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A study on the mechanism of tire/road noise

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Abstract

This paper describes the mechanism of generating tire/road noise, which contributes very much to the vehicle exterior noise, by dividing the factors of the tire/road noise into exciting force, vibration characteristics and acoustic radiation characteristics. In addition, it shows the effectiveness of suppressing the distinctive tread vibration mode, which is the main mode of vibration radiating noise of around 1 kHz with a high sound pressure level in radial tires for passenger cars.

1. Introduction

In order to reduce vehicle exterior noise generated from automobiles, it is necessary to establish steady countermeasures for the respective factors composing the noise. Even under accelerating conditions, the tire/road noise represents the largest percentage of noise, after engine noise, as shown in Fig. 1. Consequently, reduction of the tire/road noise is a very important issue.

It is pointed out that the effects of roughness of road surface [1], effects of exciting force due to patterns such as lug grooves in the tread surface [2], effects of driving torque of tires under an accelerating period [3], etc. are considered as the exciting forces generating the tire/road noise. Generally, when the noise problems of mechanical structures are considered, suppression of vibration at the responding parts having a wide area is effective, as well as reduction of such exciting forces. In the case of tires, radiation of sound from the tread surface seems strong because the area of the tread surface keeping in contact with the road surface is wide. In this paper, the mechanism of generating the tire/road noise in radial tires for passenger cars is studied, especially taking notice of this tread surface as a dominant vibration system.

2. Characteristics of tire/road noise

2.1. Effects of tread pattern

In commercially available tires for passenger cars, tread patterns formed on tread surfaces for drainage have an unequal pitch arrangement in the circumferential direction of the tires, as shown in Fig. 2. This aims at dispersing the pattern noise synchronized to the interval between neighboring patterns, from the pure tone sound, which is offensive to the ear, into sound of a wide frequency range, which is less offensive to the ear, by changing the interval between the neighboring patterns as shown in Fig. 3. For example, under the condition of a car speed of 50 km/h,

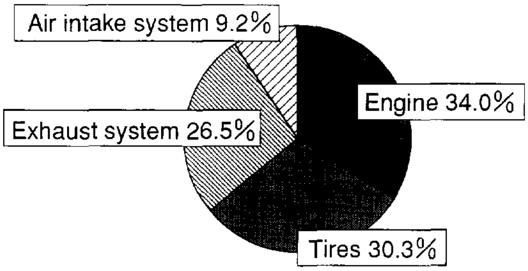

Fig. 1. Breakdown of noise source.

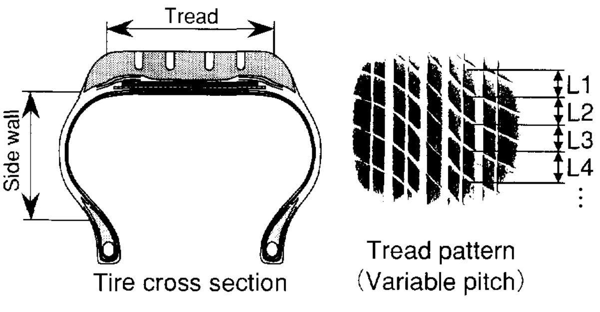

Fig. 2. Variable pitch of tire tread pattern.

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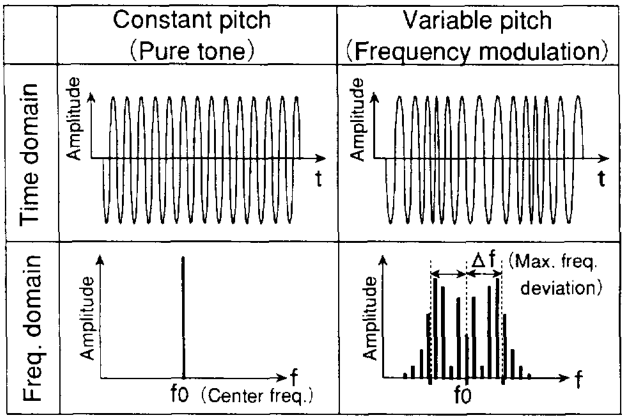

Fig. 3. Frequency-modulation due to pattern pitch [5].

the sound synchronized to the first-order component of the pattern having a central frequency of 500 Hz is dispersed into the frequency range from 400 Hz to 600 Hz, and the sound synchronized to the second-order component of the pattern is dispersed into the frequency range from 800 Hz to 1.2 kHz. Consequently, if the frequency component synchronized to the tread patterns is to be identified, it is necessary to take a wide frequency range into consideration instead of a single frequency.

In order to investigate the effect of the tread pattern on the tire/road noise, the noise spectrum of a smoothed tire, whose tread blocks were removed to smooth the surface, was compared with an original tire under the coasting condition without driving torque, as shown in Fig. 4. It is found that the sound pressure level depends upon the roughness of the road surface. In the case of the experiment conducted on a chassis dynamometer (called C/D hereafter) having a smooth surface, the sound pressure level of the smoothed tire was lowered remarkably in the frequency range from 400 Hz to 600 Hz, which seems to correspond to the first-order component of the tread pattern, and in the frequency range from 800 Hz to 1.25 kHz, which seems to correspond to the second-order component of the tread pattern. However, in the case of the experiment conducted on the actual pavement, the sound pressure level rose as a whole in the frequency range having a center frequency of about 1 kHz, compared with the case on C/D. Furthermore, it is remarkable that the sound pressure level of the smoothed tire is higher than that of the original tire in the frequency range above 1 kHz, contrary to the case on C/D.

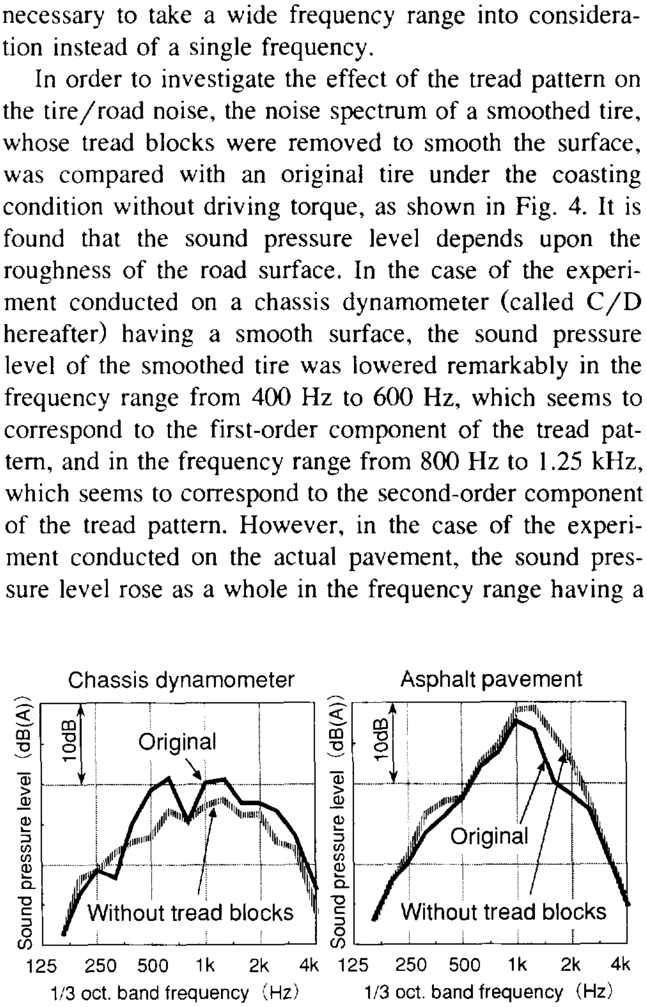

Fig. 4. Tire noise spectrum (50 km/h).

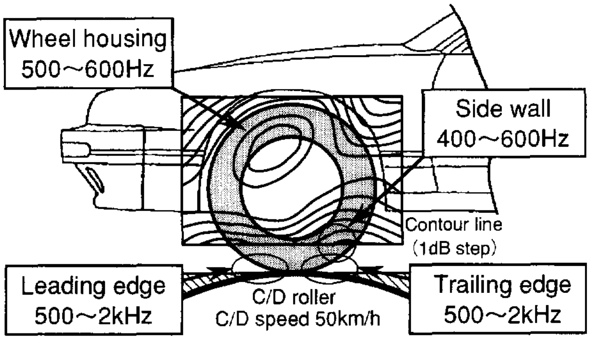

Fig. 5. Contour map of sound intensity level.

It is found from these results that the tire/road noise depends not only upon the exciting force due to the tread pattern and the roughness of the road surface, but also largely upon the structure of the tire, such as thickness of the tread blocks.

2.2. Noise generating portions of tire

Noise generating portions of the tire attached to a car were measured and investigated under the coasting condition without driving torque on C/D. As a result, four noise generating portions are identified from the contour map of sound intensity level shown in Fig. 5.

The first portion is the side wall area right above the trailing edge near the contact area of the tire. The vibration of this area was measured by using a laser displacement meter. This vibration is synchronized with the first-order component of the tread pattern of 400 Hz to 600 Hz.

The second portion is the leading edge area, which radiates the sound in a wide frequency range from 500 Hz to 2 kHz. In particular, the components of 800 Hz to 1.6 kHz are largely contributory to the noise in spite on C/D, despite having a smooth surface.

The third portion is the trailing edge area, which radiates sound having the same frequency range as that of the leading edge area, but having a slightly higher sound pressure level than that of the leading edge area.

The fourth portion is the upper area of the wheel housing, which radiates sound of frequency from 500 Hz to 600 Hz. It seems that a sound resonance system formed between the wheel housing and the road surface is excited by the main sound sources, composed of the same frequency components as those of noise radiated from these three areas, and the loop of the natural mode acts as an apparent sound source.

It was found that for the sound radiating areas of the tire, the sound corresponding to the first-order component

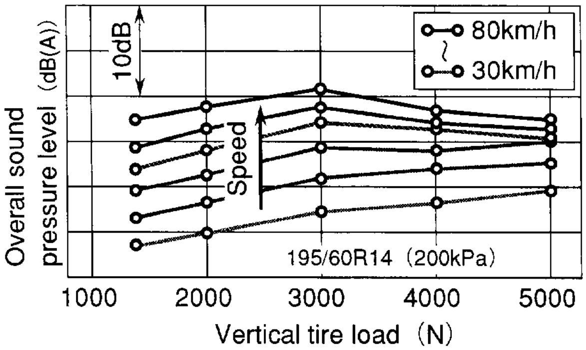

Fig. 6. Changes of tire noise due to tire load and speed.

of the tread pattern of 400 Hz to 600 Hz is radiated mainly from the side wall area of the tire, and the sound of 800 Hz to 1.6 kHz, including the second-order component of the tread pattern, is radiated mainly from the leading edge area and the trailing edge area, i.e., the tread surface.

2.3. *Factors affecting tire / road noise*

Effects of tire speed, vertical tire load, inflation pressure and driving torque on the tire/road noise were measured on C/D and the results are discussed.

The sound pressure level rises with the increase of the tire speed and the vertical tire load in general as shown in Fig. 6. However, there is also a tendency of the sound pressure level to show a peak value at a certain value of vertical tire load (3000 N in the figure) as the tire speed increases. By investigating the frequency factors of this peak, it was confirmed that change of the sound pressure level in the frequency range from 800 Hz to 1.6 kHz greatly affects the peak value.

Measuring the effects of inflation pressure and driving torque, the sound pressure level rises with the increase of driving torque in general as shown in Fig. 7. It is found that change of the sound pressure level is large in the frequency range from 800 Hz to 1.6 kHz, which is similar to the case of the dependency on the vertical tire load. However, this tendency varies remarkably with the type of tire. For example, in some cases of high performance tires for sports cars, this driving torque dependency is low.

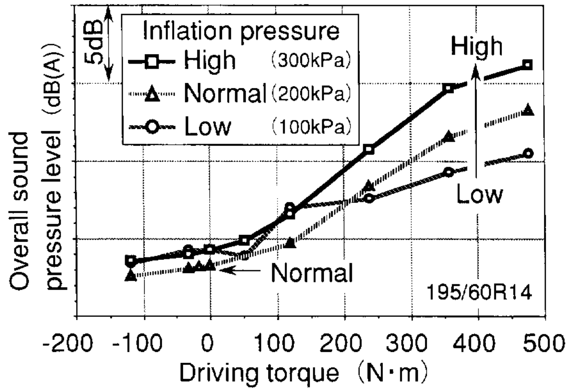

Fig. 7. Changes of tire noise due to driving torque and inflation pressure.

On the other hand, the effects of inflation pressure vary with the conditions of driving torque. Under the coasting condition without driving torque, in the region of 0 Nm in the figure, the sound pressure level shows the minimum value in the case of normal inflation pressure. However, with driving torque, the sound pressure level rises with the inflation pressure.

The sound pressure level varies depending upon the respective factors generated under the service conditions of the tire including the road surface roughness, and this variation usually occurs in a constant frequency band within the range from 800 Hz to 1.6 kHz. It is considered that this variation is due to the change of the sound radiated from the tread surface.

Consequently, it is considered that countermeasures for the tread surface vibration, which is most sensitive to the respective exciting forces, is effective for reducing the tire/road noise.

3. Vibration characteristics of tire

3.1. *Excitation test*

In order to understand the vibration characteristics of the tires, the inertance level (acceleration/exciting force) at the tread area (excitation point) and the side wall area were measured when the center of the tread surface is excited, as shown in Fig. 8.

It was found that the vibration level is high in the frequency range from 500 Hz to 800 Hz at the side wall area, and in the frequency range over 800 Hz at the tread area. Thus, the main frequency ranges of sounds radiated from the side wall area and the tread area are different.

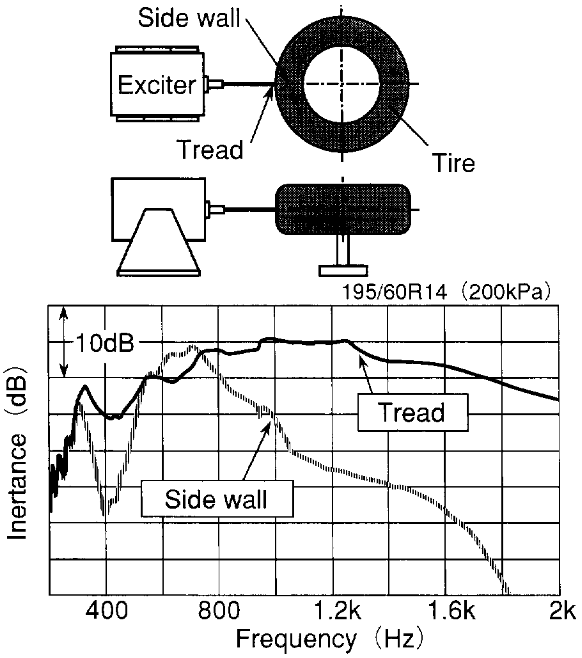

Fig. 8. Dynamic characteristic of tire vibration.

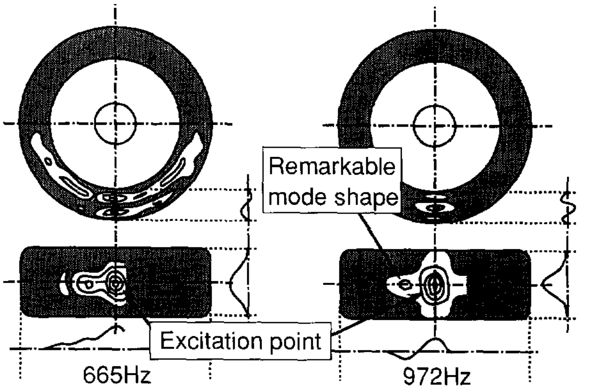

Fig. 9. Vibration analysis by holography.

In addition, it is estimated that the reason why the sound pressure level of the tire without tread blocks rose in the frequency range over 1 kHz on the actual pavement, as shown in Fig. 4, is the rise of the vibration level from excitation by the road surface roughness because of the reduction of dynamic stiffness of this tread surface area.

3.2. Measurement of vibration mode

In order to understand the vibration mode shapes at the tread surface area and the side wall area of the tire in detail, vibration mode shapes were measured by the holographic interferometry method, as shown in Fig. 9, under the same conditions as the excitation test shown in Fig. 8.

By observing the interference fringes representing the amplitude contour lines, it is found that the vibrating area at the side wall area shows a tendency to decrease in the frequency range over about 800 Hz. In addition, it is found that the vibrating area on the tread surface shows a vibration mode shape expanding longitudinally in the circumferential direction of the tire. The remarkable mode shape of an eye-like vibrating spot was generated in the neighborhood of the excitation point.

It is estimated that this eye-like vibrating spot is generated at the position just before the leading edge and right after the trailing edge when the tire comes in contact with the road and rotates. It is considered that the volume velocity of the air caused by this vibration is a direct cause of the sound radiated from the tread surface for either exciting force due to the above-mentioned factors.

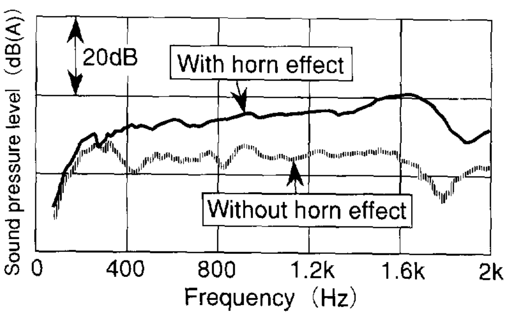

Fig. 11. Experimental data of horn effect.

4. Sound radiation characteristics of tire

It is pointed out that a horn-shaped semi-closed space formed between the tread surface and the road surface, as shown in Fig. 10, amplifies the sound pressure level [4].

This phenomenon called "horn effect" has such a characteristic that vibration at the throat area is converted efficiently into sound power in the frequency range over a certain value determined by the shape and size of the horn. In order to confirm this effect, a loudspeaker was buried in the road surface side in the neighborhood of the contact point of the tire and the road surface. When the sound radiated from the loudspeaker was measured under the conditions with a tire and without a tire, an amplification effect over 10 dB was observed in the frequency range over 300 Hz as shown in Fig. 11.

It is estimated that the sound pressure level will show the maximum value if the above-mentioned eye-like spot is located at the throat area of this horn. Thus, it is considered that the sound pressure level shows a peak value if the position of this eye-like vibrating spot changes, for example, depending upon the vertical tire load.

To confirm this hypothesis, a loudspeaker was buried in the central part of the tread surface of a tire, and variation of the sound pressure level radiated from the speaker according to its position was studied, as shown in Fig. 12. It is found that radiating efficiency of the sound radiation from the loudspeaker is the highest when its angular position is about 10° regardless of the position of the measuring microphone.

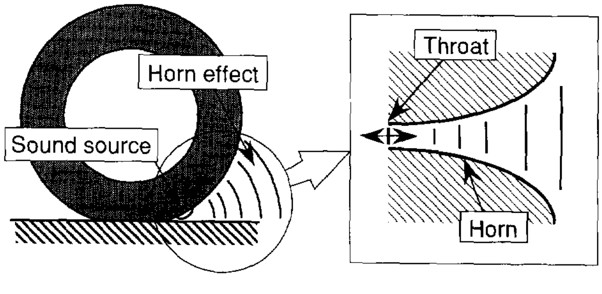

Fig. 10. Horn effect.

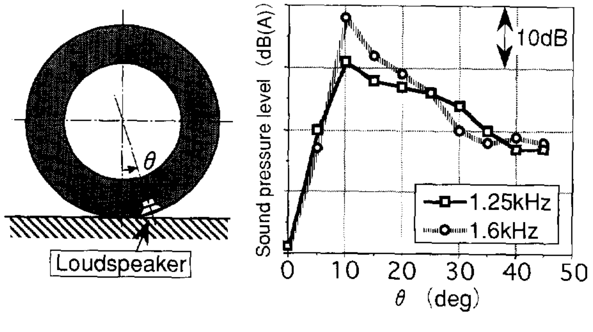

Fig. 12. Sound pressure level due to position of sound source.

5. Reduction of tire / road noise

5.1. Mechanism of tire / road noise generation

On the basis of the above results, it seems that noise generating mechanism of the tire for a passenger car is as follows:

First, in the case of a smooth road surface, the first- and second-order components of the tread pattern act as main exciting forces. Between them, the first-order component of the pattern excites the side wall area having low dynamic stiffness, in the frequency range from 500 Hz to 800 Hz, and makes the side wall radiate the sound outward directly. The second-order component of the pattern excites the tread surface area having low dynamic stiffness in the frequency range over 800 Hz, and generates the eye-like vibrating spots on the tread center part just before and after the contacting position of the tire and the road. Because this eye-like vibrating spot is generated in the neighborhood of the throat part of the horn existing in the sound radiating system, the noise is amplified and radiated outward.

Secondly, in the case of a rough road surface, the road surface roughness acts as dominant exciting force, and excites the tread surface in the frequency range from 800 Hz to 1.6 kHz. Then, the eye-like vibrating spot is generated and the sound amplified by the horn effect is radiated outward.

As the other exciting force, the tire driving force also makes the sound pressure level rise in the frequency range from 800 Hz to 1.6 kHz., although, harmonic excitation components which generate vibrations have not yet been confirmed. However, taking into consideration that the circumstances of generating noise differ greatly according to the types of tires for sports cars and popular cars, it is assumed that the tire/road noise depends also upon shapes of the tread pattern and its arrangement.

5.2. Reduction of noise by modifying the tire construction

In order to reduce the sound pressure level on the actual pavement, it seems effective to reduce the sound in the range from 800 Hz to 1.6 kHz radiated from the tread surface, and to suppress the vibration of the eye-like vibrating spot which causes the noise. On the basis of the inertance level in the case of exciting the center part of the tread shown in Fig. 8, it is estimated that the vibration in this frequency range is under the condition of over-damping, because of the strong damping of tire rubber. In this case, addition of a mass element seems effective to suppress the vibration.

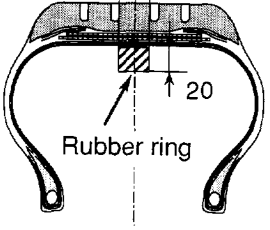

Fig. 13. Structure modification of tire.

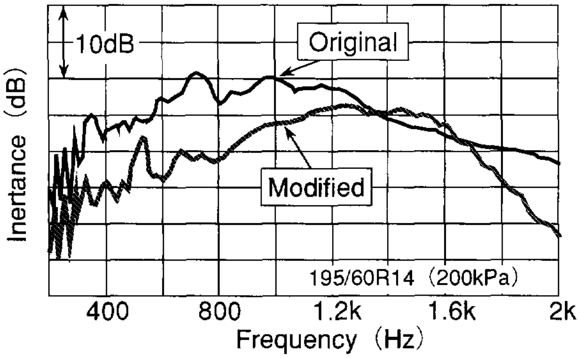

Fig. 14. Reduction of vibration where the eye-like vibrating spot is generated.

For this end, reduction of the noise was tried by local modification of the tire construction, by attaching a rubber ring on the inside surface of the center part of the tread surface, as shown in Fig. 13, aimed at reducing the vibration by the mass effect. In order to confirm the mass effect of the attachment of the rubber ring, the inertance level at the eye-like vibrating spot was measured in the same way, as shown in Fig. 8. It was confirmed that the amplitude of the eye-like vibrating spot can be reduced compared with the original tire as shown in Fig. 14. In addition, by evaluating the noise on the actual pavement, reduction of noise was obtained in the target frequency range of about 1 kHz, as shown in Fig. 15.

Although this modification of tire construction seems effective from the viewpoint of noise reduction, examination of its influence upon the performance of a car such as handling, ride comfort, fuel economy, and its manufacturing method are left as problems to be solved in future.

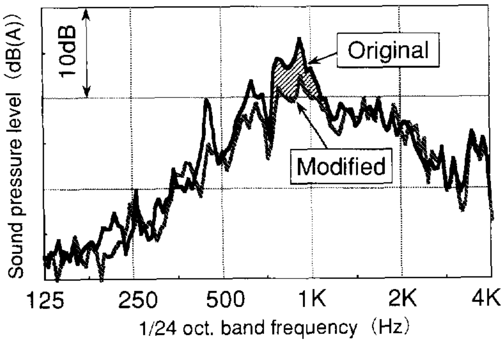

Fig. 15. Reduction of tire/road noise by structure modification (pavement).

6. Conclusions

Experimental analysis and discussions on the mechanism of noise generation of the tire for a passenger car produced the following conclusions:

(1) The dominant cause of the tire/road noise is the eye-like vibrating spot generated as vibration caused by the exciting force depending on the road surface roughness, the driving torque, etc.

(2) When this eye-like vibrating spot is exactly located at the throat of the horn effect area, the sound pressure level shows a maximum value.

(3) In order to reduce this noise, suppression of vibration at the central part of the tread, where the eye-like vibrating spot is generated, is effective. Thus, reduction of the noise can be achieved by local modification of the tire construction.

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