Designing a Metric for the Customer Relevance of Synchronous Turbocharger Whistling in the Driver’s Cabin

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ABSTRACT
Engine downsizing has led to an increasing use of turbochargers in Otto and Diesel engines. With increasing quality demands regarding the acoustics of combustion engines, the noise emitted by turbochargers (TC) becomes more and more relevant. The objective quantification of TC noise as well as its correlation with the subjective acoustic impression are the main focus of the presented study. The tonal noise emitted by a TC due to the rotor imbalance is both metrologically recorded and subjectively assessed by a large proband group including expert listeners as well as non-professionals. The signal of a well-balanced TC is amplified in pre-defined levels using a loudspeaker in the vicinity of the TC in the engine compartment. The noise is evaluated with a customized Tone-to-Noise (TTN) relation, which was found to be a good means to differentiate between the pre-defined noise levels. By combining proband ratings with these TTN values, a correlation between the subjective perception of tonal TC noise in the driver’s cabin and the acoustic measurements was successfully established. The results of the study allow a better adaption to customer expectations. Therefore, the new method is used in the design phase of TC.

Keywords: Acoustical development, Annoyance, Engine development, Objective rating, Perception, Rating methodology, Subjective Rating, tonal, Tone-to-Noise, noise, Turbocharger, Vehicle noise

I-INCE Classification of Subjects Number(s): 13.2.1, 63.2, 69.3

1. INTRODUCTION
In recent years, the development of combustion engines has been dominated by the trend of „downsizing“, i.e. the reduction of number and/or volumetric size of the cylinders. In order to increase the specific power of such new engines, while simultaneously reducing their emissions, turbocharging - today often realized as multi-stage systems - has become indispensable. Over the past decades, the customers’ expectations regarding vibration comfort and engine acoustics have risen significantly. As engine noise has been continuously reduced, the noise emitted by turbocharging systems has recently become a focal point of the engine sound design.

One of such noises originating from turbochargers (TC) is often referred to as synchronous „howling“, „whistling“ or „whining“. It originates from the imbalance of the TC rotor-bearing system. The TC can be balanced on high-speed balancing machines, however, a small imbalance is always remaining. Due to the high speed of TC (up to 300kRPM depending on its size) such imbalance noise (i.e. noise with a frequency synchronous to the rotor-speed) can be acoustically perceived in the driver’s cabin and may be rated as disturbing. The rotordynamic origin of tonal noises in TC structures has been investigated in previous works, e.g. in the simulative work of Bernhauser (3).

Much research work is done on psychoacoustic parameters in order to classify tonal noise (1, 7). While in earlier days, the purely subjective evaluation of TC noise was standard, the need for objective measurement methods has emerged. For the assessment of general tonal noises, the Tone-to-noise ratio as well as the prominence ratio are standardized and are therefore being used intensively. Peter et.al. (4) demonstrate that the objectively assessed Tone-to-noise ratio of stationary tones can be linearly

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correlated to subjective ratings. However, the standardized Tone-to-noise is not adequate to predict the tonality of time-varying tones.

In the current work a classification of transient tonal noise is performed by a new BMW specific algorithm called “turbo whining & whistling metric” (TW²M), which is based on a customized Tone-to-noise relation, henceforth abbreviated as TTN. The TW²M has proven to accurately differentiate between different levels of tonal TC noise, making it a viable parameter to account objectively for transient tonal noise.

However, the annoyance of a tonal noise is highly dependent on the individual listener. Hence, the sensitivity distribution of a large group of probands must be understood, in order to limit such TC noises in accordance to the customer’s expectations. Therefore, a large group of probands consisting of expert listeners and non-professionals was asked to subjectively rate turbo whistling noise in the car, which was artificially set to different noise levels. Combining these subjective ratings with the objective TW²M measurements, an objective limit for turbo noise could be derived.

The detailed description of the setup and the results of the study is provided in the following.

2. Experimental and Vehicle Setup

2.1 Vehicle

A BMW convertible was chosen for the psychoacoustic experiment. The vehicle with left-sided steering wheel was set up in an anechoic half-space with an integrated vehicle roller test bench.

The vehicle was equipped with a 4-cylinder BMW TwinPower Turbo Diesel engine with one TC. A well balanced TC was chosen such that its tonal noise emission (without artificial amplification) was imperceptible in the driver’s cabin. This way only the simulated tonal noise is relevant for the perception of the driver.

2.2 Experimental Setup

The tonal noise of a TC imposed by its imbalance is synchronous to its rotational speed. Therefore, the rotational speed was measured, converted into an electric sine wave signal (where the signal frequency corresponds to the TC speed) and amplified in four pre-selected stages using a power amplifier. Finally, it was altered in the following frequency ranges with an equalizer in order to obtain a realistic and reproducible TC whining noise in the driver’s cabin. The full setup is shown in Figure 1.

<table>
<thead>
<tr>
<th>Freq., kHz</th>
<th>0.00</th>
<th>0.50</th>
<th>1.00</th>
<th>1.25</th>
<th>1.60</th>
<th>2.00</th>
<th>2.50</th>
<th>3.15</th>
<th>4.00</th>
<th>5.00</th>
<th>6.30</th>
<th>8.00</th>
<th>&gt;10.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt., dB</td>
<td>-12</td>
<td>-8.5</td>
<td>-3.5</td>
<td>-2.0</td>
<td>+0</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+1</td>
<td>+0</td>
<td>+0</td>
</tr>
</tbody>
</table>

The manipulated signal was sent to a loudspeaker in the vicinity of the TC in order to give the impression that the simulated tonal noise comes directly from the TC itself. The current sent to the loudspeaker was tapped via a current probe. The current-relational voltage at the current probe was used for the main validation of both the TTN and the subjective noise ratings.

The recording instruments were arranged as following: One microphone was applied in the vicinity of the TC in the engine compartment to record the radiated sound of the TC and the loudspeaker. Two microphones were screwed onto the co-driver’s seat at the positions corresponding to the passenger’s ears and one microphone was positioned near by the second proband in 1 m distance and 1 m height of the right front wheel. The microphones, hence, are near to the position of the probands, as detailed in Section 2.4. In order to surveil the vibrational level of the TC during the study, an acceleration sensor was applied at the center housing of the TC.

The signal information was sampled at 48 kHz.
To gather the information how the probands perceived the tonal noise, two potentiometers were mounted in the vicinity of the probands in the interior and the exterior. The potentiometers returned a voltage of 0 to 12 V and were equipped with a sticker containing a color-to-word code from green ("not perceivable") over yellow ("noticeable") into red ("disturbing") for 0 V, 6 V and 12 V, respectively. The voltage was recorded during the full measurement.

A sketch of the full experimental setup of the measured channels and the TC noise simulation is shown in Figure 1.

2.3 Proband Information

The study consisted of 70 probands who were asked to complete a questionnaire. Various relevant data of the probands (such as age, gender, possession of a vehicle, etc.) were captured in an anonymous way. 67 probands filled the questionnaire partly or fully resulting to the following statistics:

![Gender and age distributions of participating probands](image)

The probands did not undertake hearing tests, nor were they asked for good hearing in order to broaden the group of probands.

2.4 Experimental Procedure

Each measurement series required the participation of two probands. One proband was sitting in the driver’s seat and followed instructions provided on a display in front of the vehicle, while the second proband was standing outside 1m in front of the right front wheel.
Immediately before the test, each proband received a standardized training with extreme amplification of the tonal noise in order to get a feeling for the noise to be rated. Here the driver’s seat proband could freely try several pedal kick-downs. During the following test phase, the amplification was set to one out of four predefined amplification stages. The proband in the car was asked to conduct a pedal kick-down and both probands were requested to subjectively rate their perception on the color-coded potentiometer. This procedure was iterated six times with preassigned stochastic amplification levels before changing the probands’ positions.

Kick-downs were defined as relevant and used for further investigation only if the TC speed and the corresponding tonal frequency exceeded 2000 Hz. The mean of the voltage at the current clamp was calculated as the arithmetic average of all values between 1000 Hz and 2000 Hz.

3. POSTULATING A NOVEL TONAL NOISE METRIC

3.1 Customized Tone-to-Noise

For the objective assessment of the tonal TC noise, a customized Tone-to-Noise (TTN) method was developed by BMW (2). This method is based on the standards DIN 45681 (8) and on DIN ISO 7779 (9). Both standards are focusing on quasi-static noise, i.e. noise with a very low frequency change rate. This precondition, however, does not apply to synchronous TC noise, where frequency changes of $\frac{df}{dt} > 1000$ Hz/s are common. Gaudé et al. (5) use the Pseudo Smoothed Wigner-Ville analysis to account for that effect. The authors of the present study propose the use of a simple Fast Fourier Transformation (FFT), while adapting the parameters of the TTN algorithm accordingly, as outlined in the following.

The TTN ratio is defined as the ratio of
- the average quadratic sound pressure of the “tone” (in a small frequency band $\Delta f_t$ around the frequency of the tone $f_t$) vs.
- the average quadratic sound pressure of the adjoining “noise” (in a defined frequency band $\Delta f_n$ around $f_t$).

The underlying psychoacoustic theory claims that a tone can only be concealed by a (broadband) noise, which occurs in the same frequency range as the tone. In typical TTN algorithms, the ratio between $\Delta f_n$ and $\Delta f_t$ is significantly larger than 1.

Obviously, if such a TTN ratio exceeds a so-called audibility threshold (which depends on the setting values of the TTN algorithm), a tone becomes perceivable, hence, in the case of TC whining or whistling, disturbing.

While $f_t$ follows from a direct TC speed measurement, or, alternatively, from a semi-automatic TC speed determination out of vibration or noise data, other TTN parameters such as $\Delta f_t$ and $\Delta f_n$ may be defined as function of the frequency change rate $\frac{df}{dt}$ of the tone.

Applying the TTN method to a certain driving cycle with monotonous turbo speed behavior, i.e. engine spool-down (for TC whining) or engine ramp-up (for TC whistling), a TTN vs. TC speed curve can be plotted for each microphone used. Out of such curves, the BMW-specific “turbo whining & whistling metric” (TW²M) was deducted. This TW²M can be determined from an arbitrary number of microphones and takes into account
- the audibility threshold (based on the selected input parameters),
- the frequency range in which the TC noise exceeds this audibility threshold, and
- the average TTN-level above the audibility threshold.

By combining the latter two parameters in a multilinear regression, the outcome of the TW²M is a single objective rating number per turbo charger test cycle, where high TC noise yields high TW²M-values.

4. RESULTS

4.1 Correlation Studies

For relevant driving cycles, the objective TW²M rating is correlated with subjective ratings, in order to define objective limit values on the TW²M scale. In the following, the correlation between the TW²M objective rating and the subjective rating of the large and heterogeneous proband group will be presented. This correlation was established for turbo whining in engine spool-down condition.
Therefore, the following diagrams are to be read from right to left, since after a kick-down the engine spools down and the TC decreases its speed and, hence, the frequency of its emitted tonal noise.

Figure 3 shows the structure-borne noise of the TC directly after the kick-downs. It is evident, that no imbalance evolution occurred during the measurement day.

The prechosen stochastic amplification levels in Figure 4 a) lead to the separate levels in the TTN-values in Figure 4 b) - d). A higher amplification of the tonal noise in the engine compartment leads to higher TTN-values in the vicinity of the loudspeaker in Figure 4 b). The tonal noises penetrate from the engine compartment into the cabin interior and the vehicle exterior, leading to Figures 4 c) and d). The TTN-values without or with only a very small amplification lie around the audibility threshold at which tones have proven to be inaudible.

For the correlations of the different microphone positions in the inside and outside of the vehicle, see Figure 5. Good correlation can be found between the voltage at the current clamp and the TTN-values in the engine compartment, in the cabin interior, as well as in the vehicle exterior.

Figure 3 – Mean and standard deviation of structure borne vibrations of all relevant kick-downs.

Figure 4 – 
a) Voltage at Current Clamp
b) Tone-to-Noise vs. Frequency near the turbocharger in engine compartment
c) Tone-to-Noise vs. Frequency at Co-driver’s seat inner ear position
Figure 4 – Mean values, standard deviations and the audibility threshold (dashed black line) vs. frequency at distinct amplification stages 1, 2, 3 and 4 of:

a) Voltage at the current clamp, b) TTN-levels near the TC in the engine compartment c) TTN-levels at the co-driver’s seat left ear d) TTN-levels near by the exterior proband.

Figure 5 – Correlation coefficients between voltage at the current clamp and TTN-levels at different microphone positions.

4.2 Validation of the Tone-to-Noise relation

The TTN relation must be validated to be a good measure to rate a tonal noise before comparing it to subjective ratings of customer probands. Since the voltage at the current clamp is directly related to the simulated tonal noise, a correlation can be done with the TW²M rating (cp. Section 3.1).

In Figure 6 the correlation of the TW²M rating is plotted versus the voltage at the current clamp of all relevant kick-downs. The coefficient of determination of $R^2 = 0.917$ is good meaning that the TW²M rating can predict the amplified voltage at the current clamp and, hence, the TC noise simulated in the engine compartment. The small deviation of the mean current at the loudspeaker comes from the manual selection of the amplification stage.

Figure 6 – a) Calculated TW²M ratings vs. mean voltage at the current clamp for all relevant kick-downs. b) Mean voltage at the current clamp vs. subjective interior proband ratings for all relevant kick-downs.
While the TC noise identification capability of the TW$^2$M rating is evident, the overall subjective ratings of the probands are extremely heterogeneous (Figure 6 - Right).

Figure 7 – Left (Right): Slope k vs. coefficient of determination $R^2$ of the linear correlation between voltage at the current clamp and interior (exterior) subjective ratings of all relevant kick-downs. The selection of the most relevant target group with a high sensitivity regarding a change in TC noise and its amplification is enclosed in the rectangle.

Due to this fact, the need of a grouping of probands emerges. The most relevant target group for TC noise limitation are customers, who rate even light tonal TC noise as disturbing. Such a target group can be identified by filtering the probands with a high sensitivity to a change in TC noise (individual probands predict the amplification of the noise well, i.e. the proband-specific coefficient of determination $R^2$ is $> 0.66$) as well as a high sensitivity towards changes in the amplification (individual probands exhibit a high slope of the linear regression $k > 100$). The identified target group is depicted in Figure 6.

4.3 Correlation of Subjective and Objective Ratings

The target group of interior (exterior) probands from Section 4.2 contains 5 (10) expert listeners and 3 (9) non-professionals, hence, it accounts for a representative group of probands. Now, the subjective rating of these probands is compared to the calculated TW$^2$M rating. A comparison of the subjective interior (exterior) rating and the objective interior (exterior) TW$^2$M rating is shown in Figure 8 left (right). The coefficients of determination $R^2 = 0.67$ for the interior ratings and $R^2 = 0.63$ for the exterior ratings are high in comparison to the ones shown in Figure 6 b), as the target group is much more homogenous than the entire proband group.

By performing these correlations, objective limits for TC whining noise in the cabin interior and in the vehicle exterior were successfully defined.
5. SUMMARY

A broad proband study was conducted, in which 70 participants were asked to carry out gas pedal kick-downs in a BMW convertible equipped with a well-balanced turbocharger (TC). An additional loudspeaker system was used to simulate tonal TC noise synchronous to the TC speed. The probands were then requested to subjectively rate their perception of the tonal noise on color-coded potentiometers, while the interior and exterior noise was captured by several microphones.

The kick-down tests were used to confirm the BMW specific TW²M rating method for tonal noises and to successfully adjust the scaling of this metric towards sensitive probands. The TW²M rating was scaled in accordance to the sensitivity of the specific proband group. The successful adjustment for a defined target group representing sensitive customers will be used in the TC rating of tonal TC noises in the cabin interior as well as in the vehicle exterior. This capability forms the basis for the enhancement of subjective TC noise ratings with objective noise measurements.

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