WTG Monopile Foundation Motion Analysis

OWPB Grid Group: Lightweight Substations

01/02/16

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Contents

References

(1)	BHATTACHARYA, SUBHAMOY. Challenges in Design of Foundations for Offshore Wind Turbines. The Institute of Engineering and Technology, Engineering & Technology Reference. ISSN 2056-4007. 2014
(2)	BRITISH STANDARDS INSTITUTE. Wind Turbines, Part 3: Design requirements for offshore wind turbines. BSI Standards Publication. BS EN 61400-3:2009.
(3)	DET NROSKE VERITAS AS. Design of Offshore Wind Turbine Structures. Offshore Standards. DNV GL AS. DNV-OS-J101. May 2014.
(4)	OFFSHORE WIND PROGRAMME BOARD. Lightweight Offshore Substation Designs. January 2016. Available at www.thecrownestate.co.uk
(5)	SIEMENS. Wind Turbine SWT-6.0-154. Technical Specification. February 2016. Available at www.energy.siemens.com

1 Background

The OWPB Grid Group has identified as a key priority the introduction of smaller offshore substations that can be installed by wind turbine installation vessels, have less auxiliary equipment and (ideally) can share foundations with a wind turbine, termed by the Grid Group as ‘lightweight substations’. This has the potential to lower costs by circa £1.7/MWhr[1].

A number of questions have been raised by the OWPB grid group in relation to the lightweight substation concept. One key point is whether or not the substation equipment (transformer in particular) is capable of withstanding and operating in the accelerations and movements that they would be exposed to when placed on a structure with a wind turbine generator (WTG).

Foundations and substructures for offshore WTGs are subject to environmental (wave and wind) dynamic loading as well as loads from the turbine. These loads can cause movement of the entire structure including the area(s) proposed for the installation of substation equipment on the turbine. The concern is that the magnitude and / or cycles of motion are larger than for a conventional offshore substation and may be higher than can be tolerated by electrical equipment.

1.1 Structural Dynamics

The dynamic response characteristics of a monopile foundation and substructure for an offshore WTG is based upon many variables including those highlighted in Figure 1. A simplified representation of the mechanical system and displacement / stiffness influences is also illustrated in Figure 1.

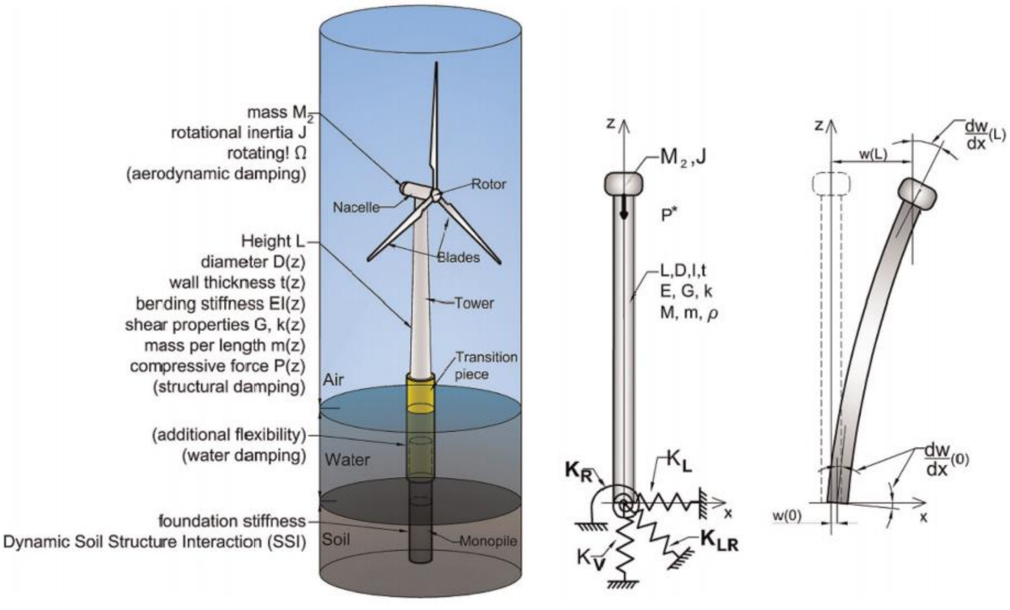


Figure 1: Simplified mechanical model of an offshore WTG monopile foundation (1)

In such a model the dynamic response of the system can be represented by basic engineering principles of spring stiffness and bending theory for the pile soil interaction and the structure

[1] Cost reduction value referenced from OWPB report (4) and is based on 2015 values.

stiffness respectively. A large number of factors can affect the dynamic response of the structure, these include (although are not limited to):

- Turbine / Rotor:
  - Mass
  - Rotational Inertia / Aerodynamic Dynamic
- Tower / Transition Piece / Monopile:
  - Height / Length / Diameter / Thickness
    - Bending / Compression / Shear stiffness
  - Mass
  - Compression / Structural Damping
- Foundation:
  - Soil Structure Interaction (Foundation stiffness)

It is assumed for this study that the list of variables above remain constant between the base case (WTG on Monopile) and the lightweight substation with shared foundation concept (WTG and substation equipment sharing a Monopile).

Assuming that the foundation and substructure design is not modified for the substation and WTG shared foundation concept (i.e. using the existing WTG foundation design) the addition of substation equipment on to the structure will in reality influence the dynamic response of the system (foundation, substructure, tower and WTG) primarily through the addition of mass. A number of variables will be affected including the additional mass, additional compressive force on foundation (structural damping), increased cross sectional area (aerodynamic loading / damping). Additionally any modifications to the substructure to accommodate the substation may also influence the bending and shear stiffness of the structure and again alter the dynamic response of the system.

Feedback from the OWPB Grid Group, section 7.4 of report (4), is that analysis has already been carried out to assess the impact on the change to dynamic response of the structure due to the additional mass of the substation equipment. It was concluded that the impact is small. It is therefore assumed in this report that the effect is negligible at this stage for the purpose of a high level analysis and shall be disregarded. Within this study the dynamic response of the WTG monopile foundation and substructure with and without the substation equipment is assumed to be equal. For future detailed studies this assumption should be re-visited and assessed.

2 Objective

The objective of the analysis documented within this report is to carry out a high level review comparing 1) the typical movements and accelerations that have been measured on an operational offshore monopile WTG support structure against 2) the acceptable tolerances on movement for transformer equipment.

A number of partners within the OWPB Grid Group have volunteered to provide data necessary for the analysis. These include:

- DONG ENERGY – Offshore Monopile WTG Data Accelerations on Structure, WTG Operation Condition, Wind Data;
- Siemens – Transformer design parameters specified to foundation/sub-structure designers.

It should be noted that this analysis is a high level study only, it is not a detailed evaluation of the feasibility of locating substation equipment on the same foundation and sub-structure as the WTG.

The purpose of this study is to provide an overview of the typical accelerations experienced on an offshore WTG structure compared to the allowable limits for the substation equipment; in order to provide context for further discussion and recommendations for continued work.

3 Analysis

3.1 Process

The following process was used to perform the analysis:

1. Data extraction and conditioning: measured WTG data was extracted and conditioned accordingly to the correct format enabling the analysis to be carried out;
2. Data analysis and review: analysis carried out on the conditioned data to define the key operational parameters from the measurements (i.e. max/min/mean/RMS accelerations). Additionally a review of the accelerations in time and frequency domains was performed to further characterise the measured data;
3. Comparison of measured data with specified limits: summarised parameters from the data analysis were compared against the limits specified by substation equipment manufacturers to assess the suitability of existing equipment.

3.2 Data

3.2.1 Monopile Sub-Structure Accelerations

24 hours of accelerometer data from a 6MW WTG monopile sub-structure was supplied by DONG ENERGY to ORE Catapult. The data was measured during 17th February 2015 during which the WTG was in non-operating condition.

A detailed assessment (beyond the scope of this study) would be required to obtain the extreme accelerations experienced by the structure, however it is typical for the foundation and structure to experience long periods of large accelerations during turbine non-operating conditions. The primary reason for reduced accelerations during operation is that the rotational inertia of the blades and turbine provide additional damping to the dynamic response of the structure. When non-operational this damping is not present, therefore the magnitude of accelerations are generally increased.

The accelerations were supplied measured at a frequency of 10 Hz in the horizontal plane (x and y directions) were supplied from two locations, 10.7m LAT (at the base of the tower) and 98.5m LAT (at the Nacelle, approximately 6.6m below Nacelle CoG). Wind speed data was also provided from measurements taken at the Nacelle, a plot of the wind speed over the 24 hour period is shown in Figure 2 and summarised data is tabulated in Table 1.

Table 1: Wind Speed Data from Nacelle 17th February 2015

Maximum Wind Speed	12 m/s
Minimum Wind Speed	6.5 m/s
Mean Wind Speed	8.7 m/s

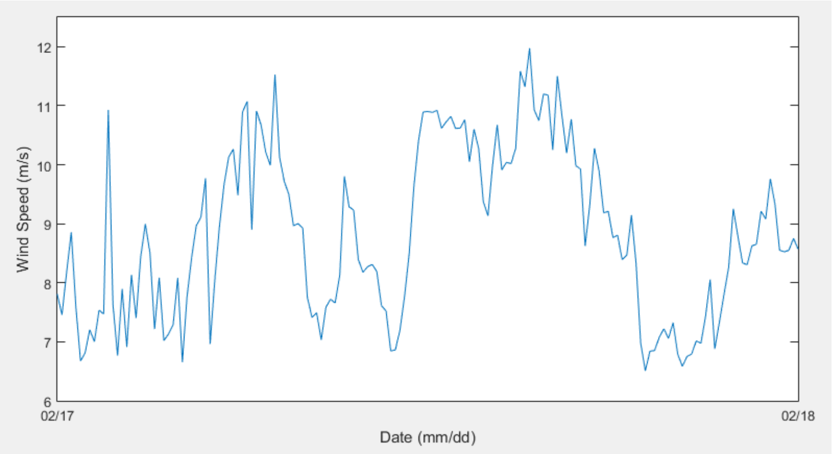


Figure 2: Wind Speed at Nacelle from 17th February 2015

With the limited wind conditions data it was not possible to provide an assessment of the conditions experienced compared to the expected conditions across its operational life.

However for indicative purposes only, offshore maximum wind speeds at 90m above MSL can are calculated using data from the Meteo Mast Ijmuiden in the Netherlands[2].

Table 2: Maximum Wind Speed during 2014 at Meteo Mast Ijmuiden

Maximum Wind Speed (Absolute)	35m/s
Maximum Wind Speed (10 Minute Average)	17m/s

The received accelerometer data was conditioned to enable the analysis to be carried out. It was noticed that the original accelerometer data was oscillating about a non-zero value, thus it was assumed that the measurements were not zeroed. In some data sets, accelerations were entirely positive or negative in value, which is unfeasible as this would imply constant acceleration in one direction. The following actions were carried out to process the data:

- Mean acceleration calculated for each sensor and direction across the entire data set;
- Data zeroed by subtracting the respective mean value from each value in the data set;
- Time data zeroed and elapsed time in seconds from the start of the 24 hours calculated for each data point;
- Resultant accelerations of the X and Y accelerations were calculated for Sensor 1 and Sensor 2 positions for each time step.

Plots of the original and conditioned data are listed in the Appendix.

The time series of resultant accelerations from the processed data were then plotted for sensors 1 and 2 with measured wind speed at the nacelle, Figure 3 and Figure 4.

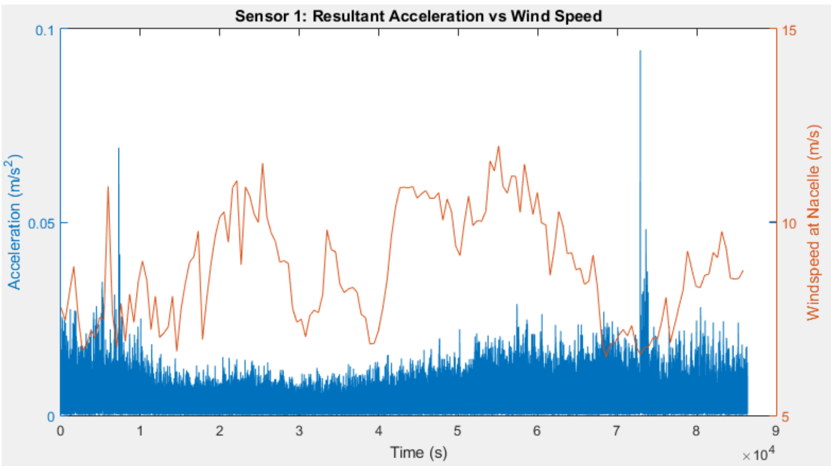


Figure 3: Sensor 1 – Base of Tower (10.7m LAT)

[2] Data from the Meteo Mast Ijmuiden is publicly available from www.windopzee.net. Maximum and Mean of Maximum recorded wind speeds at 90m above MSL were calculated using LiDAR data.

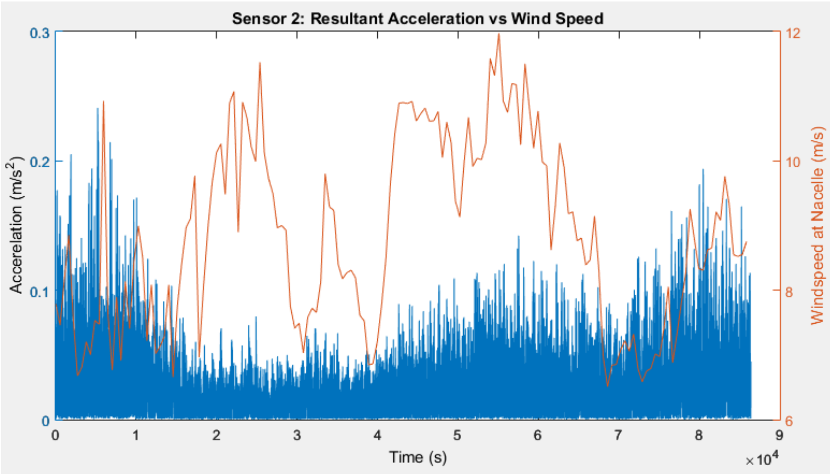


Figure 4: Sensor 2 – At Nacelle (98.5m LAT)

As expected the magnitude of accelerations from the base of the tower are lower than at the nacelle. Sensor 1 is at the base of the tower where horizontal displacement (and therefore accelerations) due to the dynamic motion are lower than at sensor 2 position at the nacelle, due to the increase in distance from the support (foundation). The data from the base of the tower and the nacelle can also be seen to be in phase, and additionally an approximate trend between wind speed and acceleration can also be noticed. This shows that the data is consistent and producing feasible results.

Statistical analysis was performed on the complete data set across the 24 hour period to obtain maximum, mean, standard deviation and RMS of the resultant accelerations from both sensors, the summarised results are tabulated in Table 3.

Table 3: Statistical Summary of Acceleration Data

Resultant Acceleration	Max (m/s^2)	Mean Magnitude (m/s^2)	Standard Deviation (m/s^2)	RMS (m/s^2)
Sensor 1	0.0945	0.0051	0.0034	0.0061
Sensor 2	0.2410	0.0306	0.0241	0.0390

Frequency analysis was performed on the acceleration data to determine the frequency of oscillations. Using MATLAB, Fast Fourier Transforms (FFT) were used across the entire 24 hour dataset for each sensor and direction to determine the oscillating frequency. Figure 5 shows a peak frequency of 0.2275 Hz for at the nacelle in x acceleration. This correlates approximately with the peak frequency at the base of the tower of 0.2267Hz, Figure 6.

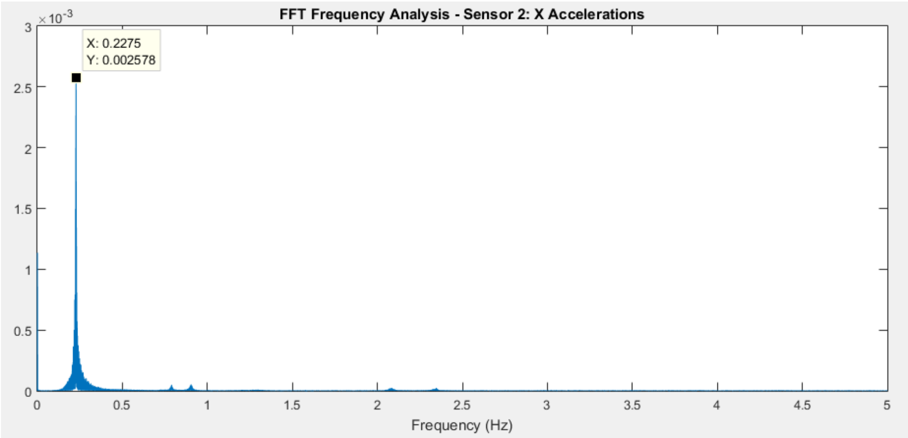


Figure 5: Frequency Analysis of Nacelle X Accelerations using FFT

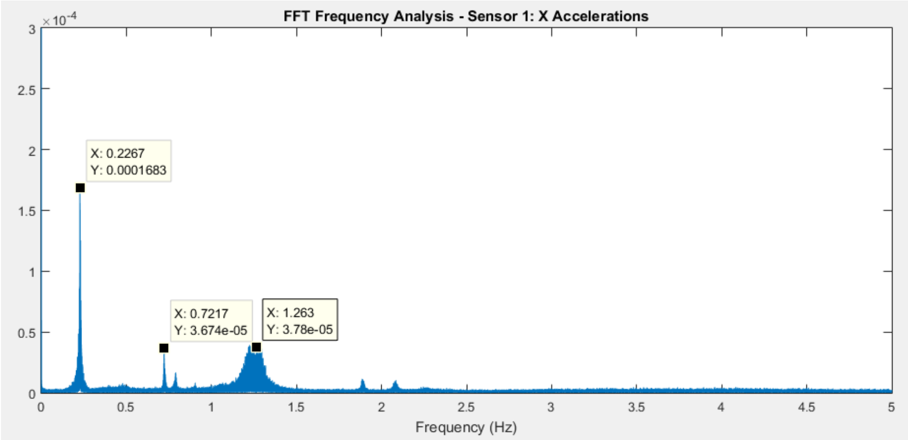


Figure 6: Frequency Analysis of base of tower X Accelerations using FFT

The peak frequencies of oscillation for X and Y directions on both sensors also correlate, a complete set of plots can be found in Appendix 3 . A summary of the peak oscillation frequencies from this analysis is shown in Table 4, where the average frequency is 0.2272 Hz.

Additional frequencies of accelerations are also highlighted in Figure 6 at 0.72 Hz and 1.26 Hz, however without detailed analysis and further data it is no possible to deduce the cause of these acceleration frequencies.

Table 4: Summary of Frequency Analysis

	Peak Oscillation Frequency (Hz)
Base of Tower: X Direction	0.2267
Base of Tower: Y Direction	0.2275
Nacelle: X Direction	0.2275
Nacelle: Y Direction	0.2271
Average	**0.2272**

The frequencies of oscillations calculated from the data provided is within the typical region expected for an offshore wind turbine. The stiffness design of the wind turbine foundation is commonly optimised such that the natural frequency of the structure is out with the operational frequencies[3]. For a Siemens SWT-6.0-154 turbine (5), an operational speed range of 5 to 11 rpm is specified, this corresponds to a 1P frequency range 0.083 to 0.183 Hz and a 3P frequency range of 0.25 to 0.55 Hz. Therefore an optimised structure should have a natural frequency between 0.183 and 0.25 Hz as to ensure the operational frequencies do not cause long term resonance. The value of 0.2272 Hz is approximately within the middle of this range.

3.2.2 OTM Equipment Limit Accelerations

Data was provided from Siemens on the maximum accelerations which their transformer equipment should be able to tolerate. These figures are as specified from Siemens to the foundation designer, and were shared with ORE Catapult.

Table 5: Siemens Substation Equipment Specification

Parameter	Limits
Horizontal Displacement	< 0.7 m
Horizontal Acceleration	< 0.49 m/s^2
RMS Horizontal Acceleration	< 0.145 m/s^2
Frequency of Movements	0.25 Hz +/- 10%

The provided data enabled a high level comparison to be performed, however for a detailed analysis further information will be required to fully define the limits of the equipment, such as limit accelerations and frequencies for different conditions (i.e. operational, non-operational, Ultimate Limit State, Fatigue Limit State etc.).

No data was provided relating the limit values against acceptable exposure times. Such data would be expected to fully characterise the fatigue life performance of the substation equipment and should be used in future detailed analysis to assess the feasibility of the foundation motion.

4 Conclusions

The data provided to ORE Catapult by DONG ENERGY and Siemens enabled a high level comparison of the design limits for substation equipment and the typical accelerations

[3] For a typical 3 bladed wind turbine the operating frequencies are primarily 1P (rotational frequency of the turbine/rotor) and 3P (the blade passing frequency)

measured on a 6MW WTG monopile sub-structure in stationary condition under mean wind speed (at nacelle) of 8.7m/s.

From the limited data set it can be shown that the levels of accelerations experienced for this case is within the specified substation equipment limits, as shown in Table 6.

The findings of this study provides evidence to support the feasibility of a shared foundation concept for a WTG and substation equipment thus increasing the confidence of such a concept. The data shows that typically experienced accelerations at the base of the tower on a monopile WTG structure, as supplied by DONG ENERGY, are within the tolerable limits of the substation equipment as specified by Siemens.

Table 6: Comparison summary of Substation Equipment limits and measured data

Parameter	Substation Equipment Limits	WTG Non-Operational Scenario at Base of Tower	Status
Horizontal Acceleration	< 0.49 m/s^2	0.0945 m/s^2	✓
RMS Horizontal Acceleration	< 0.145 m/s^2	0.006 m/s^2	✓
Frequency of Movements	0.25 Hz +/- 10%	0.2272 Hz	✓

This analysis however only performs assessment for a single scenario of the WTG structure (WTG non-operational) and therefore a conclusion on the overall feasibility of a shared foundation concept cannot be made at this point. A detailed feasibility study would be required to provide such evidence, and should include a life-cycle assessment of expected dynamic responses for the structure and be compared against detailed specification criteria for acceptable conditions of the substation equipment.

5 Recommendations

Following the high level analysis carried out by ORE Catapult, a number of recommendations can be made for future work on the feasibility assessment of a shared WTG and Substation monopile foundation concept.

5.1 Assessment of typical accelerations across the life of the structure

Due to the limited data set supplied to ORE Catapult, within this study only the accelerations on the structure during a period of 24 hours with the turbine stationary (non-operational) in a moderate wind was assessed. It is estimated that this provides a good assessment of reasonable magnitudes of acceleration – moderate accelerations over a 24hr duration where no dynamic damping from the rotating blades or turbine. However high magnitude short duration accelerations or low magnitude long duration accelerations may occur during extreme storm or normal turbine operational states respectively and should not be neglected.

It is recommended that further detailed assessment of load cases in accordance to industry standards such as (2), BS EN 61400-3, and (3), DNV-OS-J101, be considered and acceleration data for these load cases be obtained for detailed assessment against the allowable limits for the OTM equipment. For example, the load cases for structural design of wind turbine structure in accordance to BS EN 61400-3 include the following design situations:

- Power Production
- Power Production plus occurrence of fault
- Start up
- Normal shut down
- Emergency shut down
- Parked (standstill and/or idling)
- Parked and fault conditions
- Assembly, maintenance and repair

The study performed within this report only considers one of the many potential scenarios. Although this provides an indication of the typical levels of accelerations on the WTG structure, it has not assessed the accelerations to be expected across the life of the WTG.

5.2 Detailed definition of acceptable accelerations for OTM equipment

In order to fully assess the feasibility of the use of shared foundations for WTG and OTM, a detailed definition of the limit accelerations for the OTM equipment by the manufacturers must be provided.

The definition should include the design limit accelerations for the equipment for discrete high magnitude accelerations (such as that experienced during an emergency stop or Ultimate Limit State) through to the lower magnitude long term accelerations (for example those experienced during normal operation of the turbine or Fatigue Limit State) according to applicable design standards.

Due to the limited data available to ORE Catapult, only an approximate assessment of the feasibility for the equipment was possible in this study.

5.3 Analysis of Wind and Ocean Conditions

Only 24 hours of data were available for the purpose of this study. Wind data was also supplied for this period of data however it was not possible to quantify the wind conditions with respect to the conditions recorded or expected across the life of the asset.

Additionally no ocean condition data was available for this study, hence it is not possible to assess the effects (if any) that the ocean conditions had on the dynamics of the structure. However from experience it is expected that the wind conditions are the primary contribution towards the foundation oscillations (due to the increased moment arm and forces exerted from wind loads on the blades and tower in comparison to the wave and current loads on the foundation).

An analysis of the motion data coupled with the wind and ocean conditions is recommended for future studies as this can be used to characterise the level of accelerations with respect to environmental conditions. Further conclusions can then be made regarding the magnitude and duration of accelerations that the structure is likely to see across its life.

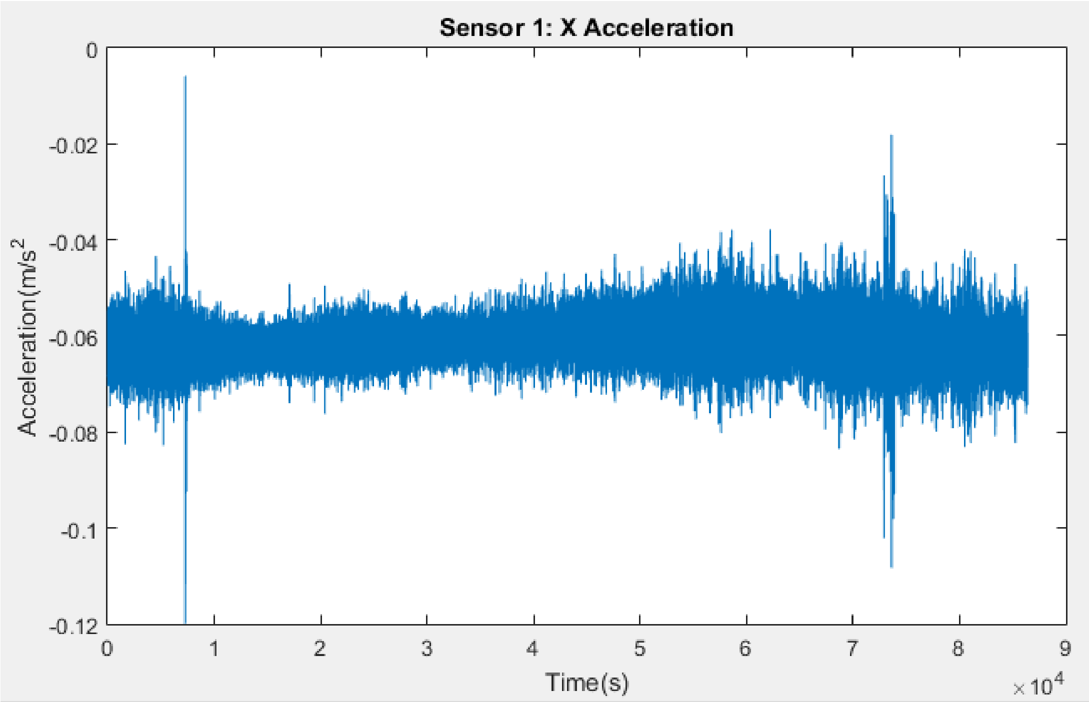
5.4 OWPB Grid Group Feedback

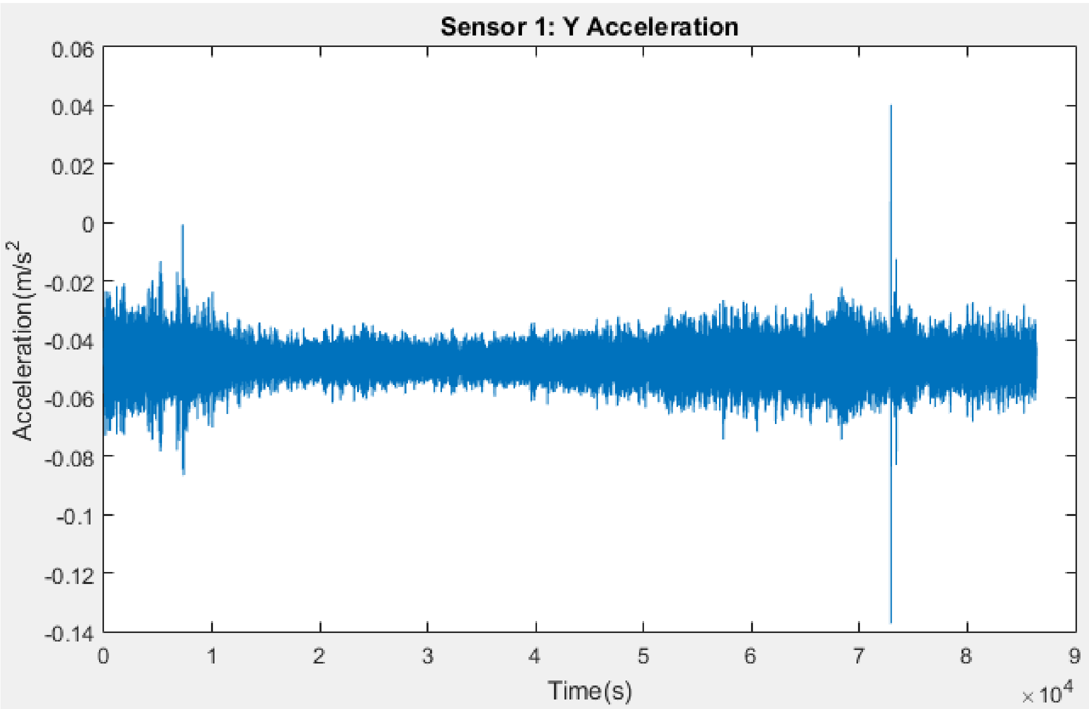
Following a review of the results from this study by the OWPB Grid Group, a number of comments were captured, however are outside the scope of this high level study. These are captured below and should be considered for future studies.

Feedback from OWPB GG	Response
"Why is the data limited to 24 hours? What is the reason that a longer period hasn't been examined?"	Only 24 hours of data was supplied for use within this study. Additional data was requested however due to resource constraints no further data was received or analysed. Recommendation 5.1 is made to address this.
"What can we say about the conditions on the day that the readings were taken: was it still / stormy / about average? I note that wind speed data is indicated, what about wave data?"	For a complete assessment further data from DONG would be required for analysis. This is not within the scope of this study. However indicative wind speeds at an alternative offshore location have been presented in this report. Recommendation 5.3 is made to address this.
"What is causing (smaller) accelerations at 1.2Hz at the tower base?"	A detailed analysis of the complete wind turbine and foundation would be required to evaluate the cause of each oscillation frequency. This is not within the scope of this study.
"Has Siemens indicated what period the 0.145m/s2 RMS acceleration is	This data was not available for this study. Recommendation 5.2 is made to address this.

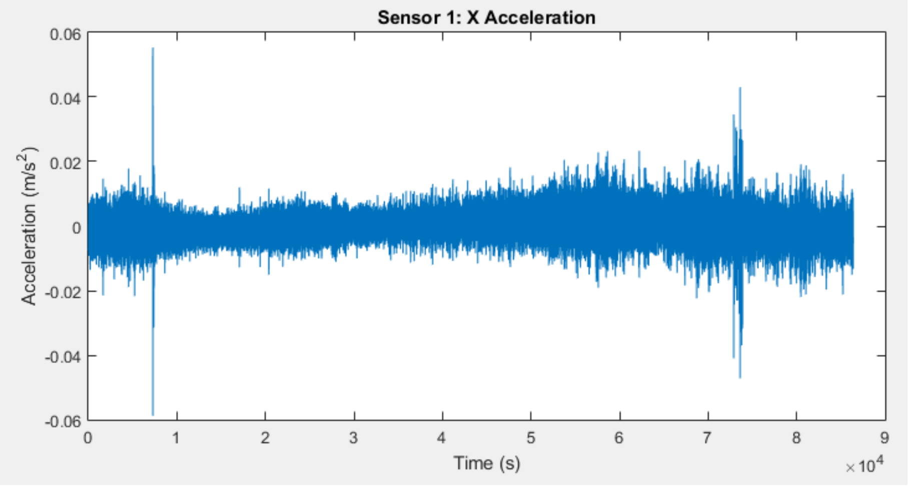
acceptable? Can it be applied every hour of every day for 40 years?"	
"Why there is such a margin between observed and allowed accelerations (1.5 orders of magnitude…). Perhaps storm conditions are more relevant?"	A conclusion cannot be made from the data analysed. Recommendations 5.1 and 5.2 are made to address this.
"Can data be obtained from Siemens regarding the transport accelerations limits for their transformers (transport limits are very high but for short periods of time only)."	This data would benefit this study however were not available. Recommendation 5.2 is made to address this.

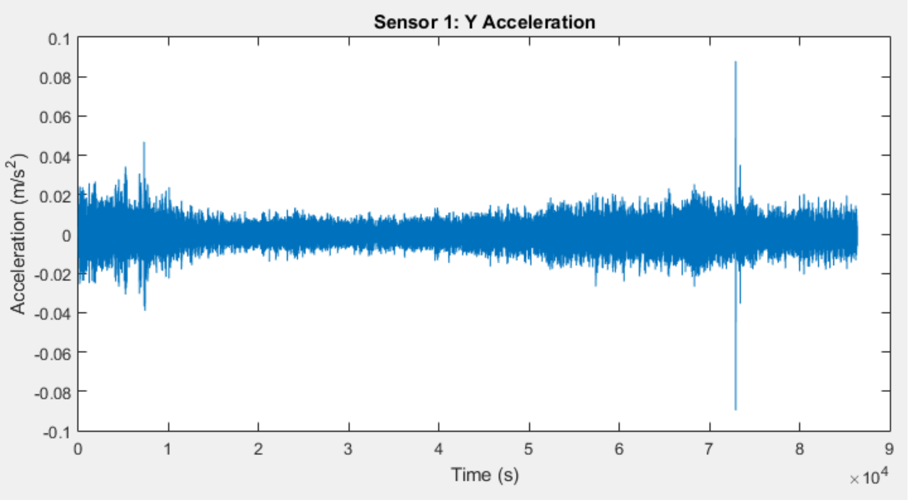
Appendix 1 DONG ENERGY Data Plots (Original)

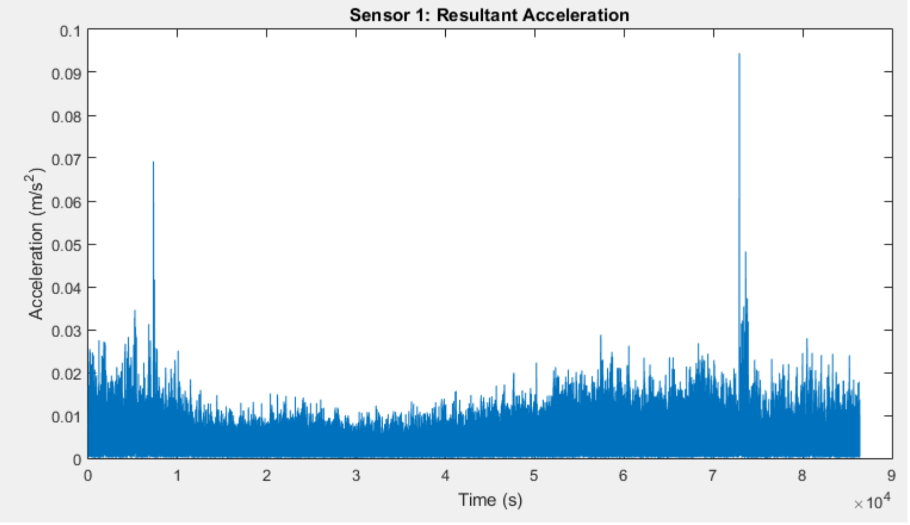


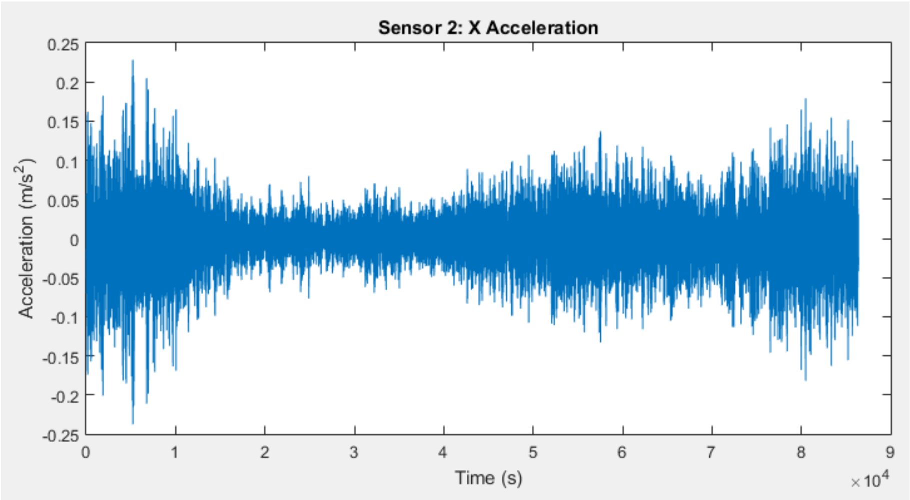


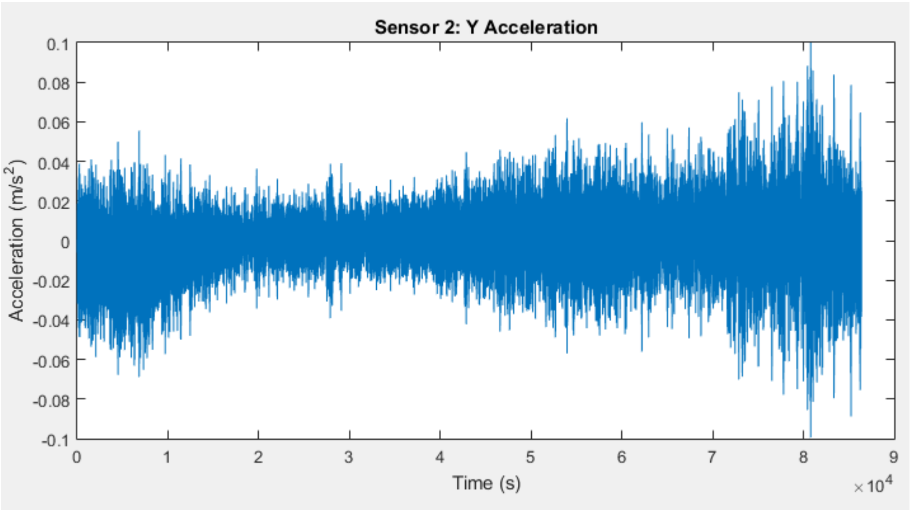
Appendix 2 DONG ENERGY Data Plots (Conditioned)

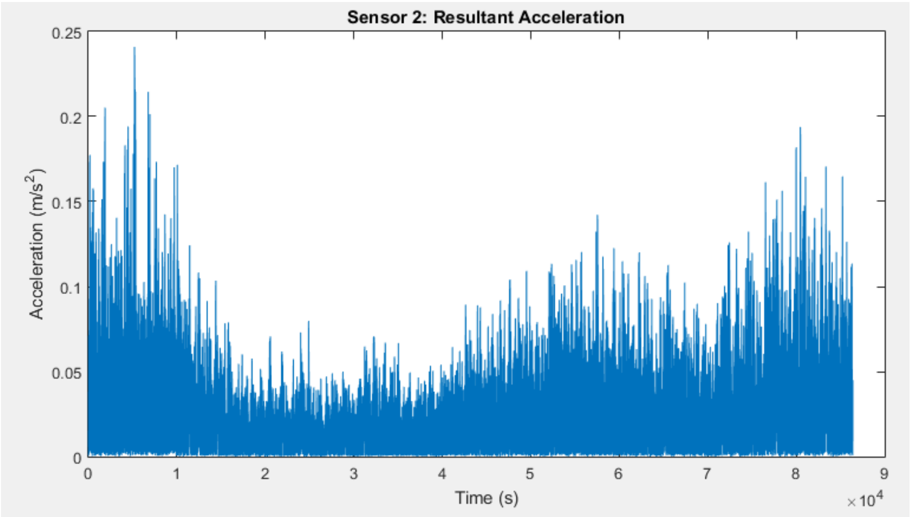




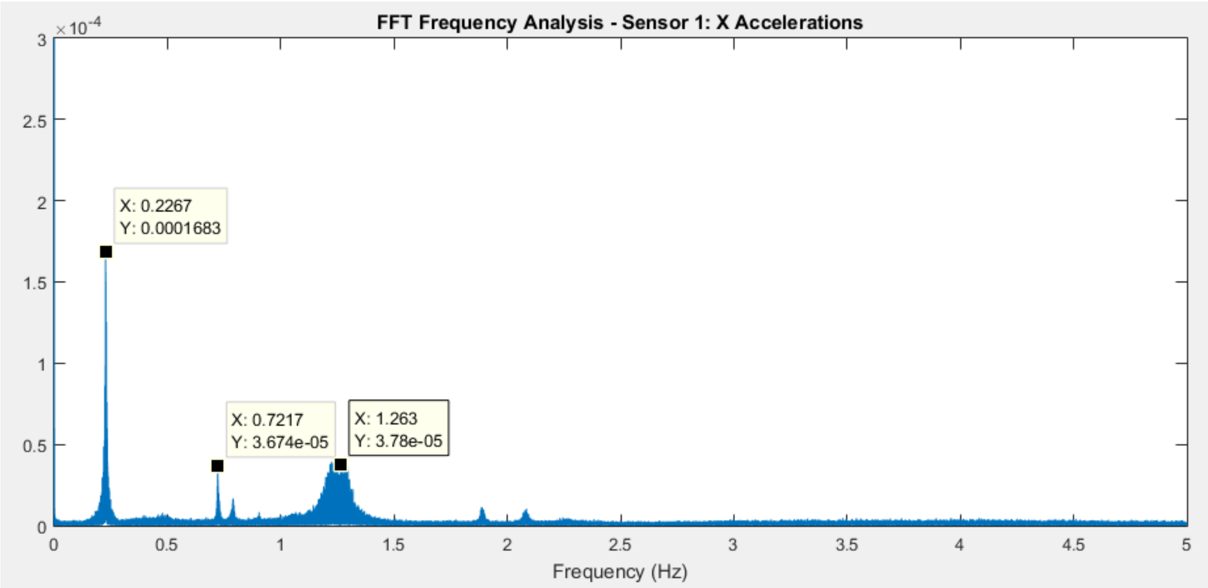


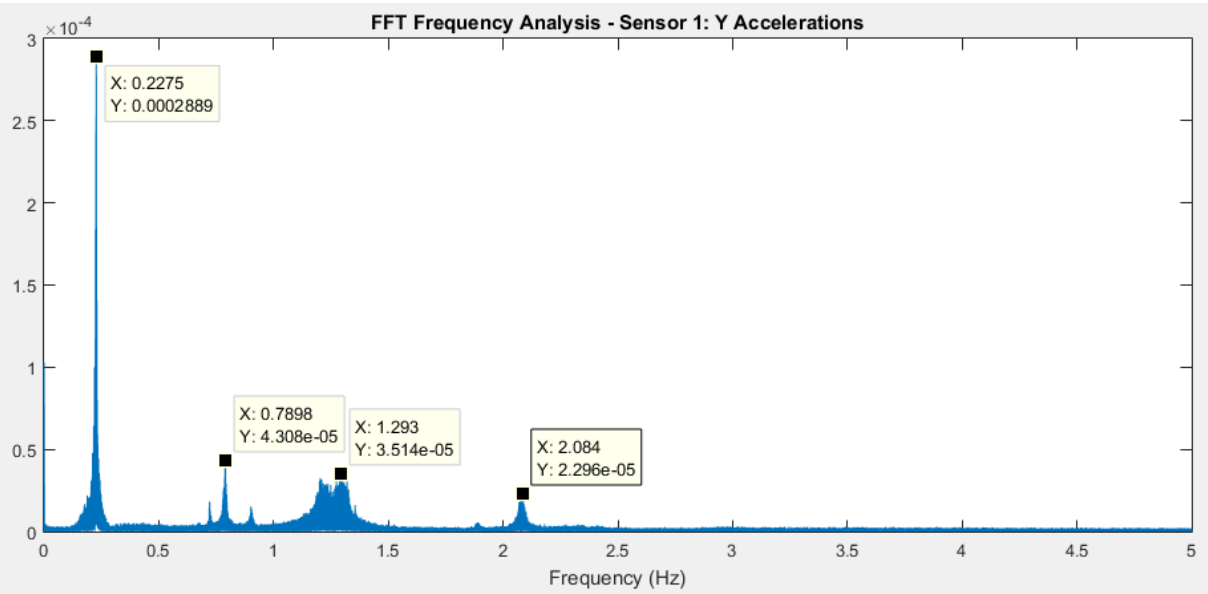

Sensor 2: X Acceleration
Acceleration (m/s²)
Time (s)
×10⁴

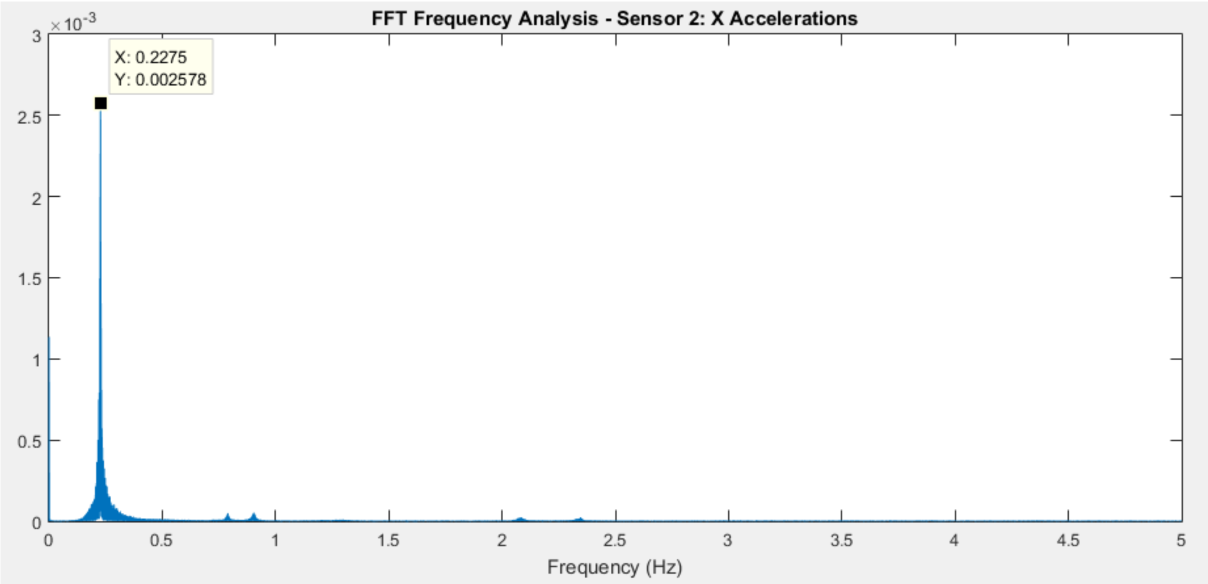

Sensor 2: Y Acceleration
Acceleration (m/s²)
Time (s)
×10⁴


Sensor 2: Resultant Acceleration
Acceleration (m/s²)
Time (s)
×10⁴

Appendix 3 Frequency Analysis



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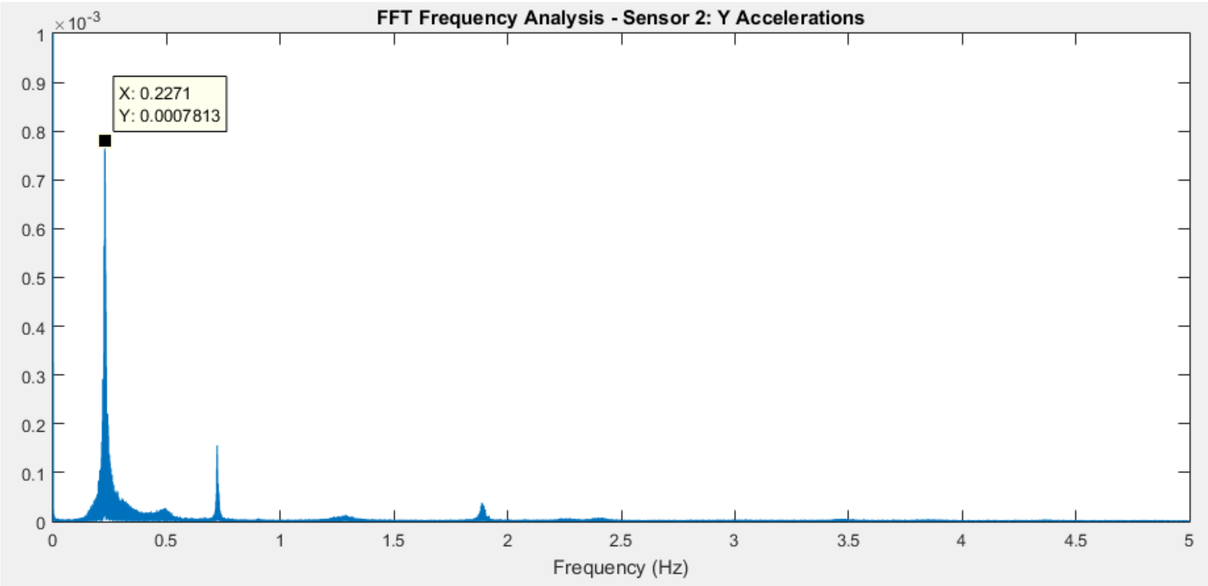
Y: 0.002578
Frequency (Hz)


FFT Frequency Analysis - Sensor 2: Y Accelerations
×10^-3
X: 0.2271
Y: 0.0007813
Frequency (Hz)

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