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Air-related mechanisms of noise generation by solid rubber tyres with cavities

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ABSTRACT

There are four main air-related noise generation mechanisms at the tyre/road interface, which were all categorised more than 20 years ago. The first one is the so-called 'air pumping' mechanism. Two other air-related phenomena that occur when there are air movements near the contact patch of the tyre are 'air resonant radiation' and 'pipe resonances' which appear at the footprint of the tyre. In addition to these, there is a forth effect, which is mentioned in the literature, that is occurring due to turbulence effects of the air surrounding the spinning tyre. There has been less focus on the air-related mechanisms than on other types of tyre noise generation mechanisms. This paper attempts to add some detail to current understanding of the air-related noise generation at the tyre road interface and gives some further information on how to identify the differences due to these mechanisms. Specifically in the present paper, a solid rubber tyre running on a vehicle chassis dynamometer is used to study the first two mechanisms. This is done with emphasis on the time history of the recorded signal and not on the frequency spectrum, as is more commonly used. A comparison with existing theoretical models of these mechanisms reveals some of the strength and weaknesses of the current understanding of these phenomena.

1. Introduction

It is well known that road traffic noise is one of the major environmental problems in industrial countries. Because of significant reductions in powertrain noise, the main noise generation left from a passenger car is the one initiated by the tyre rolling over the road [1–4].

Tyre/road noise is generally divided into generation mechanisms and amplification mechanisms. One can divide the generation mechanisms into aerodynamic and vibration related phenomena [1,4]. Furthermore, the aerodynamic noise at the tyre road interface can be subdivided into four different mechanisms. The first one is named 'air turbulence', this is produced by the air which is moved due to the spinning tyre. The second mechanism, which is called 'air pumping', was introduced by Hayden in general terms in 1971 [2]. This term is used to describe the air being squeezed out of a cavity or groove when the tread hits the road surface (at the leading edge) and being sucked in again when the tyre lifts of the road surface (at the trailing edge). Another well-known effect for grooved tyres is the groove resonance, which is being initiated by the road closing the groove at the contact patch and therefore forming acoustic pipes. When the tyre rotates further and the tread lifts off the road surface, another mechanism comes into play, the 'air resonant radiation'. Introduced by Nilsson et al. [5] in 1979, it is a resonance where the air rushing back into the tread forms a spring–damper-mass system with the air underneath the tread. In the research reported in this paper only air-related phenomena due to cavities in a tyre are considered. Note that there are also parallel investigations with a slick tyre and cavities on the road, as shown by Hamet et al. [6], for instance.

More specifically, in this paper, the 'air pumping' and 'air resonant radiation' mechanisms are examined experimentally using a cavity in a solid rubber tyre. The next section of the paper describes the existing theoretical understanding of these mechanisms. In Section 3, the specially designed tyre/road noise generation rig is described and the measurement method outlined. The resulting measurements made with this rig are analysed in Section 4. 'Air pumping' and 'air resonant radiation' mechanisms are identified and experimental results are compared to the theoretical models presented in Section 2. Finally, Section 5 summarises the main findings of the research.

2. Existing models of air-related noise generation mechanisms

The initial air pumping mechanism introduced by Hayden [2] in 1971 is based on the formula of an acoustic monopole, where the generated pressure p can be predicted by:

$$p = \frac{\rho \cdot \ddot{V}}{4\pi \cdot r}. \tag{1}$$

Here ρ is the mass density of the air, $\ddot{V}$ is the second time derivative of the volume displaced out of the cavity. The notation r is used for the distance of the measurement point to the contact

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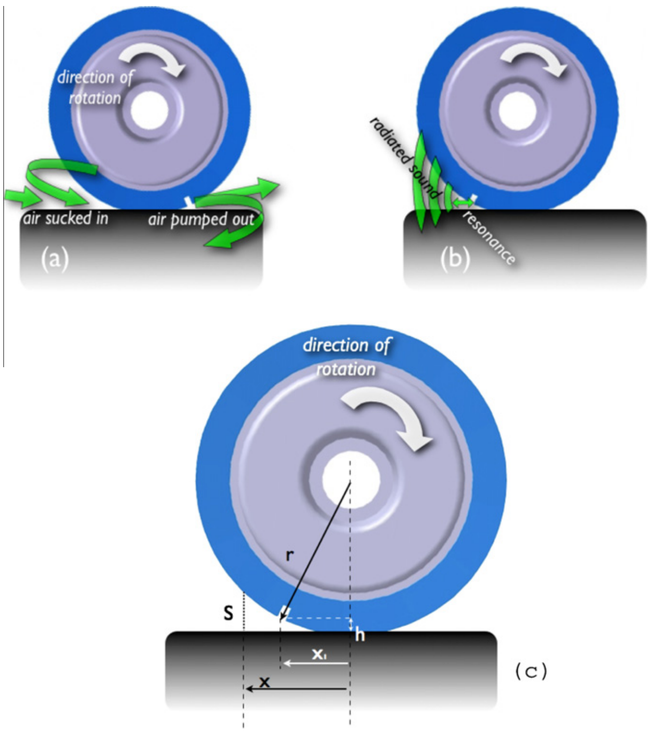

Fig. 1. Schematic illustration of the air-related effects: (a) air pumping mechanism: air is pumped out at the leading edge (right-hand side of the tyre) and sucked in at the trailing edge (left-hand side of the tyre) as the tyre groove passes the contact patch; (b) air resonant radiation: occurs at the trailing edge of the tyre; (c) on the explanation of the variables in Eq. (3).

patch. Hayden [2] assumes that at the leading and trailing edges, due to the air movements, as shown in Fig. 1a, a monopole-like sound field is generated. He then modifies Eq. (1) by incorporating the tyre tread periodicity to predict the sound pressure level at a given frequency of repetition.

A different approach regarding the air pumping mechanism was carried out by Gagen [7] in 1999. Gagen argues that Hayden's model is not suitable for the effect of air being pumped out at the leading edge of the tyre because the simplicity of the monopole model does not reflect the complex air squeezing process at the tyre/road interface. His assumption is that the air responds sluggishly to local volume changes, in a similar manner to a damped oscillator, while the monopole theory equates local air movements exactly with the volume changes of the system. According to Gagen, the kinetic energy of air expelled from a linearly squeezed groove is

$$E = \frac{\rho \cdot w \cdot A^3 \cdot l^3 \cdot v^2}{2\left(1 - \frac{A}{d_0}\right) d_0^4}, \tag{2}$$

where the vehicle forward speed is defined as v and the groove parameters are width l, length in circumferential dimensions d_0 and depth w. The variable A is defined by Gagen as the new length of the cavity when it is fully compressed.

The second air-related noise phenomenon for a tyre rolling over a road is the Helmholtz resonance or 'air resonant radiation'. In 1979, Nilsson et al. [5] identified this mechanism and proposed a model to describe it mathematically. According to reference [5], this noise source can be the dominant one in specific cases. As illustrated in Fig. 1b, the air resonance radiation only occurs at the trailing edge of the tyre as it is initiated by the tread groove or cavity leaving the roads surface. The acoustic signal, which is generated by the resonance radiation, is generally described in the form of a decaying swept sine wave. When the cavity leaves the road, a high amplitude sound of medium frequency is emitted. As the cavity proceeds further away from the contact area, the frequency rises whilst the amplitude decays. The model that Nilsson developed is for the determination of the frequency content only and does not predict the amplitude of the sound. It is based on a simple mass, spring and damper system, where the air surrounding the cavity is seen as the mass and the volume of the cavity acts as the spring and damper. With these assumptions, Nilsson et al. [5] derives the following expression to determine the frequency as a function of the position of the cavity in respect to the road surface:

$$\frac{V_0}{s_1 x_1} = \frac{1 + (kx_1)^2}{\beta (kx_1)^2 \cdot \left(1 + \left(\frac{\gamma k x_1}{2\beta}\right)^2\right)} - \frac{1 - \frac{kx_1}{\tan(kx_1)}}{(kx_1)^2}. \tag{3}$$

In this equation, k is the acoustic wavenumber. The rectangular area $S(x)$ of the air gap between the tyre and the road surface is illustrated in Fig. 1c. For the distance of the cavity from the trailing edge of the contact patch the variable x_1 is used. In Eq. (3), $s_1 = s_1(x_1) = (x_1^2/2r)W$ is the area of the rectangle formed by the gap between the groove/cavity at a height $h = (x_1^2/2r)$ above the road surface and by the width of the tyre W, where r is the tyre radius [5]. The volume of the cavity is noted as V_0. In addition, two further variables are introduced: β and γ. The values for these are adjusted empirically to account for the sideways opening of the 'acoustic horn' between the tyre and the road surface and account for the mass and the resistive impedance respectively. The Eq. (3) is used to compute the changing frequency of the sound via the wavenumber, with respect to the distance x_1.

3. Experimental setup and measurement method

Fig. 2 shows a schematic picture of the experimental rig. Only a half of the chassis dynamometer (for one tyre) was used for the experiments. The other half was fully covered by a thick wooden plate $100 \times 100 \times 3\ \text{cm}^3$ to minimize the overall noise generated by the driving mechanism of the dynamometer. In the centre of the rig, a metal frame is shown, which supported the roller that rested on one drum of the chassis dynamometer. The tyre's supporting structure was mounted on the left-hand side only, with large bolts and rubber insulation. On the right-hand side of the metal frame there was a possibility to attach weights to load the tyre. The frame design itself was inspired by a design presented by Graf et al. [8].

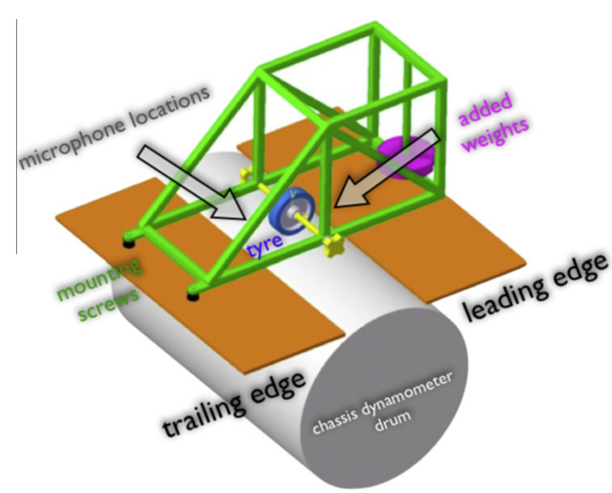

Fig. 2. Tyre mounted onto the chassis dynamometer with the two microphones (grey arrows) facing the leading and the trailing edge.