Study of high frequency noise from electric machines in hybrid and electric vehicles

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ABSTRACT

This study investigates the tonal high frequency noise characteristics which are present within the cabin of an electric vehicle. As the human ear responds differently to different frequencies of sound and this response varies with age, both the level and the frequency are considered. In addition, the amount of annoyance these sounds will cause for the occupants is a function of the tonality and the level of the noise compared to other masking noise sources present. Metrics for tonal noise taking account of these factors are evaluated for a vehicle creep load case and compared to subjective results to determine suitability for the evaluation of electric vehicles. The Stevens VI loudness metric is shown to give a good indication of the total tonal noise present in the cabin of an electric vehicle. The tone-to-noise ratio and prominence ratio are used successfully to compare the level of a tone to the masking noise present, although general prominence limits are shown to be unreliable for evaluation of electric vehicle tones. Finally the noise sources present in the vehicle are reviewed along with factors that must be considered for the diagnosis and mitigation of these different tonal noise sources.

Keywords: Sound, Vehicle, Electric, High Frequency. I-INCE Classification of Subjects Number(s): 13.2.1

1. INTRODUCTION

Since inception, the sound of a motor vehicle has been dominated by the noise of the engine and exhaust. Electric drives by comparison are quiet but still have characteristic sounds dominated by tonal noises. The tonal noises appear across a wide frequency band and can be associated with the switching frequency of the power electronics, the fluctuating magnetic field and the rotating frequency of the electrical machines along with any tonal noises from gear drives that may be in the system (1; 2; 3). Resonances of the system will reinforce these noises and they may be audible and unpleasant to the occupants of the vehicle.

This study investigates the tonal high frequency noise characteristics which are present within the cabin of an electric vehicle. As the human ear responds differently to different frequencies of sound and this response varies with age, both the level and the frequency are considered. In addition, the level of annoyance of these sounds to the occupants will be a function of the tonality and the level of the noise compared to other masking noise sources present. Metrics for tonal noise taking account of these factors are evaluated and compared to subjective results to determine suitability for the evaluation of electric vehicles. Finally the noise sources present in the vehicle are reviewed along with factors that must be considered for the diagnosis and mitigation of these different tonal noise sources.

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2. HUMAN RESPONSE TO HIGH FREQUENCY NOISES

The degree of annoyance caused by high frequency noise in the electric vehicle will be affected by the frequency, impulsiveness and level of the noise relative to other noises present in the vehicle. It is well known that the perception of sound level by humans varies with frequency. The A-weighting curve is used to correlate between measured sound pressure level at normal levels and perceived loudness. A further consideration is that hearing changes with age, differing between the sexes and also with lifestyle (rural, city, industrial worker etc.). This effect is known as presbycusis defined by Spoor (4) as *"the phenomenon that the threshold of hearing of ontologically normal ears increases with age"*. For example a male aged 45 will have a 20dB loss in hearing response at 8000Hz. This means that he would hear a sound at 8000Hz one quarter as loud as a person with no hearing loss. This phenomenon is important when considering the sound quality of electric vehicles that have significant high frequency noise components.

The perceptibility and annoyance of tonal noise is highly linked to the level of other noise sources present. These are commonly called 'masking noises' with respect to the tonal noise. As defined by Zwicker and Fastl (5) the masked threshold is the sound pressure level of a test sound, usually a sinusoidal test tone, necessary to be just audible in the presence of a masker. Of particular interest is that the level of masking noise required to mask a pure tone increases by approximately 10db per decade above 1000Hz meaning that higher frequency tones are more easily perceived by a listener than low frequency tones.

A number of complex methods exist for calculating the perceptibility of tonal noise such as the MPAS method developed by Ford motor company (6). However, more simple classical methods such as tone in band, tone-to-noise ratio and prominence ratio are generally more useful tools. These will be investigated in more detail in relation to electric vehicle noise in Section 4.

3. CHARACTERISATION OF TONAL NOISE FROM AN ELECTRIC VEHICLE

3.1 Measurement of Noise from an Electric Vehicle

Measurements were performed on a Nissan Leaf electric vehicle on the Ricardo ISO10844 pass-by track at Shoreham Technical Centre. The pass-by track has a low noise surface keeping road noise to a minimum and no acoustic reflecting surfaces in the vicinity to give a free-field measurement.

Interior noise was measured using a Head Acoustics Noisebook system that consists of a set of headphones with microphones mounted at ear position allowing binaural recording at the drivers ears via a USB acquisition system at high sample rate. The following test conditions were trialed:

1. 0-70 full load acceleration
2. 30-70 full load acceleration
3. ISO 362 pass-by test
4. 30mph steady state
5. 0-3mph drive 'creep' (no driver commanded load)

These measurements were analyzed in detail, both subjectively and objectively, for the presence of high frequency tonal noises. All measurements showed a number of tonal noise components at fixed, stepped and synchronous frequencies. The 0-3mph drive creep measurement showed high frequency tonal components most clearly as masking noises are at a minimum due to the low road speed. This test condition is relevant as it represents a slow pull away condition that would be experienced when driving in stop start traffic such as a traffic jam.

3.2 Analysis of Tonal Noise from an Electric Vehicle

In total seven clear tonal noise components were identified in the 0-3mph drive ‘creep’ test with many more less clear tones. Figure 1 below shows a spectrum of averaged sound pressure level vs. frequency over the 0-10 second measurement period on the upper plot. The lower plot shows a colourmap of the data (sound pressure level vs frequency vs time). The seven clear tones that will be considered in detail are identified on these plots.

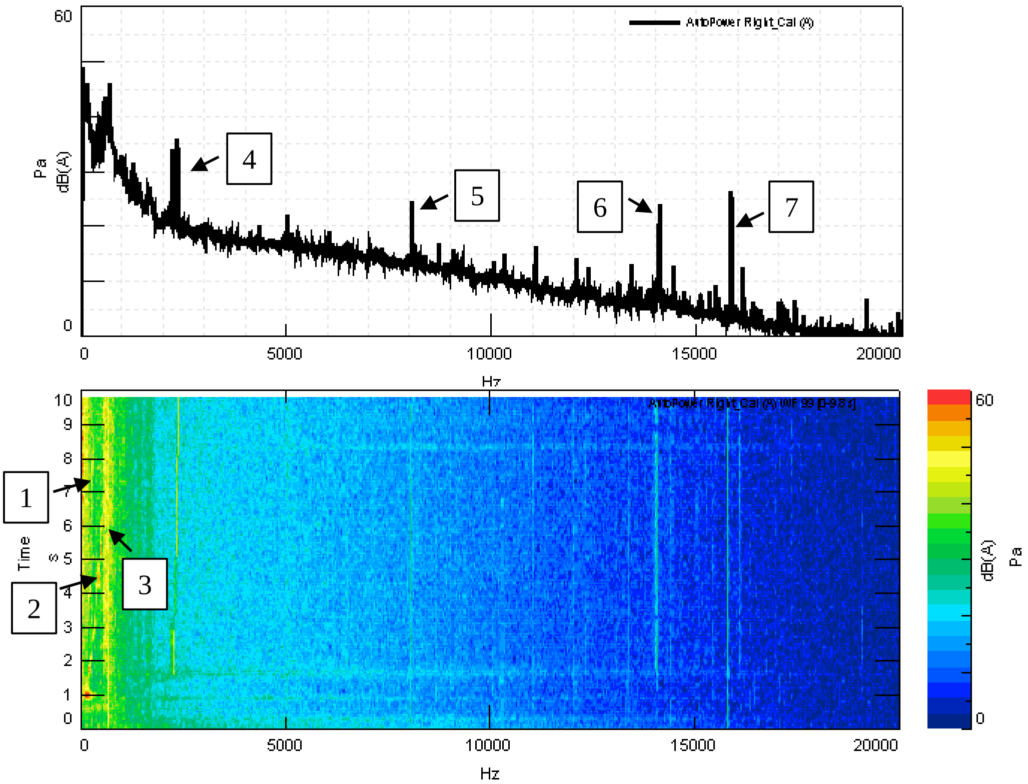

Figure 1 – Tonal noises identified in 0-3mph drive ‘creep’ test

The colormaps following show the same data as Figure 1 with a reduced frequency scale to show more clearly the different noise components. Figure 2 shows noise components 1 and 2 are synchronous related to the rotation of the electric machine. To correctly identify these noises, detailed information on the construction of the electric machine is required. From the information freely available in the public domain these synchronous noises can be related to either the pole passing frequency of the motor (likely 24th engine order) or gear whine of the final drive gear (ratio 7.9377). Noise component 3 is a constant frequency tonal noise component. Without detailed knowledge of the system architecture the source of this noise cannot be identified.

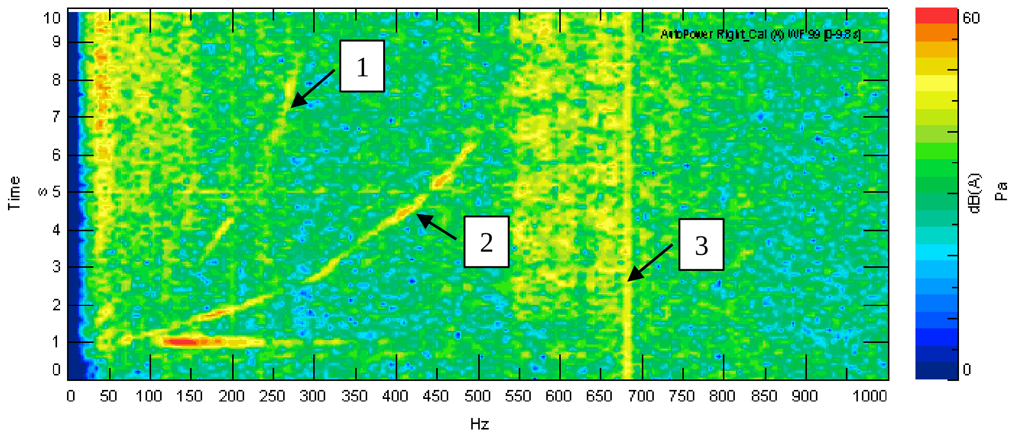

Figure 2 – Low to mid frequency noise components

Figure 3 below shows the first high frequency noise component. This is a clear tonal frequency that steps up in frequency as the motor and vehicle speed increases. This noise component is likely the main switching frequency of the power electronics. It may be stepping up in frequency as the bus voltage is increased.

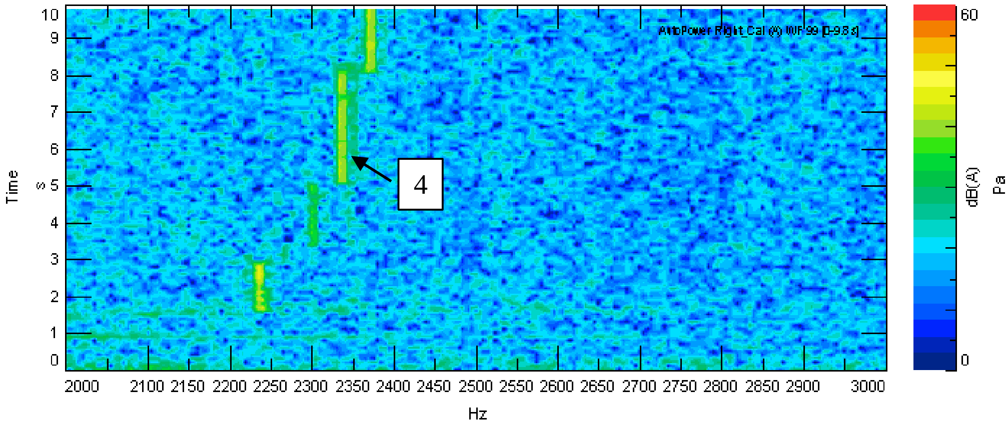

Figure 3 – High frequency stepped noise component

The remainder of the high frequency noises are shown in Figure 4 below. In addition to peaks 5, 6, and 7 that show clearly in the averaged spectrum shown in Figure 1 there are also a number of other tonal peaks at lower levels. As for the other tonal components detailed information on the system architecture is required to identify the sources of these noises.

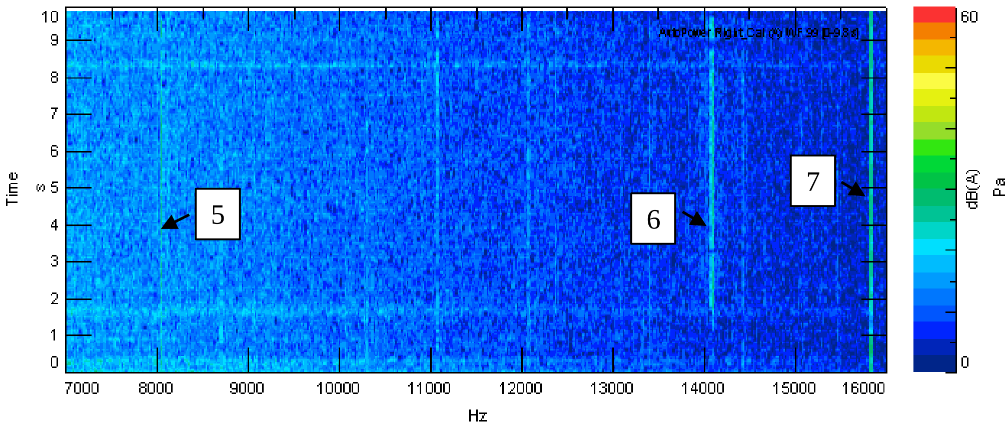

Figure 4 – High frequency noise components

4. ASSESSMENT OF TONAL NOISE COMPONENETS

4.1 Subjective Assessment

To assess the influence on sound quality of the various tonal noise components present in the vehicle sound the baseline creep file was digitally filtered to create 'new' sounds with differing high frequency noise components and varying masking noises. A number of sounds were created and assessed by a number of listeners in an initial assessment. This process removed some sounds that could not be distinguished from others resulting in eight sounds for the final subjective assessment. These sounds are listed below along with the digital filtering information that was used to create them:

1. Baseline sound
    - No filtering, included as reference
2. Noise component 2, 2nd visible order synchronous noise reduced in level
    - 20dB attenuation order tracking filter, 0.05 order width
3. Noise component 3, 1st tonal noise component reduced in level
    - 40db attenuation, 10Hz notch filter, 680Hz
4. Noise component 4, stepped frequency tonal noise reduced in level
    - Bandstop filter 2200-2400Hz
5. Noise component 5, 2nd tonal noise component increased in level
    - 6db amplification (twice the sound pressure), 20Hz notch filter, 8054Hz
6. Noise component 5, 2nd tonal noise component increased in level
    - 12db amplification, 20Hz notch filter, 8054Hz.
7. Noise component 6, 3rd tonal noise component increased in level
    - 12db amplification, 20Hz notch filter, 14095Hz
8. Noise component 5, 6 and 7 (2nd, 3rd and 4^{th}) tonal noise components removed
    - 12db attenuation, 20Hz notch filters, 8054Hz, 14095Hz and 15840Hz

A subjective assessment tool available at Ricardo was used to assess the eight sounds. The sounds are presented blind to the listener who must assess them against a described product image, in this case, *"Electric Vehicle Sound Quality - Lowest Levels of High Frequency Tonal Noise"*. Sounds are rated on a 1 to 10 scale of acceptability with 1 being poor sound quality and 10 being excellent with no concerns. The noises were assessed by experienced noise and vibration engineers and technicians who are familiar with this scale of acceptability and picking out subtle changes in sounds. The subjective assessment user form is shown in Figure 5 below.

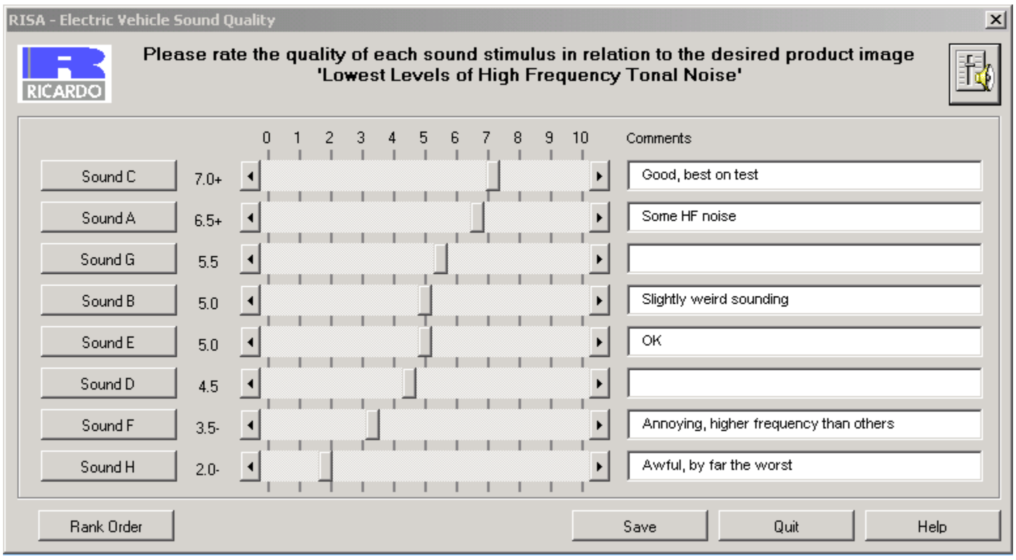

Figure 5 – Ricardo interactive subjective assessment (RISA) tool

Figure 6 shows the results from the subjective assessment. The plot shows the mean rating for each sound along with a 90% confidence interval for the data. For a clear subjective result the confidence intervals should not overlap. For the data shown in Figure 6 that means that while sound 6 can be said to be shown as clearly different than sound 2 the same could not be said for sounds 1, 5 and 3. The results should however show the correct trends.

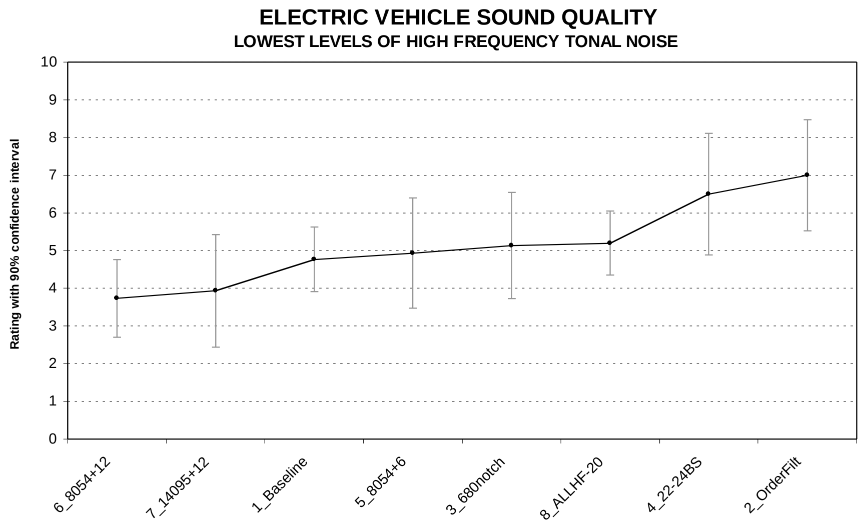

Figure 6 – Subjective Rating Results

The results show that sounds 6 and 7 with 12dB amplification on the high frequency components were identified as worse than the baseline sound. Listeners commented that these sounds were similar to the sound of a dog whistle or had very high tonal frequencies almost at the limit of hearing. This is perhaps not unexpected with such high amplification on the tonal components but shows that these very high frequency components contribute to sound quality. By comparison sound 5 with +6dB on the 8054Hz tone was rated as average with high confidence intervals indicating that not all listeners could not identify this change as clearly different to the baseline. In comparison, sound 8 that had all clear high frequency tones removed was rated as slightly improved over the baseline sound with a smaller confidence interval. This data shows a clear interaction of these high frequency tones to the overall sound quality of the vehicle.

Listeners rated sound 3 with the 680Hz tone removed as average. This indicates that this mid frequency tone is not significantly contributing to tonal annoyance or significantly masking the higher frequency tonal noises.

Sounds 2 and 4 were rated highest with very similar ratings and overlapping confidence intervals indicating that both sounds could be considered as the 'best' sound with lowest levels of high frequency noise. Interestingly sound 2 with the synchronous whine removed was rated as having low levels of high frequency noise. This rating also had a large confidence interval with listeners differing in opinion if this sound was high frequency or not. The synchronous whine is by far the loudest tonal component so it is likely that listener's rate the sound as better with this component removed even though it is not strictly a high frequency noise. Also of interest is that removal of this strong tone did not result in a worse rating for high frequency tonal noise indicating that that it did not have a strong masking effect. Some listeners commented that sound 4 with the 2.2-2.4kHz stepped tones removed was more 'whiney' indicating that removal of the stepped tone caused the synchronous whine (noise component 2) to become more prominent. Further development on this vehicle to remove these sounds would improve the sound quality.

One of the objectives of this study was to understand the sensitivity of a listener's age to the level of annoyance of high frequency noises tones. The theory being that older listeners would have lower high frequency hearing sensitivity and therefore find high frequency tones less annoying. Listeners age in this study varied by 20 years. According to Spoor (4) this spread of age should give a reduction in 8000Hz hearing sensitivity of approximately 18dB. This should mean that sound 6 (+12dB 8054Hz) would be rated similar to the baseline sound by older listeners. In reality, this was not the case, with results consistent across listeners of all ages. The fact that no correlation between age and identification of high frequency tonal noise was found in this study is likely due to the relatively small age range of listeners and also by the NVH profession of the listeners, who are experienced in discerning sounds that are only subtlety different.

4.2 Assessment of Objective Metrics

In this section objective metrics will be compared to subjective results to understand which best describe tonal noise.

4.2.1 Single Number Metrics

Single number metrics commonly used to describe overall sound pressure level and tonality of sounds were calculated for each of the sounds. Full detail of how these metrics are calculated is available in literature (7).

As most of the metrics produce lower numbers for 'better' sounds they should be compared to the reverse of the subjective rating. For each of the objective metrics the coefficient of determination has been calculated compared to the subjective result to give an indication of the goodness of fit of the metric to the subjective data. This data is shown in Table 1 below.

Table 1 – Correlation between subjective results and objective metrics

Sound	Subjective Rating	Sound Pressure Level dB(A)	Loudness Diffuse Field (Phon)	Loudness Stevens VI (Sones)	Articulation Index	Sharpness (acums)
6_8054 +12	3.7	60.62	23.23	20.38	38.26	3.53
7_14095+12	3.9	60.61	23.2	20.4	38.26	3.52
1_Baseline	4.8	60.6	23.16	20.32	38.26	3.31
5_8054+6	4.9	60.6	23.18	20.34	38.26	3.36
3_680notch	5.1	59.94	22.92	20.24	38.33	3.43
8_ALLHF-20	5.2	60.59	23.15	20.29	38.26	3.27
4_22-24BS	6.5	60.55	23.04	20.24	38.48	3.3
2_OrderFilt	7	59.74	22.68	20.03	38.47	3.62
Coefficient of Determination		0.36	0.65	0.81	0.78	0.01

The best correlation of an objective metric and the subjective results was the Stevens VI loudness with a coefficient of determination of 0.81. The subjective results are shown in Figure 7 along with the Stevens VI loudness value. The Stevens VI loudness compares the loudness of each octave band to that of a critical band at 1kHz weighted using standardized curves. Each band level is then converted to a partial loudness and then combined into a total loudness. This metric is thought to give the best correlation as it looks at each octave separately, assessing the multiple tones in the electric vehicle sound before they are combined to form a total loudness. Other metrics appear to be dominated by the most prominent tone or broadband masking noise in the sound.

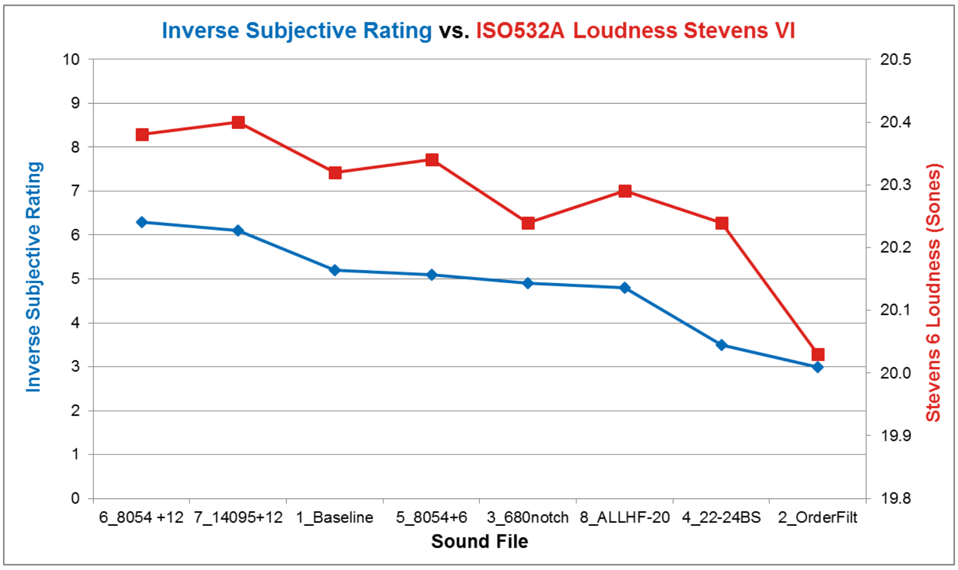

Figure 7 – Inverse subjective rating vs. ISO532A loudness Stevens VI

4.2.2 Single Tone Metrics

Of interest is which tones have the highest contribution to the overall tonal impression of the vehicle so that these tones can be targeted for reduction to improve sound quality. Objective methods such as tone-to-noise ratio and prominence ratio compare the level of the tone to the masking noise present. In the case of tone-to-noise ratio, the level of the tone is compared to the level of the critical band that contains the tone. In the case of prominence ratio, the level of the critical band that contains the tone, or tones, is compared to the level of the adjacent critical bands.

Tone-to-noise ratio is expected to be more accurate in the case where multiple tones are in adjacent critical bands. If multiple tones are within the same critical band, prominence ratio may be more effective. In the case of an electric vehicle where a high number of tones are present there may be tonal components in the same critical band as the tone of interest and also in adjacent bands meaning that neither method is clearly more appropriate.

General limits have been defined (7) to classify tones as prominent for both the tone-to-noise and prominence ratio methods. In the tone-to-noise ratio approach, the level of a prominent discrete tone must be at least 8dB above the level of the masking noise. This is valid for frequencies higher than 1000Hz and it should be slightly more for lower frequencies. In the prominence ratio method, a discrete tone candidate is said prominent if the average SPL (Sound Pressure Level) of the "critical band" centered on the tone is at least 9dB higher than the average SPL of the adjacent critical bands (lower and upper).

Figure 8 shows the narrow band averaged sound pressure level for the baseline sound, sound 5 (8054Hz tone +6dB) and sound 8 (8054Hz tone +12dB). The cursors on the plot define the tonal and critical bands. For each band the Root Mean Square (RMS) sound pressure level is calculated as shown in the box inset upper right.

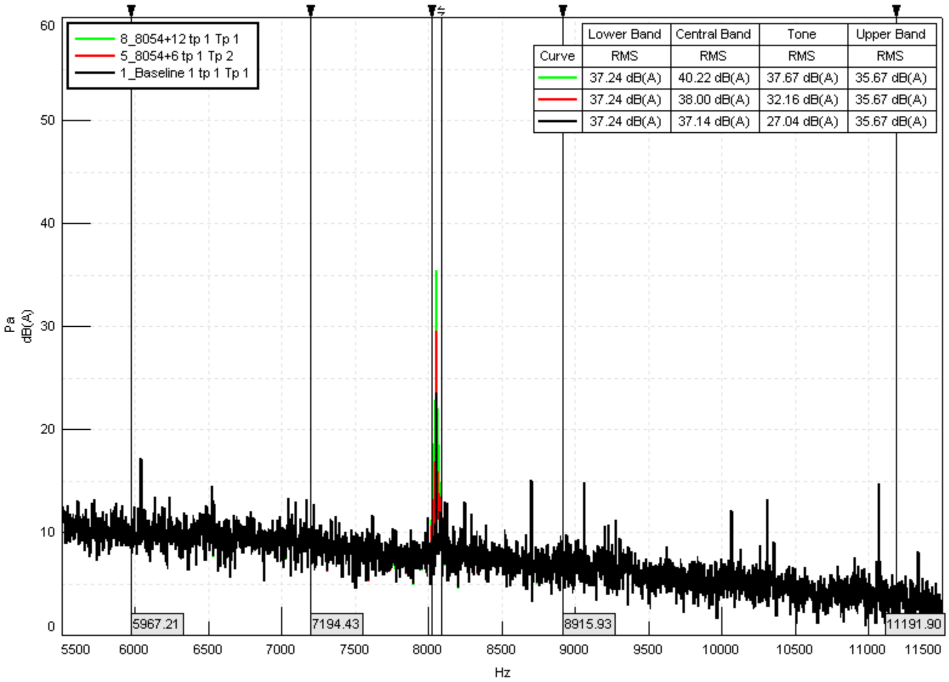

Figure 8 – Narrowband noise data showing critical and tone bands

From the data shown in Figure 8 the tone-to-noise ratio and the prominence ratio can be calculated. The levels used and calculated results are shown in the following two tables.

Table 2 – Tone-to-Noise ratio

Sound	Tone Peak	Central Critical Band Level	Masking Level (calculated)	Tone-to-Noise Ratio
1_Baseline	27.04	37.14	36.87	-9.8
5_8054 +6	32.16	38.00	36.87	-4.7
8_8054+12	37.67	40.22	36.88	0.8

Table 3 – Prominence Ratio

Sound	Lower Critical Band Level	Central Critical Band Level	Upper Critical Band Level)	Prominence Ratio
1_Baseline	37.24	37.14	35.67	0.6
5_8054 +6	37.24	38.00	35.67	1.5
8_8054 +12	37.24	40.22	35.67	3.7

Both metrics show the sounds with amplified tones as worse than the baseline sound so are useful indicators to show the difference between different tones. However, neither of these metrics would class the sound 8 with the 8054Hz +12dB tone as prominent using the general limits as provided on the previous page. This does not align with the subjective results that show this sound as clearly worse than others. This is likely due to the fact that the metrics look only at tones in a fairly narrow band that does not take into account the tonal masking noises present at other frequencies such as the synchronous whine present in this data.

5. REDUCTION OF TONAL NOISE COMPONENTS

The noise measured in the interior of a Nissan Leaf electric vehicle showed a number of different tonal components across a broad frequency range. Noise components were tracked with electric motor speed, stepped as motor speed increased and fixed frequency arising from a number of different components within the electric drive system. Engineers must take a systems engineering approach and carefully consider the interactions of the power electronics, electric drives and noise transmission paths in order to design a quiet electric vehicle.

6. CONCLUSIONS

Stevens VI loudness was shown to be a good single number metric for objective comparison of tonal noise data from electric vehicles. Tone-to-noise ratio and prominence ratio proved to be useful metrics for analyzing single tones within the data however classical limits for audibility of tones were shown not to hold for the complex noise from the electric vehicle.

Further work on the subject would look at a number of different electric vehicles with varying test conditions and have a higher number of listeners assess the data. With more data, true objective targets for electric vehicle tonal noise at different frequencies, with different masking levels could be produced.

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