inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

Influence of Circumferential Tread Pattern Stiffness on Tire Road Noise Generation under Driving Torque

Frank STALTER[1]; Frank GAUTERIN[2]

[1,2] Karlsruhe Institute of Technology KIT, Germany

Abstract

Concerning the sound emission of electric vehicles there are two main challenges: On the one hand, the exterior noise is on a very low noise level and approaching electric vehicles might not be recognized in city traffic. On the other hand, compared to internal combustion engines, electric drives develop a considerably high torque from the standstill which might increases tire road noise of about 10 dB in the near-field. Since combustion engine noise gets eliminated, tire road noise will not be masked anymore during acceleration but instead occurs as a disturbing, dominant acoustic source.

The paper describes first an inner drum test rig which allows the reproducible measurement of tire road noise on real road surfaces at driving and braking torque. Then, test results of special tires with different rubber compounds and pattern designs are presented. The influence of pattern stiffness and tire torque on tire road noise generation is analysed. Additional the inner drum test results were validated by pass-by measurements on different road surfaces. Finally, the effects and mechanisms of the noise phenomena are discussed and tire pattern design concepts for low noise emission under driving torque are derived.

Keywords: Tire Road Noise, Tread Pattern, Driving Torque
I-INCE Classification of Subjects Number(s): 11.7.1 Tires and road-tire interactions
(See http://www.inceusa.org/links/Subj%20Class%20-%20Formatted.pdf .)

1. INTRODUCTION

With the increasing use of electric vehicles, tire noise will become important especially in urban traffic. Two aspects must be considered in this connection. Electric vehicles are equipped with very quiet drive trains which make them difficult to perceive by blind persons (1, 2). In ambient noise in city centres, more than 30 % of the people are unable to recognize electric vehicles approaching at low speeds (3). On the other hand, electric vehicles, unlike those with conventional drive trains, operate at maximum torque when starting to move after standstill, which produces increased tire noise especially at low speeds (4). Studies in an inner drum test facility of the Institute of Vehicle Systems Technology (FAST) at the Karlsruhe Institute of Technology (KIT) reveal an increase in tire noise by up to 10 dB in the near field (5, 6, 7). As electric vehicles have no internal combustion engines, their tire noise is unabated, representing a rather disturbing and dominant source of noise.

Within the Quiet Road Traffic 3 joint project funded by the German Federal Ministry of Economics and Energy (BMWi) our work is focused on the mechanisms of noise generation by tires on the road under tangential forces. As torque-induced tire road noise is caused by deformation of the tread in the contact area, acoustic tire measurements are compared with measurements by a triaxial force sensing box in the driving surface. Forces acting in the normal and tangential directions were analysed. Tests are run in an inner drum to study coasting, driving and braking vehicles. The results of these studies will be compared below. The relations obtained allow to set up design requirements for vehicle tires under driving and braking torque. The design chosen were validated in pass-by measurements.

[1] frank.stalter@kit.edu
[2] frank.gauterin@kit.edu

2. DESCRIPTION OF THE TEST FACILITIES

2.1 Inner drum testing facility

The inner drum test facility of the KIT Institute of Vehicle Systems Technology (FAST) can be used for measurements under driving torque. The tire runs at loads of up to 8,000 N and speeds of up to 200 km/h on the inner side of the drum (diameter 3.8 metres) where different road types can be simulated. Tangential forces of up to 6,000 N can be applied by means of a drive shaft.

2.1.1 Installation and use of real roads

For realistic measurements in the inner drum test facility, test conditions must be as close as possible to those prevailing on the road. For this reason, real road surfaces were installed in the test rig. A number of installation scenarios were studied in an effort to create in the test rig realistic acoustic levels found on road surfaces. In this way, optimum installation parameters were determined by means of preparatory tests of small road surface specimens (cf. Fig. 1) and their evaluation as a function of rolling load, void content, density, and sound absorption capability. In this way, the road surface in the inner drum test facility corresponds to that found on public roads.

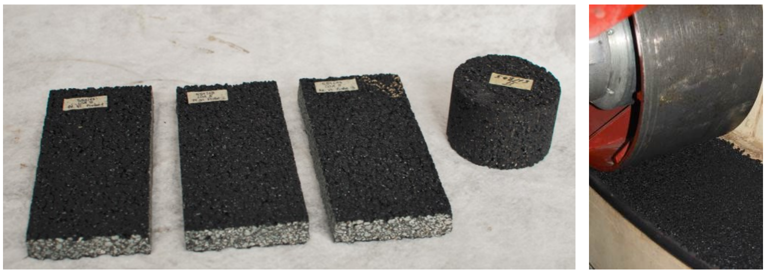

Figure 1 - Analysis of road surface samples after application of different rolling load.

2.1.2 Acoustic measurement

Acoustic optimization has reduced the disturbing noise generated by the test rig drive train and the wheel load cylinder such that acoustic near-field and diffuse-field measurements can be conducted without any disturbing impact on the tire (6) (cf. Fig. 2). Sound emission was measured in five different positions around the tire. The microphone positions at the leading edge and the trailing edge of the tire are based on the positions used in the CPX trailer (8) measurements.

Figure 2 - Acoustically optimised inner drum test facility using real road pavement at KIT

2.1.3 Force measurement

The inner drum test facility offers the major advantage of allowing a variety of road surfaces and measuring equipment to be installed. As the tire road noise is produced in the contact zone between the tire and the road surface, this zone was analysed in more detail. For this reason, a triaxial force sensor was installed in the road surface (cf. Fig. 3, arrow) to record dynamic longitudinal, lateral and vertical forces. Both the height and the location of the measuring pin (d=10 mm) perpendicular to the rolling direction can be adjusted, in this way allowing all tracks of contact patch to be scanned. To ensure a sufficient special resolution also at high speed, forces are sampled at 12.8 kHz. At speeds customarily found in urban traffic, more than 250 measurement points per pass are scanned.

Figure 3 - Triaxial force sensor placed in a road surface in the internal drum test facility.

2.2 Pass-by measurement

The passes validating the results found in the test rig were run at the NATO airbase in Geilenkirchen, Germany (cf. Fig. 4). Numerous road surfaces were installed in that facility within the "Quiet Road Traffic 3" joint project and are now available for test rides. The road pavements installed on the test site and in the inner drum test facility were made using identical compound. The test rides were performed by an electric vehicle built at the KIT.

Figure 4 - The KIT electric vehicle passing the measuring setup at Geilenkirchen, Germany.

The car used has the advantage of direct interventions into the engine torque management. A photoelectric barrier automatically activates a pre-set torque when the car passes by, thus causing the vehicle to accelerate in a defined way. Reproducible tangential forces can be applied. Both the torque applied and the instantaneous speed are recorded on-board the vehicle and synchronized with the external microphones.

3. INFLUENCE OF CIRCUMFERENTIAL STIFNESS AND RUBER COMPOUND

3.1 General effects

A number of tire tread pattern variations under driving torque are studied within the Quiet Road Traffic 3 project. Tests run in the inner drum test facility under tangential force reveal significant increases in noise level at the leading and trailing edges. An increase in tangential force by 1,500 N causes a rise in tire noise on the road surface by 3 to 5 dB. Raising the tangential forces to 3,500 N (approx. 1,020 Nm per wheel) increases the noise level, as a function of frequency, by up to 10 dB compared to the coasting condition. This increase in noise under tangential forces may be due to a separation of the contact area into a slip zone and a grip zone. The higher the tangential forces, the larger the slip zone in the contact area. A slipping tire produces more high-frequency noise at a higher sound pressure level (7).

3.2 Research into the circumferential stiffness of tread patterns

Two different geometries of tread pattern of three different rubber compounds each were studied (cf. Fig. 5). The tires shown in Fig. 5 exhibit a simple, non-randomized tread pattern. The tread blocks in tire R12 (right) are longer than in tire R11 (left). Longitudinal tread stiffness thus is clearly higher in tire R12 because of the bigger tread pattern. The rubber compounds have a spread in excess of 25Shore (Compound A = soft, B = medium, C = hard). All tires are identical in structure, merely the rubber compound was varied. All tires were produced by carving from smooth tires.

Figure 5 - Different geometry of tread pattern (R11 left, R12 right).

3.2.1 Influence of circumferential stiffness on tire noise emission

This paper is about studies of the influence on circumferential stiffness by variations of the rubber compound and tread pattern size. For this purpose, three tires with different rubber compounds were analysed for each tread geometry (R11 and R12). The tests were conducted on chipping mastic asphalt (SMA8) at a speed of 30 km/h on the inner drum test facility of the KIT.

The noise produced by the tire coasting on the road surface, i.e. without any driving or braking torque, was clearly lower for the soft tire (compound A), both at the leading and the trailing edges. The sound pressure level of rubber compound C, compared to the level produced by compound A, under coasting conditions (cf. Fig. 6) is up to 6.1 dB higher in the trailing edge. The tire with the medium rubber compound is positioned between tires A and C. Analysis of the frequency spectra even shows differences of more than 10 dB above 2000 Hz. The soft tire is better able to accommodate stresses in the contact area, exposing the tread pattern to less tension and, consequently, produces clearly less noise already under coasting conditions.

When a drive torque of 3,500 N (roughly corresponding to 1,020 Nm) is applied to the tire, the sound pressure level of all rubber compounds rises at the trailing edge of the tire. The tire with the soft rubber compound (A) continues to produce low noise levels also under drive torque. The hard rubber compound (C) is clearly louder, its overall sound pressure level being higher by 3.3 dB. Analysis of the frequency ranges shows a difference in sound pressure level of up to 7 dB beyond 1,500 Hz. Hardly any differences can be found in the low-frequency range up to approx. 1,000 Hz.

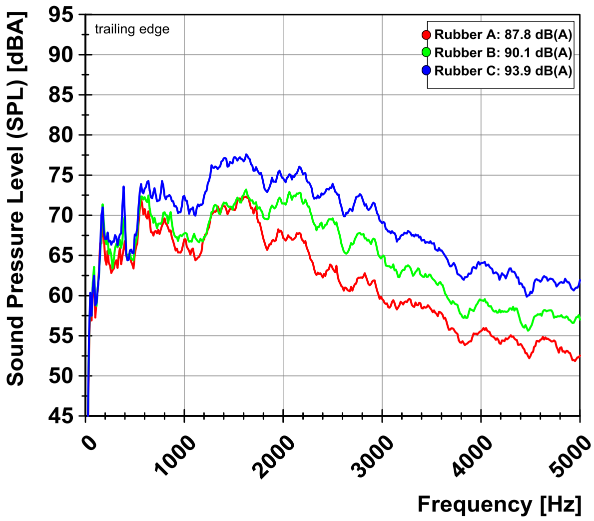

Figure 6 - Comparison of tire compounds, coasting, 30 km/h, SMA 8, trailing edge.

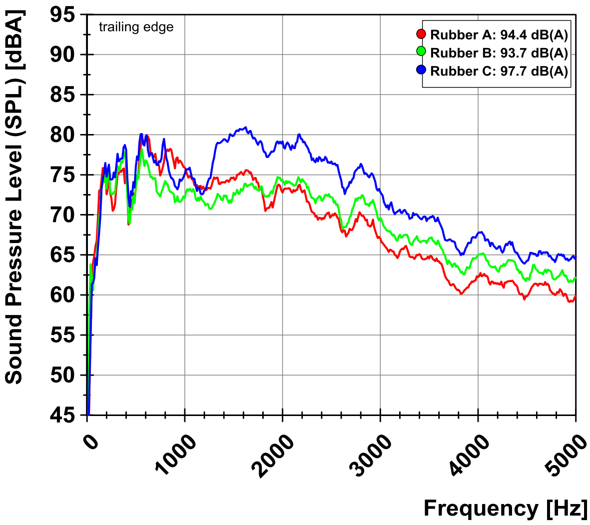

Figure 7 - Comparison of tire compounds, 3500 N circumferential force, 30 km/h, SMA 8, trailing edge.

The tire with the harder rubber compound emits more noise. The assumption for this is that the tire starts to slip earlier on the area contacting the ground, which leads to sound at a higher frequency being emitted. Snapping of the tread pattern at the trailing edge of the tire does not prevail over the slip effect. As the tread pattern in a soft tire show the largest deflection when subjected to the drive torque, they also snap out most strongly when leaving the surface contact point. However, the increase in sound level as a result of these snap-out effects is clearly less pronounced than that caused by slip effects.

For verification of this assumption, the tires with the different rubber compounds were rolled across the force sensor described in 2.1.3 above. The examples shown here are the force curves in the road contact area in the longitudinal direction of rubber compounds A and C (cf. Fig. 8). The asymmetrical curve of forces relative to the x-axis is due to the force being recorded in a lateral position close to the middle of the tires. As tires have a larger circumference in the middle, the tractive forces prevailing there are slightly higher. Tire circumference is smaller at the outside of the shoulders and so braking forces are dominating. Averaged over the whole tire cross section, the force curve is symmetrical.

A comparison of the curves under drive torque clearly shows that the hard tire with compound C begins to slip over large parts of the contact area at a circumferential force as low as 1,500 N. When the tractive force is increased to 1,900 N, the tire shows almost complete slipping (blue curves, horizontal area). It builds up force again at the end of the tire contact patch and returns to the grip zone. This process can be described quite well by the force development in a coasting tire: The free-rolling stress of the tire with the hard compound decreases strongly at the trailing edge of the tire. As shear stresses under circumferential force result from the sum total of the basic stress in the coasting mode and the force under driving torque, it is evident that the tire regains grip at the trailing edge.

On the other hand, the tire with the soft compound A shows no slip region even at a higher circumferential force of 1,900 N. At no point in time the limits of grip are exceeded, and the tire is able to transmit its full force potential. It is seen that the soft tire of low shear strength can offset the relative motion between the tire and the road surface under tractive force largely by deformation of the tread pattern. The (hard) tire of high shear strength is not able to do so and needs to balance out the displacement by slipping.

In addition the variation of the longitudinal tread stiffness by the block size shows an identical trend. The comparison of the two tread pattern designs (tire R11 small tread blocks and R12 with big tread blocks) show that the stiffer blocks (R12) start to slip earlier. We notice this for all three compounds.

These findings allow a connection to be established between slip effects and excessive noise generation under driving torque conditions. Rising circumferential force also causes noise emission to increase. Evaluation of the passes across the pin shows that also the slip zones become larger as the circumferential force increases. This constitutes a direct connection between the increasing slip zone and the emission of high-frequency noise.

3.2.2 Validation of results obtained in pass-by measurements

These findings will be analysed now under pass-by conditions. For this purpose, individual pass-by measurements were run at a speed of 30 km/h on SMA 8, among other surfaces. In the acceleration mode, the driving parameters of the test vehicle were set so that a circumferential force of 3,500 N was applied at the position of the measurement microphone at a speed of 30 km/h. Initially, comparison of the sound levels generated in passing showed no major differences at constant driving conditions for soft and hard tires (cf. Fig. 9, left). However, when the vehicle is accelerated, the sound pressure level generated during pass-by rises by more than 6 dB for both tire compounds (cf. Fig. 9, right). Detailed analysis again shows that the noise-abating effects referred to above of soft rubber compounds under driving torque conditions are found also during pass-by. The soft tread is 1.5 dB lower in its overall sound level during the pass-by, as the tread pattern in this case show clearly less slip and thus emit less sound. Tests under passing conditions were carried out also on road surfaces optimized for noise generation (LOA 5 D, PMA 5). Findings show similar trends.

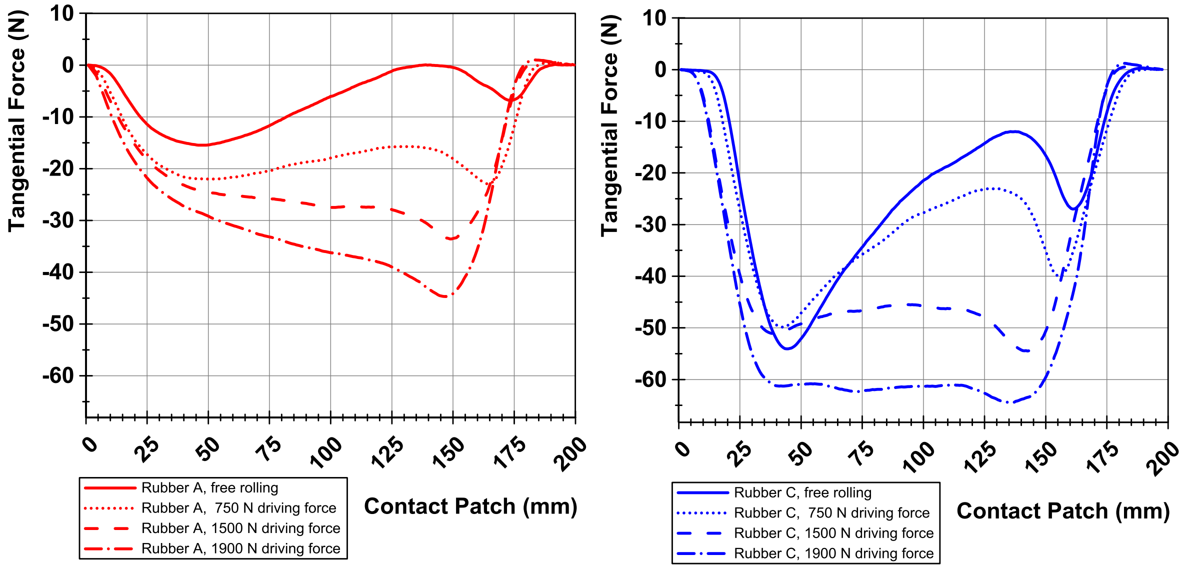

Figure 8 - Comparison of force curves of different rubber compounds under driving torque conditions, (0 mm = leading edge, Rubber A left, Rubber C right)

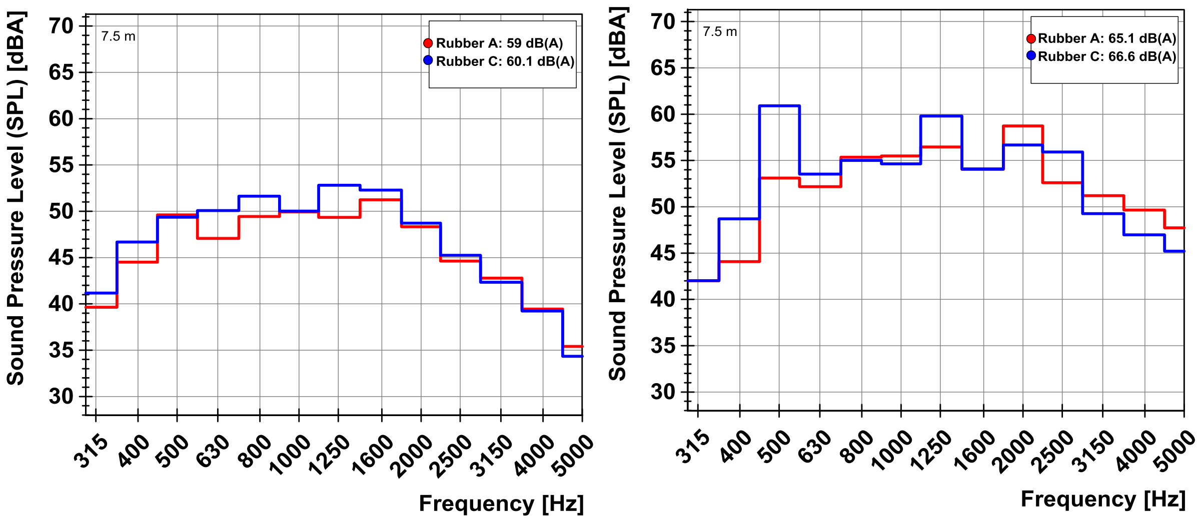

Figure 9 - Sound level generated during coast-by s (left) and during accelerated pass-by (right) for different tire tread compounds.

4. CONCLUSIONS

A relation is shown in this paper between the circumferential stiffness of tire tread pattern and the noise emitted by the tire road contact under driving torque. First, the internal drum test facility with its different measurement options was presented. For reproducible measurements, real road surfaces were installed in the test facility, and acoustic measurements were performed under driving torque. For better understanding of the conditions in the road contact area, the generation of forces in the contact area was logged in the longitudinal, transversal, and vertical directions. The rig was used to study tires of the same design, but different Shore hardness of the tread. In this way, different circumferential stiffness can be achieved. The tires made from a softer rubber compound of lower shear strength show a reduction in sound emission under driving torque. This can be explained by the assumption that the soft tread blocks would be more able to balance out the displacement between road surface and tire carcass by bending, which would keep them sticking longer on the road surface. Stiff tread pattern, on the other hand, are expected to slide under the shear stress generated by driving torque. This hypothesis was confirmed by the detection and analysis of forces and slip in the contact zone. Under driving torque, slip effects were found to dominate tread block snap-out noise. Finally, outdoor pass-by noise measurements were made under identical conditions. Again, the assumption was confirmed that soft tires produce a lower sound level under driving torque.

ACKNOWLEDGEMENTS

This work was performed within the Quiet Road Traffic 3 (Leiser Straßenverkehr 3 – LeiStra3) joint project funded by the German Federal Ministry of Economics and Energy (BMWi). The study presented here is part of the research conducted by the Institute of Vehicle Systems Technology (FAST) at the Karlsruhe Institute of Technology (KIT), Germany.

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