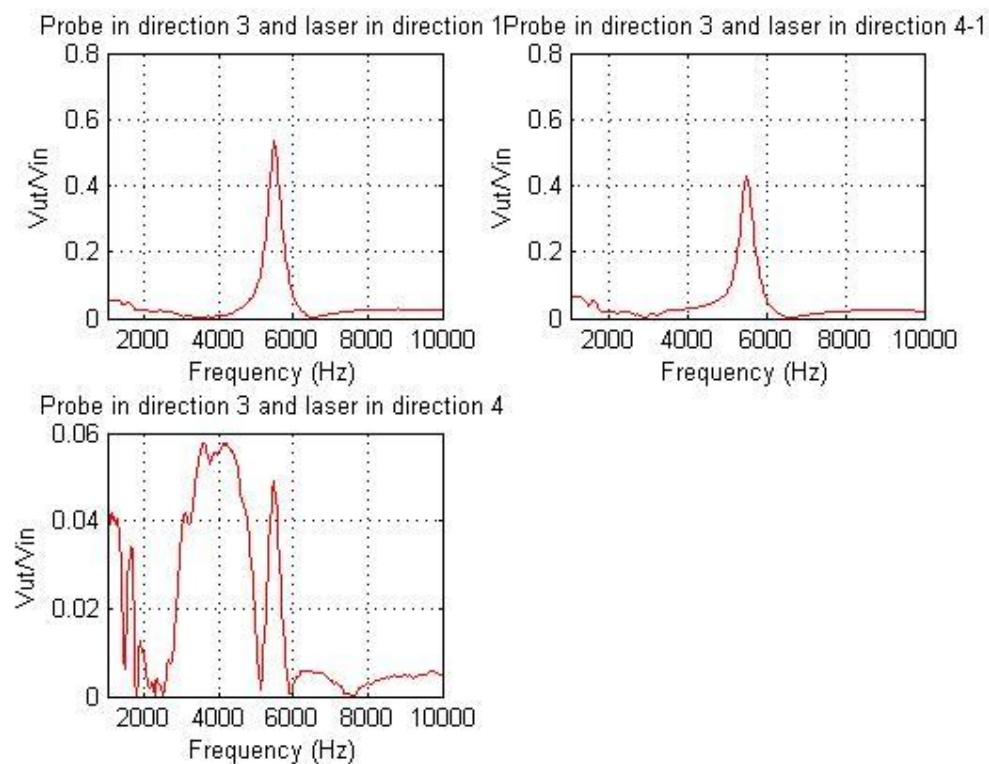


Figure 32. Probe in direction 3 and laser in different directions on bottom part of Smartpeg™.

Appendix 3.6: Probe Direction 2, Different Laser Directions, Bottom Part of Smartpeg™

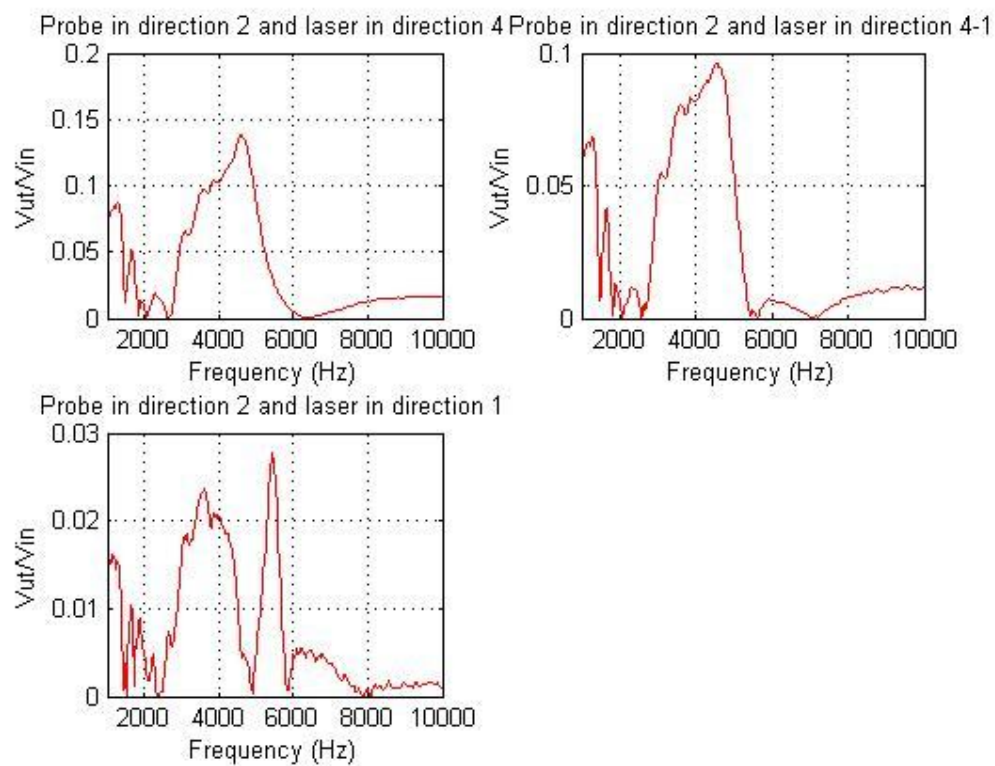


Figure 33. Probe in direction 2 and laser in different directions on bottom part of Smartpeg™.

Appendix 4.1: Plastic Jaw, Implant 3, Direction 1 to 1-22

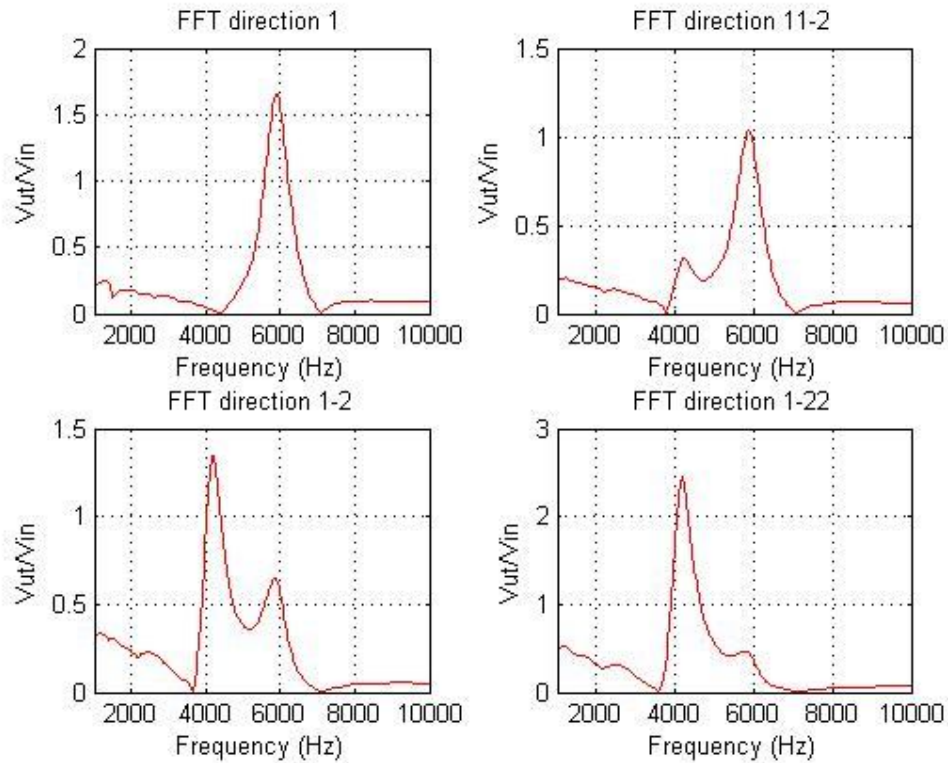


Figure 34. The lowest frequency peak is at 4169Hz and the high peak is at 5855Hz.

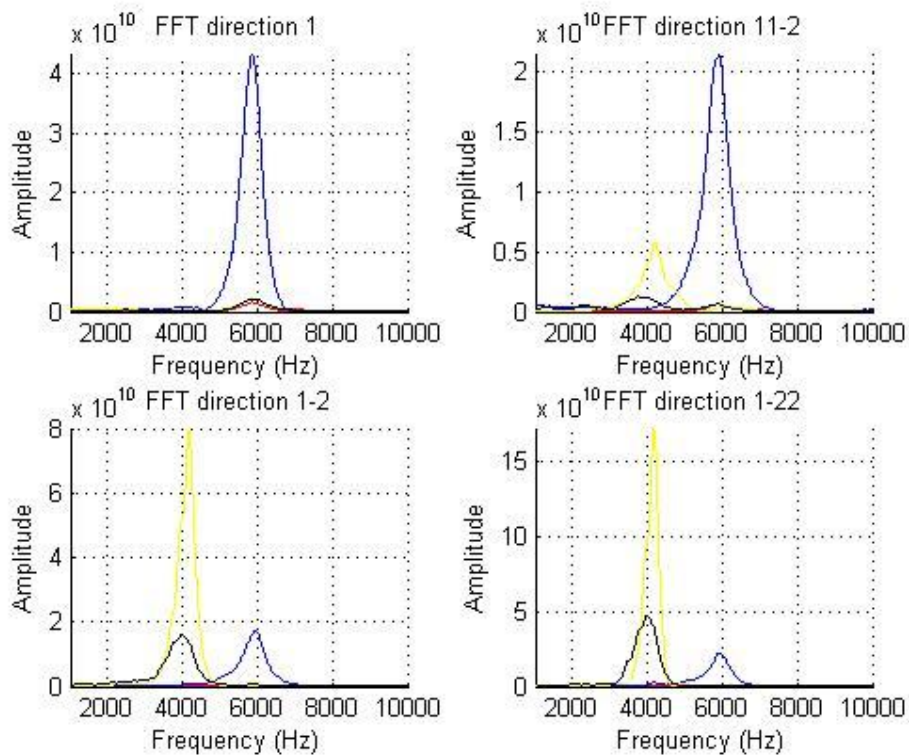


Figure 35. ISQ1=70, ISQ2=58 and 70, ISQ3=57 and 71, ISQ4=57 and 71.

Appendix 4.2: Plastic Jaw, Implant 3, Direction 2 to 2-33

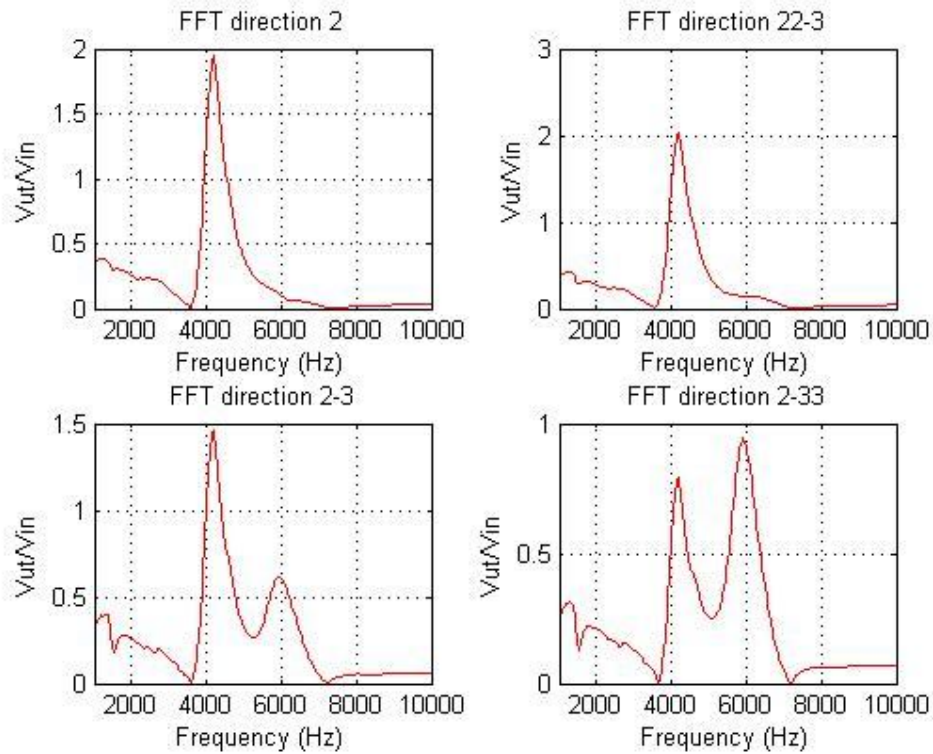


Figure 36. The lowest frequency peak is at 4169Hz and the high peak is at 5922Hz.

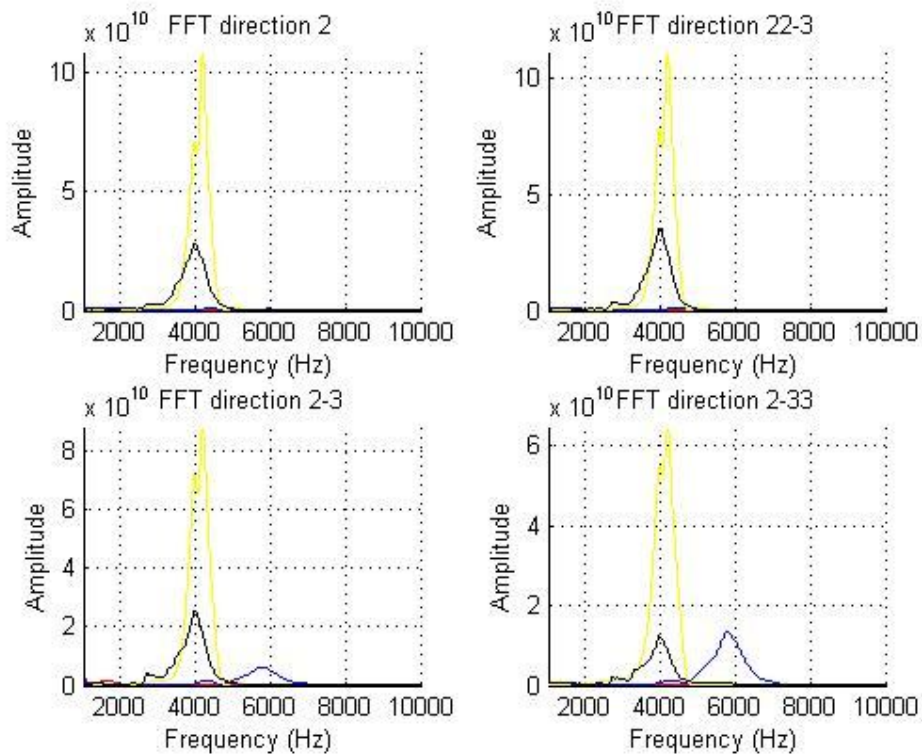


Figure 37. ISQ1=37 and 57, ISQ2=57, ISQ3=57, ISQ4=57.

Appendix 4.3: Plastic Jaw, Implant 3, Direction 3 to 3-44

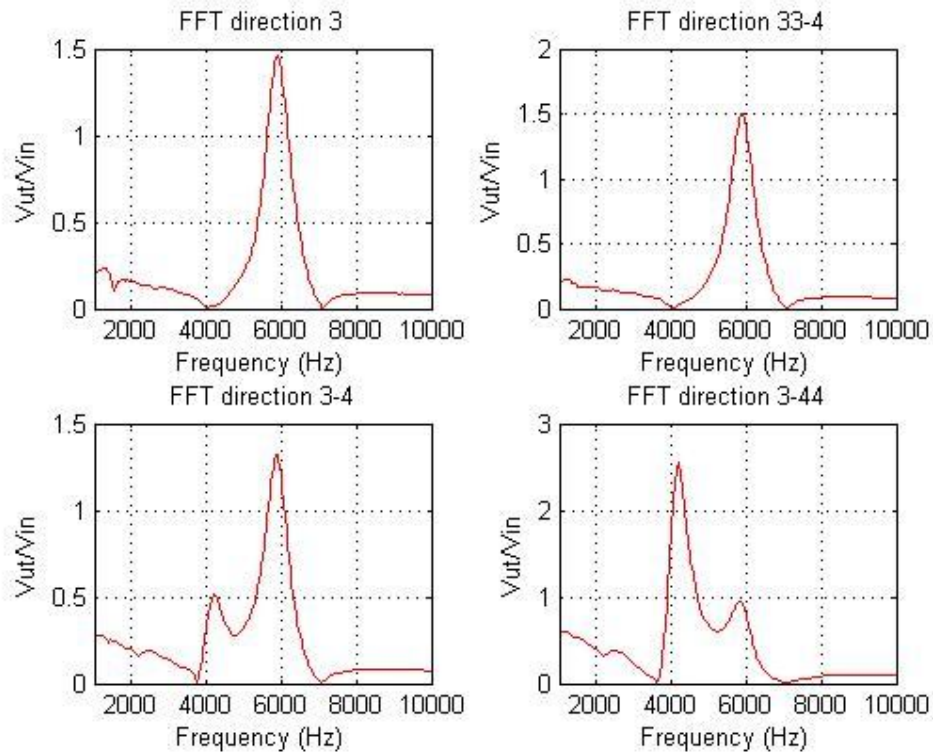


Figure 38. The lowest frequency peak is at 4169Hz and the high peak is at 5888Hz.

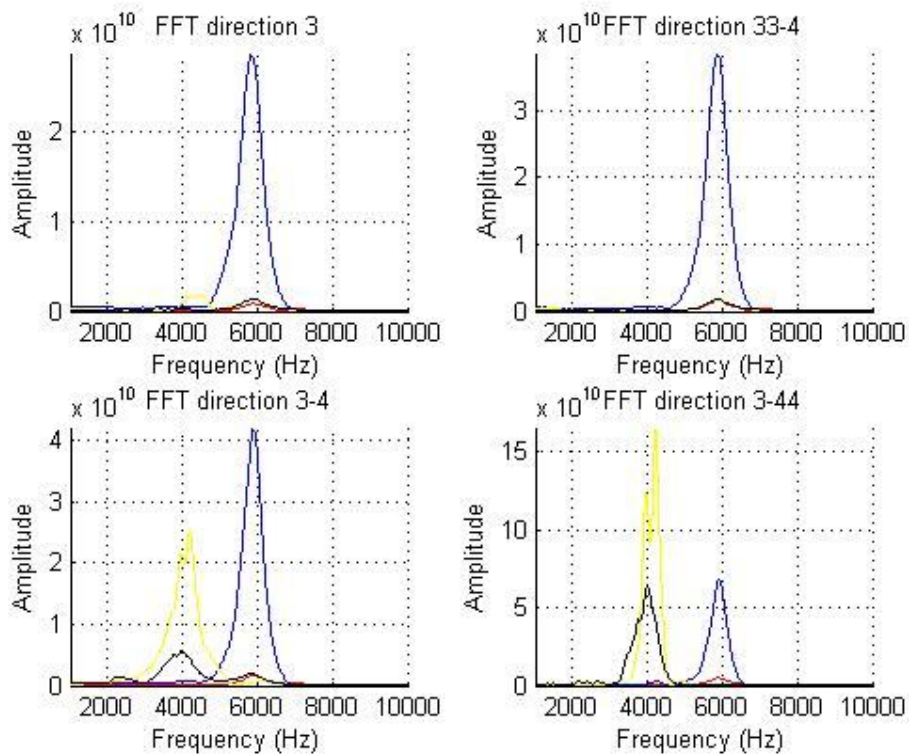


Figure 39. ISQ1=59 and 70, ISQ2=70, ISQ3=57 and 71, ISQ4=57 and 71.

Appendix 4.4: Plastic Jaw, Implant 3, Direction 4 to 4-11

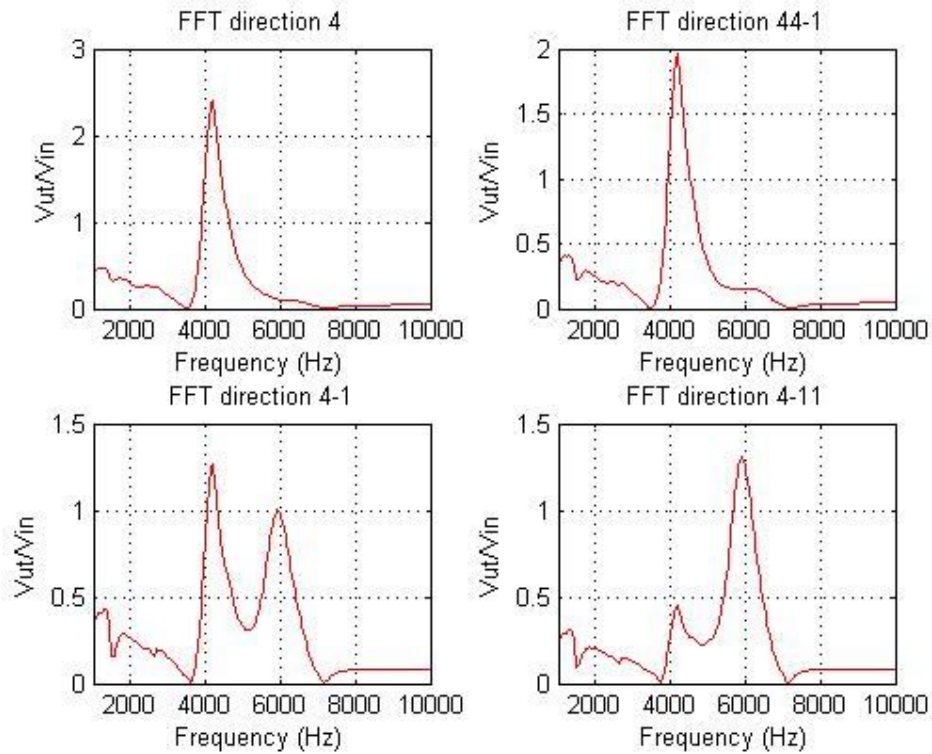


Figure 40. The lowest frequency peak is at 4169Hz and the high peak is at 5922Hz.

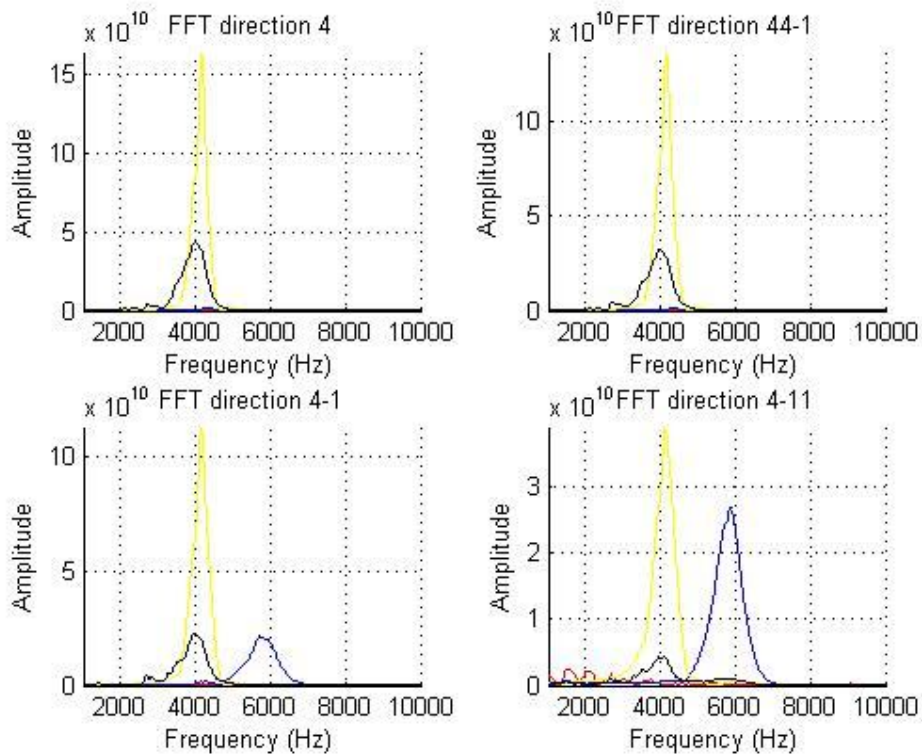


Figure 41. ISQ1=59 and 70, ISQ2=70, ISQ3=57 and 71, ISQ4=57 and 71.

Appendix 4.5: Plastic Jaw, Implant 3, Measurements on the Bone

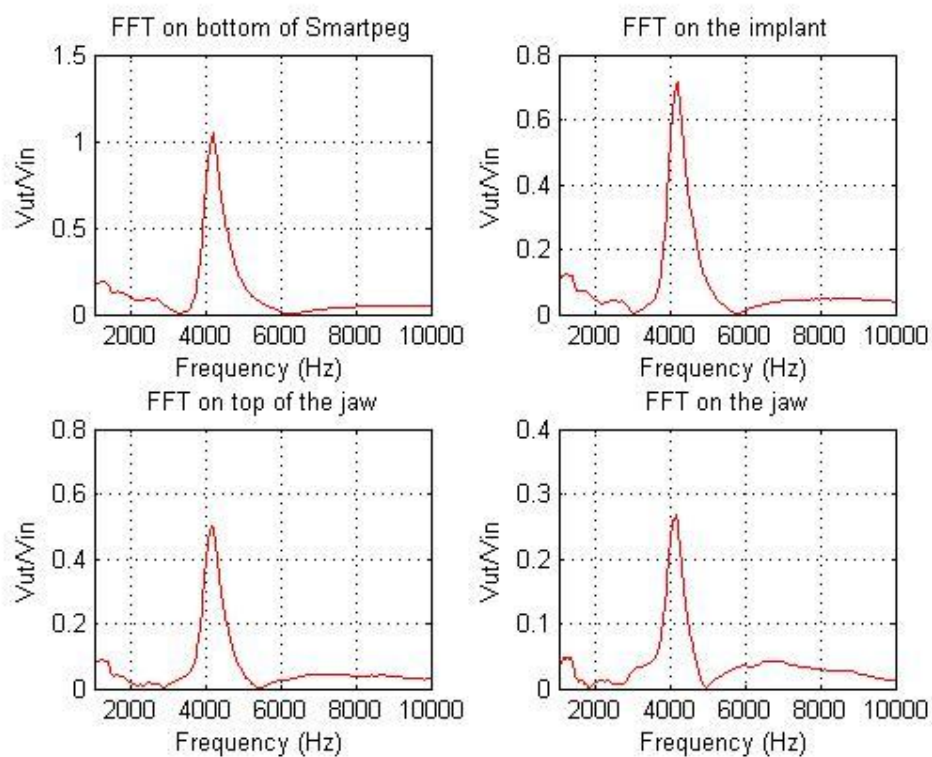


Figure 42. Peak on bottom of Smartpeg™ is 4169Hz, on the implant 4169Hz, on top of jaw 4145Hz and on the jaw 4121Hz.

Appendix 5.1: Plastic Jaw, Implant 4, Direction 1 to 1-22

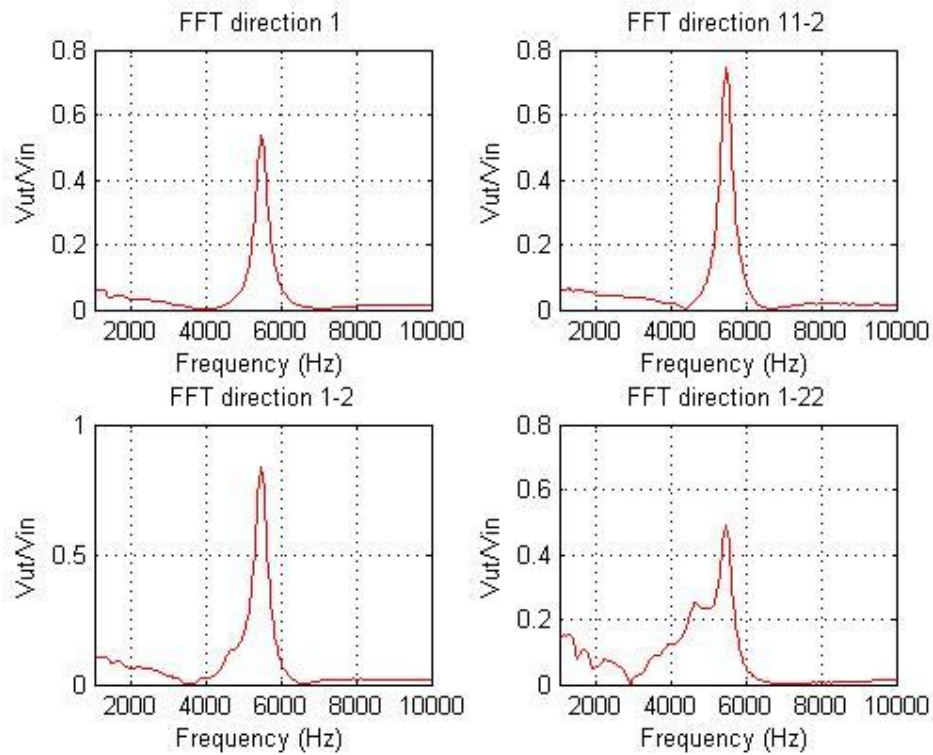


Figure 43. The frequency peak is at 5464Hz.

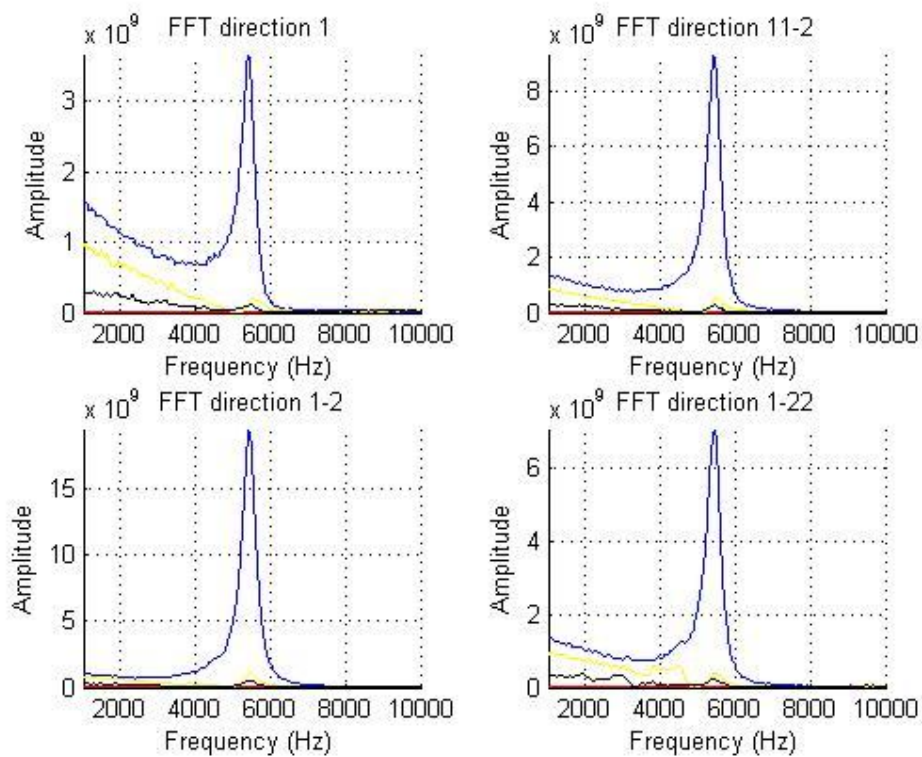


Figure 44. ISQ1=68, ISQ2=68, ISQ3=68, ISQ4=68.

Appendix 5.2: Plastic Jaw, Implant 4, Direction 2 to 2-33

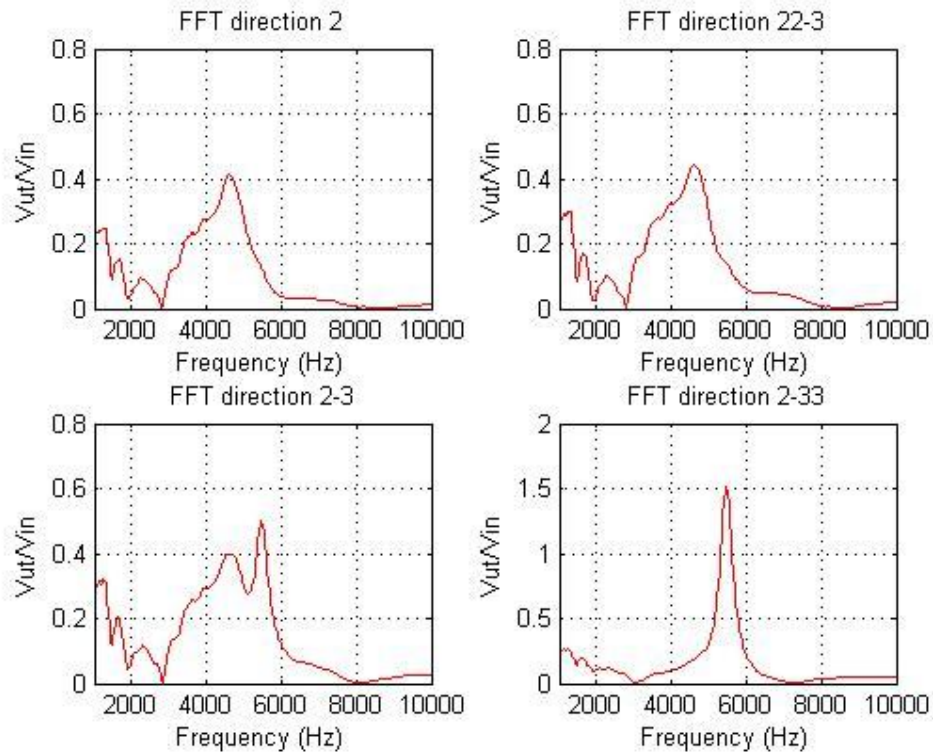


Figure 45. The lowest frequency peak is at 4571Hz and the high peak is at 5464Hz.

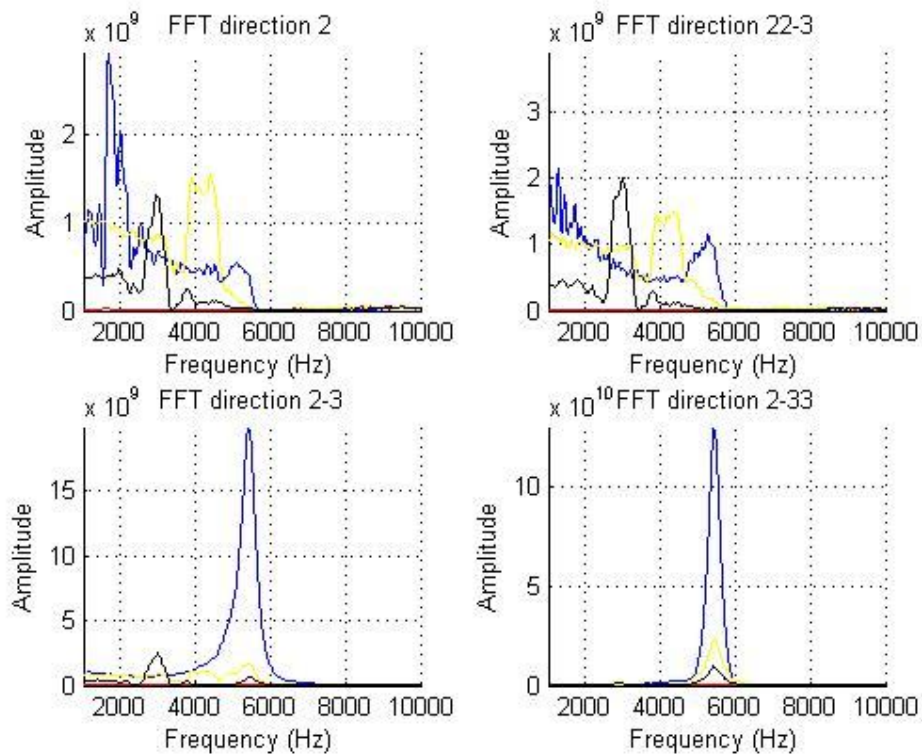


Figure 46. ISQ1=60, ISQ2=46 and 59, ISQ3=44 and 68, ISQ4=68.

Appendix 5.3: Plastic Jaw, Implant 4, Direction 3 to 3-44

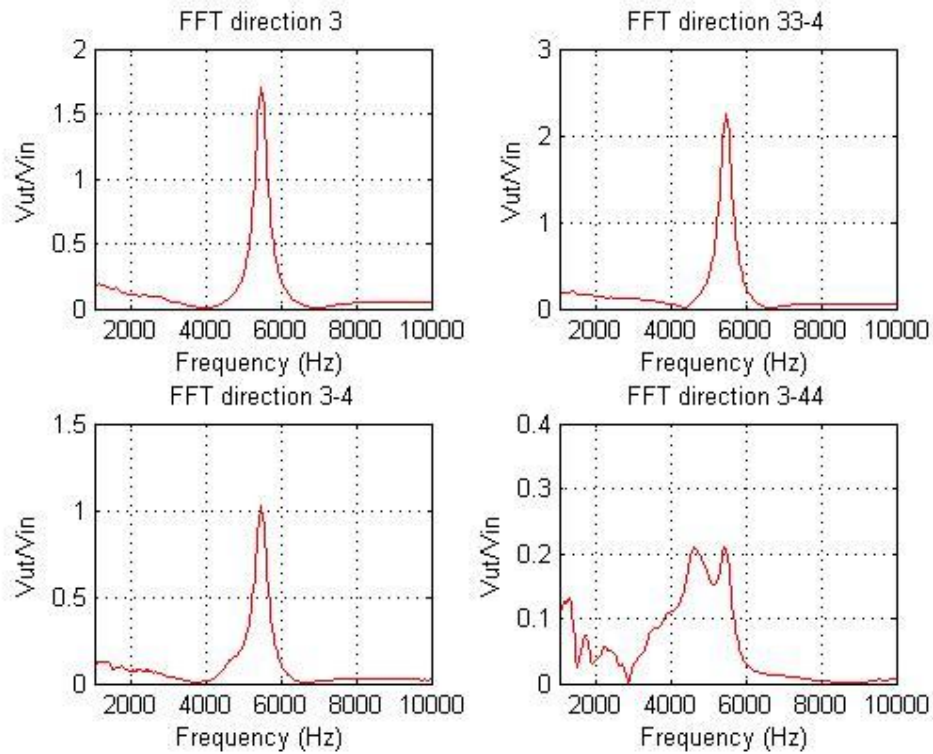


Figure 47. The lowest frequency peak is at 4597Hz and the high peak is at 5432Hz.

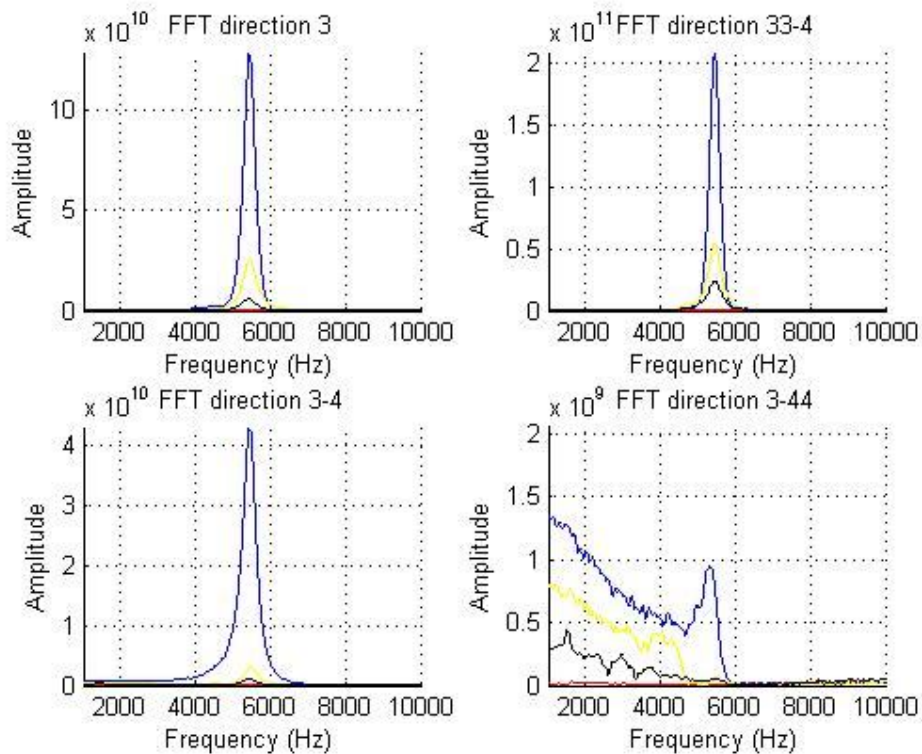


Figure 48. ISQ1=68, ISQ2=68, ISQ3=60 and 68, ISQ4=68.

Appendix 5.4: Plastic Jaw, Implant 4, Direction 4 to 4-11

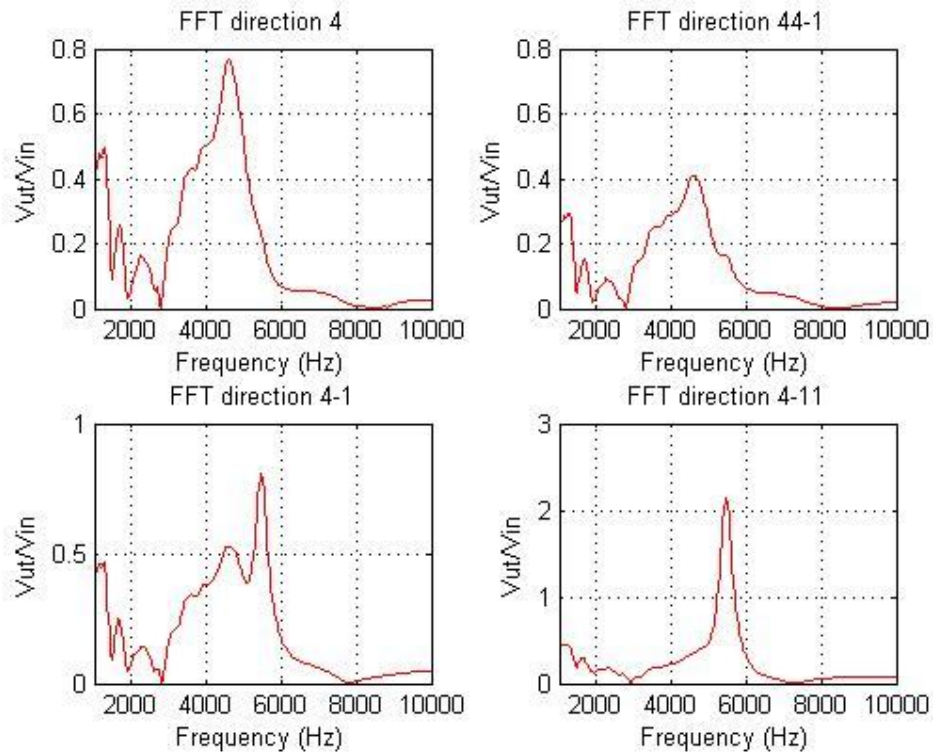


Figure 49. The lowest frequency peak is at 4597Hz and the high peak is at 5464Hz.

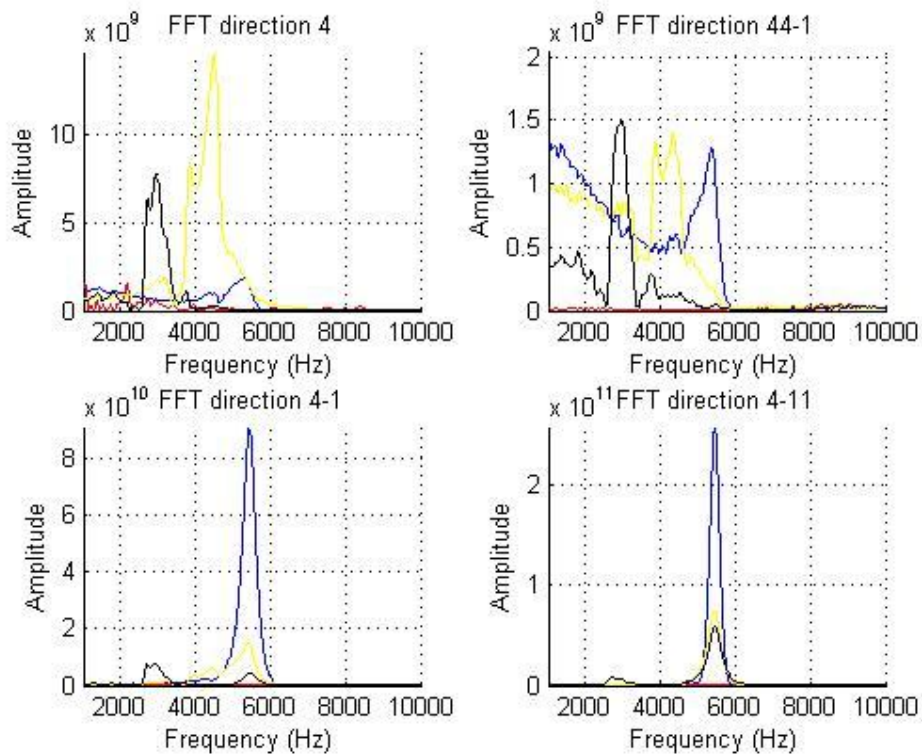


Figure 50. ISQ1=46 and 60, ISQ2=59 and 68, ISQ3=68, ISQ4=44 and 68.

Appendix 5.5: Plastic Jaw, Implant 4, Measurements on the Bone

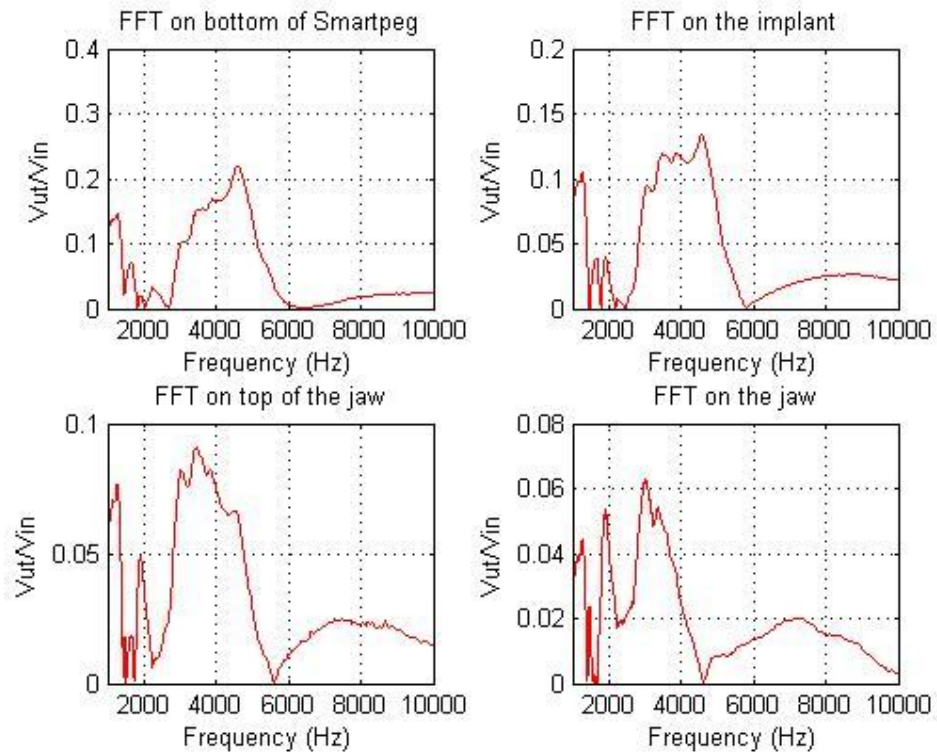


Figure 51. Peak on bottom of Smartpeg™ is 4597Hz, on the implant 4571Hz, on top of jaw 3447Hz and on the jaw 2985Hz.

Appendix 6.1: Smartpeg™ Attached into Plastic Cylinder, Implant 1

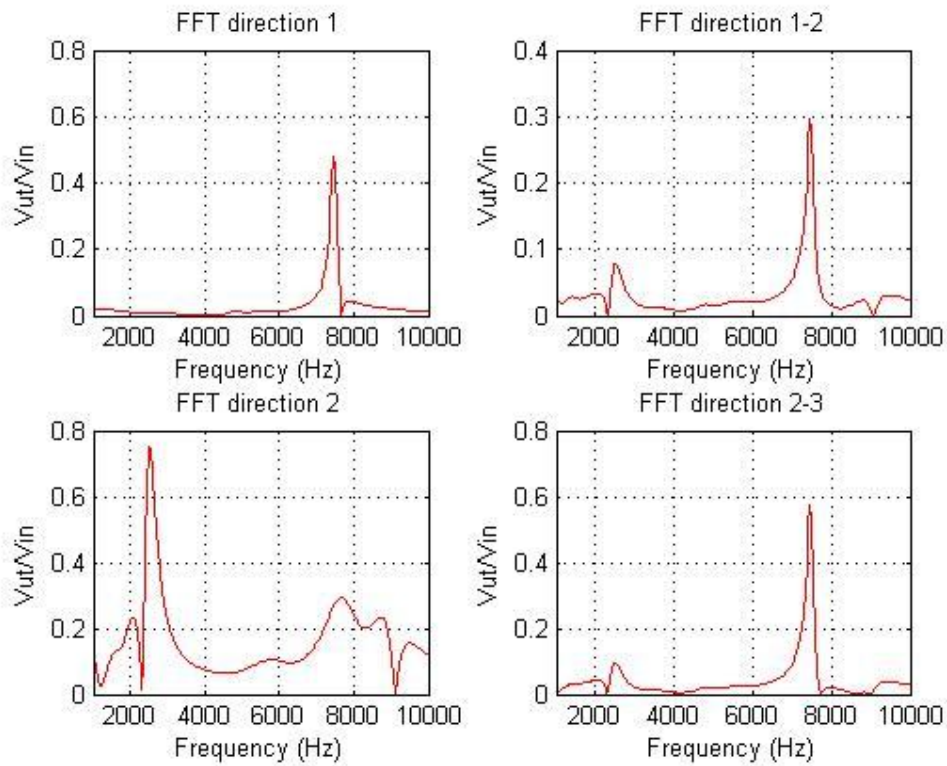


Figure 52. The lowest frequency peak is at 2512Hz and the high peak is at 7456Hz.

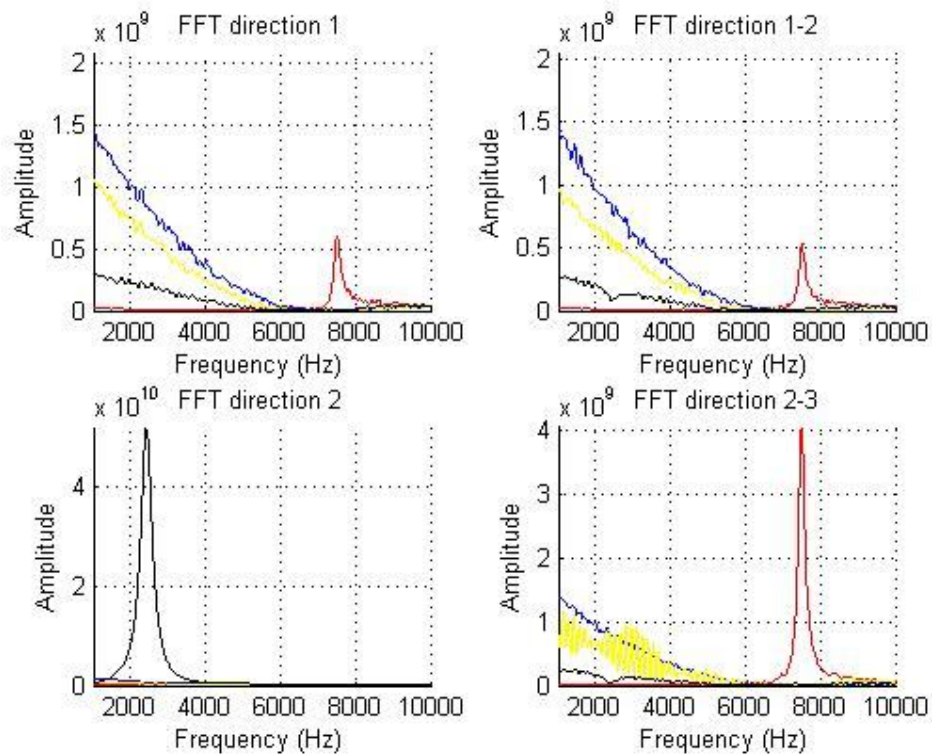


Figure 53. ISQ1=81, ISQ2=81, ISQ3=35, ISQ4=81.

Appendix 6.2: Smartpeg™ Attached into Plastic Cylinder during Pressure, Implant 1

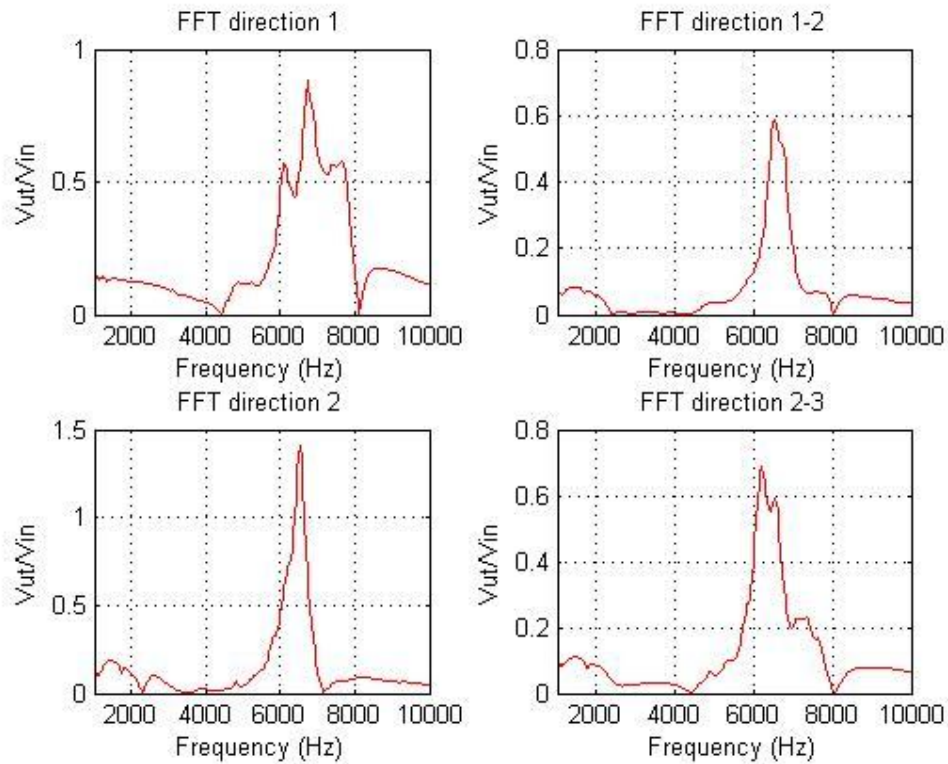


Figure 54. In direction 1 the lowest frequency peak is at 6095Hz, the strongest at 6722Hz and the highest at 7674 Hz. In direction 1-2 and 2 at 6531Hz. In direction 2-3 at 6201 Hz, 6531Hz and at about 7330 Hz.

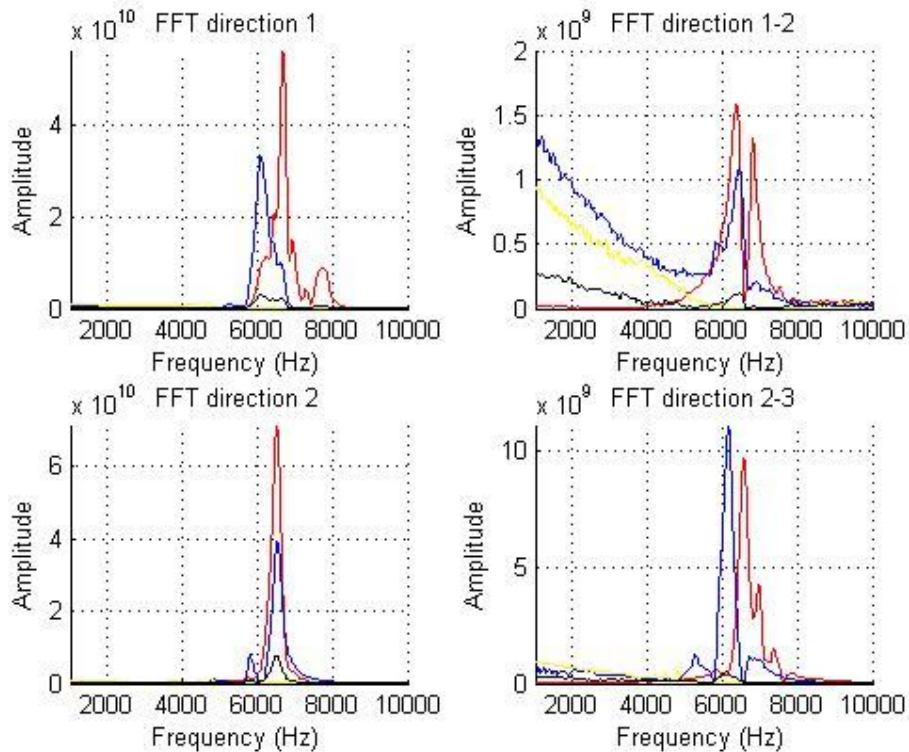


Figure 55. ISQ1=72 and 75, ISQ2=75, ISQ3=70 and 75, ISQ4=62 and 72.

Appendix 6.3: Smartpeg™ Attached into Plastic Cylinder, Implant 2

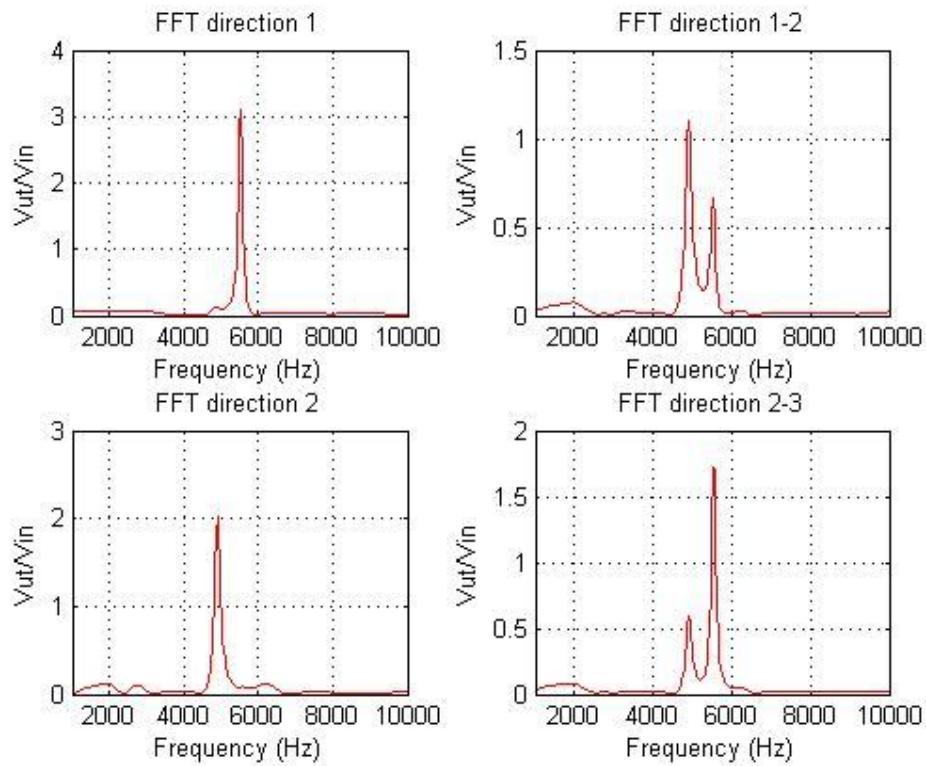


Figure 56. The lowest frequency peak is at 4898Hz and the high peak is at 5527Hz.

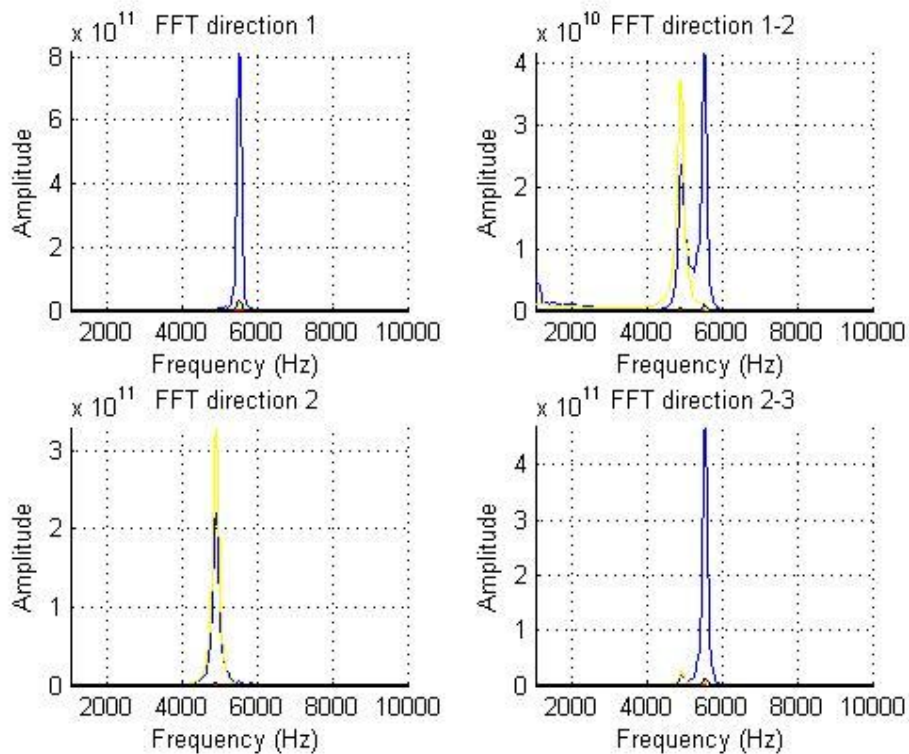


Figure 57. ISQ1=68,ISQ2=63 and 68,ISQ3=63, ISQ4=63 and 68.

Appendix 6.4: Smartpeg™ Attached into Plastic Cylinder during Pressure, Implant 2

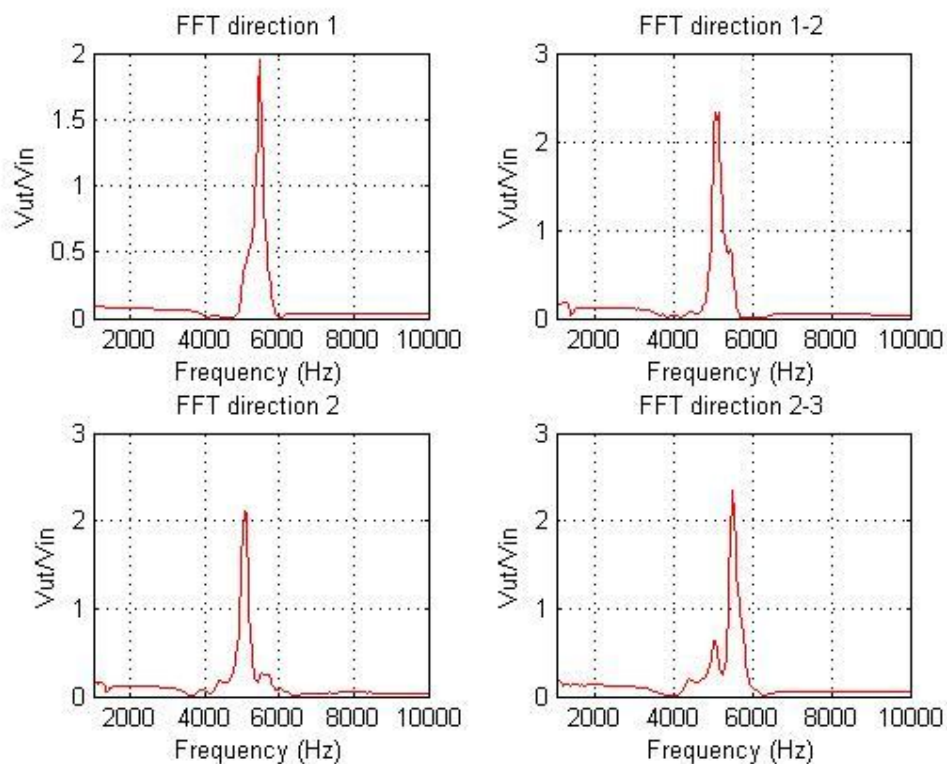


Figure 58. The lowest frequency peak is at 5070Hz and the high peak is at 5464Hz.

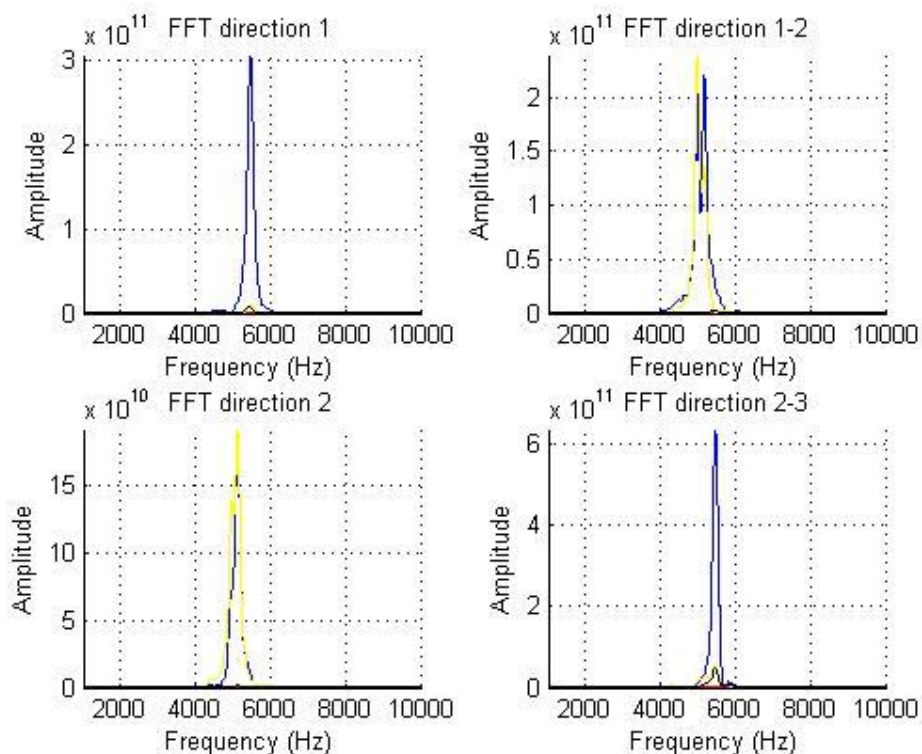


Figure 59. ISQ1=68,ISQ2=65,ISQ3=64, ISQ4=59 and 68.

Appendix 6.5: Smartpeg™ Attached into Plastic Cylinder, Implant 3

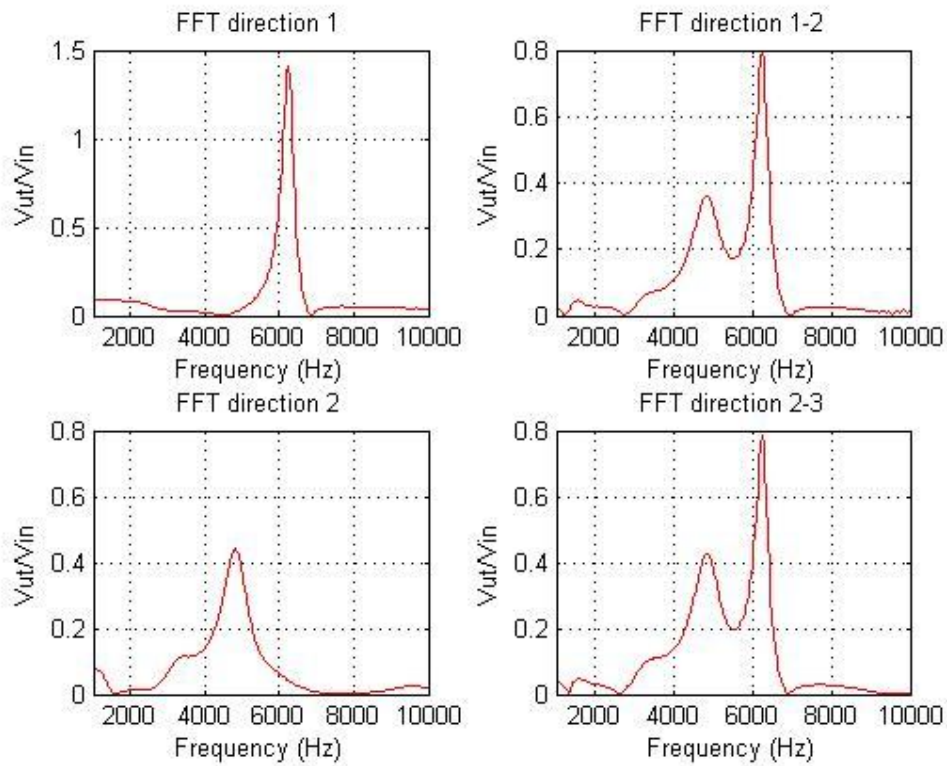


Figure 60. The lowest frequency peak is at 4814Hz and the high peak is at 6237Hz.

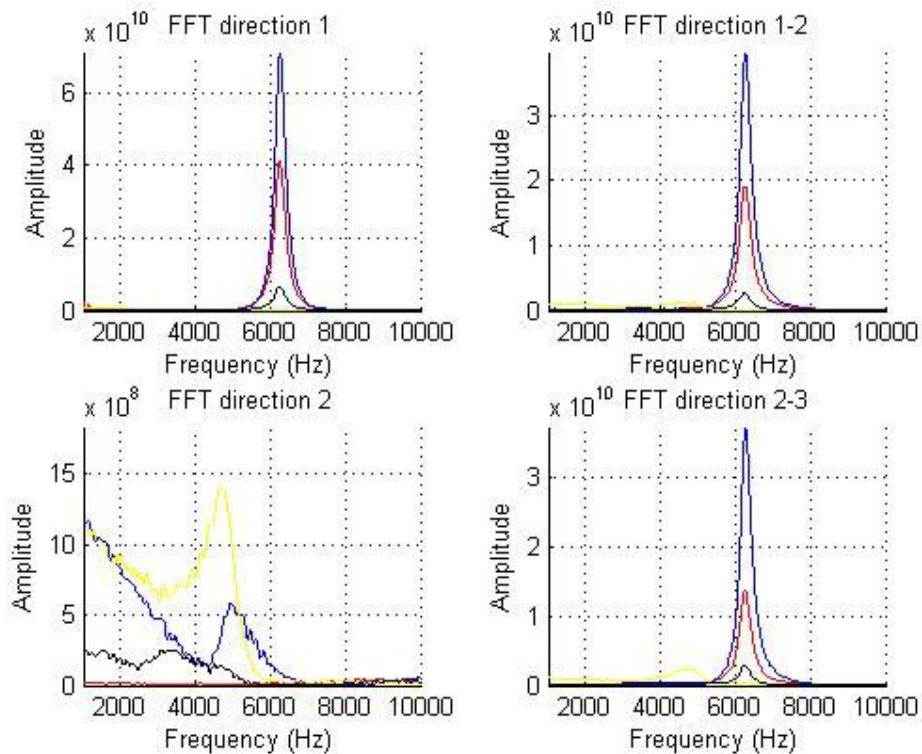


Figure 61. ISQ1=73,ISQ2=73,ISQ3=63, ISQ4=63 and 73.

Appendix 6.6: Smartpeg™ Attached into Plastic Cylinder during Pressure, Implant 3

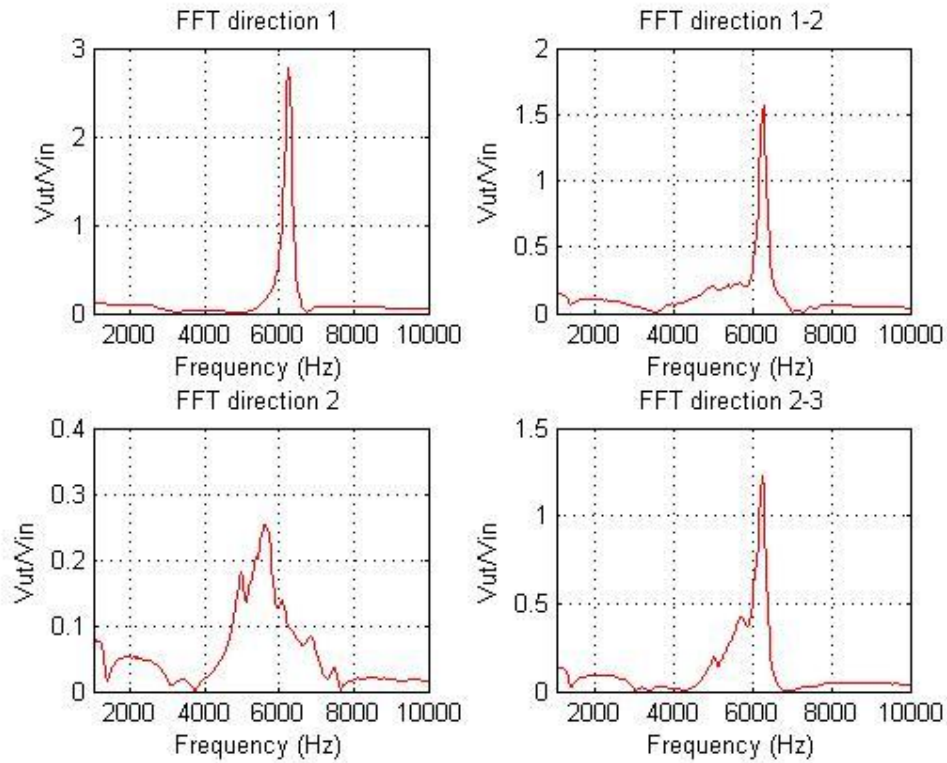


Figure 62. The lowest frequency peak is at 5623Hz and the high peak is at 6237Hz.

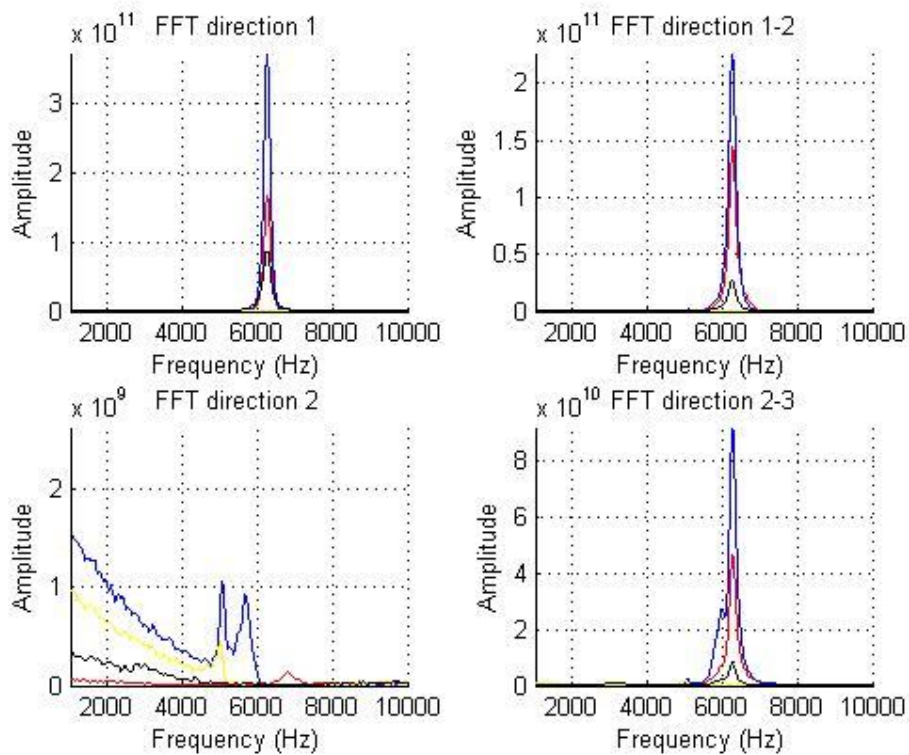


Figure 63. ISQ1=73,ISQ2=73,ISQ3=70, ISQ4=65 and 74.

Appendix 7.1: Error made by a Straw of Hair and Glue, Normal 1

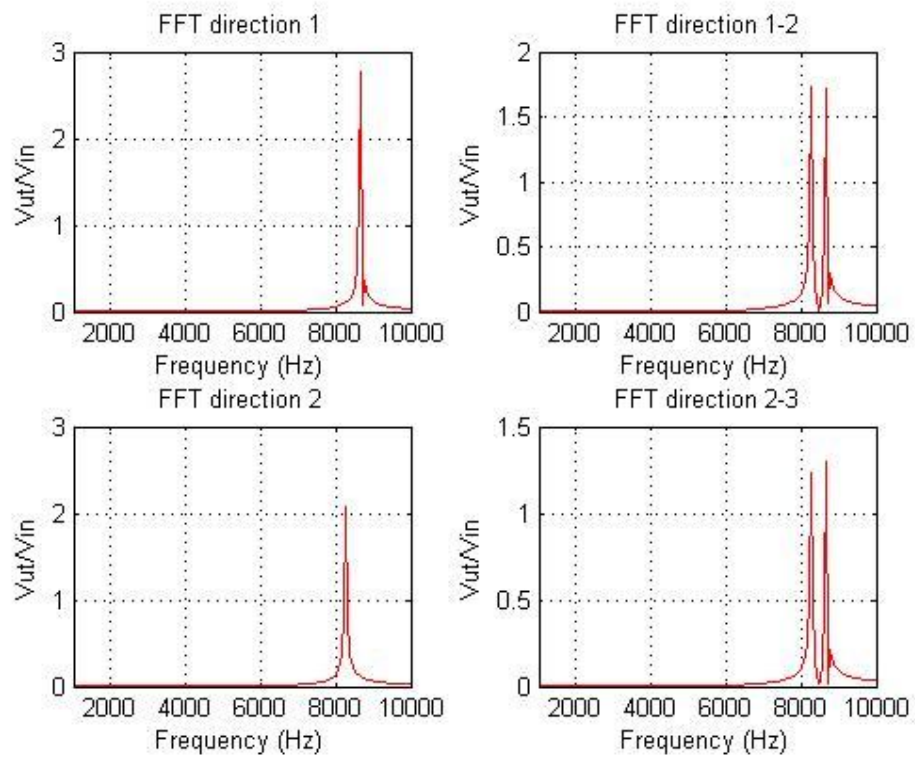


Figure 64. The lowest frequency peak is at 8270Hz and the high peak is at 8660Hz.

Appendix 7.2: Error made by a Straw of Hair and Glue, Normal 1 Repeated

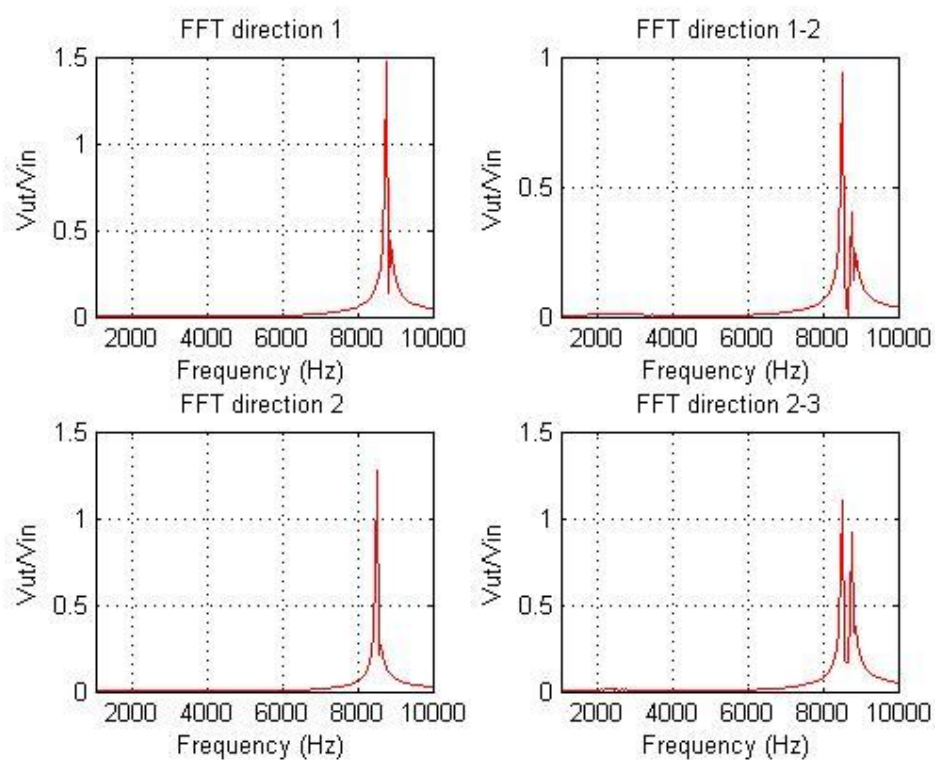


Figure 65. The lowest frequency peak is at 8511Hz and the high peak is at 8760Hz.

Appendix 7.3: Error made by a Straw of Hair and Glue, Error 1

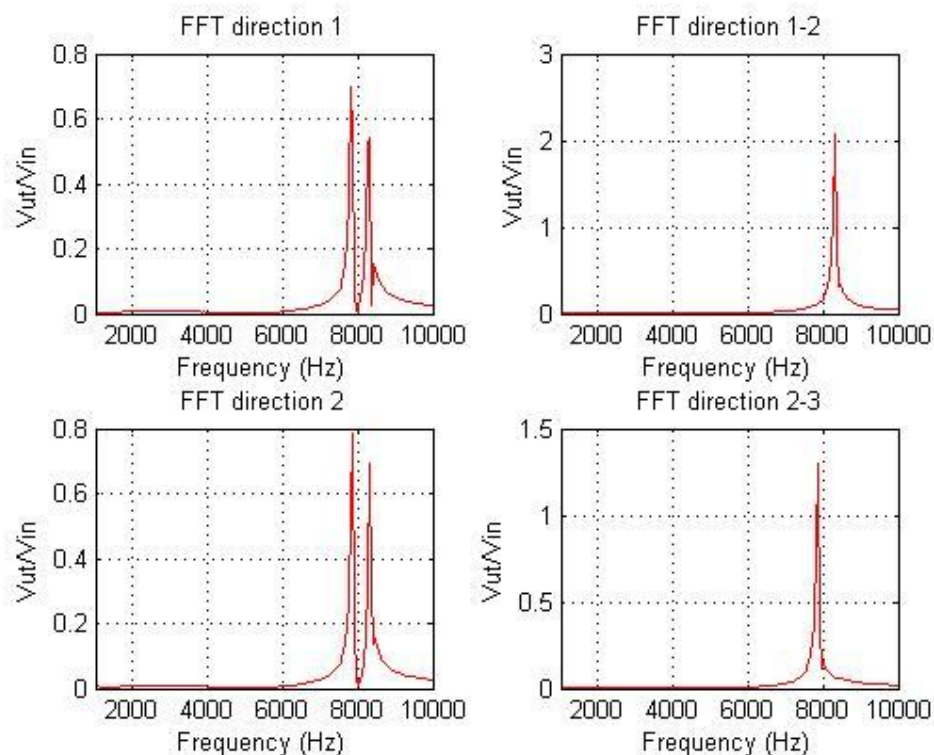


Figure 66. In direction 1 the lowest frequency peak is at 7807Hz. In the other directions the lower frequency peak is at 7852 and the high peak is at 8318Hz.

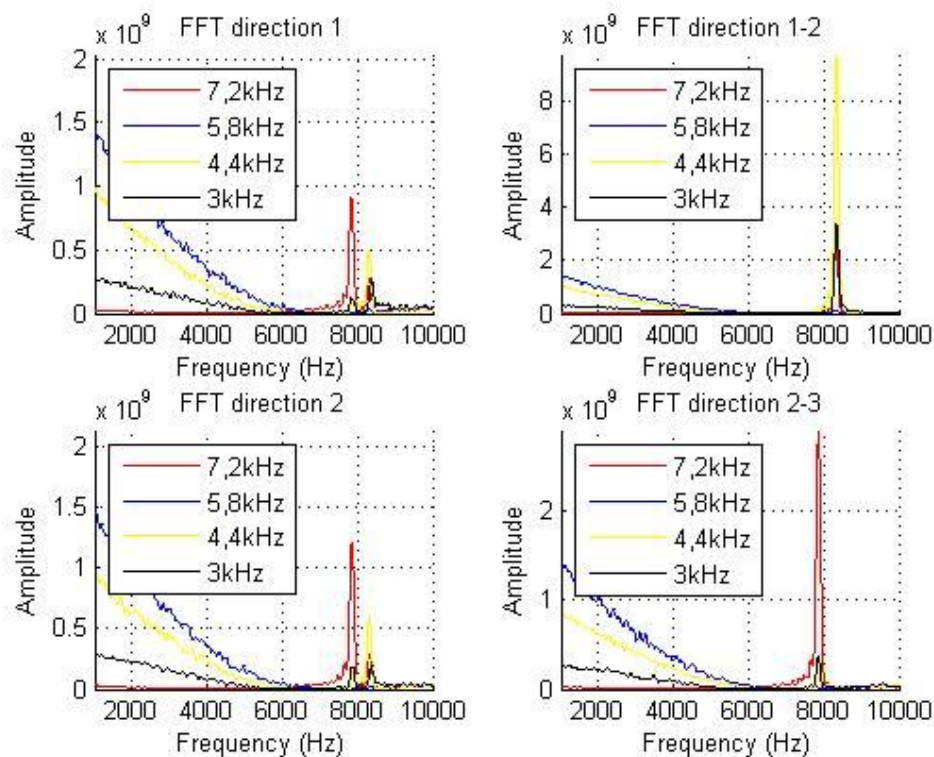


Figure 67. ISQ1=85, ISQ2=88, ISQ3=85, ISQ4=85

Appendix 7.4: Error Made by a Straw of Hair and Glue, Error 1 Repeated

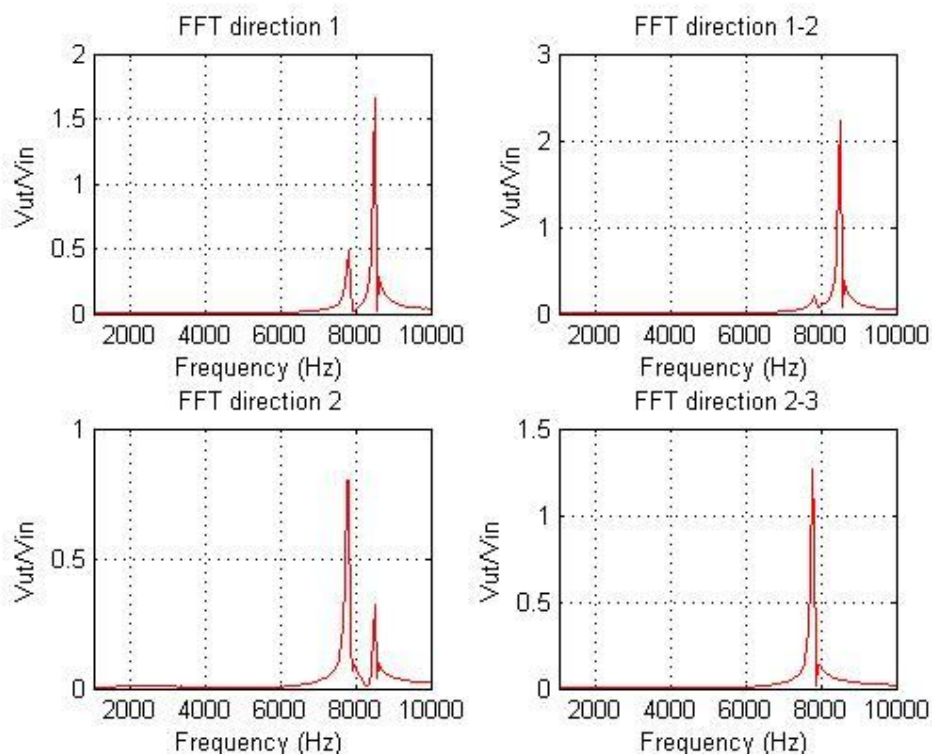


Figure 68. In direction 2-3 frequency peak is at 7762Hz. In the other directions the lower frequency peak is at 7807 and the high peak is at 8511Hz.

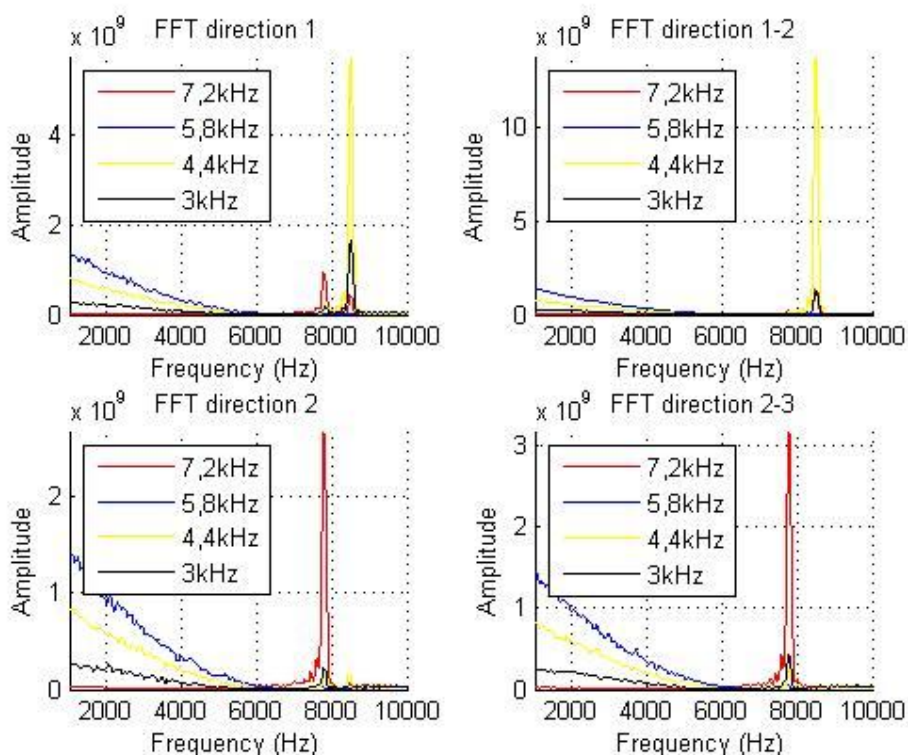


Figure 69. ISQ1=84, ISQ2=88, ISQ3=84, ISQ4=83.

Appendix 7.5: Error made by a Straw of Hair and Glue, normal 2

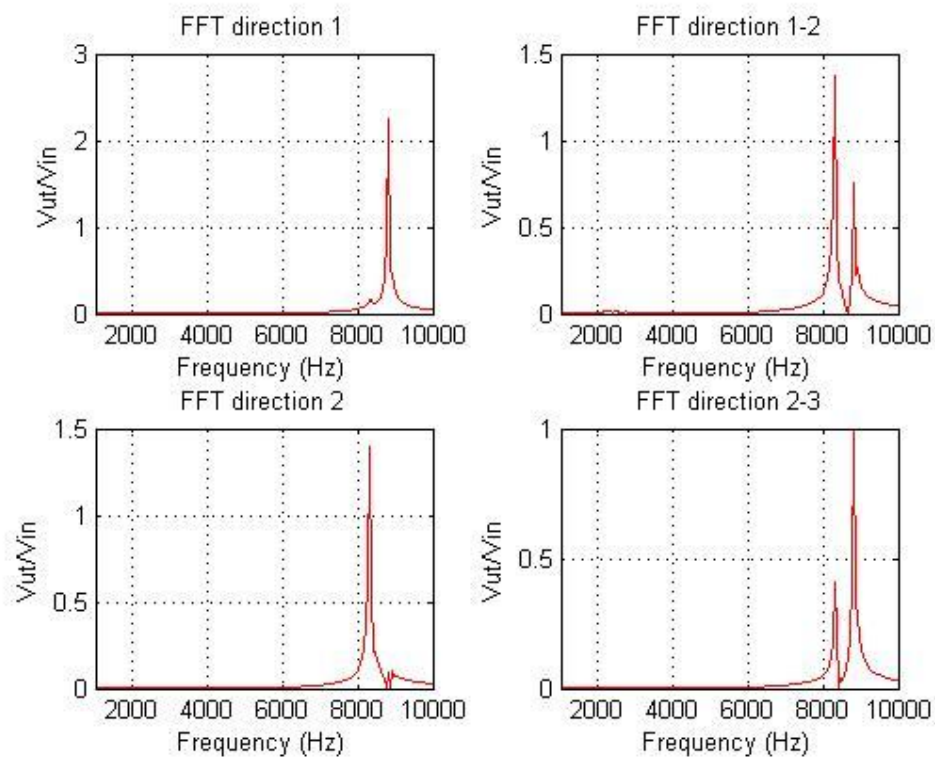


Figure 70. The lowest frequency peak is at 8318Hz and the high peak is at 8810Hz.

Appendix 7.6: Error made by a Straw of Hair and Glue, Normal 2 Repeated

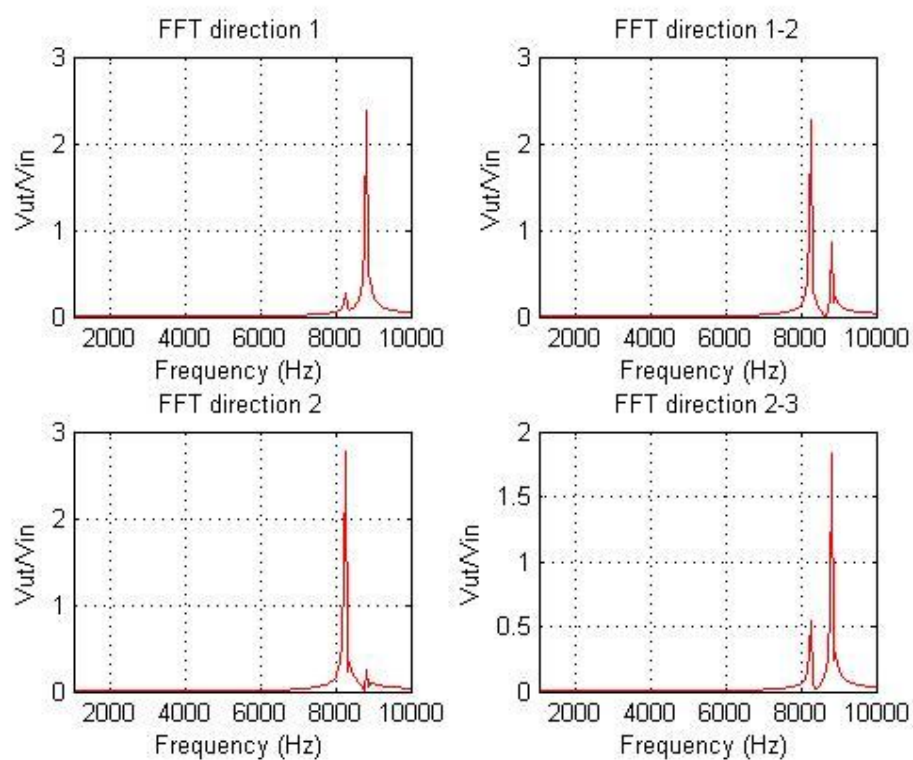


Figure 71. The lowest frequency peak is at 8270Hz and the high peak is at 8810Hz.

Appendix 7.7: Error made by a Straw of Hair and Glue, Error 2

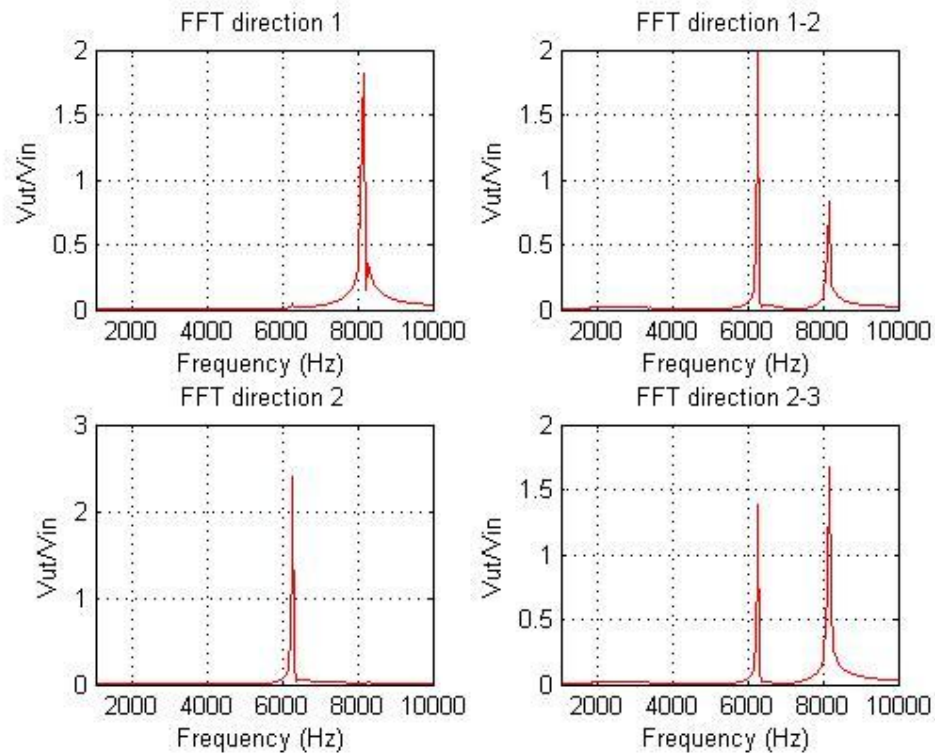


Figure 72. The lowest frequency peak is at 6273Hz and the high peak is at 8175Hz.

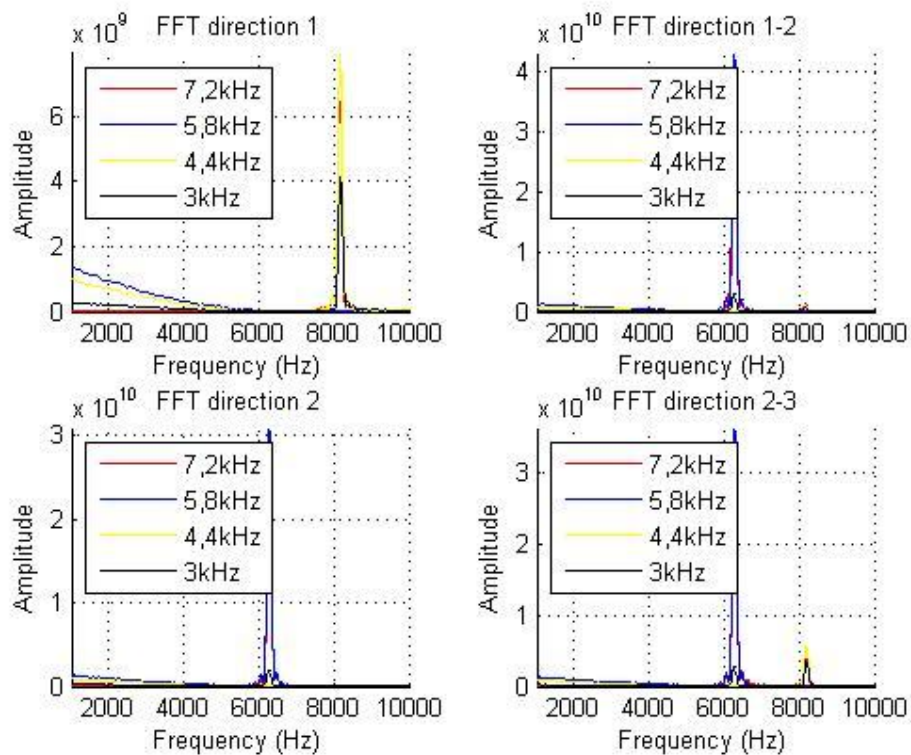


Figure 73. ISQ1=89, ISQ2=82, ISQ3=82, ISQ4=82.

Appendix 7.8: Error made by a Straw of Hair and Glue, Error 2 Repeated

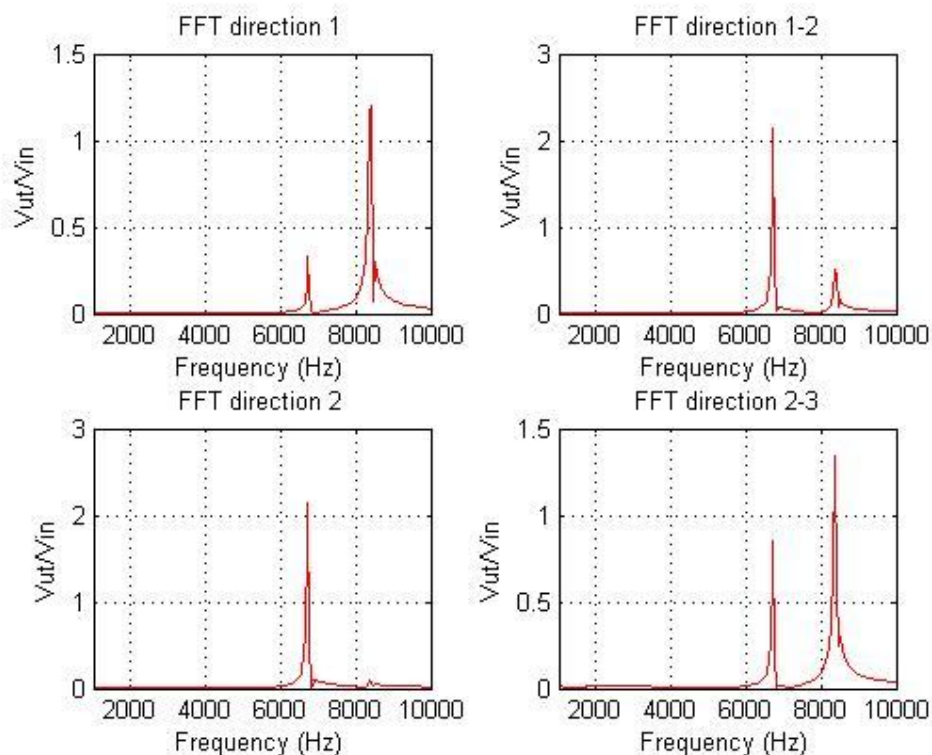


Figure 74. The lowest frequency peak is at 6722Hz and the high peak is at 8366Hz.

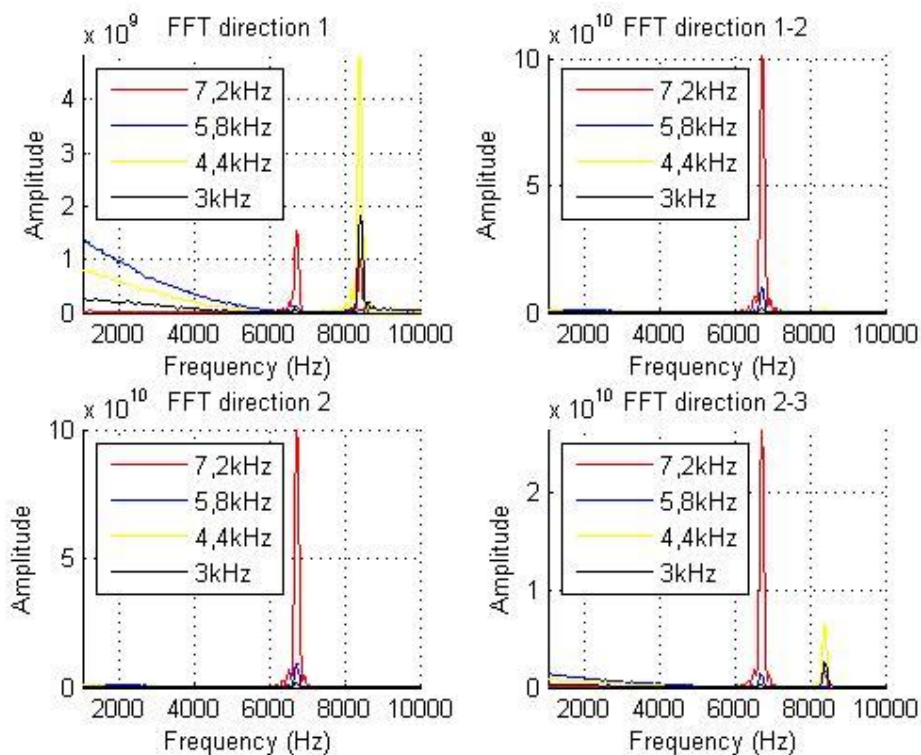


Figure 75. ISQ1=86, ISQ2=74, ISQ3=74, ISQ4=74.

Appendix 7.9: Error made by a Straw of Hair and Glue, Normal 3

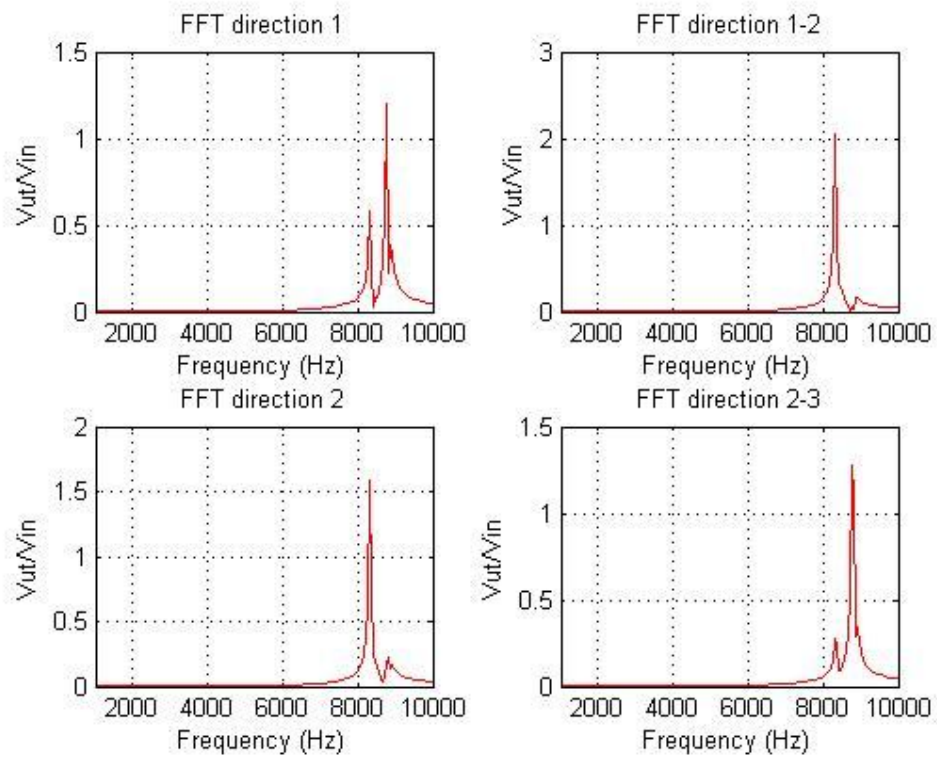


Figure 76. The lowest frequency peak is at 8318Hz and the high peak is at 8760Hz.

Appendix 7.10: Error made by a Straw of Hair and Glue, Normal 3 Repeated

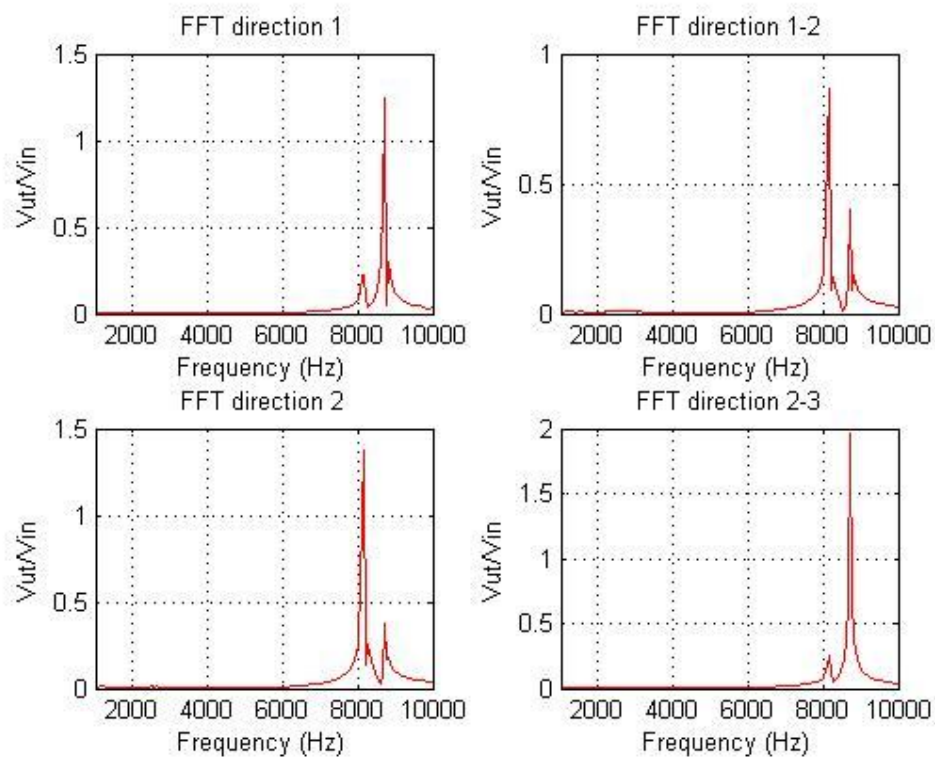


Figure 77. In direction 1 the lowest frequency peak is at 8128Hz. In the other directions the lower frequency peak is at 8175 and the high peak is at 8710Hz.

Appendix 8.1: Error made by Metal and Glue, Normal 1

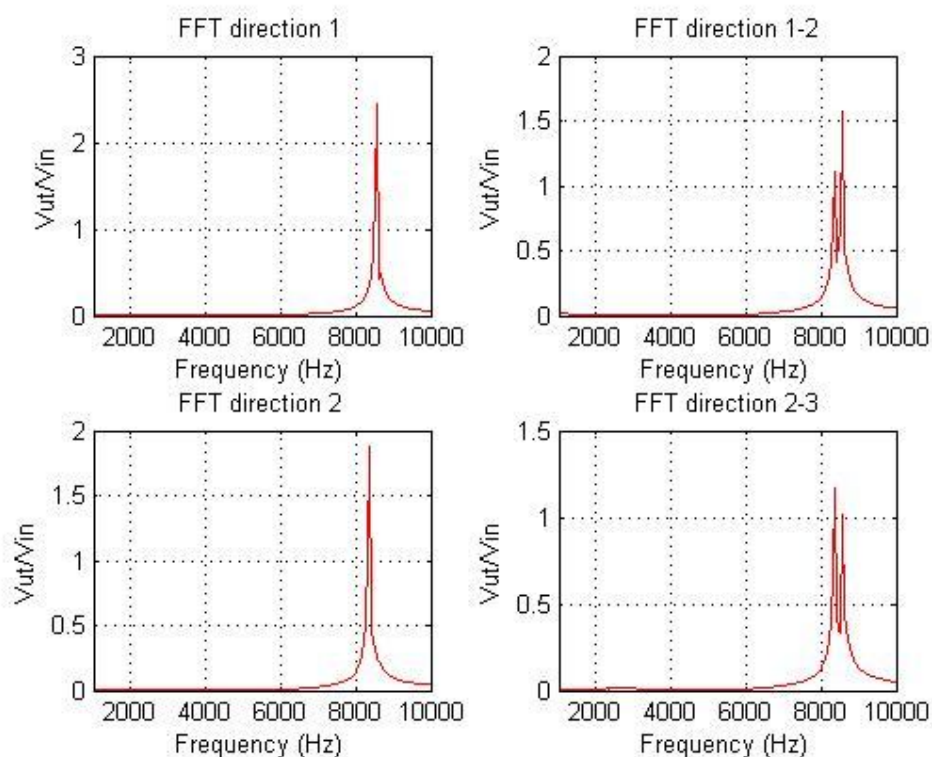


Figure 78. The lowest frequency peak is at 8366Hz and the high peak is at 8561Hz.

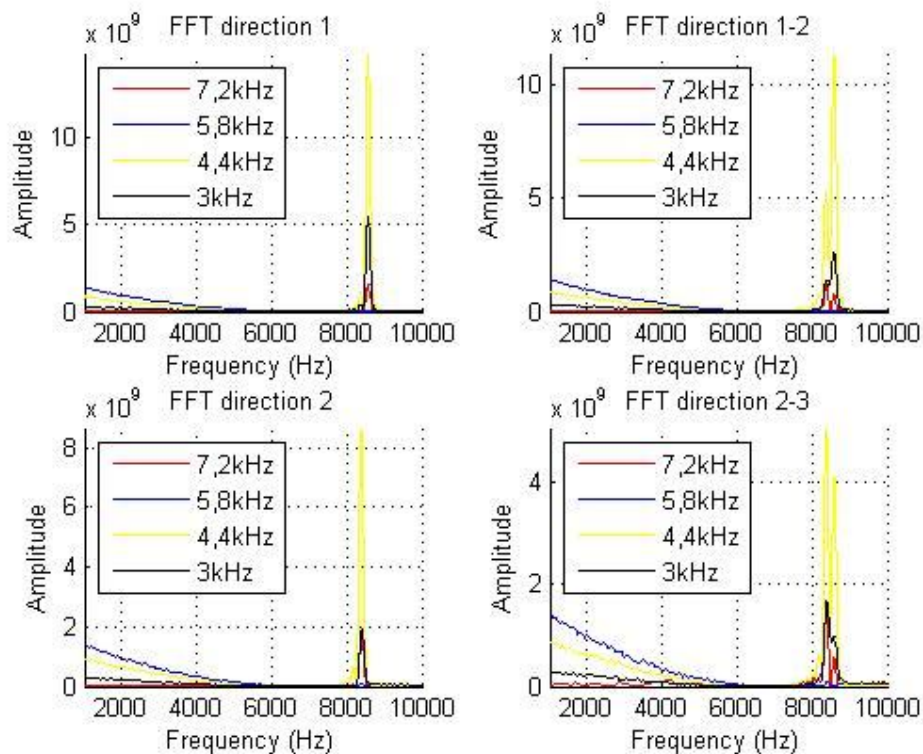


Figure 79. ISQ1=90, ISQ2=88, ISQ3=87, ISQ4=88.

Appendix 8.2: Error made by Metal and Glue, Normal 1 Repeated

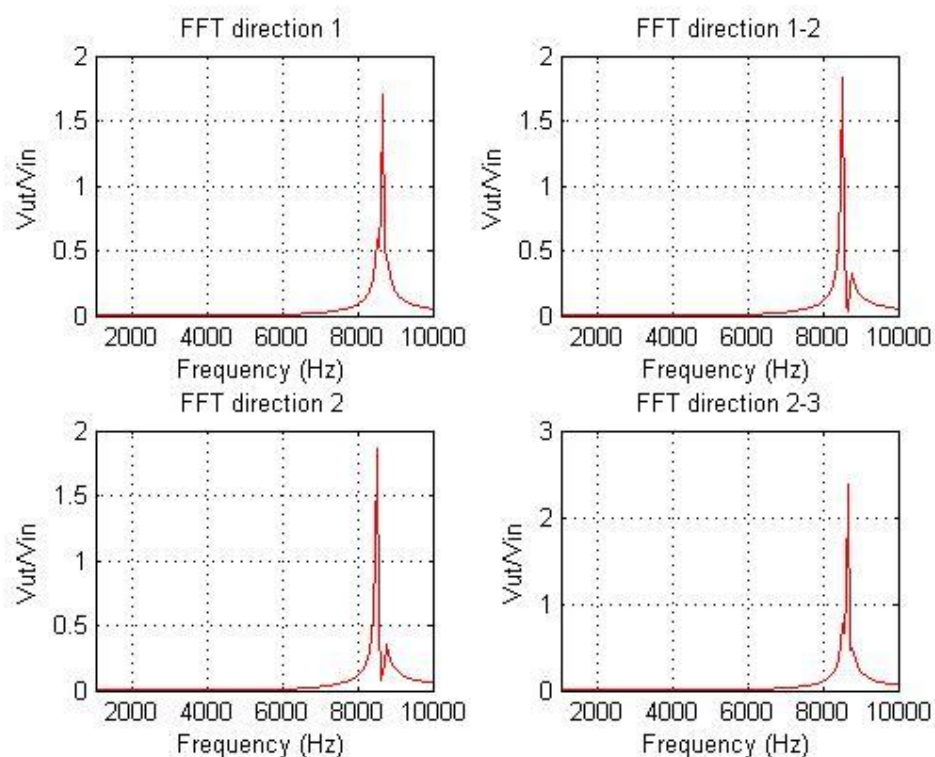


Figure 80. The lowest frequency peak is at 8511Hz and the high peak is at 8660Hz.

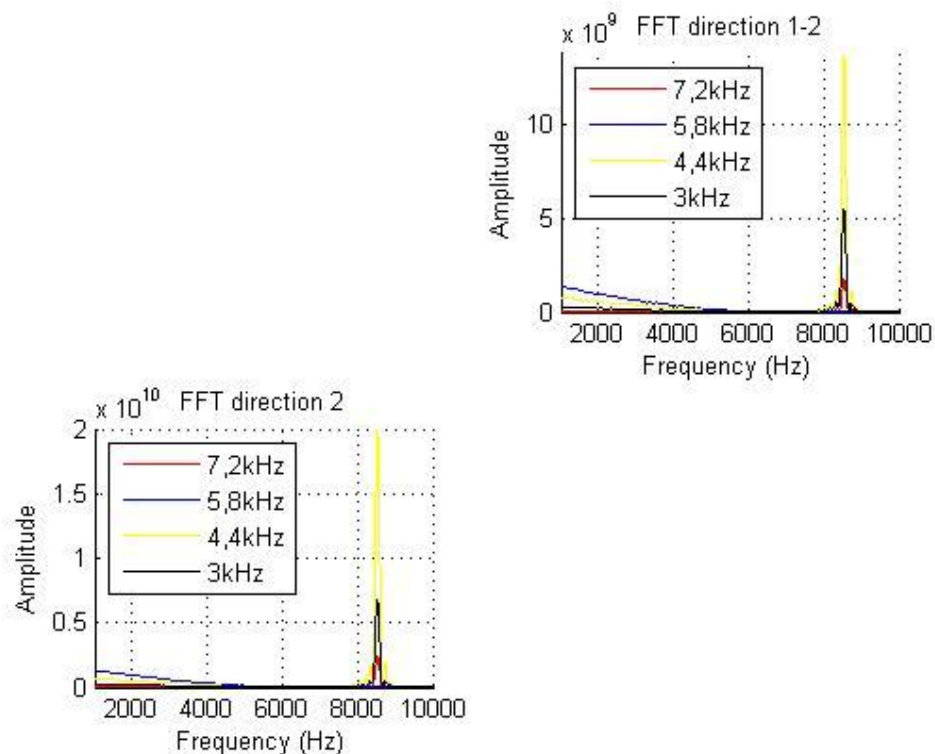


Figure 81. ISQ2=88, ISQ3=88.

Appendix 8.3: Error made by Metal and Glue, Error 1

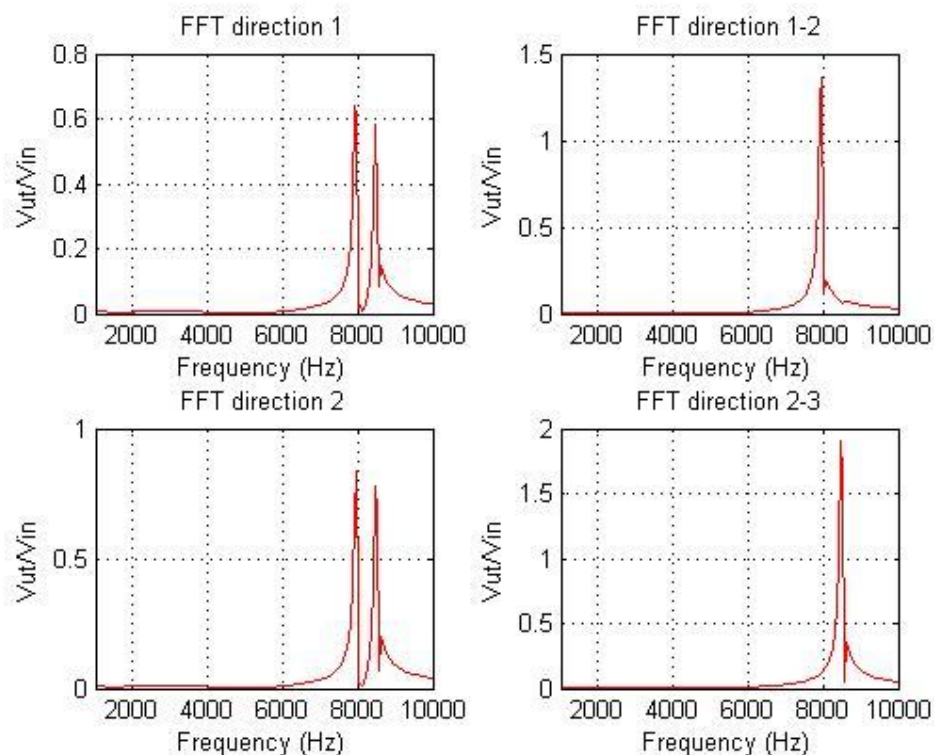


Figure 82. The lowest frequency peak is at 7943Hz and the high peak is at 8463Hz.

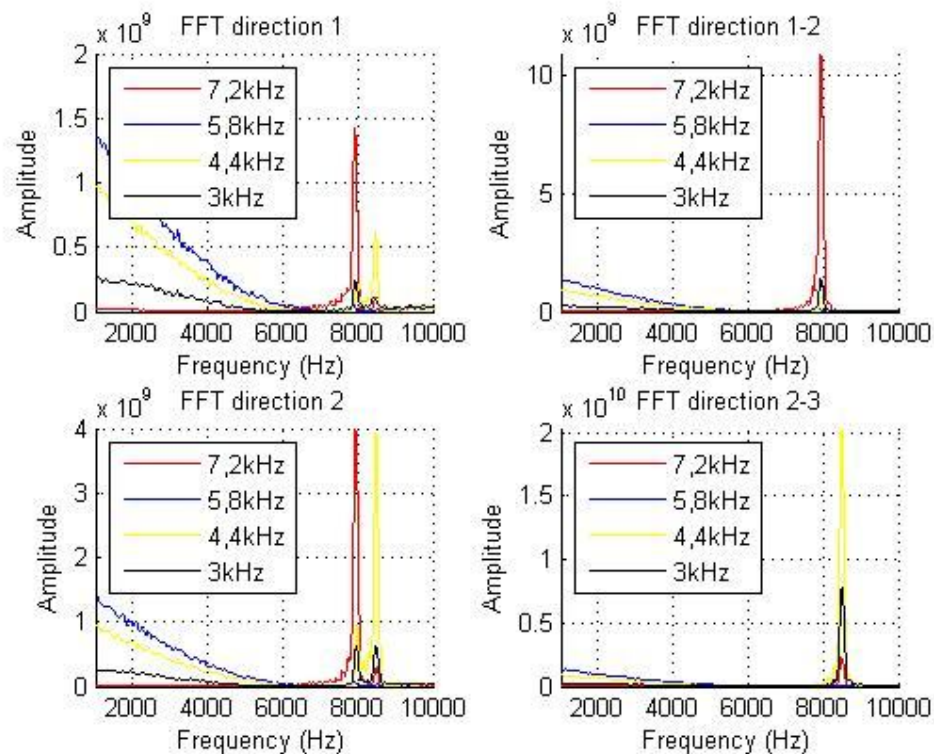


Figure 83. ISQ1=85, ISQ2=85, ISQ3=85, ISQ4=88.

Appendix 8.4: Error made by Metal and Glue, Error 1 Repeated

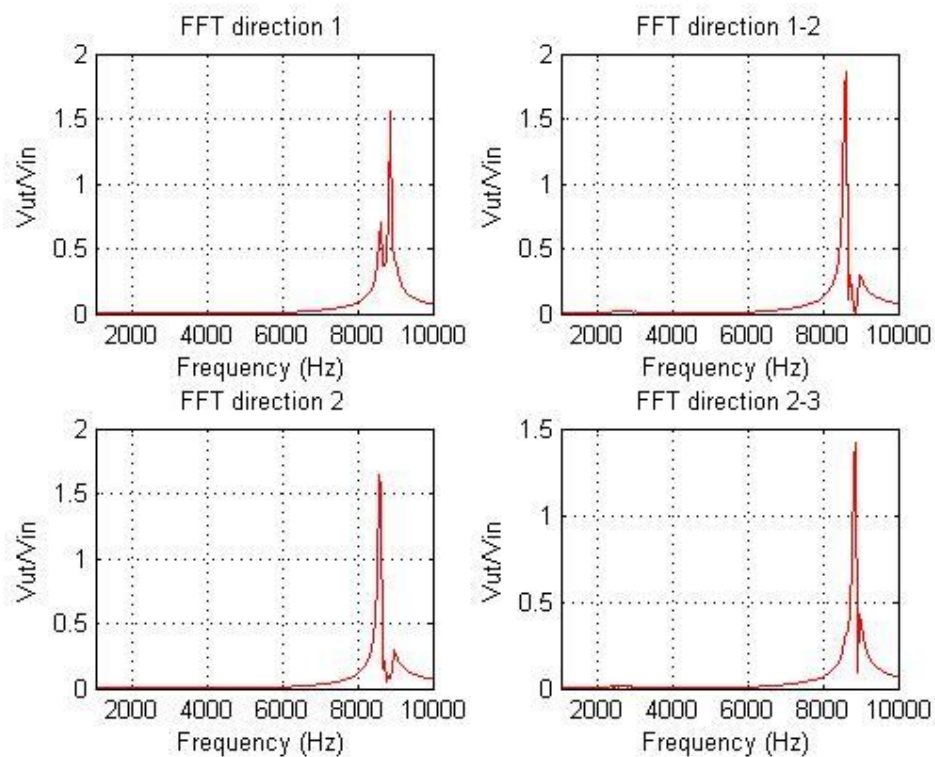


Figure 84. The lowest frequency peak is at 8610Hz and the high peak is at 8861Hz.

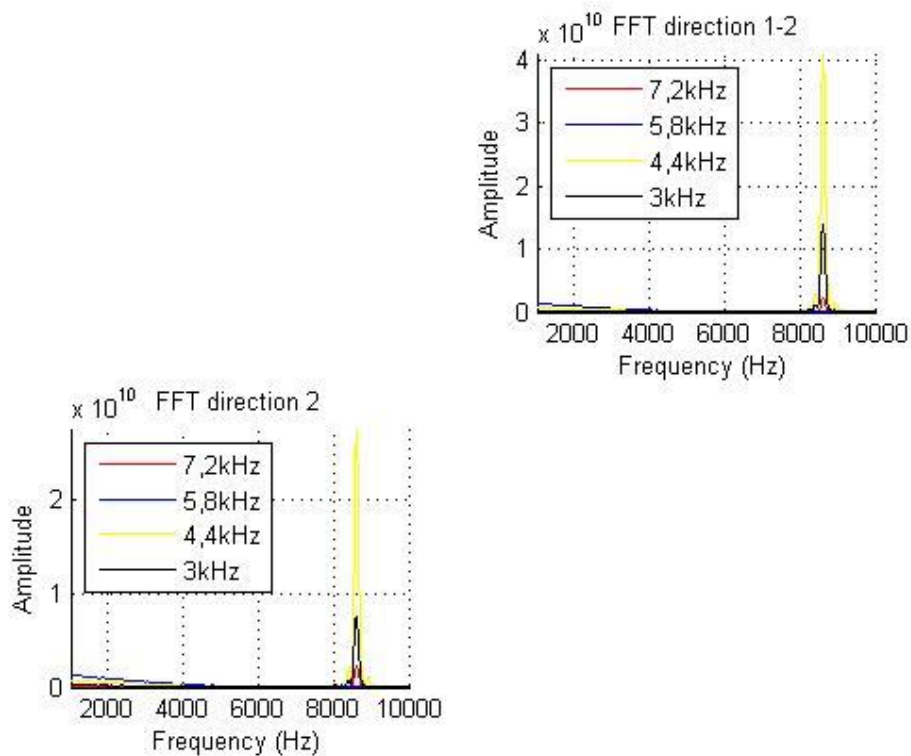


Figure 85. ISQ2=89, ISQ3=89.

Appendix 8.5: Error made by Metal and Glue, Normal 2

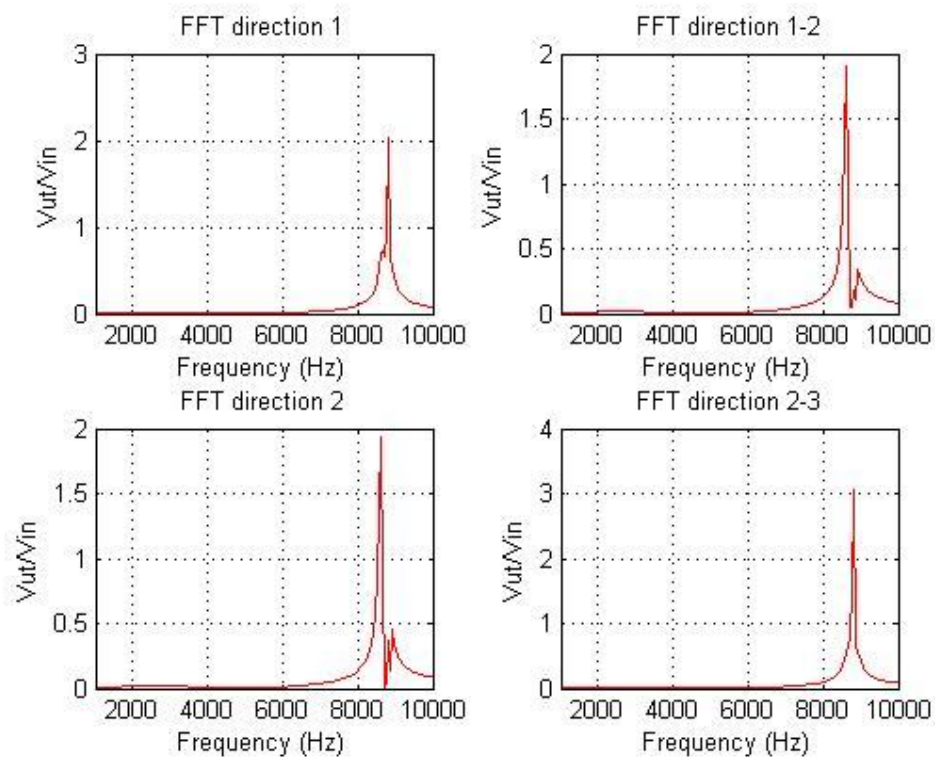


Figure 86. The lowest frequency peak is at 8610Hz and the high peak is at 8810Hz.

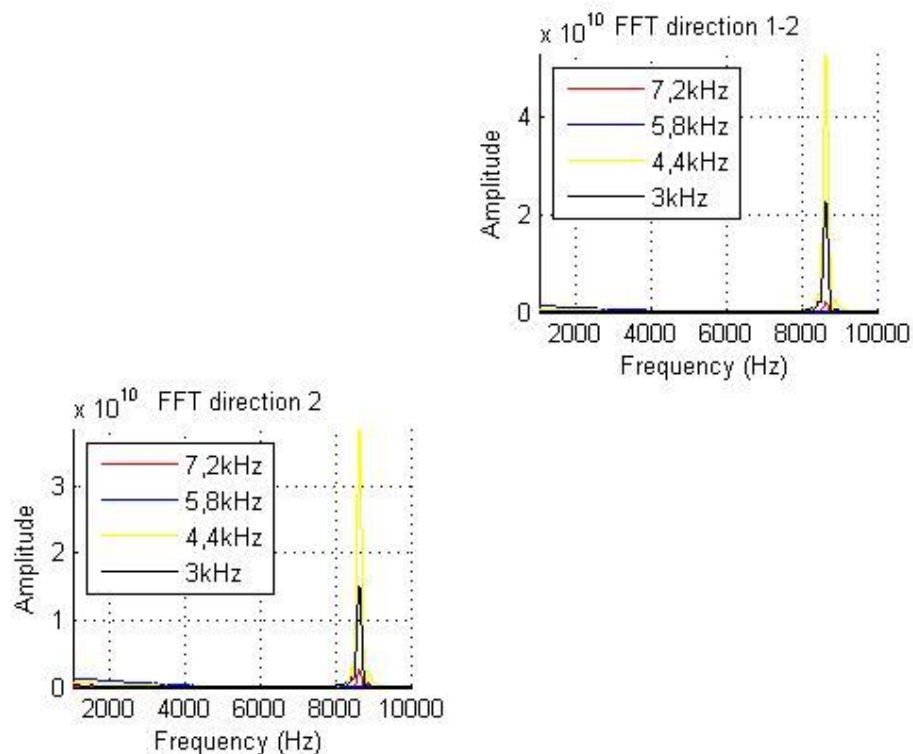


Figure 87. ISQ2=89, ISQ3=89.

Appendix 8.6: Error made by Metal and Glue, Normal 2 Repeated

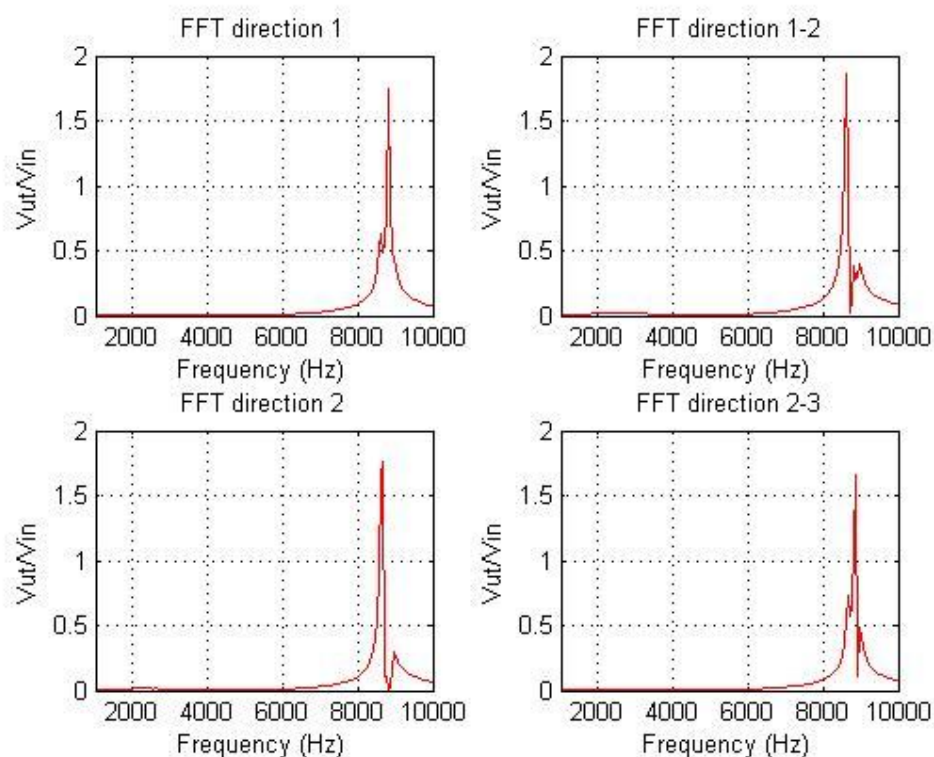


Figure 88. In direction 1 frequency peak is at 8810Hz, in direction 1-2 and 2 at 8610Hz and in direction 2-3 at 8860Hz.

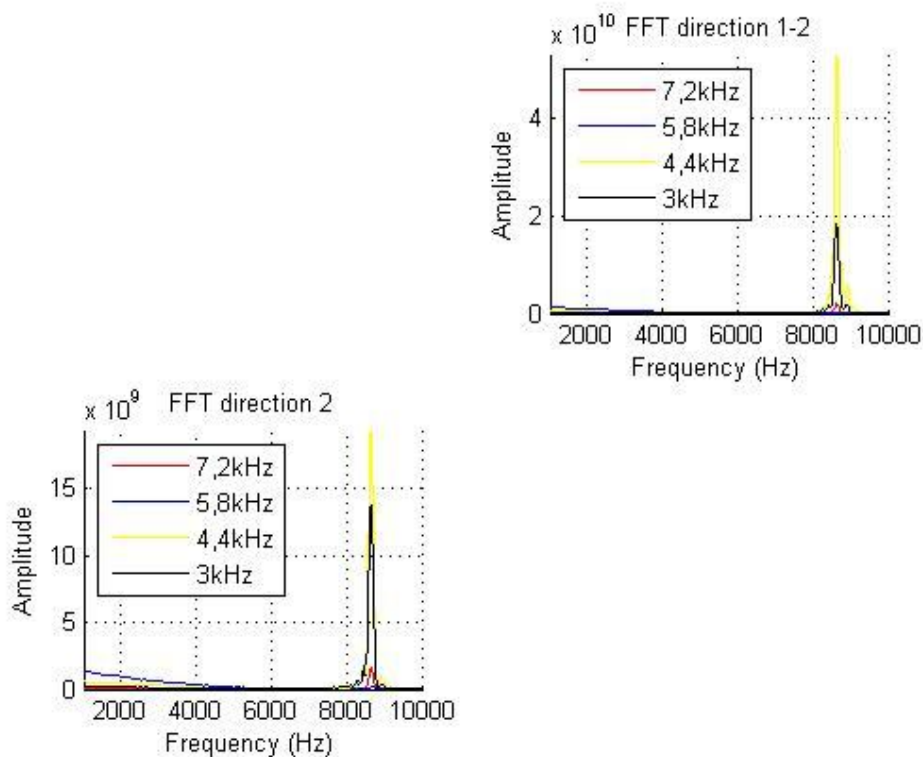


Figure 89. ISQ2=89, ISQ3=89.

Appendix 8.7: Error made by Metal and Glue, Error 2

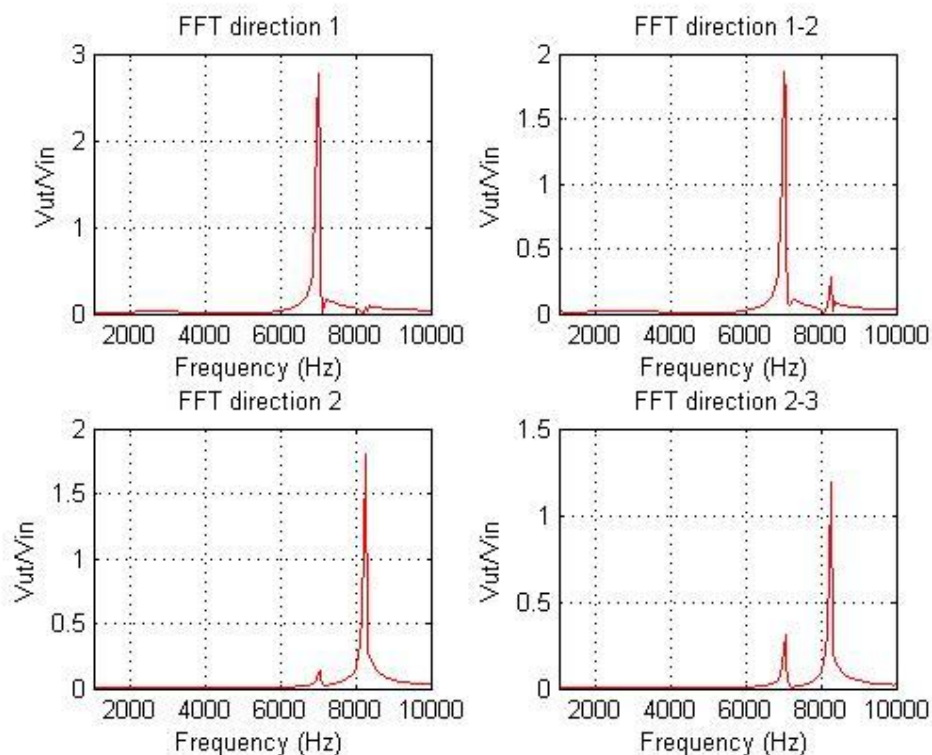


Figure 90. In direction 1 frequency peak is at 6998Hz, in direction 1-2 at 6998Hz and at 8270Hz, in direction 2 at 7039Hz and at 8270Hz and in direction 2-3 at 7039Hz and 8270 Hz.

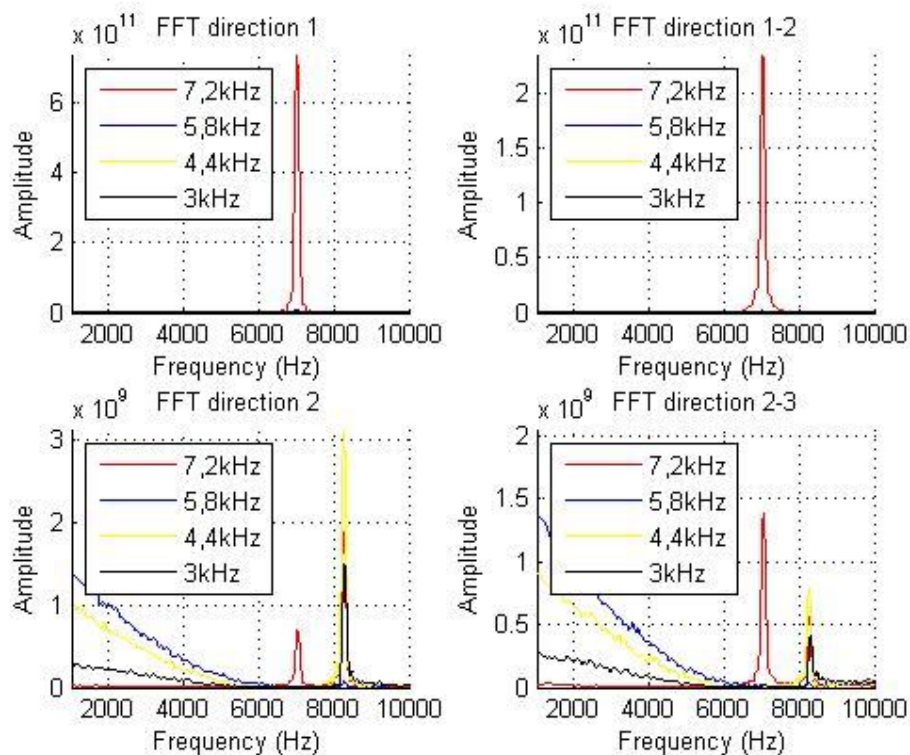


Figure 91. ISQ1=78, ISQ2=78 ISQ3=86, ISQ4=79.

Appendix 8.8: Error made by Metal and Glue, Error 2 Repeated

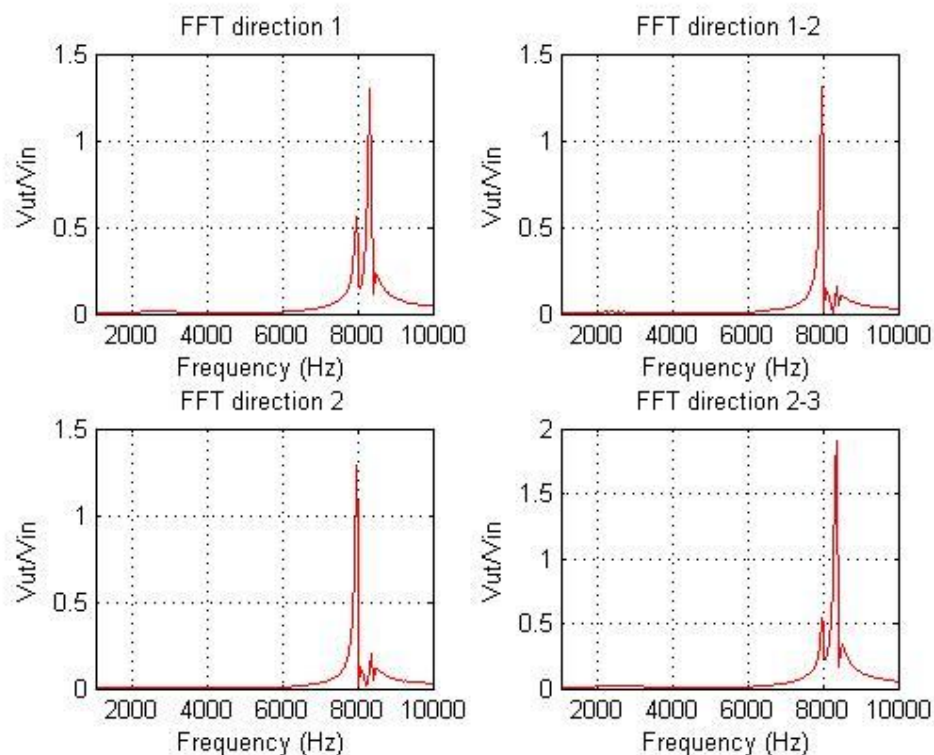


Figure 92. In direction 1 frequency peaks are at 7943Hz and at 8318Hz, in direction 1-2 at 7943Hz, in direction 2 at 7943Hz and at 8365Hz and in direction 2-3 at 7943Hz and 8365 Hz.

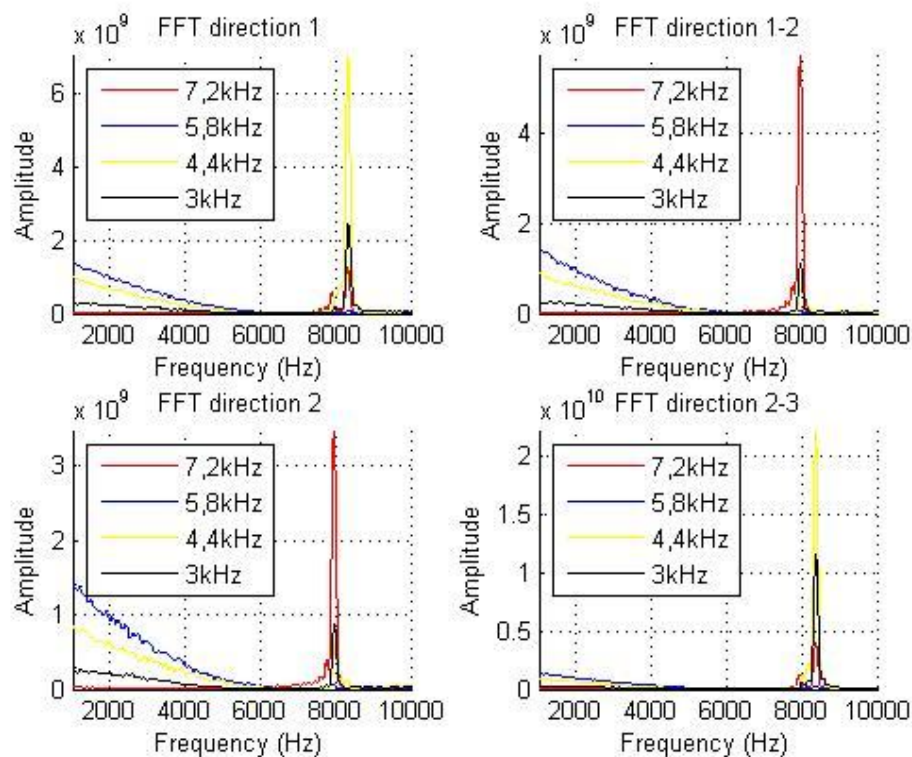


Figure 93. ISQ1=87, ISQ2=87, ISQ3=85, ISQ4=87.

Appendix 8.9: Error made by Metal and Glue, Normal 3

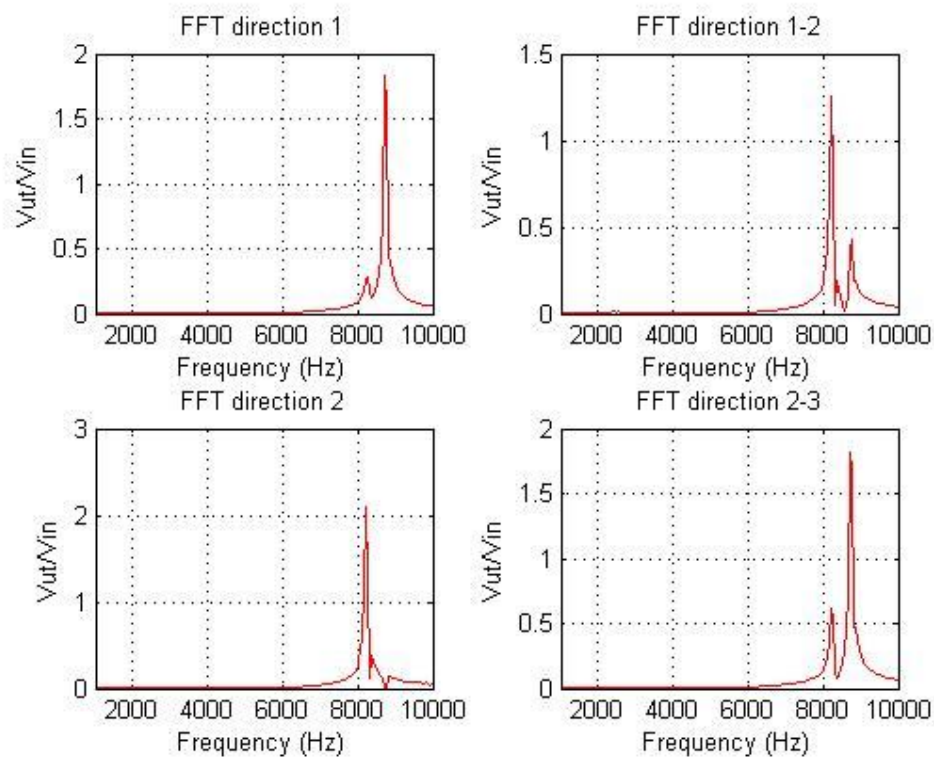


Figure 94. In direction 1 frequency peaks are at 8270Hz and at 8710Hz, in direction 1-2 at 8222Hz and at 8760Hz, in direction 2 at 8222Hz and in direction 2-3 at 8222Hz and at 8710Hz.

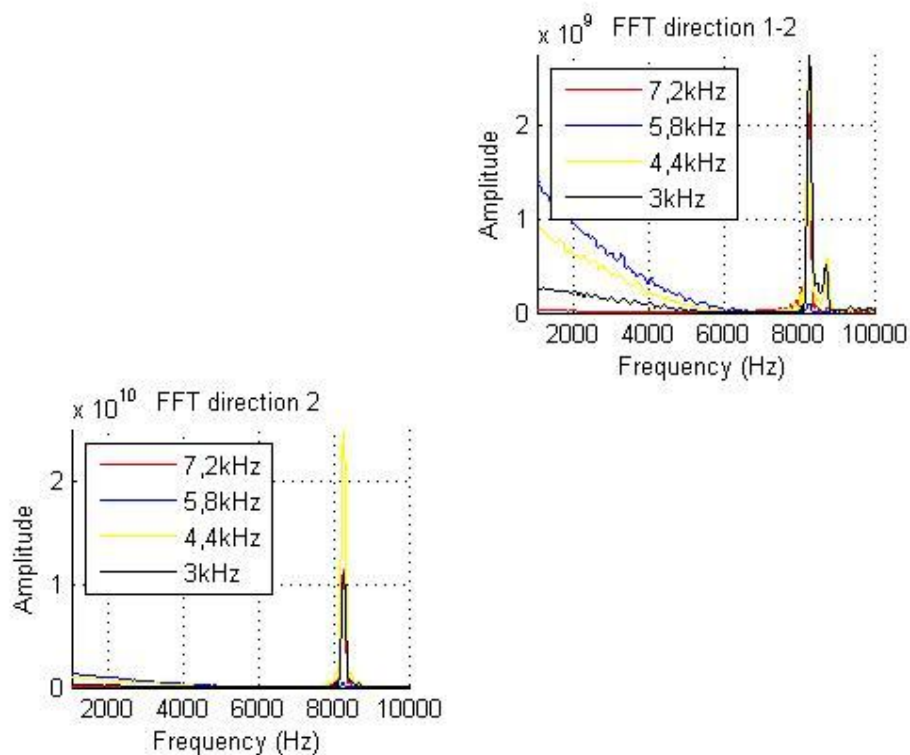


Figure 95. ISQ2=85, ISQ3=86.

Appendix 8.10: Error made by Metal and Glue, Normal 3 Repeated

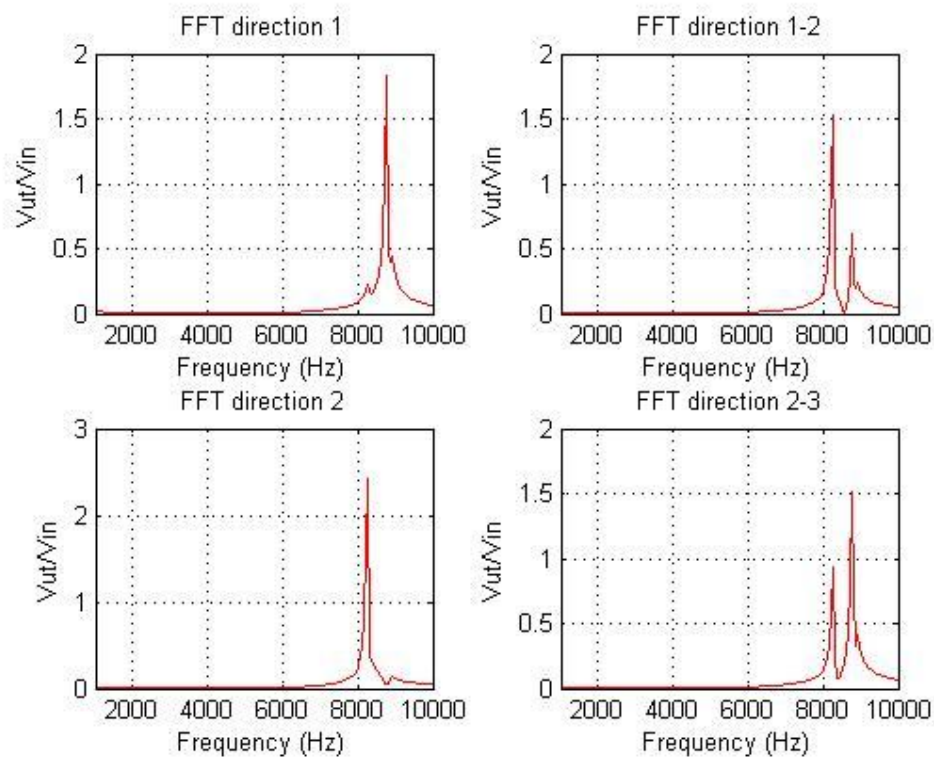


Figure 96. In direction 1 frequency peaks are at 8270Hz and at 8760Hz, in direction 1-2 at 8270Hz and at 8760Hz, in direction 2 at 8270Hz and in direction 2-3 at 8270Hz and at 8760Hz.

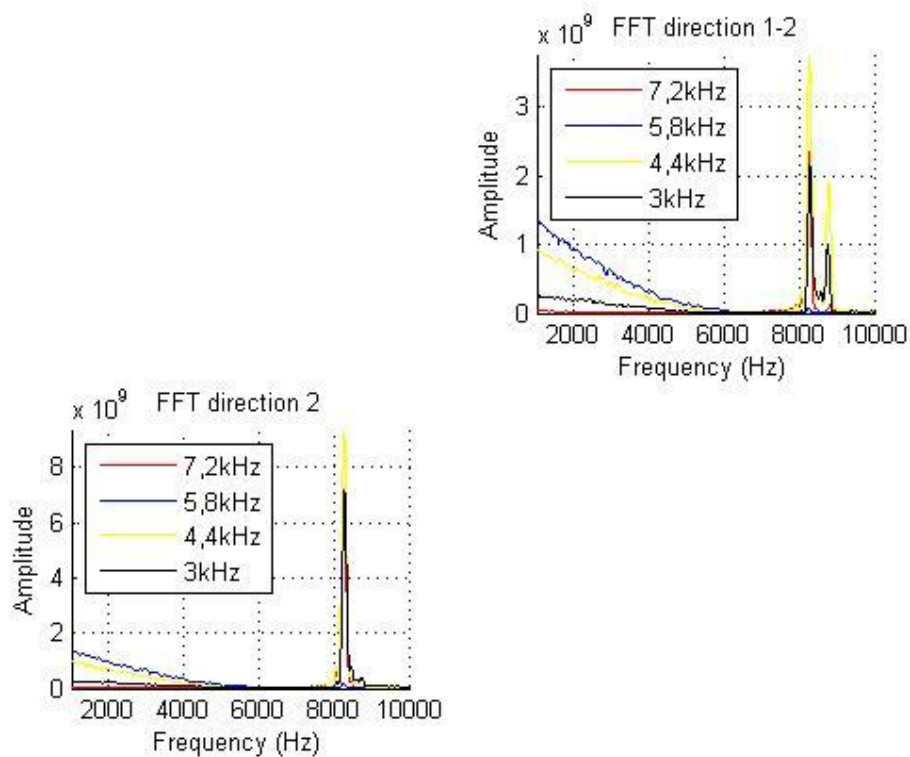


Figure 97. ISQ2=86, ISQ3=87.

Appendix 9.1: Error made by Welding, Normal 1

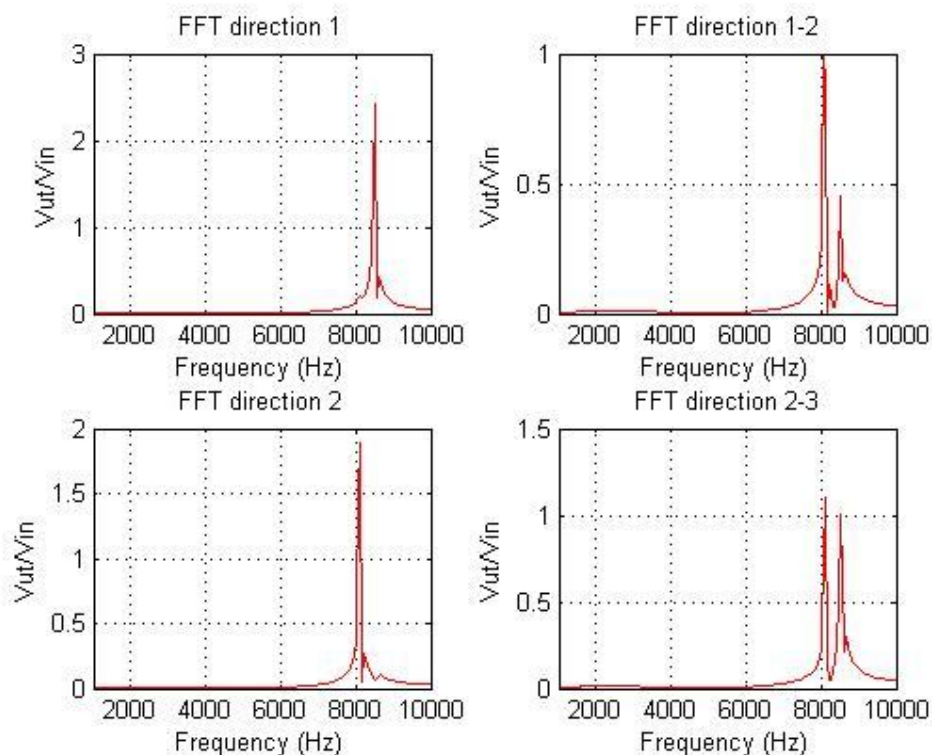


Figure 98. In direction 1 frequency peaks are at 8511Hz, in direction 1-2 at 8082Hz and at 8511Hz, in direction 2 at 8128Hz and in direction 2-3 at 8128Hz and at 8511Hz.

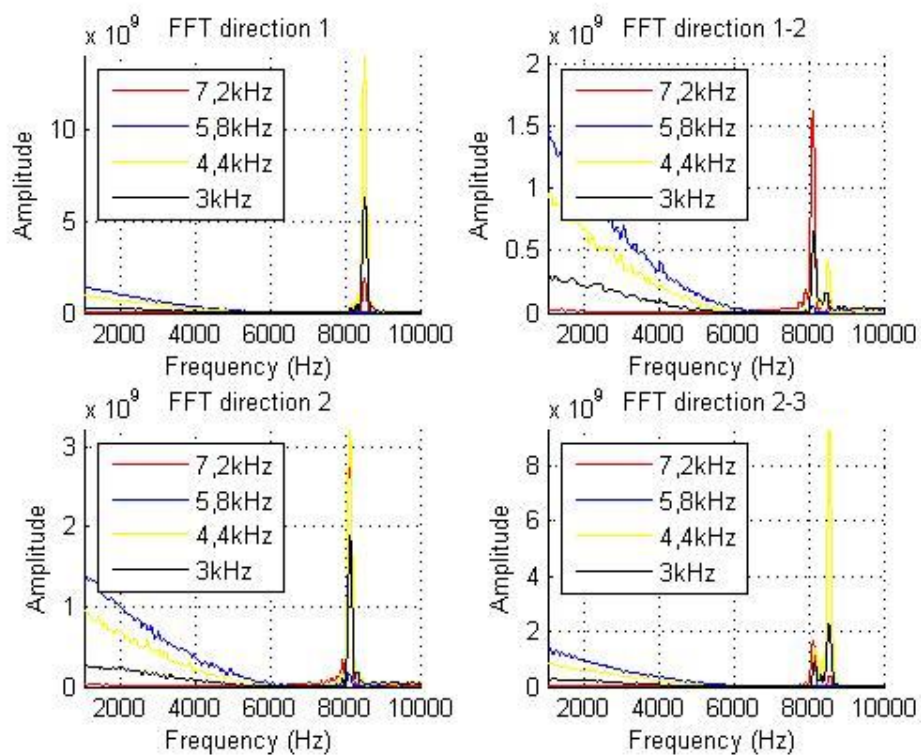


Figure 99. ISQ1=88, ISQ2=86, ISQ3=85, ISQ4=86.

Appendix 9.2: Error made by Welding, Normal 1 Repeated

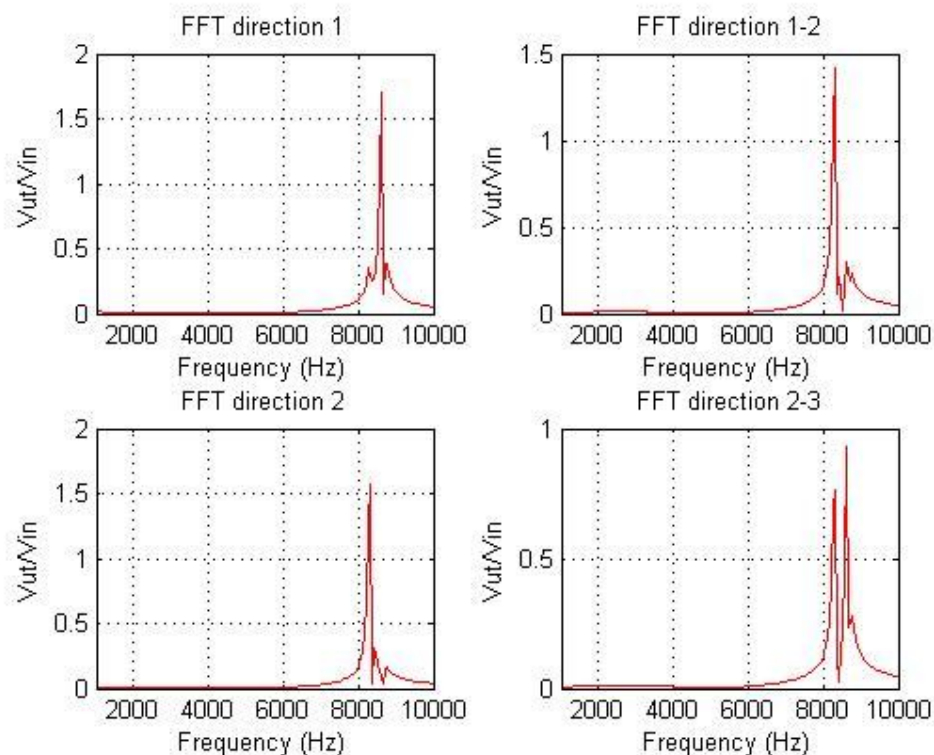


Figure 100. In direction 1 frequency peak is at 8610Hz, in direction 1-2 at 8318Hz and at 8610Hz, in direction 2 at 8318Hz and in direction 2-3 at 8318Hz and at 8610Hz.

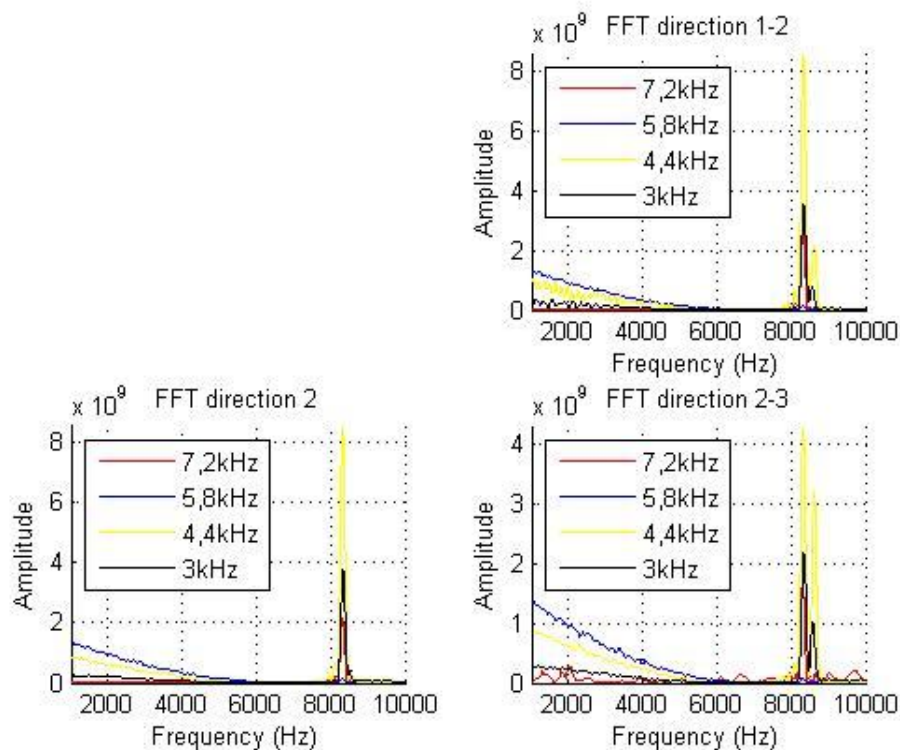


Figure 101. ISQ2=88, ISQ3=88, ISQ4=88.

Appendix 9.3: Error made by Welding, 3 Weldings on Ledge

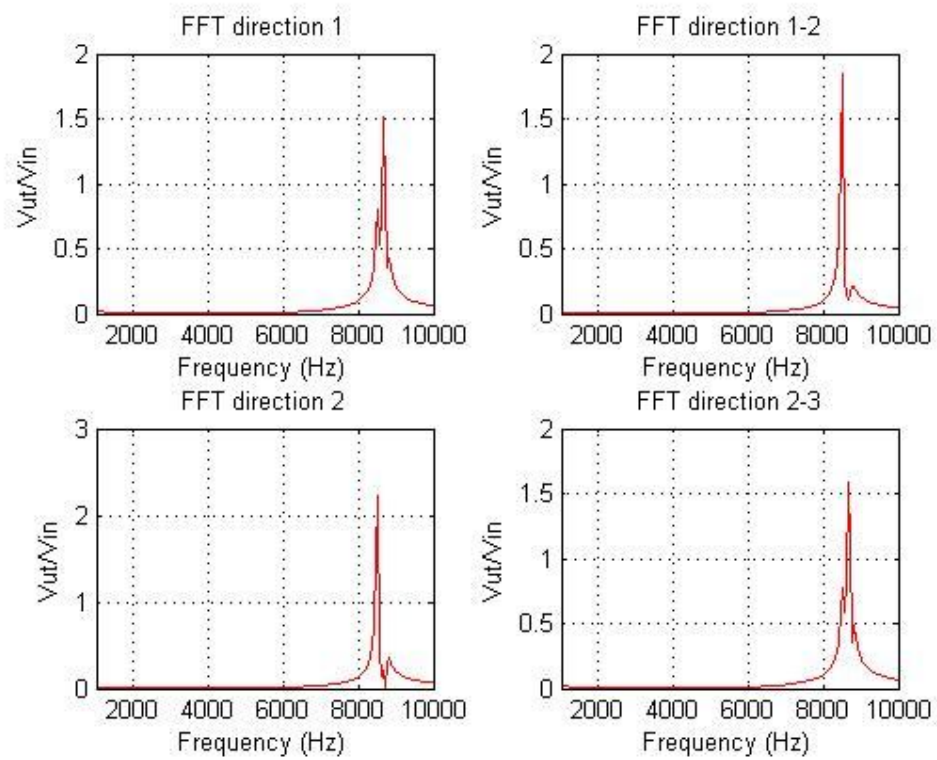


Figure 102. The lowest frequency peak is at 8511Hz and the high peak is at 8660Hz.

Appendix 9.4: Error made by Welding, 3 Weldings on Ledge Repeated

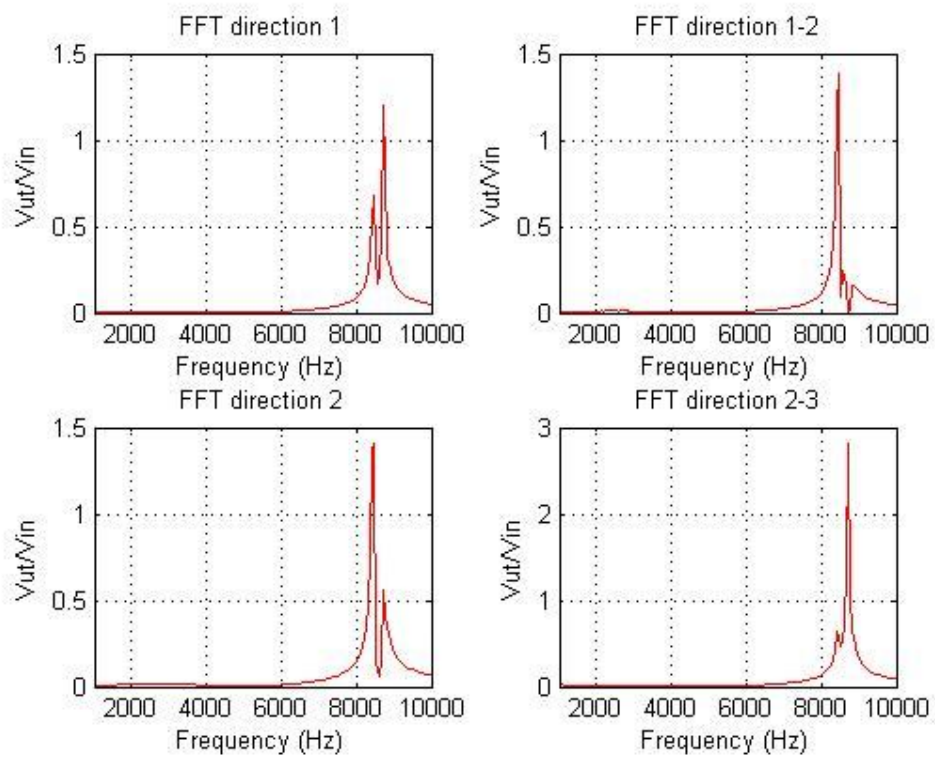


Figure 103. The lowest frequency peak is at 8463Hz and the high peak is at 8710Hz.

Appendix 9.5: Error made by Welding, 8 Weldings on Ledge

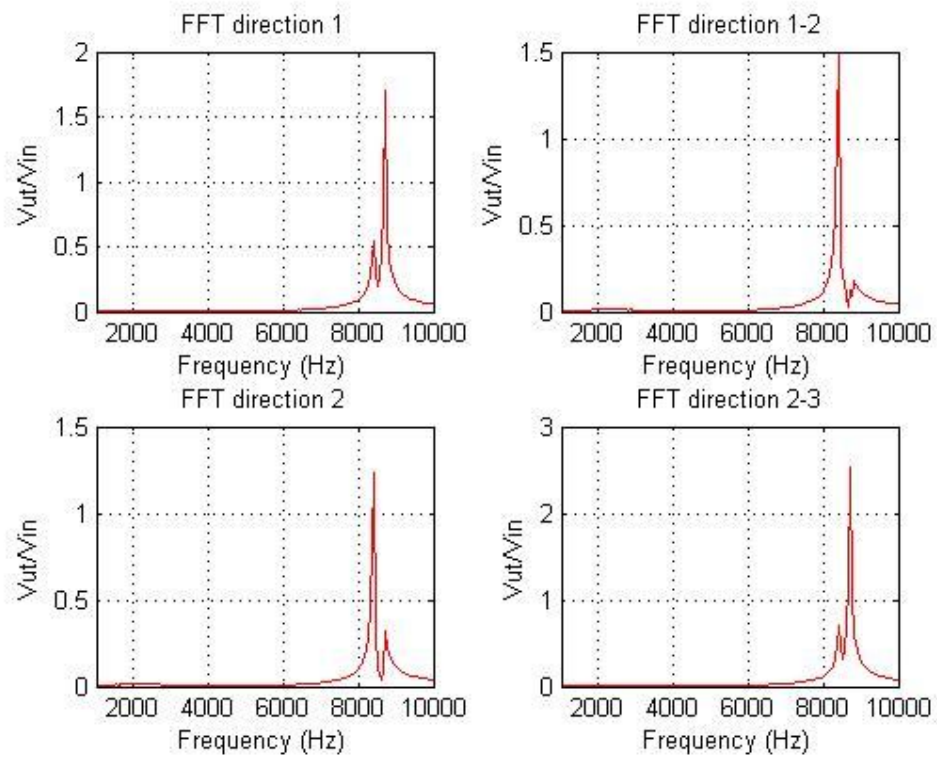


Figure 104. The lowest frequency peak is at 8414Hz and the high peak is at 8710Hz.

Appendix 9.6: Error made by Welding, 8 Weldings on Ledge Repeated

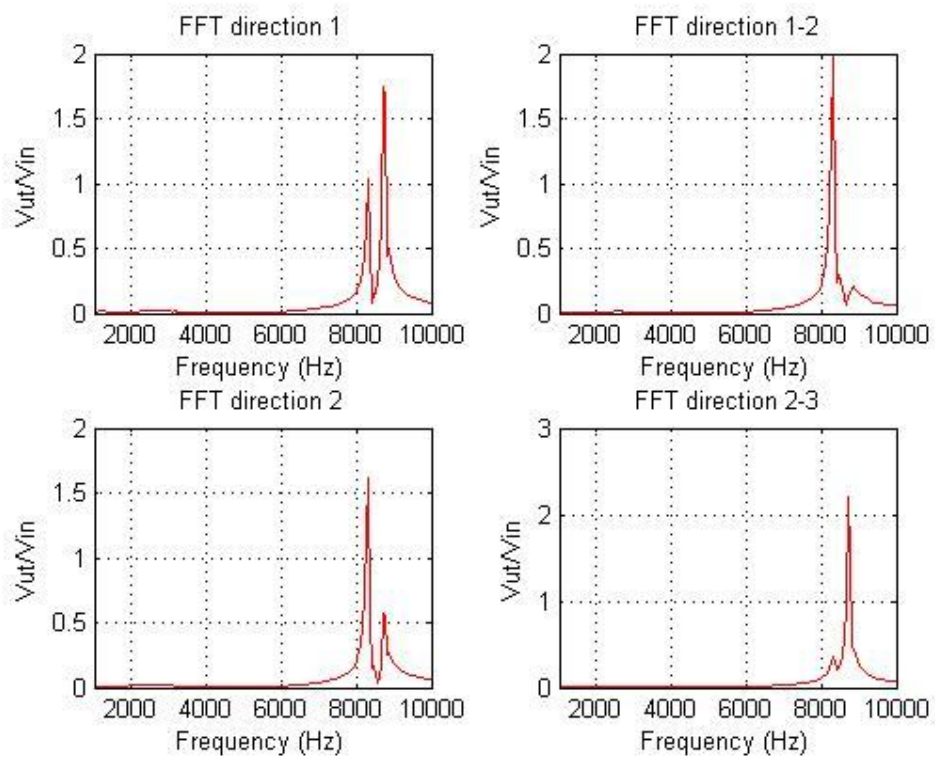


Figure 105. The lowest frequency peak is at 8318Hz and the high peak is at 8710Hz.

Appendix 9.7: Error made by Welding, whole Ledge Surface

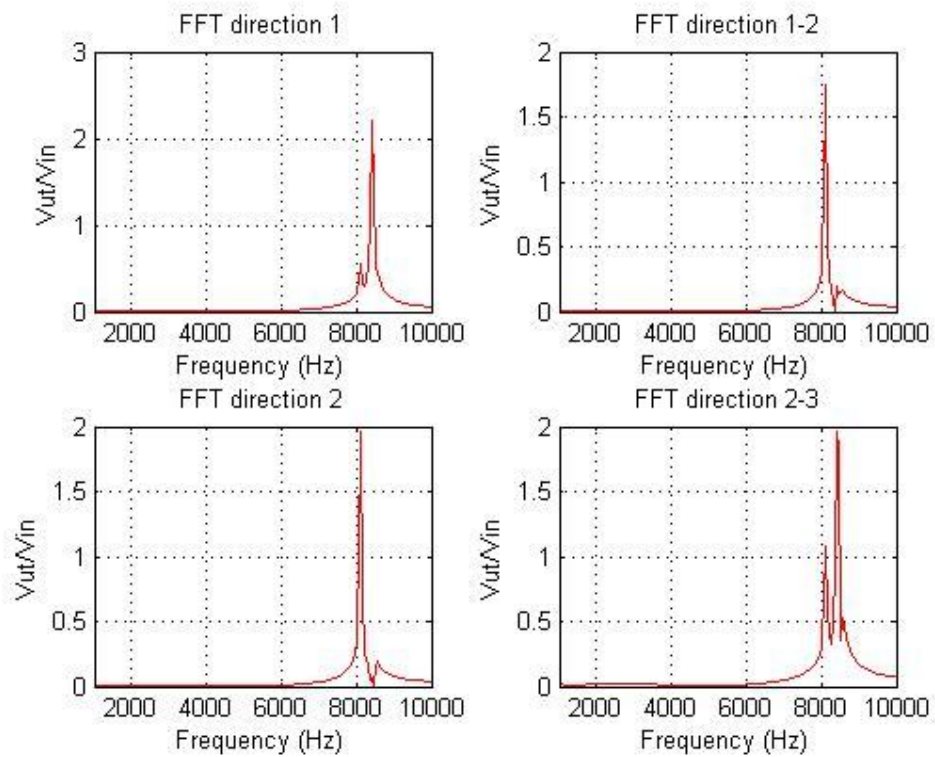


Figure 106. The lowest frequency peak is at 8128Hz and the high peak is at 8414Hz.

Appendix 9.8: Error made by Welding, Whole Ledge Surface Repeated

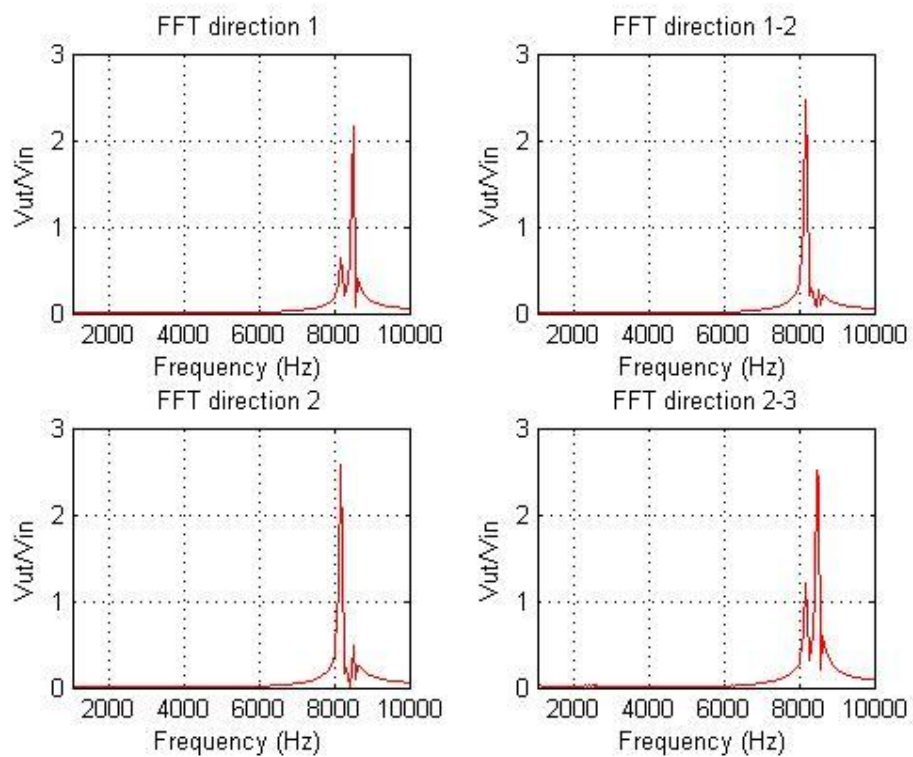


Figure 107. The lowest frequency peak is at 8175Hz and the high peak is at 8511Hz.

Appendix 9.9: Error made by Welding, whole Bottom Side

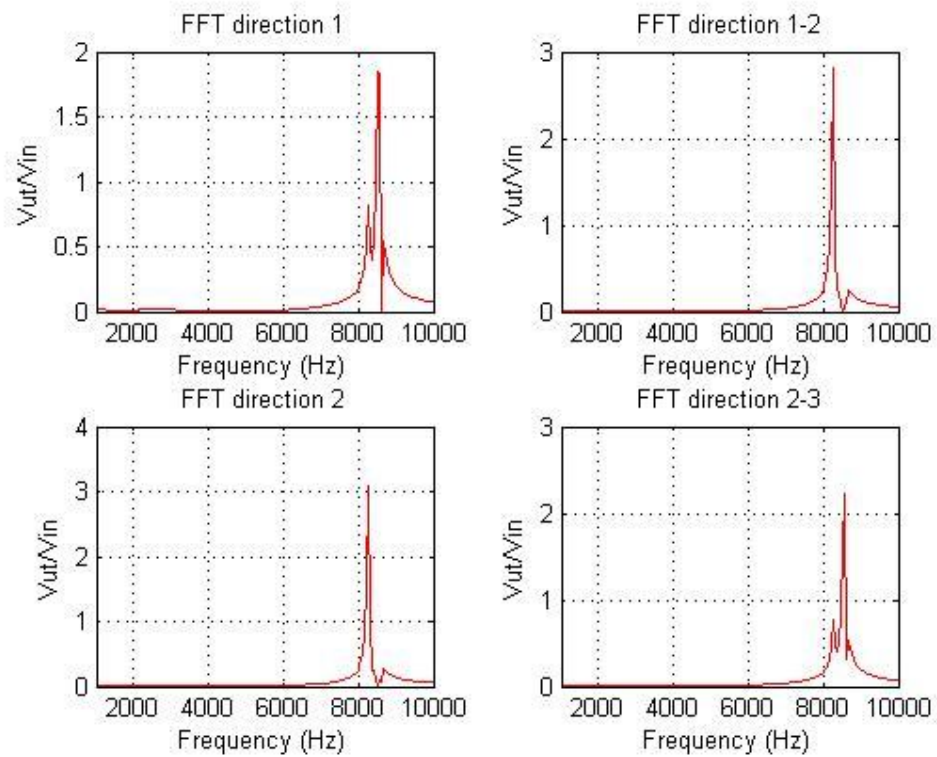


Figure 108. The lowest frequency peak is at 8270Hz and the high peak is at 8560Hz.

Appendix 9.10: Error made by Welding, whole Bottom Side Repeated

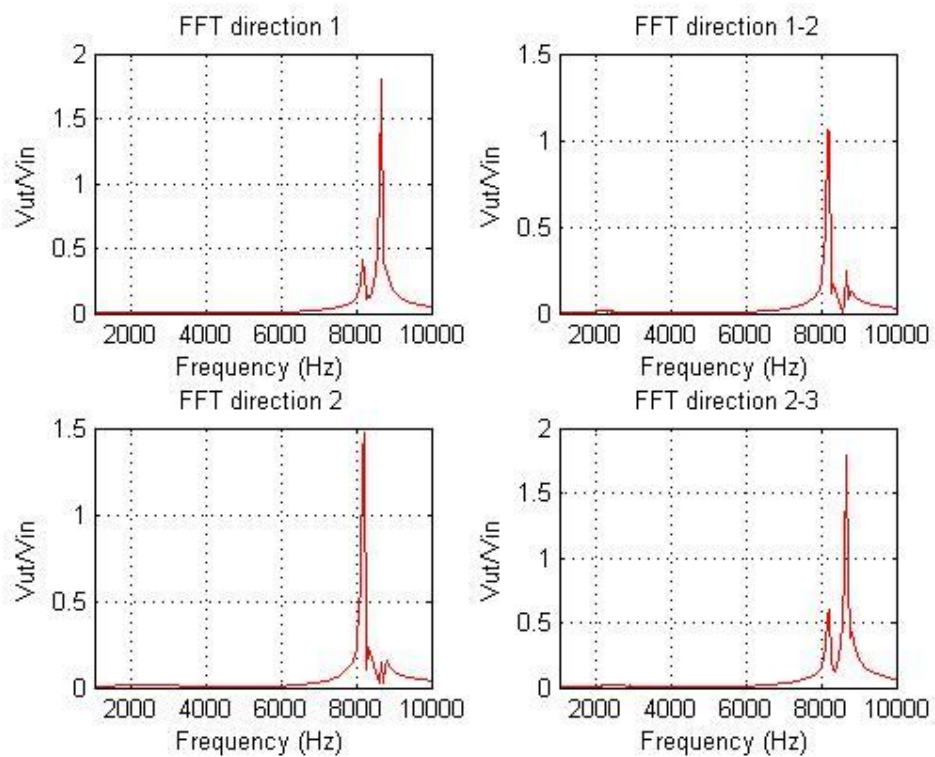


Figure 109. The lowest frequency peak is at 8222Hz and the high peak is at 8660Hz.

Appendix 9.11: Error made by Welding, whole 45 Degree Surface

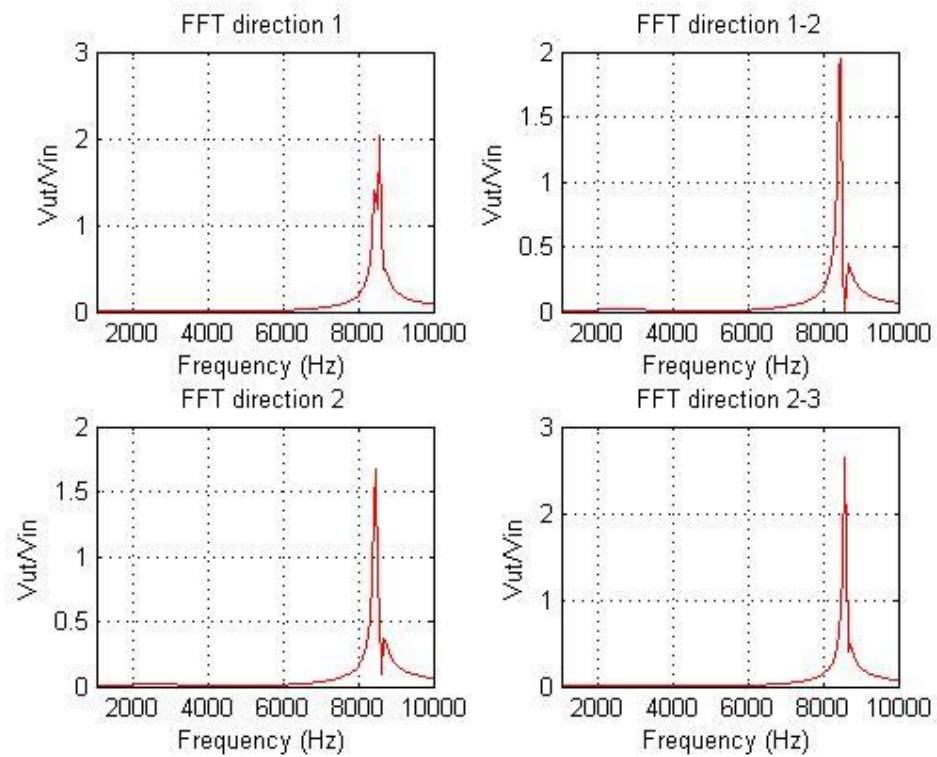


Figure 110. The lowest frequency peak is at 8463Hz and the high peak is at 8561Hz.

Appendix 9.12: Error made by Welding whole 45 Degree Surface Repeated

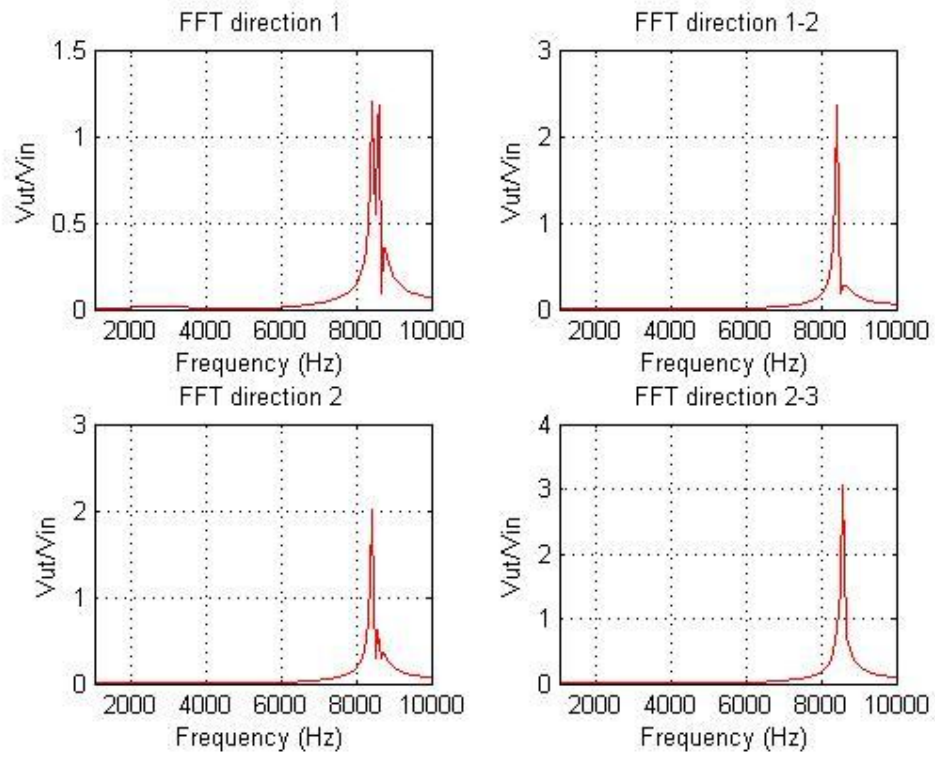


Figure 111. In direction 1 frequency peaks are at 8414Hz and 8610Hz, in direction 1-2 and 2 at 8414Hz and in direction 2-3 at 8561Hz.

Appendix 10.1: Wear on Threads, Normal

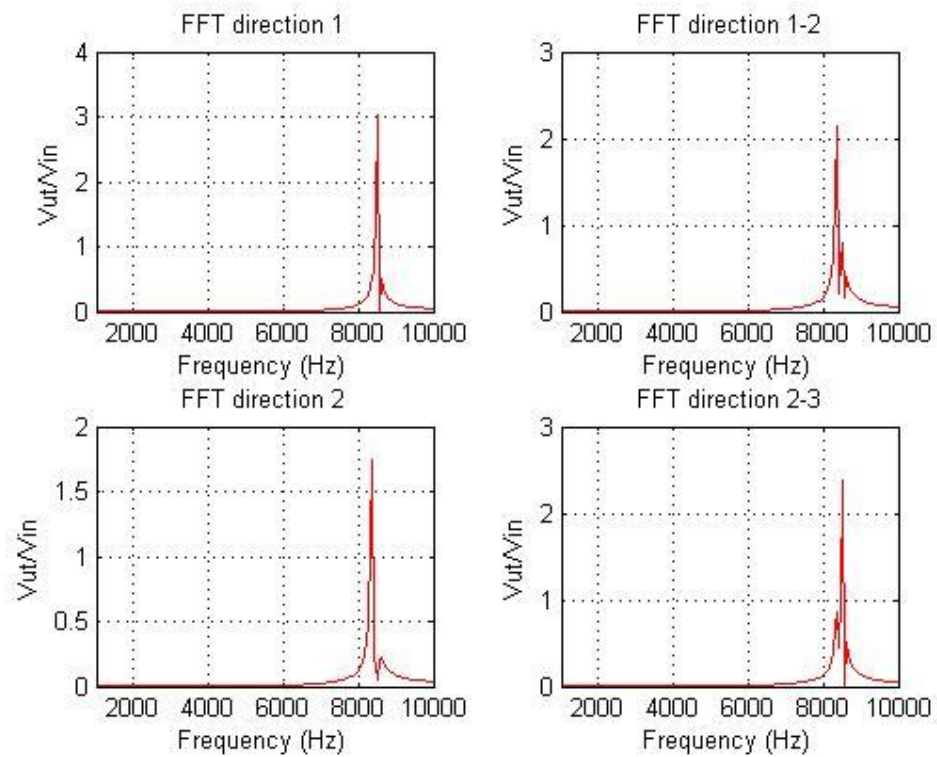


Figure 112. The lowest frequency peak is at 8366Hz and the high peak is at 8511Hz.

Appendix 10.2: Wear on Threads, Normal Repeated

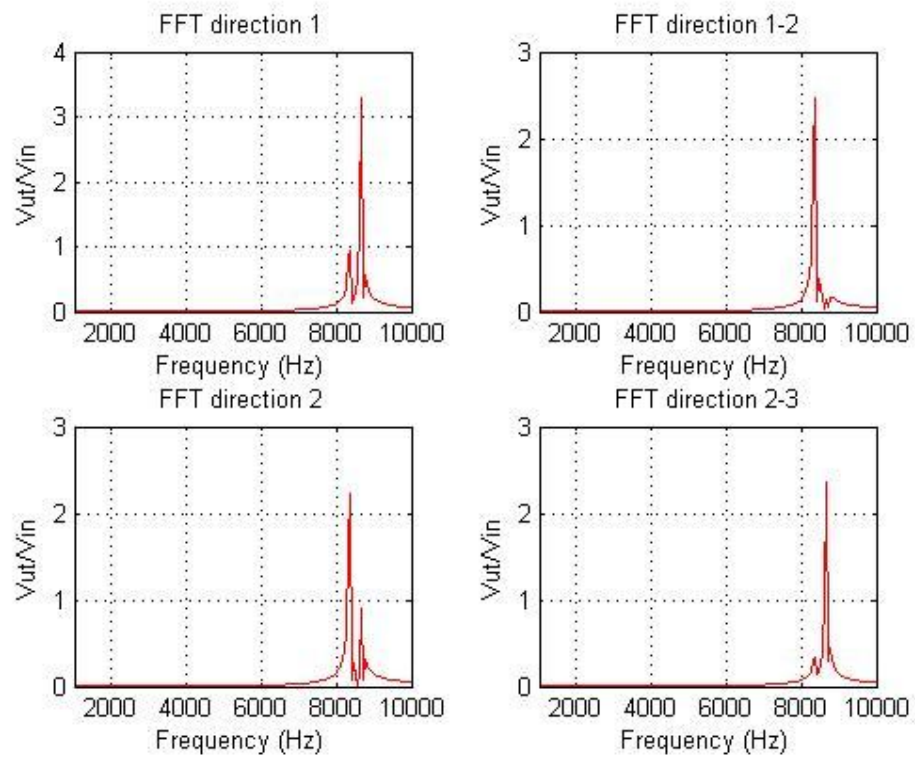


Figure 113. The lowest frequency peak is at 8366Hz and the high peak is at 8660Hz.

Appendix 10.3: Wear on Threads, Error 1

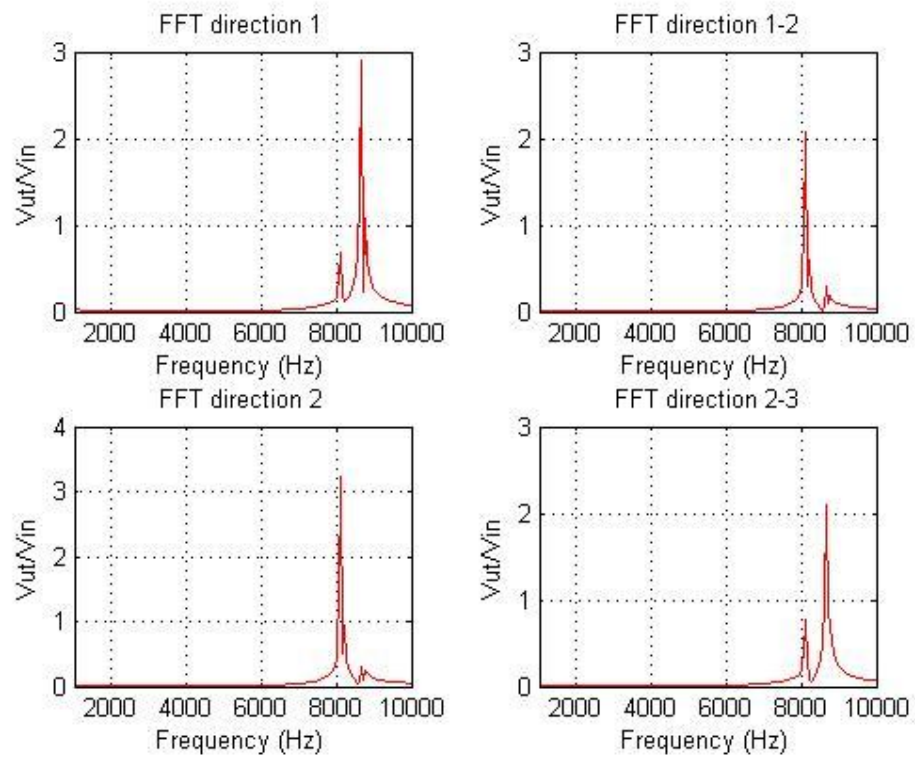


Figure 114. The lowest frequency peak is at 8128Hz and the high peak is at 8660Hz.

Appendix 10.4: Wear on Threads, Error 1 Repeated

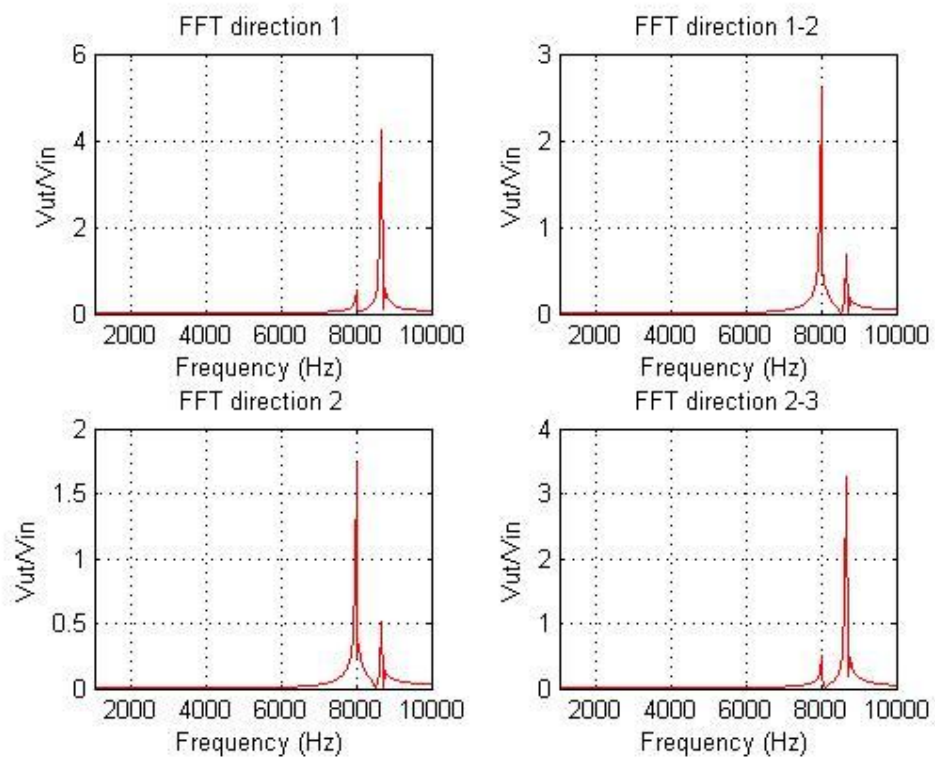


Figure 115. The lowest frequency peak is at 7989Hz and the high peak is at 8660Hz.

Appendix 10.5: Wear on Threads, Error 2

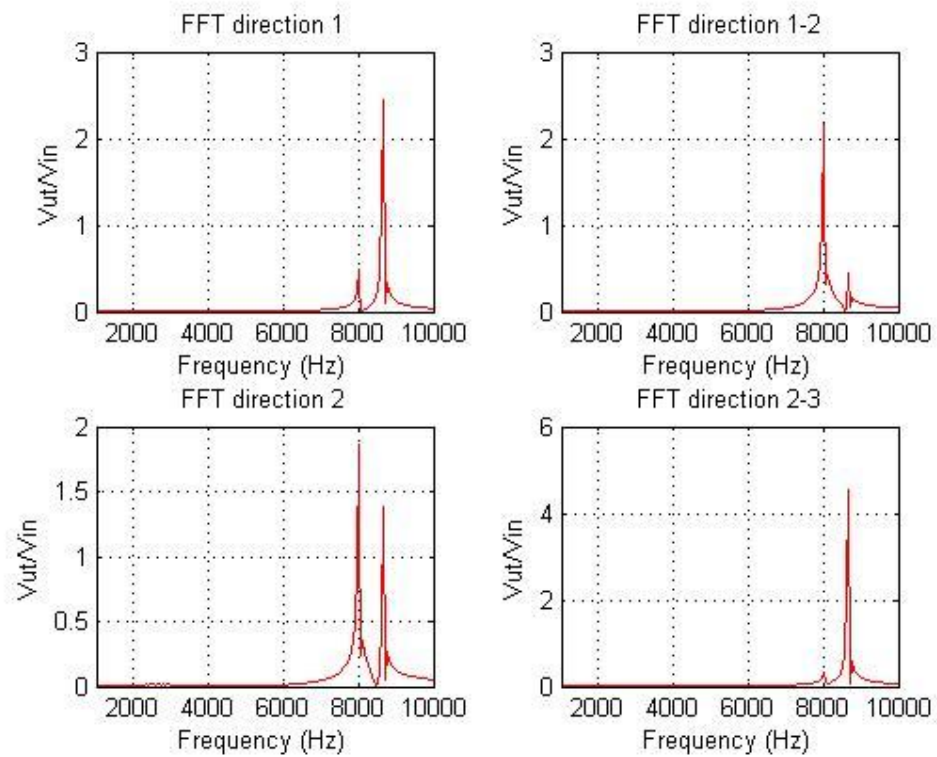


Figure 116. The lowest frequency peak is at 8035Hz and the high peak is at 8660Hz.

Appendix 10.6: Wear on Threads, Error 2 Repeated

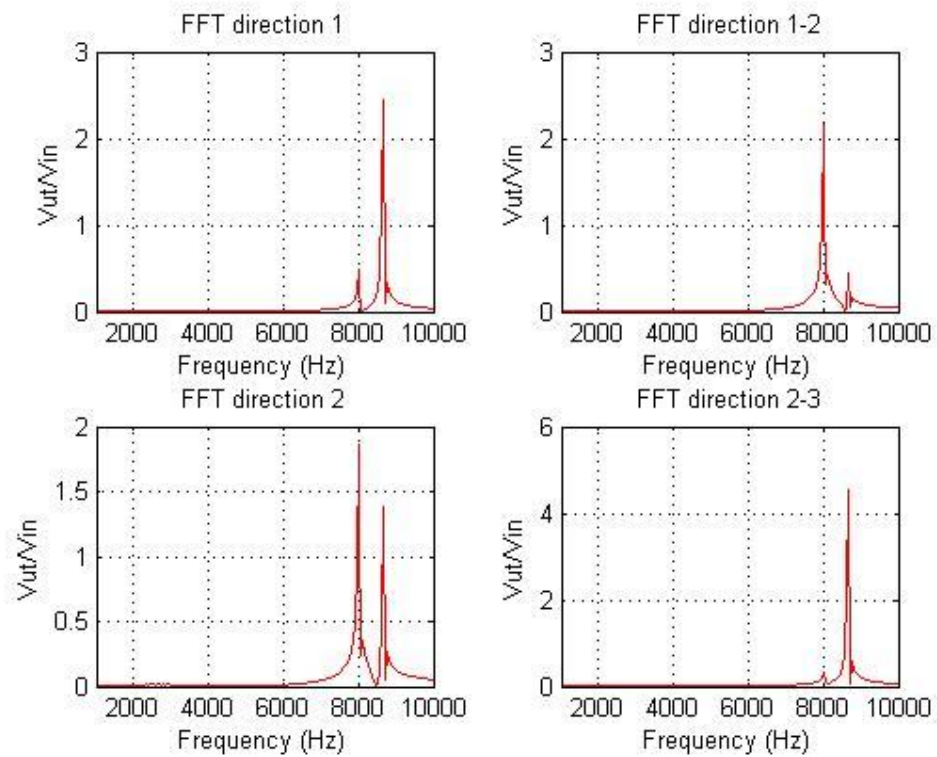


Figure 117. The lowest frequency peak is at 7989Hz and the high peak is at 8660Hz.

Appendix 10.7: Wear on Threads, Error 3

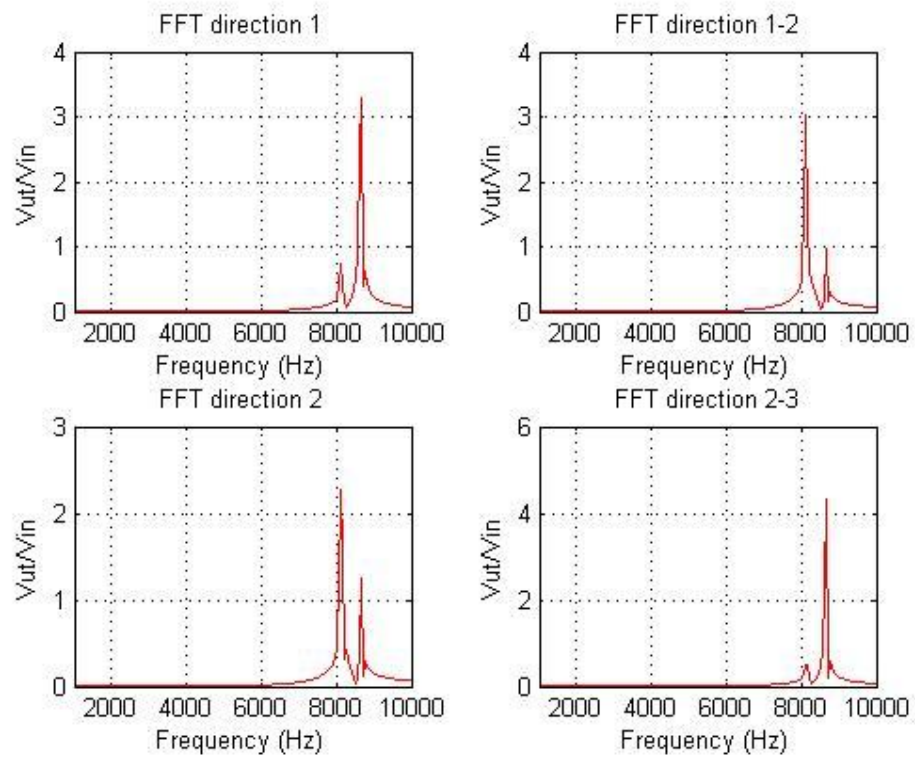


Figure 118. The lowest frequency peak is at 8128Hz and the high peak is at 8660Hz.

Appendix 10.8: Wear on Threads, Error 3 Repeated

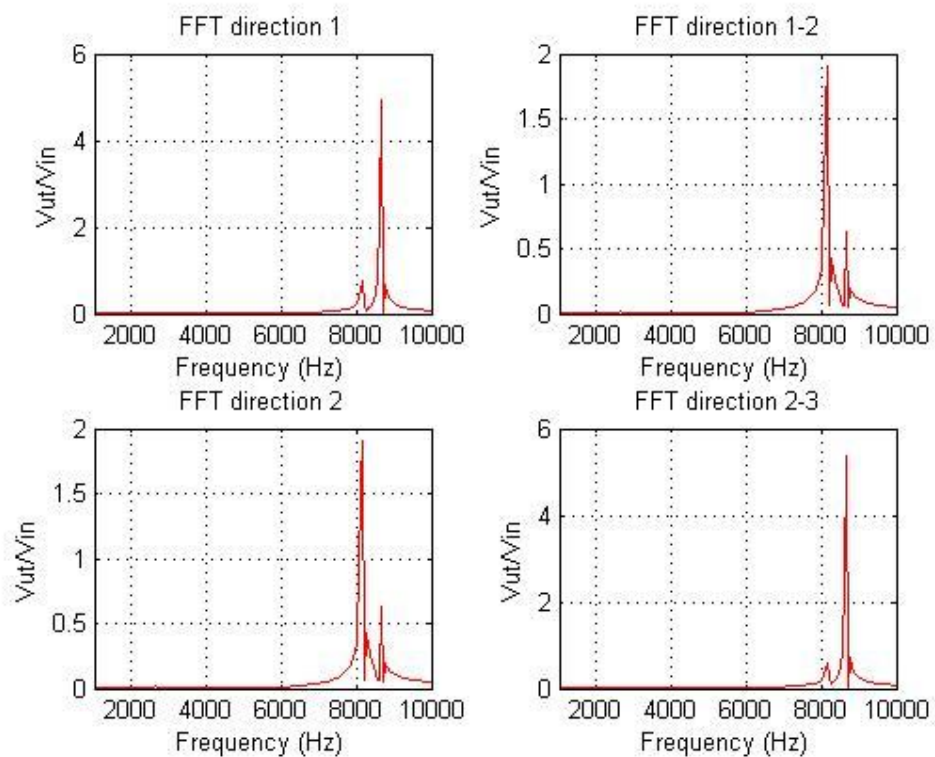


Figure 119. The lowest frequency peak is at 8175Hz and the high peak is at 8660Hz.

Appendix 10.9: Wear on Threads, Error 4

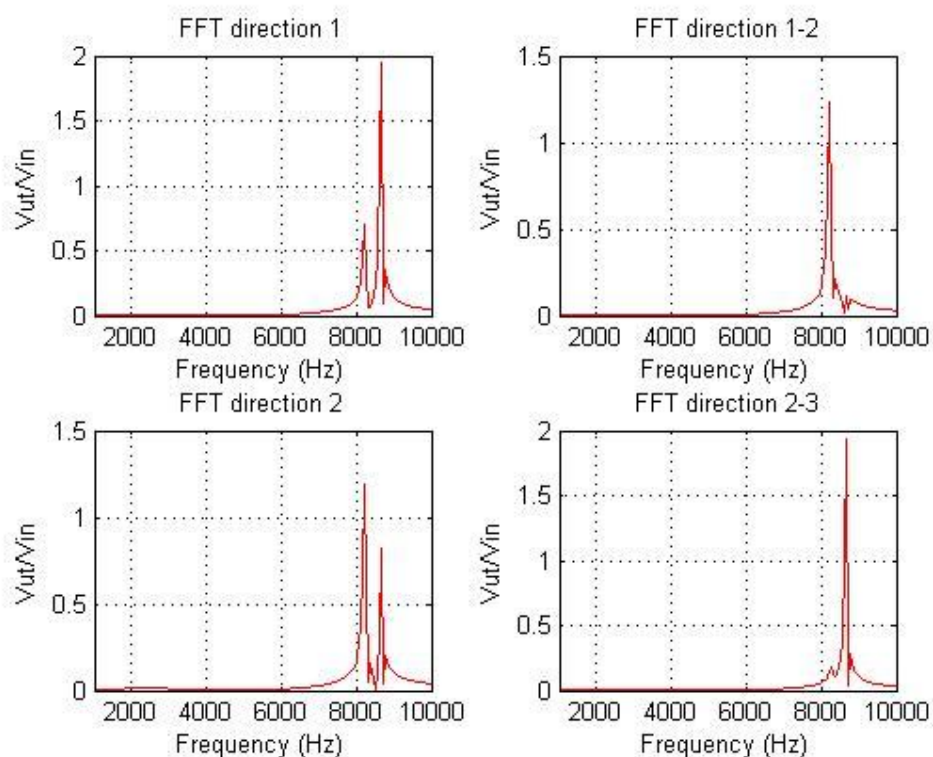


Figure 120. The lowest frequency peak is at 8222Hz and the high peak is at 8660Hz.

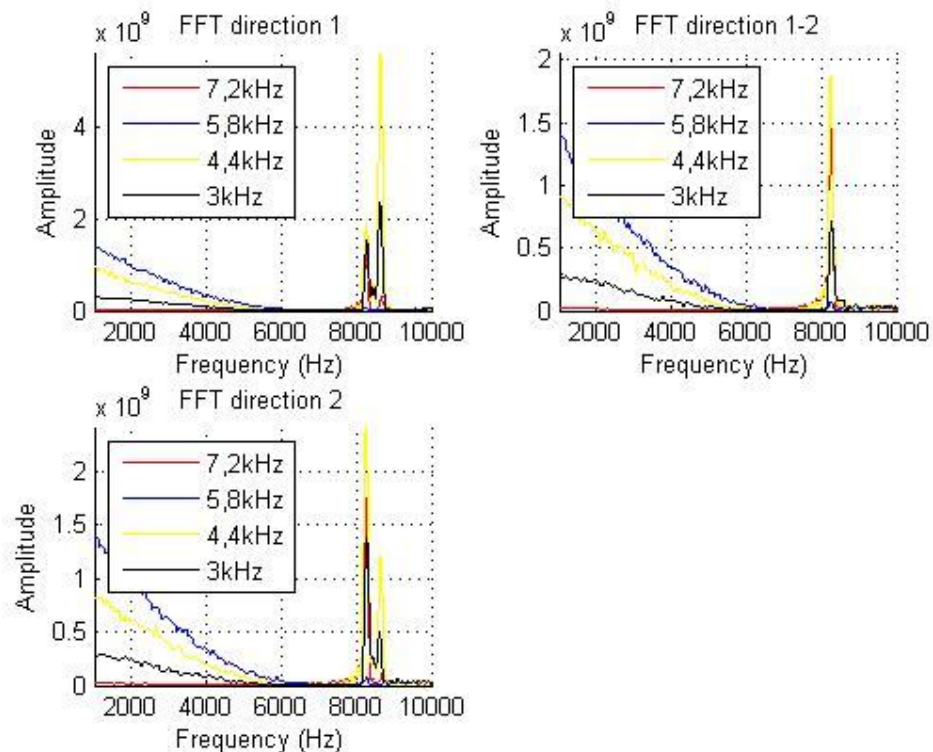


Figure 121. ISQ1=86, ISQ2=86, ISQ3=86.

Appendix 10.10: Wear on Threads, Error 4 Repeated

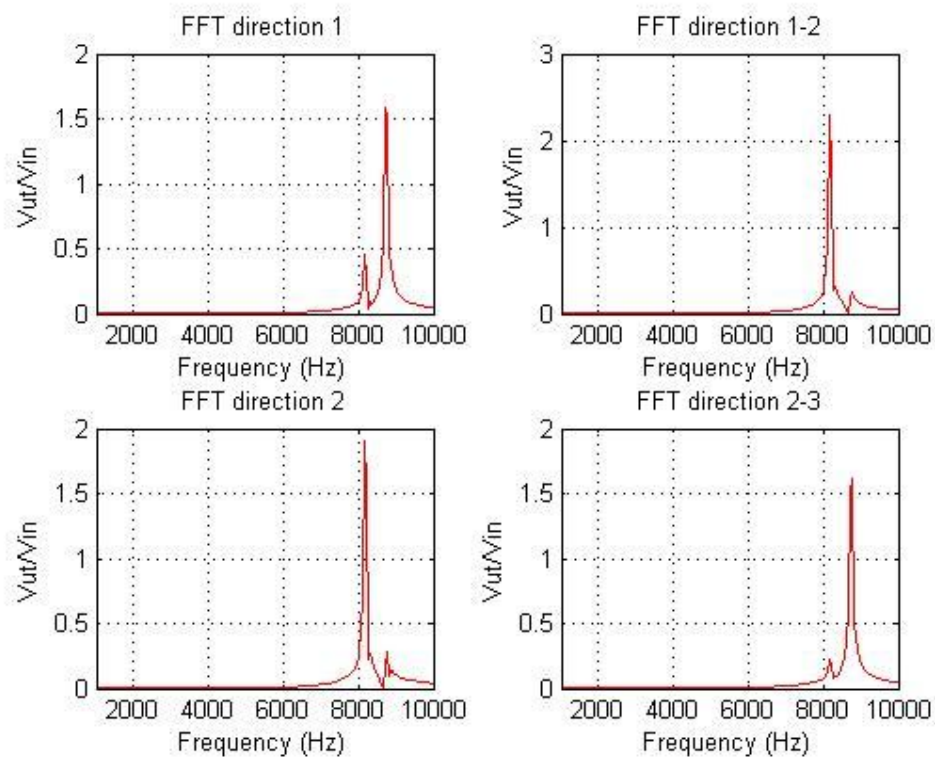


Figure 122. The lowest frequency peak is at 8175Hz and the high peak is at 8760Hz.

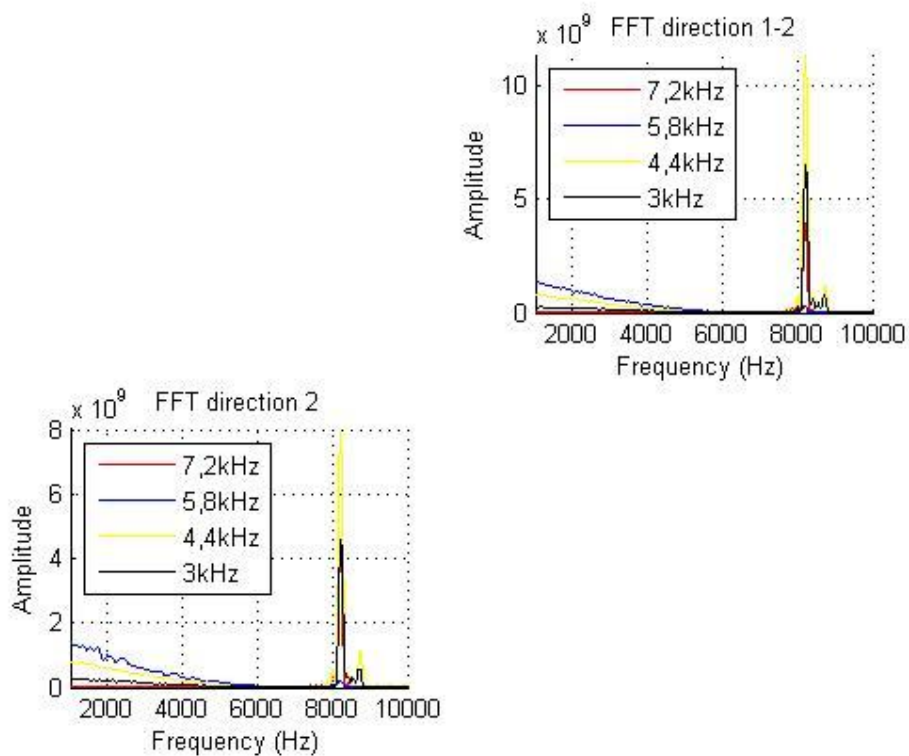


Figure 123. ISQ2=87, ISQ3=87.

Appendix 10.11: Wear on Threads, Error 5

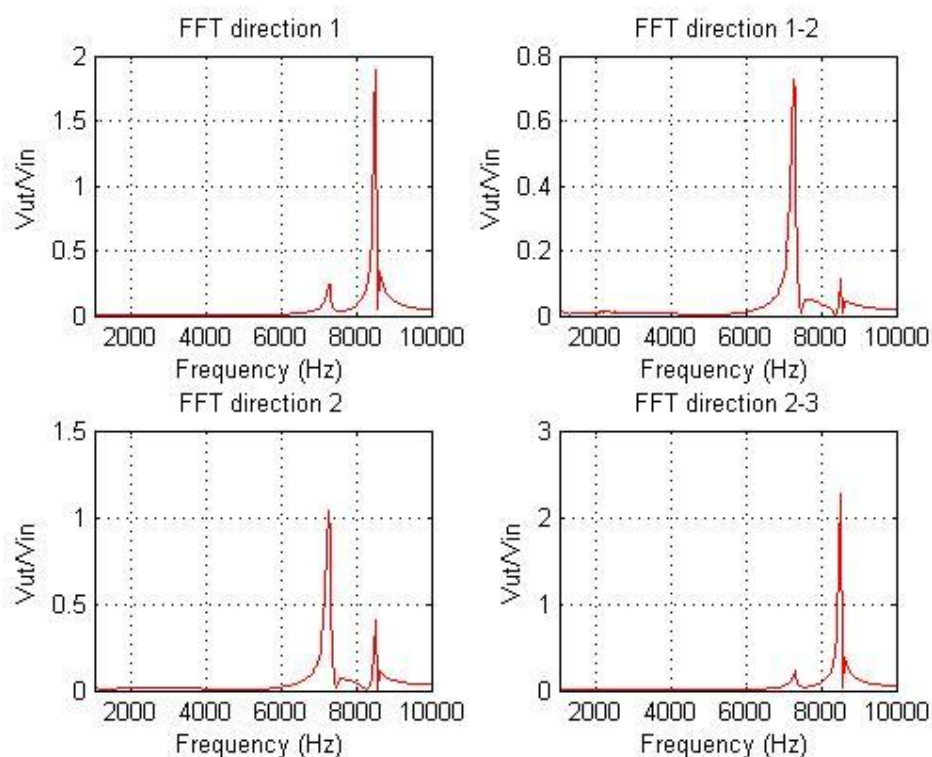


Figure 124. The lowest frequency peak is at 7244Hz and the high peak is at 8511Hz.

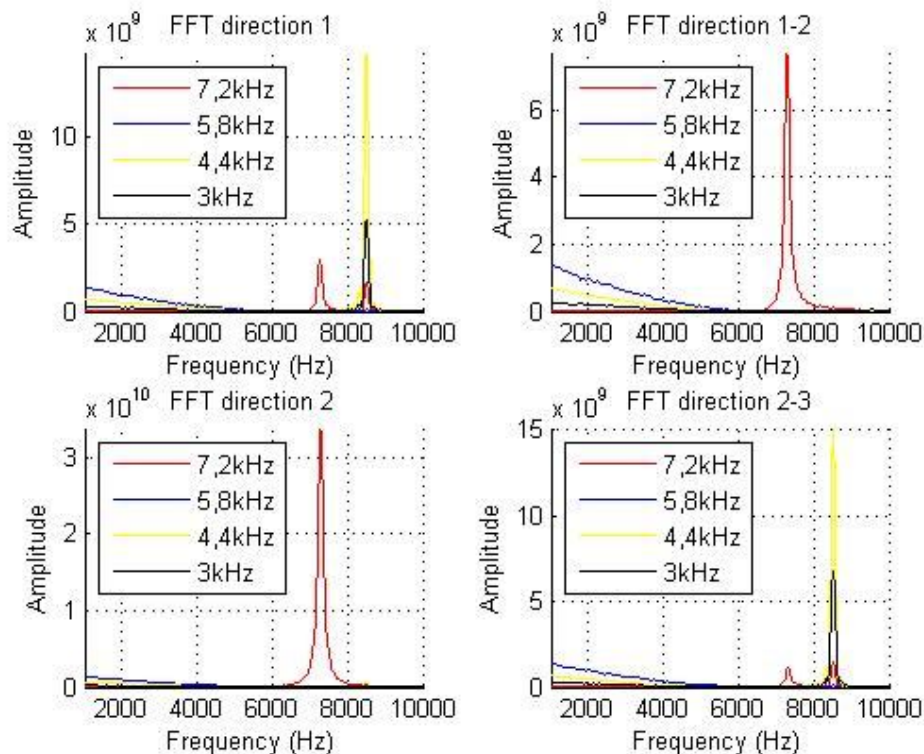


Figure 125. ISQ1=88, ISQ2=80, ISQ3=80, ISQ1=80.

Appendix 10.12: Wear on Threads, Error 5 Repeated

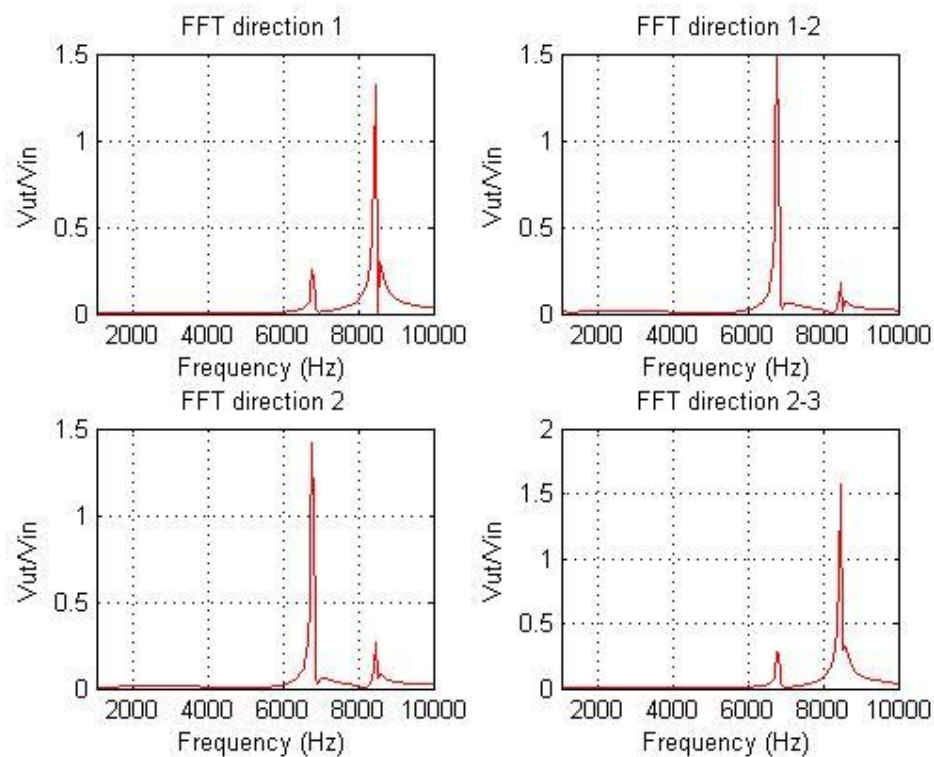


Figure 126. The lowest frequency peak is at 6761Hz and the high peak is at 8463Hz.

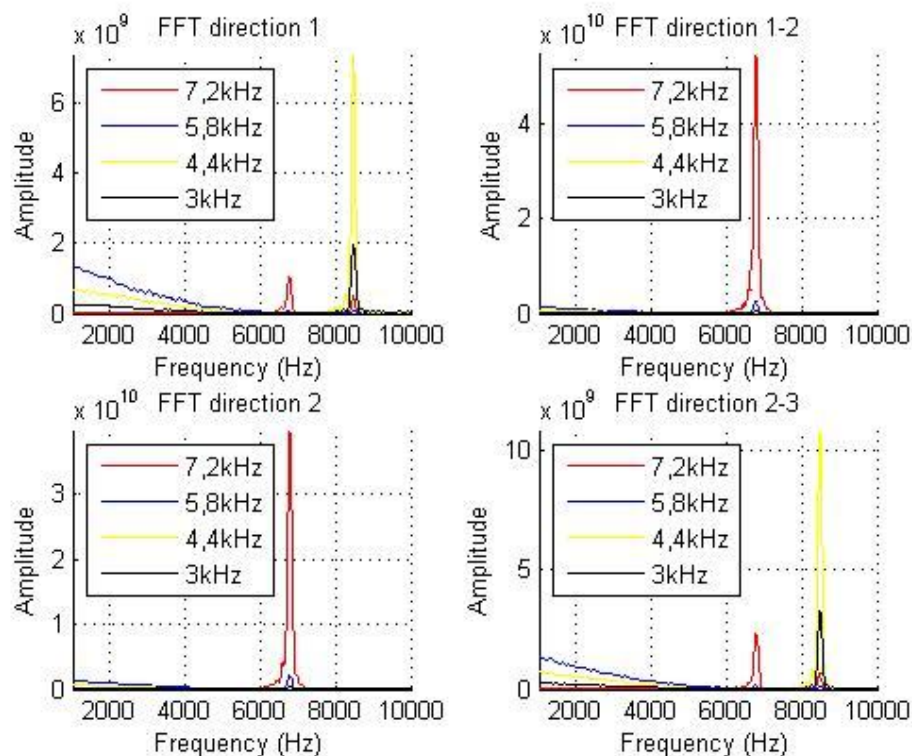


Figure 127. ISQ1=76, ISQ2=76, ISQ3=76, ISQ4=76.

Appendix 11.1: Disturbance: 1 kHz, 3 Volt

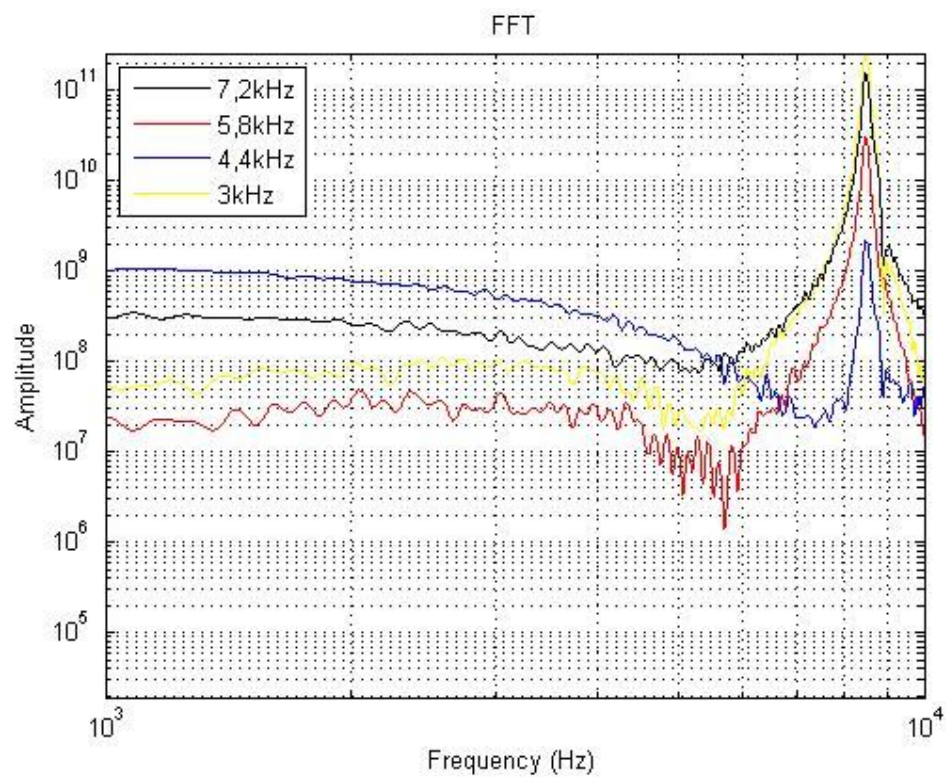


Figure 128. Disturbance at 1 kHz.

Appendix 11.2: Disturbance: 2 kHz, 3 Volt

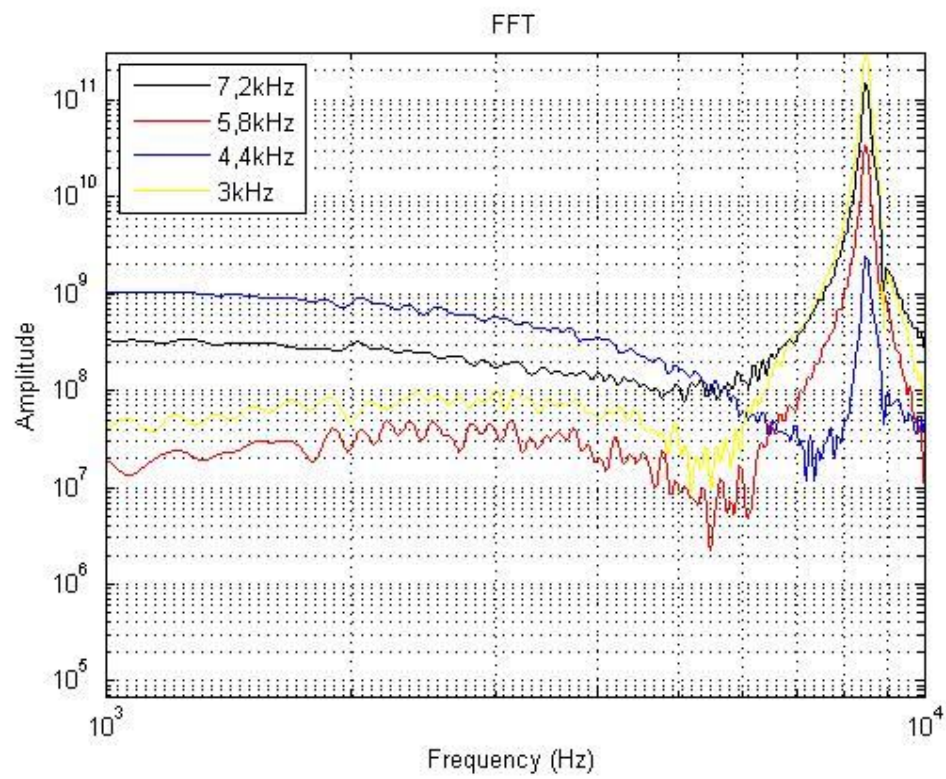


Figure 129. Disturbance at 2 kHz.

Appendix 11.3: Disturbance: 3 kHz, 3 Volt

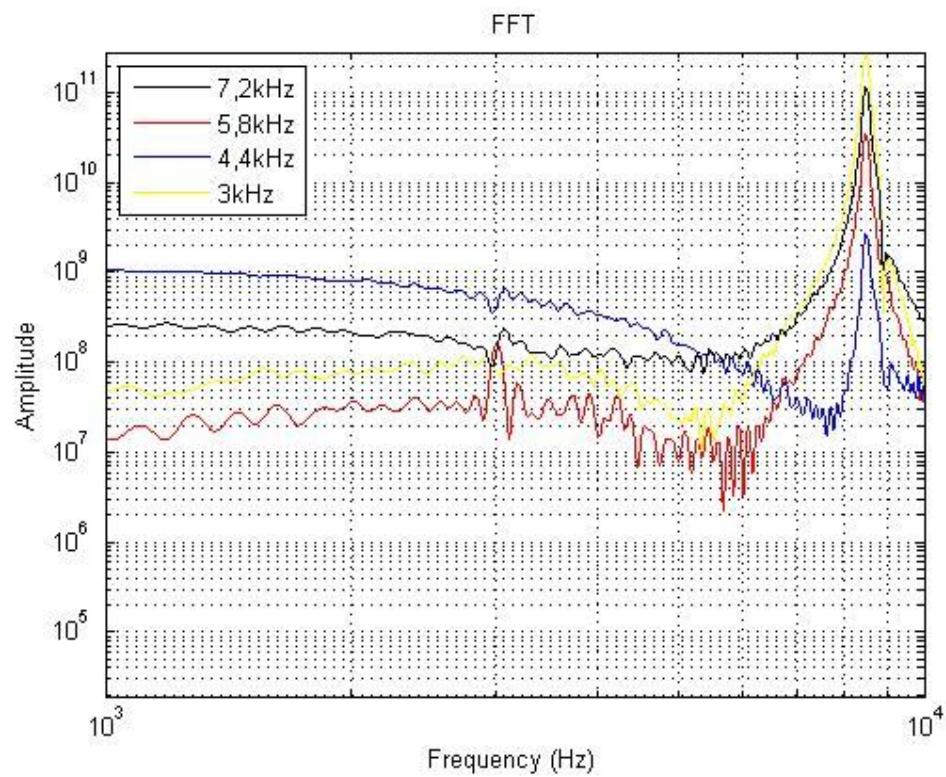


Figure 130. Disturbance at 3 kHz.

Appendix 11.4: Disturbance: 4 kHz, 2 Volt

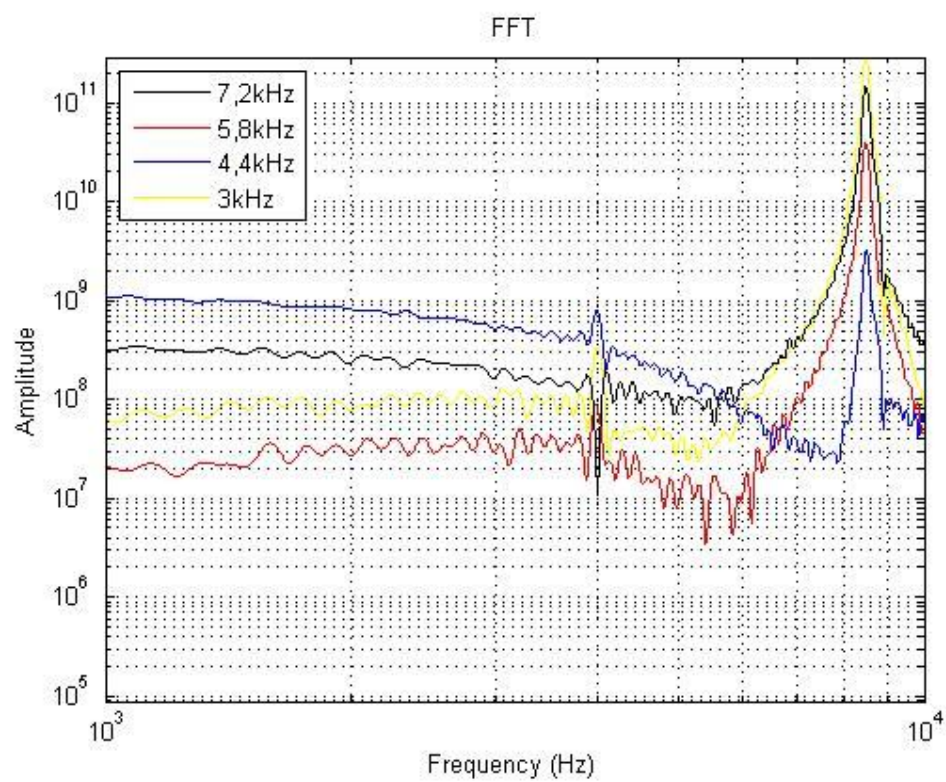


Figure 131. Disturbance at 4 kHz.

Appendix 11.5: Disturbance: 5 kHz, 1.5 Volt

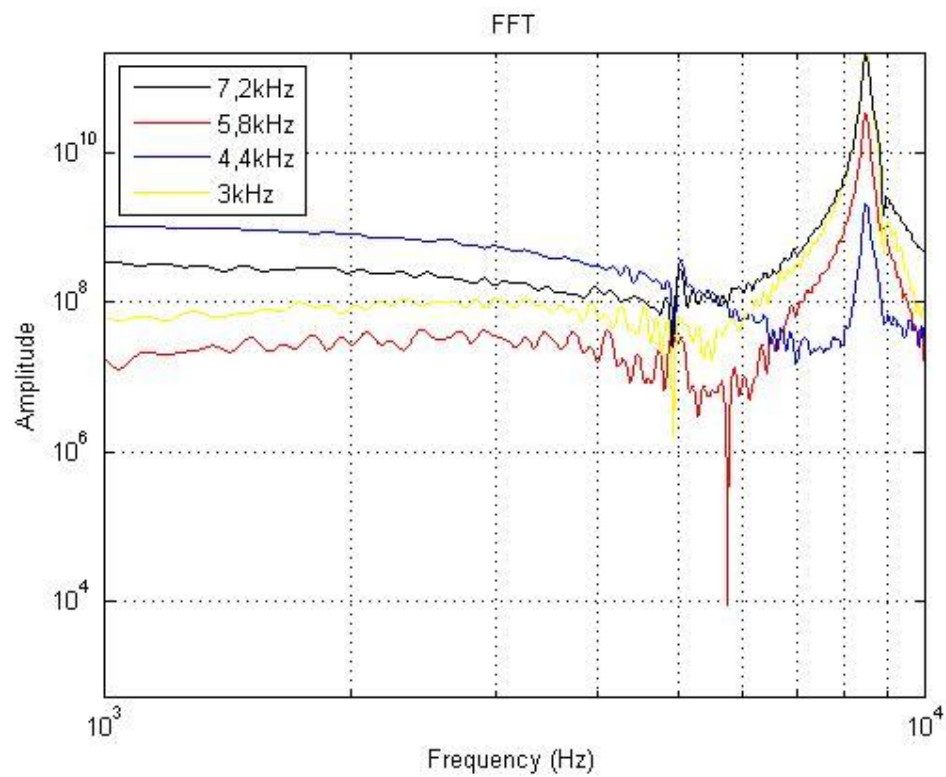


Figure 132. Disturbance at 5 kHz.

Appendix 11.6: Disturbance: 6 kHz, 0.9 Volt

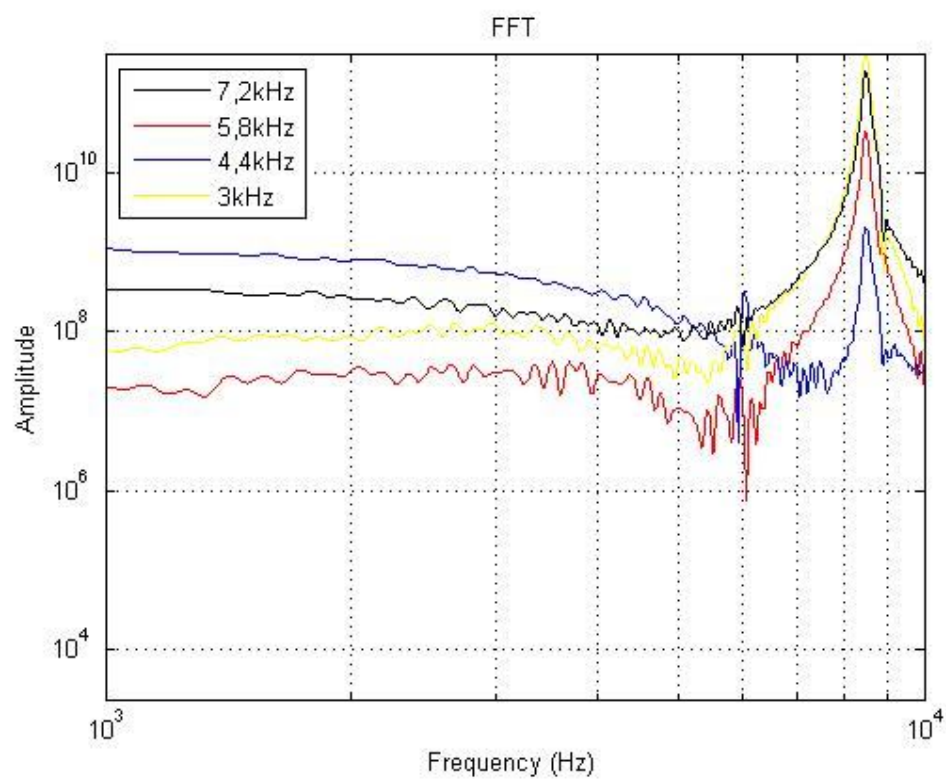


Figure 133. Disturbance at 6 kHz.

Appendix 11.7: Disturbance: 7 kHz, 0.7 Volt

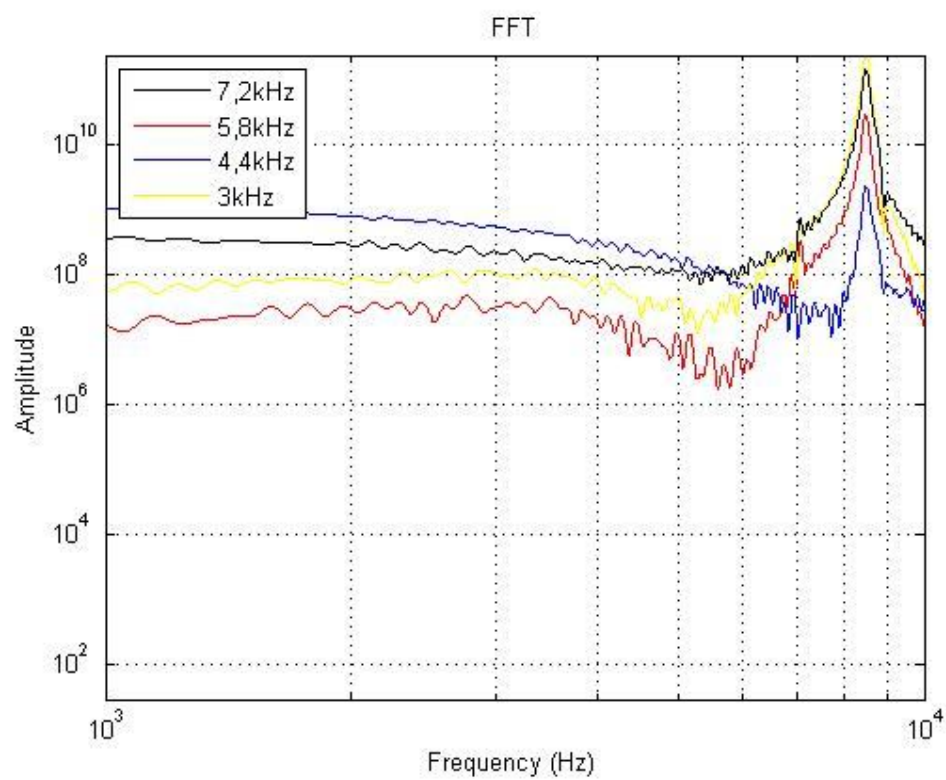


Figure 134. Disturbance at 7 kHz.

Appendix 11.8: Disturbance: 8 kHz, 0.5 Volt

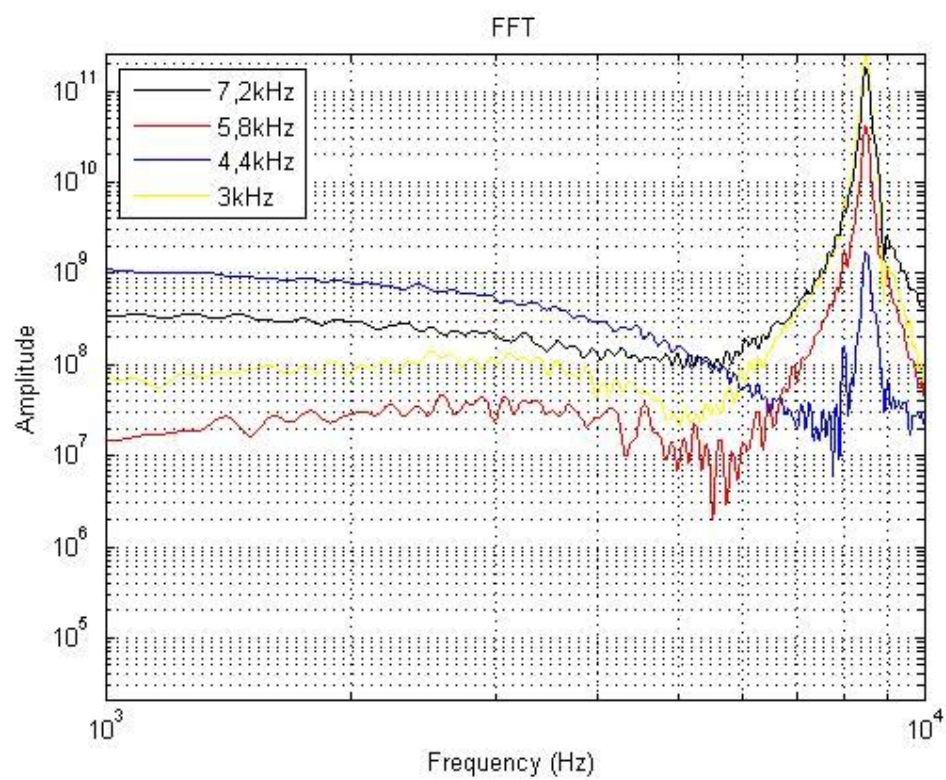


Figure 135. Disturbance at 8 kHz.

Appendix 11.9: Disturbance: 9 kHz, 0.4 Volt

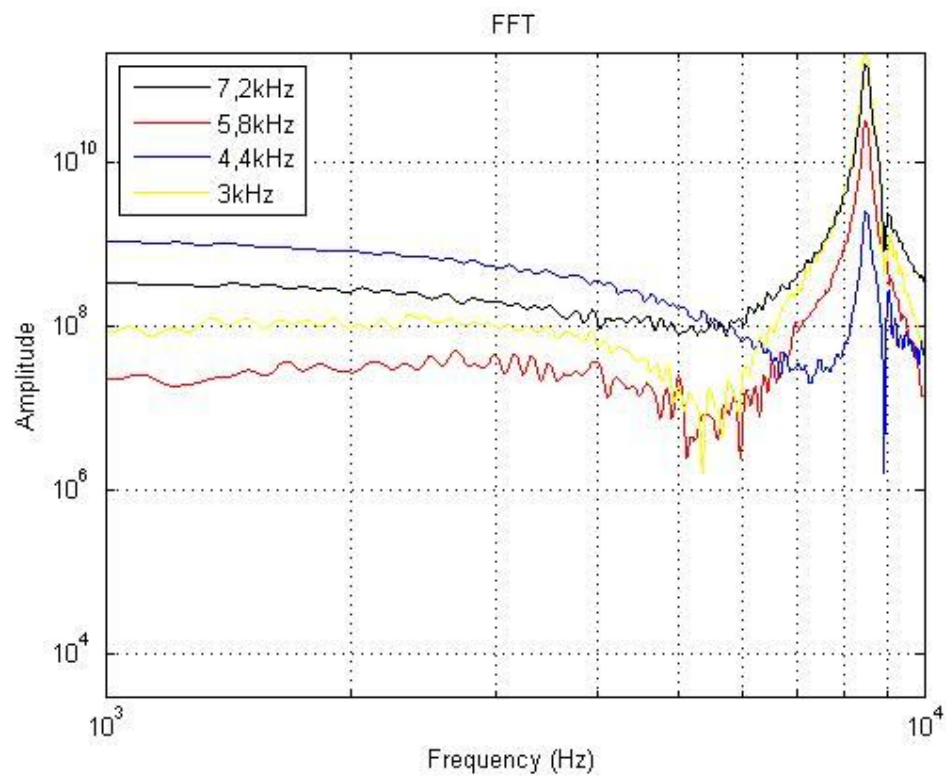


Figure 136. Disturbance at 9 kHz.

Appendix 11.10: Disturbance: 10 kHz, 0.3 Volt

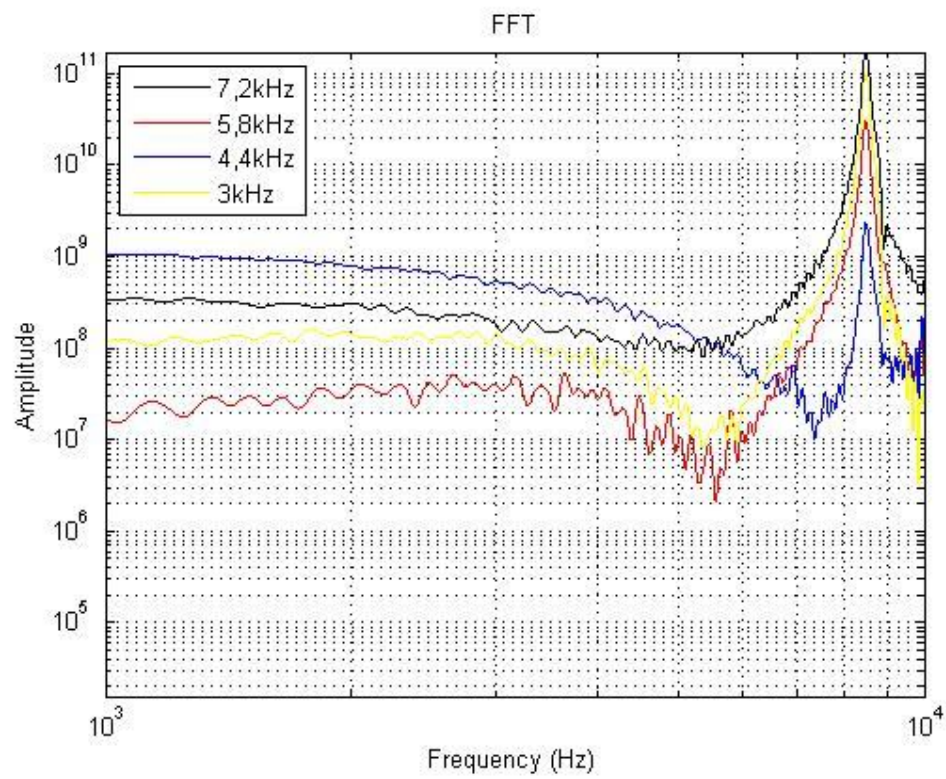


Figure 137. Disturbance at 10 kHz.