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Theoretical Analysis on Influences of Road Porosity on Tire Pumping Noise Using Simple Pulsation Model

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ABSTRACT

Drainage pavement can reduce tire pumping noise. However, it has a disadvantage of high cost of construction and maintenance. To solve this problem, clear understanding of the true function of drainage pavement against pumping noise is necessary. As the pumping noise is caused by pulsation phenomenon in which air flows in and out from grooves due to their deformation, drainage pavement should reduce energy of this pulsation phenomenon or its acoustic radiation efficiency. According to the author's past study, the amount of the groove deformation and the pulsating air flow rate on air-tight road surface can be simulated using finite element method. In this study, drainage pavement was expressed by homogeneous media that allows sound propagation from the bottom of a tread groove. The specific acoustic impedance of this drainage pavement was adopted from conventional acoustic experiment data. Other elements controlling pumping action, such as volumetric spring action and wall flow resistance are modelled using thermodynamics and fluid dynamics theories. All these elements are placed as impedances in an equivalent electric circuit that distributes the forced air flow from the source i.e., the groove deformation, to the other elements. Using this model, we can calculate the air flow distribution and dissipation easily using simple Kirchhoff's theory. The calculated results show the pulsating air flow due to the groove deformation escapes into the drainage pavement. The estimated pumping noise reduction generally agreed with the experimental results.

Keywords: Tyre, Pumping noise
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

Drainage pavement can reduce tire pumping noise.(1) However; it has a disadvantage of high cost of construction and maintenance. To solve this problem, clear understanding of the true function of drainage pavement against pumping noise is necessary. As the pumping noise is caused by pulsation phenomenon in which air flows in and out from grooves due to their deformation, porous pavement should reduce its acoustic radiation efficiency. According to the author's past study(2), the amount of the groove deformation and the pulsating air flow rate on air-tight road surface can be simulated using finite element method.

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Therefore, the objectives of this study are; 1) To know why porous pavement can reduce tyre pumping noise. 2) To know what physical indices of porous pavement control the noise reduction. 3) To know how much can we expect or cannot expect to porous pavement in noise reduction. And 4) To obtain the simplest method of getting answers to the above issues.

In this study, drainage pavement was expressed by homogeneous media that allows sound propagation from the bottom of a tread groove. The specific acoustic impedance of this drainage pavement was adopted from conventional acoustic experiment data. Other elements controlling pumping action, such as volumetric spring action and wall flow resistance are modelled using thermodynamics and fluid dynamics theories.

2. GENERATION PROCESS OF PUMPING NOISE AND ITS WAVEFORM, FREQUENCY RANGE, RELATIONSHIP WITH TIRE DIMENSIONS

2.1 Volumetric change of lateral grooves at the top/tail edges of road contact patch

The source of the pumping sound is the action of forcibly moving the air inside the groove as the tire groove deforms. The grooves widen for a short time just before the tire is grounded, and their width narrows after full contact with road surface. The depth of those grooves shallow immediately after contacting road, then it maintains the shallow depth till the end of road contact. These process was studied by the author (2) both experimentally and numerical structural analysis. For typical passenger car tyre having dimensions as 205/15/60 with 200kPa inflation pressure, the amount of groove volume changes were such figures as below. (Fig.1) Here we need to be aware that the excitation is not the groove volume change itself, but its rate of change over time. In other words, volume flow entering and exiting the groove is the excitation.

2.2 Waveform of the Air Motion Pumped by the Groove Volumetric Change

As mentioned above, the air flow in the groove occurs in two short time sections, beginning and end of tire-road contact. As a result, the time fluctuation of the air flow entering and exiting the groove has a waveform as shown in the Fig.1. Here, let us set the vehicle speed at around 20 [m/s] at which tires cause noise problems.

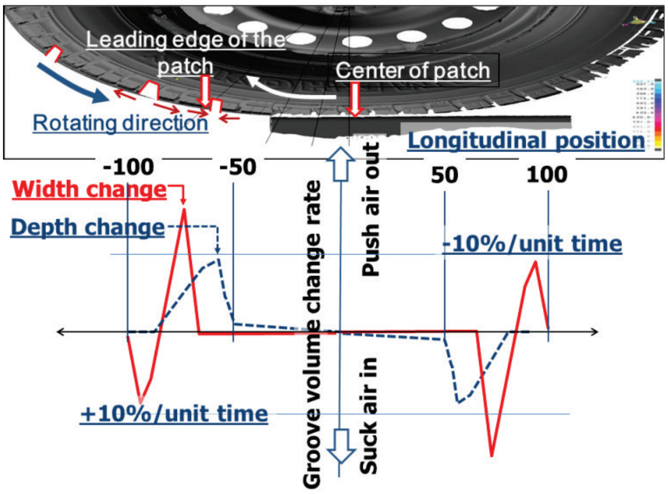


Fig.1 Forced volumetric airflow caused by a groove deformation

2.3 Magnitude of Volumetric Flow Forced by Groove Deformations

The symbols used here are; *H, W, L*: groove depth[m], width and length. V_G: groove volume, dV_{GW} and dV_{GD}: groove volume increment [m^3] by width change and depth change, respectively. In this example dV_G= 8x10^{-5} [m^3/s]=0.08[L/s] is its amount per one lateral groove.

Measured volumetric changes

$$V_G = HWL = 10\times10\times50\left[\text{mm}^3\right] = 5\times10^{-4}\left[\text{m}^3\right]$$

$$dV_G = dV_{GW} + dV_{GD}$$

$$dV_{GW} \approx 0.12V_G = 6\times10^{-5}\left[\text{m}^3\right], dV_{GD} \approx 0.09V_G = 4.5\times10^{-5}\left[\text{m}^3\right]$$

Let the vehicle speed $\upsilon = 20[m/s]$

Then, the maximum volumetric air flow i_g

and flow velocity at the groove end $u_g\big|_{\max}$ are

$$i_g\big|_{\max} \approx 8\times10^{-5}\left[\text{m}^3/\text{s}\right],\quad u_g\big|_{\max} \approx 4\left[\text{m/s}\right]$$

2.4 Frequency Range of Volumetric Flow Forced by Groove Deformation

As transition distances around the leading and trailing edges of tire-road contact patch are short, the wavelengths of the air motion waveform are short in time. Accordingly, the relevant frequency range of this air motion is around 1 kHz.

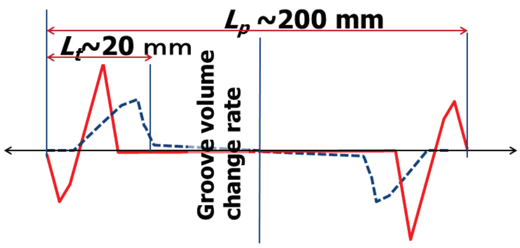


Fig.2 Wavelength of groove volume change

Let the vehicle speed $\upsilon = 20[m/s]$, then

The time durations in which tread travels one transition zone $L_t : T_t$

$$T_t = L_t/\upsilon \approx 0.2/20 = 0.01[s],\ f_p = 1/T_t = 1\,\text{kHz}$$

3. CONVENTIONAL KNOWLEDGE ON THE NATURE OF PAVEMENT POROSITY AND ITS RELATIONSHIP WITH NOISE REDUCTION

3.1 Sound Absorption as a Compromised Substitute Index of Water Drainage

The drainage performance of pavement is officially evaluated at the water draining speed. However, sound absorption rate is used as a substitute characteristic of drainage performance for measurement at a road site (3). Although this is a convenient method, correlation with drainage performance is not necessarily high. The reason for this should be that the drainage performance is dominated by the resistance of waterways in the vertical direction, while the sound absorption rate is not so. In spite of such inconsistency, some people assume that the reason of drainage pavement's ability of tire noise reduction is its sound absorption characteristic.

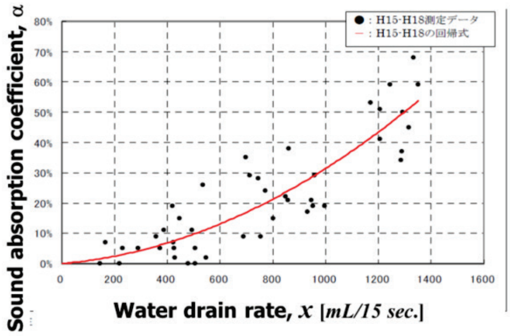


Fig.3 Correlation of sound absorption and drainage of porous pavement [3]

3.2 Measured Acoustic Properties of Porous Asphalt and Noise Reduction

In order to clear up the above misunderstanding, Prof. Iwase measured the acoustic impedance of drainage pavement and compared it with tire noise reduction characteristics [4]**.** According to the results of his study, in the case of typical drainage pavement specification with a pebble having average diameter of 10 mm, and 43 mm layer depth, the real part of the impedance around 1 kHz is three times that of the atmosphere. (Fig.4)

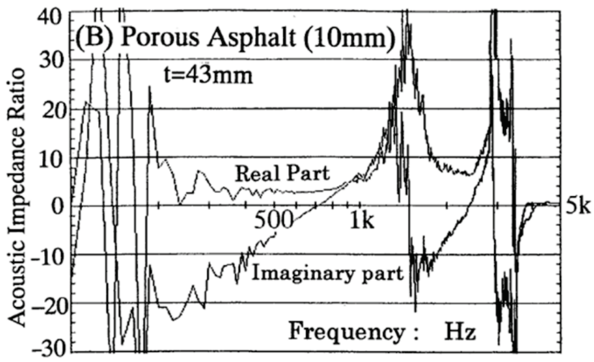


Fig.4 Measured acoustic impedance of typical porous pavement

The tire noise reduction effect by this pavement showed 6 dB or more in the high frequency region above 1 kHz. In other words, additional effect of 4 dB or more is observed than 2 dB which is the sound absorption effect.

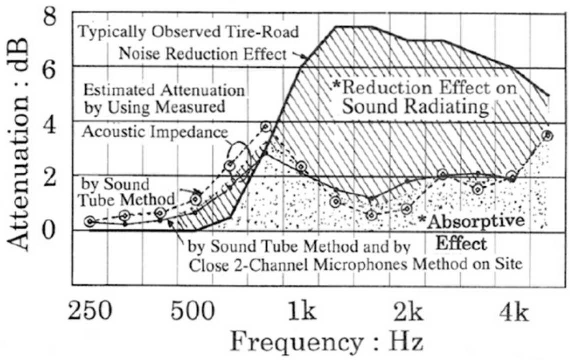


Fig.5 Typical measured tire noise reduction

4. EQUIVALENT ELECTRIC CIRCUIT OF PUMPING NOISE GENERATION PROCESS

4.1 From Groove Deformation to Wave Propagations into Air and Pavement

As a tire noise reduction effect of drainage pavement other than sound absorption characteristics, the author considered the hypothesis that the cause is the reduction of the amplitude of air pulsation coming in and going out from the end face of the groove. To illustrate this hypothesis, the author modelled how air volumetric flow fluctuations caused by compression and expansion due to groove deformation propagate, as shown in Fig.6. Here, porous pavement is modelled as a medium which leaks a part of the air flowing only on the end face of the groove in the case of dense asphalt-concrete pavement. Drainage pavement has a very complicated shape when viewed microscopically. However, compared with the wavelength of sound wave of about 1 kHz, its complicated shape can be neglected. Therefore, it was treated as a medium with uniform properties in this study.

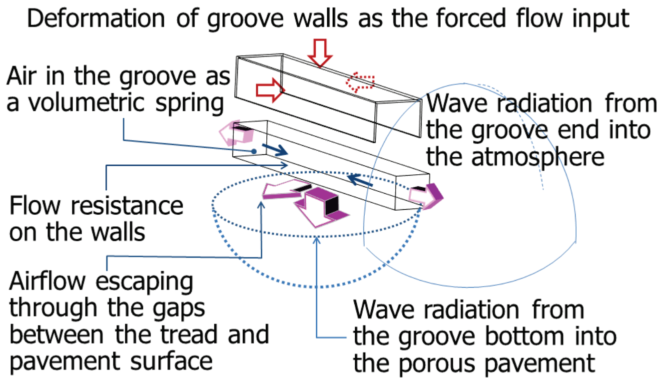
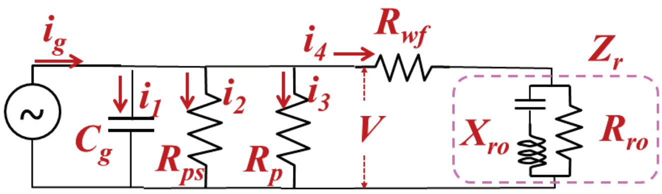


Fig.6 Air motion originating from groove deformation to acoustic radiation

4.2 Relationships of Flows and Potentials in the Equivalent Circuit

Based on the consideration using fluid dynamics and acoustics as above, we devised an equivalent circuit of the pumping sound generation process [5]. (Fig.7)



i_g : Forced volumetric flow input
i_1, i_2, i_3, i_4 : Volumetric flows into each element
V: Air pressure in the groove
C_g : Compliance of groove air volume
R_{ps} : Airflow resistance of the tread/pavement gaps
R_p : Real part of porous pavement acoustic impedance
R_{wf} : Airflow resistance of the groove walls
R_{ro}, X_{ro} : Real & Imaginary parts of radiation impedance *Zr* at the groove end

Fig. 7 Equivalent electrical circuit of pumping noise generating system

As can be observed from the circuit diagram, the air in the groove, drainage pavement and clearance between the tread and the road surface act as a branch of the air flow. Using the Kirchhoff's law, we made an equation with the flow rate of air flowing in each circuit element and the pressure inside the groove as unknowns.

$$i_1 + i_2 + i_3 + i_4 = i_g$$
$$\int \left(i_1 / C_g \right) dt = \mathrm{V}, \quad i_2 R_{ps} = V, \quad i_3 R_p = V, \quad i_4 \left(R_{wf} + Z_{ro} \right) \approx V$$

$$i_g = I_g e^{j\omega t}, i_m = I_m e^{j\omega t} \; m = 1 \cdots 4$$
$$\begin{bmatrix} 1 & 1 & 1 & 1 & 0 \\ 1/j\omega C_g & 0 & 0 & 0 & -1 \\ 0 & R_{ps} & 0 & 0 & -1 \\ 0 & 0 & R_p & 0 & -1 \\ 0 & 0 & 0 & R_{wf} + Z_{ro} & -1 \end{bmatrix} \begin{Bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ V \end{Bmatrix} = \begin{Bmatrix} I_g \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix}$$

4.3 Theoretically Derived Properties of Elements in the Equivalent Circuit

Let's express the values of each element in the circuit diagram using the theory of thermodynamics and fluid dynamics.

4.3.1 Volumetric flow supplied to the groove end that radiates pumping noise

As shown in the last equation below, the air flow rate flowing into the groove terminal is governed by the product of the series combination of the flow resistance R_{wf} of the groove and the acoustic radiation impedance Z_{ro} at the terminal and the total mobility G_{total} of the entire circuit.

$$I_1 + I_2 + I_3 + I_4 = \left(j\omega C_g + \frac{1}{R_{ps}} + \frac{1}{R_p} + \frac{1}{R_{wf} + Z_{ro}} \right) V = I_g$$
$$j\omega C_g + \frac{1}{R_{ps}} + \frac{1}{R_p} + \frac{1}{R_{wf} + Z_{ro}} = G_{total} : \text{Total circuit mobility}$$
$$\text{Pressure in the groove} : V = \frac{I_g}{G_{total}}$$
$$\text{Volumetric air flow to the groove end} : I_4 = \frac{I_g}{\left(R_{wf} + Z_{ro} \right) G_{total}}$$

4.3.2 Groove volumetric spring stiffness

Since the groove on the tread has a small volume, its volume spring constant [6] is much larger than the acoustic radiation resistance to the atmosphere.

$$\text{Adiabatic compression} \quad \triangle P = \left(\gamma P / V_{groove} \right) \triangle V_{groove}$$
$$\text{Groove volumetric spring stiffness} : 1/C_g = \gamma P / V_{groove}$$
$$\gamma = 1.4, P \approx 100 \mathrm{kP}_a, V_{groove} = 5 \times 10^{-6} \left[\mathrm{m}^3 \right]$$
$$\frac{1}{C_g} \approx \frac{1.4 \times 1 \times 10^6}{5 \times 10^{-6}} = 0.28 \times 10^{12}, C_g \approx 3.6 \times 10^{-12}$$
$$For\ f = 1kHz, \quad \frac{1}{\omega C_g} \approx \frac{1}{2\pi \times 10^3 \times 3.6 \times 10^{-12}} = 4.4 \times 10^7 \gg \rho c \left(\approx 420 \right)$$

4.3.3 Groove wall flow resistance estimation

Acoustic impedance due to the groove flow resistance is proved to be small enough to be neglected as calculated below [7].

Pressure drop $\triangle P = \lambda \rho u^2 / 2d$

ρ: air density=1.25 $\left[kg/m^3\right]$, u : flow velocity $\approx 4\left[m/s\right]$

d : tube diameter $= 0.01[m]$

$$R_e : \text{Reynolds number} = \frac{ud}{\nu} \approx \frac{4\times 0.01}{1.42\times 10^{-5}} = 2.8\times 10^3$$

$$\lambda : \text{flow resistance coefficient} \approx \frac{64}{R_e} \approx \frac{64}{2.8\times 10^3} = 0.023$$

Acoustic impedance of the tube :

$$z_t = \frac{d\triangle P}{du} = \frac{\lambda \rho u}{d} \approx \frac{0.023\times 1.25\times 4}{0.01} = 11.5\left[P_a s / m\right]$$

4.4 Measured Airflow Resistance of the Tread/Pavement Gaps

4.4.1 Estimation of gap area between tread and pavement surface from contact pressure distribution and pavement surface texture.

As shown in Fig.8, there are many gaps between the tread and the road surface [2]. However, most of the continuous length of the gap is less than 10 mm. Therefore, it can be expected that the probability of air flowing out from the groove on the tread through these gaps is low.

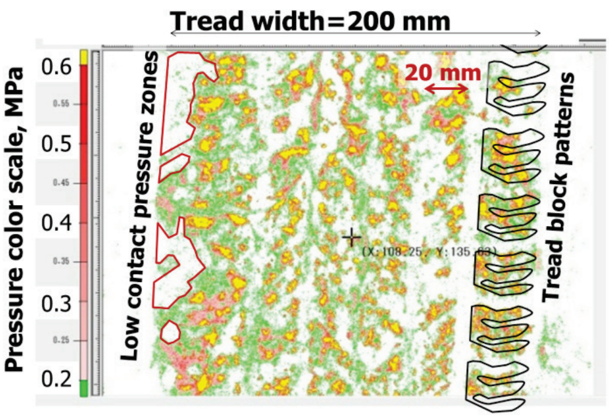


Fig.8 Gap area estimation from contact pressure distribution on a patch

4.4.2 Measurement of flow resistance as the gap acoustic impedance

It is difficult to predict the air flow passing through the clearance between the tread and the road surface only from the geometrical road surface shape. So we measured the magnitude of resistance against the air flow through these gaps using a simple experimental setup. (Fig.9). A cylindrical suction mouth was placed so that its edge is in contact with the road surface. The width of the suction mouth edge was set at 2 levels; i.e., 1 mm and 25 mm. The air was sucked by a vacuum cleaner. The pressure drop was measured by a manometer. The air flow quantity was measured with an large plastic bag.

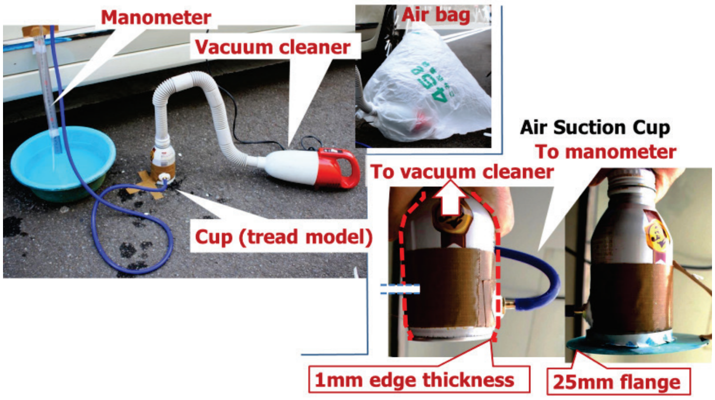


Fig.9 Equipment for measuring resistance to airflow through gaps on pavement surface

Measured airflow resistance of the tread/pavement gaps:

$$R_{ps} = \frac{V}{I_2}$$

Measured *values* :

$$\text{for thin edge cup:} R_{ps} = \frac{1.5kPa}{2.25\times10^{-3}\left[m^3/s\right]} = 0.67\left[MPas/m^3\right]$$

$$\text{for flanged cup: } R_{ps} = \frac{1.6kPa}{0.22\times10^{-3}\left[L/s\right]} = 7.3\left[MPas/m^3\right]$$

For comparison with other specific impedances, normalize these values by dividing with suction area of 3x10^{-3}[m^2].

$$\text{for thin edge cup:} R_{ps}\big|_{norm} = \frac{0.67}{3\times10^{-3}} = 220\left[MPas/m\right] \gg \rho c_{atmosphere}$$

$$\text{for flanged cup:} R_{ps}\big|_{norm} = \frac{7.3}{3\times10^{-3}\left[L/s\right]} = 2430\left[MPas/m\right] \gg \rho c_{atmosphere}$$

The measured resistance of this suction cup was much larger than the other impedance values in the equivalent circuit. Therefore, leakage through the gaps can be neglected.

4.5 Influence of Pavement Impedance to the Pulsation at the Groove Opening

As a result of the examination so far, it turned out that most of the elements in the equivalent circuit can be neglected. The remaining elements are the acoustic radiation resistance to the inside of the drainage pavement and to atmosphere from the groove end. Both were modelled as acoustic radiation due to the motion of a rectangular piston fitted in a baffle (8, 9).

In comparing the two, it is necessary to be aware of the following differences.

1) Sound velocity in drainage pavement is about 30% of sound speed in the atmosphere. This will increase the wave number during drainage pavement by approximately 3 times.

2) Since the input is volume flow, the larger the piston area becomes, the more it can suck air flow and can lower the impedance. In other words, the effect of drainage pavement on long grooves will increase.

3) The sizes of the sound radiation surface in both cases are extremely small compared with the wavelengths of the sound waves.

$$G_{total} = j\omega C_g + \frac{1}{R_{ps}} + \frac{1}{R_p} + \frac{1}{R_{wf} + Z_{ro}}$$

$$\omega C_g, \frac{1}{R_{ps}} \ll \frac{1}{R_p} + \frac{1}{R_{wf} + Z_{ro}}, R_{wf} \ll Z_{ro}$$

$$G_{total} \approx \frac{1}{R_p} + \frac{1}{Z_{ro}}$$

In this specific case; $\frac{1}{R_p} \approx \frac{1}{Z_{ro}}$

$$\rightarrow G_{total} \approx 2 \times \frac{1}{Z_{ro}}$$

Porous pavement reduces acoustic radiation from groove end to half.

As a result, the impedance of the porous pavement in the equivalent circuit has almost the same amount with that of the radiation impedance at the groove end opening. This means typical porous pavement can reduce acoustic power of pumping noise about to half of that would be used in pumping noise radiation, or by 3dB in short.

5. CONCLUSIONS

1. Typical porous pavement reduces the air pulsating motion at the groove end opening up to a half of dense asphalt pavement.

2. Groove volume plays only a small role as a passive element in pumping action, but it is almost proportional to generate volumetric air flow at the origin.

3. Airflow through gaps between tread and pavement surface do not have much influence to pumping noise generation.

4. Clogging of porous pavement may be modelled as higher acoustic impedance than that of fresh one.

6. ACKNOWLEDGEMENTS

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