Frequency Responses of the Breathing Sound Signals

M Harun[1, a)] M Z Ramli[1, b)], M A A Ahmad[1, c)], M Mohd Mokji[1, d)], A Yahya[1, e)], S Z Abdul Hamid[1, f)] J Kasim[1, g)]

Author Affiliations
[1]*School of Electrical Engineering, Universiti Teknologi Malaysia*

Author Emails
[a)] Corresponding author: mokhtarharun@utm.my
[b)] zulhairy@graduate.utm.my
[c)] muhammad_aasim64@yahoo.com
[d)] musa@fke.utm.my
[e)] azli@fke.utm.my
[f)] szaleha@fke.utm.my
[g)] joharikasim@utm.my

Abstract. The response of the breathing signal of an individual is different with respect to activities such as phonation and physical, and the condition of the lungs itself. This response can be gauged in terms of amplitude and frequency of the breathing signals. Compare to doing the physical activities alone, one's duration of inhalation is twenty percent lower when ones commit physical actives and talking at the same time. The purpose of this paper is to determine, from power spectral density (PSD) responses, the features, and their significance of the three types of breathing signals in terms of amplitude and frequency. PSD response of eighteen breathing signals had been investigated for the purpose. The samples were six each of normal breathing, wheeze, and crackles. The amplitude and its corresponding frequency of the PSD responses of these samples were taken from the highest first and second peak. For the frequency, two additional terms had been derived from the half-power amplitude of the PSD response. In terms of amplitude, for both the first and second peak, wheeze has manifested the highest value, while crackles breathing signals possess the lowest. On the other hand, among the three types of breathing signals, the frequencies of normal breathing are the highest both at the first and second peaks. There are no significance pairs, in terms of the amplitude and frequency at the second peak of the PSD responses. In terms of amplitude, at 5% significance level, there is one significance pair at the first peak of the PSD response, which is between wheeze and crackle breathing signals. There are two significance pairs in terms of the frequency of the PSD response, which are at f_{PSD1} and $f_{(low)1}$. However, at 10% significance level there are three significance pairs in terms of the frequency. In conclusion, the frequency of the PSD responses has more significant features than the amplitude for the recognition of the normal breathing and the abnormal breathing signals wheeze and crackle.

INTRODUCTION

Efficient breathing requires coordination between the diaphragm, abdominal muscle, and muscle in the rib cage. Tracking respiratory flow in terms of amplitude and frequency is a good marker to determine the features of the respective types of breathing signals [1]. Furthermore, respiration have been shown to be relevant for communication, for example, breathing pauses has been shown to be distinct from silence in speech communication [2]. However, searching for the features or signatures of breathing signals is quite a complicated task to deal with. The breathing signals have manifested a unique result in phonation or the production of utterance of a speech sound, communication, and when one is doing physical tasks while speaking or singing.

In a relaxed and uncontrolled set up experiment, Włodarczak and Heldner [3] had conducted an experiment to evaluate amplitude of inhalation, the ratio of inhalation-to-exhalation amplitude, and the duration of inhalation of breathing signals. Twenty-four participants that include 12 males and 12 females had been tested 24 minutes of each setup while having uninterrupted breathing (silent breathing), breathing while uttering very-short-utterance

(VSU), and breathing while speaking Swedish words. The authors found out that amplitude of inhalation is the highest during breathing while speaking which is 42.9% SV (speaking volume) compared to silent breathing (36.4% SV) and VSU (35.7% SV). The authors had come across an interesting and yet profound finding what speech can do to breathing amplitude. For silent breathing, the ratio of inhalation-exhalation amplitude is about 0, which means inhalation and exhalation amplitude is about the same. However, for breathing signals with VSU, and while the participants were breathing and speaking at the same time, it had been found that the logarithmic ratios turned out -0.04 and -0.16 respectively. It shows that with VSU and speaking, one exhales more than inhales, indicating that there is a shortage of oxygen supply in the body. For the inhalation duration that is measured in log2 ms, it has been found that its mean value equals 0.07, -0.11, and -0.27 for silent breathing, VSU, and breathing with speech, respectively. The result shows the inhalation duration of breathing of the participants while speaking is only 830 ms compared to the duration of inhalation during silent breathing which is 1.2 seconds.

In another study, Fuch et al. [4] had experimented breathing cycles in six conditions - quiet breathing, speaking, biking at ease and while speaking, and biking with effort alone and while speaking. Among the six conditions, the breathing cycle is the lowest, which is 0.15 cycles per second when the participants were speaking. Breathing cycles were found to be about the same when the participants were biking at ease and biking with effort, which is 0.35 cycles per second. Surprisingly, when the participants were biking and speaking at the same time, the breathing cycle dropped to 0.27 cycles per second. This finding indicates that there are 20% drops of the ventilation of the body. As for singing, Sundberg and Thalen [5] had found out that there is no significant breathing pattern during inhalation when six professional singers sang a song in belt and neutral styles. Belt singing is also known as high chest voice. Voice recording of belt and neutral singing was analyzed in terms of flow glottograms to determine the effect on lung volume in the percentage of vital capacity (VC), and the cross-sectional area of the rib cage and abdominal wall. In addition, belt and neutral singing were analyzed with respect to the positions of rib cage (RC) and abdominal wall (AW) of the singers. The differences are only on the sound level produced by the singers which is 8 dB higher for belt singing. As a note to be reckoned with, to investigate breathing patterns, the authors had concluded that the information in the beginning and in the end of inhalation phases are less reliable than the rest of the phases. Secondly, the amplitude of the fundamental frequency was found higher in belt singing.

TABLE 1. Study parameters and analysis methods for automatic recognition of breathing signals

Authors	Purpose	Study parameters	Analysis method
This paper	Determine the features of normal and abnormal breathings	PSD	Amplitude and frequency of PSD response
Manir [6]	Determine lung sound signature for patients with breathing related disease	Zero crossing, turn count, form factor, and mean variance of inspiration-exhalation ratio	DSP and PSD of lung sound signal
Wlodarczak and Heldner [7]	Detection of breathing pauses and silent pauses	Pauses of breathing inhalation between speech and normal breathing	Decide the pause from phrases stimuli listened through the headphones
Aras [8]	Determine the boundaries of respiratory cycles	Respiratory cycles	Dynamic Time Warping (DTW) algorithm
Mondal [9]	Develop automated pulmonary sound analysis AI	Data distribution patterns of normal wheeze and crackle breathing signals	Features extraction and computer aided diagnostic classifiers (ANN, SVM and GMM)
Mohd Ariff [10]	Vibration patterns in the thoracic cavity	Vibration of human chest wall	FFT and PSD
Chauhan [11]	Authentication of biometric signature of breathing gestures	Sniff, normal, and deep breathing sound	Spectrogram and GFCC classifier

Table 1 indicates that the study parameters of breathing sound signals were more in terms of magnitude rather than frequency of the signals. Digital signal processing tools and artificial intelligence classifiers are heavily depended on for the analysis of the data. When one's breathing is not normal, the symptom may warrant or indicate medical condition or a disease in the lung of that person. Auscultation is a simple and feasible method to detect abnormalities or diseases in the lung. Compared to radiography, auscultation process is non-invasive and convenient with the use of the stethoscope. Even though auscultation is a feasible method used most of the time, auscultation has become challenging once the physician gets old. As one gets older, one's hearing capability is also deteriorates, especially on hearing the lower frequency sound. With the frequency of wheeze sound that can go as low as 80 Hz, and heart sound that is the region lower than 100 Hz, the interpretation of auscultation may be difficult for those with difficulty in hearing low frequency sound. Because auscultation is performed only by highly trained physician, the type of the breathing abnormalities may be interchangeably interpreted [3], [12], [13]. According to Bohadana et al. [13] that has acquired auscultation verdicts from 143 participants with medical background, normal breathing and pleural friction rub sound signals have been poorly interpreted. The participants had been asked to classify acoustically 5 types of breathing sound signals – normal breathing, wheeze, crackles, stridor, and pleural friction rub. Well trained staff physicians have had only 21% correct auscultation verdict for normal breathing, and mere 35% for pleural friction rub. It is the intention of the authors to design automated auscultation for the identification and monitoring of abnormal breathings. Therefore, in this paper, the investigation to determine the features of normal, and abnormal breathings was carried out. By having significance features of the breathing signals, automatic determination of the types of abnormal breathing can be determined automatically. In addition to the verdict of the types of breathing signals from the trained physician through manual auscultation, the automated auscultation may be able to cross check the verdict or to train new physician to perfect his manual auscultation verdict.

METHODOLOGY

This paper reports a segment of findings of the larger part of the project, which is to design automatic auscultation for determining the types of abnormal breathing. Sixteen breathing signal samples in *.wav* file (six samples from each breathing signals - normal breathing, wheeze, and crackle), had been investigated for the purpose. The *.wav* files of the breathing signals were acquired at various free public websites over the internet.

The authors had conducted the experiment to determine the features of the breathing signals in terms of amplitude and its corresponding frequency from the power spectral density (PSD) response of the breathing signals.

Process flow of the experimentation is shown in Figure 1. PSD of the breathing signal was acquired by using Welch's power spectral density estimation (Pwelch). PSD response was generated using 50% overlapped Kaiser window. Figure 2 show a sample of abnormal breathing signal wheeze in *.wav* file, Fast Fourier Transform (FFT), and PSD. The first two peaks from the PSD response of each breathing sound signal had been chosen for the analysis. For each peak, the magnitude and its corresponding frequency had been analyzed for the significance of the features. As illustrated in Figure 3, at the peaks, four features had been recorded from the corresponding PSD response. In terms of magnitude, they are PSD1 and PSD2. The features f_{PSD1} and f_{PSD2} are the corresponding PSD's frequency at the peaks. The authors believe it is beneficial to derive the information of the width of the peaks among the different types of the breathing signals. It is from the width of the peaks of PSD response, one may be able to quantify the magnitude of resonance in the breathing signal. To include the feature of the resonance in the breathing signals, the authors had recorded the lower and the higher frequency at the half-power amplitude of the peak of the PSD response [14], [15]. Four more features in terms of the frequency were derived - f(low)1 and f(high)1 (for the first peak), and f(low)2 and f(high)2 (for the second peak).

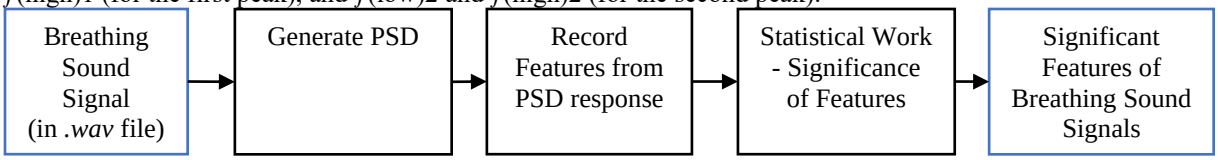
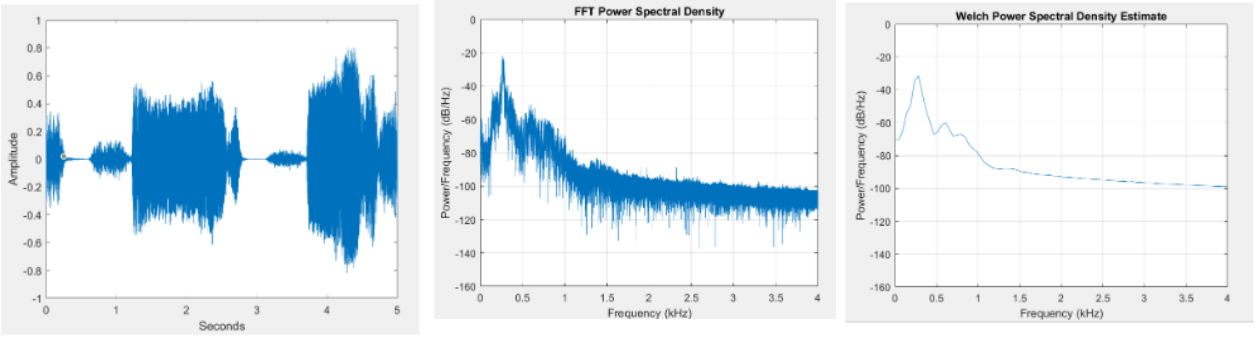


FIGURE 1. Process flow of the experimentation

The statistical analysis was done, in a pair, by extracting statistical data such as minimum, average, and maximum from a type of breathing signal and then compared them against the other type of breathing signal. The statistical significance between two breathing signal data was performed by using Student's t-test; the test was done

by using the relevant statistical functions provided by Microsoft Excel 2007. Also, the regression and the relationship between the breathing signal data were obtained by manipulating statistical regression function in Microsoft Excel 2007.



(a) (b) (c)

FIGURE 2. Abnormal breathing signal wheeze: (a) in *.wav* file, (b) FFT, and (c) PSD

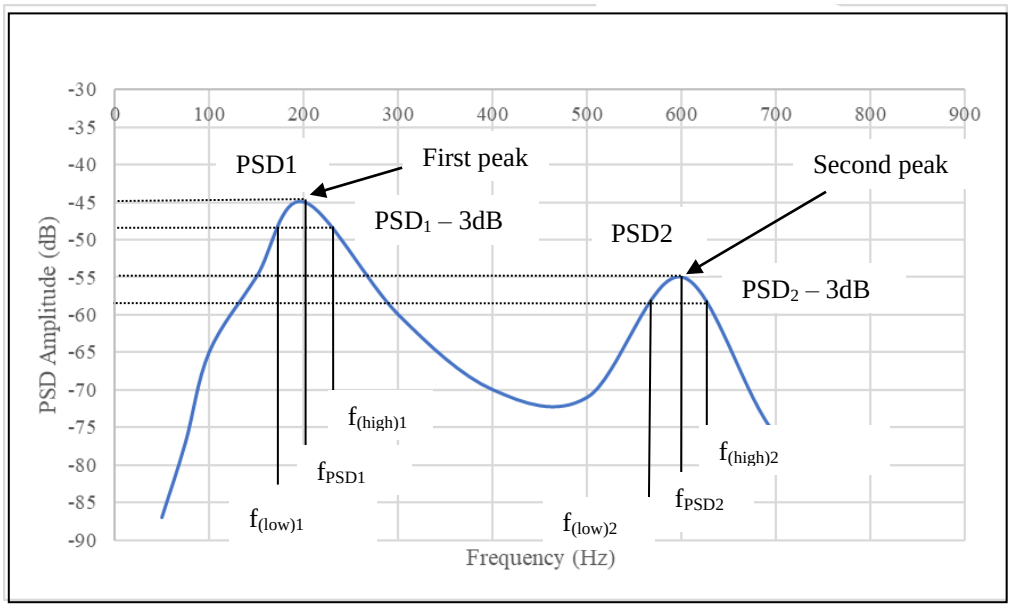


FIGURE 3. Analysis of PSD response

RESULTS AND DISCUSSIONS

Table 2 tabulates the PSD responses at the peaks and half-power amplitude. At the peaks, two types of information have been gathered – the maximum amplitude, PSDi, and the frequency *f*PSDi. At half-power amplitude, two additional frequency terms have been analyzed – *f*(low)i and *f*(high)i. There are two features in terms of the amplitude, and six features in terms of the frequency. Altogether, there are eight features derived from the two peaks of the PSD responses of the breathing sound signals. The data in Table 2 and Table 3 have been transformed into Figure 4, Figure 5, and Figure 6, respectively. In Figure 4, except the maximum amplitude at the second peak, amplitude of breathing signal wheeze was the highest among the three types of breathing signals tested, in terms of minimum and average amplitude of the PSD response. In terms of minimum, maximum, and average amplitude, the amplitude of breathing signal crackle was found the lowest.

The frequencies of normal breathing signals have been found the highest among the three types of breathing signals. Also in Figure 5, at the first peak, the second and the third highest frequency are wheeze and crackle respectively. However, at the second peak, the order changes with crackle the second and breathing signal wheeze the third.

TABLE 2. PSD response at the peaks and half-power amplitude

Sample	PSD (dB/Hz)							
	First peak				Second peak			
	$f_{(low)1}$ (Hz)	PSD1 (dB)	f_{PSD1} (Hz)	$f_{(high)1}$ (Hz)	$f_{(low)2}$ (Hz)	PSD2 (dB)	f_{PSD2} (Hz)	$f_{(high)2}$ (Hz)
N1	423	-62.1	470	417	856	-52	903	950
N2	223	-35.9	270	317	548	-55.9	595	642
N3	370	-71.8	417	464	870	-74.1	917	964
N4	558	-45.3	605	652	883	-54.7	930	977
N5	601	-62.3	648	695	919	-62.3	966	1013
N6	209	-39.4	256	303	558	-47.6	605	652
W1	223	-31.7	270	317	561	-60	608	655
W2	331	-58.6	378	425	467	-59.3	514	561
W3	210	-33.8	257	304	561	-49	608	655
W4	228	-32.3	275	322	553	-61.3	600	642
W5	278	-47.5	325	372	841	-55.6	888	935
W6	478	-29.4	525	572	541	-58.7	588	635
C1	187	-56.8	234	281	599	-58.1	646	693
C2	184	-54.8	231	278	594	-56.1	641	688
C3	191	-56.9	238	285	591	-57.7	638	685
C4	376	-72.9	423	470	876	-74.8	923	970
C5	184	-56.8	231	278	620	-58.7	667	714
C6	178	-55.5	225	272	578	-56.1	625	672

TABLE 3. Descriptive statistics of the breathing signals

Breathing Type	Statistical Data	PSD (dB/Hz)							
		First peak				Second peak			
		$f_{(low)1}$ (Hz)	PSD1 (dB)	f_{PSD1} (Hz)	$f_{(high)1}$ (Hz)	$f_{(low)1}$ (Hz)	PSD2 (dB)	f_{PSD2} (Hz)	$f_{(high)2}$ (Hz)
Normal	Min	209	-72	256	303	548	-74	595	642
	Max	601	-36	648	695	919	-48	966	1013
	Ave	397	-53	444	475	772	-58	819	866
Wheeze	Min	210	-59	257	304	467	-61	514	561
	Max	478	-29	525	572	841	-49	888	935
	Ave	291	-39	338	385	587	-57	634	681
Crackle	Min	178	-73	225	272	578	-75	625	672
	Max	376	-55	423	470	876	-56	923	970
	Ave	217	-59	264	311	643	-60	690	737

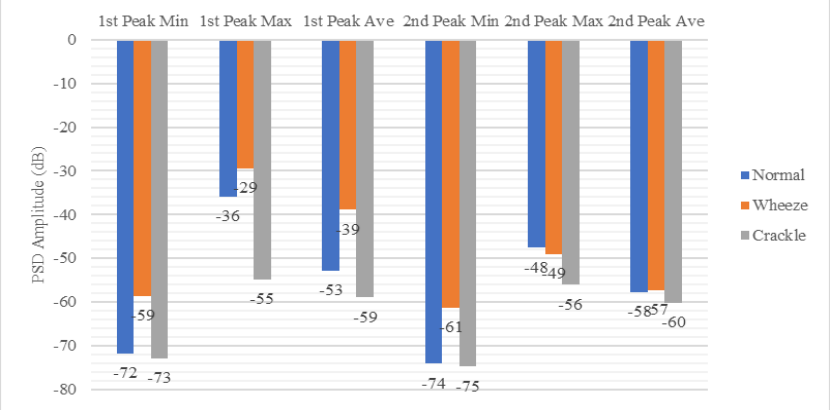


FIGURE 4. Amplitude of PSDi of the breathing signals

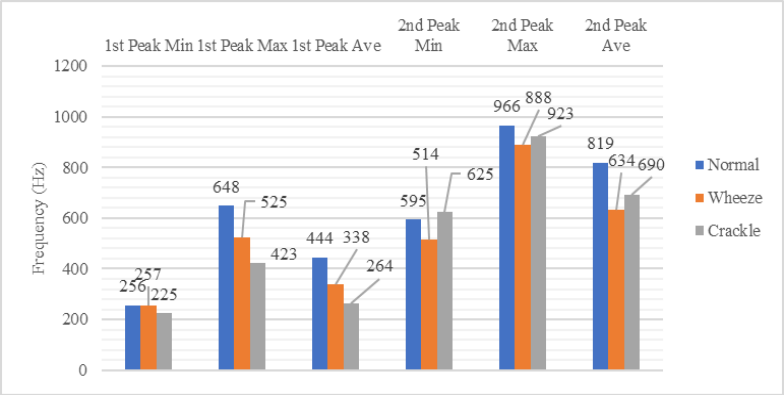


FIGURE 5. Frequency of PSDi of the breathing signals

At the half-power amplitude of the PSD peak, again, in Figure 6, the lower frequency band at the first peak (f(low)1) follows the same pattern as those in Figure 5. However, at the second peak there is no consistent pattern is observed. As for the higher frequency band, again at the first peak, in Figure 6, the highest to the lowest f(high)2 is in the order normal, wheeze and crackle. For f(high)2, the frequency of normal breathing is still the highest. However, f(high)2 of crackle is second and wheeze the third.

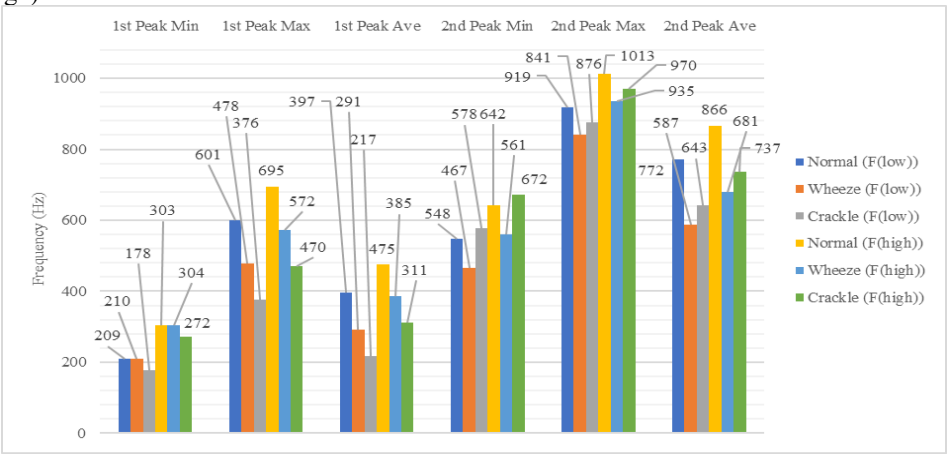


FIGURE 6. $f_{(low)i}$ and $f_{(high)i}$ of the breathing signals

to Figure 5, except the minimum value at the second peak, the frequencies of normal breathing signals are the highest. The average frequency value of normal breathing signals is 444Hz and 819Hz for the first and second peak, respectively. On the other hand, the frequencies of abnormal breathing signals crackle (264Hz at the first peak) and wheeze (634Hz at the second peak) are the lowest.

Table 4, Table 5, Table 6, and Table 7 tabulates the results of significance tests among the three types of breathing signals (Note: "N" stands for "normal"; "W" stands for "Wheeze"; "C" stands for "Crackle").

In terms of amplitude, as evident in Table 7, none of the pair at the second peak are significant. In Table 5, however, PSD amplitude at the first peak (PSD1) has been found highly significant for the pair between wheeze and crackle with p-value equals 0.007. In terms of frequency of the PSD response, in Table 4, the features f(low)1 and fPSD1 (both for the pair normal and crackle) are significant at significance level 5% with p-value of 0.045.

In Table 6, at significance level 10%, the features f(low)2, fPSD2 and f(high)2 (all are at the pair normal and wheeze) are significant with p-values equals 0.045. In terms of the distribution of the PSD responses at the first and second peak, it is evident from Figure 7 that they are more disperse at the first peak, both in terms of the amplitude and frequency. In addition, at the second peak the small change of amplitudes of the PSD response are lumped into two groups: 5 dB deviations (frequency range 590Hz to 680Hz) and 6 dB deviations in the frequency range 890Hz – 980Hz. This finding in Figure 7 explains why there is no significant pairs in terms of amplitude, at the second peak.

TABLE 4. P-value of First Peak Frequencies across Normal, Wheezing, and Crackle

First Peak Frequencies									
	$f_{(low)1}$			PSD1			$f_{(high)1}$		
	N	W	C	N	W	C	N	W	C
N		0.216	0.045		0.216	0.045		0.294	0.065
W			0.188			0.225			0.188

TABLE 5. P-value of First Peak Amplitude across Normal, Wheezing, and Crackle

First Peak Amplitude									
	$f_{(low)1}$			PSD1			$f_{(high)1}$		
	N	W	C	N	W	C	N	W	C
N		N/A	N/A		0.097	0.381		N/A	N/A
W			N/A			0.007			N/A

TABLE 6. P-value of Second Peak Frequencies across Normal, Wheezing, and Crackle

Second Peak Frequencies									
	$f_{(low)2}$			PSD2			$f_{(high)2}$		
	N	W	C	N	W	C	N	W	C
N		0.064	0.159		0.064	0.159		0.063	0.159
W			0.449			0.449			0.443

TABLE 7. P-value of Second Peak Amplitude across Normal, Wheezing, and Crackle

Second Peak Amplitude									
	$f_{(low)2}$			PSD2			$f_{(high)2}$		
	N	W	C	N	W	C	N	W	C
N		N/A	N/A		0.918	0.619		N/A	N/A
W			N/A			0.422			N/A

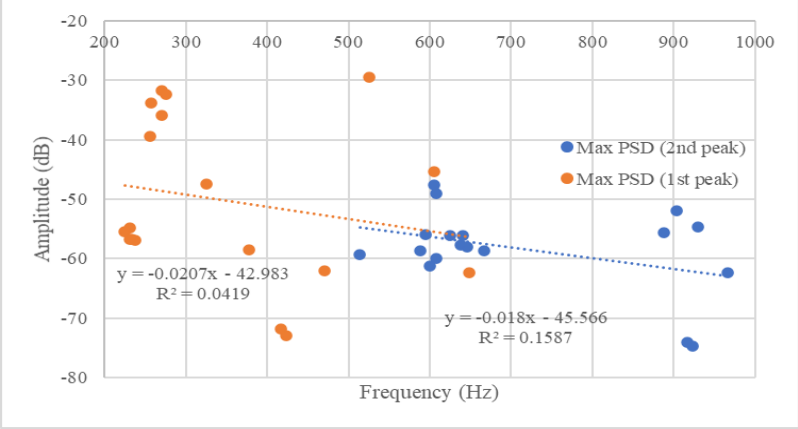


FIGURE 7. The linear regression between max PSD amplitude and max PSD frequency for the first peak

CONCLUSION

In conclusion, from the first and second peak of the PSD response, the study has been able to identify two features of breathing sound signals in terms of the amplitude and six features in terms of the frequency. Therefore, this study has been able to identify eight features of the breathing sound signal from the peaks and at half-power amplitude of the PSD response. In terms of the usefulness and significance of the features at the peaks of the PSD response, the second peak bears no useful feature in terms of the amplitude. As in Figure 7, this happens since the amplitude of the breathing signals at the second peak does not change much in two frequency ranges. The amplitude of the tested breathing signals deviates only about 5dB and only lumped at two frequency ranges: 590 Hz to 680 Hz, and 890 to 980 Hz. The frequency features f(low)1 and fPSD1 at the first peak is worth explored further to identify

breathing signal characteristics, especially for the normal breathing and the abnormal breathing wheeze. As the frequency features f(low)2, fPSD2 and f(high)2 are statistically significant at 10% significance level, it hints the authors to revise the process flow of the experimentation. The finding indicates that there is the possibility to increase the usefulness of these features by achieving the statistical significance of the features at 5% significance level.From the findings in this paper, the authors believe that the automated auscultation is very promising by gaining more distinct characteristics of the breathing sound signals by harnessing the frequency components of the PSD response at the first peak – both at the peak and half-power amplitude.

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