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Enable Vehicle Interior Noise Measurements on Public Roads by Statistic Analysis

Joerg BIENERT[1];

[1] Technische Hochschule Ingolstadt, Germany

ABSTRACT

Vehicle interior noise measurements are a standard procedure in vehicle NVH development. Main attributes are powertrain, road and wind noise. To record each of them, different driving conditions are chosen. Unfortunately the signals are disturbed during measurements of public roads, so that OEMs use special test facilities. To overcome this extra effort, statistical tools can be applied to achieve reliable results on public roads with normal traffic. Example one is the road noise recorded during slow constant drives on rough roads. Here bumps and noise by the neighborhood traffic can be identified statistically. A transformed normal distribution is the basis. Then the disturbed contribution is identified and removed from the quantitative sound pressure level. Example two is even more sophisticated. Usually wind noise can only be assessed from measurements in aero-acoustic wind tunnels. On normal road drives it is covered by road and powertrain noise. The statistic method shows a correlation between the interior noise fluctuation and the aerodynamic flow fluctuation. The correlation gradient can be used as metric to describe the wind noise performance of cars. It even can be integrated to the wind noise contribution in the total cruise noise.

Keywords: Automobiles, Road Traffic Noise, Statistical method

1. INTRODUCTION

Acoustic comfort in the vehicle interior is one of the main targets in the vehicle attribute development. One class build the road and wind noise. They are broadband noises that occur inherently during driving and low levels of these class are aimed for. They contribute significantly to a low noise comfort on one side and do not bring any character into the vehicle sound on the other side. The other class of noises are the powertrain noises. They build the character of the sound and enhancement is wanted in some driving conditions. To enhance theses sounds and not to overcome overall noise levels a low level of road and wind noise is again wanted.

As a consequence a lot of testing has to be performed to reduce road and wind noise. Simulation methods for vehicle NVH improve continuously but the prediction nowadays do not match the test result exactly. Automotive OEMs therefore build test tracks and wind tunnels. On test tracks with well defined surfaces that guaranty a reproducibility of excitation road noise measurements are performed. Such test tracks are expensive to build or to hire (e.g. Idiada, Nardo). Alternatives like road noise roller dynos are not less extensive.

This becomes more valid for wind noise development. As wind noise becomes significant only at high speeds it is usually not possible to find a driving condition to exaggerate the wind noise versus the other sources. The only possibility was to perform a wind tunnel test where the airflow is the only sound source. Testing time will cost a higher four digit amount in Euros per hour.

The aim is now obvious that NVH testing on public roads would reduce the effort tremendously. Also smaller companies then would be able to afford these tests. For road noise the measurement system should be able to find disturbances from road failures and surrounding traffic. For wind noise the algorithms should be able to estimate the wind noise contribution in the total signal. These two requirements are shown in this paper by applying statistical methods.

[1] joerg.bienert@thi.de

2. IDENTIFICATION OF DISTURBANCES IN ROAD NOISE MEASUREMENTS

Road noise measurements are usually done on roads with stationary roughness and without road failures at constant moderate speed e.g. 50 kph. To vary the excitation from the road another stationary road has to be used as test track. This procedure has to be taken over for measurements on public roads. Here we also need different roads with stationary surfaces of a length for e.g. 30 seconds of data recording. The differences on public roads are:

- Road disturbances like holes, lids, gaps or joints exist. This will modify the recording and in most of the cases the sound pressure level will rise.
- The interior noise is disturbed by other traffic especially the two-way traffic.

The idea is to automatically identify these events during data processing. After the identification these short time events can be excluded from the processing to get corrected results. Typical results are averaged metrics like overall or bandwise sound pressure levels (SPL), but also other stationary metrics like articulation index are applicable.

2.1 Typical distribution of sound pressure levels

Figure 1 shows a typical series of runs on a public road in Ingolstadt. Each run is about 40 to 50 seconds and the SPL in dB(A) shows a more or less stationary variance with some overlay of disturbances. In the following examples the number and significance of disturbances are low. These conditions have been chosen to demonstrate the sensitivity of the method.

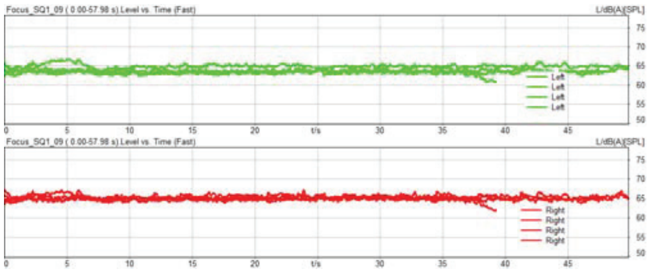

Figure 1 – Typical repeatability for a binaural SPL for 4 runs on a public road with 50 kph

The identification of disturbances should be based on statistical methods therefore it should be known which kind of distribution the random data has. For the example of SPLs in dB(A) and third octaves it will be shown in figure 2 and 3. Here 16 individual runs are plotted in an overview. The first assumption is that the SPLs are normally distributed. This is not obious as the SPL processing, here with time constant fast, is already a logarithmic metric. So it is astonashing but nice that the normal probability plot with according axis of ordinate is nearly a straight line in Figure 2 for 125 Hz.

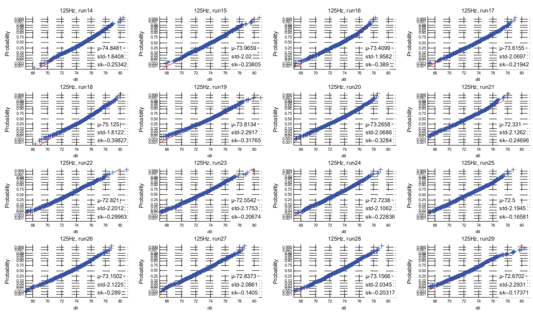

Figure 2 – Normal probability plot for 16 runs in 125 Hz third octave band

But this is not a must. Figure 3 shows a clear distorsion from the normal distribution in the 4 kHz band. The application of methods based on normal distributions will not be possible.

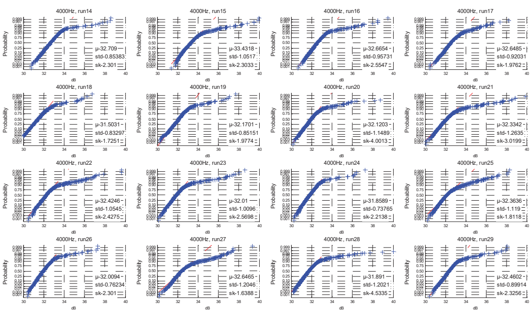

Figure 3 – Normal probability plot for 16 runs in 4 kHz third octave band

2.2 Test for difference of measurement runs

Before we want to correct the data it should be checked if the effort of repeated runs is beneficial in terms of statistical significance. Each run represents a random sample set in the chosen metric. The Kolmogorow-Smirnow-Test is able to test two samples for a difference of the statistical distribution. One of the samples in this case is a very precise reference measurement taken without any additional traffic and without driving over disturbances.

As usual procedure in statistics a hypothesis test on a significance level of 90% was performed:

- Null hypothesis H0: the compared measurement has the same distribution as the reference measurement.
- Alternative hypothesis H1: the compared measurement is different to the reference.

The result is dependent of the observed frequency. For low frequencies there is the trend that the 15 measurements are only sometimes significantly different from the reference. This would mean that a usage of many runs is not strongly recommended.

On the other side the stochastic test for the high frequencies show that nearly all runs differ from the reference. Therefore an averaging of several runs is strongly recommended.

But before doing the averaging the data has to be cleaned from disturbances.

2.3 Transformation of data to normal distribution

Figure 2 and 3 showed that data might be normal distributed or not. So the idea is to transform the data so that they will get normally distributed by a transformation $y = f(x)$. But which function is feasible to do that? After several trials the Johnson transformation was found as suitable:

$$y = a_0 + a_1 \cdot \operatorname{arcsin} h\left(\frac{x - a_2}{a_3}\right) \tag{1}$$

There are open parameters a_0 to a_3 that have to be found. a_2 and a_3 are already known by average shift and standard deviation scaling. To find good parameters for the transformation it is referred to the best possible data set, the undisturbed reference run. By a Gauss-Newton procedure, which adapts a dataset to a model function, the reference measurement delivers the parameter for an optimal transformation to a normal distribution. These parameters then can be used for all other runs in that frequency band. So there is a set of parameters a_0 to a_3 for each frequency band.

It is expected that these parameters can also be used for further tests of different cars on the same surface.

Figure 4 shows an example for the data before and after Johnson transformation.

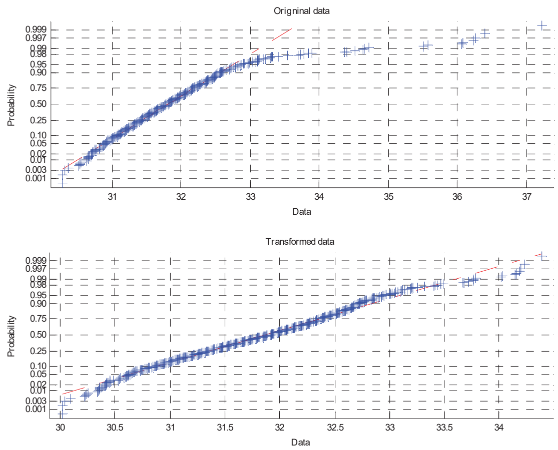

Figure 4 – uncorrected and transformed data of 4 kHz band

2.4 Identification of disturbances

After the transformation to normal distribution each measurement run can be treated with common tools for outlier identification. One easy to use method is the usage of deviation in terms of standard deviation of more than the factor of e.g. three. The example here in 4 kHz octave bands show the improvement of 16 runs in the 4 kHz band after the cleaning of data above the threshold of three times the standard deviation. The basic data of figure 5 only showed minor disturbances that could be identified by the method.

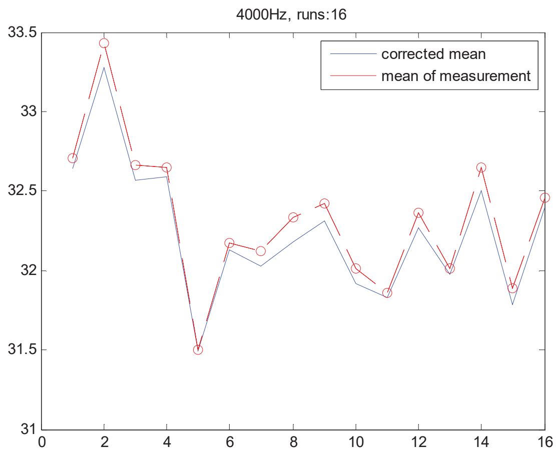

Figure 5 – uncorrected and cleared data of 4 kHz band

2.5 Summary of the road noise outlier identification

The method can be organized in the following steps:

- acquisition of a disturbance-free measurement on the road surface for investigation
- best fit estimation of the Johnson transform parameters in each frequency band
- transformation of the measurement runs by the Johnsons transformation
- identification and deletion of the outliers with extended distance from mean of the transformed data
- calculation of the averaged metric without outliers

3. ESTIMATION OF WINDNOISE CONTRIBUTION FROM HIGHWAY DRIVES

3.1 Basic idea of the method

Wind noise measurements are the challenging ones in vehicle acoustics. As they occur only at high speeds there are no driving conditions to significantly emphasize them versus road noise and powertrain noise. The consequence is to perform wind tunnel test that are extremely expensive.

The idea presented here is to get information about the contribution of wind noise in the total cruise noise by correlation analysis. While driving on a motorway at constant speed there is always a small fluctuation of the wind noise which is also audible in the vehicle interior. This fluctuation must be correlated to the fluctuation of the airflow around the vehicle.

If the airflow speed u is then correlated to the sound pressure Level L_p a gradient L_p versus u can be found in a statistical regression.

$$\left.\frac{d\,L_P}{d\,u}\right|_{v=const.} \tag{2}$$

If the gradient is given for the whole speed range until the maximum speed v_e, then the total level of the wind noise can be estimated by the integration from L_p=0 at u=0 until v_e.

$$L_P(v_e) = \int_0^{ve} \frac{d\,L_P}{d\,u}\,du \tag{3}$$

This could be applied either for overall levels or band levels.

3.2 Measurement setup in a vehicle

The method requires a parallel measurement of the interior noise with a standard microphone and the flow speed with a high time resolution. A measurement system based on a hot wire flow probe by SVM is appropriate for this.

The mounting of the flow probe on the roof of the vehicle is shown in figure 6. It should be checked if the average speed measured by the probe is equal to the vehicle speed. Smaller distances of the tip to the roof may occur with a factor between airflow and the vehicle speed.

Figure 6 – SVM Data acquisition system; flow sensor (left), frontend (right)

The noise fluctuation versus time is shown in figure 7 for a typical motorway cruise.

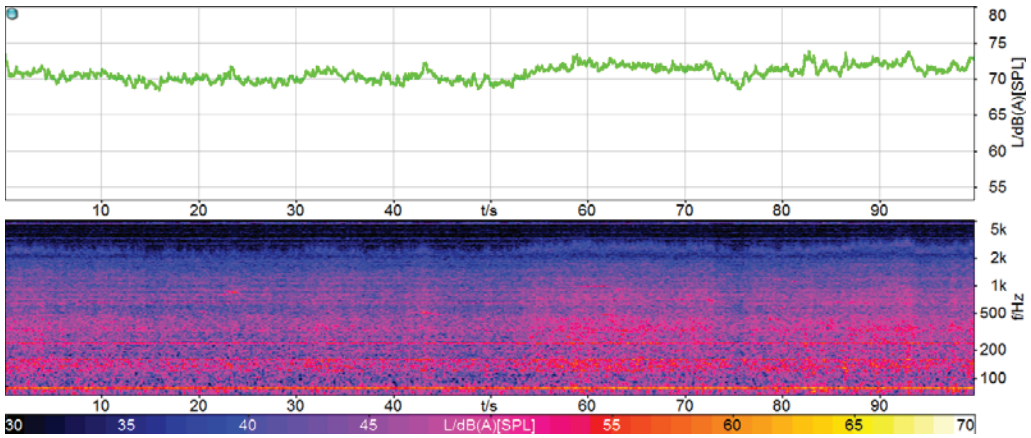

Figure 7 – Typical fluctuation of interior noise during constant speed drive on a motorway

3.3 Correlation results for constant speed drive

First investigations are done for constant vehicle speeds. Although the total wind noise contribution cannot be estimated the gradient is already a performance metric at this constant speed. Higher gradients show worse wind noise performance than lower gradients.

The base data for correlation are shown in figure 8. The sound pressure level is A-filtered with time constant "fast" in this case and the flow speed is lowpass filtered with 50 Hz to emphasize the relevant fluctuations.

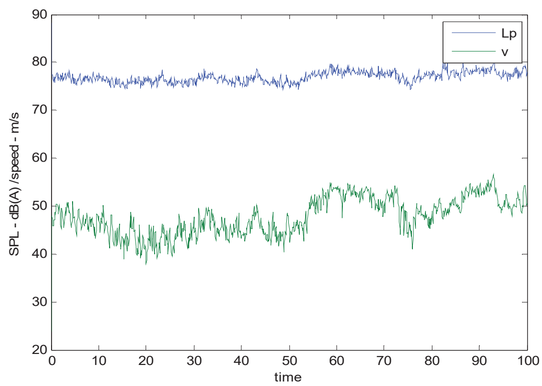

Figure 8 – Time plot of interior noise level and exterior flow speed

The important result follows from the regression analysis of both functions of time. In figure 9 the gradient is found by 0.22 for $\left.\frac{d L_P}{d u}\right|_{v=130 kph}$ for an upper class vehicle at a speed of 130 kph.

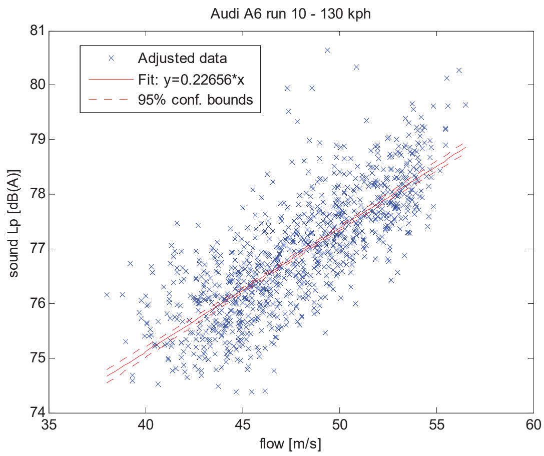

Figure 9 – Correlation plot of interior noise level and exterior flow speed

The fit quality usually can be judged by the distribution of the residuals. Figure 10 shows the residuals according to figure 9 in a normal probability plot. The distribution is nearly Gaussian noise that indicates a proper fitting in the correlation.

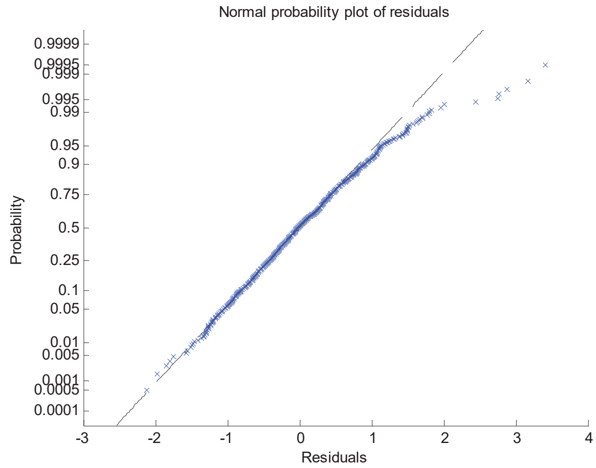

Figure 10 – Residual plot for correlation of interior noise level and exterior flow speed

Based on constant speed drives the gradient metric has been used to access the wind noise performance for different vehicle conditions at different speeds between 80 and 130 kph.

The expected trends are obvious in the results. The performance metrics rise with higher vehicle speeds. The high class vehicle Audi A6 is better than the mid class vehicle VW Golf. A modification of the Audi by a tiny window gap leads to higher values.

The data were acquired during normal motorway cruises on less good road surfaces and much traffic including trucks on the German A9 motorway. So the data have some shortfalls under these harsh conditions.

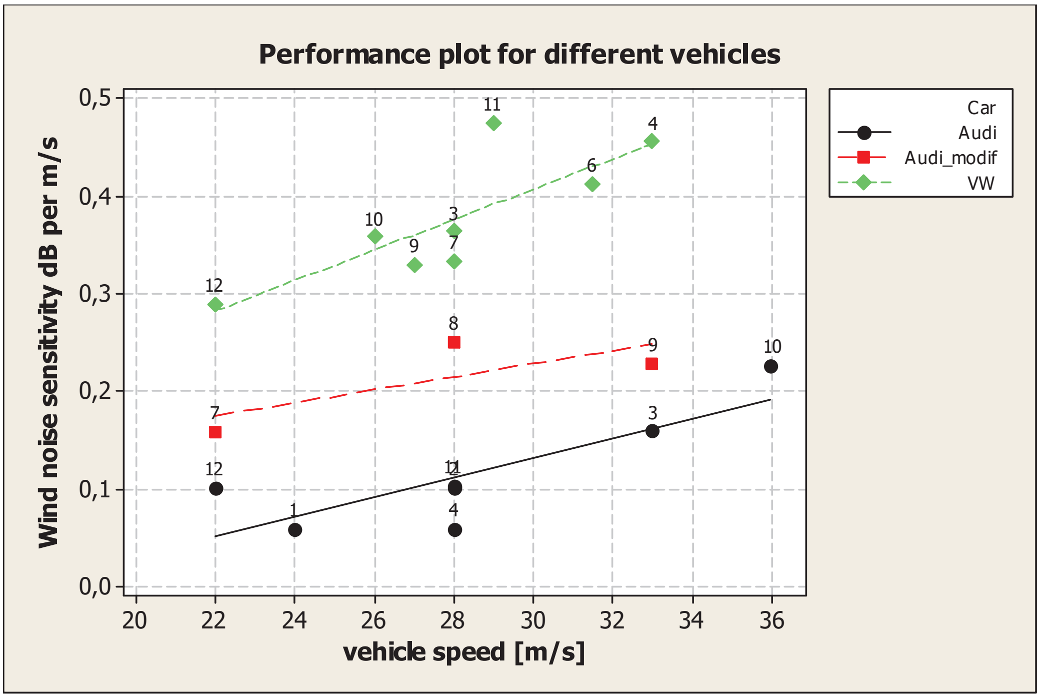

Figure 11 – Correlation gradient for different vehicle speeds and vehicle types

3.4 Extension to variable speed drive

To get the gradients as function of vehicle speed it is desirable to acquire the data during continuous motorway runs with variable speed. As the flow speed v is acquired in parallel this channel can be used to make a speed classification.

After the classification the regression is performed step by step in each class. Then the overall wind noise is integrated under the assumption, that the additional wind noise by increasing speed is not correlated to the former integration step.

$$L_{P,wind,OA} = 10 \cdot \log\left(\frac{p^2_{wind,OA}}{p^2_0}\right) \tag{4}$$

$$p^2_{wind,OA} = \int_0^{ve} \frac{\partial \Delta p^2_{eff}}{\partial v} dv \tag{5}$$

The additional effective value to the sound pressure depends on the total noise level L_{P0}.

$$\Delta p^2_{eff} = \left(10^{\Delta L_{wind}/10} - 1\right) p^2_0 \; 10^{L_{p0}/10} \tag{6}$$

Figure 12 shows the gradient and the according total wind noise contribution.

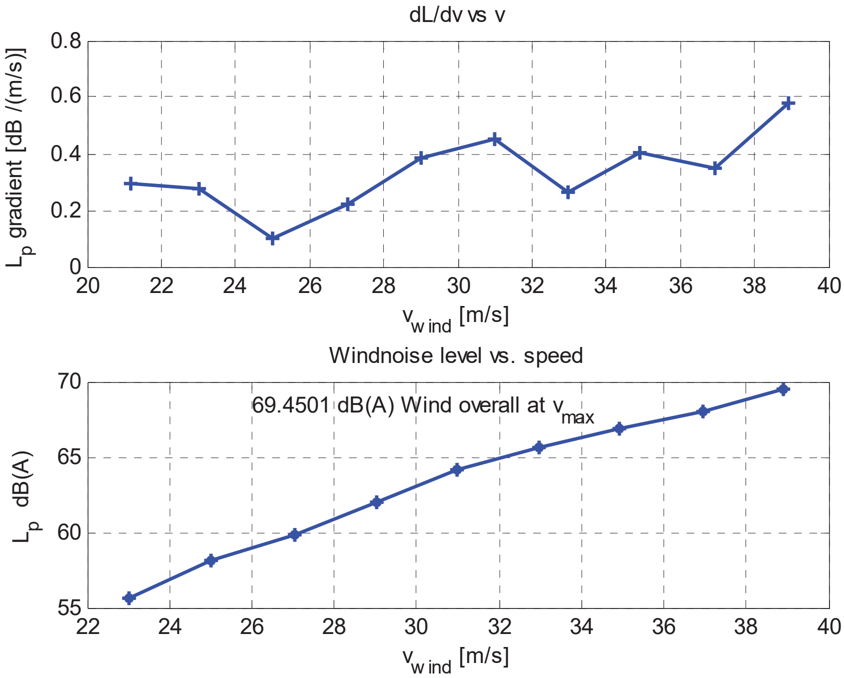

Figure 12 – resulting gradient and total wind noise from variable speed motorway recordings

These results are first steps and a method validation to compare the overall wind noise contribution with will follow.

3.5 Summary of the wind noise metric for variable speed

The method can be organized in the following steps:

- acquisition of interior noise and flow speed during motorway drive at variable speed
- build blocks with length of about 0.1 seconds
- bin data in classes of vehicle speed in the blocks
- calculate regression for each speed class
- integrate gradients to total wind noise contribution

4. CONCLUSIONS

Beside averaging statistical methods are not that often used in acoustics. Also for vehicle NVH there is usually a lot of acquired data available. With sampling rates of 44 kHz and time constants of

125 ms there is sufficient data for a statistical approach.

In this paper the focus was on the measurement of interior noise on public roads. Common practice is to have special facilities to measure road and wind noise.

The risk of data deviation by disturbances on public roads can be sorted out with an automated algorithm to eliminate outliers.

The approach to separate wind noise contribution from motorway drive recordings will reduce the effort of wind tunnel test. The correlation of wind noise fluctuation and according airflow fluctuation delivers a gradient that is promising to exaggerate the wind noise contribution.

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