A Procedure to Simulate the Turbulent Noise Interior of Cars

S. Krampol[1], M. Riegel[2], J. Wiedemann[3]

[1]FKFS, 70569 Stuttgart, Germany, Email: susanne.krampol@fkfs.de
[2]FKFS, 70569 Stuttgart, Germany, Email: matthias.riegel@fkfs.de
[3]FKFS, 70569 Stuttgart, Germany, Email: jochen.wiedemann@fkfs.de

Introduction

The development effort has been expended on lowering the aerodynamically generated noise as the powertrain noise and the tyre-road noise of motor vehicles have been reduced continuously over the past decades [1]. The classic wind noise optimisation is performed in full-size wind tunnels under flow conditions which are considered invariant in space and time. The noise generated under so-called smooth flow conditions leave a steady auditory impression on the occupants. The natural wind environment differs significantly from the flow conditions simulated in the wind tunnel. A turbulent on-road flow condition arising from the atmosphere and wakes of other vehicles generates an instationary wind noise. Human hearing is quite sensitive to time-related structures as audible in the modulated, instationary wind noise. Variations in flow velocity have an effect on the sound pressure level (SPL). The acoustic signal is amplitude-modulated and correlates with the approaching flow velocity. Variations in flow direction have an influence on the frequency spectrum because cross winds lead to changing flow conditions along the vehicle (e. g. A-pillar, mirror) [2]. Changes in amplitude and frequency in a short period of time are thus clearly perceptible to the human ear and leave an unpleasant hearing impression. Hence, a detailed knowledge of the turbulent flow field and their impact on the instationary wind noise is essential. Acoustic effects of changing flow conditions, however, have so far been largely neglected in the vehicle development process. In order to provide a high level of noise comfort, it should be possible to examine the acoustic behaviour of a vehicle under these conditions as well.

The passive turbulence generation method is a commonly used experimental approach for generating turbulent flow in the wind tunnel. Special active vortex generators have already been used in different wind tunnels, too. An example of such an installation in the nozzle exit of the wind tunnel is the Pininfarina Turbulence Generation System (TGS) [3]. It consists of five groups of Vortex Generators (VG) and has been operative since 2003. Such systems are suitable for the simulation of instationary wind noise in the wind tunnel only to a certain extent, as the large turbulent length scales occurring under atmospheric conditions cannot be reproduced by this technique [4].

The Research Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS) has therefore developed a procedure for the computer-aided simulation of instationary wind noise. The noise synthesis represents an innovative approach for the integration of instationary wind noise into noise assessment, without having to carry out extensive modifications to the wind tunnel hardware or time-intensive measurements on the road.

Procedure of Noise Synthesis

The aim of the noise synthesis is the simulation of realistic instationary wind noise. The noise sythesis is based on wind tunnel interior noise measurements carried out for each vehicle under smooth flow conditions at varying flow velocities and yaw angles (by using the wind tunnel turntable). Different noise sequences taken from the stationary measurements are then combined to form the corresponding instationary wind noise. The input data required to carry out a noise synthesis consists of a chosen flow condition with which the noise sequences to be combined can be determined and the noise database, where the measured stationary wind noise is stored (see Figure 1).

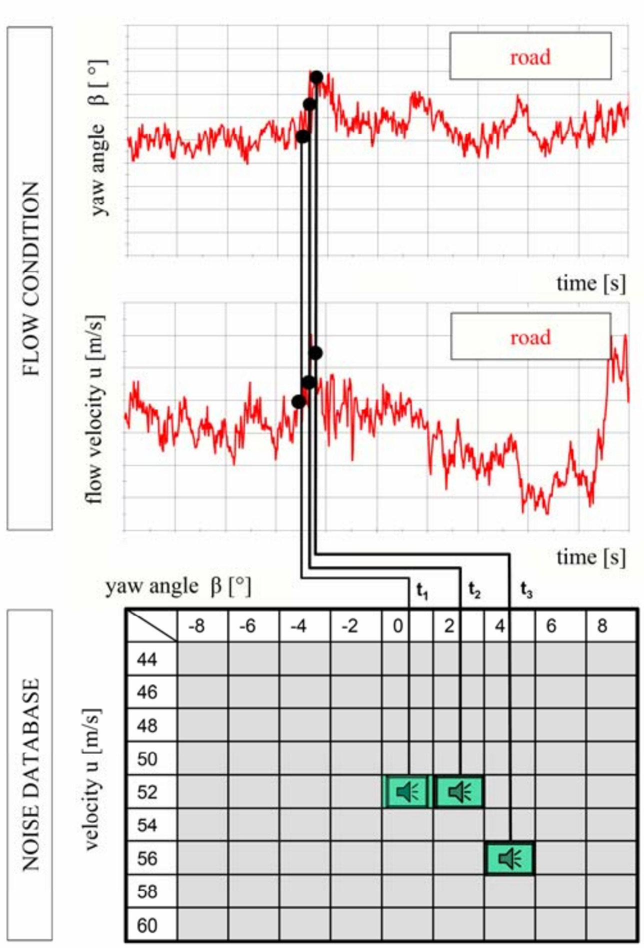

Figure 1: Schema of noise synthesis

The flow condition for which the instationary wind noise is to be synthesised must be available as a time signal and must contain the spatial flow velocity components so that yaw angle and flow velocity in the longitudinal direction (u-component) of the vehicle can be determined.

The flow condition can be available as an actually measured time signal or it can be a computer-generated time signal.

The basic principle of noise synthesis is reading the values of the flow velocity and yaw angle from the flow condition at a discrete point in time as well as loading the corresponding stationary noise file from the noise database. By sampling the time signal of the flow condition, as shown in Figure 1, the sequential order and length of the different noise sequences from the noise database are determined. Sampling the flow condition with 10 Hz means that within a second, ten stationary noise files are combined consecutively to form the synthesised wind noise sample. By using a crossfader one stationary noise file is faded out while the next one is faded in. In this way synthesised sound samples of any length and for selected flow conditions can be generated and assessed for any vehicle measured in the wind tunnel.

Definition of Tasks

It is necessary to assess methods of measurement and analysis technology in order to minimise time and work and to guarantee that the received results are significant. An automated run of instationary wind noise synthesis ensures a fast comparison of synthesised sound samples. Among others, the following points must be clarified:

- Which position near the vehicle is most suitable for measuring the local approaching flow? At which measuring positions do vortices occur which have the highest influence on the instationary wind noise?
- Which factors must be considered when compiling the noise database? Which range of flow velocity and yaw angle are relevant for noise synthesis?
- What sampling frequency of the flow condition provides optimum results? How can the sampling frequency be selected optimally on the basis of the flow spectrum?
- How should the stationary noise files be combined? What fade-over time is best?

Validating Noise Synthesis

In order to find answers to these questions a method for validating noise synthesis must be found. Due to disturbing noise sources, measurements made on the road are of only limited use. Validation examinations were thus carried out in the full-scale aeroacoustic wind tunnel of the University of Stuttgart.

Figure 2 illustrates the full-scale aeroacoustic wind tunnel of the University of Stuttgart including the measurement set-up for validation. It shows the situation for the case of turbulent flow with a vehicle driving ahead. The measuring set-up consists of a vehicle as a turbulence generator placed inside the nozzle area and the vehicle to be measured positioned in the collector downstream.

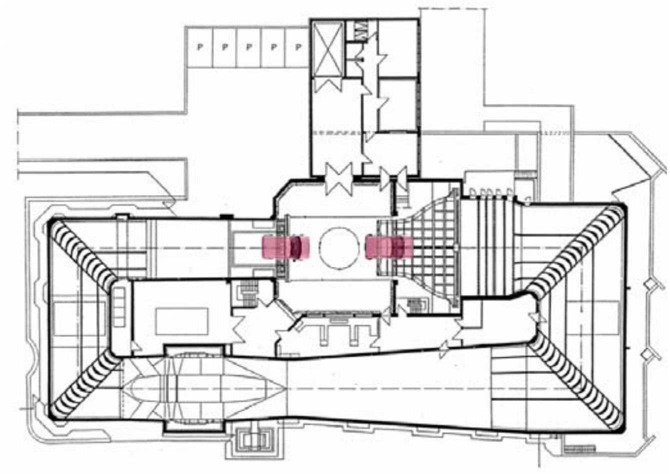

Figure 2: Plan view of the full-scale aeroacoustic wind tunnel of the University of Stuttgart including the measuring set-up (right: turbulence generating vehicle in the nozzle exit, left: test vehicle in the centreline of the collector)

Measurements under this turbulent flow condition were carried out consecutively on a SUV, on an upper-middle class car and on a vehicle of the compact-size category while the turbulence generating vehicle remained unchanged in the nozzle exit. Acoustic time signals were recorded at a velocity of 160 km/h by means of an artificial head placed on the driver's seat. In each measurement the sampling frequency of the artificial head was set to 44.1 kHz with a high pass filter of 20 Hz. The instationary wind noise recorded for each test vehicle under this turbulent flow condition was used as a reference signal with which the synthetically produced sound samples were compared during validation.

Furthermore it was necessary to determine the local turbulent flow close to the vehicle. A four-hole probe was used for measuring the flow velocity components (also at a velocity of 160 km/h). The sampling frequency was 625 Hz. The four-hole probe was located at various measuring positions near the test vehicle. Since the flow condition in the area of the front vehicle has a significant effect on the generation of aerodynamic noise, the measuring positions were primarily positioned there. Among others, they were in the centre of the hood, over the fender and above the A-pillar. In addition to the turbulent flow data, a noise database must be compiled. For this, wind noises were measured and stored in a noise database for various flow velocities and yaw angles under smooth flow conditions.

With the time history of the turbulent flow data and the noise database the basic preconditions for noise synthesis are fulfilled. The measured data can be loaded with a noise synthesis audio mixer developed on the basis of Matlab. The synthesised noise can be subsequently calculated for different measuring positions and different sampling frequencies of the flow.

Findings

Stationary noise files with velocity increments of 2 km/h and yaw angles with increments of 2.5° proved to be optimal for compiling the noise database. The stationary wind noises were recorded at the respective yaw angles (range from -20° to +20°) by means of speed ramps (from 60 km/h to 200 km/h) which guarantee time- and cost-savings. It was found that the flow measured with the four-hole probe strongly depends on the measuring position and the shape of the test vehicle. Since the composition of the stationary noise files is based on the flow condition, the measuring position significantly affects the synthesised noise.

Hearing comparisons were performed to verify the applicability of noise synthesis. A group of 25 persons had to compare different synthesised noises with the corresponding reference noise. The results showed the highest similarity of reference noise and synthesised noise for the measuring positions above the fender and sampling frequencies for the flow condition at 10 or 15 Hz.

For an objective examination and the visualisation of the instationary auditory perception, the modulation spectrum of the acoustic signal over time is an appropriate tool. In this context, it is important to know that human hearing reacts with high sensitivity to amplitude modulations of $f_m = 4$ Hz. Figure 3 shows the modulation spectrum of the synthesised noise and the recorded reference noise under turbulent flow conditions as well as the modulation spectrum of the stationary noise (160 km/h, 0°) for the compact-size car.

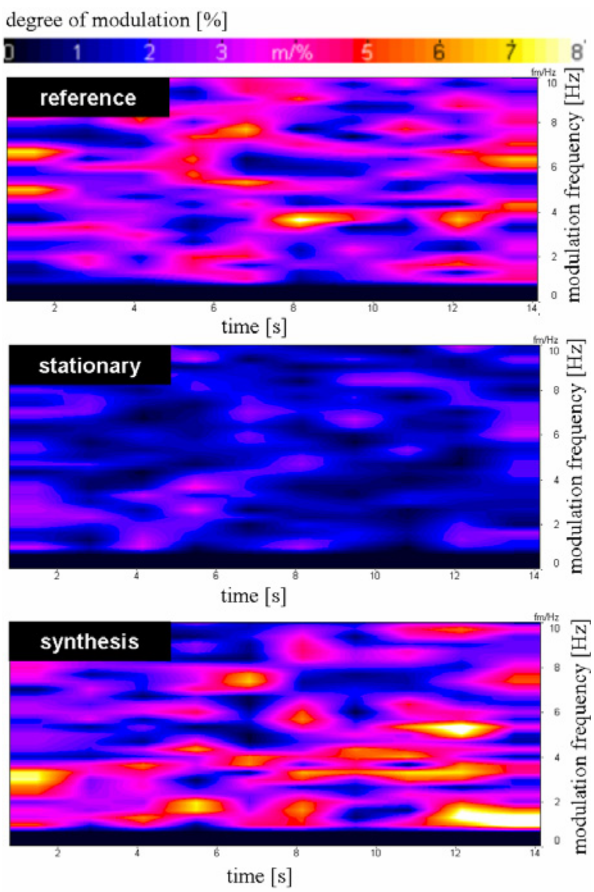

Figure 3: Modulation spectra over time in the 5.6-kHz octave band for the compact class car, left ear

The modulation analysis is based on the calculation of the envelope of the band-pass filtered noise signal using the Hilbert transform. The last step of the modulation analysis is a Fourier analysis of the envelope which shows the resulting modulations. The strength of the modulation is given by the degree of modulation m which is generally defined as the ratio of an alternating component to a constant component of an amplitude-modulated signal .The degree of modulation m is colour-coded. The result of the synthesised noise is shown in Figure 3 for a sampling frequency of 15 Hz and the flow condition measured above the fender. Synthesised noise and reference noise showed similar degrees of modulation. As expected, the stationary noise measured under a yaw angle of 0° has the lowest modulation degrees. The similarity of the modulation spectra and the subjective impression of the hearing comparison prove the basic applicability of noise synthesis for analysing instationary wind noise.

Conclusions and Outlook

In order to be able to meet the increasing demand for higher acoustic comfort in the future, it will be crucial to include the optimisation of instationary wind noise in the vehicle development process. One approach to this end is the application of noise synthesis processes for simulating the acoustic behaviour of vehicles in turbulent flows. The method developed at the FKFS shows promising initial results. The audio mixer developed on the basis of Matlab permits an optimised procedure in the generation of synthesised noise as well as a flexible implementation of parameters. With the help of this method for acoustic development time-consuming road measurements and complex turbulence generation mechanisms in aeroacoustic wind tunnels can be avoided. Before noise synthesis can be integrated into the vehicle development process on a regular basis, however, more extensive optimisation of the method is required, above all the determination and validation of other relevant flow situations. Additional effort should go into determining an index for describing a vehicle's sensitivity to interior noise with respect to turbulent flow. This would permit the fast and easy comparison of different vehicles in benchmark studies.

References

[1] Blumrich, R.: Vehicle Aeroacoustics – Today and Future Developments. 5th Int. Styrian Noise, Vibration & Harshness Congress "Optimising NVH in future vehicles" Graz; 2008

[2] Riegel, M.; Helfer, M.; Wiedemann, J.: The effect of turbulence on in-cabin wind noise – a comparison of road and wind tunnel results. In: 6th MIRA International Vehicle Aerodynamics Conference; 2006

[3] Lindener, N.; Miehling, H.; Cogotti, A.; Cogotti, F.; Maffei, M.: Aeroacoustic Measurements in Tubulent Flow on the Road and in the Wind Tunnel. SAE paper No. 2007-01-1551; 2007

[4] Watkins, S.; Saunders, J.: A review of the wind conditions experienced by a moving vehicle. SAE paper No. 981182; 1998