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EXPERIMENTAL INVESTIGATIONS INTO THE AIR PUMPING EFFECT AT THE TYRE/ROAD INTERFACE

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1 INTRODUCTION

Environmental noise pollution is an important issue that affects health and quality of life of millions of people in the modern world. One of the main sources of environmental noise pollution is the noise generated by road traffic. To reduce road traffic noise, the automotive industry has done a great deal of research and development in the recent decades. As a result of these efforts, such earlier important contributors to the overall automotive noise, as powertrain and exhaust noise, have been reduced considerably for nearly all driving conditions, so that the dominant contributor has become tyre/road noise. According to the tyre/road noise reference book written by Sandberg and Ejsmont\(^1\), there are two different groups of generation mechanisms for tyre/road noise: (i) tyre vibrations; and (ii) aerodynamical effects in or around the tyre. In contrast to noise generated by tyre vibrations, the aerodynamical mechanisms of tyre noise generation have received relatively little attention in the past. Therefore, the main aim of the research reported in this paper was to undertake comprehensive experimental investigations of aerodynamically related mechanisms of tyre/road noise.

2 AERODYNAMICALLY RELATED MECHANISMS OF TYRE/ROAD NOISE

In the literature there are four different noise generation mechanisms that are generally combined under the topic of aerodynamically related mechanisms of tyre/road noise. Air turbulence is one of them. This phenomenon is best described as noise generated by air that moves around the tyre either due to the tyre displacing air or air being dragged around by the spinning tyre. A second possible mechanism is pipe resonance, which occurs at the contact patch of the tyre where the grooves, closed by the road effectively become pipes and hence allow acoustic resonances to occur. Another mechanism is the so-called air pumping mechanism. This can be considered as noise generated by air being pumped out of the grooves at the leading edge and air sucked into the grooves at the trailing edge. The last mechanism is called air resonant radiation, a phenomenon which is also known as Helmholtz resonances. This is because of an air displacement resonance that occurs when the contact patch leaves the road, either due to cavities of the road or the tread. The latter two mechanisms are described in more detail below.

2.1 Air Pumping Mechanism

In 1971 Hayden\(^2\) presented a definition of the so-called air pumping effect. In tyre noise literature the expression ‘air pumping’ is sometimes used to refer to different mechanisms of aerodynamic noise, as noted by Kropp\(^3\). In the present paper, the term ‘air pumping’ shall be used referring to Hayden’s definition. Another paper, that describes the air pumping effect, has been written by Gagen\(^4\). However his model, based on fluid dynamics has not been experimentally validated. The air pumping mechanism occurs on the leading and the trailing edges of the tyre contact patch. In the following illustrations (see Figures 1, 2 and 4) the leading edge, the one where there tread is...
about to hit the road, shall always be on the right hand side. The trailing edge of the tyre, where the tread has just left the contact with the road, is, therefore, displayed on the left hand side of Figure 1, 2 and 4. Figure 1 shows a tyre spinning clockwise around its axle as indicated with the white arrow. The leading and trailing edges are as described. The (green) arrows indicate the direction of the air movement that is assumed due to the air pumping effect as the cavity travels over the contact patch, as shown. Hayden’s theory assumes deformation of the tread grooves as they enter the contact patch. Thus air is compressed and then expelled at the leading edge of the tyre. At the trailing edge there will be air displacement as well, due to the tread expansion, which generates an induction effect. Thus the air squeezing out of the compressed grooves and rushing into the expanded grooves gives rise to air fluctuations. Although in Figure 1 the effect is illustrated as occurring at the leading and trailing edges, Hayden’s work concentrates on the trailing edge. To predict the generated sound pressure level of a tyre at an observation point away from the trailing edge of the tyre Hayden proposed a simple formula based on the reoccurrence frequency of the tread cavity contacting the drum surface. With the dimensions of the cavity, the distance of the recording point, and an assumed change of cavity volume, the sound pressure level can be predicted. According to Sandberg and Ejsmont\textsuperscript{1} air pumping occurs in the frequency range from 1 Hz to 10 kHz. The air pumping mechanism can occur as a result of pockets in a tyre tread as well as due to pockets in the road surface as investigated by Hamet\textsuperscript{5}.

### 2.2 Air resonant radiation

Another aerodynamically related noise generation phenomena to be considered in this paper are the ‘Helmholtz resonances’ or air resonant radiation. Helmholtz resonance can be modelled by a simple mass, spring vibration system. For tyre/road interaction noise, the air can be considered to act as the mass and the volume of the cavity can be considered to act as the spring. This phenomenon only occurs at the trailing edge of the tyre, and is displayed in Figure 2. In some cases this mechanism can be the main source of tyre/road noise, as noted by Nilsson et al.\textsuperscript{6}. The phenomenon illustrated in Figure 2 is the Helmholtz resonator effect for a tyre, which occurs as the cavity leaves the ground at the trailing edge. It is considered to be a high amplitude, medium frequency sound, which fades with increasing frequency.

### 3 EXPERIMENTAL SETUP AND MEASUREMENT METHOD

The measurements reported in this paper were taken at the rolling road facility of Loughborough University. The chassis dynamometer consists of two pairs of plain steal drums. The signals were recorded very close to the source (contact patch of tyre) to minimise the effect of reflections from the walls of the laboratory. Essential for a fundamental study of potential aerodynamic noise mechanisms is the use of a simple and small tyre that avoids the complexity and design of a real gas filled vehicle tyre. Therefore a plain, solid rubber castor on a plastic rim, as illustrated in Figure 3, (diameter: 121mm, width: 22mm) is used for the experimental studies. Because of the simple roller design noise generation mechanisms like cavity resonance and also belt vibration and tread vibrations, which are mentioned by Sandberg\textsuperscript{1} as potential causes for the so called Multi-
Coincidence peak at around 1000 Hz, can be neglected. Furthermore, the solid rubber tyre of just 121mm in diameter gives a very good tyre/drum ratio of approximately 1/4.

As can be seen in Figure 3, a cylindrically shaped cavity (diameter: 9mm, depth: 5.5mm) was cut out of the solid rubber tyre. The roller itself is fixed by a metal frame onto the top of one drum of the chassis dynamometer. Additional weights were introduced to apply load to the roller. The frame itself weights 15kg, an additional 20kg of weights is put onto the frame for better compression of the solid rubber tyre. A photograph of the experimental setup can be seen in Figure 4. A similar approach was used by Graf to investigate the pipe resonance and horn effect in real tyres.

Figure 3 Illustration of the cavity cut into the solid rubber tyre

Figure 4 Experimental setup with microphones at trailing (left) and leading (right) edges of the solid rubber tyre
The dynamometer was driven at a speed of 41 km/h, which corresponds to a frequency of rotation of 7.25 Hz for the drum and 29.96 Hz for the solid rubber tyre. Also shown in Figure 4 are two microphones located at 0.02 m from the trailing and leading edges of the tyre. Time histories of the sound pressure measured by the microphones were recorded and post processed on a multi-channel spectrum analyser. In comparison to a typical 17" tyre, equivalent vehicle speeds for the small roller can be calculated. A factor of about 3.6 is the difference between the solid rubber roller and a real tyre of 17" diameter. So, for a drum speed of 41 km/h the equivalent speed of the solid rubber tyre is about 150 km/h.

4 RESULTS AND DISCUSSIONS

Figure 5 shows an eight-second recording of the sound pressure measured at the trailing edge of the solid rubber tyre with a cylindrically shaped whole. This is a long enough time duration to capture over 200 rotations of the small tyre when driven at a dynamometer speed of 41 km/h. It can be seen in Figure 5 that the sound pressure consists of a succession of pulses occurring 0.033 seconds apart. This repetition frequency of 29.96 Hz corresponds to the dynamometer rotational speed of 41 km/h. Hence, the pressure pulses can be attributed to the tyre cavity travelling over the dynamometer drum.

When one of these peaks is viewed in more detail, the nature of the pressure pulses can be identified further. Figure 6 displays the leading (solid, blue) and the trailing (dashed, red) edge microphone recordings of the signal. First of all, at the leading edge there is a small pressure fluctuation identifiable just after 0.1 seconds. This is attributed to be the event when the hole is just reaching the contact patch and some air is squeezed out. Between this and the much larger pressure pulse at the trailing edge is the time when the hole is in direct contact with the road surface. It is completely covered, so there is no air movement.

The pressure oscillations at the trailing edge are of higher amplitude than at the leading edge. It can be seen in Figure 6 that the frequency of the pressure oscillations is changing with the duration of the trailing edge pulse. By noting the period of the oscillation, it can be calculated that the pulse starts at a frequency of approximately 2800 Hz and finishes at approximately 6200 Hz. This is similar to the phenomena, termed ‘air resonant radiation’, reported by Nilsson while investigating crossbar tyres.
Figure 6. Time history of a single pressure pulse recorded at leading and trailing edges of the tyre.

Figure 7. Frequency spectrum of the sound pressure recorded at the trailing edge.

Figure 7 displays the amplitude of the Fourier transform of the eight-second recording of the sound pressure from the trailing edge of the tyre. The spectrum is displayed over the frequency range 0 Hz to 16 kHz. It can be seen from Figure 8 that there is very little signal energy above 7000 Hz. It is also apparent that the signal contains broadband frequency content over the frequency range 2000 Hz to 6000 Hz. This corresponds to the frequency sweep of a single pulse recorded from the trailing edge, as shown in Figure 6. Also displayed in Figure 7 are some high amplitude resonances below 2000 Hz. However, further investigation with the solid rubber roller lifted away from the dynamometer drum revealed these peaks to be due to the chassis dynamometer drive mechanism and not due to the roller/drum interaction.

Figure 8 displays an expanded version of the spectrum of the sound pressure recorded at the trailing edge over the frequency range 5500 Hz to 6000 Hz. It can be seen in Figure 8 that the ‘broad band’ frequency content shown in Figure 7, in fact, consists of harmonics 30 Hz apart. Thus, the broadband frequency content shown in Figure 7 between 2000 Hz and 6000 Hz is controlled by the oscillations of a single pulse. However, the fine structure of this frequency region is controlled by the repetition frequency of the tyre cavity at the 29.96 Hz, as suggested by Hayden².
5 CONCLUDING REMARKS

Experimental results have been presented on tyre/road noise generated by a small solid rubber tyre running on a chassis dynamometer. Specifically, the sound generated by a small cavity in the rubber tyre has been shown to have a broadband frequency content, similar to the ‘air resonant radiation’ effect noted by Nilsson⁶, and a fine harmonic structure, which is due to the repetition frequency of the cavity contacting the dynamometer drum (air pumping effect). Further work is now under way on theoretical modelling of air resonant radiation and air pumping.

REFERENCES


Figure 8 Frequency spectrum of the sound pressure recorded at the trailing edge over the frequency range of 5500 Hz to 6000Hz