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Tonality Analysis of Wind Turbine Noise Based on IEC Standard

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Abstract: The tonality is a notable factor during the development of wind farms. Tonality is a component of acoustic noise emission from the wind turbine which annoys the surrounding area of the wind farm. This paper focuses to evaluate the tonality of the wind turbine acoustic measurement data based on the standard IEC 61400-11 AMD 2018: ed. 3.1. The narrowband analysis of the wind turbine tonal noise component is fully evaluated as given in the standard. The identification of tone and classification of spectral lines is performed for all spectra of the specified wind speed bin. The results are obtained based on the IEC approach: masking level, tonality, and tonal audibility for the sample data of a specific wind speed bin. The audible tones are found for all spectra and reported in the results. The IEC method gives a good prospect of tonality assessment for wind turbine noise measurement from this result.

Keywords: Tonality, masking, audibility, acoustics, wind turbine, narrowband, spectral lines

I. INTRODUCTION

Wind energy is one of the harmless renewable sources of energy that attract worldwide energy industries. But the noise generates by the wind turbine during the energy generation is a more risk factor in the environment [1]. Noise emission in wind turbines is a serious environmental issue and is highly considered and assessed in many countries. The limitations and guidelines are prepared and provided to the wind farm for noise assessment. The noise in wind turbines is produced from two sources: aerodynamic noise and mechanical noise. Due to the interaction between air and turbine, the aerodynamic noise is created and this is classified into turbulence noise, tonal noise, and airfoil noise [2]. The tonal noise is one of the components that makes risk factors even at low levels. The residential surrounding environment of wind farms may affect due to the increasing annoyance of tonal components. In some countries, there is a penalty for high annoyance due to tonal components [3].

The international standard of ISO 1996-2:2017 explains the components for evaluation of tonal audibility using psychoacoustic principles [4] and the procedure for tonal analysis implies the energy ratio of a tonal component to masking noise with the masking index obtained from the test conducted repeatedly in the machine ISO/PAS 20065: 2016[5]. The assessment of tones based on the same manner of the listener is provided in the NZ6808. It used the concept of Psychoacoustics in the critical band for assessing tonal components. This standard includes adjustments in tonality in the sound levels of the wind farm [6]. Most of the wind farm complaints are the high annoyance caused by the tonal component. The complaints are found from the survey and the potential of tonal noise that annoyed is obtained and penalized. The extent of the tone appropriate to the penalty is imposed in BS 4142 and ESTU-97[7]. The international electrotechnical commission for wind turbine generator systems gives the standard of acoustic noise measurement technique in part 11 (IEC61400-11). In this standard, the narrowband analysis is used to find the tones in the noise for different wind speeds [8]. Evans et al [9] reviewed and compared the tonal noise assessment regulations used in Australia as well as internationally. In these methodologies, the penalty has been added to the measured spectrum when the peak frequency exceeded the criterion level. And also they studied the differences in regulations for tonal noise from different sources. Arana et al [10] studied the tonality assessment based on IEC 61400-11 and used this procedure to develop the algorithm to evaluate the tonal noise from wind turbines. Cooper et al [11] identified the frequency level of audible tones in the residence nearer to the wind farm using IEC 61400-11 assessment method. They resulted in the tonal frequency of 124HZ being audible in the larger and smaller wind speed conditions at night. Also, the wind speed and direction in which the audible tones evolved were assessed based on the standard. Kobayashi and Yokoyama [12] used the narrowband analysis in wind turbine noise for roughly estimating tonal audibility. The maximum tonal component level and average masking noise levels present in the critical band centered by the tonal component were compared in the roughly estimated tonal audibility applied in the FFT spectrum. Liu et al [13] evaluate the tonality by using the new method of Gabor filtering used for the separation and processing of noise in the sound from the wind turbine. They evaluate the noise that the procedure illustrated in the IEC standard.

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The major objective of this paper is to evaluate the tonal components of IEC 61400-11 sample spectra of wind turbine noise. The narrowband analysis of wind turbine noise is based on the procedure of standard IEC61400 part 11 editions 3.1. By using this principle, the masking level, tonality, and tonal audibility of the 30 sample spectra are evaluated. This paper consists of a work methodology explaining the principle and method of evaluation in section 2. The noise measurement and tonality analysis method are explained in section 3. The results obtained from the analysis are discussed in section 4 and the summary of the future scope of this work is discussed in the conclusion of section 5.

II. WORK METHODOLOGY

The tonality analysis of the sample spectra for wind turbine noise measurement is evaluated in this paper. The evaluation of tonal components is based on the principle and procedures of the IEC 61400-11 standard. The A-weighted sample spectra of tonal noise are measured at the energy average period of 10s is considered in this paper. The narrowband analysis sample spectra at the specified bin center wind speeds are evaluated hence the frequency range for the analysis is limited from 20HZ to 11200Hz. And its frequency resolution for the spectra is 2Hz. In this sample analysis, 30 spectra are considered for tonality evaluation. The wind speed bin should contain a narrowband spectrum of not less than 6 identified tones of similar origin thus it determining the tonal audibility. If the tone has a similar origin, it is taken as a single tone. The detailed methodology of tonality analysis based on the IEC standards is given in the flow chart in fig.1.

The following results are obtained for each spectrum of the selected wind speed bin with the identified tone:

1) Sound pressure level of tone $L_{Pt,j,k}$
2) Sound pressure level of masking noise $L_{Pn,j,k}$
3) Tonality $\Delta L_{tn,j,k}$
4) Tonal audibility $\Delta L_{a,j,k}$

The tonal audibility obtained from the same origin of the spectrum is used to find out the overall tonal audibility. The conditions are given to the tonal component to identify the audibility. if it satisfies the condition then reported as audible otherwise it is reported as no relevant tone.

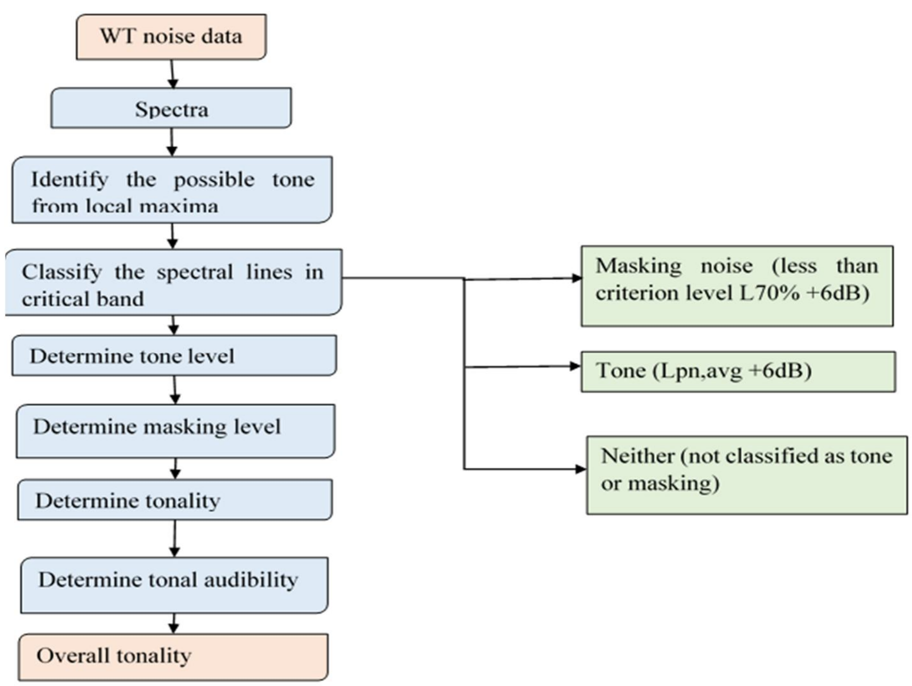

Figure 1: Tonality analysis methodology

III. TONALITY ANALYSIS METHOD AND MEASUREMENT

A. *Tonality Analysis Method*

The evaluating principle of tonal audibility is explained in the standard of IEC 61400-11 [8]. The major scope of this standard is to provide the procedure for the wind turbine acoustic noise measuring, analyzing the data, and reporting. In tonality analysis, the initial step is identifying the possible tones in each spectrum. The tones are identified by using the local maxima of the spectrum. The critical bandwidth of the spectra is calculated by using the frequency of local maxima in the equation:

$$CB = 25 + 75 \cdot \left(1 + 1.4 \cdot \left(\frac{f_c}{1000}\right)^2\right)^{0.69} \tag{1}$$

Where f_c denotes the critical frequency of local maxima. The average energy of the critical band is calculated by excluding the local maxima and their two adjacent lines. The average energy is calculated by using:

$$Avg.\ Energy = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{Li}{10}}\right) \tag{2}$$

The tone is classified if it is above 6dB than the average energy. The classification of spectral lines is done by placing the critical band in the spectra with the local maxima as the center frequency. In this critical band, every line is classified as tone, masking, and neither. For this classification, the energy average of 70% of the lowest level spectral lines in the critical band is calculated. The criterion level is noted as L70% +6dB. The spectral lines less than the criterion level are called masking and their energy average is L_{pnavg}. The spectral lines which are classified as tones are higher than the value of L_{pnavg} + 6dB. If there are more spectral lines classified as tones in the spectrum, then the lines within the 10dB level from the highest level are called tones. If the spectral line does not present in either tone or masking is classified as neither.

- To determine the tone level ($L_{pt,\ j,\ k}$) the identified possible tones of spectral lines in the critical band are energy summed. The obtained tone level is subtracted by 1.8 dB if there are more than 2 adjacent lines.

$$Energy\,sum = 10\log\left(\sum_{i=1}^{n} 10^{\frac{Lpt,i}{10}}\right) \tag{3}$$

- The masking noise level ($L_{pn,\ j,\ k}$) is determined by using the average masking level. The masking is calculated by using the equation:

$$L_{pn,j,k} = L_{pn,avg,j,k} + 10\log\left(\frac{CB}{Effective\ noise\,bandwidth}\right) \tag{4}$$

  Where CB is critical bandwidth, the effective noise bandwidth is obtained by 1.5*frequency resolution and the frequency resolution in the narrowband analysis is 2Hz.

- The difference between tone level and masking noise level is called tonality.

$$\Delta L_{tn,\,j,k} = L_{pt,j,k} - L_{pn,j,k} \tag{5}$$

  If there is no tone obtained in the critical band then the tonality is identified by using the equation:

$$\Delta L_{tn,j,k} = -10\log\left(\frac{CB}{Effective\ noise\,bandwidth}\right) \tag{6}$$

- It is the sense of the human ear to the tonal noise that is called audibility. The correction should be considered in tonal components based on the human ear response level. The tonality of the component is calculated by using:

$$\Delta L_{a,\,j,k} = \Delta L_{tn,\,j,k} - L_a \tag{7}$$

In this equation, La denotes the audibility criterion which is obtained by:

$$L_a = -2 - \log\cdot\left[1 + \left(\frac{f}{502}\right)^{2.5}\right] \tag{8}$$

Where *f* is the maximum tone frequency. In this, the tone from the same origin is taken as one tone. The tonal audibility should meet the condition $\Delta L_{a,j,k} \geq -3.0dB$ which is reported as audible else it is reported as no relevant tone. The tonal audibility higher than 20% at less than 6 spectra should be reported but if it is less than 20% in 10 spectra should not be reported. The overall tonal audibility is defined as the energy average of individual tonality of the spectra.

B. Wind Turbine Noise Measurement

The acoustic measurement conducted on the wind turbine is based on the principle and procedure given in the standard IEC61400-11[8]. The measurement of tonal audibility is done at a hub height of the turbine at bin center wind speeds. The tones present in the wind turbine noise and its tonal audibility are measured. The limitation of wind speed for measurement is based on the specification of the turbine. The approximate range of wind speed for the 10m height of the turbine is 6m/s to 10m/s. Due to the effects of terrain, the measurement should be taken nearer to the turbine. The dimension of the wind turbine is used to fix the reference distance. The microphone used for the measurement is placed on the ground. From this, the spectra of the sound pressure levels are measured for different wind speed bin centers.

The equipment used for measuring narrowband spectra should meet the requirements of the IEC 61672 series class 1[14] standard for instrumentation and its frequency within the range of 20Hz to 11200Hz. The microphone reference position is in the downwind direction and is placed on a round hardboard with a diameter of 1m and a thickness of 12mm and its axis points to the vertical centerline turbine. The acceptable signal-to-noise ratio is obtained at low frequencies by using the windscreen in the microphone. The acoustic measurement instruments are calibrated before the measurement which fulfills the standard requirements of the IEC 60942: 2003 class1[15]. The downwind direction of the wind turbine is fixed for the reference position of measurement. The reference distance between the wind turbine and microphone position is calculated by using the correlation of:

$$R_0 = H + \frac{D}{2} \tag{9}$$

Where the distance from the ground to the rotor center is denoted as H, rotor diameter is denoted as D and R_0 is the reference distance. During the measurement, the intruding background noises are omitted and the acoustic signals are recorded and stored. The measurement of all wind speed ranges is covered and more than 10 measurements are taken for each wind speed bin. The narrowband spectra are measured with the energy average period of 10s. It is A-weighted, a Hanning window is used with 50% overlap and used 2Hz frequency resolution. The tonal analysis of data from the measurement is combined with the pooling of available data and analyzing the result. The acoustic measuring and data analyzing system setup is given in Figure 2.

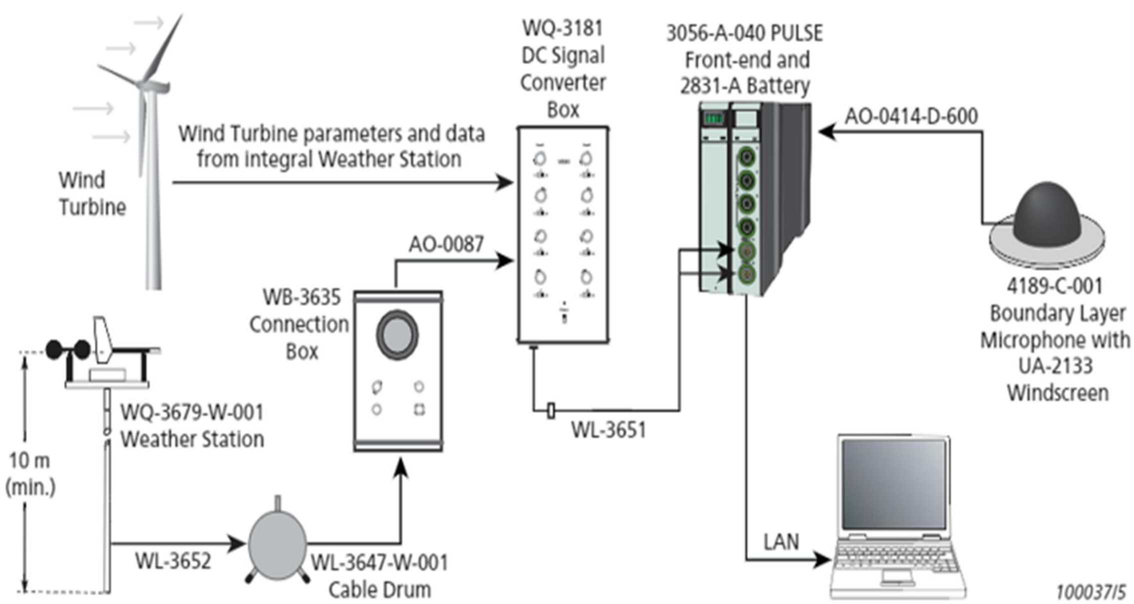

Figure 2: Typical wind turbine noise measurement setup [16]

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IV. RESULT AND DISCUSSION

The tonality result obtained from the IEC 61400-11 sample spectra of wind turbine noise measurement is given in this section. The result analysis is done on the sample spectra based on the IEC 61400-11 standard. In the narrowband analysis, the tonality calculation is performed in 30 spectra of the different frequency bands. These spectrum bands are analyzed in the frequency resolution of 2Hz. The frequency of first spectra S01 is given in Figure 3.

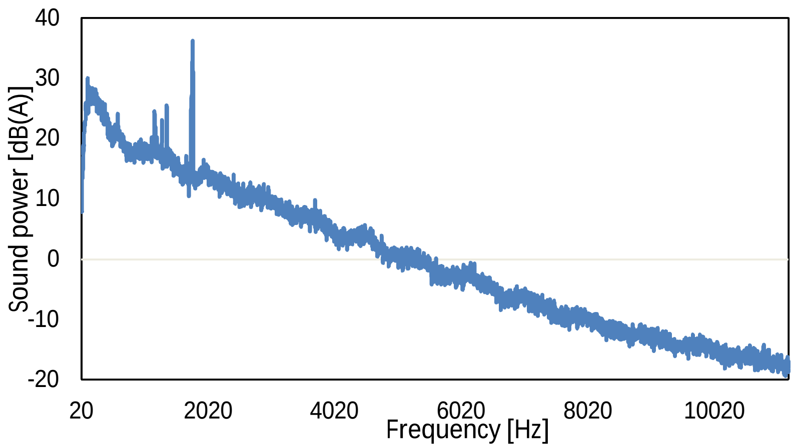

Figure 3: Frequency spectrum S01

The tonality analysis begins with the identification of possible tones in the spectrum. The local maxima obtained in the spectra S01 is 36.21 dB in the maximum tone frequency of 1776Hz. By using the maximum tone frequency, the critical bandwidth of 266 is obtained from equation 1. The critical band of the S01 is placed using the maximum tone frequency as the center frequency. In this spectrum, the critical band contains 133 spectral lines which are half of the critical bandwidth measured from the frequency range of 1644Hz to 1910Hz respectively. The energy average of the critical band is calculated by using equation 2. During the calculation, the highest level of spectral line and its two adjacent lines are neglected. The obtained energy average of spectrum S01 is 20.29 dB and it is explained in Figure 4

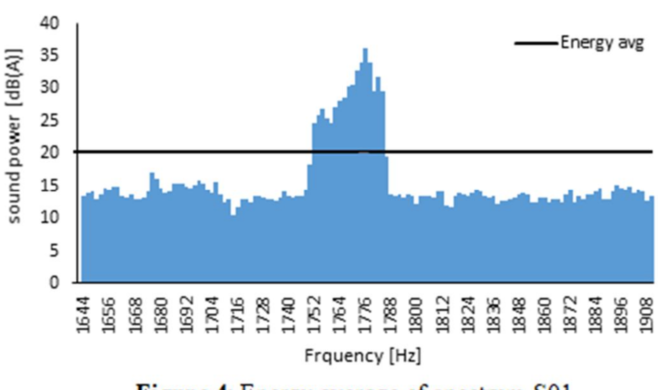

Figure 4: Energy average of spectrum S01

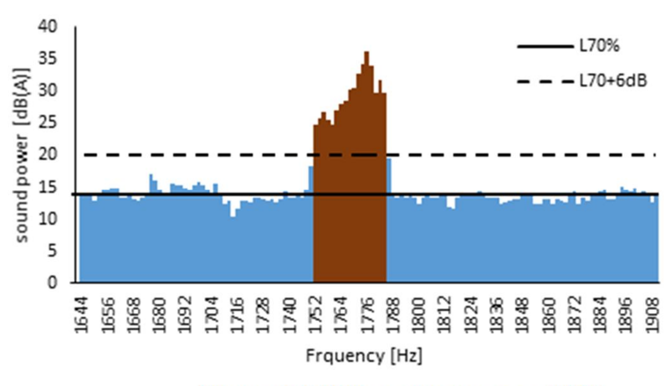

Figure 5: L70% energy average of S01

The spectral lines with 6 dB above the energy average are classified as tones. For further classification of spectral lines in the critical band, the 70% energy average of the lowest level spectral lines is calculated (13.99dB) given in Fig. 5. To define the 70% of the lowest level, the spectral lines are sorted in the ascending order, and then find 70% of the lines.

The criterion level was also noted which is the addition of 6dB to the L70% energy average (19.99 dB). Based on this criterion level, masking, tone, and neither lines are classified. The lines below the criterion levels are masking and the average masking level obtained is 13.96 dB. The masking level of the critical band is given in Fig.6.

The tones are classified where the spectral lines are above the level of $L_{pn\ avg}$ +6 dB is 19.96 dB. In this critical band, there are more than two spectral lines are classified as tones hence the actual tones are classified by considering the lines within the 10dB from the highest tone level. The obtained $L_{pt\ max}$-10dB is 26.21 dB. In this critical band, the lines which are not included in either tone or masking noise are considered as Neither. The Tone, Masking, and Neither classification of spectral lines are given in Fig.7.

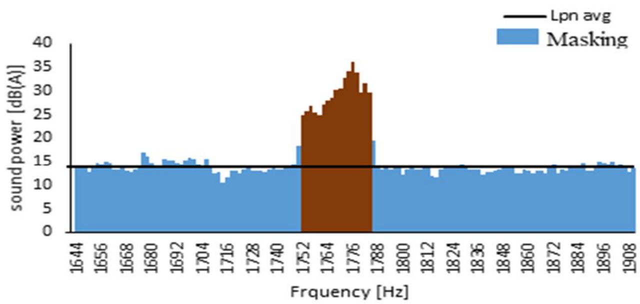

Figure 6: Masking noise level of S01

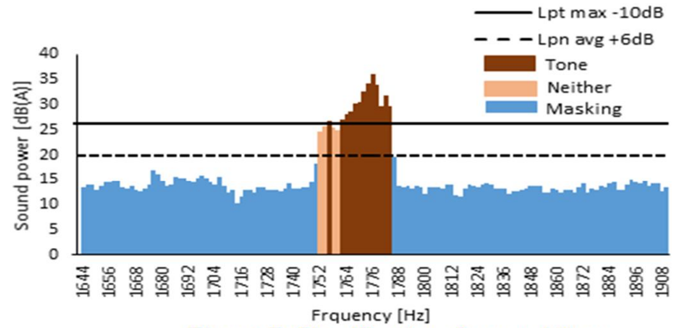

Figure 7: Classification of spectral lines

The tonal level of the critical band is calculated by using equation 3. It is obtained by energy summing of classified tones. In the S01 spectrum, the tonal level obtained for the spectral lines is 42.79 dB. In this band more than 2 spectral lines are classified as tone hence it requires correction using the Hanning window. This correction indicates the subtraction of 1.76 or 1.8dB from the obtained tone level and the final tone level for S01 is 41.04 dB. The $L_{pn\ avg}$ obtained is 13.99 dB is used to find the masking level of the critical band. By using equation 4, the masking noise level of $L_{pn,\ j,\ k}$ is calculated and it is 33.44 dB. The tonality of the critical band is 7.59 dB obtained by using equation 5. If there is no tone identified, then the tonality is calculated by using equation 6. Finally, the tonal audibility of the spectrum is calculated by using equation 7. The tonal audibility of the S01 spectrum is 11dB with the audibility criterion of -3.4. The condition required for tonal audibility is it is to be reported. For spectrum S01, 11dB is greater than -3 dB hence it should be reported as audible. The observed results of the S01 spectrum are given in table 1.

Table 1: Tonality result of S01

Spectrum No.	Tone (dB)	Tone frequency (Hz)	Critical bandwidth	Energy average (dB)	Masking level $L_{pn,\ j,\ k}$ (dB)	Tonality $\Delta L_{tn,\ j,\ k}$ (dB)	Audibility $\Delta L_{a,\ j,\ k}$ (dB)	Result
S01	36.21	1776	266	20.29	33.44	7.6	11	Reported audible

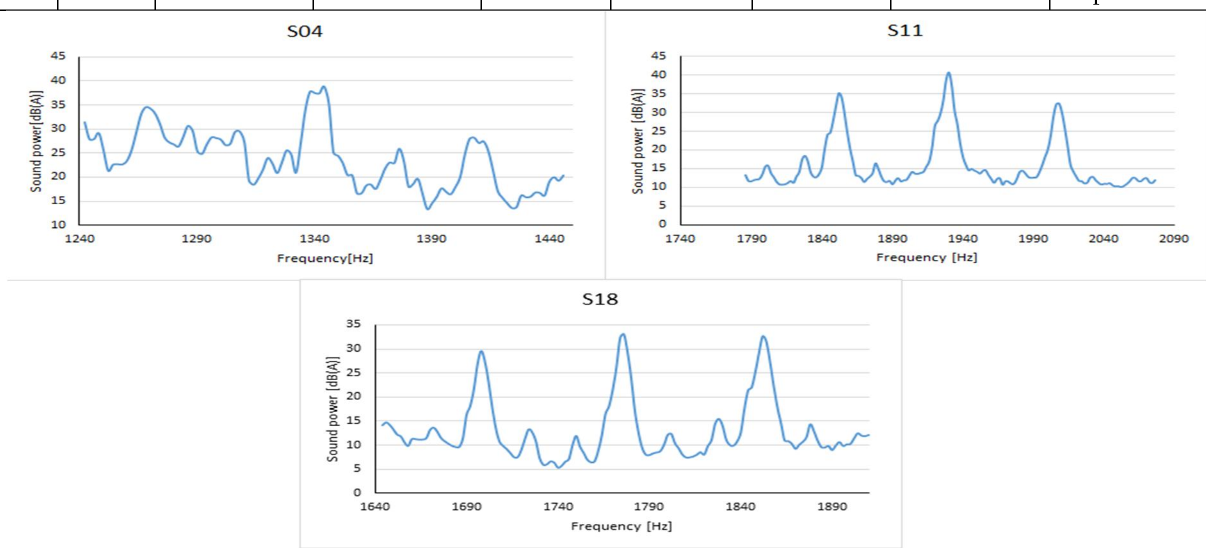

Figure 8: Critical bandwidth of spectra S04, S11, and S18

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In some spectra, multi tones are identified in its critical band. In that case, the value tonal audibility gives the large deviations, especially in the frequency range of tones within 1 to 2KHz and it is considered a bias or random error. For example, the sample spectra S04, S11, and S18 are the multi-tone spectrum. These spectra would have the values differences in 0.7 dB. Figure 8 represents the critical bandwidth frequency line of these sample spectra.

Similarly, the critical band of all the spectra is calculated and illustrated in Fig. 9. The classification of the spectral lines in all spectrum is performed and the tonality of these spectra are analyzed. The different tone frequencies are identified in all spectra. The tonal audibility is obtained in the frequencies of 70, 98, 104,126, 136, 152, 162, 224, 380, 698, 740, 748, 888, 1172, 1344, 1750, 1776, 1930, 2096, 6984, and 6986 HZ. The result obtained from these spectra is given in table 2.

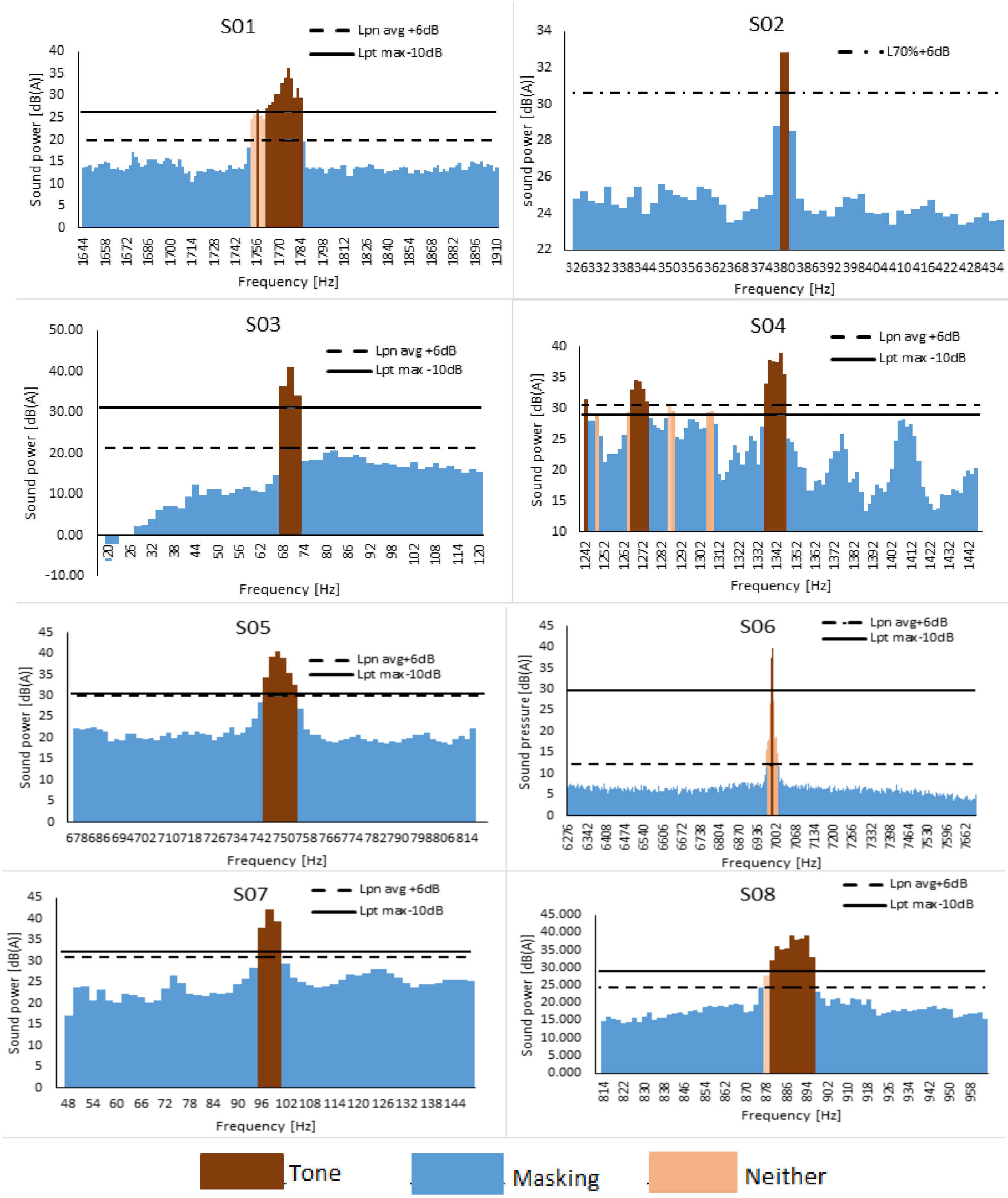

Figure 9: Classification of the spectral line for all spectra

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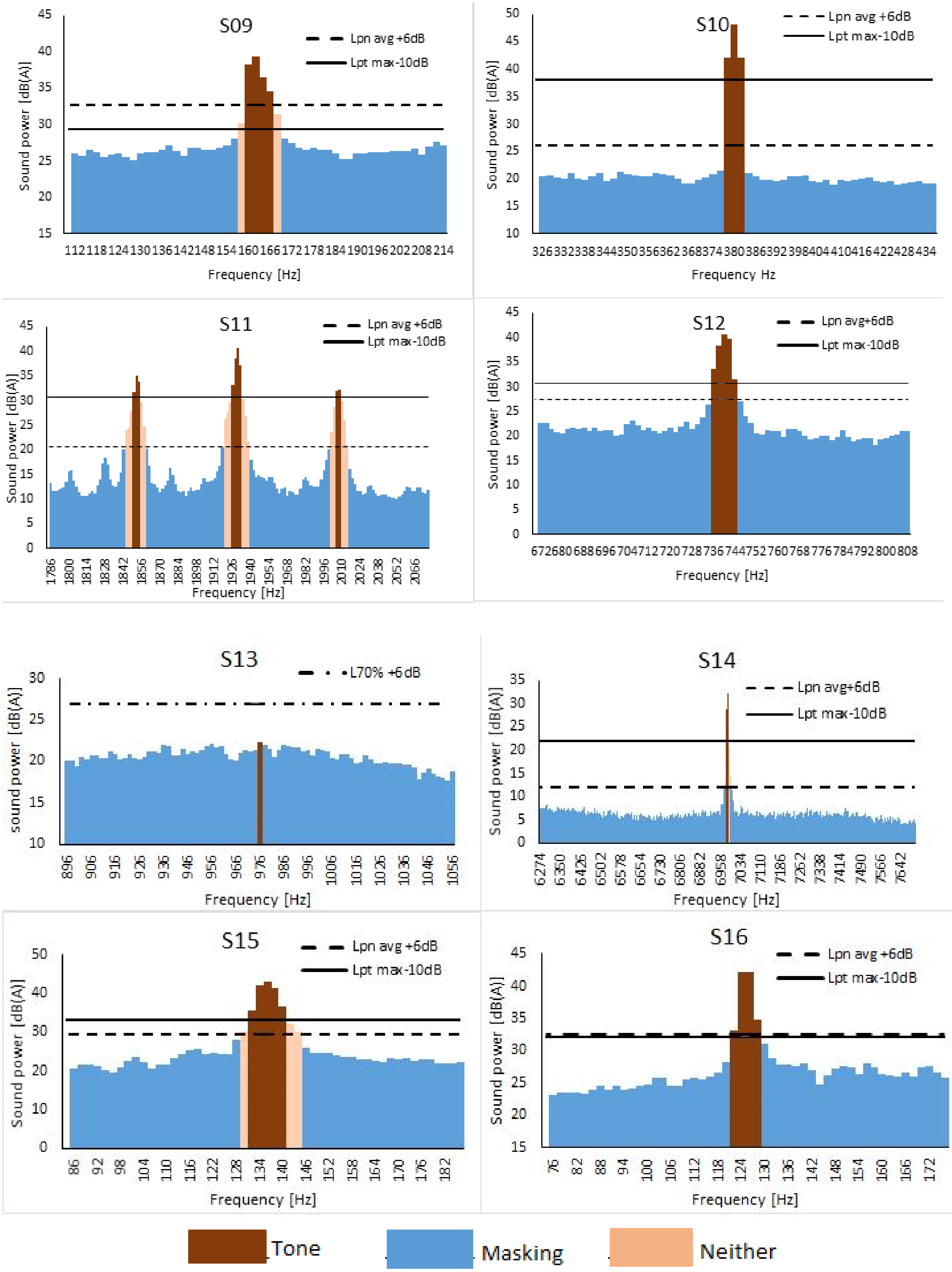

Figure 9: Classification of the spectral line for all spectra(continuation)

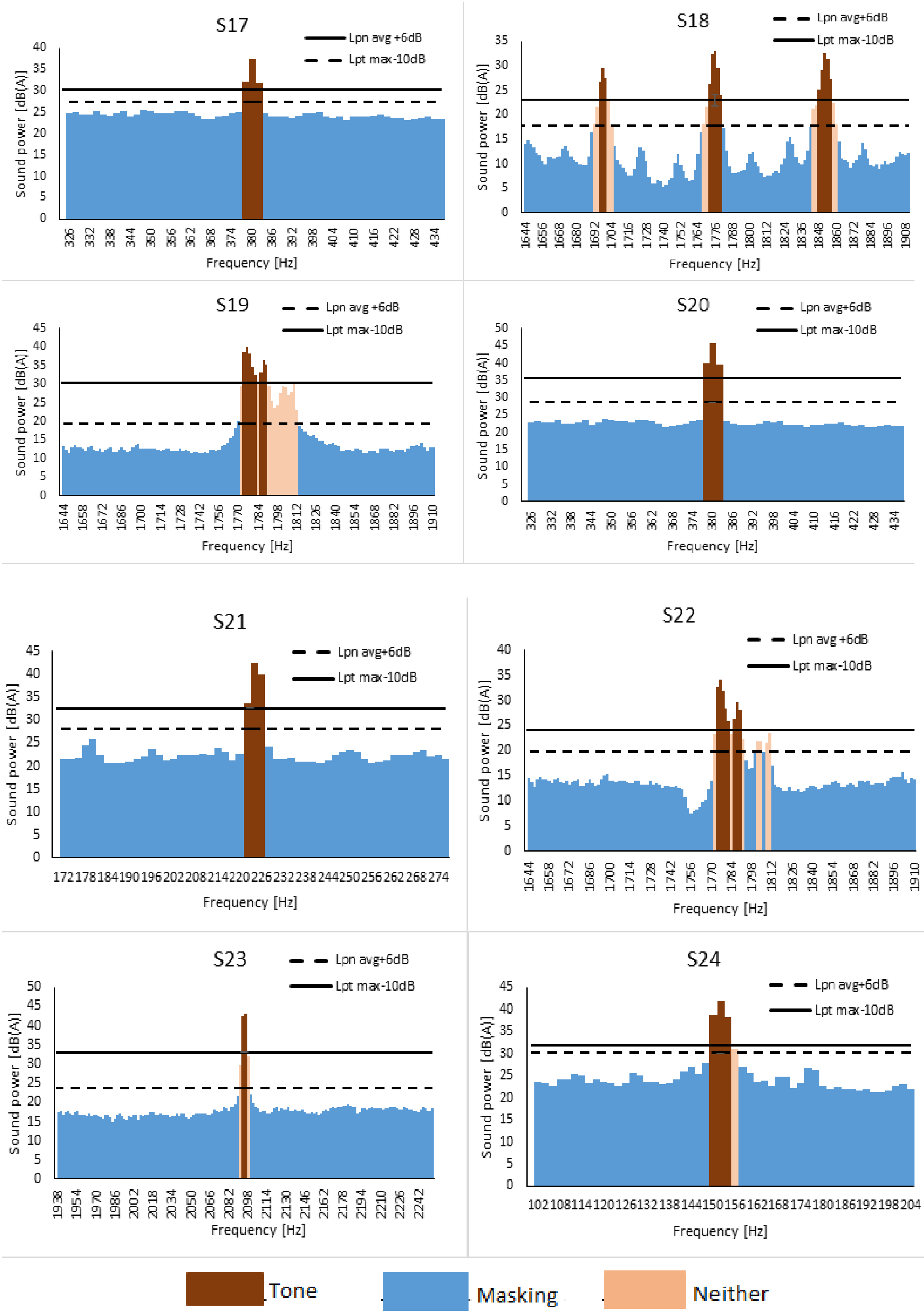

Figure 9: Classification of the spectral line for all spectra(continuation)

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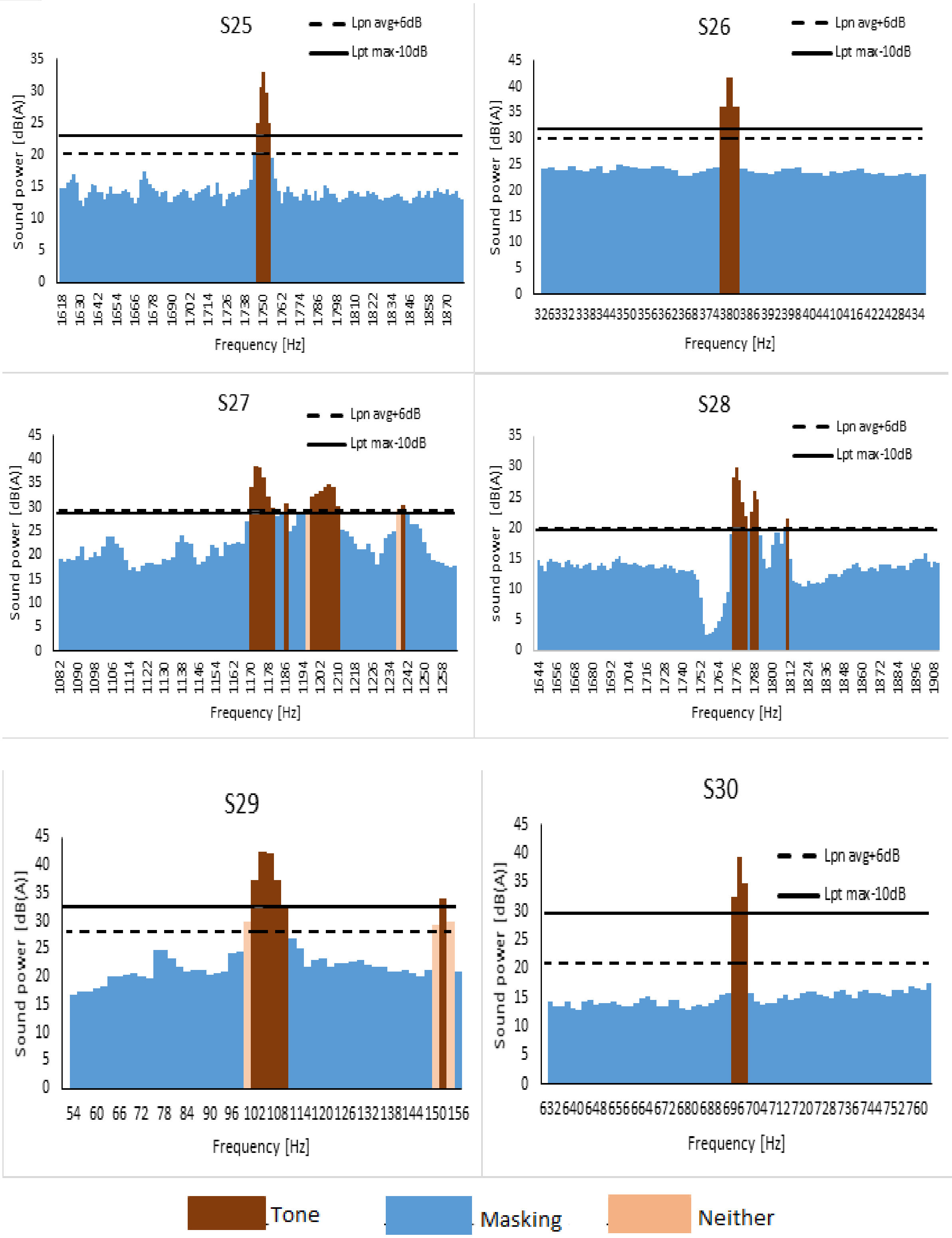

Figure 9: Classification of the spectral line for all spectra(continuation)

Note: *S- Sample spectra, S02 and S13 have no identified tone hence L70%+6dB is taken*

Table 2: Tonality results of all spectra

Spectrum No.	Tone (dB)	Tone frequency (Hz)	Critical bandwidth	Energy average (dB)	Masking level $L_{pn, j, k}$ (dB)	Tonality $\Delta L_{tn, j, k}$ (dB)	Audibility $\Delta L_{a, j, k}$ (dB)	Result
S01	36.21	1776	266	20.29	33.44	7.6	11	Reported
S02	32.84	380	110	24.47	40.36	-7.55	-5.4	No relevant tone
S03	41.16	70	100	15.46	30.7	10.95	12.9	Reported
S04	38.91	1344	204	27.17	39.79	4.7	7.8	Reported
S05	40.42	748	137	23.91	37.27	6.44	9	Reported
S06	39.81	6986	1422	9.01	32.98	7.66	12.5	Reported
S07	42.12	98	101	24.81	40.1	3.07	5.1	Reported
S08	39.16	888	150	26.29	35.46	9.21	11.9	Reported
S09	39.28	162	102	27.18	42.06	-0.44	1.6	Reported
S10	48.08	380	110	20.15	35.79	12.31	14.5	Reported
S11	40.61	1930	290	22.26	34.55	9.3	14.5	Reported
S12	40.76	740	136	22.83	38.01	5.27	7.8	Reported
S13	22.6	976	160	20.59	17.27	-17.27	-14.5	No relevant tone
S14	32.07	6984	1422	6.58	32.88	0.19	5.1	Reported
S15	43.13	136	101	26.43	38.62	7.29	9.3	Reported
S16	42.22	126	101	26.43	41.64	2.43	4.4	Reported
S17	37.6	380	110	24.31	39.95	-2.33	-0.2	Reported
S18	33.06	1776	266	18.92	31.31	9.59	12.9	Reported
S19	40.26	1776	266	22.86	32.85	11.34	14.7	Reported
S20	45.59	380	110	22.62	38.27	7.37	9.5	Reported
S21	42.62	224	104	22.68	37.67	5.43	7.5	Reported
S22	34.06	1776	266	17.42	33.31	4.46	7.8	Reported
S23	43.07	2096	316	18.15	37.98	6.36	9.7	Reported
S24	41.84	152	102	24.41	39.39	3.53	5.6	Reported
S25	33.06	1750	262	15	33.74	1.3	4.7	Reported
S26	41.82	380	110	23.84	39.48	2.44	4.6	Reported
S27	38.57	1172	182	26.54	41.05	5.02	8.0	Reported
S28	30.83	120	101	26.83	33.43	0.45	3.8	Reported
S29	42.51	104	101	25.99	37.24	7.91	9.9	Reported
S30	39.59	698	132	14.95	31.38	8.29	10.8	Reported
Note: S- sample data, Reported- reported as audible, No relevant tone – reported as no relevant tone								

V. CONCLUSION

The evaluation of tonal components in the wind turbine noise measurement data was performed based on the principles and procedure of standard IEC61400-11 ed.3.1. the narrowband analysis procedure was applied for the entire tonality analysis. The possible tones and classification of spectral lines are explained for the first spectrum S01 of the specified wind speed bin. The tonal audibility of all the spectra of the wind speed bin was calculated and explained in the graphs. The obtained results were possible tone, tone frequency, critical bandwidth, energy average, masking level, tonality, and audibility. The tonality evaluation of the IEC approach was done in a 10s energy average period. The uncertainties in the IEC method may affect the wind turbine noise quality. The accuracy and effectiveness of the method were further studied as a future assessment.

VI. ACKNOWLEDGMENT

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