Background noise reduction using spectral subtraction for enhanced vibration analysis in precision manufacturing applications

A. Iqbal[1]*, N. S. Mian[2], A. P. Longstaff[2], S. Fletcher[2]
[1]*College of Aeronautical Engineering, National University of Sciences and Technology (NUST),H-12, Islamabad, Pakistan*
[2]*Centre for Precision Technologies, University of Huddersfield, Queensgate, Huddersfield HD1 3DH, United Kingdom*
**Email: ali.iqbal@cae.nust.edu.pk*

Abstract

Vibration is an important indicator of machine tool health and for prediction of the surface finish of a manufactured component. Most research has concentrated on the analysis of the dominant sources, usually the machine element under investigation or the process parameters being used on the machine. The quantification of the impact of inevitable background vibration in machine tools has received far less attention but is an underlying factor when determining the fidelity of predictions from vibration measurements. Sources of background vibration could be outside the workshop, such as nearby road vehicles, or within the workshop, such as air handling, operation of other machines, etc.

Previous work has shown the characterisation of internal signal and mechanical noise arising from vibration sensors and its effect on vibration analysis. This paper presents a method for the characterisation of influence of background vibration, along with the identification of baseline background noise encountered in a typical machine shop in accordance with ISO 230-8:2010.

Spectral subtraction is proposed to minimise the effect of background vibration noise in the analysis. The method can be effective for improving the quality of vibration signals affected by broadband and spectral background noise. This can lead to improved in-situ decision-making by determining the useful, and irrelevant, parts of the signal for different applications. Results from this study will provide viability and improved vibration analysis through the application of spectral subtraction on machine vibration signatures and careful consideration of contributory sources of vibrational background noise in metrology applications.

1 Introduction

Noise is an ever-expanding area in engineering that poses practical problems and warrants further research. Noise can include both unavoidable intrinsic noises contributing to the system and noise of extrinsic nature due to operating conditions. Previous work has shown the characterisation of internal signal and mechanical noise arising from vibration sensors and its effect on vibration analysis in precision manufacturing applications [1]. This paper presents a method for the characterisation of influence of background vibration, along with the identification of baseline background noise encountered in a typical machine shop in accordance with ISO 230-8:2010 [2].

There are several applications where the objective of vibration measurement desires a low-noise floor, such as seismic applications, structural health monitoring (SHM), IoT devices, medical sensors, inclination sensing, etc. While it can be argued that a low-noise floor is often not desired or of minimal interest in machine tools when the value of vibration being measured is large, such as an imbalance in a large rotating machine. However, in machine tool metrology, the effects of such noise phenomena on vibration measurements during real-time process monitoring can often be misconstrued as regenerative chatter during a machining process, such as metal cutting, milling, or drilling [3]. Especially if these problems appear in subcritical regimes of a machining process, it could result in machine or workpiece damage, leading to lower productivity or precision in the process.

Therefore, quantification of background noise in machine tools for precise and accurate workpiece-tool interaction, which can be vulnerable to vibration-induced performance degradation, may be of interest to users [2]. Identifying background noise in condition monitoring and prognostics can help to reduce false failure modes, which can cause unnecessary production or process delays.

This accentuates the need for investigation of noise in precision manufacturing setups where the application requires maintaining tight tolerances. This current work proposes the use of Spectral subtraction to minimise the effect of background vibration noise in the analysis. The method can be effective for improving the quality of vibration signals affected by broadband and spectral background noise. This can also ultimately lead to an improved in-situ decision-making by determining the useful, and irrelevant, parts of the signal for different applications. Results from this study will provide viability and improved vibration analysis through the application of spectral subtraction on machine vibration signatures and careful consideration of contributory sources of vibrational background noise in metrology applications.

2 Background Noise Estimation on Machine Floor

In research and precision manufacturing, it may be necessary to conduct experiments or take measurements in a vibration-free environment [4]. Practical scenarios in the machine tool environment, however, do not allow for this because background noise sources are multiple and inevitable. Air conditioners, heat pumps, and road and rail transportation systems, coupled with random sources, all contribute to a largely unavoidable vibrational background noise [3, 4]. This section provides a quick overview of potential background noise sources on the machine floor. The work also identifies the baseline background noise on a machine tool in a progressive state of operation in an experimental setting.

2.1 Sources of Noise on Machine Floor

Background noise in the context of this work refers to unwanted external vibrations (‘noise’) [5] that can be classified into four categories [4]. One of these categories is seismic noise, which is caused by vibrations transmitted through the machine floor and can be caused by sources such as operation of machine tools in close proximity, heavy machinery, construction work, vehicular and foot traffic. Another category is acoustic noise, which is transmitted through the air as a result of variations in air pressure and can be caused by sources such as wind and building ventilation fans.

Mechanical noise due to forces applied directly to the machine tools also contribute significantly to background vibration. These sources, such as a moving worktable or tool and vibrations transmitted by the machine tool's motor, gears, and rotary components, are significant because they are mechanically coupled to the experimental setup and are difficult to reduce. One key contribution comes from the machine tool spindle as it can cause unwanted vibrations due to cutting forces, unbalance, and preload, chatter and damaged bearings. Additionally, electronic noise from sources such as lights, bulbs, motors, and other electrical sources can electromagnetically induce inference in sensors installed on the machine tool.

2.2 Characteristics of Background Noise

Vibration noise can be classified as random, pseudo-random or periodic in nature. Random sources can be linked to unpredictable behaviour, such as the blowing of wind gusts or the operation of construction equipment, etc. While periodic sources can be the turning on and off of ventilation systems, coolant pumps, temperature control and so on. In order to minimise the effect of such background vibration noise, determination of their amplitude and frequency is important from an analysis point of view. Typically, the frequency of ambient vibrations will range from 4 Hz to 100 Hz [4, 6] . Within the analysis, it must also be considered that many sources of noise contribute, through multiple mechanisms, to the overall vibration of the experimental setup. When analysing a noise source, both of these vibration channels should be considered. In machine tools, seismic vibrations and mechanically coupled vibration directly applied to the system contribute the most to overall background noise.

As previously stated, it is common in laboratories to find an ambient noise spectrum with structural and acoustic inputs as the dominant inputs. The most common sources of noise, as well as their frequency and amplitude, for determination of sources of vibration which are most likely to have the largest amplitudes and whether their frequencies are close to the resonant frequency of a given system are well documented [4]. On a machine floor or workshop, ISO dictates RMS vibration velocity to be below $800\mu m/s$ ($8\ Hz$ to $80\ Hz$) to fulfil noise severity criteria [7]. Therefore, the background noise vibration must be kept below this value.

A key source of background noise which is noteworthy to mention is temperature-induced vibrations. While it is difficult to model in terms of its severity it cannot be discounted in this analysis. Thermal disturbances from air conditioning systems and cooling fans can also cause relative motion between components, resulting in unwanted vibrations in machining due to material expansion and contraction caused by temperature fluctuations [4] that this can be further exacerbated if there is turbulent airflow (non-laminar) over the machine tool, introducing local thermal changes to the machine tool structure. These vibration errors can be additive to positioning errors encountered in machine tools due to thermal changes. The next section describes the methodology for computing background noise for machine tools based on experimental case studies.

Figure 1 : Machine Tool Configuration (Left) and Cincinnati Arrow 500 (Right) [8]

3 Methodology for Background Noise Estimation

An experiment was designed with the aim of computing the effect of background noise at various stages of machine operations under static conditions. The methodology was formulated while adhering to the guidelines presented in ISO 230-8:2010 [2], which provides a test code for determining vibration levels on machine tools. However, the ISO does not provide a detailed guideline for noise effects due to internal mechanisms of a machine tool, such as drive systems, etc. An experiment was setup on the Cincinnati Arrow 500 CNC machine tool to compute background noise and baseline performance. The Cincinnati Arrow 500 CNC is a three-axis machine tool with a vertical machining centre. The current scope of work focuses on vibrations encountered at the worktable. In the future, the study will expand to include unwanted spindle vibration or vibration between the tool and the workpiece, as they can also negatively impact the machining process by causing poor surface finish, tool edge damage, and reducing tool life. The machine tool configuration can be seen in Figure 1.

Three vibration sensors (02 MEMS + 01 IEPE) were installed on the worktable of the machine to capture the effect of noise vibrations at the location where the machining on a workpiece typically takes place. Two case studies were formulated to capture the effect of background noise on the workpiece and machine tool, i.e., the effect of external noise sources and the effect of noise sources internal to the machine. For each stage in Case Study 1 (Section 3.1) and Case Study 2 (Section 3.2), the test was conducted for a duration of 10 minutes and repeated five times according to industry practise. Stagewise estimation of time series data was then conducted to compute the contribution of various sources on a typical machine floor. Furthermore, spectral subtraction was performed to determine and mitigate the impact of any contributary periodic sources background noise.

3.1 Case Study No. 1

The first case study explored the effects of background noise due to sources external to the machine on the shop floor. The tests for the case study were conducted according to the test profile seen in Figure 2 , which summarises the progressive sensor data collection done at each stage of machine operation. The test involved two stages, i.e., recording the baseline noise performance of the machine tool when it is powered off and exploring the effect of machining taking place in close proximity to the machine tool on background noise characteristics while the machine remains powered off. In the second stage, we simulated machining on a nearby machine tool (XYZ 750 LR CNC Machine) with a constant spindle rate of 8000 RPM. The results from both stages were compared in both the time and spectral domains.

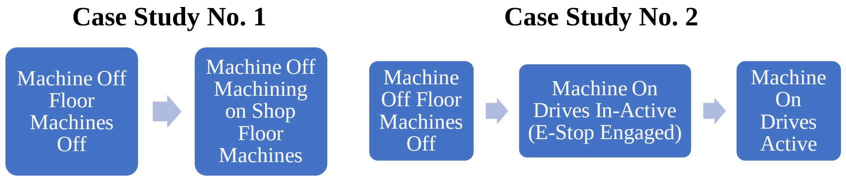

Figure 2 : Background Noise Test Case Study No.1 (Left) and Case Study No.2 (Right)

3.2 Case Study No. 2

The second case study explored the effect of background noise due to sources internal to the machine tool during the progressive operational states of the machine. Figure 2 demonstrates the process flow for internal background noise estimation. The test is comprised of three stages, i.e., recording baseline noise while the machine is powered off, then recording background noise with the machine turned on but with inactive drives (EMG Stop engaged), and lastly, recording machine noise parameters when the machine is powered on, and the drives are active and ready for machining. The final stage simulates the machine state before any actual CNC machining begins.

3.3 Experimental Setup

An industrial grade tri-axial digital MEMS sensor (ADXL355) [9] was selected as a representative vibration sensor for modelling the machine noise parameters. A detailed performance evaluation of the selected sensor in terms of its specifications [10], self-noise [1] and uncertainty [11] for machine tool metrology applications has already been presented in previously published works [12]. The sensor offers ultralow noise characteristics that may be expected from traditional high-end accelerometers with the added capability of providing the digital communication options (I2C/SPI) and configurable sensitivity suitable for low amplitude measurements.

The setup consists of two identical ADXL355 [9] sensors and an IEPE PCB356A02 [13] sensor employed as a traceable standard mounted on a 110 mm x 80 mm aluminium plate of 5 mm thickness and secured using bolts. Based on the results of the tests, the use of a dual MEMS sensor setup may allow for the implementation of common mode noise cancellation methods in future work. The MEMS sensors were named for unique individual identification as Node 102 and Node 103. Digital temperature sensors (Maxim DS18B20) were also installed to monitor any temperature variations in the setup, during the entire duration of test . Clamps were used to secure the sensor plate to the machine worktable, and cable ties and adhesive pads were used to secure the sensor wires. During installation, the sensor axes were aligned with the machine axis, however all tests were performed in static machine conditions. The setup can be seen in Figure 3.

4 Results and Modelling of Machine Floor Noise

The results and modelling of machine floor background noise are presented in this section of the work. The first part of this section discusses results from Case Study No. 1, while the second part of the section presents findings from Case Study No.2.

4.1 Case Study No.1: Effect of External Background Noise

The first case study explored the effects of background noise due to sources external to the machine tool. For all three axes of MEMS vibration sensors, the Root Mean Squared (RMS) and standard deviation (SD) of the recorded vibration data were computed. Considering the RMS vibration of all axes of both sensors, the change in RMS value is quite insignificant. For example, considering Node 102 the change in RMS value is only $0.01\,mg$ i.e., $9.39\,mg$ to $9.40\,mg$ (milli-g's). While for X-axis of Node 103 the value only changes by $0.02\,mg$ i.e., $2.45\,mg$ to $2.47\,mg$. The variation in RMS values within two sensors can be attributed to individual sensor baseline values underscoring importance of individual calibration. Table 1 presents the representative overview of results for each axis of Node 102 sensor.

Typically, noise is measured by variance, so the SD value of vibration were taken into account. Considering the Z-axis standard deviation of the Node 102 sensor, the value increases from 0.66 mg to 0.8 mg i.e., 0.14 mg. To investigate the cause of the increase in noise variance due to external effects on the machine tool, a moving standard deviation for the Z-Axis of Node 102 was computed using 100 samples for each computation to compare both states of the machine. While the standard deviation plot for Stage 1 (Machine Off, Shop Floor Off) does not demonstrate any variation, the plot for Stage 2 displays significant variation resulting in standard deviation values ranging from 0.6 mg to 1.25 mg,as seen in Figure 4.

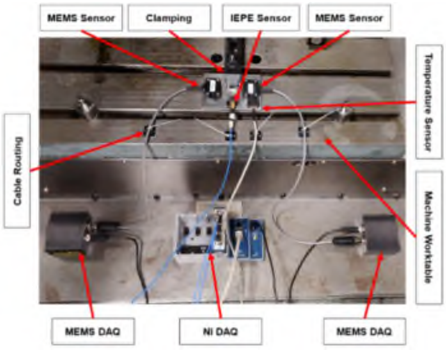

Figure 3 : Machine floor noise experimental setup

Table 1: Machine Floor External Background Noise RMS Vibration and Std Deviation Summary

S No	**Test Name (Machine State)**	**MEMS ADXL 355 Sensor 1 (Node 102)**					
		X-Axis		**Y-Axis**		**Z-Axis**	
		RMS (mg)	Std Dev (mg)	RMS (mg)	Std Dev (mg)	RMS (mg)	Std Dev (mg)
1	Machine Off Baseline	9.39	0.43	11.74	0.41	11.59	0.66
2	Machine Off Shop Floor Machining	9.40	0.51	11.74	0.46	11.53	0.80

Examining the data in the spectral domain (Figure 4) confirms the effect of contributary background noise due to undertaking machining activity in near vicinity on the vibration readings, as a peak of 132.1 Hz corresponding to 7926 RPM (~8000 RPM) is detected by the sensors. This can be attributed to the spindle RPM set at 8000 RPM for machining on the XYZ 700 LR machine.

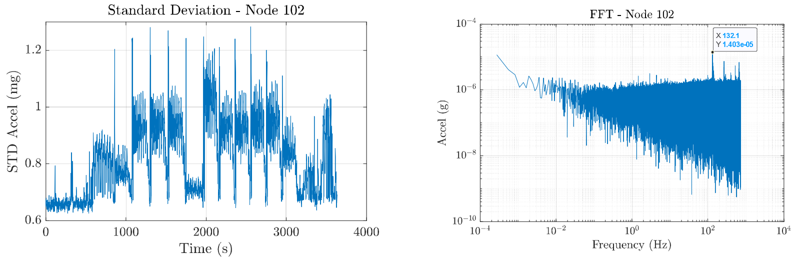

Figure 4 : Moving Standard Deviation (Right) and Spectral Analysis (Left) (Case Study No. 1)

Further investigation revealed that both machine tools shared a portion of the shop floor's foundation slab, resulting in a noticeable noise effect. It is evident from the analysis presented here that external noise from machining on the shop floor can affect machine tools, which must be considered during condition monitoring, prognostics, or maintenance data pre-processing routines. An in-situ filtering or compensation method can then be formulated to remove the effect of background noise during machine operational decision-making processes. One of the proposed techniques to overcome the issue is spectral subtraction, which is proposed as part of the current work.

4.2 Case Study No.2: Effect of Internal Background Noise

The second case study explored the effect of background noise internal to the machine tool. The detailed results for each stage and axis of the machine are for Node 102 are tabulated in Table 2 The vibration data was recorded for three stages of the machine tool. The first stage recorded the baseline machine noise data. The results for the first stage are reproducible to the results seen in Case Study 1.It was observed that RMS vibration and SD for Stage 2 and Stage 3 of the machine tool increased from the value recorded in Stage 1. Considering the RMS vibration for the Z-Axis of Node 102 the values increase from $11.59\ mg$ (Stage 1) to $11.62\ mg$ (Stage 2), while the increase from Stage 2 to Stage 3 is quite small, i.e., $0.01\ mg$ $(11.62\ mg$ to $11.63\ mg)$. Using the ISO 20816-1 [7] vibration severity criteria $(\leq 17.93\ mg)$ and comparing the computed RMS background noise values in the case study, it is possible to conclude that the investigated machine tool vibration limit is 'Good', satisfying the vibration criteria for long-term stable operation.

Table 2: Machine Floor External Background Noise RMS Vibration and Std Deviation Summary

S No	**Test Name (Machine State)**	**MEMS ADXL 355 Sensor 1 (Node 102)**					
		X-Axis		**Y-Axis**		**Z-Axis**	
		RMS (mg)	Std Dev (mg)	RMS (mg)	Std Dev (mg)	RMS (mg)	Std Dev (mg)
1	Machine Off Baseline	9.39	0.43	11.74	0.41	11.59	0.65
2	Machine Off Shop Floor Machining	9.39	0.45	11.73	0.42	11.62	0.66
3	Machine On Drives Active	9.4	0.50	11.73	0.44	11.63	0.78

Considering the SD of the same Z-Axis of Node 102, while the change in value is very small, i.e., $0.01\ mg$ when the machine state transitions from Stage 1 to Stage 2, an increase in internal noise deviation is noticed when drives are turned on (Stage 3). In this case, the SD value increases from $0.66\ mg$ to $0.78\ mg$ i.e., by a value of $0.12\ mg$. The source of this increase is logical, as all the motors and drives are powered on and ready to operate. Considering Node 103 for the same Z-Axis in stage 3 the value is $0.76\ mg$. Therefore, taking in account values from both sensors in Z-Axis $0.77\ mg \pm 0.01\ mg$ can be considered the background noise in Cincinnati machine tool when the machine is a state ready for machining operation. Similarly for X and Y axis the background noise values were computed to be $0.505\,mg \pm 0.005\,mg$ and $0.445\,mg \pm 0.005\,mg$ respectively. Use of additional sensors is likely to aid estimation as it can lead to the removal of sensor-specific contributions to machine background noise variance.

4.3 Spectral Subtraction for Machine Tools

Filtering methods are typically used to deal with the effect of background spectral noise, which requires a good understanding of filter design and implementation to ensure no actual data is lost. The spectral subtraction method restores the power magnitude spectrum of a signal that has been corrupted by additive noise by subtracting an estimate of the average noise spectrum from the noisy signal spectrum. Typically, the noise spectrum is estimated and updated from periods when the signal is absent and only noise is present. As illustrated in Figure 5, in order to recover original time-domain signals, a spectral estimate of the noisy signal is derived, from which the noise is eliminated, and the signal is then transformed back to the time domain using an inverse discrete Fourier transform [14].

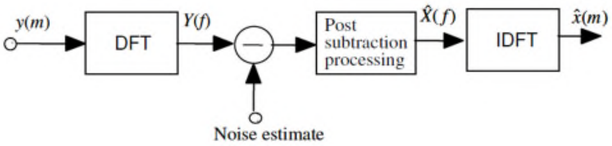

Figure 5 : A block diagram illustration of spectral subtraction [14]

The method has been demonstrated for improving the quality of speech signals [15] affected by broadband [16] and spectral [17] background noise. This is due to the fact that, computationally, the method is inexpensive. One limitation of the technique is that variation in random noise can result in negative estimates of the noise spectrum, necessitating the use of non-linear variants of the spectral subtraction method to reduce signal noise variance.

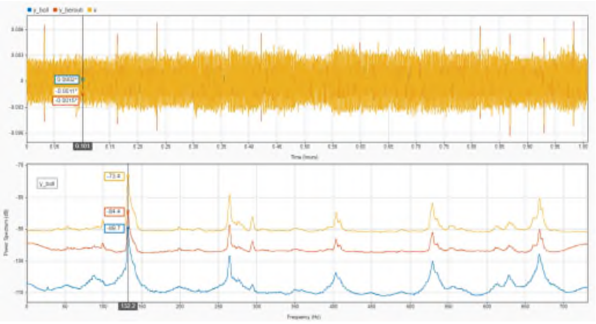

Figure 6 : Spectral Analysis FFT via PSD Node 102 (Case Study 1) Spectral Subtraction

Spectral subtraction (SS) based on techniques proposed by Berouti, et al. [16] and Boll [17] was applied to noisy sensor data recorded from the Z-axis of Node 102 (Figure 4) to demonstrate the viability of the method. As seen in Figure 6, the original signal has a spectral noise peak at $132.2\,Hz$ with a magnitude of $-73.4\,dB$, while after spectral subtraction, this is reduced to $-84.4\,dB$ and $-89.7\,dB$, respectively. Other spectral noise frequencies are also reduced as part of the application. The spectral subtraction method proposed by Boll [17] promises the most suitable noise reduction in the current comparison, with a $16.3\,dB$ reduction in dominant spectral noise content. Further work can be done to investigate the method in terms of its suitability for machine tool condition monitoring [18, 19].

5 Conclusion

The work presented in this paper proposes to model and gauge the effect of background noise through sensors installed on a machine tool. To achieve this, key sources of noise, in conjunction with their transmission phenomena, affecting a machine tool installed on the shop floor are established. To accurately model the background in a typical machining scenario, these two case studies were formulated to capture the external and internal noise recorded by MEMS vibrations installed on a machine tool.

Internal noise estimation of the Cincinnati machine tool was also explored. The standard deviation of noise was progressively computed for each stage of machine operation. The background noise assessment of investigated Cincinnati machine tool found the value of noise to be within $0.505\,mg\ \pm\ 0.005\,mg$, $0.445\,mg \pm 0.005\,mg$ and $0.77\,mg \pm 0.01\,mg$ for X, Y and Z axis of the machine. While the RMS vibration for the machine was found to be $15.59\,mg$ which is within the vibration severity criteria (≤17.93 mg) set by ISO 20816-1:2016 [7]. The greatest contribution from noise sources internal to the machine tool can be attributed to the drives and motors. The baseline noise contribution must be considered during machining tasks for improved manufacturing quality.

The use of spectral subtraction has been proposed in the current work for improving vibration-based analysis through mitigation of spectrum specific noise in addition to RMS and SD noise indicators. The work presented in this paper also underscored the critical requirement for establishing noise models along with quantifiable metrics that can aid in-situ decision making, as well as serve basis for developing compensation models to support vibration monitoring and residual error reduction in high-end industrial manufacturing.

Acknowledgements

The authors gratefully acknowledge the UK’s Engineering and Physical Sciences Research Council (EPSRC) funding of the Future Metrology Hub (Grant Ref: EP/P006930/1) and UKRI-funded Advanced Machinery and Productivity Initiative (84646).

References

[1] Iqbal A, Mian N, Longstaff A, and Fletcher S 2021 *14th International Conference and Exhibition on Laser Metrology, Coordinate Measuring Machine and Machine Tool Performance*. 78-87 euspen

[2] ISO/TR 230-8:2010 - Test code for machine tools — Part 8: Vibrations 2010

[3] Buckwar E, Kuske R, L'esperance B, and Soo T 2006 *International Journal of Bifurcation and Chaos* **16** 2407-2416

[4] Thorlabs I. (2022). *Sources of Vibration and noise*.

[5] Crocker M and Sommerfeldt S 2008 *Handbook of Noise and Vibration Control* p. 1898.

[6] Thorlabs I. (2022). *Sources of Vibration*.

[7] BS ISO 20816-1:2016 : Mechanical vibration. Measurement and evaluation of machine vibration. General guidelines 2016

[8] Widiyarto M H N 2006. Modelling and passive correction investigation of vibration induced machining errors on CNC machine tools, University of Huddersfield,

[9] Devices A 2018 ADXL354/ADXL355 Low Noise, Low Drift, Low Power, 3-Axis MEMS Acceleromters Data Sheet (Rev. A)

[10] Iqbal A, Mian N, Longstaff A, and Fletcher S 2020 *20th International Conference of the European Society for Precision Engineering and Nanotechnology*. 535-538 euspen

[11] Iqbal A, Mian N, Longstaff A, and Fletcher S 2021 *21st International Conference of the European Society for Precision Engineering and Nanotechnology*. 513-516 euspen

[12] Iqbal A, Mian N, Longstaff A, and Fletcher S 2022 *International Journal of Automation Technology*

[13] Piezotronics P 2019 PCB 356A02 Tri-axial Accelerometer Data Sheet

[14] Vaseghi S V 2008 *Advanced digital signal processing and noise reduction*.(John Wiley & Sons).

[15] Indumathi A and Chandra E 2015 *ICTACT Journal on Communication Technology* **6** 1218-1222

[16] Berouti M, Schwartz R, and Makhoul J 1979 *ICASSP '79. IEEE International Conference on Acoustics, Speech, and Signal Processing* **4**. 208-211

[17] Boll S 1979 *IEEE Transactions on Acoustics, Speech, and Signal Processing* **27** 113-120

[18] Bouchikhi E H E, Choqueuse V, and Benbouzid M E H 2013 *IEEE Transactions on Energy Conversion* **28** 135-144

[19] Aghazadeh F, Tahan A, and Thomas M 2018 *The International Journal of Advanced Manufacturing Technology* **98** 3217-3227