Prominence of tones in electric vehicle interior noise

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ABSTRACT

The rapid increase of various types of electric vehicles introduced creates new challenges also in respect to noise control and sound quality. With the absence of acoustic emissions from an operating internal combustion engine, the presence of high pitched tonal components from the electric traction motor can be pronounced in many driving conditions. In order to fulfill the customer’s expectations of interior acoustic comfort, further knowledge needs to be gained about the perception of tonal components appearing in a mix of random noise from wind and tires. This paper presents a study on the relationship between the psychoacoustic metric prominence ratio (PR) and the threshold of detecting the tones and also the perceived annoyance for both constant speed and acceleration in a pure electric vehicle. The listening test results reveal that below 800 Hz, a higher PR value is required for audibility compared to tones above 2.5 kHz. For all driving conditions, the perceived annoyance was relatively low with small differences between the frequency ranges for the low audibility stimuli (PR ≤ 2 dB). With higher audibility (PR ≥ 3 dB), the perceived annoyance was significantly increased for frequencies above 5 kHz compared to frequencies below 800 Hz for the constant speed cases. The acceleration cases yielded similar conclusions. The findings are intended to support in the requirement specification process for sounds in electric vehicles.

Keywords: Prominence Ratio, Annoyance

1. INTRODUCTION

With the introduction of various types of hybrid electric and pure electric vehicles (PEV), several new challenges have arisen for noise and vibration engineers. With the internal combustion engine (ICE) shut off during operation, sound originating from other sources such as auxiliary drives and components can be pronounced. Not only does the sound from ICEs contribute to masking of unwanted noise sources, it also provides audible feedback of operation and with a good sound quality it can boost the impression of powerfulness and effortlessness [1]. Sound quality refinement of ICEs has been an ongoing activity for many decades among car manufacturers. Sound quality of electric traction motors replacing the ICE in hybrid/electric vehicles is on the other hand a rather unexplored area. The signature sound from automotive e-motors, typically permanent magnet synchronous motors (PMSM), is completely different from ICEs. Besides being in general quieter, they are characterized

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by multiple high-frequency tonal components originating from harmonics of the electromagnetic force waves acting on the stator housing. High frequency tones appearing in a broad band mix of sound has been found to be perceived as annoying in many different contexts. Parizet et. al. [2] showed that perceived unpleasantness increased with increasing level and frequency for pure tones ranging from 150 to 2900 Hz appearing in a uniformly masking noise. For automotive applications, Lennström et. al [3] found that an increase in levels of individual high frequency components (>1 kHz) resulted in higher rating in perceived annoyance, sharpness, aggressiveness and powerfulness and also lowered the impression of overall sound quality satisfaction. This paper presents a more detailed study on the relationship between objective measures of e-motor tones appearing in a mix of random noise from tires and wind and the perceived annoyance. Prominence ratio (PR) was found to be an appropriate metric for quantifying the relative levels of the tones compared to the adjacent broad band random noise. The objective of the study was to investigate at what PR level the e-motor tones could be detected and also how perceived annoyance relates to PR for different frequencies. The findings from this work were primarily intended to support complete vehicle target setting of e-motor noise. Another approach aiming for target setting of e-motor noise was reported by Bézat et. al. [4] where Gammatone filters based upon equivalent rectangular bandwidth instead were used to predict hearing thresholds. A proposal of how PR could be integrated in the target setting process is described in chapter 5.

2. THEORY – PROMINENCE RATIO (PR)

Prominence ratio is a psychoacoustic metric intended for detection and evaluation of prominent tones in noise emissions. The method is described in the ECMA-74 international standard [5] which describes how to conduct measurements of noise emission from information technology and telecommunication devices. It also provides criteria for if a tone should be classified as prominent or not, illustrated in Figure 1.

Figure 1: Criteria for prominence for prominence ratio and tone-to-noise ratio.

PR is defined between 89.1 Hz and 11220 Hz. PR is calculated from the sound pressure levels of the critical band of the tone and the adjacent critical bands. The critical band is the frequency range of a noise, centered at the frequency of a tone, which effectively can mask the same tone [6]. The bandwidths of the critical bands are similar to the 1/3 octave bands, but in contrast they do not have fixed frequency limits. The procedure of calculating PR can be described as follows: First, the frequency limits and squared sound pressure level of the critical band of the tone of interest (the middle band) is determined. The magnitudes should be derived from FFT data with Hanning window, no frequency weighting added and linear averaging. The tones should be narrower than 15% of the critical band width. Secondly, the frequency limits and squared sound pressure levels of the two adjacent critical bands (upper and lower bands respectively) are determined. PR is then calculated from the ratio between the levels in the middle band and the average of the levels in the upper and lower bands.
3. METHOD

The procedure for the study can be summarized in the following steps:

1. Test track binaural head recordings of PEV vehicle
2. Suppressing and creating tones in recorded files
3. Conduction of listening test
4. Statistical analyses of the data

3.1 Test track recordings

A Volvo C30 PEV was used for the recordings. A Head Acoustics HMS III binaural head was positioned in the co-driver’s seat (see Figure 2). Head Acoustics DataRec 4 front end system was used to acquire the time data. The sampling frequency was set to 44.1 kHz and the binaural head used ID (independent of direction) filter. The rpm and velocity was recorded from the vehicle CAN. The driving conditions consisted of two constant speeds, 50 and 80 km/h, and a 0-100 km/h max acceleration on flat, smooth asphalt.

![Figure 2: Binaural head used for recordings, positioned in the co-driver’s seat.](image)

3.2 Synthesization of sound stimuli

For the listening test, sound stimuli with varying magnitude of the e-motor tones were constructed. The first step included removal of present tones/orders from the original recordings so that only the background random noise from wind and road was present. This was accomplished by using band stop (for the constant speed stimuli) or order tracking filters (for the acceleration stimuli). To ensure that the filter parameters were correctly set, a filtered sound file should yield a PR of 0 dB. Figure 3 illustrates this fulfilled requirement for a constant speed case and Figure 4 for an acceleration case.

![Figure 3: Example of a sound file from constant speed recording that was filtered to reach PR=0 dB.](image)
The next step in synthesizing sound files was to add sinusoidals with fixed frequencies for the constant speed cases and rpm-dependent frequencies for the acceleration case. The fixed frequencies were created by using the signal generator in the software Head Acoustics Artemis. The process for creating speed-dependent tones was more comprehensive and was done by using the software synthesizer Pure Data. Three different e-motor orders; 6, 36 and 72, all being contributors in the original recordings, were recreated with the software with a stepwise increase of approximately 2 dB. In total, there were 61 sound files with PR values ranging from ~0 dB to ~7 dB. The duration of each sound file was between 5 and 15 seconds.

3.3 Listening Test

27 individuals took part in the listening test of which 15 were male and 12 female. The mean age was 33. Prior to the test, the audibility of a 10 kHz tone had been checked and confirmed for each subject. None of the subjects were specialists in the field of sound and vibration. The appraisal was conducted in a studio intended for listening tests, with calibrated playback through headphones. In a previous study with a very similar test vehicle and stimuli, it was concluded that subjects tend to have similar ratings of e-motor sounds during test track evaluation as with laboratory headphone evaluation [3]. After the presentation of the test procedures and an introduction which aimed to familiarize the subjects with the type of sounds appearing in the test, the subjects were asked to rate each sound file with respect to the e-motor noise. The attributes “annoying” and “well sounding” were rated with respect to the e-motor sound quality on a scale from 0 to 10. In addition to the attribute rating, a “yes/no/unsure” regarding the audibility of the tone was registered. Even if a tone was not detected, the subjects were asked to rate the stimuli anyway. The listening test took about 50 minutes to complete. An excerpt from the appraisal is illustrated in Table 1.

<table>
<thead>
<tr>
<th>Sound #</th>
<th>Did you hear a tone/beep?</th>
<th>Rate the sounds with a number from 0-10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yes</td>
<td>Unsure</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. RESULTS

4.1 Audibility of tones

To investigate the subjects hearing threshold of the tones as a function of PR, binary logistic regression (BLR) was performed on the data. With BLR, a prediction model is derived that constrains the data between 0 (corresponding to not have heard the tone) and 1 (heard the tone). If “unsure” was replied to the question on if a tone/beep was heard, it was grouped together with the “no” answers. Figure 5a and 5b show the fitted model (p<0.05) for the constant speed cases and the acceleration case respectively for order 6, 36 and 72. For the constant speed cases (50 and 80 km/h respectively), order 6 corresponds to ~450 and ~700 Hz, order 36 corresponds to ~2700 and ~4200 Hz and order 72 to
~5400 and 8400 Hz. For the acceleration case, order 6 ranges from 100-800 Hz with an emphasis (duration dominance) on frequencies located between 350 and 800 Hz due to the e-motors torque characteristics. Order 36 ranges from ~700 Hz to 5 kHz with emphasis on 2.5-5 kHz and order 72 ranges from ~1400 Hz to 10 kHz with emphasis on 2.5-10 kHz. For the constant speed cases in Figure 5a, it can be observed that the audibility is lower for all PR-levels for order 6 compared to the two higher orders.

<table>
<thead>
<tr>
<th>order 6</th>
<th>order 36</th>
<th>order 72</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Constant speed, 446 Hz" /></td>
<td><img src="image2" alt="Constant speed, 2676 Hz" /></td>
<td><img src="image3" alt="Constant speed, 9352 Hz" /></td>
</tr>
<tr>
<td><img src="image4" alt="Constant speed, 703 Hz" /></td>
<td><img src="image5" alt="Constant speed, 4220 Hz" /></td>
<td><img src="image6" alt="Constant speed, 8440 Hz" /></td>
</tr>
</tbody>
</table>

Figure 5a: Fitted logistic regression model with 95% confidence intervals for the likelihood of detecting tones during constant speed. From left to right: order 6, order 36 and finally order 72.

For the acceleration case plotted in Figure 5b, the audibility is lower for low PR-values for the 36th and 72nd order compared to the constant speed cases but the likelihood for detecting tones is high for PR>3 dB.

| ![Acceleration, order 6](image7) | ![Acceleration, order 36](image8) | ![Acceleration, order 72](image9) |

Figure 5b: Fitted logistic regression model with 95% confidence intervals for the likelihood of detecting tones during acceleration, order 6, 36 and 72.

4.2 Annoyance and PR

The relationship between perceived annoyance and frequency content is dependent on the PR-level of the tones. As illustrated in Figure 5a and 5b, the audibility of the tones varies significantly with PR-level and also depending on the order (proportional to frequency). Based upon the curves in Figure 5a and 5b, the PR-levels were divided into three intervals; PR≤2 dB (low audibility), 3 dB≤PR≤4 dB (mid audibility) and PR≥5 dB (high audibility). ANOVAs were performed on the three different groups to reveal statistical differences.
Figure 6a: Annoyance rating for different frequencies/orders, constant speed driving condition. The ANOVAs are done for three ranges of PR-levels corresponding to low, middle and high audibility.

Figure 6a reveals that there are rather small differences in annoyance rating depending on frequency content of the tones for PR-levels below or equal to 2 dB. When the levels of tones have PR-values between 3 dB and 4 dB, the annoyance rating from the tones belonging to order 36 and 72 is clearly higher while the annoyance from order 6 still is relatively low. Noticeable is that for f=4220 Hz, annoyance is clearly higher compared to adjacent tones. One explanation could be that the ear is very sensitive in this frequency range which can be visualized in isophone-curves [6]. For even higher PR-values, the annoyance rating from all three orders is further increased, but the pattern from the mid audibility group is unchanged; the frequencies belonging to order 36 and 72 yield higher annoyance rating than order 6.

For the acceleration case, there were not enough sound files with PR-values of 5 dB and higher. There was no significant difference in perceived annoyance between the different orders for PR-values of 2 dB or lower. Figure 6b reveals that for PR-values between 3 dB and 4 dB, the annoyance from the 72nd order was significantly higher than order 6 and 36. The conclusions from the acceleration cases are a little different compared with the constant speed cases, but it is important to point out that the frequency content for the different orders varies for the respective cases.

Figure 6b: Annoyance rating for different orders, acceleration driving condition. The ANOVAs are done for two ranges of PR-levels corresponding to low and middle audibility.

In comparison to the prominence criteria from ECMA-74 in Figure 1, both audibility and annoyance are increased when frequencies exceed 1 kHz. However the PR-levels that contribute to high annoyance are clearly lower than the PR-levels for the prominence criteria.

5. USING PR FOR TARGET SETTING

As mentioned in the introduction, the findings from this work were intended to support target setting for electric vehicles. Once the accepted PR levels for all potentially occurring e-motor harmonics are decided for an upcoming vehicle, the corresponding maximum allowed sound pressure level for the respective harmonics need to be derived. Those will probably differ from the prototype vehicle since road and wind noise loads are expected to be different and need to be estimated. If the harmonics are expected to be airborne (typically those harmonics that originate from radial electromagnetic forces), the allowed radiated sound power from the stator housing can be determined if the acoustic transfer functions can be estimated. Similarly for the structure borne shares, the noise transfer functions (NTF) at e.g. body attachment points relating sound pressure to force, are required in order to determine the maximum allowed dynamic forces. As for the loads, the transfer functions of the future vehicle will be different compared to the prototype and the delta needs to be estimated. A
schematic presentation of how the complete vehicle and component targets for a future vehicle can be derived from the prominence ratio requirement from a prototype vehicle is shown in Figure 7.

![Figure 7: Receiver and source target derivation from prominence ratio requirement](image)

6. Conclusions

This study addresses the perception of tonal components from the electric traction motor for hybrid/electric vehicles. The main objective was to gather more information on the tolerable levels at different frequencies of the tones during constant speed and accelerating driving conditions. If the most common noise level metric, dB(A), would be used for quantifying the subjective tolerable limit for e-motor tones, it would need to be defined for all relevant speeds, road surfaces etc. Prominence ratio (PR) is a psychoacoustic metric that relates a tone’s level with the adjacent broad band noise shares. By using this metric to relate the subjective acceptance limits, the target process becomes more straight-forward. By sound synthesizing, numerous sound stimuli with the same background noise but with step-wise increments in magnitude of the tones were created. Listening tests were conducted where the threshold of detecting the tones and the perceived annoyance was rated. By performing binary logistic regression on the audibility threshold data, the probability of detecting the tones at different PR-levels for different motor orders (proportional to frequency) was derived. Three different motor orders were included; 6, 36 and 72 and only one were present in each sound stimulus. The results reveal that frequencies up to ~800 Hz are more difficult to detect compared to frequencies above ~2.5 kHz. This holds for all PR-levels for the constant speed cases. From the findings regarding the audibility threshold, the sounds were grouped into three categories with different PR-level intervals; low, mid and high audibility. The rated annoyance was compared between orders and audibility groups. For all driving conditions, the perceived annoyance was relatively low for the low audibility group (PR≤2 dB). With higher audibility (3 dB≤PR≤4 dB and also PR≥5 dB), the perceived annoyance was significantly higher for order 36 (corresponding to frequencies between 2.5 and 5 kHz) and order 72 (with tones containing frequencies above 5 kHz) compared to order 6 for the constant speed cases. For the acceleration case, there was no significant difference in annoyance rating between the three orders for the low audibility stimuli. With higher audibility, there was a significant increase in annoyance with increasing order. To summarize, a general recommendation from these analyses would be to aim for a PR-level below 3 dB for tones exceeding 800 Hz. For tones with lower frequency content, the PR-level can reach values around 5 dB and still not induce high annoyance ratings. If e-motor audible feedback from driving is desired, this would be the preferred frequency range. However, more information is required to understand the complete picture regarding sound quality of e-motor noise in hybrid/electric vehicles. This study is limited in respect to the fact that only one single tone was evaluated at the time. Further, there was a gap in the frequency content of the orders where an absence of pure tones between 800 and 2500 Hz perhaps was the most critical fact.

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REFERENCES


