TRANSFER PATH BASED TYRE ABSORPTION TESTS

E. Tijs[1], B. Makwana[2], O. Peksel[1], S. Amarnath[2], D. Bekke[2]

[1]*Microflown Technologies, Tivolilaan 205, 6824 BV, Arnhem, the Netherlands*

[2]*Apollo Tyres, Colosseum 2, 7521 PT, Enschede, the Netherlands*

e-mail: tijs@microflown.com

The development process of a tyre usually involves a combination of simulation and testing techniques that are focused on characterizing acoustic/aerodynamic and vibrational phenomena. One of the acoustic phenomena of interest are the absorption properties of the tyre, which affect the sound radiated. Those properties are mainly related to local resonant effects, which can be changed by modifying the geometry of the tyre tread. In this paper, a procedure is presented to determine the attenuation achieved due to a change in tyre tread configuration. The acoustic transfer path from sound produced at one side of the tyre-pavement contact area to the other is measured. A miniature microphone and a small monopole with a known output have been developed to allow measurements inside the tyre grooves. Tyre sections with a circumferential groove only, as well as sections with additional side branches, have been evaluated.

1. Introduction

When a tyre makes contact with the pavement, noise is generated by several mechanisms (e.g. tread impact, air pumping, slip-stick, etcetera) [4]. Sound is then radiated by sidewall vibrations or radial vibrations, or at the tyre-road interface. Two effects affect the degree of attenuation of airborne sound generated at the tyre-road contact point. Firstly, there is the horn effect. A flat road surface and a circular tyre create a geometry similar to that of a horn, which is known to be an efficient acoustic radiator. Consequently, sound generated near the throat of the horn is attenuated little. Porous asphalts are increasingly being used to reduce the horn effect [5]. Secondly, there are pipe resonances. When the pavement and tyre make contact, holes in the road surface and groves in the tyre from cavities that act like resonators. Their behaviour is similar to resonators such as quarter lambda or Helmholtz resonators, see figure 1. Depending on the size and shape of the cavity sound is attenuated at certain frequencies.

Apart from the properties of the pavement, the horn effect and pipe resonances are also affected by the geometry of the tyre. Therefore, the study of these attenuation mechanisms is of concern to tyre manufactures. In [3] the influence of these effects was analyzed simultaneously by measuring the attenuation from sound produced at the centre point where the tyre contacts the pavement to the side of the tyre. A monopole was placed at the side of the tyre and a microphone was installed inside one of the grooves. The transfer function between the volume velocity of the monopole and the sound pressure measured by the microphone was obtained. This transfer path is equal to the transfer path from the tyre-pavement interface to the side of the tyre due to the reciprocity principle.

Figure 1. Holes in the pavement (left) and groves in the tyre (middle) form cavity resonators (right).

In this paper, the influence of pipe resonances is studied separately. When a tyre is loaded, the rubber is compressed and the tyre tread and its side branches form cavities between the flat contact surface of the tyre and the pavement. The attenuation of the side branches is determined by measuring the acoustic transfer path from one side of the tyre to the other. The acoustic transfer path describes the amplitude decrease and phase change from sound waves propagating from a source to a receiver. The transfer path can be determined by measuring the sound radiation of well-defined source such as a monopole and the resulting sound pressure at the receiver position.

For these test, a small monopole source that fits in the tyre tread, and a miniature microphone that could even fit in the side branches, have been developed. The monopole loudspeaker is positioned inside a groove at one side of the flat contact surface. The microphone is positioned inside the groove at the other side. The transfer function between the volume velocity radiating from the monopole source and the sound pressure captured by the microphone is measured.

In the following chapter, the monopole sound source is introduced. Thereafter, the method to determine the transfer path is described. Finally, results of transfer path measurements on a loaded tyre are presented and analyzed.

2. Monopole theory

An effective way to create a small and easy to control monopole is with a tube that is open on one end, and connected to a loudspeaker inside an enclosure at the other. Sound will radiate spherically from the open end of the tube due to diffraction. If the size of the opening is small enough compared to the wavelength, sound will radiate uniformly in each direction, and a monopole sound source is created. Consequently, the upper frequency $f_{\max}$ is limited by the size of the opening. As a guideline, $f_{\max}$ should be smaller than $40/d$, where d is the inner diameter of the tube [1-2].

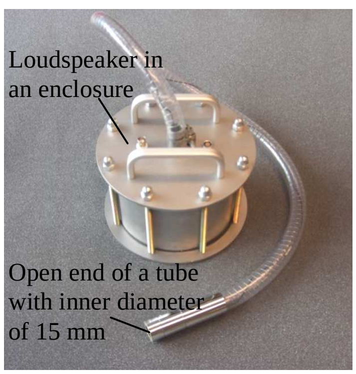
Broadband monopole loudspeakers with sufficient sound power are complicated to manufacture because of the low radiation efficiency of the tube. In practice, the choice for a monopole is a trade-off between the maximum sound level reached and the upper frequency limit. A large tube opening is required to generate sufficient sound power at low frequencies, while the opening should be small compared to the wavelength to ensure onmi-directional radiation at high frequencies. More than one sound source may be needed to cover a broad band.

The loudspeaker input signal is unsuitable for proper predicting the sound radiated because variations in temperature and geometry (for a flexible tube) affect the acoustic impedance in the tube, and thus the tube's radiation efficiency. Moreover, the damping in the tube is hard to calculate, and the relation between the loudspeaker output and radiated sound level may be non-linear. Therefore, a reference sensor should be used at the end of the tube.

In [1-2] three potential choices for a reference sensor were described. Firstly, the sound pressure can be measured by a single microphone. The radiated sound level can then be calculated using the predicted radiation impedance. However, the radiation impedance depends on temperature variations and on the presence of nearby obstacles. In addition, the relation between sound pressure and the sound radiated may be non-linear at high sound levels, and there can be positioning errors at high frequencies. Instead of using sound pressure, the particle velocity $u_{monopole}$ may be measured at the end of the tube. The particle velocity is linearly related to the radiated volume velocity Q, even if there are surrounding obstacles; $Q = u_{monopole}A$, where A is the tube's opening area.

One method of measuring particle velocity is with a pair of closely spaced and phase matched microphones. The sound pressure gradient is proportional to the particle velocity if the sound field is linear. However, at high sound levels this assumption violated, and accurate measurements at low frequencies are hard because of phase errors.

Alternatively, the particle velocity can also be measured directly with a Microflown sensor. Provided that the sound level does not exceed the maximum level of the sensor, the volume velocity can be estimated straightforwardly. The monopole used for the measurement in this paper also uses the latter approach to estimate the radiated sound, see figure 2 left.



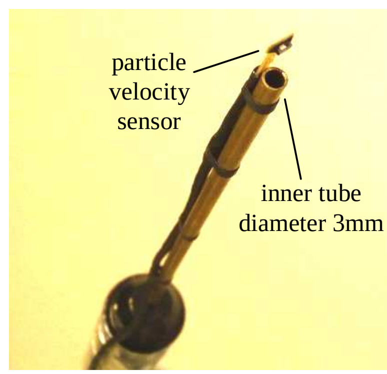


Figure 2. Left: Mid-high frequency monopole. Right: extension piece and miniature reference sensor.

The sound pressure p at a distance r from the centre of a monopole given by [1-2,6]:

$$p(r) = i\frac{\rho f}{2r}Qe^{-ikr} \tag{1}$$

where ρ is the density of air and f is frequency. The monopole source is positioned in the tyre tread for the direct transfer path tests. The end of the standard monopole as shown in figure 2 (left) is too large for this. Therefore, an extension piece consisting of a narrow tube has been developed, see figure 2 (right). The reference sensor cannot be installed at the end of the tube because it is too narrow and because very high velocity levels can be generated that would overload the particle velocity sensor. For example, a volume velocity of $6.7e^{-6}m^3/s$ is required according to equation 1 to generate a sound pressure level at 1kHz of 60dB at 0.2m distance. The resulting particle velocity for the tube with an inner diameter of 0.003m is almost 1m/s. Therefore, the particle velocity sensor is positioned 10mm from the centre of the monopole. The acoustic impedance of a monopole is:

$$Z = \frac{p}{u} = \rho c\frac{ikr}{ikr+1} \tag{2}$$

Combining equation 1 and 2, the particle velocity can be obtained by:

$$u(r) = \frac{Q}{4\pi} \frac{ikr + 1}{r^3} e^{-ikr} \qquad (1)$$

There are disadvantages of positioning the reference sensor outside the tube. The configuration is more fragile and measurements might be affected by reflections from surrounding obstacles. The latter might cause discrepancies during tests described in this paper because the monopole extension piece will be positioned inside a tyre groove. However, these discrepancies are less relevant because a similar position will be used for all measurements, and only the relative variation amongst these tests is analyzed.

3. Transfer path tests

3.1 Test description

For these tests, a tyre with four different sections is studied, see figure 3. The first section consists only of one circumferential groove of 10 mm wide and 8.5 mm deep. The second tyre section contains an additional side branch that is 2.5 mm wide and perpendicular to the circumferential groove. The third section contains a similar side branch at an oblique angle. The forth section contains two oblique side branches of different lengths.

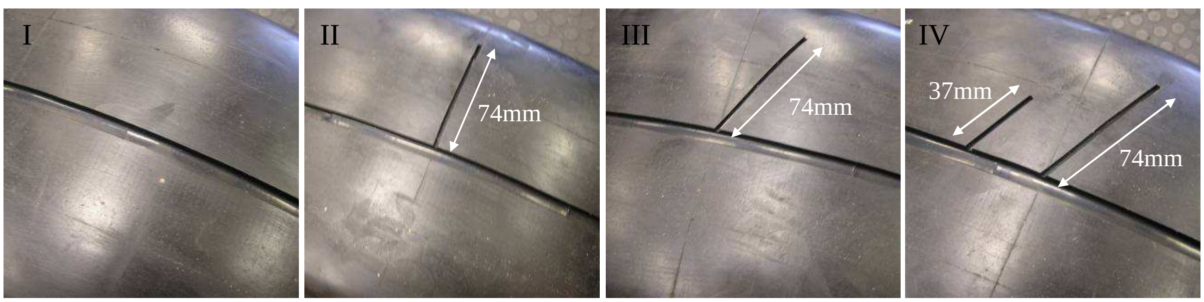


Figure 3. Four different tyre sections that are tested.

A flat pavement section is pressed with 6500 N downward onto the tyre. To determine the acoustic transfer path, the monopole extension piece (figure 2, right) is placed at one side of the flat tyre-pavement contact surface between the circumferential groove. A miniature microphone with a diameter of 3 mm is produced, which is positioned inside the groove at the other side of the contact surface, see figure 4. The monopole loudspeaker is excited with a pink noise signal.

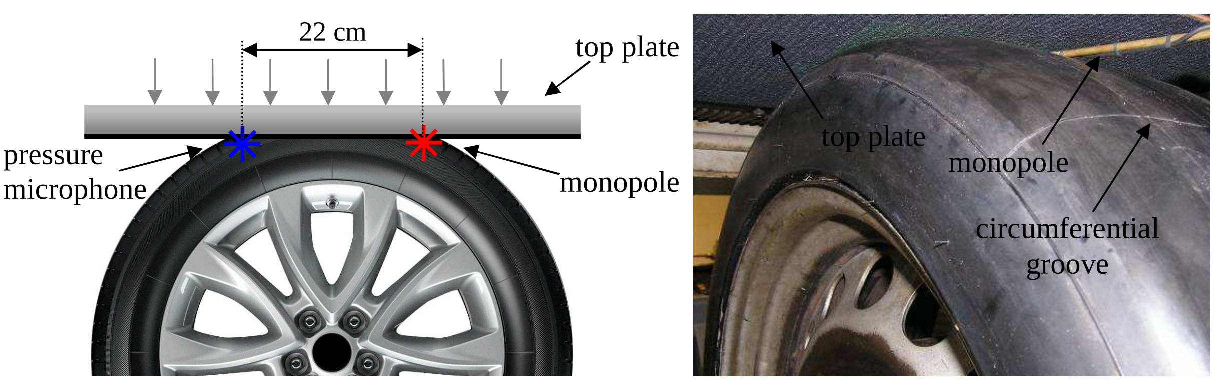


Figure 4. Description of the measurement set-up. Left: Schematic overview. Right: right side view.

3.2 Measurement results

Figure 5 shows the absolute part of the measured transfer function between the sound pressure of the microphone and the volume velocity of the monopole loudspeaker. The right figure shows the differences between the sections with side branches relative to the section without side branch. The scales of the y-axis have been removed for confidentiality reasons. Figure 6 shows the measured phase. The right figure shows the phase difference compared to the condition without side branches.

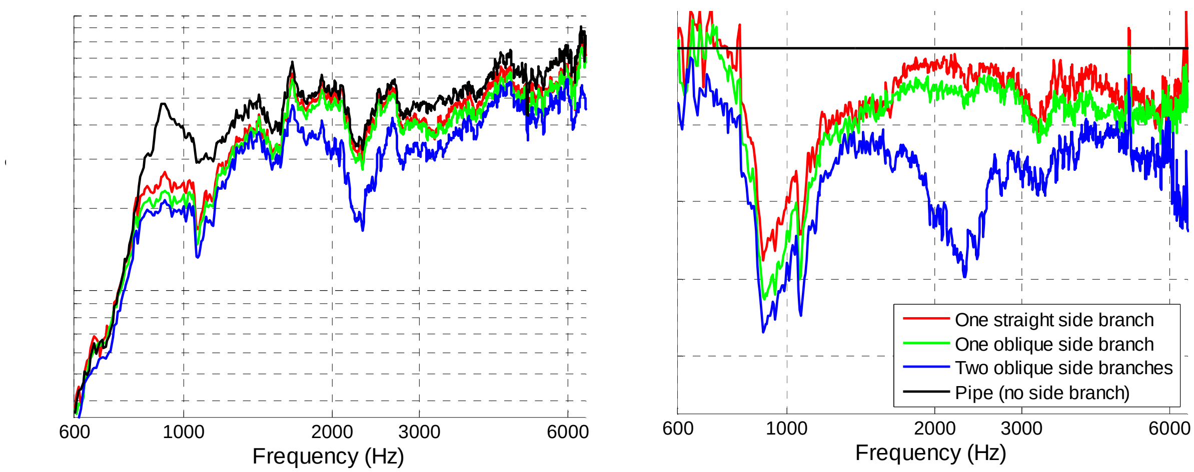


Figure 5. Left: absolute part of the transfer function. Right: discrepancies compared to the pipe without side branches.

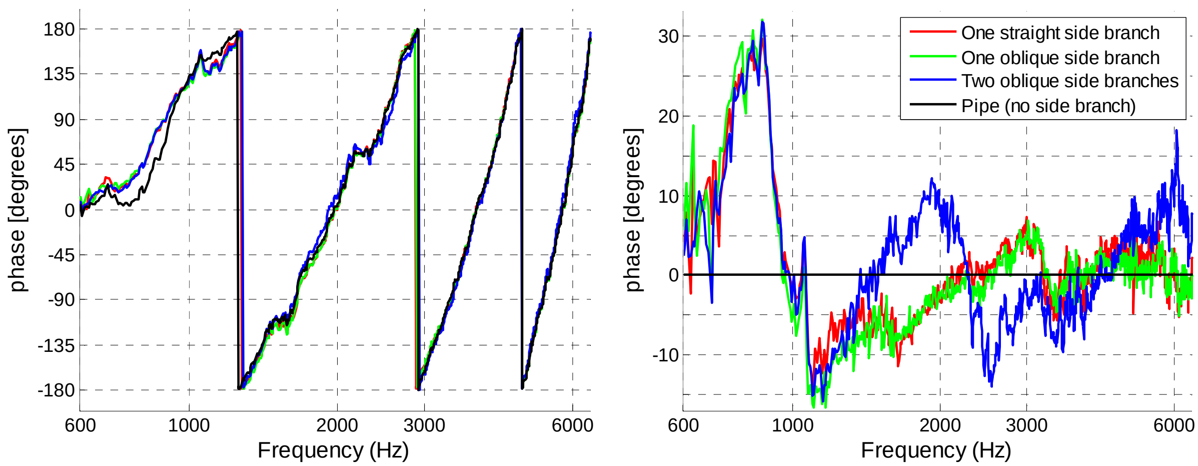


Figure 6. Left: transfer function phase. Right: relative phase compared to the pipe without side branches.

Both figures show that damping is achieved by the additional side branches. Attenuation is achieved in the band around 1 kHz, depending on the configuration. For the section with two side branches there is additional damping for frequencies around 2.3 kHz.

The frequency where damping occurs is determined mainly by the length of the side branch. The measured frequencies are similar to the ones expected for quarter lambda resonators. A quarter lambda resonator consist of a tube that is open on one end and closed on the other. Absorption is achieved due to viscous damping at the opening and at the walls of the tube [7-8]. Furthermore, there is interference of the incident and reflected wave because the sound pressure amplitude of sound waves travelling towards the tube is in anti-phase with that of the reflected waves if the length of the tube is equal to a quarter wavelength, or an odd multiple of that. Actually, the acoustic length of the tube is slightly longer than the geometrical length. The additional length depends on the size and shape of the opening, and on the length of the tube, and lies between $0.25\pi r$ and $8/3\pi r$ for a cylindrical opening (with r being the radius) [8].

Given that the side branches can be modelled by a quarter lambda resonator, their acoustic lengths can be approximated using the frequency where the highest damping is measured, which in this case is $\frac{1}{4}\cdot\frac{c}{f}\approx\frac{1}{4}\cdot\frac{343}{1000}=86\,\text{mm}$ for the long side branch, and $\frac{1}{4}\cdot\frac{343}{2300}=37\,\text{mm}$ for the small side branch. This seems plausible as the acoustic length can be longer than the geometric lengths.

4. Conclusions

The surface geometry of a tyre affects the way sound produced at the tyre-road interface is radiated. In this paper, a procedure is presented to determine the attenuation of the side branches of a tyre groove. The transfer path from one side of the flattened surface of a loaded tyre to the other side is measured, and the degree to which the amplitude and phase of sound waves are changed is captured. To enable such tests, a miniature monopole and a microphone have been created, which are small enough to fit in a tyre groove. A particle velocity sensor has been installed at a small distance from the centre of the monopole to measure its radiation. A method has been to introduced to correct for the sensor-monopole distance, and to calculate the sound pressure radiated.

The measured values were similar to those expected from rather simple models for the rather simple tread geometries used in this research. Depending on the number of side branches and their orientation, damping was achieved at certain frequencies. The extend to which the results match with simulations for different tyre tread designs has to be investigated further. The test method presented is particularly interesting for more complex tyre tread designs that are difficult to simulate.

The frequency range of the monopole extension piece was sufficient for these measurements. A monopole with a higher output is required if frequencies below ~600 Hz are of interest. However, such a sound source will probably be too large to fit into the tyre tread.

With the same equipment, different types of transfer paths may be assessed also. An example, is the transfer path investigated in [3], which describes the attenuation of sound produced at the tyre-pavement contact point to a position outside the tyre.

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