MSc Advanced Manufacturing Technology & System Management (AMT)

Group Project by Group number 4

Experimental method

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Contents

List of Figures

List of Tables

1. Introduction and Background

Machining process is one of the required procedures of a manufacturing process. Machining operation can be described as a material cutting process under several desired conditions (Yusoff et al., 2011). As it is mentioned, machining operation involves some conditions, which are known as ‘Parameters’. There are various parameters such as the type or shape of tools, feed rate, cutting speed, cutting force, depth of cut and so on. Amongst several parameters, ‘Force’ is one of the most significant requirements of a machining process since force is directly related to tool wear, quality of surface, power consumptions, design accuracy and others. Therefore, optimisation of the machining processes could assure the quality of the products, reduction of tool wear, high productivity, and cost efficiency. To optimise the machining operations, experimental measurement needs to be carried out since some methods such as theoretical calculation or simulations would occur inaccuracies due to the complexity of tool configurations and machining conditions (Yaldız et al., 2007).

There are several studies to examine the cutting forces during machining processes. According to Wan et al., cutting forces can be measured by using dynamometer. The authors have mentioned that the structural dynamics could occur some errors on cutting forces’ data plots. Thus, they have applied some signal-processing techniques such as curve fitting, Fourier transform, Kalman filter and extra. As a result, the errors of the measured cutting forces were corrected (Wan et al., 2016). Moreover, Yaldiz et al. measured the cutting forces during machining operation by implementing experiments, using dynamometer and the cutting force data is acquired in voltage output through data acquisition device. Based on the given experimental description and literature reviews, we set-up the methodology which is given in Section 2.

As a part of optimising the machining operations, the cutting force data is collected by the experiment. The data is recorded at a sampling rate of 10 kHz and under 9 different conditions by using LabVIEW programme, national instruments my RIO 1900, 2-component Kistler 9271A dynamometer and 5001 charge amplifiers. After that, the recorded and post-processed data are presented in Section 3 and 4. The specific experimental methodology is depicted in Section 2, demonstrating applied spindle speeds and feed rates, scheme of LabVIEW and Matlab programming in detail, and experimental devices set-up.

2. Experimental Methodology

The core of the experiment is using dynamometer to measure torque and thrust force during drilling under different factors. The given experimental parameters are as follows in Table 1. By using these two factors and three levels of each factor, 9 combinations come out thus, there is 9 different thrust force and 9 different torque data at the end. In addition, the drill depth is 1.5 times of the given drill bit’s diameter.

Table 1 Experimental parameters

% Of recommended manufacturers guidelines	**70**		**100**		**130**	
Drill Type	Spindle speed (rpm)	Feed (mm/min)	Spindle speed (rpm)	Feed (mm/min)	Spindle speed (rpm)	Feed (mm/min)
Walter A3379XPL-8 Drill bit	1700	267	2450	380	3190	496

I. Device and Software

Besides wires and power supply, experimental devices are indicated in Table 2. All devices are provided by the University of Manchester.

Table 2 Experimental devices

Data acquisition system	Sensor System	Machining system
NI myRIO-1900	Two-component Kistler 9271A dynamometer	Haas VF-2SS CNC machining centre
	Two 5001 charge amplifiers	

Moreover, two software are used for the project which are LabVIEW and Matlab. LabVIEW is used to control NI myRIO-1900 and Matlab is used for post data processing.

II. Drilling process

Under aforementioned 9 experimental parameter combinations, nine holes are made on the specimen by the CNC machine's drilling process. The specimen of the experiment is a cubic metal part as can be seen in Figure 1 which indicates the specimen after the experiment has been carried out. The specimen has been mounted on the holder by the expert assistant of machining process. In addition, the order of drilling process can be seen in Figure 1. Applied spindle speeds and feed rates for each hole are presented as follows.

1) Feed rate (mm/min): 267
   Spindle speed (rpm): 1700
2) Feed rate (mm/min): 380
   Spindle speed (rpm): 1700
3) Feed rate (mm/min): 496
   Spindle speed (rpm): 1700
4) Feed rate (mm/min): 267
   Spindle speed (rpm): 2450
5) Feed rate (mm/min): 380
   Spindle speed (rpm): 2450
6) Feed rate (mm/min): 496
   Spindle speed (rpm): 2450
7) Feed rate (mm/min): 267
   Spindle speed (rpm): 3190
8) Feed rate (mm/min): 380
   Spindle speed (rpm): 3190
9) Feed rate (mm/min): 496
   Spindle speed (rpm): 3190

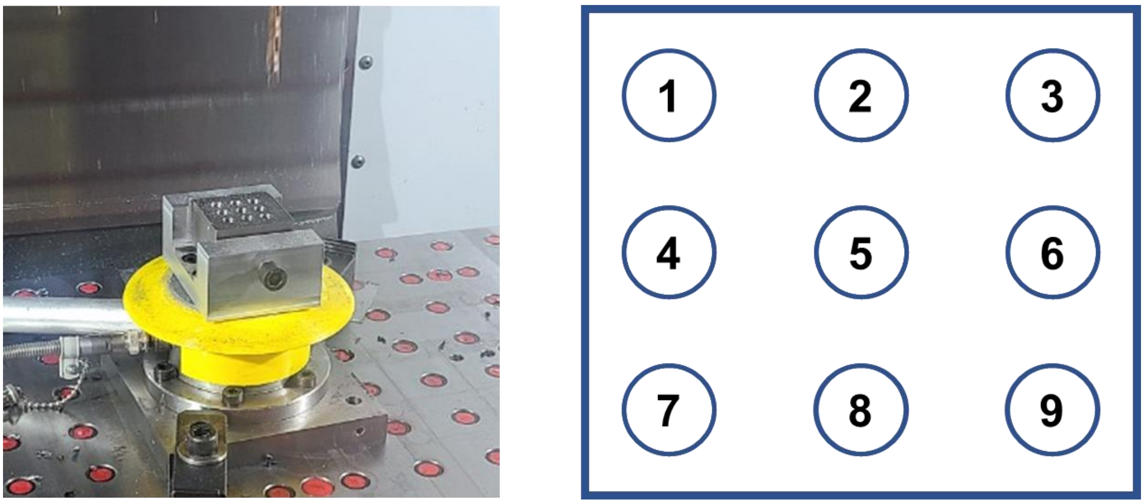


Figure 1 Specimen after experiment & Order of drilling process

III. Measuring mechanism

According to the datasheet of the dynamometer, when it is measuring thrust forces and torques, it releases a charge from each component to the amplifiers. After that, the amplifiers with maximum range of $\pm$10V convert the signals from the components of the dynamometer into output voltages. The amplifier is adjusted in such way that each 2N·M of torque would generate 1V output voltage and each 500N of thrust force would generate 1V output voltage.

Figure 2 Kistler Dynamometer 9271A

Figure 3 Kistler 5001 Amplifiers

IV. Installation of Devices

The wire connection is shown below in Figure 4. The torque voltage flow is connected into AI0 channel in C portal and the thrust voltage flow is connected into AI1 channel. Both AI0 and AI1 channels have positive and negative input channels for differential purposes. Ground wire is connected into both negative input channels.

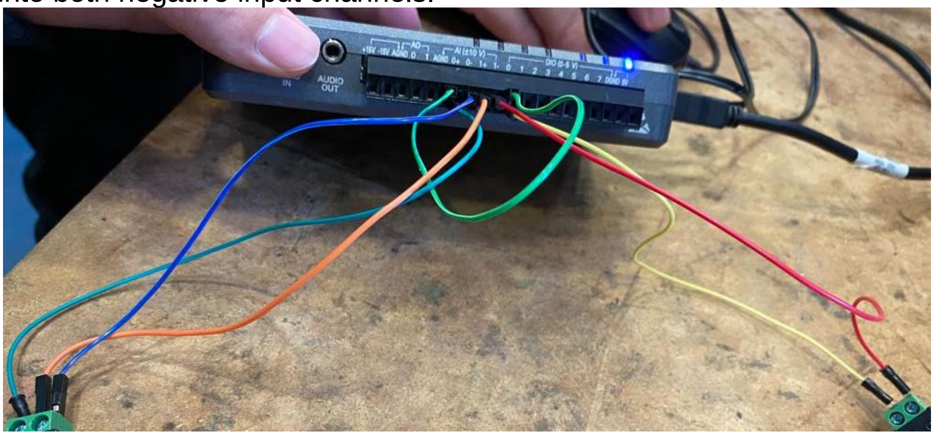


Figure 4 Wire connection on myRIO 1900

V. Overall Methodology

Figure 5 demonstrates the overall methodology in logical order. To begin with, the experiment is conducted by using CNC machine, under 9 different combinations of spindle speeds and feed rates. Then, dynamometer measures thrust forces and torques. At the same time, the three types of data such as thrust forces, torques, and time are acquired as an output in the form of voltage and saved through myRIO device which is programmed by using LabVIEW. The sampling rate is at 10kHz. The LabView programme is composed of one main programme and the FPGA. In the FPGA part, we set the frequency to 10kHz and read data from both AI0 and AI1 channel. We set a tick count to record the specific time when each group of data was recorded. The main programme will revoke the sub VI, separate the data from the buffer into three data flow, and write each dataflow into a TDMS file. In addition, the voltage output is converted to N and N·m according to the data sheets of amplifier and dynamometer, and set-up of the devices. After that, signal processing is implemented by using the software called Matlab. The programming processes and codes of LabVIEW and Matlab are described in Section 3 in detail. At the last, further analysis of each result is presented in this paper.

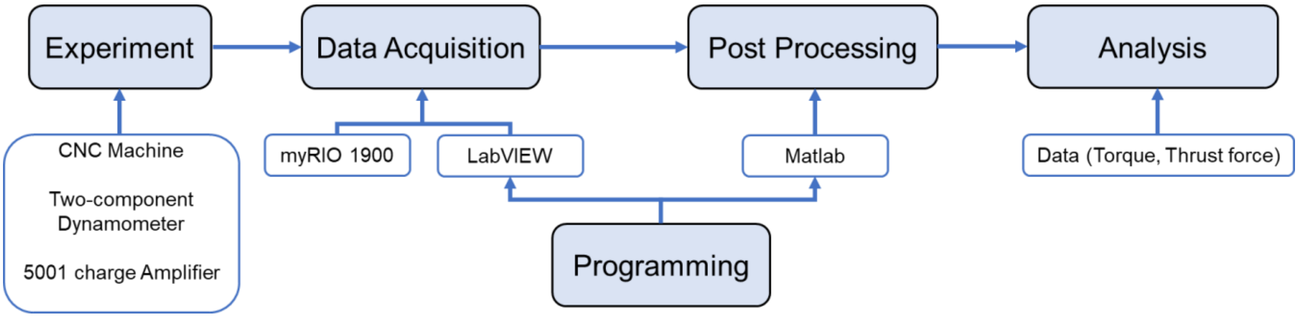


Figure 5 Methodology Schematic view

3. Experimental Results

The experiment lasted approximately 51.2 second in accordance with the time data and data was recorded at a sampling frequency of 10 kHz. During the experiment, the NI myRIO-1900 records a group of three data, which are thrust force, torque and the current time in the programme. As a result of the data acquisition, each dataset collects 512,032 samples and hence the total amount of data is 1,536,096. The original raw data is indicated in Figure 6. Since there are noises and outliers in both thrust force and torque data, post-processing is needed to extract the useful information. The signal processing is described in Section 4 in more detail.

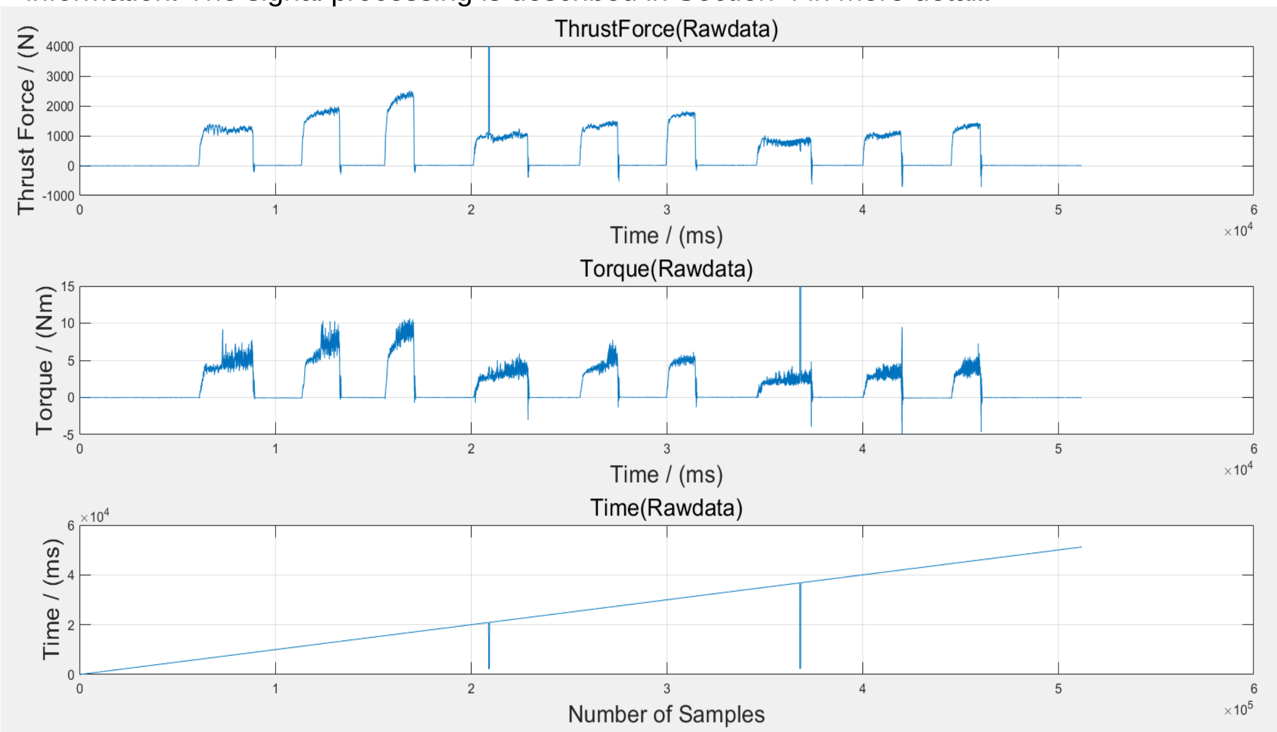


Figure 6 Overview of the Original raw data

4. Analysis of the data

The overall process of the signal processing is presented in schematic view in Figure 7. The process is for acquiring the desired output (Thrust force and Torque) and making the data more readable and informable.

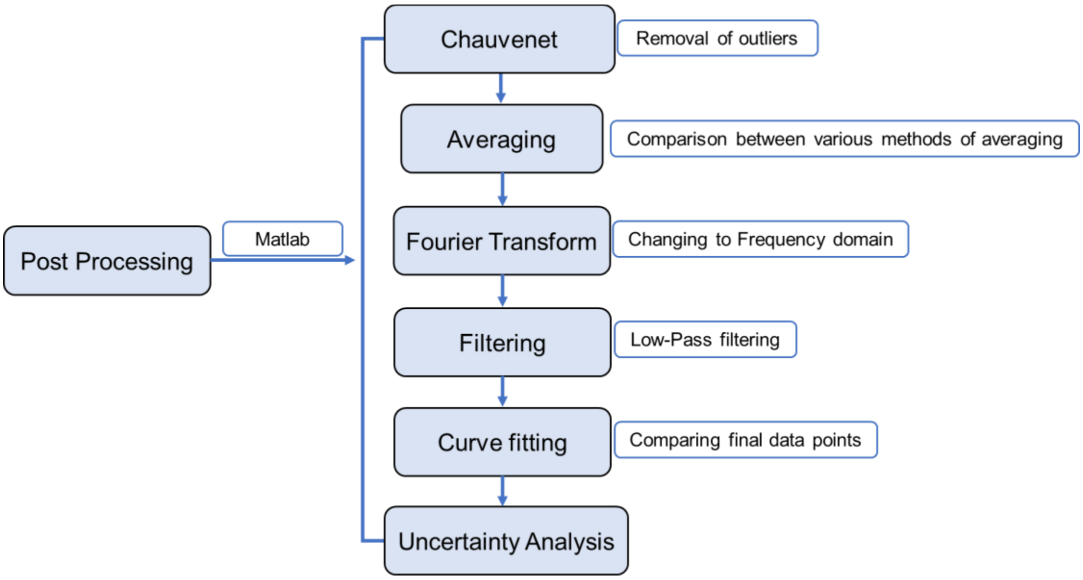


Figure 7 Schematic view of Post Processing

To begin with, Chauvenet's criterion is used for removing the outliers within the data. The data after the removal of outliers is presented in Figure 8. When it is compared with Figure 6, it can be said that the obvious outliers are removed from the data. After that, each torque and thrust force are separated by using Matab code. Therefore, 9 segments of data come out for torque and thrust force, respectively. The process from averaging to filtering is carried out on each segment of torque and thrust force data.

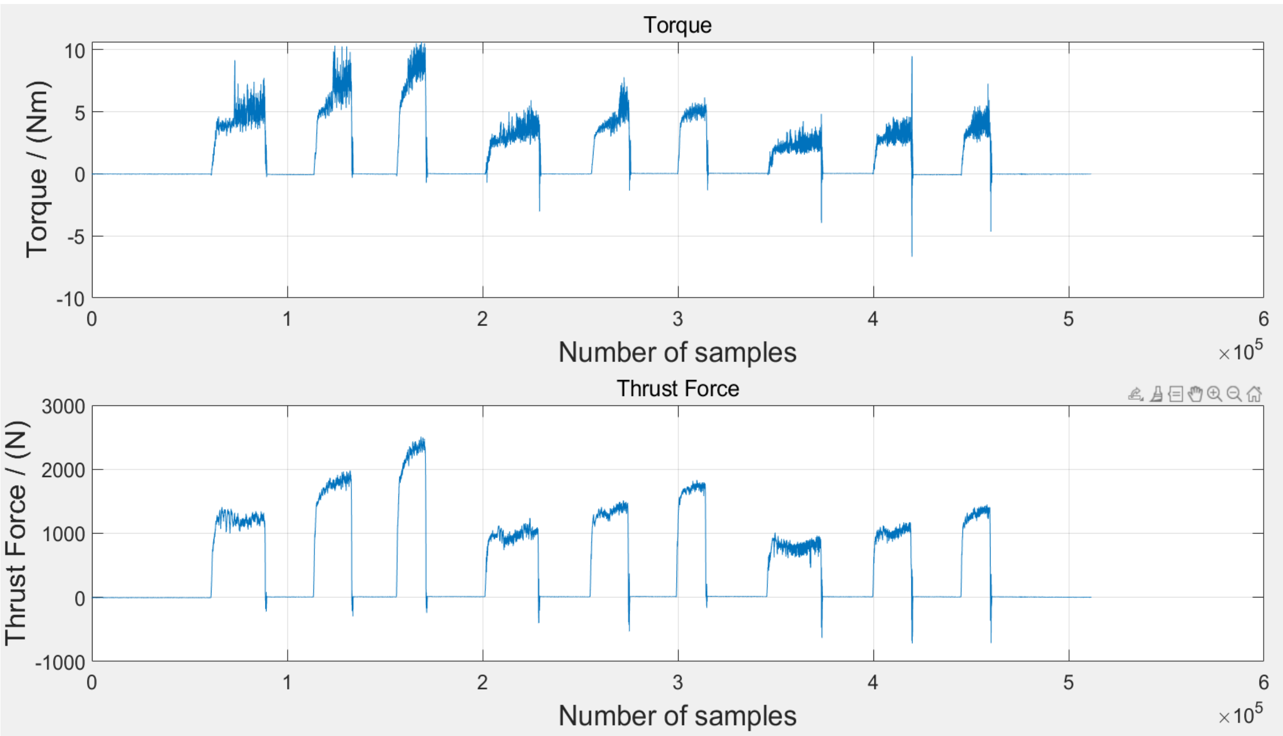


Figure 8 Outlier removal using Chauvenet's criterion

Sequentially, averaging process is applied to each segmented data and each average value is subtracted from the raw data which is known as 'detrending procedure'. Therefore, the biased error can be avoided, and the noise can be reduced in some extent. The reason that we used arithmetic average is that ensemble average method cannot be applied since there is only one measurement for the project. Moving median is not used because the outliers are removed at the first stage. Moreover, we decided to use arithmetic average to be taken off from the raw data after the comparison between other method such as Moving average. Both plots showed similar trend therefore, we selected the arithmetic averaging method for better efficiency of computing times. Furthermore, since we have relatively many data, the arithmetic average would show a reduction of error (Than fewer numbers of data). From Figure 9 to Figure 11 indicate the data after removing the arithmetic mean from each segmented Torque data. As a result, all signals are oscillating around value ‘0’.

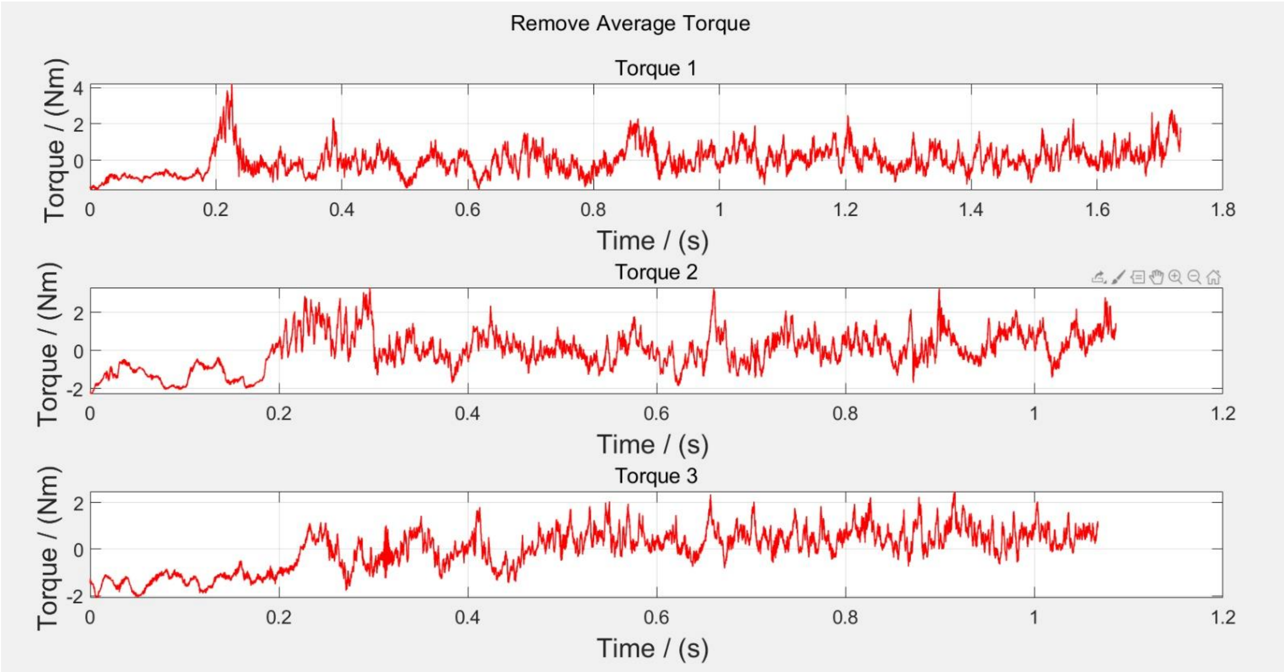


Figure 9 Torque 1 to Torque 3

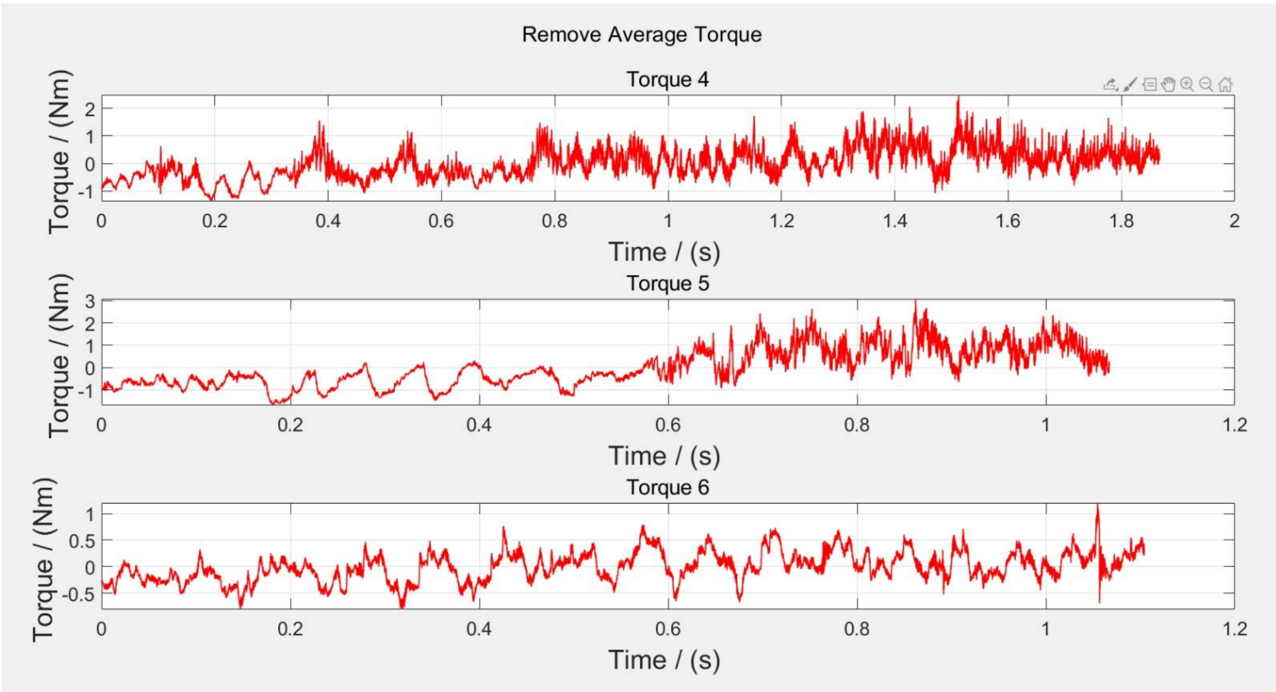


Figure 10 Torque 4 to Torque 6

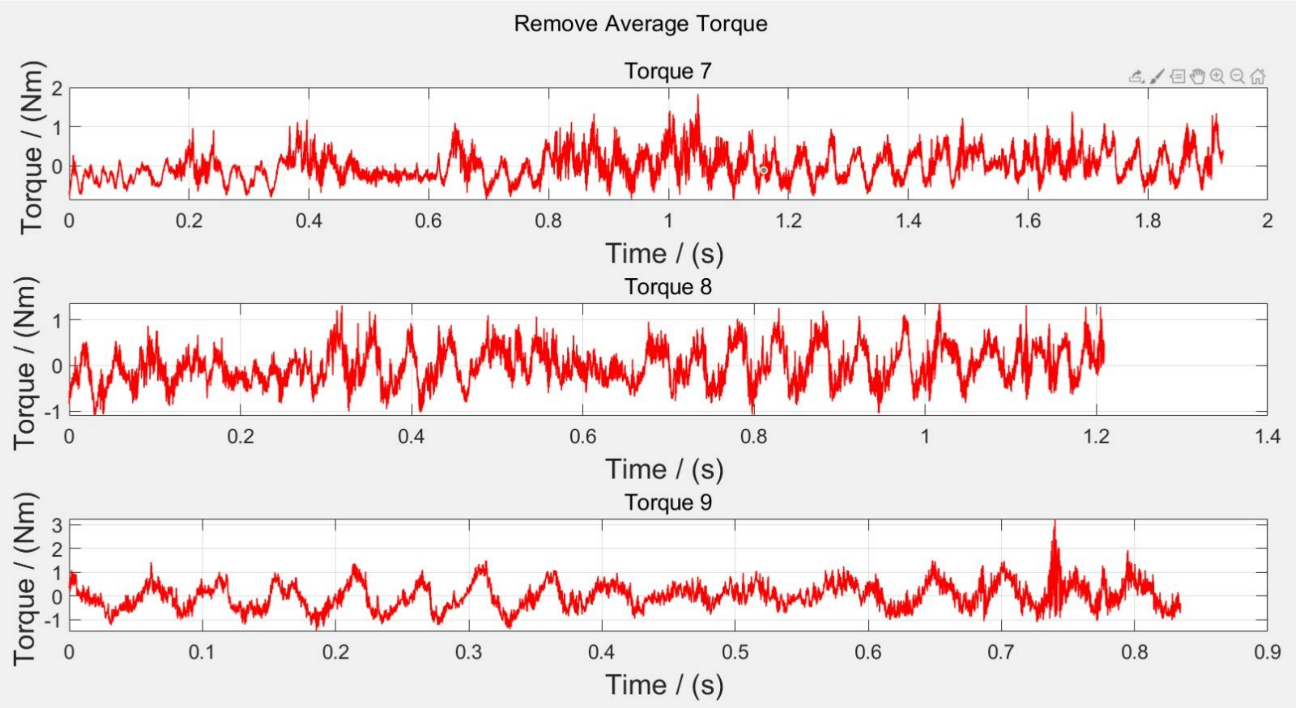


Figure 11 Torque 7 to Torque 9

From Figure 12 to Figure 14 depict the plots of Thrust forces. Consequently, the graphs are oscillating around the zero value like the Torque data are.

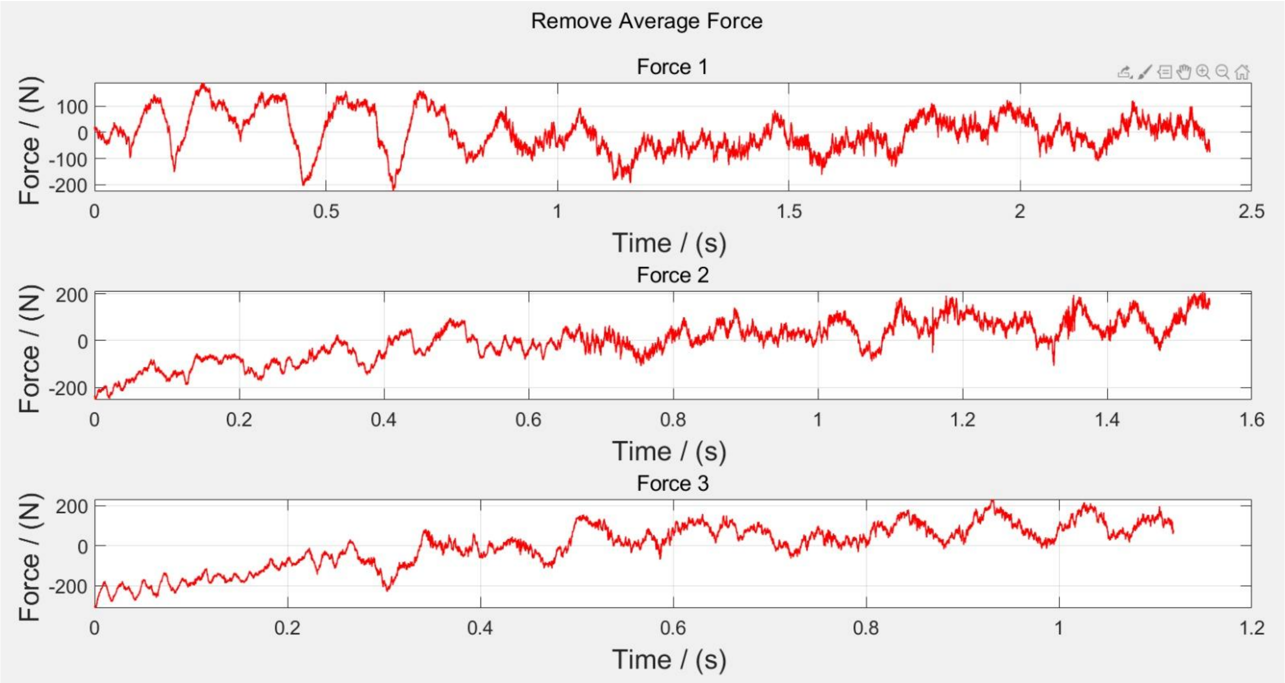


Figure 12 Force 1 to Force 3

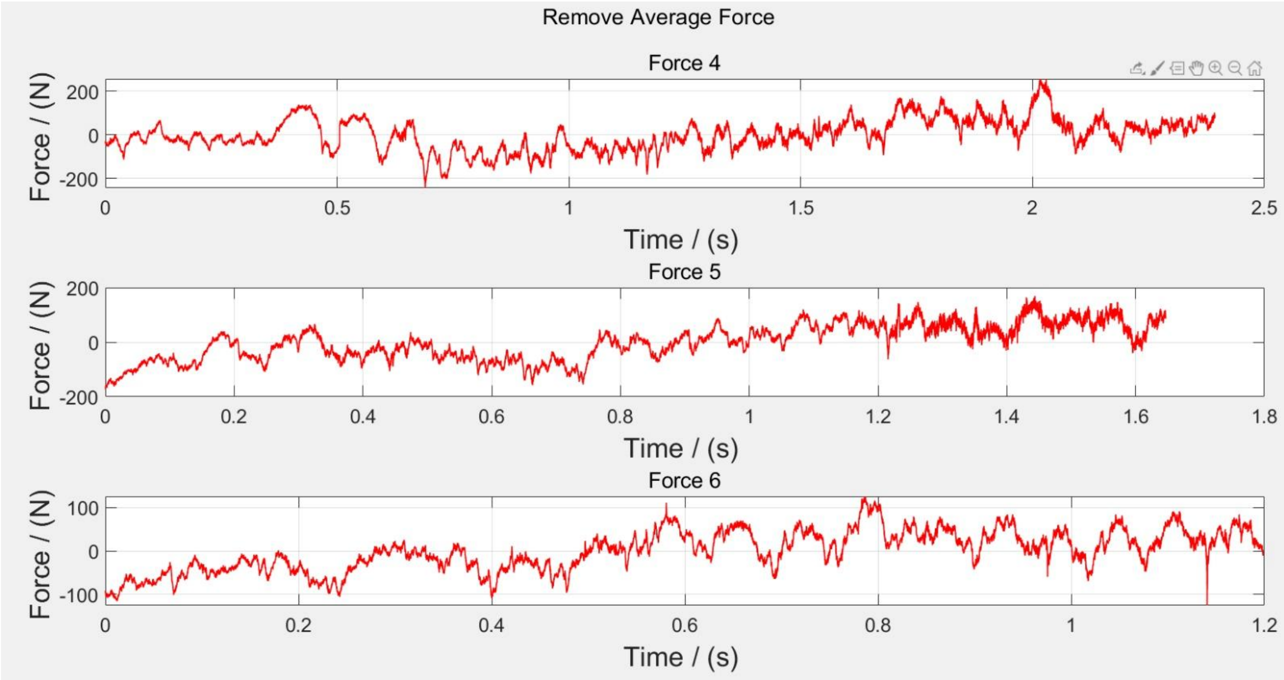


Figure 13 Force 4 to Force 5

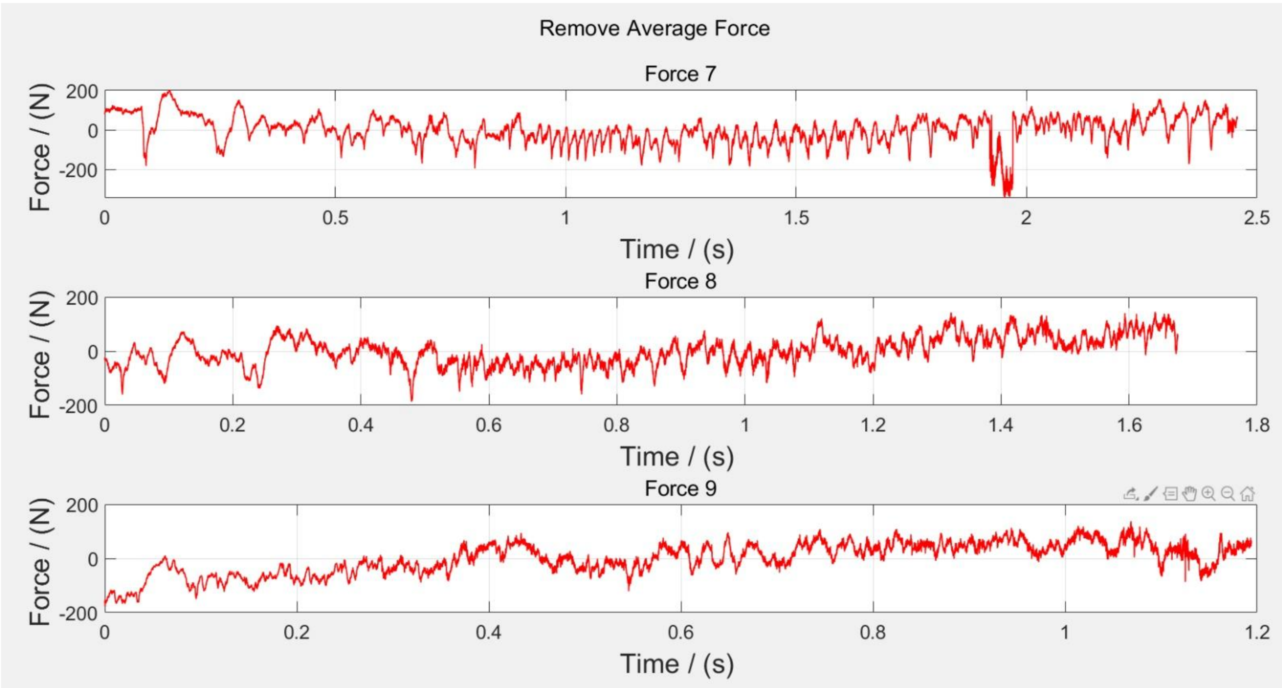
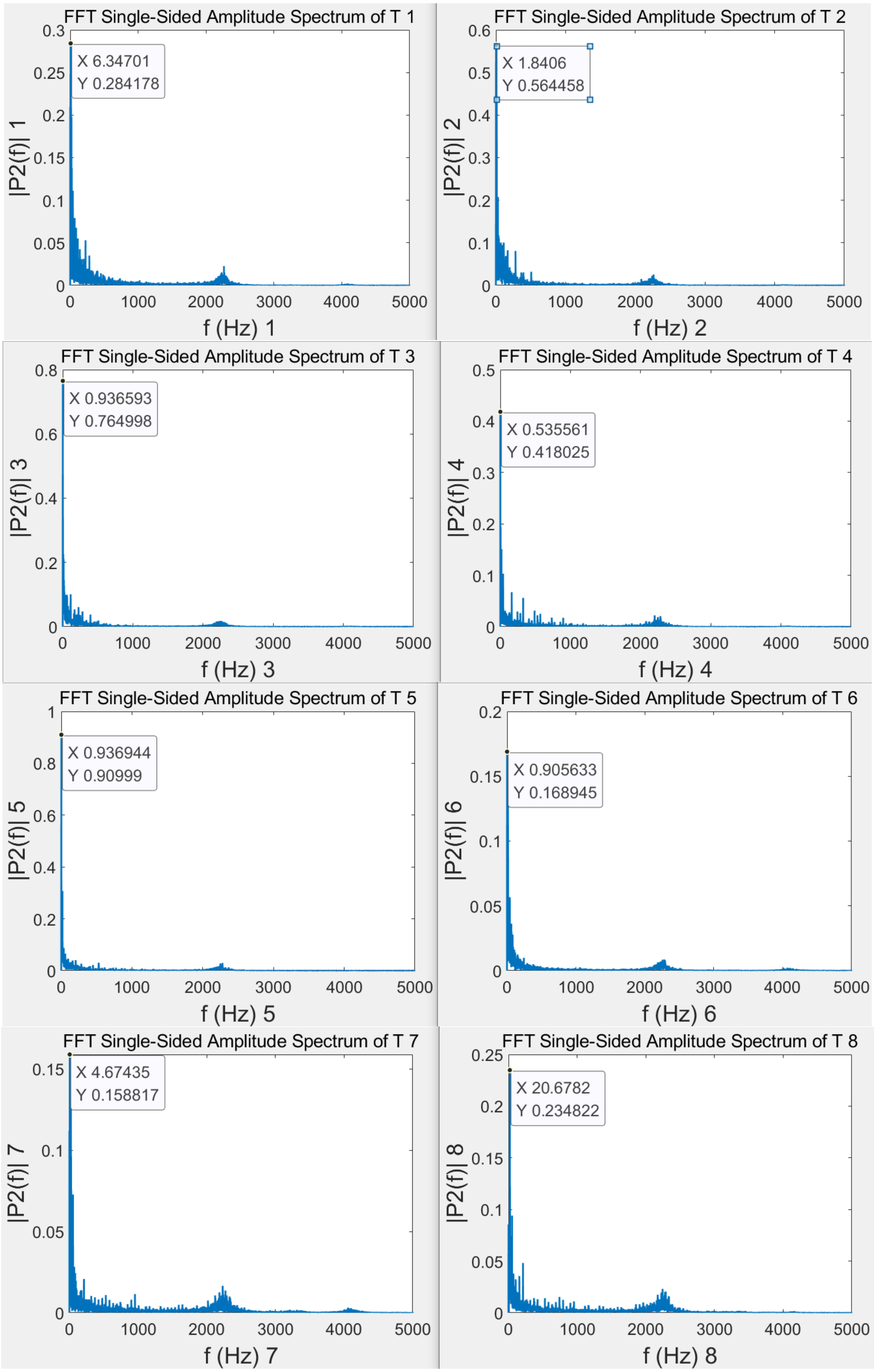


Figure 14 Force 7 to Force 9

After that, Fourier transform is used to analyse the data in frequency domain which makes the signal more clearly. Moreover, filtering process can be applied to the amplitude spectrum. The results of Fourier transform of Torque and Thrust force data are plotted in single-sided amplitude spectra as in Figure 15 and Figure 16, respectively where |P2(f)| indicates the integrity of the amplitude. As can be seen in the figures, dominant contents are placed in low frequency. Therefore, we decided to maintain the frequency contents with the highest integrity of amplitude after filtering. In order to filter the data and preserve the low frequency contents, Low-pass filter is applied to them. The authors selected the cut-off frequency for the Torque data as '90' to preserve actual data and reduce the noise as much as possible at the same time.


FFT Single-Sided Amplitude Spectrum of T 1
X 6.34701
Y 0.284178
|P2(f)| 1
f (Hz) 1
FFT Single-Sided Amplitude Spectrum of T 2
X 1.8406
Y 0.564458
|P2(f)| 2
f (Hz) 2
FFT Single-Sided Amplitude Spectrum of T 3
X 0.936593
Y 0.764998
|P2(f)| 3
f (Hz) 3
FFT Single-Sided Amplitude Spectrum of T 4
X 0.535561
Y 0.418025
|P2(f)| 4
f (Hz) 4
FFT Single-Sided Amplitude Spectrum of T 5
X 0.936944
Y 0.90999
|P2(f)| 5
f (Hz) 5
FFT Single-Sided Amplitude Spectrum of T 6
X 0.905633
Y 0.168945
|P2(f)| 6
f (Hz) 6
FFT Single-Sided Amplitude Spectrum of T 7
X 4.67435
Y 0.158817
|P2(f)| 7
f (Hz) 7
FFT Single-Sided Amplitude Spectrum of T 8
X 20.6782
Y 0.234822
|P2(f)| 8
f (Hz) 8

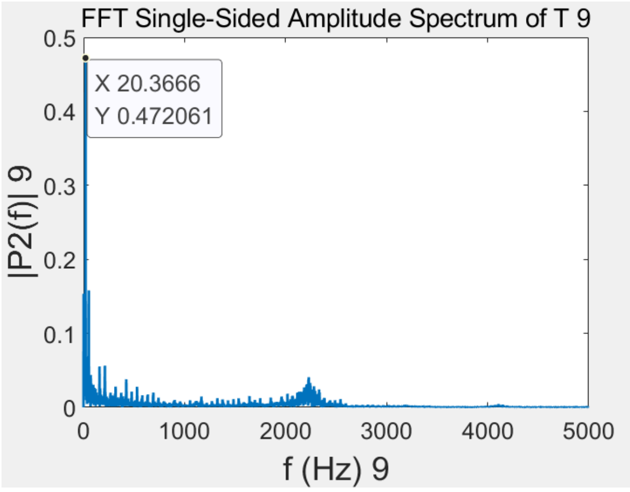
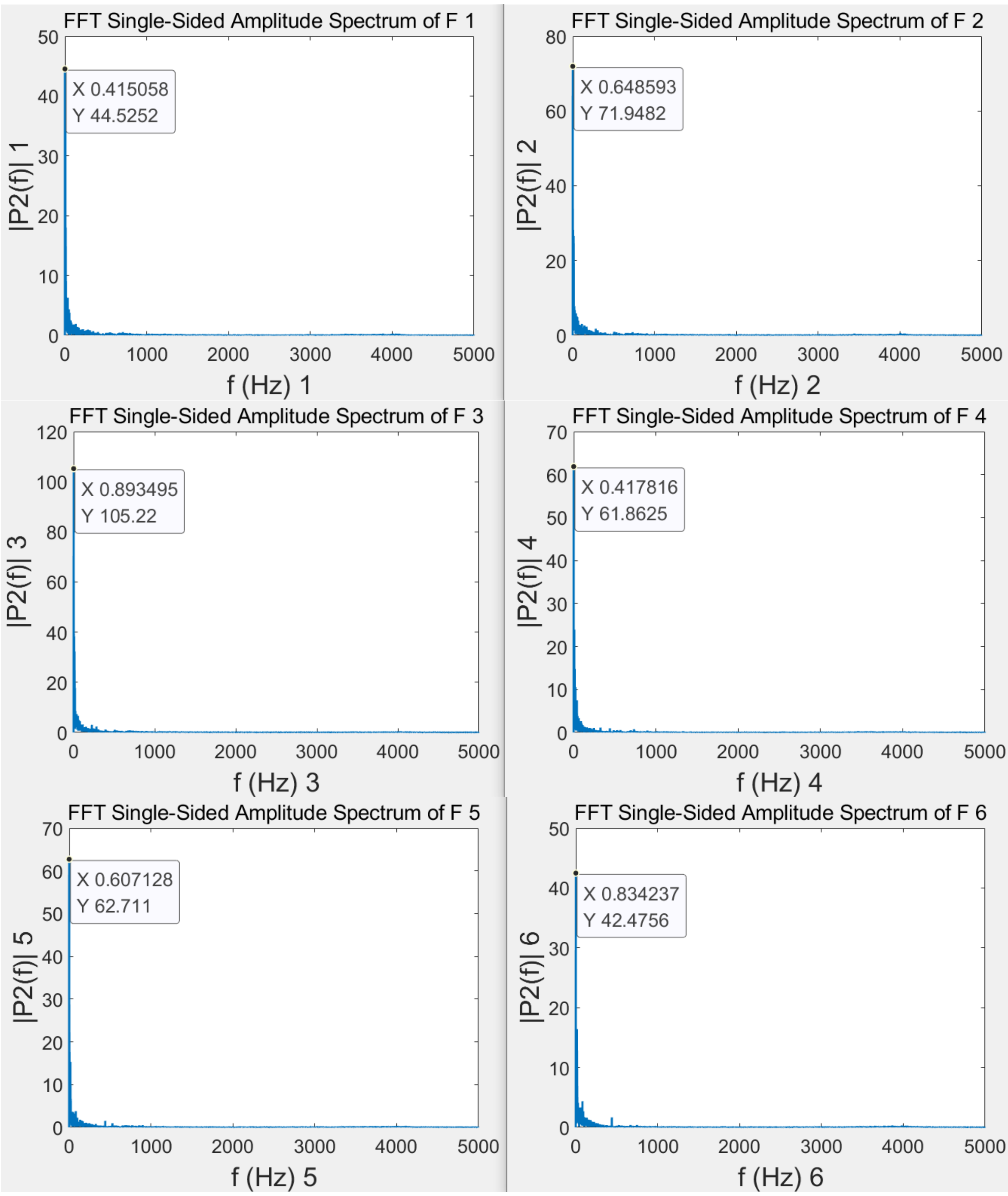


Figure 15 Single-Sided Amplitude Spectrum of Torque 1 to 9



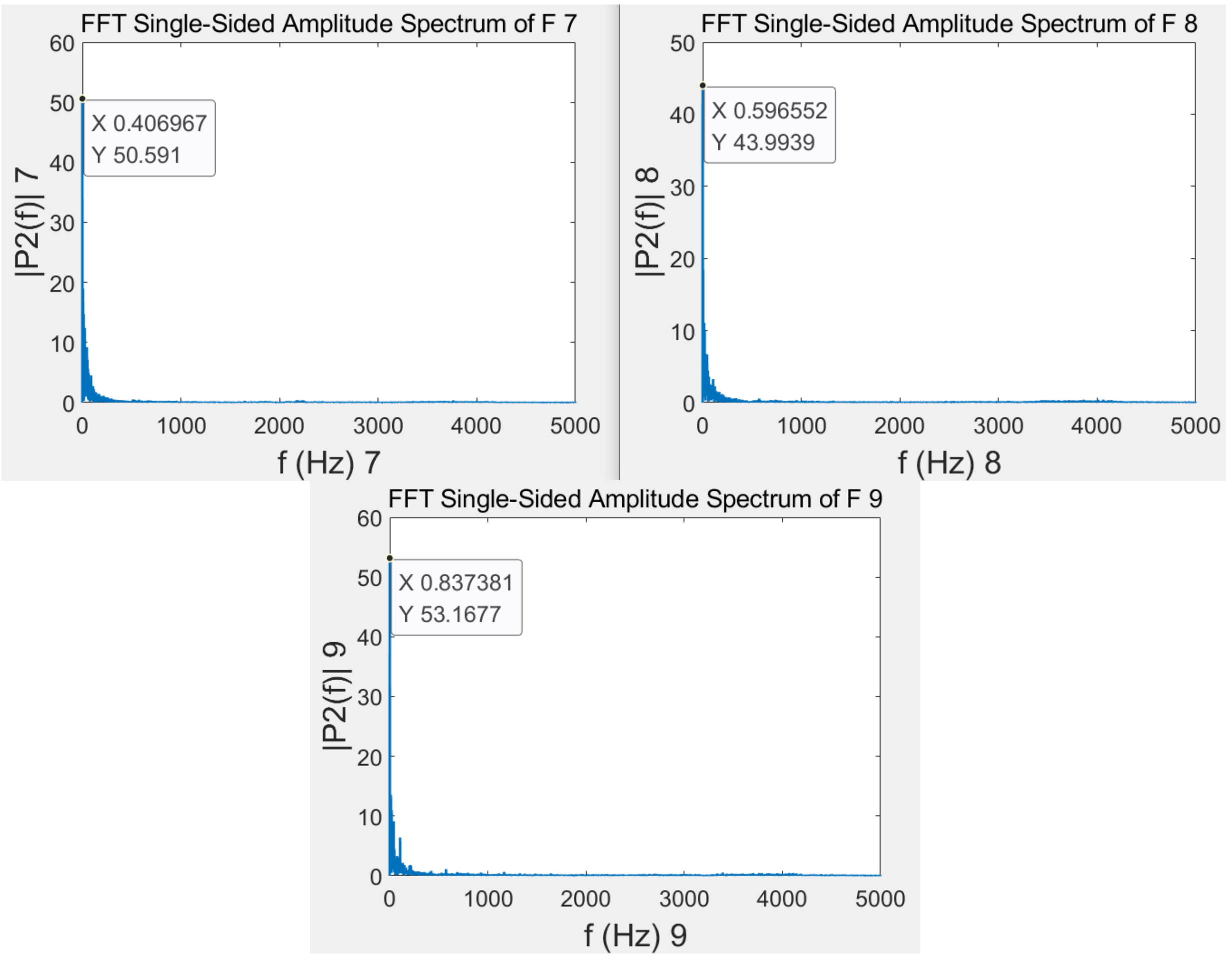


Figure 16 Single-Sided Amplitude Spectrum of Thrust Force 1 to 9

The filtered data are derived as Figure 17 to Figure 22. From Figure 17 to Figure 19 demonstrate Torque 1 to Torque 9. As can be seen in the figures, noises are significantly reduced from the original data which are presented in Figure 9 to Figure 11. In addition, Figure 20 to Figure 22 indicate Thrust force 1 to Thrust force 9. Not only the noises within torque data are removed but also, huge number of noises within thrust force data are significantly attenuated. Moreover, the applied low-pass filter seems reasonable since the actual data are preserved (Oscillation shape is quite similar with the original data.) and noises are considerably reduced.

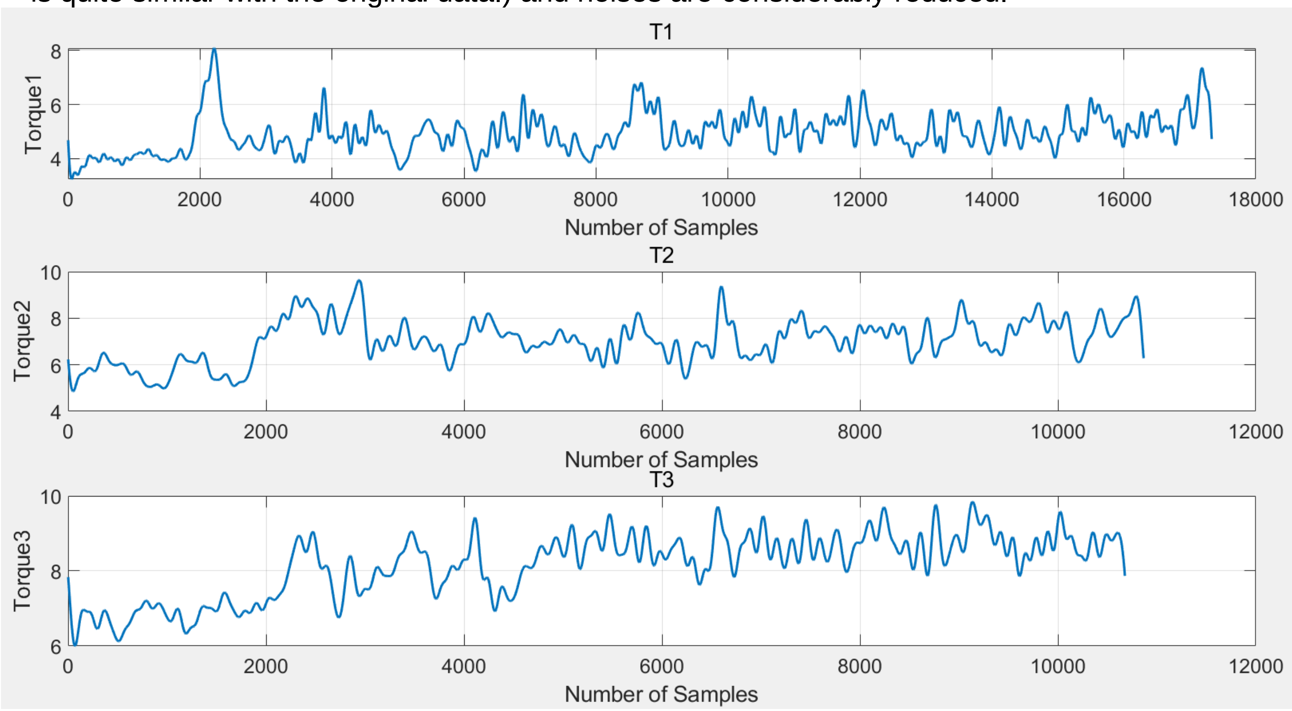


Figure 17 Filtered Torque 1 to 3

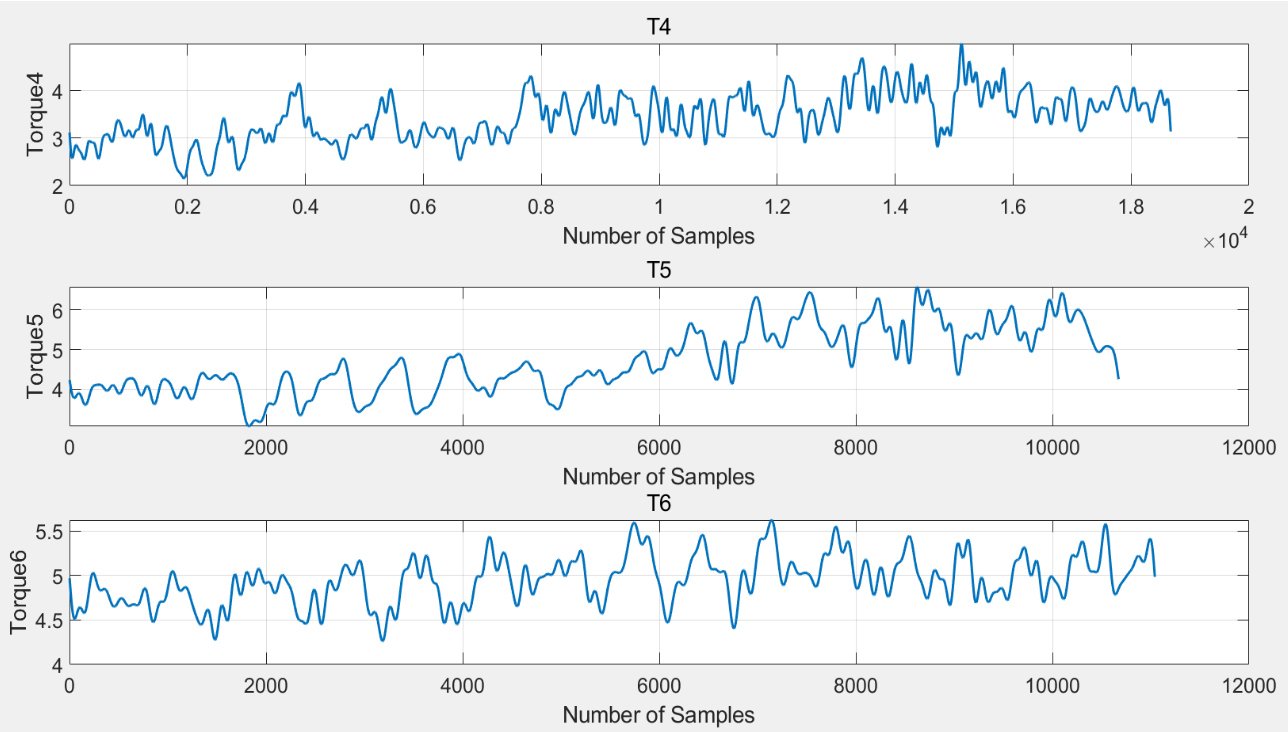


Figure 18 Filtered Torque 4 to 6

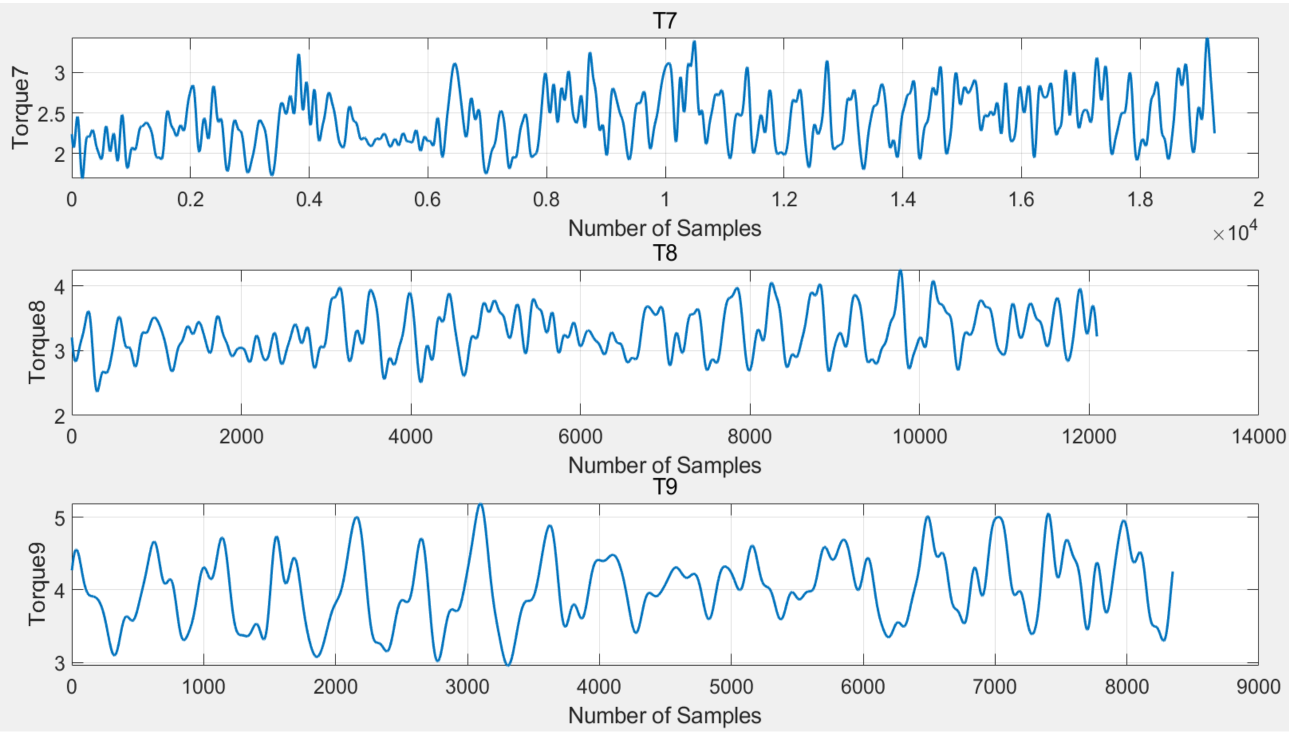


Figure 19 Filtered Torque 7 to 9

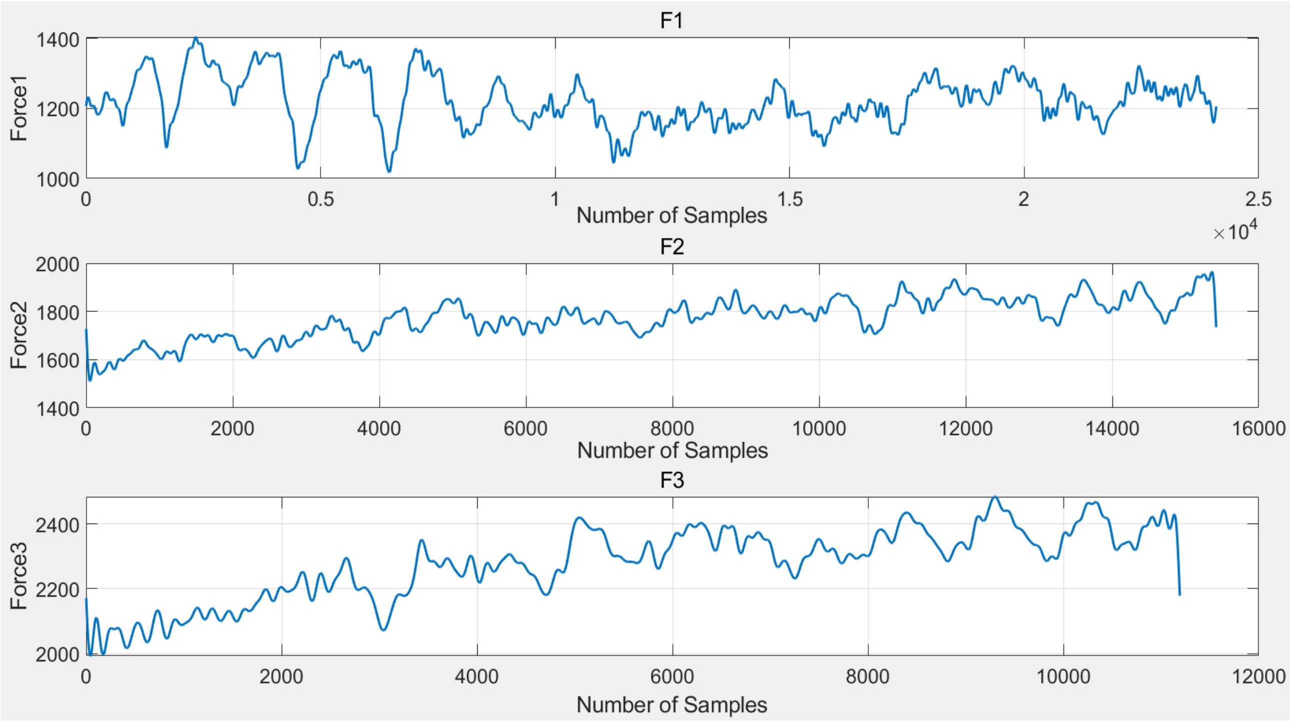


Figure 20 Filtered Thrust force 1 to 3

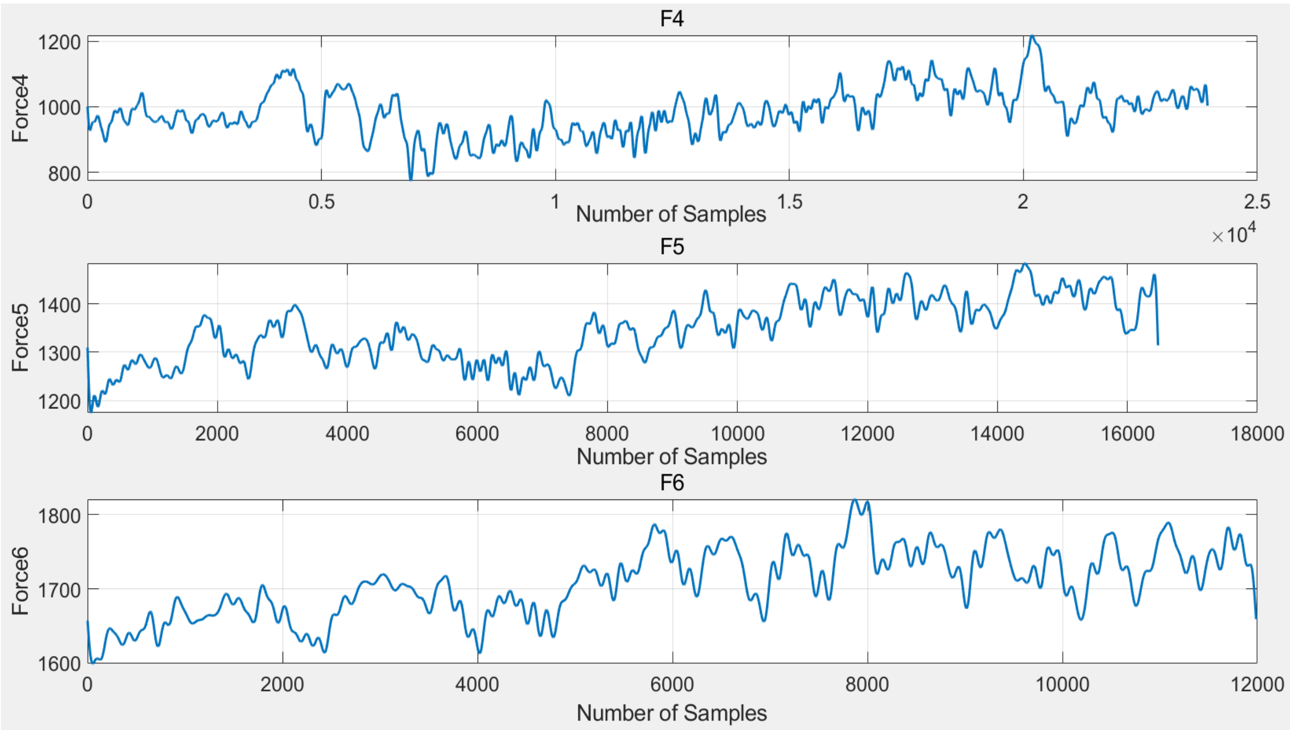


Figure 21 Filtered Thrust force 4 to 6

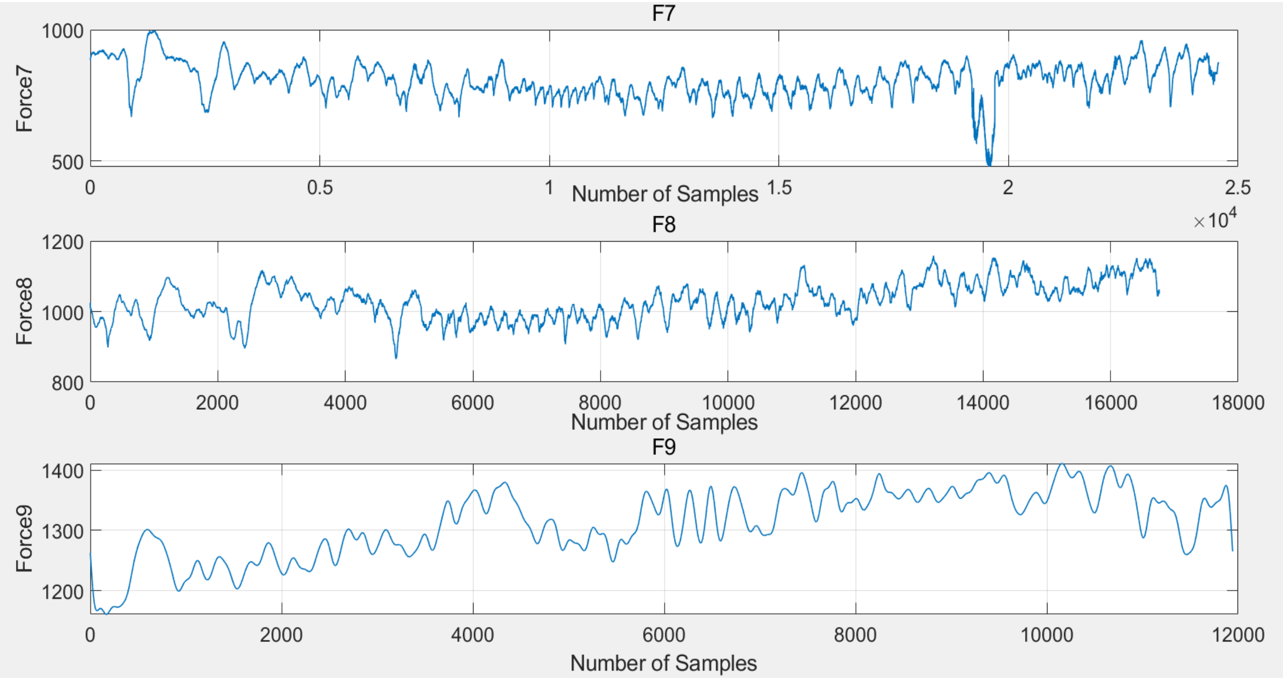


Figure 22 Thrust force 7 to 9

The presented filtered data are created by applying inverse Fourier transform to the filtered amplitude spectra and add the calculated averages to each proper data again.
The values of Torques and Thrust forces are indicated in maximum and mean values as can be seen in Table 3. The interesting point of the results is that each torque and force value are increasing when the feed rate is getting faster. On the contrary, data results are decreasing when the spindle speed is getting faster. Besides that, the smallest value of the results can be found from 7th hole which followed the conditions which are 130% of recommended spindle speed and 70% of recommended feed rate. Therefore, it is suggested to follow the condition to assure the longer tool life since weak cutting force would not affect the distortion or wear of tool more than other cases. The justification of the results is presented in the Discussion section.

Table 3 Values of Torques and Thrust forces

	Hole 1	Hole 2	Hole 3	Hole 4	Hole 5	Hole 6	Hole 7	Hole 8	Hole 9
Mean Torque (N·m)	4.93	7.02	8.17	3.43	4.69	4.95	2.42	3.27	4.01
Maximum Torque (N·m)	8.08	9.64	9.85	5.00	6.59	5.63	3.43	4.25	5.19
Mean Force (N)	1221.49	1770.50	2278.41	982.51	1344.43	1707.70	807.52	1028.97	1312.36
Maximum Force (N)	1403.93	1965.12	2484.97	1218.04	1483.96	1820.50	997.97	1158.36	1410.99

4.1. Uncertainty Analysis

For the Uncertainty analysis, we referred to the GUM (Guide to Uncertainty in Measurement) process. The process of the uncertainty analysis consists of Curve fitting, Define the measurement process, Develop the error model and Calculation of uncertainty.

4.1.1. Curve fitting

The curve fitting process is conducted by comparing average data point of each combination of spindle speed and thrust force. The plots of curve fitting are presented in Figure 23. They show that both data point and trend fit on the derived polynomial curve.

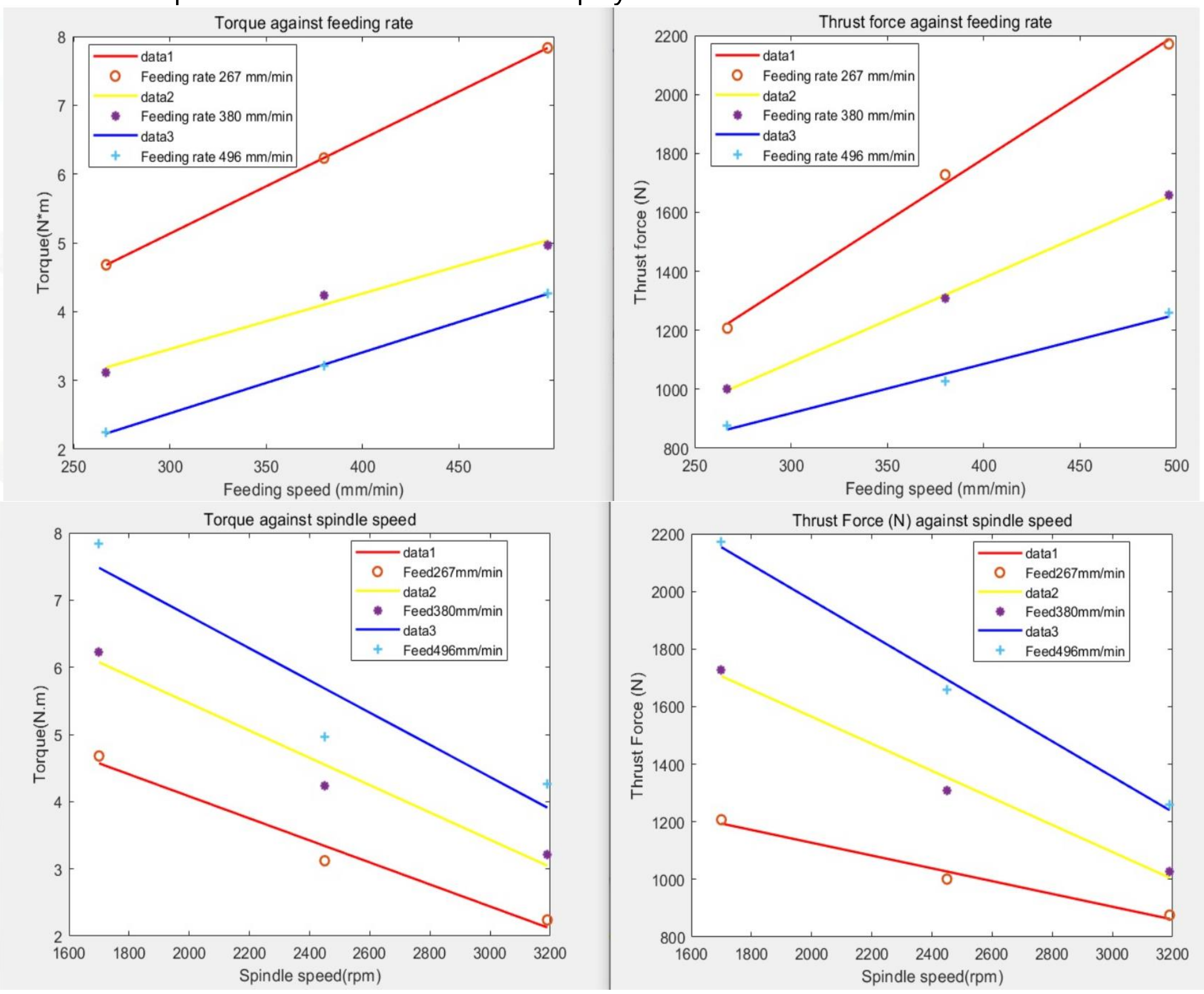


Figure 23 Curve fitting

4.1.2. Define the measurement Process

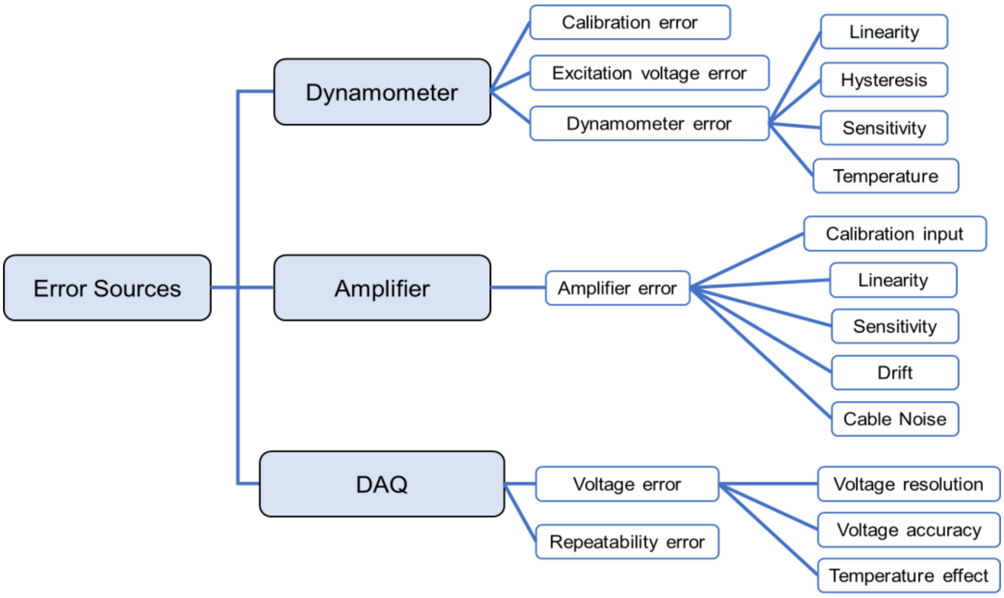


Figure 24 Defined Measurement Process

4.1.3. Develop the Error model

By using the derived equation from the curve fitting process, we can develop the error model. The equations are divided in four cases as below.

- Torque vs spindle speed

$y = -1.68 \times 10^{-3} x + 7.72$ R2 = 0.9888
$y = -2.52 \times 10^{-3} x + 11.15$ R2 = 0.9820
$y = -2.79 \times 10^{-3} x + 12.54$ R2 = 0.9018

- Thrust force vs spindle speed

$y = -2.78 \times 10^{-1} x + 1683.84$ R2 = 0.9928
$y = -4.98 \times 10^{-1} x + 2599.32$ R2 = 0.9933
$y = -6.49 \times 10^{-1} x + 3353.09$ R2 = 0.9899

- Torque vs feeding rate

$y = 1.41 \times 10^{-2} x + 1.33$ R2 = 0.9700
$y = 6.59 \times 10^{-3} x + 1.85$ R2 = 0.8670
$y = 6.96 \times 10^{-3} x + 0.58$ R2 = 0.9977

- Thrust vs feeding rate

$y = 4.61 x - 1.26$ R2 = 0.9991
$y = 3.17 x + 138.39$ R2 = 1.0000
$y = 2.21 x + 209.27$ R2 = 0.9960

After that, the calculation of uncertainty can be conducted however, it is not going to be presented in this paper.

5. Discussion

In the previous sections, aforementioned methodology is favourably conducted. Therefore, the methodology and the results should be justified in this section. Figure 25 indicates the result of the measurement of force and torque during drilling process by G.Totis et al.. According to G.Totis et al., they conducted the experiment under similar conditions with our project. They used charge amplifiers, dynamometer, DAQ device and LabVIEW programme to collect the data. Moreover, they used Matlab for their data analysis (Totis et al., 2014). As can be seen in the figure, the configuration of the raw data plot of the results are immensely similar with the raw data plot which is presented in Figure 8. Therefore, it can be said that the derived data collection of the project is reasonable enough.

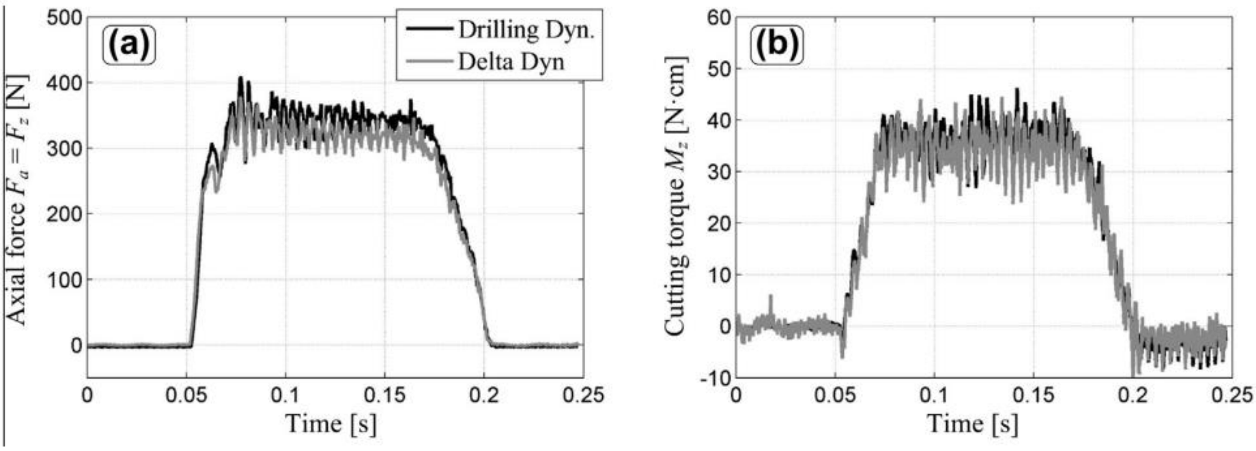


Figure 25 Measurement result of drilling process (G.Totis et al., 2014)

In addition to the justification of the data acquisition, the trend of the results is justified as well. According to A. Prabukarthi et al., they conducted the experiment to optimise the tool life in drilling process. As a part of the optimisation, they carried out the measurement of thrust force and torque force. As a result, the trend of the results showed exactly same as the derived data in this paper. The trend of the data showed that thrust forces and torque forces are getting smaller when the spindle rate is increasing (Prabukarthi et al., 2013).

Experiment number	Spindle speed (rpm)	Feed rate (mm/rev)	Thrust force (N)
1	700	0.05	336
2		0.09	546
3		0.13	586
4	850	0.05	323.33
5		0.09	496.67
6		0.13	570.00
7	1,000	0.05	293.33
8		0.09	450.00
9		0.13	533.33

Experiment number	Spindle speed (rpm)	Feed rate (mm/rev)	Torque force (N-cm)
1	700	0.05	63.33
2		0.09	113.33
3		0.13	150.00
4	850	0.05	60.00
5		0.09	100.00
6		0.13	136.67
7	1,000	0.05	53.33
8		0.09	66.67
9		0.13	120.00

Figure 26 Justification of results (Prabukarthi et al., 2013).

However, there are some limitations of some processes in this project so, there must be some future works of this project as well. The first limitation is that the number of measurements is only one due to the limited amount of specimen. Hence, some other averaging method such as ensemble average is not able to be applied therefore, it cannot be compared with the result of arithmetic mean so the use of arithmetic mean cannot be fully justified.

The second limitation is that the uncertainty analysis cannot be accurately quantified since we have not acquired sufficient data reduction equation for the development of the error model. Therefore, it is needed to be researched more in depth about the uncertainty analysis and examine a more accurate confidence level of the data results.

The third limitation is in pre-experiment session that there is no action to reduce the vibration during the drilling process. Since dynamic noises can be made by the vibration, it should be reduced by using certain methods for the clearer acquired data.

The fourth limitation is that Chauvenet function to remove the outliers from the torque and thrust force data caused discontinuity hence, the processed data cannot fully correspond to the original time data. Therefore, some other methods can be applied instead of the Chauvenet’s criterion for instance, moving median would be used for the original data with outliers due to the robustness of the moving median method against significant spikes or sharp gradients. Perhaps the repetition of the experiment could lead to clearer data without outliers as well.

The fifth limitation is that the highest spikes of the amplitude spectra are mostly placed near 0Hz. Therefore, we inevitably removed the broad range of frequency content. It can be solved by the data sample reduction method such as decimation. However, it cannot be the certain solution because the altered shapes of the amplitude spectra might be happened due to the distortion of the actual data results which is derived by the decimation method.

Apart from the limitations and future works which are mentioned, there is another recommended future work which is that we should conduct the profound analysis with the tool wear, hole quality in real to derive the reasonable suggestion of the spindle speed and feed rate conditions.

6. Conclusion

In this project, we measured torque and thrust force by using DAQ devices such as myRIO 1900, dynamometer and two amplifiers. To get the data with high sampling frequency (10kHz) and make it deterministic, LabVIEW code which contains FPGA, FIFO buffer, TDMS file saving sequence, and others has been programmed. The plot of the original raw data without any application of data-processing methods showed that they need proper signals processing. Chauvenet’s criterion for removal of outliers have been applied as a first process. As a result, the raw data demonstrated the figures without significant outliers. Then, arithmetic average has been used for the calculation of single value of each force and for the next stages such as detrending, Fourier transform, and filtering. The torque and force values examined that the values are decreasing along the increment of the spindle speed. Moreover, the values are increasing along the increment of the feed rate and these results are justified in the Discussion section by comparing with the literature.

After that, for the proper analysis of the data in frequency domain, mean values have been subtracted from the segmented torque and force data. When each data's time domain configuration is converted into frequency domain, we plotted single-sided amplitude spectrum of each data to make it clearer to be analysed. Based on the analysis of amplitude spectra, range of the low-pass filter has been decided which makes it possible to preserve the actual data and reduce noises at once. Thus, the final filtered data showed significant reduction of the noises and preservation of the original shape of each raw data. Therefore, it can be said that the post-processing for creation of readable and informable data has been successfully carried out.

As one of the overall processes of this project, curve fitting based on the value of each experiment data and uncertainty analysis based on the GUM process have been conducted. The curve fitting process showed that the collected data fit on the derived polynomial curve well in terms of trend and data. The further uncertainty analysis will be carried out in the future project.

7. References

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