Application of Wind Tunnels for Automotive Aeroacoustic Development

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1. IMPORTANCE OF AERODYNAMIC NOISE IN VEHICLE ACOUSTICS

Noise emitted by motor vehicles basically comprises drive train noise, tire-road noise and aerodynamic noise. At low speeds and high engine load it is the drive train noise that dominates. At low speeds and with a low engine load tire-road noise contributes the most significant part to the overall noise. Even at full-load acceleration tire-road noise can play a dominant role due to the occasional sharp increase in generated noise caused by the high tractive forces acting on the tires. At increasing speeds the aerodynamic noise of the vehicle dominates more and more the overall level. Its acoustic power increases at about the 5th to 6th power of speed, whereas tire-road noise generally only increases at the 3rd to 4th power.

While there was increased research activity for drive train and tire-road noise as early as in the 1960s and especially the 1970s, intensive research and development in the field of aerodynamic noise only started in the early 1990s. However, the significance of aeroacoustics for the exterior noise of motor vehicles has been known for a long time. Already in 1983 Dobrzynski [3] found in accelerated pass-by tests with a passenger vehicle that from a speed of approx. 130 km/h and higher the aerodynamic noise showed higher levels than the sum of all other noise sources of the vehicle.

When several noise generating mechanisms are superimposed it is very helpful if isolated measurements of the individual sources can be performed. Additionally, the test environment shall not significantly influence the relevant boundary conditions. In the field of acoustic development such test stands have long been in use for researching drive train and tire-road noise (see for example [14]).

For investigations of the aerodynamic noise, engineers and researchers originally tried use conventional wind tunnels. Especially with respect to the aerodynamic exterior noise this proved to be difficult or even impossible, due to the strong interference caused by the wind tunnels' inherent noise. The use of psychoacoustic assessment methods usually failed due to exceedingly high background noise. Thus, more and more special aeroacoustic wind tunnels have been brought into operation since the 1990s and partly earlier.

The new test stands have led to new findings in the field of aeroacoustics. For example investigations to determine the relevance of aerodynamic noise in relation to the overall noise have been carried out with various vehicles. It turned out that in the case of quiet tire-road combinations the threshold velocity beyond which aerodynamic noise dominates both exterior and interior noise amount to approx. 130 km/h for passenger vehicles, see **Figs. 1-1 and 1-2**. As can be seen in Fig. 1, for small van-type trucks this threshold can be even lower. Spectral evaluations show that aerodynamic noise can contribute significantly in passenger vehicles also at lower speeds for specific part of the spectra. For a medium-size car it was found, for example, that for velocities of 70 km/h and more the frequency range between 350 and 900 Hz is dominated by aerodynamic noise (**Fig. 1-3**).

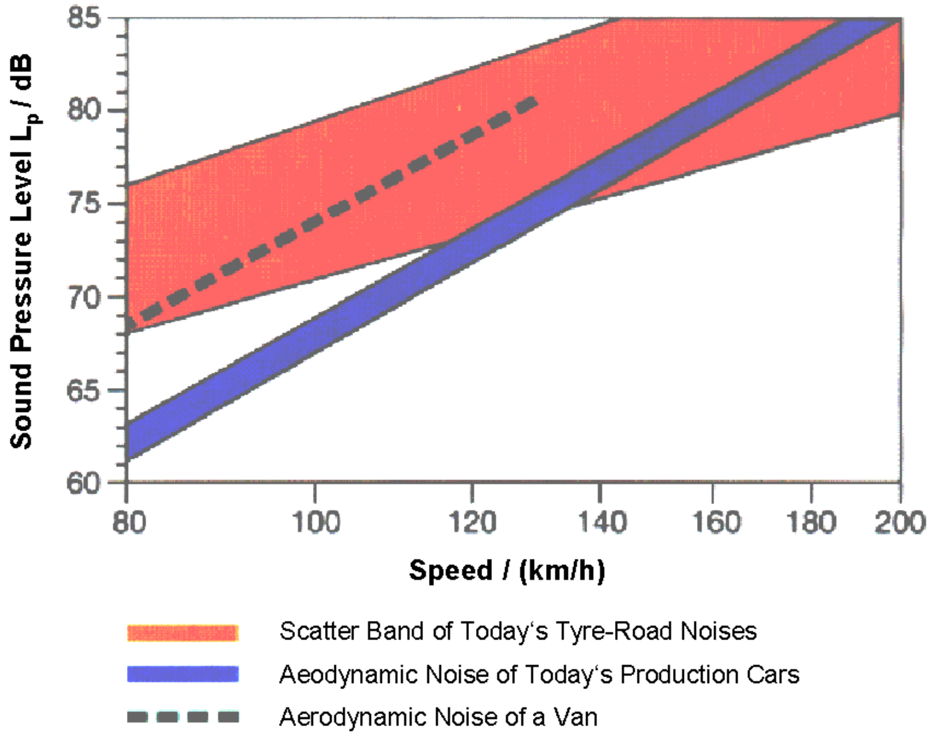

Fig. 1-1: Aerodynamic exterior noise compared to tire-road noise [6]

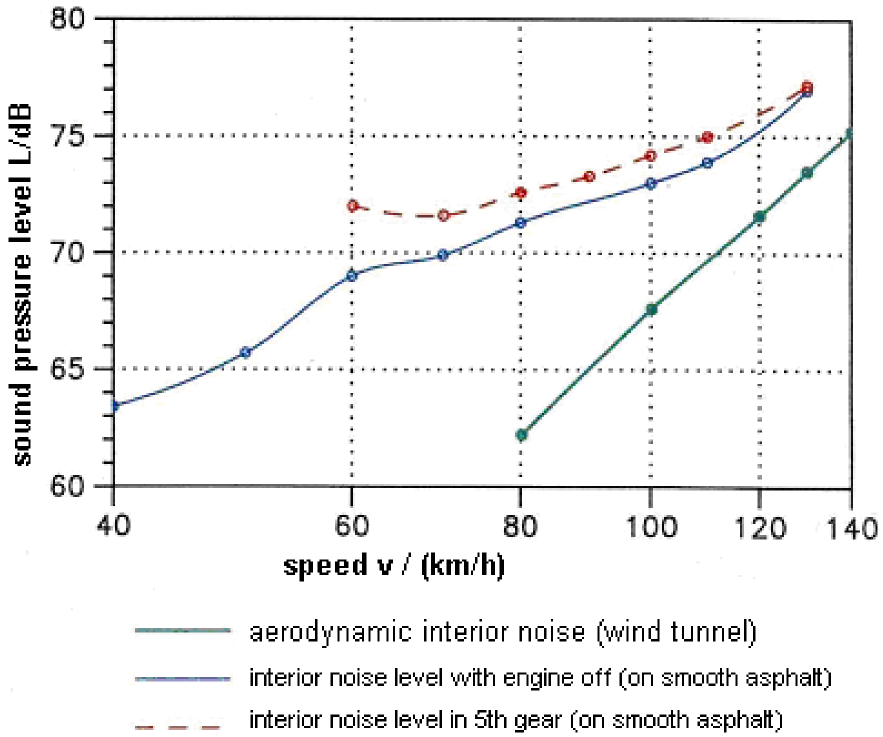

Fig. 1-2: Comparison of the aerodynamic interior noise measured in an aeroacoustic wind

tunnel and interior noise measured during driving; lower middle-class vehicle [6]

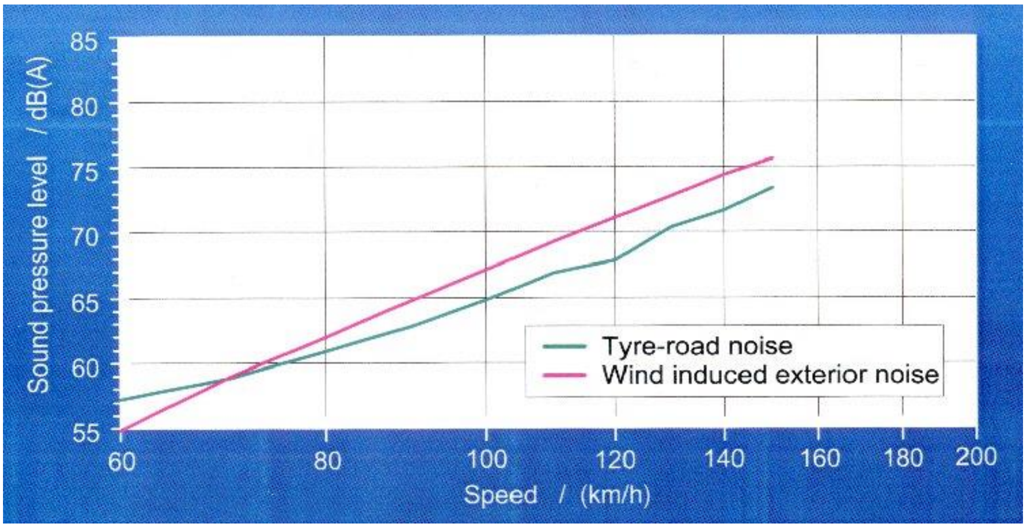

Fig. 1-3: Sound pressure level during pass by at a distance of 7.5 m in the frequency range of 350 to 900 Hz for tire-road noise and aerodynamic noise of a medium-size vehicle on smooth asphalt [9]

Figs. 1-4 and 1-5 show the various noise source components contributing to the interior noise of an upper middle-class vehicle at various speeds. At 50 km/h it is definitely the rolling noise which dominates, whereas at 160 km/h that range is dominated by the aerodynamic noise. Only for typical engine orders, the drive train noise still contributes noticeably.

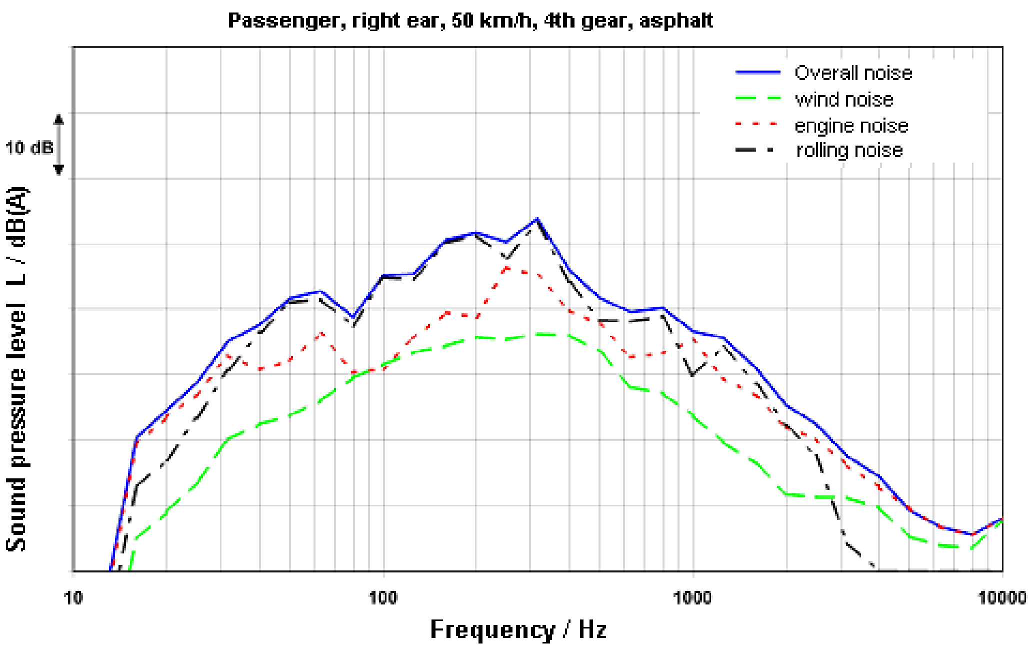

Fig. 1-4: Overall noise and noise components of an upper middle-class passenger vehicle at *v* = 50 km/h [14]

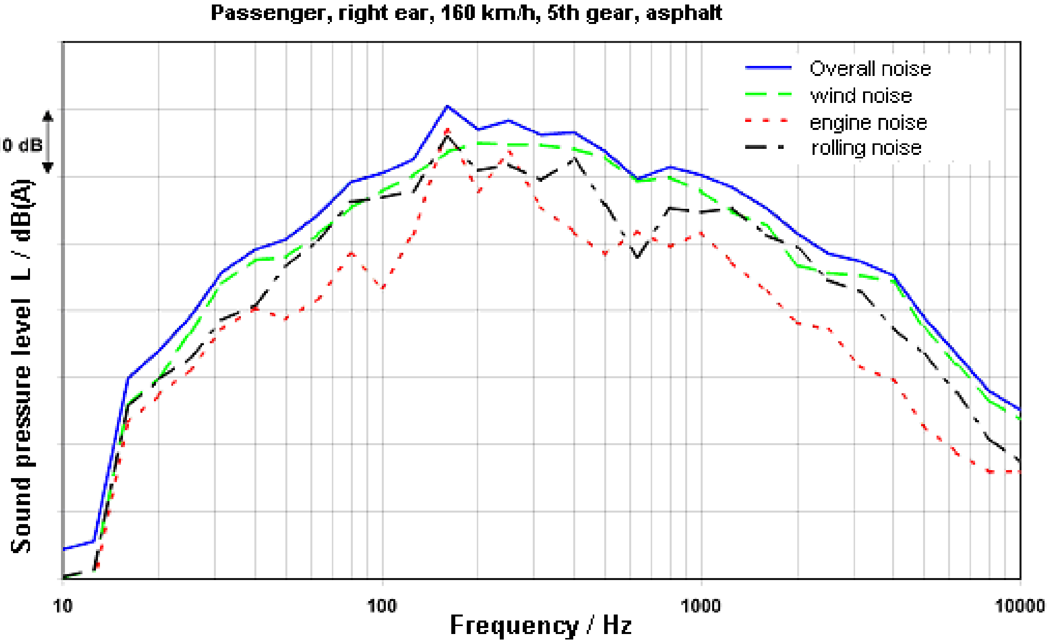

Fig. 1-5: Overall noise and noise components of an upper middle-class passenger vehicle at v = 160 km/h [14]

2. MECHANISMS OF AERODYNAMIC NOISE

Aerodynamic noise is essentially caused by three different mechanisms:

- pulsating volume flow through small openings;
- impact pressure variations on hard surfaces;
- turbulent shear stresses.

All these generation mechanisms also have effects in the aeroacoustics of motor vehicles. However, each causing component is of differing significance.

Idealized approximation models can be used to characterize the individual mechanisms:

- Volume flows causing varying pressures can be represented by monopole sources. Examples of this type of noise source are leakages in sealing systems or a vehicle's exhaust pipe outlet.
- The acoustic effect of pressure changes on a hard surface can be represented by a dipole source. This type of noise emission can always be found when a free or separated flow impacts a surface. On vehicles there are always several areas with separated flow.
- Turbulent shearing stress creates quadrupole sources. Sources of this type are for example caused in turbulent shearing layers or in the vehicle wake.

Fig. 2-1 shows a schematic representation of the three source types.

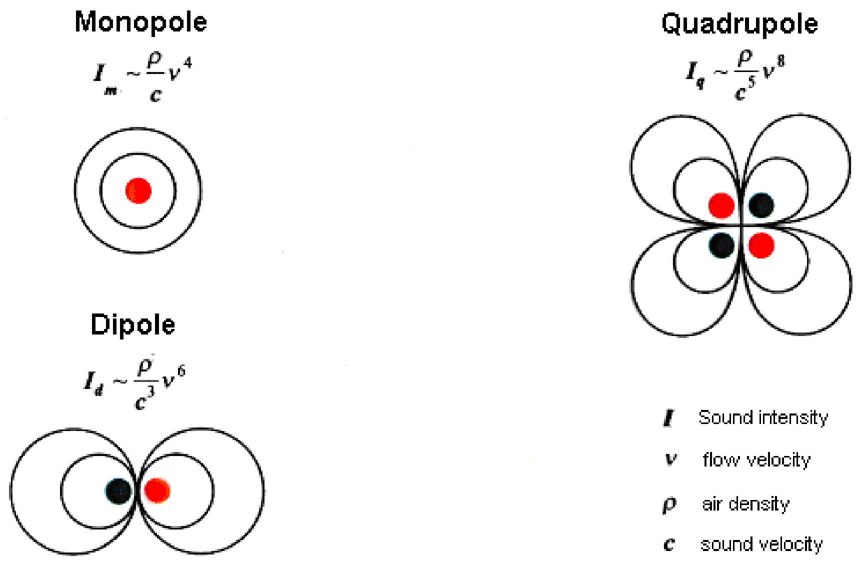

Fig. 2-1: Schematic representation of the source types relevant in aeroacoustics [9]

As has been mentioned above, the intensities of these three source types vary greatly. With flow speed v, density ρ, sound velocity c and Mach number Ma the following are obtained, for a monopole source:

$$I_m \sim \frac{\rho}{c} v^4 = \rho \cdot Ma \cdot v^3 \tag{1}$$

a dipole source:

$$I_d \sim \frac{\rho}{c^3} v^6 = \rho \cdot Ma^3 \cdot v^3 \tag{2}$$

and a quadrupole source:

$$I_q \sim \frac{\rho}{c^5} v^8 = \rho \cdot Ma^5 \cdot v^3 \tag{3}$$

Comparing the intensities shows that at low flow speeds (Mach numbers smaller than 1) the monopole source is the most effective, followed by the dipole source. The lowest emission is caused by the quadrupole sources, which can be neglected in most cases in vehicle aeroacoustics. Thus, if a monopole source is present it will generally be the loudest source. Only if all monopole sources are eliminated, can one of the remaining dipole sources dominate.

As can be seen from the above equations, the sound power level of a monopole source is proportional to the 4th power of the flow speed, whereas the sound power level of a dipole source increases with the 6th power of speed. As the most significant aerodynamic noise-generating mechanisms in motor vehicles can generally be represented by a combination of monopole and dipole sources, experiments usually yield an increase in sound power of the 4th to the 6th power of speed. Typical locations of the different source types at vehicles are shown in the sketch of **Fig. 2-2**.

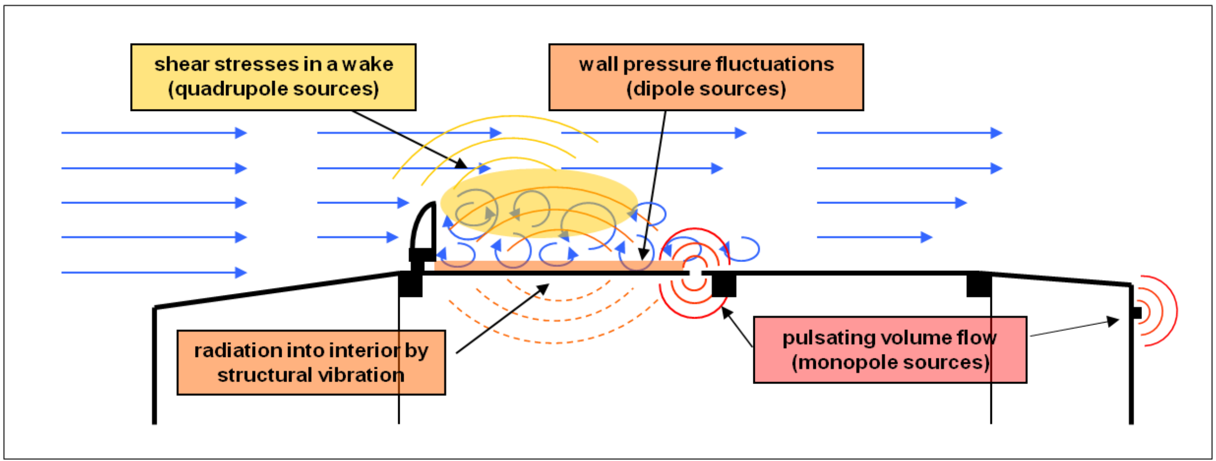

Fig. 2-2: Sketch of typical locations at a vehicle of the source types relevant in aeroacoustics [20]

Thus, speed must be maintained accurately during aeroacoustic measurements. Even small deviations in the settings can result in marked changes of noise level. This means that aeroacoustic measurements carried out on the road under unpredictable wind conditions are only conditionally indicative unless relative flow speed and directions were also recorded.

As the distribution of the flow speed over the entire vehicle surface is highly irregular, the potential noise excitation in dependence of the locus of excitation varies greatly. If dipole behavior is assumed, the sound generated in one place is 9 dB louder than at an adjacent spot, if the local pressure coefficients prevailing there are cp -1 or 0. With pressure coefficients of 0 and -2 (a value not unusual for the area around the A-pillar) this difference even reaches 14 dB. This shows that the positioning of add-on parts such as exterior mirrors can be of high significance to the aeroacoustic behavior of a vehicle.

The frequency of the emitted noise depends on the characteristic dimensions of the part and the flow speed around it. The frequencies resulting from the vehicle body and its add-on parts and details can be estimated with the equation

$$f = \frac{St \cdot v}{l} \tag{4}$$

where l is a characteristic measurement (e.g. height or width) of the individual vehicle component or detail and St the Strouhal number. Generally, a Strouhal number of approx. 1 can be assumed for add-on parts. However, for parts with a cylindrical shape it must be assumed as 0.2. Here, the diameter is selected as characteristic measurement. Hence, an antenna with a diameter of 5 mm and at a flow speed v of 40 m/s generates a frequency f of approx. 1,600 Hz. Antennas can thus be conspicuous for irritating whistling noises.

3. AEROACOUSTIC MEASURING TECHNOLOGY

Sound level determination as well as sound source localization is an important topic in the field of sound & vibration, from the product development stage to the end off line control of products. In the following, several sensors and measurement systems are introduced which are in use specifically for aeroacoustic investigations of vehicles, in the cabin as well as for exterior noise.

3.1 Measurement of Interior Noise

3.1.1 Microphones

As is general practice in machine acoustics also in aeroacoustics single microphones are deployed. Their use is of special advantage if measurements are to be carried out at points of noise intrusion, where artificial heads frequently are impractical due to their larger volume, or when many measuring positions are to be recorded.

3.1.2 Artificial Heads

Measurements with artificial heads are actually special microphone measurements. Since approx. 1980 they have become increasingly established for the measurement of noise inside vehicles and for the subjective assessment of the acoustic climate prevailing there. Thus, they are useful for interior aeroacoustic measurements.

Fig. 3-1: Artificial head at the driver's position to perform binaural recordings

3.1.3 Sound Intensity

For the higher frequency range, where the sound field in a vehicle can be described as almost anechoic, sound intensity measurements can be used in order to estimate the radiation pattern of the compartment surfaces. In most cases the intensity probe is moved hand held from one measurement position to the other. Intensity probes can also be used for inflow measurements to record exterior noise of a vehicle in a wind tunnel (see chapter 3.2).

3.1.4 Spherical Array

Spherical beamforming can provide a complete omnidirectional noise map in any acoustic environment, based on one simple measurement. Depending on the kind and manufacturer of the array one or more cameras are used to map the surroundings. The images of the cameras are used as background for the resultant acoustic map. Spherical beamforming can be used in both free-field and a reverberant room since the beamforming does not make any assumptions about the acoustic nature of the environment. The spherical beamforming is commonly in use for the generation of sound maps in confined and semi-damped spaces like vehicle and aircraft cabins. **Figure 3-2** shows two examples for different spherical arrays.

Fig. 3-2: Two Examples for spherical beamforming arrays. Left: Sphere 48-35 AC Pro by gfai tech GmbH. Right: Spherical Beamforming Type8606 by Brüel & Kjær

3.1.5 Near-field Acoustic Holography

Near-field Acoustic Holography (NAH) provides a mathematical model describing the sound field based on a set of sound pressure measurements typically taken in a plane fairly close to the source. From this description the parameters of the sound field, sound pressure, sound intensity, particle velocity, etc., can be derived in target planes parallel to the measurement plane. The model can also be used to calculate far-field responses, estimating the sound pressure distribution along a line in the far-field based on the Helmholtz Integral Equation. Further potential noise reduction schemes can be applied to evaluate the impact of various source reduction possibilities. The Data is usually collected with a hand-held-array, see **Fig 3-3**.

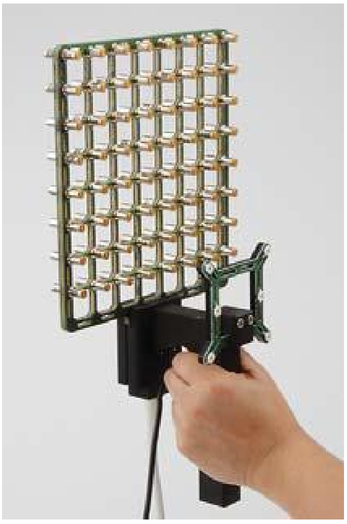

Fig. 3-3: Hand-held-array by Brüel & Kjær, used to gather data for noise mapping based on the near-field acoustic holography approach.

3.1.6 PU probes

The PU probes consist of a microphone and a particle velocity anemometer, mostly hot wire anemometer. They measure the sound intensity directly without recalculation from two microphones as the classical intensity probes do. They can be used also in the near-field. Hence, they are specifically suited for in-cabin measurements to locate leakages or other points of noise intrusion during wind tunnel experiments. The system Scan&Paint is such a tool which includes the visualization of stationary sound fields with acoustic band-width coverage from 20 Hz to 10 kHz. There is no requirement for anechoic condition. [21].

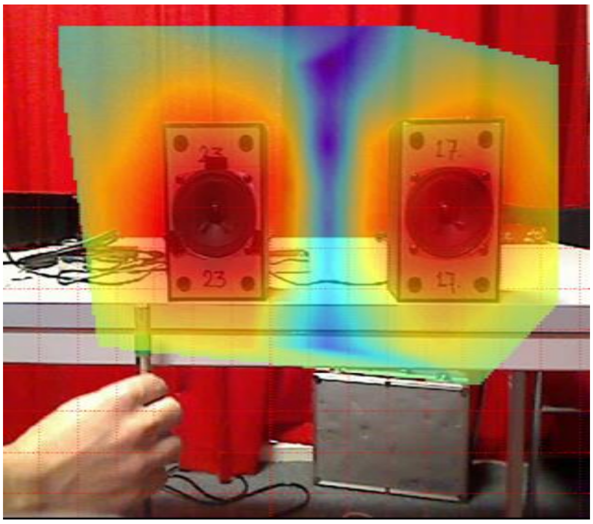

Fig. 3-4: Colour map of the sound pressure level of two loudspeakers calculated after a measurement by means of Scan&Paint [Microflown]

3.2 Measurement of Exterior Noise

Conventional acoustic measuring techniques for recording exterior noise in wind tunnels are problematic due to the air flow at the object of measurement. On the one hand so-called pseudo sound develops at the microphones as a result of the measuring membrane being exposed to varying airflow pressures. In contrast to "real" sound these changing pressures propagate with approximately the same speed as the airflow (turbulences) and not with the speed of sound. They thus have an interfering effect in noise measurement. On the other hand, microphone housings, pre-amplifiers and holders also cause flow noise and thus extraneous noise, which is undesirable during measurement. Thus measuring techniques developed especially for the measurement of exterior noise are mostly used. They will be described in the following.

3.2.1 Intensity Measurements with Special Probes

Sound intensity measurements for recording aerodynamic exterior noise are generally carried out within the airflow, as intensity probes in the measuring direction have only poor directivity, thus necessitating measurement close to the object. Commercially available probes are unsuitable for this purpose as was already explained in chapter 3. Special probes must therefore be used. **Fig. 3-5** shows such a measurement set-up. The probe must be positioned into the direction of airflow. However, deployment in zones with highly alternating flow pressures is not possible (e.g. behind the exterior mirror), as this would lead to pseudo sound.

Using the dual microphone technique an accurate determination of sound intensity is theoretically only possible without flow or with flat sound waves in a one-dimensional flow. However, aerodynamic sound sources neither emit flat waves (monopole, dipole or quadrupole sources, see Section 2), nor is the flow around a vehicle one-dimensional. Tests revealed, however, that with commonly practiced driving speeds measurement errors remain very small. **Fig. 3-6** shows the results of sound intensity measurements along the side of a vehicle, in whose door an exterior loudspeaker had been integrated. If the sound deflection caused by the airflow is rectified by a longitudinal position correction of the entire probe as well as by a displacement in length of the two microphones corresponding to the deflection angle[1], measurement errors remain below approx. 0.5 dB.

Fig. 3-5: Sound intensity probe with microphones with nose cones in parallel set-up above the exterior mirror of a passenger vehicle [8]

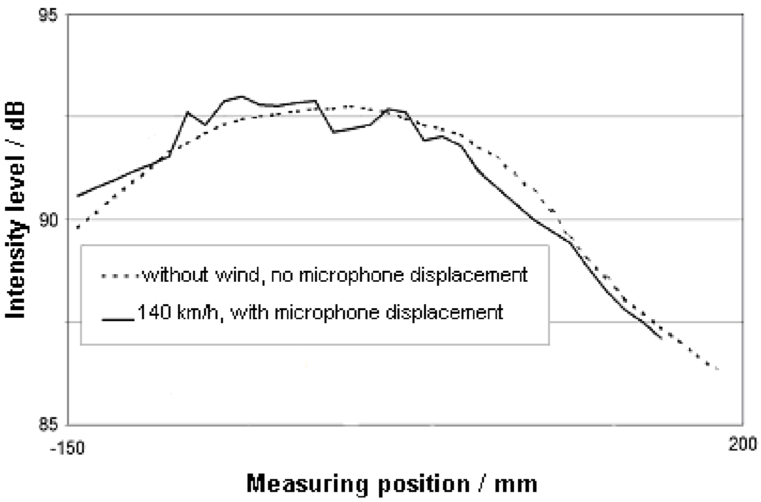

Fig. 3-6: Sound intensity level along the side of a passenger vehicle with an exterior loudspeaker integrated into the door which reflects towards the outside; loudspeaker output: tone at 5 kHz; distance from vehicle surface: 300 mm [8]

[1] As sound is convected by the airflow, the probe must be positioned further downstream compared to a measurement without flow. Moreover, the microphone which is more distant to the loudspeaker must be displaced a small distance further back compared to the other microphone according to the sound deflection angle, in order to adapt the measuring direction of the probe.

3.2.2 Microphone Arrays

Microphone arrays are mostly used in open-jet test sections. The complete array is then set up outside the airflow. Of course, in this case the influence of the airflow and the shear layer at the airflow boundary of a wind tunnel must be eliminated mathematically. However, there are also arrays with microphones set flush into the walls of the wind tunnel working section [4].

Rail vehicle technology and aeronautics were previously the main fields of application for arrays [12]. In the meantime, however, they are also frequently used in aeroacoustic wind tunnels [4, 8]. **Fig. 3-7** shows an array in an aeroacoustic wind tunnel with microphones in a spiral set-up whereas **Fig. 3-7a** shows an example of a large three-planar array in a wind tunnel.

Fig. 3-7: Example for a mobile microphone array (source: FKFS)

Fig. 3-7a: Example of a large microphone array consisting of three planar arrays in a wind tunnel [22]

3.2.3 Acoustic Mirrors

Acoustic mirrors are frequently used in wind tunnels with an open test section for the determination of exterior noise. One example is shown in **Fig. 3-8**. In closed test sections, however, this technology cannot be deployed as the system is not suited for being set up in the airflow.

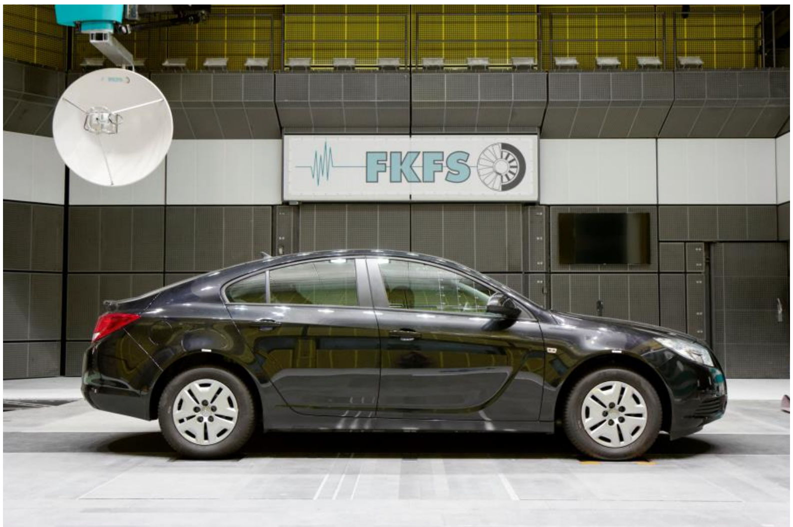

Fig. 3-8: Parabolic microphone in the measuring range of an aeroacoustic wind tunnel

3.3 Measurement of Structure-Borne Sound

Structure-borne sound measurements are frequently carried out in order to determine transmission mechanisms in the vehicle structure and to identify highly resonant body areas. Piezoelectric acceleration sensors are generally used for this purpose. When measuring on thin-walled sheet-metal structures it must be ensured that the vibrating behavior is not significantly affected by the mass of the sensor. Thus, miniature sensors that weigh only a few grams are used on vehicle structures. If possible, however, Laser Doppler Vibrometry (LDV) is used, so that it is possible to entirely do without sensors. This method uses the change in frequency of a laser beam reflected at the measuring point as a measure of the vibrating velocity. Thus, this method of measuring is completely without reactive effect. Here it is advantageous to use a system which permits automatic scanning of a large number of measuring points. In this way measuring time can be greatly reduced, which - with wind tunnel costs of a few thousands of Euros per hour - will effect considerable savings of expenditure.

3.4 Localization of Sound Sources with the Help of Special Instruments

3.4.1 Leakage Tests with Ultrasound

In many cases it is not so easy to identify leakages in the vehicle interior with simple acoustic means. Thus frequently an ultrasound transmitter is placed on the inside of the vehicle, then ultrasound leaks on the outer skin paneling or underfloor are seeked. This can be done outside the wind tunnel.

Commercially available transmitters emit sound hemispherically and generate frequencies of approx. 40 kHz. They are positioned inside the vehicle so that the surfaces to be investigated are exposed as effectively as possible. With this sensor - accomodated in a hand-held housing - door or window seals for example can be selectively scanned. If the sensor detects an ultrasonic leak, the detector emits an audible sound signal. The volume of the signal is an indicator of the intensity of the ultrasound leak at this particular spot. Defective seals can thus be quickly recognized. Other kinds of noise leaks can also be easily identified.

3.4.2 Microphone Probes

Apart from stethoscopes special microphone probes can also be used to track down noise sources in vehicles. Probes of this type consist of a small - sometimes flexible - tube set into the microphone. This tube is mounted into a housing which also accomodates a headphone amplifier with volume control and power supply. Headphones can be connected to this housing so that the microphone's signal can be monitored audibly. **Fig. 3-9** shows an example of such a device.

Fig. 3-9: Microphone probe with headphones

4. MAIN SOUND SOURCES AND MEANS OF REDUCTION

Various major sources of noise must be considered in the aeroacoustic development of motor vehicles. When optimizing details it is advantageous when the noise source of interest can be observed in isolation. The more sound sources combine to make a noise, the more difficult it is to judge changes in one of them during measurement and subjective acoustic assessment.

If one sound source is the sole emitter, it is of course solely responsible for the resulting noise level. If this source is modified, and a noise reduction by, for example, 4 dB is effected, this change will also be noticeable by a level reduction by precisely these 4dB. However, if a second equally loud sound source participates in the noise generation, the same reduction at the first source merely yields a noise level reduction of approx. 1.5 dB.

The higher the number of sound sources involved, the more this effect is reinforced. For example, if with ten equally loud sound sources the level of one sound source is reduced by 10 dB, this will result in a barely measurable reduction of the overall noise level by approx. 0.4 dB. In order to actually achieve a noise level reduction of 10 dB, 9 of the 10 sound sources must be eliminated completely. In this case, the subjectively perceived volume is reduced by only 50 %.

In order to optimize a certain sound source it should thus be recorded in isolation. Thus, in the aeroacoustic development of the rear view mirror all window and door seals are covered by fabric or aluminum tape to avoid interference caused by leaks (see Section 4.1). Equally, all other add-ons such as antennas and wind-shield wipers are removed if necessary. If the A-pillar vortex is not fundamentally changed by this measure, the water gutter can also be covered with tape to obtain a level surface. At the mirror itself, too, sound sources which are not to be investigated can be eliminated. This, for example, applies to the taping over of all gaps at the mirror base plate when the water gutter on the mirror housing is acoustically optimized.

When investigating other sound sources one can proceeded in the same way to obtain more marked changes in the noise level. However, when the necessity for individual acoustic optimizations must be assessed - which can also be expensive - a check in "series condition" is ultimately required.

4.1 Leakage

As has already been mentioned in Section 2, avoiding leaks is especially important due to the monopole character of the noise generated by them. In motor vehicles this applies mainly to the development of window and door seals, which must be carried out with great care. Particularly at higher speeds, where the pressure difference between interior and exterior increases, the risk of leakage increases when the doors are lifted out of their seals by the high negative pressures acting on the outside of the car.

Even outside the wind tunnel the presence of leaks in the body can be detected with the help of ultrasound devices, as has been explained in Section 3.5.1. In order to determine the influence of seals on interior noise in the wind tunnel all gaps and grooves of the vehicle body are first of all taped flush. By comparing the measuring results with and without tape the overall contribution of all gaps to aeroacoustic noise can be determined. If the contribution from one individual seal section is to be determined, this particular section is opened exclusively, while all other gaps remain taped. For the investigation of other gap sections the first opening is taped over again and the new area of interest is exposed. These individual measuring results are compared with the results of the entirely taped-over gaps. In this way the contributing shares of individual areas to interior noise can be determined separately and can be compared.

Fig. 4-1 shows the influence of a sealing system on the sound pressure level at the left ear of the driver in a series production car compared to the influence of add-on parts (exterior mirror, wind-shield wipers, antenna). The dominating contribution of the sealing system to interior noise can be clearly recognized. An effective but relatively expensive measure to reduce this contribution is the use of multiple sealing systems.

The sealings at the mirror base plate, between the wheel housings and the area of the A-pillar must be implemented with great care. The sound here is not generated directly in the passenger cell, but there is the possibility that noise is introduced into the vehicle through the cavities in doors and body.

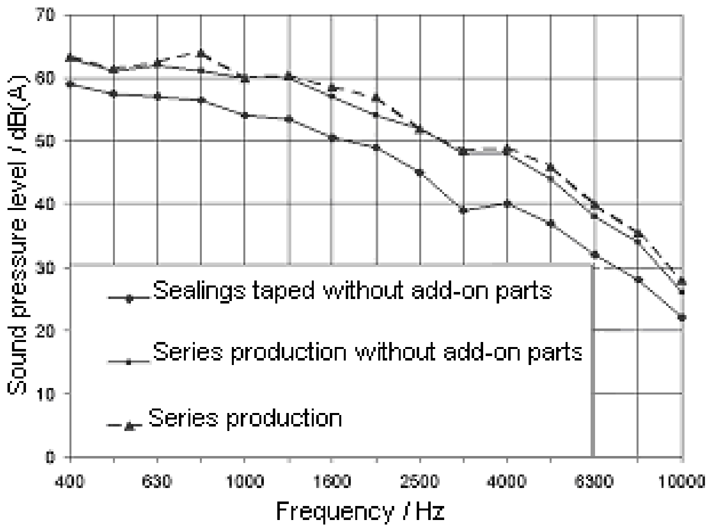

Fig. 4-1: Influence of a poor sealing system on the sound pressure spectrum in the vehicle interior compared to the influence of the add-on parts [2]

4.2 Rear View Mirror

A great part of aeroacoustic research deals with exterior mirrors. They protrude into zones of high flow speeds and thus pose a particular acoustic problem. The mirror shape is determined to a large degree by design, but functional aspects must also be considered. Measures aiming at acoustic improvement thus concentrate mainly on details such as the depth and form of water gutters, gaps for folding mirrors and mirror cavity drains. Frequently noises here have a tonal character (whistling). Often it is vortex generators which help with such noises. They are positioned in front of the noise source and interfere with its periodicity. **Fig. 4-2** shows two examples. Similarly, this method is also applied with other noise sources as is shown in sections 4.4 and 4.6. Moreover, noise excitation can also be reduced by positioning the mirror in zones of lower flow speeds; one result is shown in **Fig. 4-3**.

Fig. 4-2: Vortex generator to avoid tonal noise in the area of two exterior mirrors of production vehicles

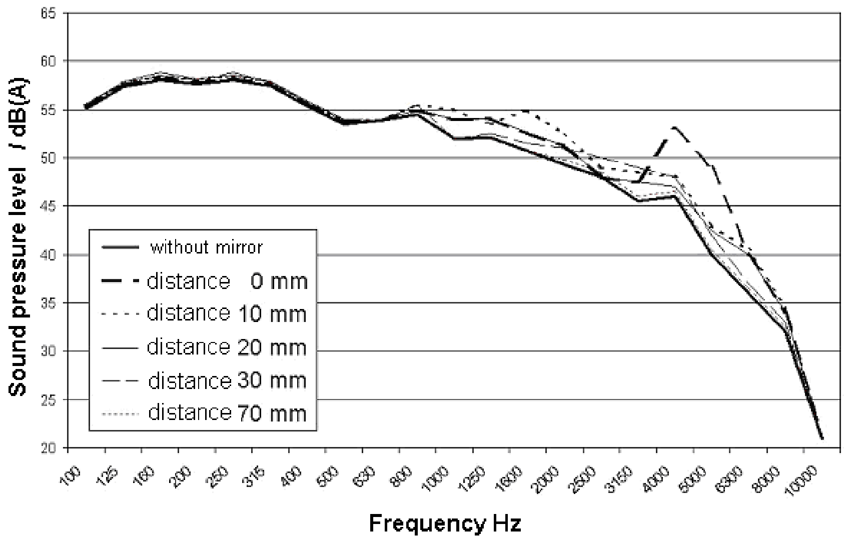

Fig. 4-3: Influence of the distance of the left exterior mirror from the vehicle surface to the sound pressure level at the driver's left ear [10]

4.3 Windshield Wipers

Windshield wipers also play a highly significant role in aeroacoustic optimization. In their resting position they are frequently hidden under the hood. In some cases however, e.g. in modern minivans, they are exposed directly to the air stream, which leads to marked increases in interior noise [17]. As can be seen in **Fig. 4-4** this can be remedied by attaching spoilers in front of the windshield which conduct the airflow over the wipers.

With its distinct fluctuation the noise of windshield wipers can also be annoying while they are in operation. **Fig. 4-5** shows the course of noise spectra of two windshield wiper designs during operation. The acoustically optimized version generates much lower noise levels. It can be clearly seen that the highest levels are generated when the wipers are approximately in a position perpendicular to the direction of airflow.

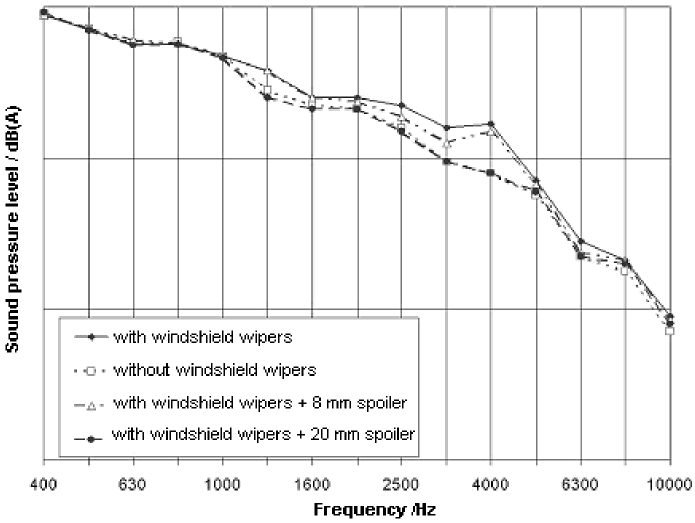

Fig. 4-4: Effect on interior noise of add-on spoilers of different height in front of the windshield; wipers in resting position [2]

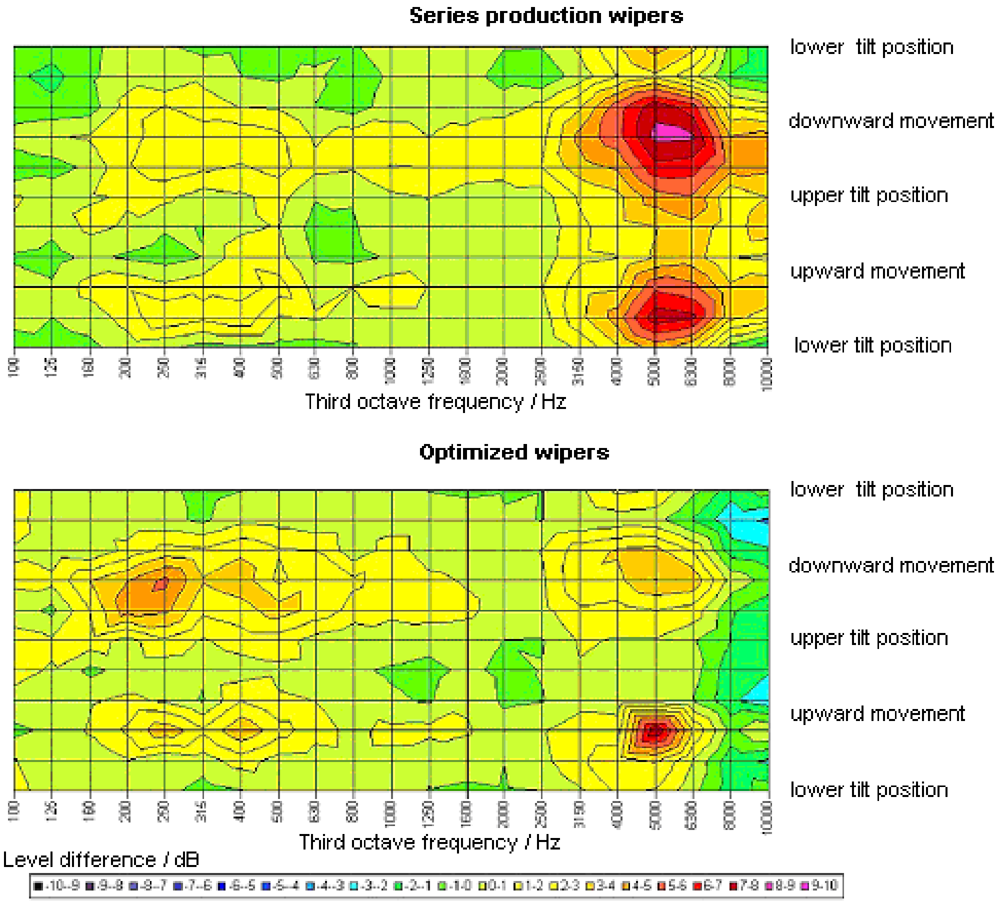

Fig. 4-5: Noise spectra at the driver's right ear during wiper operation recorded by an artificial head (differences from comparison with levels during wipers at rest); 140 km/h flow speed, series wipers and optimized wipers

4.4 Antennas

Antennas can generate tonal noise (so-called aeolian noise, as described in section 2). Noise reduction can be effected by positioning the antenna as inclined as possible and by a wire spiral around it. This measure prevents formation of the typical Karman vortices behind cylindrical bodies. An industrially manufactured antenna of this type is shown in **Fig. 4-6**. **Fig. 4-7** shows the effect of such a spiral on interior noise.

Fig. 4-6: Series antenna with wire spiral

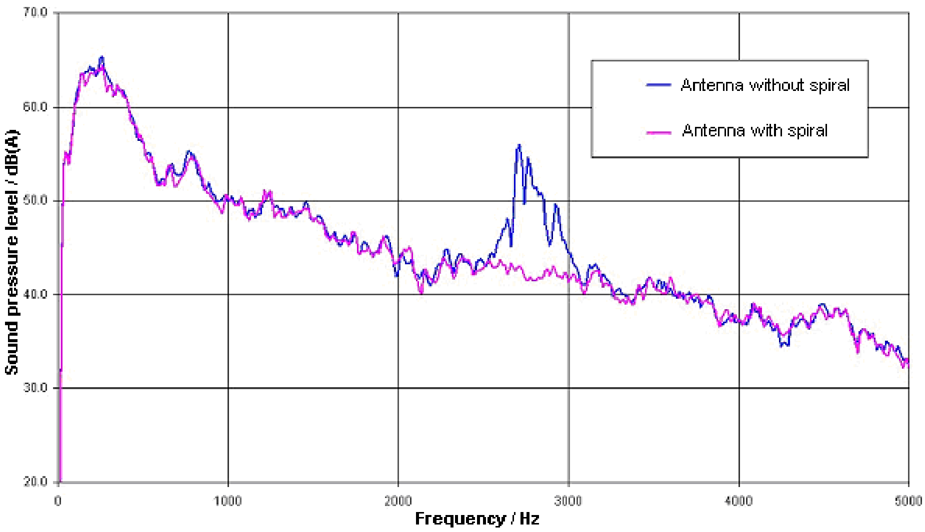

Fig. 4-7: Sound pressure spectra at the driver's left ear with spiraled and non-spiraled antenna, flow speed 180 km/h

4.5 A-Pillar

The design of the A-pillar has a marked effect on the generation of aerodynamic noise. It determines the volume and shape of the separation vortex on the side window, which can also influence noise emission from the exterior mirror. Moreover, the run-off grooves integrated into the A-pillar are noise-generating elements. Thus, optimizations are usually implemented iteratively here. As can be seen in **Fig. 4-8** the potential for optimization can be considerable. The graph shows the results of measurements with a parabolic microphone from above. With this method of measurement it is possible to begin the work of aeroacoustic development for this body area as early as on the hard model.

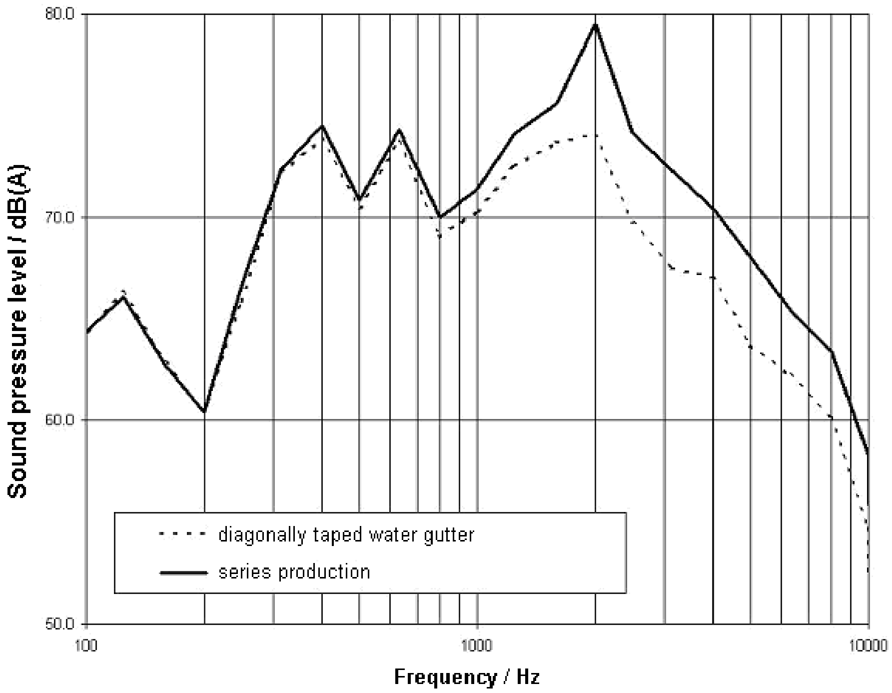

Fig. 4-8: Influence of water gutters on noise emission; measurement from above with a parabolic microphone at 140 km/h, focus on the center of the A-pillar

The curve radius of the A-pillar is also an important parameter for aerodynamic noise generation. **Fig. 4-9** shows the increase in sound pressure level at the driver's ear when changing from a flow angle of 0° to 10° for various A-pillar profiles. The level difference is plotted in "points" calculated from the total of noise level differences in the individual third-octave frequencies between 400 Hz and 10 kHz. It can be seen that with small curve radii of up to 10 mm and yaw the change in level is small at first. With larger radii, however, there is a marked drop. This means that vehicles with larger A-pillar radii have a less distinct acoustic reaction to yaw and thus generate fewer modulations (volume variations) in interior noise in real traffic conditions with turbulent flows. It should be noted in this context, that modulations generally have a highly negative effect on the acoustic comfort (see Section 5).

The fact that sharp-edged A-pillars are acoustically distinctly more unfavorable under yaw conditions than rounded ones is also obvious from the fact that – under yaw conditions - noise levels are considerably reduced when A-pillar edges are rounded. **Fig. 4-10** shows the measured level differences in "points" (analogous to Fig. 4-12).

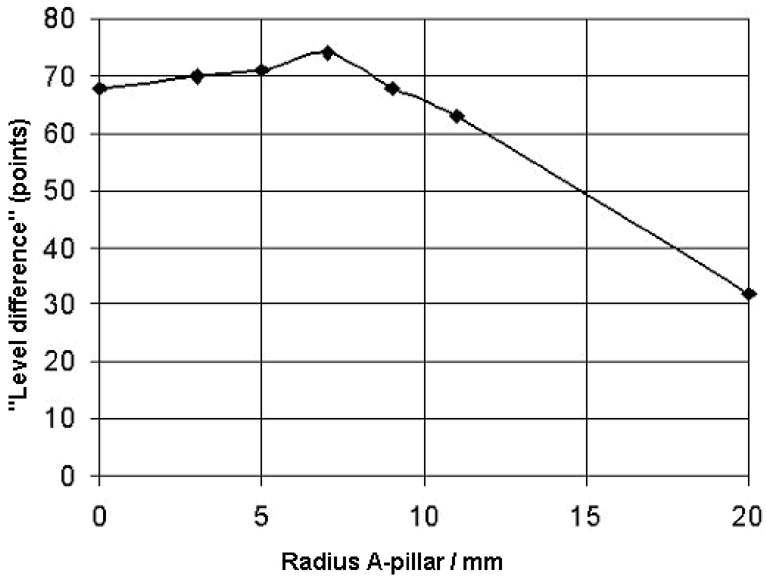

Fig. 4-9: Difference in sound pressure level of the interior noise between 0° and 10° yaw angle, with different A-pillar radii [2]

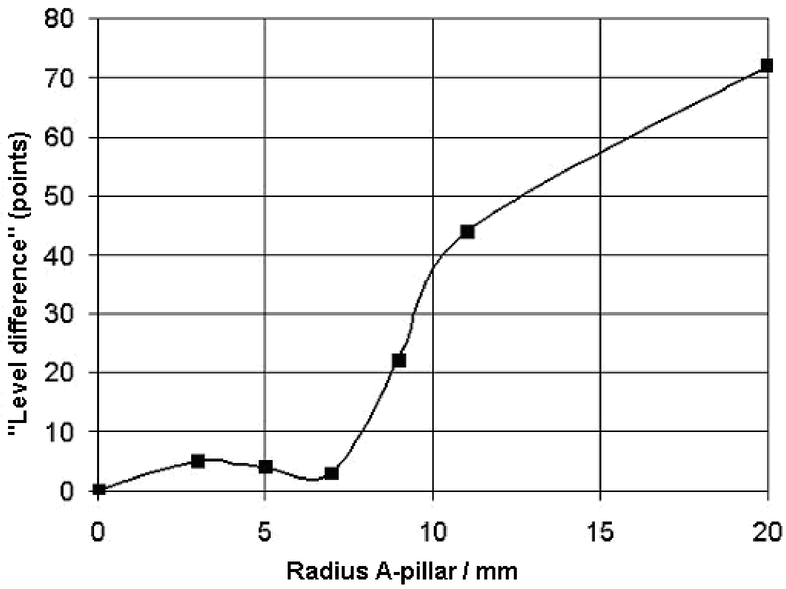

Fig. 4-10: Change in sound pressure level of the interior noise at a yaw angle of 10°, with different A-pillar radii, compared to sharp-edged A-pillar [2]

4.6 Cavity Resonances

Two types of cavity resonances occur in motor vehicles: for one, resonances where the whole vehicle interior is excited, e.g. caused by an open window or the open sunroof; for another, aerodynamic vibrations in smaller cavities such as slots, gaps, grooves or bore holes. These resonances are excited in a similar way as the tones that are generated when air is blown over a bottleneck. The hollow space acts as a kind of Helmholtz resonator, whose inherent frequency depends strongly on the volume of the hollow space. In a resonance case, coherent vortex structures separate at the front edge of the opening, then impact the back edge and there result in pressure waves which in turn excite the interior space and again lead to the formation of new vortex separation at the front edge.

Whether a resonance forms or not depends to a considerable degree on the relative speed of the vortex structures, these in turn are determined by flow speed or driving speed. Buffeting noise with the sunroof open thus only occurs in a narrow speed range (mostly somewhere between 40 and 90 km/h). If the inherent frequency of the interior space is detuned, e.g. by changing the number of passengers, the speed range where a buffeting noise occurs is also changed.

Sunroof buffeting generates sound pressures up to approx. 130 dB at frequencies around 20 Hz and presents a significant reduction in comfort. Lowering of the sound pressure can be achieved through preventing that the vortex structures impact the back edge of the sunroof. This can be implemented by defining a so-called comfort position of the sunroof, where the opening path is restricted. Only when the roof is opened further does buffeting occur. Furthermore wind deflectors are installed in front of the sunroof which can on the one hand shift the point of impact of vortex separation formed at the front (trailing) edge to areas behind the sunroof opening, and which on the other can also be equipped with vortex generators (such as notches, slits, grooves, burls, apertures) which destroy the regularity of these flow separations, see **Fig. 4-11**. These will basically increase background aerodynamic noise within the airflow noise, **Fig. 4-12**, the buffeting noise however will be lowered markedly, as can be seen in **Fig. 4-13**. An acceptable compromise can be found in most cases.

Fig. 4-11: Wind deflector with notches and apertures

Apart from these possibilities other methods for reducing sunroof buffeting could become significant in the future. For example, it could make technical sense to install a movable lip at the front edge of the sunroof which could be activated by an actuator via a noise signal thus disturbing the periodic excitation. Similar set-ups at wind-tunnel nozzles successfully reduced buffeting noise without significantly increasing the aerodynamic flow noise [15]. The transition to 42-V on-board electrical systems moreover encourages an increased use of actuators.

Smaller cavities also contribute to the generation of tonal noise, as has been mentioned above. E.g., bore holes in the axle body can generate whistling noises at several kHz, which can also be perceived in a disagreeable manner in the passenger compartment. In order to avoid noise excitations of this kind of gaps and bore holes in the outer paneling of the vehicle body and underbody should be avoided where possible, or covered.

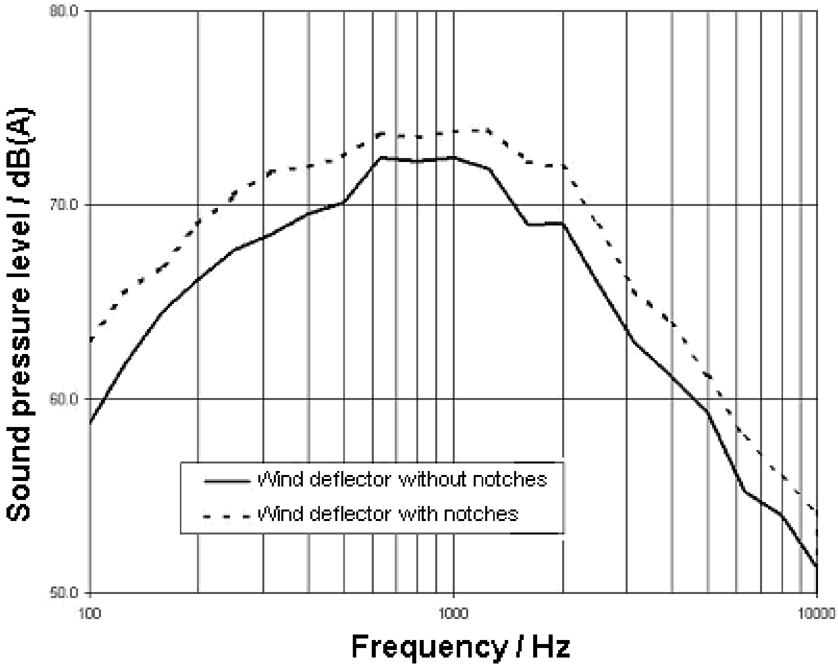

Fig. 4-12: Interior noise peaks with open sunroof with notched and unnotched wind deflector in front of the sunroof at 140 km/h air speed

4.7 Wheel Housings

The front wheel housings particularly are the main source of aerodynamic noise over almost the entire frequency range. However, they only have little effect on interior noise, amongst others due to the highly muffled engine compartment rear bulk. **Fig. 4-14** shows the noise emission of a passenger vehicle for two frequency ranges at a flow speed of 140 km/h. The contribution of the front wheel housing to the entire frequency range can be seen clearly. Typically, the rear wheel housing contributes much less to noise emission and only in the upper frequency range. The influence of the antenna is visible on the back fender.

It is not known so far how wheel rotation affects noise excitation in the wheel housings, as the rolling noise of the tires cannot be separated from aerodynamic noise when the wheels are turning. It can be assumed, however, that it is more likely that noise excitation increases due to the additional rotational motion of the wheel disk exposed to the aerodynamic flow. Cases are also known where vortex structures generated at the front wheels resulted in noise emission at the rear side windows.

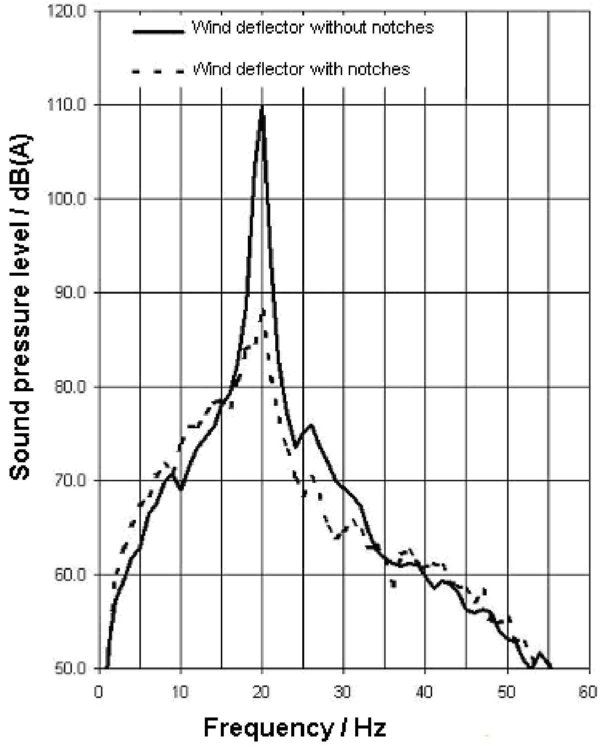

Fig. 4-13: Interior noise spectra with completely opened sunroof with notched and unnotched wind deflector in front of the sunroof at 50 km/h flow speed

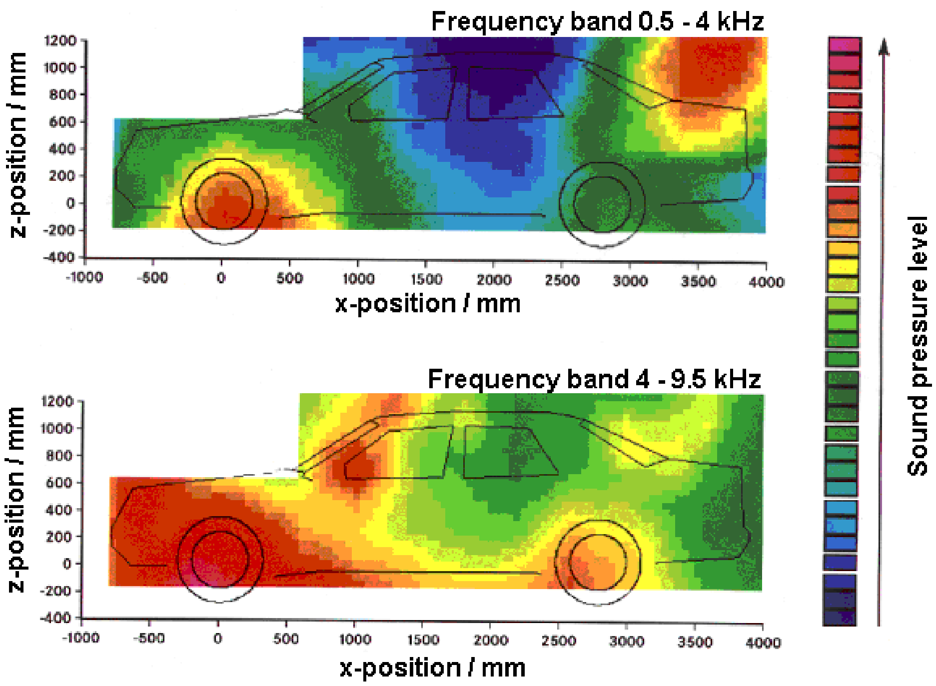

Fig. 4-14: Noise emission characteristics of a passenger vehicle in two different frequency ranges at 140 km/h air speed [8]

4.8 Underbody

Apart from rolling noise caused by driving on rough road surfaces, low-frequency interior noise is especially caused by aerodynamic flow over the underbody. This type of noise can be very annoying and can considerably reduce passenger or driver comfort inside the car. Aerodynamic forces are introduced into the car body on the underside. From there structure-borne sound propagates into the vehicle structure and is then reflected into the car interior by certain parts of surfaces. These can also be roof areas, for example. Deep-drawn front spoilers and an optimally smooth underbody can help here. **Fig. 4-15** shows the effect of a sealing between front bumper and road on interior noise. This clearly illustrates the comprehensive acoustic influence of the aerodynamic flow underneath the vehicle. It is particularly the frequency range under 1 kHz where the effect of the underbody flow is perceptible.

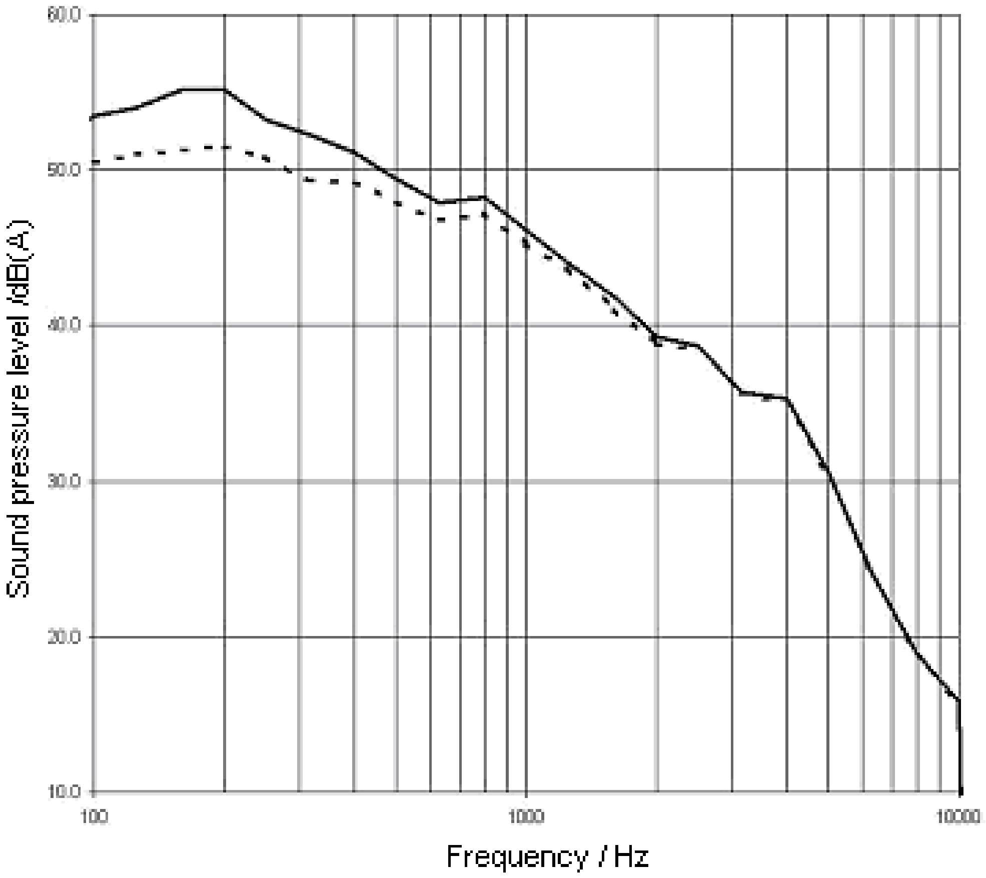

Fig. 4-15: Sound pressure level at the driver's left ear in a series production vehicle, without (——) and with sealing between front bumper and road (- - - - -)

Another possibility for reducing noise excited at the underbody is to change the body structure in the area of the reflecting body parts. In order to be able to do so, these parts must at first be identified. This can be done with accelerometers or by using laser-Doppler vibrometry (see Section 3.2.2.2). **Fig. 4-16** shows the vibration speed distribution in the area of the roof and rear window of a passenger vehicle when excited by aerodynamic flow.

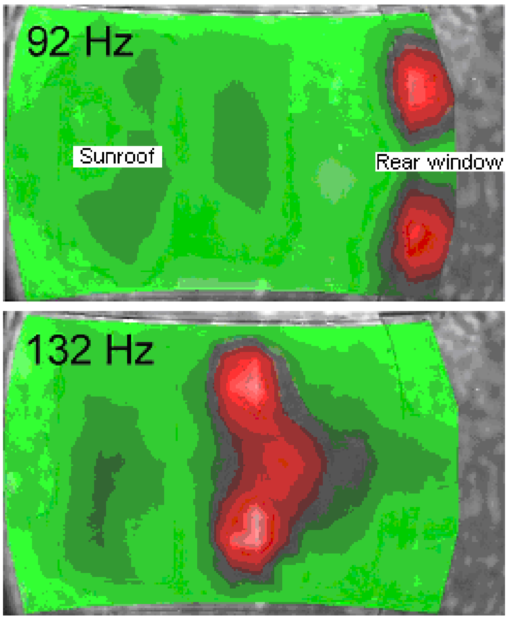

Fig. 4-16: Vibration speed distribution for two frequencies at the roof and rear window of a passenger vehicle when excited by aerodynamic flow; result obtained by measurement with a laser-scanning vibrometer at 140 km/h flow speed; red areas: approx. 180 µm/s

4.9 Reduction of Interior Noise by Increasing Glass Thickness

The thickness of the car window panes also has considerable influence on interior noise. Zaccariotto [17], Burgade [2] and Melchger [11] show that thicker panes significantly reduce interior noise. As is shown in **Fig. 4-17** marked noise reduction can also be achieved in dual-layer glass by a highly muffling intermediate foil.

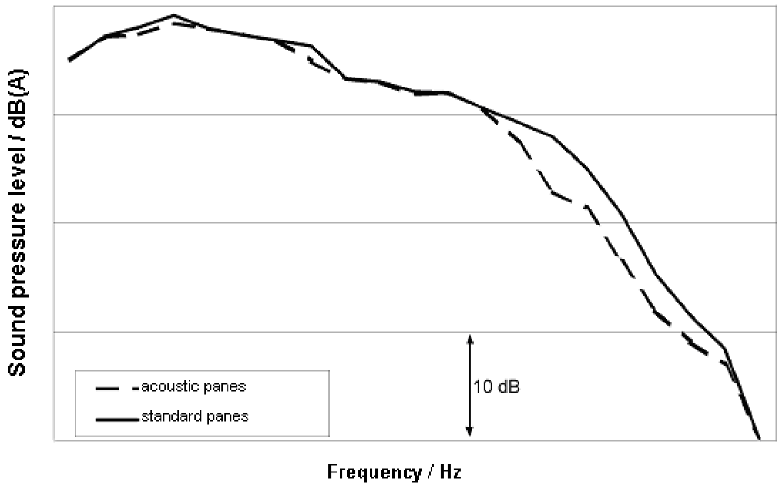

Fig. 4-17: Sound pressure level in a vehicle with standard panes and "acoustic" panes with special intermediate foil [11]

4.10 Convertibles

In recent years marked improvements have been made with convertibles. For one, lined tops have increasingly come into use, which apart from having advantages in interior air conditioning also have favorable acoustic effects. For another, sewn-in cross members and higher-tensioned fabrics also prevent undesired top movements, which improves both acoustics and ballooning. As can be seen in **Fig. 4-18**, convertibles are nevertheless still acoustically inferior compared to coupes, even with a similarly good sealing system. The impact of noise intrusion can be seen clearly in the lower frequency range.

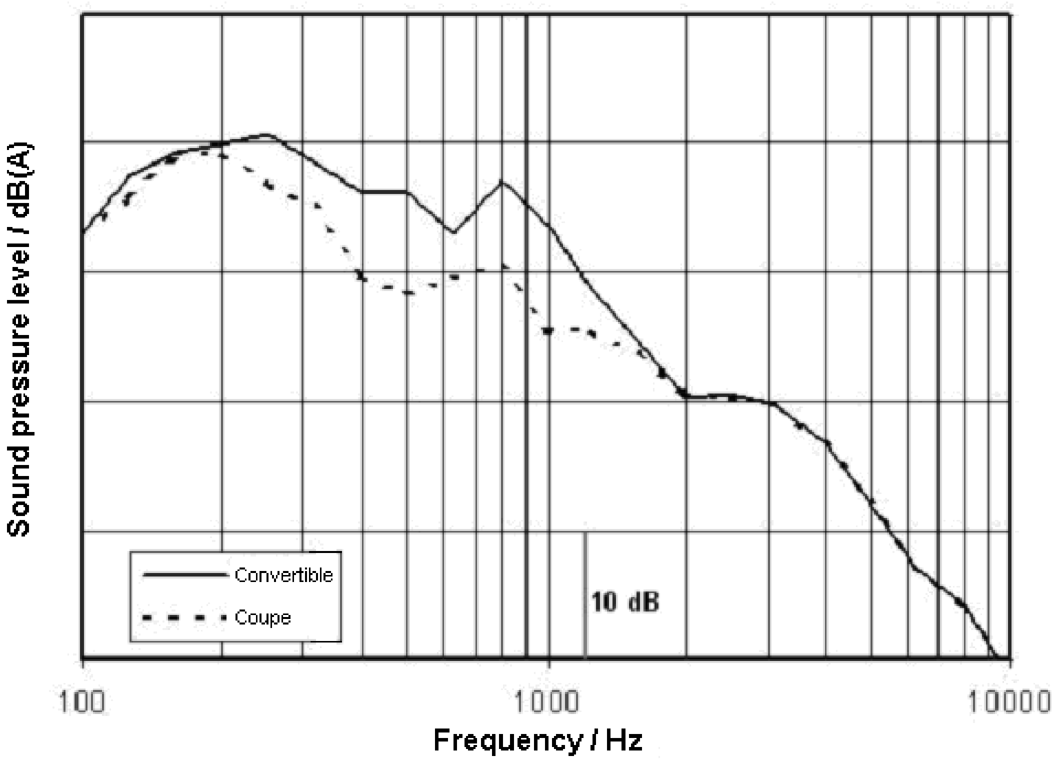

Fig. 4-18: Comparison of sound pressure spectra in a convertible and a coupe of the same vehicle type

In convertibles the sealing system also must be developed meticulously. Special attention must be given to the branching points. **Fig. 4-19** shows the improvement made possible by taping a small sealing area at the point where the sealings of the roof front edge, side window along the A-pillar and roof edge at the side window come together. Even if the noise reduction at 1 dB seems relatively small, it is nevertheless considerable when it is taken into account that it was achieved in series production condition[2].

Convertibles also show acoustic idiosyncrasies with the top open. When it is "designed" appropriate to vehicle type, the passengers usually assess engine noise entering the passenger cabin positively. Extreme draft side effects and airflow noise are usually assessed negatively. However, it is exactly draft prevention by a draft-stop which can influence noise development adversely, as can be seen in **Fig. 4-20**.

[2] see initial remarks in Section 4

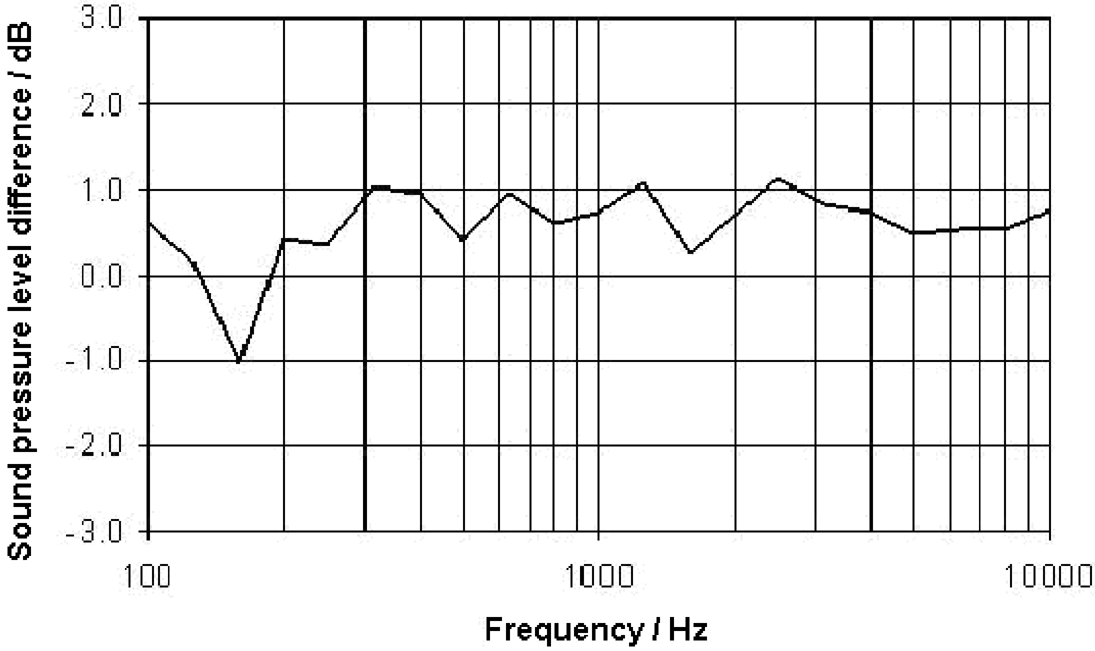

Fig. 4-19: Sound level measurement in a vehicle with the sealing area at the upper corner points of the windshield of a convertible taped, in series production condition

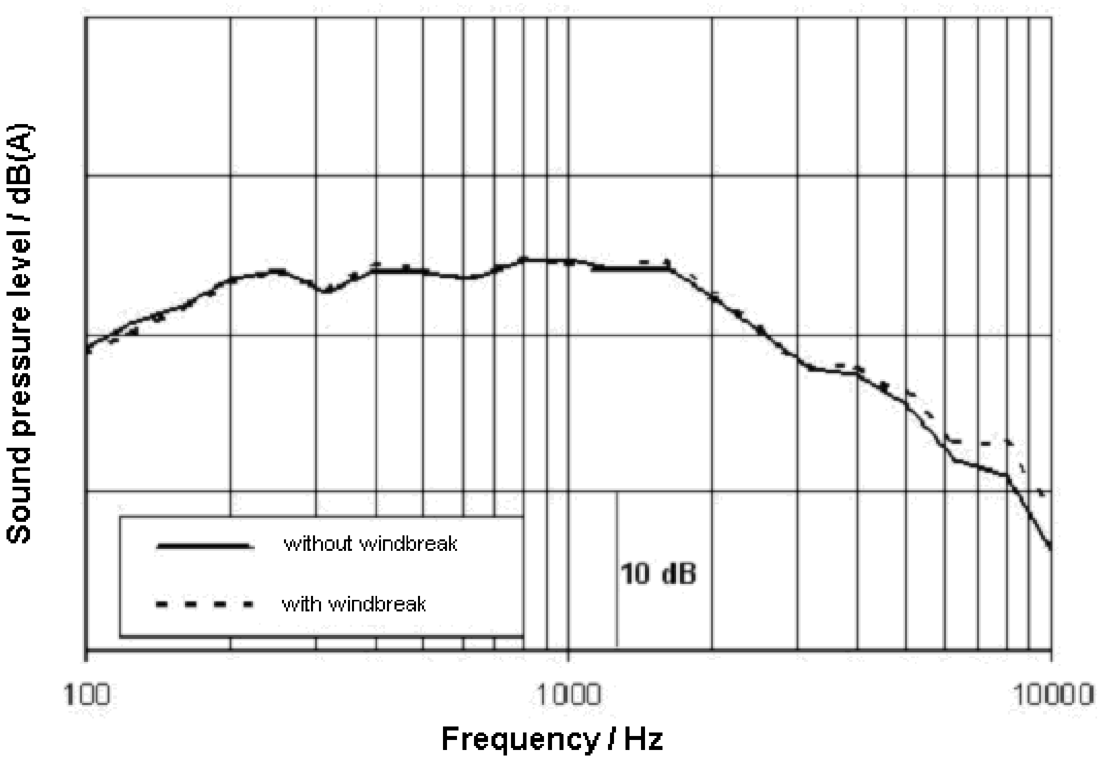

Fig. 4-20: Influence of a draft stop on the sound pressure level at the convertible driver's right ear

5. PSYCHOACOUSTIC CONSIDERATIONS

Psychoacoustics deals with the *subjective* perception of noise and with methods to objectively describe it. Known psychoacoustic quantities are for example loudness, roughness and sharpness.

The irritating character of aerodynamic noise is generally assessed subjectively. There are however attempts to assess it also objectively [13]. It has also been long known that the sharpness of interior noise is determined almost exclusively by aerodynamic noise [6]. This was confirmed in later investigations for further vehicles, as can be seen from **Fig. 5-1**.

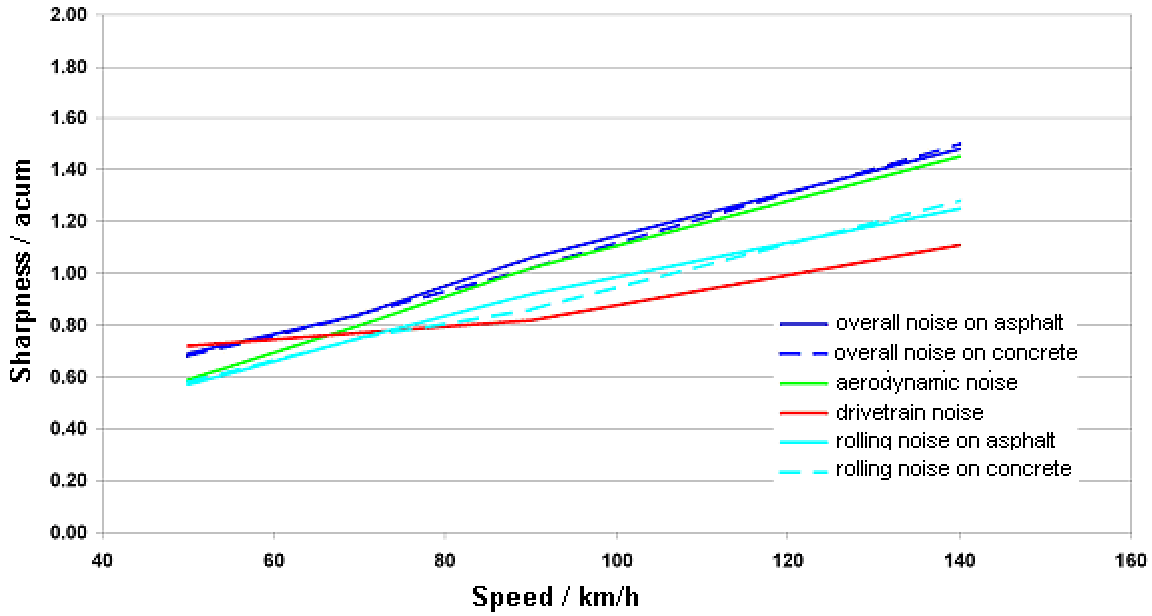

Fig. 5-1: Sharpness at the driver's right ear in an upper middle-class vehicle for various noise components relative to speed [14]

Fluctuations caused by cars driving in front or by gusts of wind can also be perceived as especially annoying components of the aerodynamic noise. These do not really change the averaged interior noise spectra perceptibly, but they modulate the sound pressure signal and can thus be recorded by measuring devices, as can be seen in **Fig. 5-2**. The turbulence occurring on the road cannot be simulated entirely in wind tunnels. It is thus attempted to use the acoustic sensitivity to changes in the flow angle of various vehicles as a measure for the extent of annoyance possible on the road.

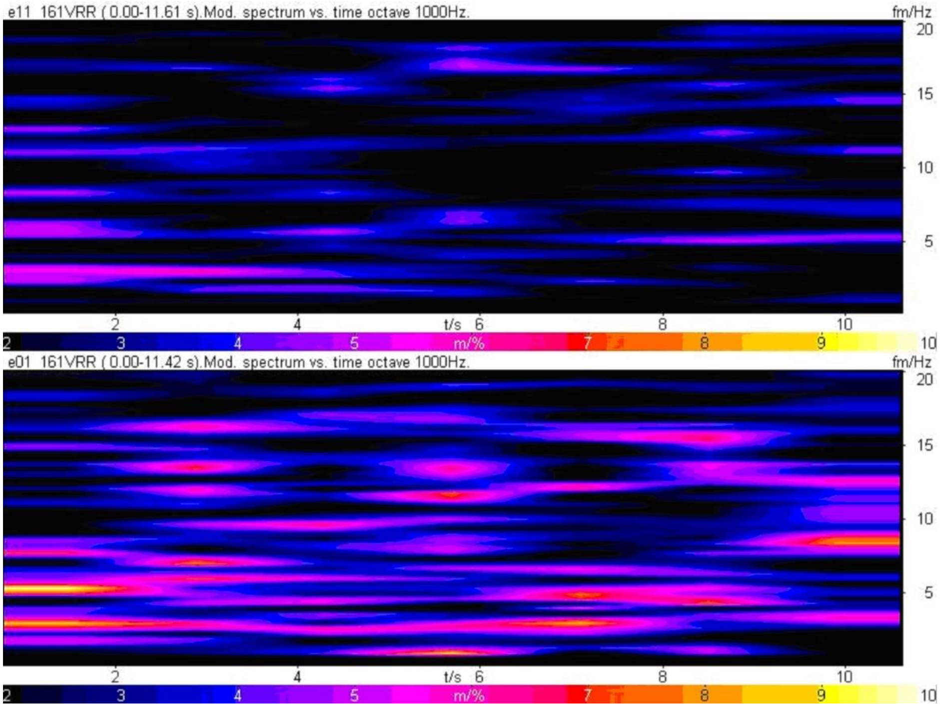

Fig. 5-2: Modulation spectrum for the 1 kHz octave band of the interior noise in a middle-class vehicle versus time (abscissa); plotted modulation frequencies 0 to 20 Hz (ordinate); plotted degree of modulation (color scale) 2 to 10 %; top: in the wind tunnel without turbulence generator, bottom: in the turbulent wake of a vehicle [16]

6. AEROACOUSTIC MEASUREMENTS IN UNSTEADY CONDITIONS

As mentioned in a previous paper of this lecture series (Helfer et al.), an increasing interest to investigate wind noise under realistic on-road flow conditions can be observed. Thus, active side-wind gust and turbulence generators have been developed and implemented in wind tunnels. One example is the system which has been implemented in the full-scale aeroacoustic wind tunnel of Stuttgart University. The system, called FKFS ***swing***® (side wind generator), has been introduced in the previous paper. It has been demonstrated that the turbulence system reproduces the time series of the flow yaw angle measured on the road in the wind tunnel within an adequate accuracy. Additionally, it has been shown in a previous publication that the variation of the yaw angle of the incoming flow leads to the most significant modulation of the interior noise including frequency content changes [23].

To demonstrate a possible investigation process and to assess the performance of the turbulence system regarding unsteady acoustic investigations, two vehicles with different unsteady acoustic behaviour were chosen. In Vehicle 1 only slight modulations of the interior noise can be perceived while driving in turbulent flow whereas in Vehicle 2 distinct noise fluctuations are observable.

Wind tunnel tests with harmonic oscillation of the turbulence system at specific frequencies showed that in Vehicle 2 these fluctuations were perceived most prominently at oscillation frequencies of 4 to 6 Hz. As discussed in section 1, modulation frequencies of around 4 Hz are most disturbing [24] which has been confirmed in earlier tests [25] Therefore, special attention should be given to this modulation frequency range during investigations of unsteady aeroacoustics.

For acoustic vehicle development it is of importance which part of the frequency spectrum of the interior noise is mostly affected by modulations of around 2 Hz to 6 Hz. The modulation depth which occurs in the noise levels of the octaves from 500 Hz to 8 kHz for Vehicle 1 and Vehicle 2 shows that the negatively rated Vehicle 2 produces higher values especially in the 4-kHz octave (see **Fig. 6-1**). Therefore, this octave band was chosen for further analysis of unsteady aeroacoustic measurements.

Figure 6-2 shows the modulation spectra of the 4-kHz octave band of the interior noise of Vehicle 1 (blue line with diamonds) and Vehicle 2 (red line with squares). The vehicles were exposed to the same turbulent flow taken from road measurements and reproduced in the wind tunnel by FKFS ***swing***®. As can be seen in **figure 6-2**, the modulation depth for Vehicle 2 (poorly rated) is considerably higher than that for Vehicle 1 (better rated) over the whole frequency range. This indicates that these modulation spectra can be used for rating vehicles with respect to their acoustic behaviour in turbulent flow.

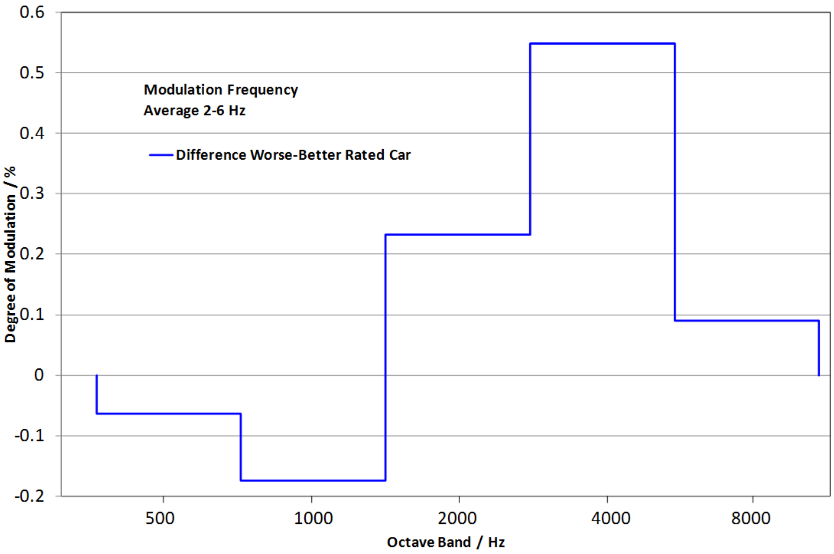

Fig. 6-1: Average difference of modulation depth between Vehicle 2 and Vehicle 1 for the modulation frequency range from 2 Hz to 6 Hz; measurement with FKFS *swing*® reproducing a flow field measured on road [23].

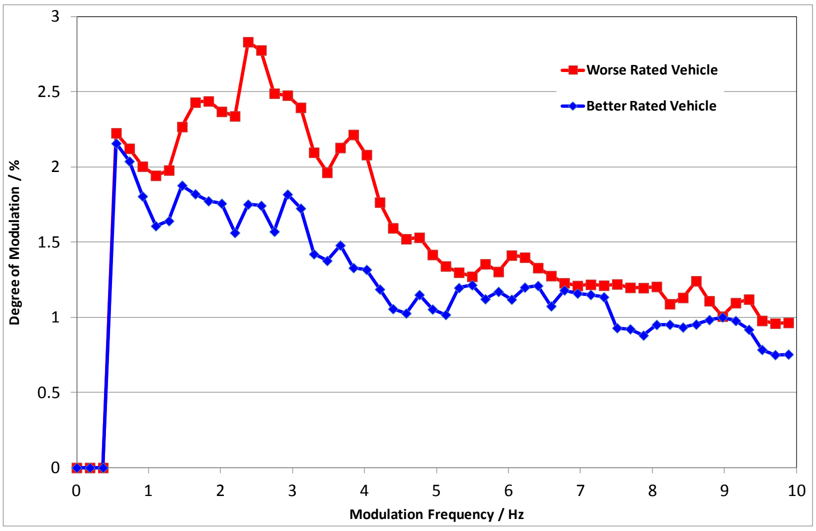

Fig. 6-2: Modulation spectra in the 4-kHz octave for the interior noise from two differently rated passenger cars exposed to same flow characteristics from road measurements reproduced by FKFS *swing*® in the wind tunnel [23].

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