APPLICATION OF PSYCHOACOUSTIC METRICS FOR THE ASSESSMENT OF TONALITY OF INDUSTRIAL SOUNDS

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1 INTRODUCTION

According to BS 4142:2014[1], assessments of impact of industrial sound sources on residential amenities must take into account the presence of the acoustic features in the specific sound source, including tonality, impulsivity, intermittency and other perceptible features. Presence of an acoustic feature can be identified using either subjective or objective methods, with preference given to the former. In the subjective method, a penalty is added to the specific sound based on the strength of the audibility of the feature, while a penalty based on the objective methods is calculated by applying a formula. With regard to the subjective method, the penalty applied strongly depends on the experience of the assessor and thus can be applied incorrectly. However, penalties given by the objective methods are based on sound pressure level calculations and do not include perceptual features of sound and the evoked auditory sensation, which are crucial for the assessment of annoyance and disturbance.

This paper attempts to bridge the assessment of impact and audibility of industrial sounds from the human perspective with their physical attributes. This is realised by applying calculations of psychoacoustic metrics to binaural sound recordings made in the vicinity of industrial sound sources with prominent acoustic features. The research presented in this paper focuses on tonality; it compares the assessment of tonality using the Joint Nordic Method recommended by BS 4142 with alternative methods such as the DIN 45681[2] Tonality Method and the Tonality Hearing Model of Professor Sottek[3,4].

2 TONALITY ASSESSMENT METHODS

2.1 The Joint Nordic Method

The Joint Nordic Method (JNM) is recommended by BS 4142 as a reference method to establish the penalty due to tonality of a specific sound when the subjective method and/or the one-third octave method is not sufficient for assessing the audibility of tones. The JNM is based on the prominence of a tone within a critical band positioned with its centre frequency at the tone frequency. The tonal audibility (ΔL_{ta}) is then calculated as a difference between the total SPL of the tone (L_{pt}) within the critical band and the total SPL of the masking sound (L_{pn}) in the critical band with an added correction factor related to the central frequency of the critical band. Three adjustment (penalty) ratings K_T (to be added to the specific sound) are derived based on the following:

$$
\begin{aligned}
&10\text{ dB} < \Delta L_{ta}: && K_T = 6\text{ dB}\\
&4\text{ dB} \le \Delta L_{ta} \le 10\text{dB}: && K_T = \Delta L_{ta} - 4\text{ dB} \qquad (1)\\
&\Delta L_{ta} < 4\text{ dB}: && K_T = 0\text{ dB.}
\end{aligned}
$$

Although the reference method of identifying tonality has been claimed to be robust, BS 4142 still requires listening to the sounds (recordings) to examine if the identified tone is actually associated with the sound source under consideration.

2.2 Tonality Hearing Model

Although the JNM is based on calculations of tones and masking sounds in critical bandwidths (a psychoacoustic factor) it still operates with sound pressure levels, which is a physical parameter. Other similar methods of calculating tonality that are also based on the SPL levels calculation include Tone-to-Noise Ratio, Prominence Ratio, the DIN 45681 Tonality Method, and Tonality vs Time[2,3]. All these methods have been reported to significantly penalise the magnitude of tonality which was not actually reflective of perception, particularly near or below the threshold of hearing.

Over two decades ago a new mathematical model of sound perception was proposed by Prof. Sottek (Hearing Model of Professor Sottek or HMS)[5]. The model is based on an auditory filter bank consisting of overlapping asymmetric filters that emulates the frequency-dependent critical bandwidths and the tuning curves of the frequency-to-place transform of the inner ear. The transform mediates the firing of the auditory hair cells as the wave from an incoming (to the ear) sound travels along the basilar membrane. The shape of the auditory filters matches the gammatone filters. After a number of further sequential processes, the hearing model transforms calibrated sound pressure data into psychoacoustic loudness, from which further psychoacoustic calculations can be made[4,6].

Based on the HMS a Tonality Hearing Model (THMS) also known as a Psychoacoustic Tonality Method has been derived[3]. The method is based on psychoacoustic loudness, and determines the loudness of tonal and non-tonal components of sounds in a frequency band by means of running (constantly updating) autocorrelation function. The perceived tonality is not only dependent on the tonal content in each band, but also on the signal-to-noise ratio over all bands at each time instance l. Thus, to finally model the tonality of the signal, the overall loudness signal-to-noise ratio is evaluated across all bands. The Tonality Hearing Model considers the threshold of hearing and the relationship of tonality perceptions to psychoacoustic loudness levels and provides a high time resolution to measure transient and rapidly changing tonalities (not possible in other methods of tonality assessment). The unit of the tonality is given in tu_{HMS}, with 1 tu_{HMS} corresponding to a 1 kHz tone with a sound pressure level of 40 dB. In the 15th and later editions of ECMA-74 standard the method is described and used as a basis for further psychoacoustic analyses[4,6].

The Tonality Hearing Model of Sottek was first successfully applied for sound quality assessments[8]. More recently it has become a standard assessment method for noise emitted by information technology and telecommunications equipment[4,6]..

3 METHOD

3.1 Data collection

Binaural audio recordings have been carried out at six assessment locations near an industrial plant: four locations were placed along a straight line behind the plant site (location 1 – location 4), one next to a residential area (location 5) and one at the back of the plant (location 6) as shown in Figure 1. The locations were at 180 metres (location 1), 160 metres (location 2), 115 metres (location 3), 50 metres (location 4), 87 metres (location 5) and 45 metres (location 6) from the plant site boundary. The first four locations were to the north-west and uphill from the plant, with a positive elevation difference of approximately 22 metres between location 4 and location 1. All of the first four locations were among a dense wood. Location 5 was to the south-east of the site boundary on a pavement in front of residential houses. The residential area and the plant were separated by a river, a 45 metre wide tree-belt and a dual carriageway. Location 6 was to the north of the site boundary, among the trees and next to a river. Location 6 was approximately at the same height as location 4, while location 5 was approximately 9 metres higher, as the road is elevated above the plant.

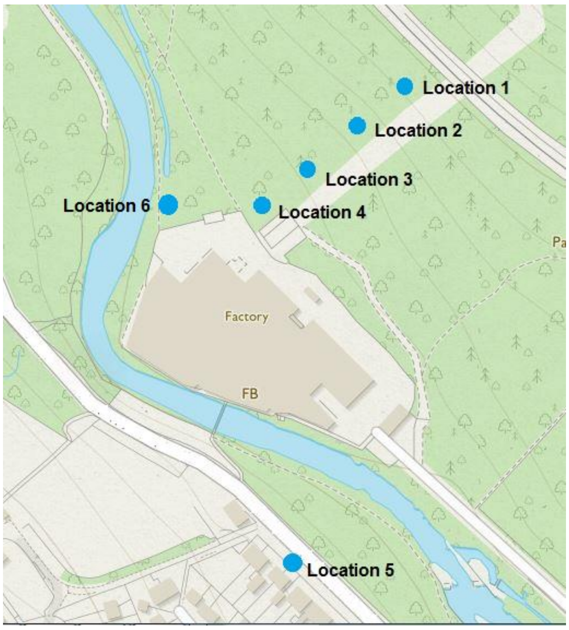

Figure 1: Assessment locations

The binaural recordings (24 bit rate and 48 kHz resolution) were made with the SQobold acquisition system and a binaural headset, both of HEAD acoustics[7,8]. The recordings were supplemented with a GPS track recording and a video recording with the SQobold acquisition system[8]. Additionally, measurements of objective acoustic parameters and monaural audio recordings (24 bit rate and 48 kHz resolution) were carried out with a B&K 2250 SLM. The headset was worn by the author of this paper and thus was at approximately 1.6 metres above the ground. The SLM was positioned at 1.2 metres above the ground.

The recordings at location 1 – location 4 were carried out on 26 February 2020 between 12:00 -13:00 hours. The weather conditions were favorable with a wind speed below 5 m/s. Broadband and strong tonal sounds from the plant were the dominant sounds. Birdsong and sounds from passing aeroplanes were present nearly all of the time and were considered as background sounds. The recordings at each location lasted approximately 1 minute, however for the analysis in this Section, all bangs, impulses and sounds not belonging to the industrial source were not included in the analysis. The altered audio samples included in the analysis were of 15 - 30 second duration.

The recordings at location 5 and location 6 were carried out on 13 April 2020 between 16:00 – 16:30 hours, on the Bank Holiday during the lockdown due to the Coronavirus. The recording at location 5 contained passing vehicles but also prolonged lulls in the traffic during which a tonal sound from the plant and birdsongs were audible. Note, no sound originating from the plant was audible at this location before the lockdown due to masking from other environmental sounds. Data collection at location 5 lasted approximately 2 minutes. At location 6 the dominant sound was a strong tone from the plant. Background sounds included birdsong and the sound of water flow from the river. The recording lasted approximately 45 seconds.

The broadband $L_{Aeq,\,T}$ calculated for each location (for the samples included in the analysis) is shown in Table 1.

Table 1: Sound pressure level, $L_{Aed,T}$, dB calculated for the audio sample from each measurement location

Location/ Channel	Location 1, dBA	Location 2, dBA	Location 3, dBA	Location 4, dBA	Location 5, dBA	Location 6, dBA
Left	54.4	60.8	65.5	67.3	70.0	50.6
Right	55.1	58.9	61.2	66.4	70.0	51.4

Assessment of tonality of the audio sample from each measurement location has been carried out applying the JNM, the DIN 45681 Tonality Method and the Tonality Hearing Model. Assessment based on the JNM was made using BZ5503 software of B&K, while calculations of tonality based on the other two methods were carried out via ArtemiS SUITE software of HEAD acoustics. ArtemiS SUITE enables calculations of the magnitude of tonality vs. time, the frequency vs. time of maximum tonality, 3D spectrum of tonality and other tonality assessment metrics[7]. The monaural and binaural recordings were synchronised for further analysis.

3.2 Tonality assessments at location 1 – location 4

Tonality assessment has been performed utilising subjective and objective methods. The subjective assessment was carried out by listening to the recorded sounds via the same the SQobold acquisition system (auralisation). During the playback the correct level and the spectral distribution of sounds at both ears have been achieved by applying appropriate equalization settings. This auralisation method enabled the delivery of an acoustic impression that would resemble the original sound field[9].

Table 2 shows results of tonality assessments for location 1 – location 4. The tonality ratings obtained by the THMS are calculated based on the average spectrum of tonality or so-called Specific Tonality[7].

It can be noted that all assessment methods gave higher tonality values for locations 2 and 3 than for locations 1 and 4. Listening to the recordings has confirmed that tones were indeed less audible at locations 1 and 4. Location 1 is the furthest from the plant, while at location 4 the tonal components were partially masked by the overall broadband sound generated by the plant. Locations 2 and 3 were closer to the plant, compared to location 1, and they were also elevated higher than location 4 and thus were possibly more exposed to the dominant tonal sources of the plant.

Table 2: Tonality assessment: location 1 – location 4

Location	Channel	JNM			DIN 45681			Tonality Hearing Model of Sottek	
		Tone Hz	Tone Audib. dB	Penlt. dB	Tone Hz	TNR dB	Penlt. dB	Tone Hz	tu HMS
1	**Mono**	790.6	7.8	3.8	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	791	8.7	4	791	0.417
	Right	N/A	N/A	N/A	791	7	4	None	None
2	**Mono**	790.6	14.7	6	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	791	15.3	6	791	1.19
	Right	N/A	N/A	N/A	791	14.8	6	791	0.984
3	**Mono**	790.6	12.4	6	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	791	16.7	6	791	1.53
	Right	N/A	N/A	N/A	791	10.1	5	791	0.519
4	**Mono**	790.6	7.2	3.2	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	791	10.6	5	791	0.726
	Right	N/A	N/A	N/A	791	10.1	5	791	0.675

The JNM and method based on DIN 45681 show little variations between locations 1 and 4 and between locations 2 and 3 in terms of the penalty rating. The assessment of tonality using the Tonality Hearing Model (THMS) provides much higher variations in terms of the tonality ratings between all locations, which are reflected in the sensation of tonality experienced at each assessment location identified by listening to the audio signals. This can be further proved by analysing the FFT plots calculated for each location shown in Figure 2 – a strong tone at approximately 790Hz can be observed at each graph, however it is more prominent at the FFT plot of location 3. The research is scarce, however, regarding the relationship between tu HMS ratings and the evoked subjective sensation of tonality, particularly when applying to environmental sounds.

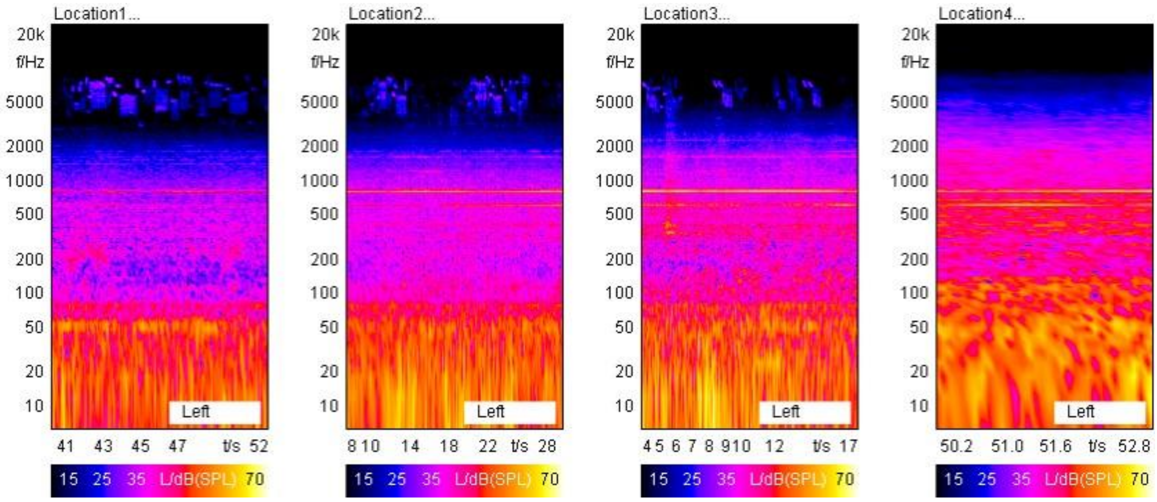

Figure 2: FFT vs time plot to show the energy distribution and to give a visual aid that can be related to the perceived tonal sensation.

3.3 Tonality assessments at location 5 and location 6

Table 3 shows the tonality ratings for location 5 (total recording), location 5 (only during the lull in traffic where the tone from the plant was clearly audible) and location 6, calculated using three different objective methods. At location 5 (total recording) all three methods identified no prominent tonal sound components that can be explained by the traffic masking just before the lulls. However, at location 5 during the lull in traffic, presence of the tone has been identified using the JNM and DIN 45681 method (for the right channel only).

At location 6, all three methods identified tonality between 1189 – 1920 Hz. The JNM gives no penalty, while DIN 45681 (for left channel) gives a 3dB penalty rating. Assessment based on the THMS also gave higher values of tonality for the left channel.

Table 3: Tonality assessment: location 5 – location 6

Location	Channel	JNM			DIN 45681			Tonality Model	Hearing
		Tone Hz	Tone Audib dB	Penlt dB	Tone Hz	TNR dB	Penlt. dB	Tone Hz	tu HMS
5	**Mono**	None	None	None	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	None	None	None	None	None
	Right	N/A	N/A	N/A	None	None	None	None	None
5*	**Mono**	1194	4.7	0.7	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	None	None	None	None	None
	Right	N/A	N/A	N/A	1195	3.29	2,00	None	None
6	**Mono**	1194	0.6	0	N/A	N/A	N/A	N/A	N/A
	Left	N/A	N/A	N/A	1189	5.95	3	1220	0.279
	Right	N/A	N/A	N/A	1189	0.4	0	1220	0.127

*Assessment at location 5 only during the lull in traffic

Figures 3 and 4 show FFT, time-dependent Specific Tonality and Specific Tonality (Hearing Model) distributions for location 5 (total recording) and location 6, respectively. The time-dependent Specific Tonality (Specific Tonality vs time) presents strength of specific tonality at particular frequency band and at particular time instance. Specific Tonality (Hearing Model) is calculated by averaging (over time) the time-dependent Specific Tonality[6].

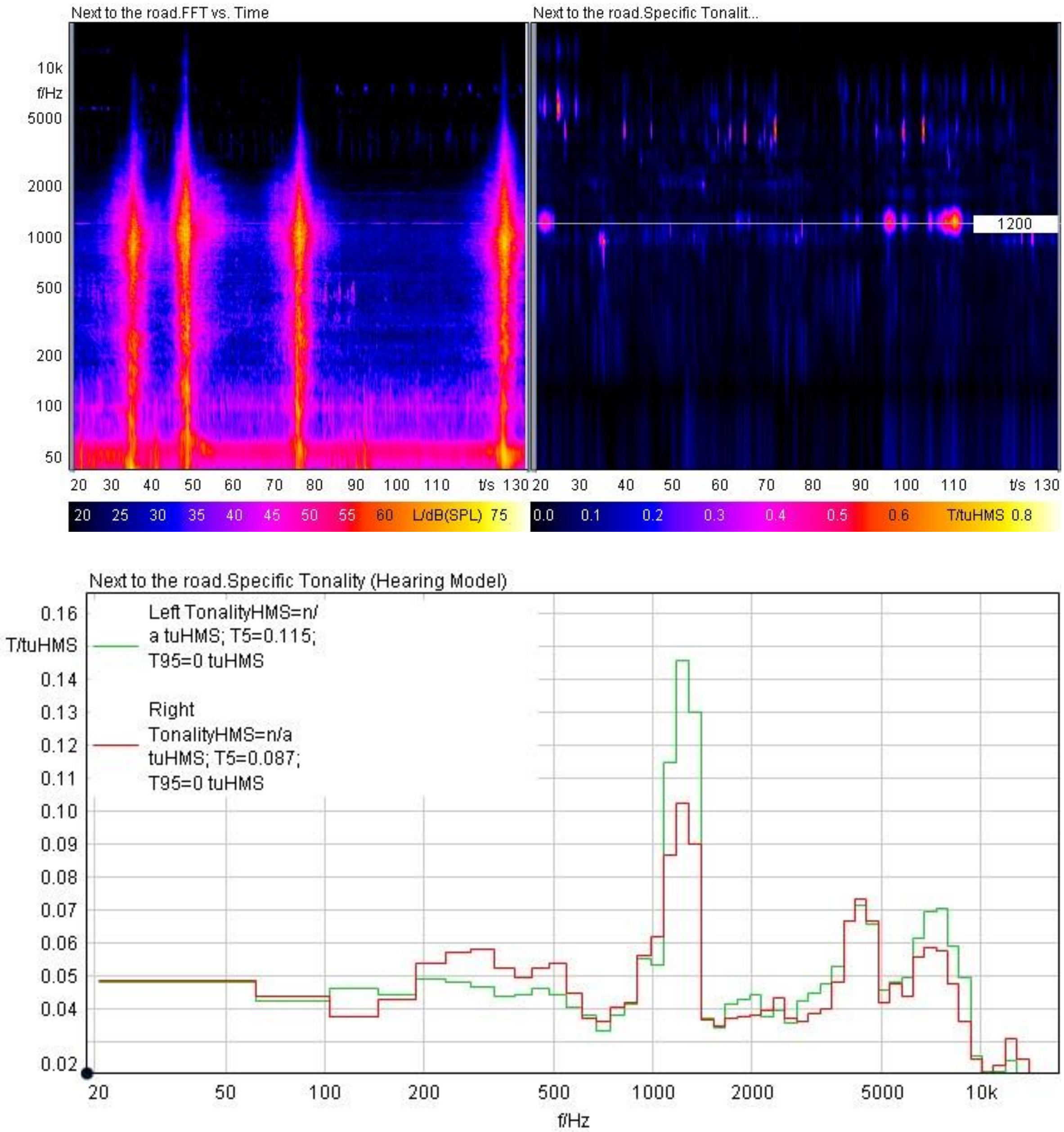

Figure 3: Location 5: FFT (top left), Specific Tonality vs time (top right) and Specific Tonality (Hearing Model) (bottom)

Through listening to the recordings and plots presented in Figure 3 and 4, presence of tones around 1200 Hz at locations 5 and 6 can be aurally and visually identified. Specific Tonality (Hearing Mode) shows that at both locations tonality is higher for the left channel than for the right channel, which was again confirmed via auralisation. This demonstrates advantages of the binaural over the monaural technology for capturing the spatial auditory impression in an aurally accurate way.

Specific Tonality (Hearing Mode) graphs also show 5th and 95th values of the average tonality, which are tonality exceeding 5 and 95 percent of the time interval, respectively. Use of 5th and 95th percentiles of psychoacoustic metrics are recommended by ISO/TS 12913-3[10]. A quotient of 5th and 95th percentiles of loudness has been proved to be linked with a degree of sound variability[11], although application of those percentiles to the assessments of tonality is yet to be investigated.

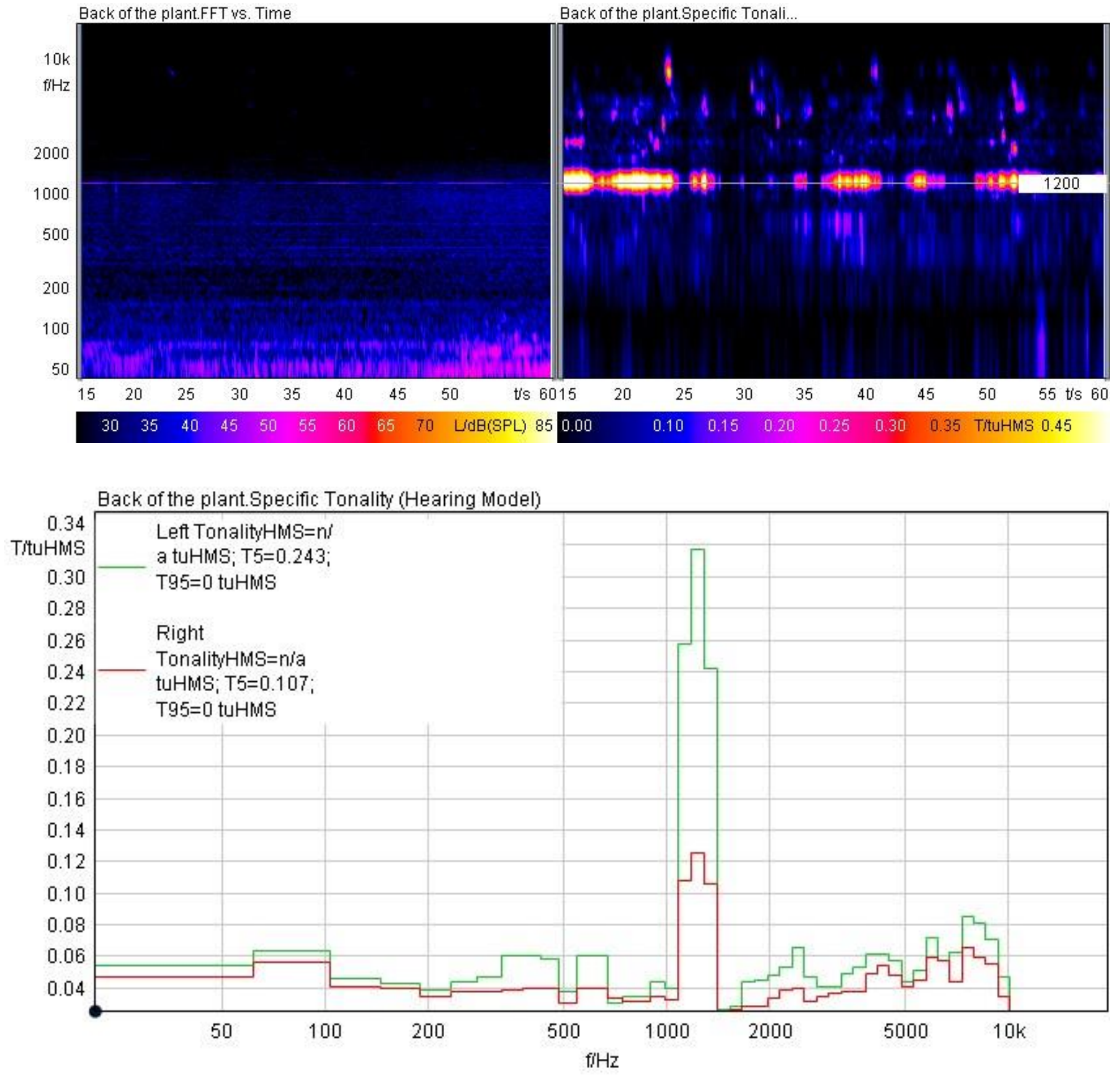

Figure 4: Location 6: FFT (top left), Specific Tonality vs time (top right) and Specific Tonality (Hearing Model) (bottom)

As shown in Table 3, the THMS (as the other two methods) has identified no tone for both channels of audio sample at location 5 (total recording), although their presence was identified aurally and was also demonstrated in the plots of Specific Tonality vs time and Specific Tonality (Hearing Model). According to ECMA-74, the tolerance (threshold) for reportable prominent tonality in THMS is a constant of 0.4 tu HMS. This value was deducted through subjective tests carried out with signals emitted by information technology and telecommunication equipment. Further research is need in order to establish applicability of the recommendations of the above standard, including value of the threshold of tonality in tu HMS, to the tonality assessments of industrial sounds.

4 CONCLUSIONS

This paper compares results of tonality assessments of sounds from an industrial plant applying the Joint Nordic Method, the DIN 45681 Tonality Method, and the Tonality Hearing Model of Professor Sottek. Similarities between the JNM and the method based on DIN 45681 for both the identification of the prominent tones and penalty ratings have been demonstrated,

For the four assessment locations arranged in a straight line with descending distance to the plant, the Tonality Hearing Model proved to be the closest to the sensation of tonality that was proven in reality by the auditory evaluation via auralisation.

Tonality assessment using the three objective methods was also applied to the recordings made near a road in the vicinity of the same plant with a tone from the plant clearly audible at the lulls in traffic. Although no tones were identified using either of the applied methods, presence of the tone was detected through calculations of Specific Tonality and Specific Tonality vs time, available only for the THMS. Calculations applied to the part of the recordings that contain no traffic also identified prominent tones.

It has been also pointed out that further research is needed in order to identify the threshold of tonality in THMS for industrial sounds and to establish the relationship between the scale of the subjective sensation of tonality and THMS`s tonality ratings in tu HMS.

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5 REFERENCES

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