Determination of the Windnoise Contribution from Vehicle Noise Measurements on Roads

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Summary

Measurements of vehicle acoustics are highly developed. Beside road and engine noise the windnoise is an important contribution at high speed.
Unfortunately there is no driving condition to separate the windnoise during normal drive. Therefore windnoise development is mainly done in the windtunnel, which is very expensive.
The proposed method uses a correlation technique between the interior noise measurement and the airflow fluctuation on the vehicle exterior.
From the correlation a gradient of the sound level and the speed change can be found. Based on that gradient the total windnosie can be integrated.
Finally by this method the windnoise, even in 1/3-octaves, can be found from public road drives.

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1. Introduction

1.1. Windnoise testing for vehicles

The development of the interior noise of passenger cars is one of the largest fields for acoustic engineers. Interior noise comfort belongs to the crucial areas for customer satisfaction and the OEMs spend a lot of (also financial) effort to develop the three main subjects that are powertrain, road and windnoise. Where powertrain noise is part of the design to give the vehicle a character, road and windnoise are unwanted. So reduction of these broadband noises is the target.
The roadnoise development on full vehicle level is relatively easy as slow drive condition generates nearly exclusive roadnoise that can be measured with standard microphones.
Windnoise occurs only at higher driving speeds above 100 kph and is than mixed with the other noise components. So there is no real driving condition to pick-up the windnoise separately. This yields in testing in aeroacoustic windtunnels. These full scale windtunnels need special interior acoustic treatment. Investments are a higher number of millions of euros and operating costs are also high because of the fan power with several MW.
An alternative method would be much appreciated.

1.2. The idea in general

The new idea is based on the sound level gradient due to increasing outer flow speed. Each driver encounters some non-steady noise fluctuation even if he drives with a constant speed on a motorway. These fluctuations are caused by the non-steady flow around the vehicle.
The idea is now to measure the exterior airflow u with a speed probe parallel to the interior noise at constant vehicle speed v.
In the analysis the main element is the correlation between the time variant sound pressure level and the airflow fluctuation. The statistical regression over a minute of time deliver the base metric as sound level vs speed gradient.
This gradient

$$\frac{dL}{du_{v=const}} \qquad (1)$$

already can be used as metric, but in the final analysis it will be integrated to the total windnoise level.

2. Measurement setup

Base for the correlation is a speed probe that is able to acquire the flow at a high frequency. The model used is from the manufacturer SVM and was originally designed to make vortices audible.

This is more than enough in terms of frequency resolution. In practice the signal can be lowpass filtered up to 50 Hz.

Figure 1. Flow probe on vehicle roof.

The speed probe is connected to the NVH data acquisition system with the same acoustic sampling rate as the microphones. For data reduction only the sampling frequency was set to a sufficient range of 10 kHz.
As shown in Fig. 1 the probe was attached rigidly like an antenna to the front roof of the car. An alternative position on the rear roof lead to similar results. Due to the circulation of the flow around the vehicle body a slight correction factor close to one will scale the flow to the vehicle speed.

3. The gradient as metric

The raw data is processed into small blocks as usual for a time variant sound pressure level (SPL) in setting fast with 125ms. Fig. 2 shows both quantities as function of time, where the correlation is not obvious, yet.
The resulting SPL weighted as dB(A) is then correlated with the flow speed averaged in this time blocks. Fig. 3 shows the correlation plot for a period of time around 30s at constant vehicle speed. From this the regression delivers the gradient according to Eq. (1).

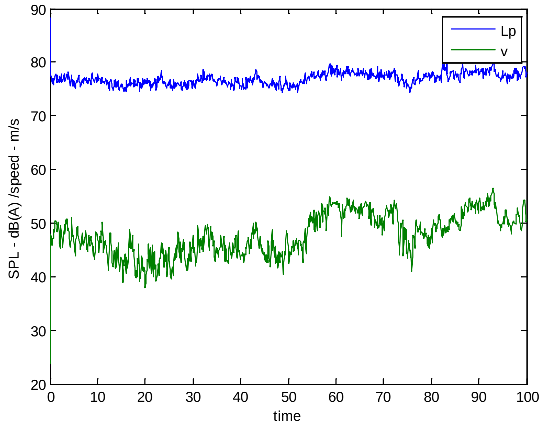

Figure 2. Flow speed and SPL vs time.

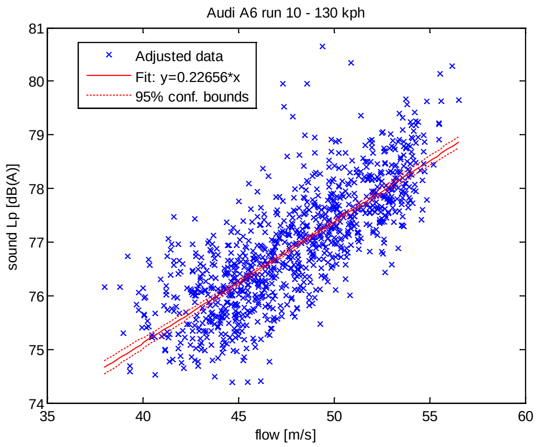

Figure 3. Regression of flow and SPL.

3.1. Correlation quality

Although the scatter in Fig. 3 is relatively large the quality of the regression is useful. The metric at a vehicle speed of 130kph yields to 0.226 dB(A)/ms^{-1}.

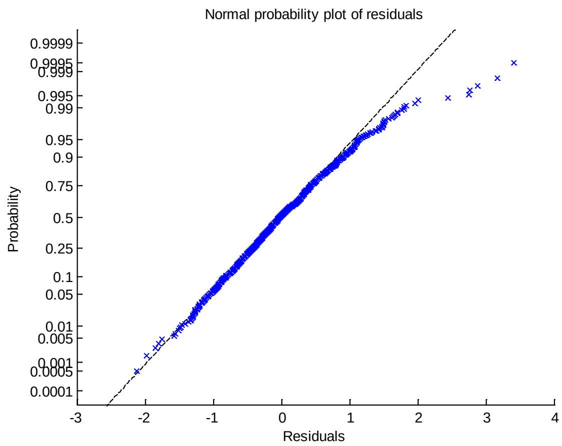

Figure 4. Normal plot of the regression residuals.

The residuals of the regression are nearly in a normal distribution what is the desired result. It should be noticed, that the result was obtained during a normal drive on a public motorway with additional traffic from passenger cars and trucks as well. The pass-by to other cars will generate uncorrelated additional noise with leads to a distortion of the distribution curve.

3.2. Vehicle benchmark

The gradient function can already been used as a benchmark metric. Higher gradients will lead to more audible fluctuations. These fluctuations are already recognized as acoustic discomfort. Secondly higher gradient will at the end also lead to higher overall SPLs of the windnoise contribution.

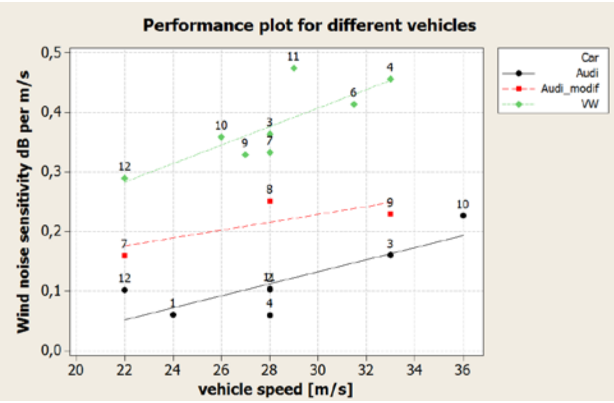

Figure 5. Gradients at diffent speeds for different vehicles.

So in the first step the benchmark is done on the gradient basis. Fig. 5 shows results at speeds between 80 kph and 140 kph. Each color represents a vehicle type. The VW has as expected a lower performance – higher values – as the Audi. By opening the side window in the Audi very slightly a deterioration to “Audi_modif” results.

3.3. Constant speed vs variable speed

The method proposed until here is based on drives with constant speed. Results for the gradient at different speeds are usually required, which makes a series of discrete runs necessary.
An alternative method is to vary the speed slowly but continuously e.g. between 60 kph and 140 kph. As the flow probe records the speed it would be possible to place the results into bins e.g. with a range of 10 kph, so that the whole range is covered for the evaluation.

The results showed very similar metrics for the constant and variable speed approach

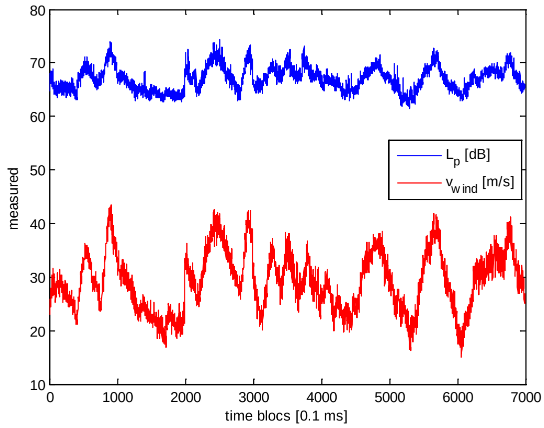

Figure 6. Variable speed test.

4. Validation for OA level

Even more interesting is the overall windnoise level from road drives that could be directly compared to the gold test in the windtunnel. It was decided to acquire the data on a test track for one vehicle model.

4.1. Methodology for Integration

To obtain the total windnoise contribution the gradient has to be integrated with an upper integration limit of the speed which is intended to be evaluated. The question to answer before is: How to add the additional windnoise contribution at rising speeds. The assumption was made that the additional windnoise is uncorrelated to the existing one at the current point of speed. So for uncorrelated contribution the squares of the effective values have to be added. The current effective sound pressure level L_{p0} is the base to get the effective value of the SPL increase ΔL_{Wind} from the gradient.

$$\Delta p_{eff}^2 = \left(10^{\Delta L_{Wind}/10} - 1\right) p_0^2 \; 10^{L_{p0}/10} . \qquad (2)$$

Then the uncorrelated addition is done in terms of integration. Theoretically the lower integration limit is zero. In practice this would a lower speed where windnoise is expected to play a role and where the first gradient is determined e.g. 60 kph.

$$p_{Wind,ges}^2 = \int_{v=0}^{v_{max}} \frac{\partial \Delta p_{eff}^2}{\partial v} dv . \qquad (3)$$

From the summarized effective pressure the level can be calculated.

$$L_{p,Wind,\,ges} = 10\ log\left(\frac{p^2_{Wind,ges}}{p^2_0}\right). \qquad (4)$$

This represents at the end the wind noise contribution at a given speed comparable to the windtunnel test.

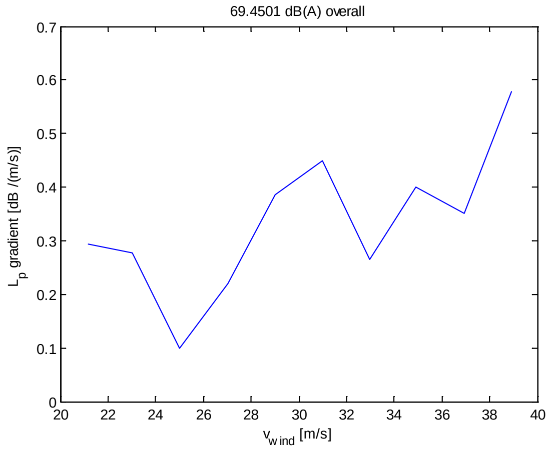

Figure 7. Stepwise SPL gradients with the final windnoise OA level.

4.2. Comparison of data

For a C class vehicle the windtunnel test resulted in an OA level L_{OA} of 67.2 dB(A) at 140 kph measured on the front seat with an artificial head.

In the phase of the method validation some parameters of the test have varied. In the interior there have been two classical microphones, one near the front headrest, one below the inner windscreen mirror. Additionally there was a variation of the outer flow probe between a front roof and a rear roof position.

Except one outlier (with 4.0 dB(A) deviation) all results showed a maximum deviation in the range of -0.4 to +2.7dB(A) to the windtunnel test.

This proved the general feasibility of the method.

5. Validation for 1/3 octaves

The final aim was to get the windnoise contribution as 1/3-octave levels in comparison to the windtunnel result (Fig. 8) for one vehicle model.

The methodology that has been used in chapter 4 can also be used for this case. The only change that is necessary is a filtering of the raw sound data. If the raw data is filtered to a certain 1/3-octave band, then the result of the analysis is exact the result in a band. So the analysis gets a loop over all frequency bands to get the aimed result like in Fig. 9.

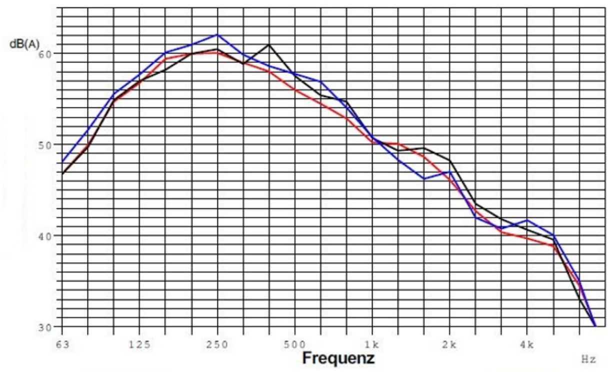

Figure 8. windtunnel result (3 slightly different versions) at 140kph in 1/3-octaves (OA level green 68.7 dB(A).

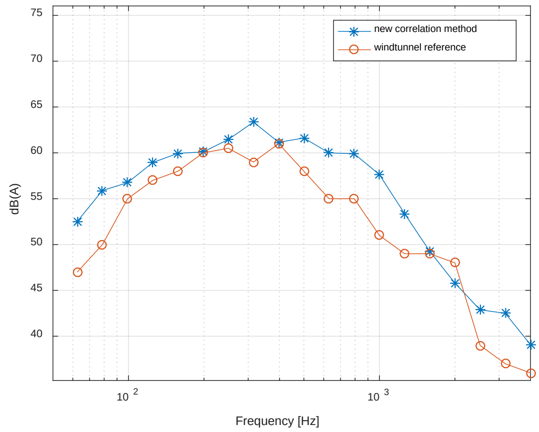

Figure 9. 1/3-octave results for 140 kph (var. speed).

In this case the result has been obtained with the variable speed method (see also Fig. 10).

After the successful comparison the model of the correlation method can also be used to estimate the windnoise contribution at different speeds 1/3-octave wise (Fig.11). In each band it can be observed that the SPL in that band increases with speed (blue curve). The red dots indicate the current overall SPL in the vehicle, so that the windnoise converges the overall SPL for high speeds. This is in line with the experience in vehicle NVH.

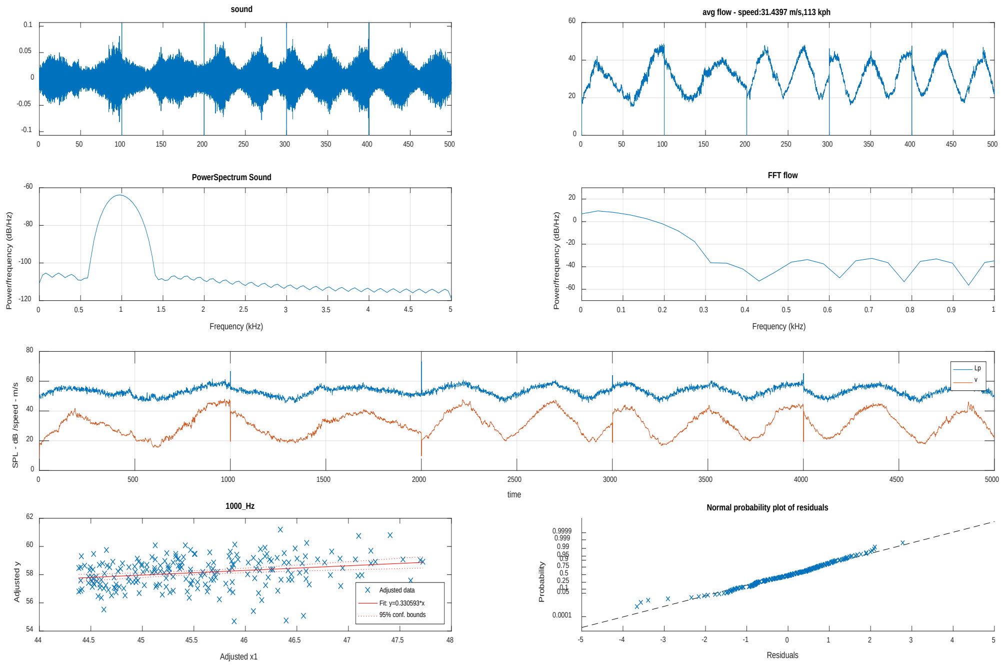

Figure 10. Analysis overview for variable speed test and 1 kHz band.

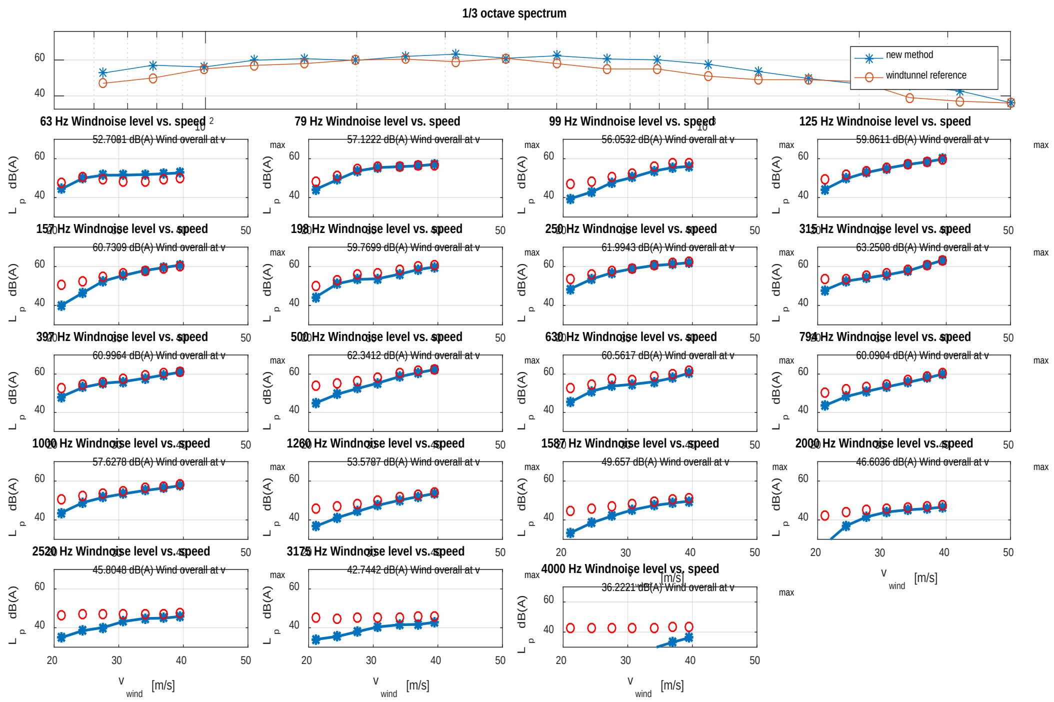

Figure 11. Analysis as function of speed in all 1/3-octaves.

The constant speed method has also to be taken into account and in deed it is closer to the windtunnel test and seems to be the preferred method (Fig.12).

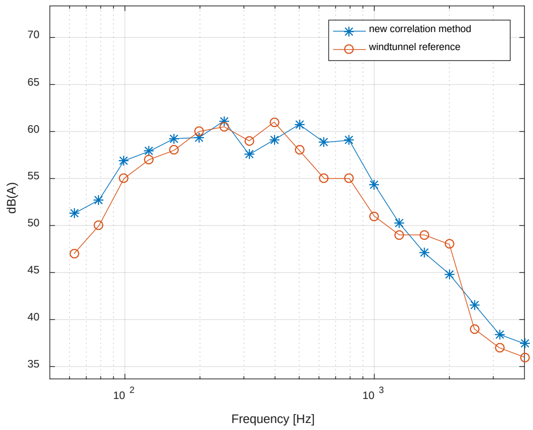

Figure 12. 1/3-octave results for 140 kph (const. speed).

The function over speed is then also possible. Unfortunately not many integration points for different speeds had been recorded. Therefore Fig. 13 shows only 5 gradients and 4 speed evaluations.

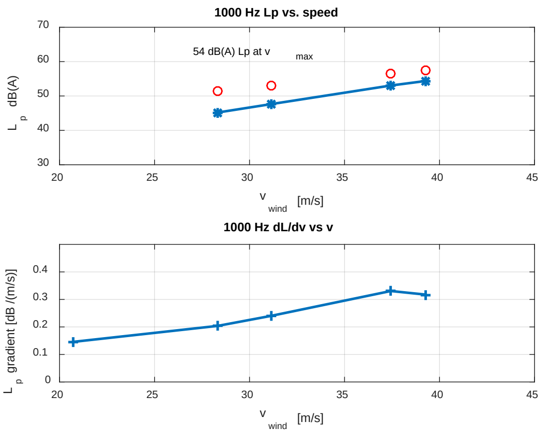

Figure 13. Gradient and windnoise level for constant speed recording in 1/3-octave.

6. Summary and outlook

The paper presents a completely new approach to identify the windnoise level in the vehicle interior. This approach requires a flow speed probe that is feasible to measure quick fluctuations of the flow. Then it is possible to correlate this to the interior noise fluctuation.

A new metric is the result that represents the SPL increase with speed. With a series of analysis at different vehicle speeds it is possible to get the isolated windnoise level only by integration / summation of the gradients.

This method is a tremendous simplification of the measurement infrastructure as windtunnel tests can be replaced. This opens the ability to many NVH developers instead of the limitation to OEMs who usually own an acoustic windtunnel.

The next step would be a more detailed validation based on an industrial project.

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