

Method of Experimental Identification of Change in Dynamic Characteristics of Rolling Tires

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ABSTRACT

Development of simulation technology for road noise while a vehicle is in operation has become an important issue. Because a fixed technological architecture has been established for simulation of the body and the suspension, the issue in realizing road noise simulation is how to accurately identify the force transmitted to the suspension through the tires and wheels by vibration input due to contact between the road surface and the tires. The issue here is that there are significant variations between static state characteristics, which are easy to measure, and vibration characteristics of tires in motion, which are challenging to measure. A variety of expertise regarding the sources of this discrepancy has been published. Among these, the effects of Coriolis and centrifugal forces resulting from the rolling motion are known. However, knowledge is still lacking in areas such as the specifics of how the input from the tires changes due to these fluctuations in characteristics. In this project, a simple method was proposed that makes it possible to verify fluctuations of transmission force in the range from 0 to 200Hz, using mass-production tires and wheels. The method also describes the contents of research in which fluctuations in characteristics were evaluated and analyzed with a particular focus on characteristics that contribute significantly to the road noise performance of the tires. The results of this method were verified using a CAE model implementing physical formulas for gyro moment and Coriolis force.

CITATION: Uesaka, T. and Suma, T., "Method of Experimental Identification of Change in Dynamic Characteristics of Rolling Tires," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(2):2015, doi:10.4271/2015-01-1523.

INTRODUCTION

The need to reduce in-vehicle vibration and noise caused by road surface input has been increasing in recent years, as a result of vibration and noise from combustion engines being greatly reduced by the electrification of automobiles. The ability to simulate road noise during actual motion is also being examined as an important technological issue for lowering development costs by reducing development time and the number of prototype vehicles. Because a fixed technological architecture has been established for simulating the body and suspension, the main technological issue for simulating road noise is to develop precise identification technology related to input vibrations from the tires. The issue here is the difference between static-state tire characteristics, which are easy to measure, and the characteristics of the tires in motion, which are difficult to measure. Several findings on the causes of the differences have been published, and these include elastic module reduction of rubber materials due to repeated loading from grounding and rolling, and Coriolis force and centrifugal effects due to rolling. It has been difficult to compare tire unit characteristics with velocity as a parameter, because input is difficult to measure with ordinary equipment, and frequency characteristics change greatly depending on the velocity. Methods of estimating velocity, especially the effects of the Coriolis force, that have been reported and have gained

attention in recent years include estimations(1) from suspension vibration in numerical calculations and actual vehicle measurements and analysis(2) of resonance frequency shift by installing a sensor inside the tire and conducting measurement. However, these methods require the use of special equipment, such as special wheels for tests, and because there is a limit to resolution, it is difficult to capture the resonance frequency shift of a tire in the low-frequency region. A simple method is proposed herein that can be used to make precise calculations of the resonance frequency shift of tires in low-frequency regions by re-verifying test methods using mass-produced tires, wheels and existing roller test devices. The results of that method are also verified by using a CAE model that incorporates physical formulas for the Coriolis force.

ROAD NOISE AND TIRE CHARACTERISTICS

Analysis Frequency Range

In automobile development, the frequency region in which the structural resonance of tires is problematic spans all the way from 0 Hz to 500 Hz, the region in which structural transmitted noises are dominant. However, the frequency region in which the resonance

frequency shift of tires due to rolling is particularly problematic is at or below 250 Hz. This is because, in the region at or below 250 Hz, the mode density is high (stated simply, “there are no mountains or valleys”) and there are few frequency characteristic changes in the input due to resonance frequency shift. Also, the region from 200 to 250 Hz is where so-called “cavity resonance” is the principal resonance, so this region is not addressed in this report, which analyzes tire structure. Therefore, the range that is analyzed in this report is from 0 Hz to 200 Hz.

Mode Form of Tire at or Below 200 Hz

In order to track the resonance frequency shift in that frequency region, first, the characteristic mode that exists in that region in a non-grounded, non-rolling state must be identified. Because a tire is rotationally symmetric, its resonance modes can be broadly divided into rotational displacement, radial displacement, and axial displacement, depending on the direction of the deformation. Fig. 1 shows the mode forms of these at or below 200 Hz and their frequency distributions. There is only one rotational mode.

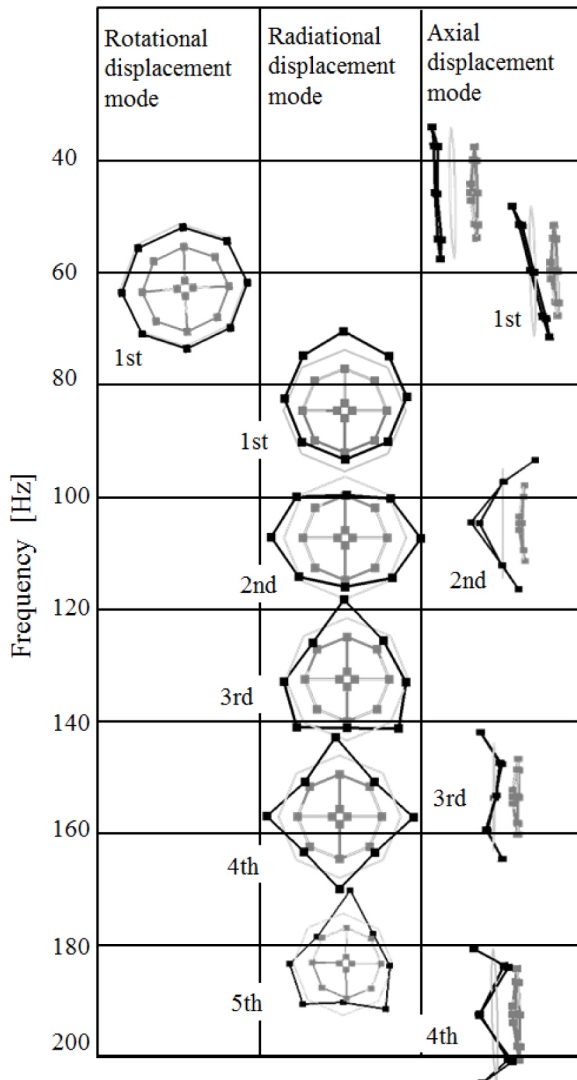


Figure 1. Tire resonance mode morphologies in stationary

Transmission Direction to be Noticed

The coordinate system shown in Fig. 2 is established for a vehicle and tires. As far as how the transmission force of the tires and the hubs, the junctions between the wheel and vehicle, contribute to transferrable road noise, the primary contribution is X-direction transmission force F_X at 0 to 60 Hz, and at the higher frequencies of 60 to 100 Hz and 100 to 200 Hz, the hub axis Z-direction transmission force F_Z and the RX-direction transmission moment M_X are known to be the primary inputs. Therefore, an analysis is performed as to the resonance frequency shift in both the tire modes: the radial displacement mode in which amplification of the vertical force transmitted to the tip of the hub axis is possible, and the axial displacement mode in which amplification of the moment is possible.

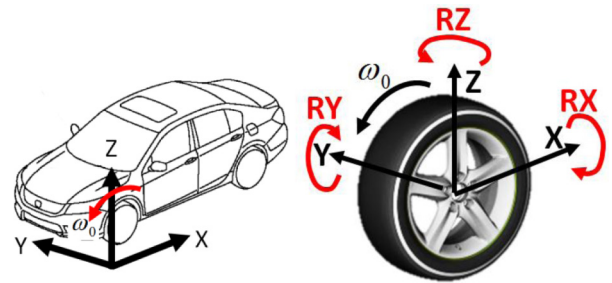


Figure 2. Coordinate system

PRINCIPLE OF CORIOLIS FORCE AND GYROSCOPIC MOMENT

A steady-state rolling analysis, which can analyze characteristic values in a coordinate system in which the rolling tire is stopped, is extremely effective for analyzing rolling tires. The benefits of this analysis are that 1) characteristic values can be analyzed by static implicit method, 2) the coordinates of the input point are fixed, and 3) it is easy to make calculations for a full vehicle, including the tires, during a full vehicle simulation. Coriolis force and gyroscopic moments are the apparent forces observed when analyses are made in a coordinate system that rotates together with an object. Because the rolling velocity is 0 in the Lagrangian formulation, which is the non-rolling component isolated by the previously described steady-state rolling analysis, it is similarly necessary to add that effect. Here, the Coriolis force generated on the small element of the tire is considered $[F_c]$ and the gyroscopic moment is considered $[T_j]$, which are represented by Eq.(1) and Eq.(2), respectively.

$$[F_c] = i\omega [C_c] * d$$

$$= i\omega \begin{bmatrix} 0 & 0 & -2m\omega_0 \\ 0 & 0 & 0 \\ 2m\omega_0 & 0 & 0 \end{bmatrix} * \begin{Bmatrix} d_x \\ d_y \\ d_z \end{Bmatrix} \quad (1)$$

$$\begin{aligned} \begin{bmatrix} T_j \end{bmatrix} &= i\omega [C_{rj}] * d_r \\ &= i\omega \begin{bmatrix} 0 & 0 & \omega_0 I_{yy} \\ 0 & 0 & 0 \\ -\omega_0 I_{yy} & 0 & 0 \end{bmatrix} * \begin{bmatrix} d_{rx} \\ d_{ry} \\ d_{rz} \end{bmatrix} \end{aligned} \quad (2)$$

Here: ω : angular velocity of calculated frequency ω

ω_0 : angular velocity of tire rotation

d : displacement of small element

m : mass of small element

d_r : angular displacement of small element

I_{xy} : Inertia moment of small element

Formulas that incorporate this into the normal motion equation take rolling effects into account. This is represented in Eq.(3) and Eq.(4).

$$-\omega^2 [M]d + i\omega [C]d + [K]d = [F] + [F_c] \quad (3)$$

$$-\omega^2 [I]d_r + i\omega [C]d_r + [K_r]d_r = [T] + [T_j] \quad (4)$$

These effects are thought of as any small section on the tread. The radial displacement of the tire generates the rotational force of the tire as a result of the Coriolis force. This causes rotational movement in the XZ plane on the tread, specifically, longitudinal waves in the rotational direction of the tire. Also, because the axial displacement is also angular displacement of two axes perpendicular to the rotational axis of the tire, a gyroscopic moment causes rotational motion on the surface of the tread, specifically, horizontal waves in the rotational direction of the tire. The resonance around the tire tread is circular resonance that is generated because an integral multiple of the wavelength of the wave that transmits the tread matches the tire circumference. Therefore, the forward wave generated by these phenomena increases the characteristic value, and the backward wave decreases it. This is the mechanism of resonance frequency shift due to rolling. Also, these phenomena are only for velocity, so it is clear that Coriolis forces and gyroscopic moments are proportional to rolling velocity.

EXPERIMENTAL IDENTIFICATION METHOD

Test Summary

Fig. 3 shows an overall diagram of the test device.

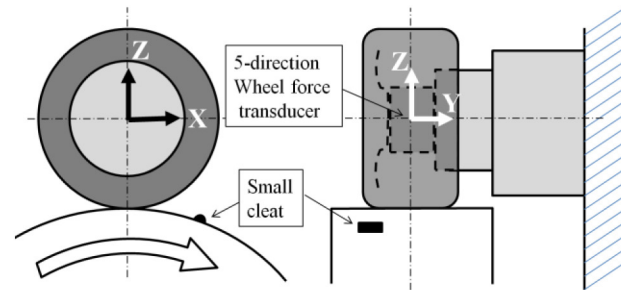


Figure 3. Overview of test equipment

This is almost completely identical to the simple tire test that is generally performed. The representative specifications of the test device are shown in Table 1.

Table 1. Test equipment specifications

Roller diameter	1500 mm
Max. speed	200 km/h
Roller surface	Alloy smooth
Tire size	205-60/R16
Temperature	25°C
Cleat width	30 mm
Cleat height	5 mm
Cleat length	10 mm
Hub axis load sensor	RoaDyn P530 / KISTLER
Roller surface load sensor	260A1 3direction load sell / ICP

These are used in the minimum grounding forces capable of rolling the tire. The grounding force was set at approximately 50 N in the test. This is to minimize the changes in rubber material properties caused by tire deformation and the restraint caused by grounding(3). Here, a simple projection is installed on the roller surface as the input source to the tire. Because the hub axis Z-direction transmission force FZ and the RX-direction transmission moment force MX are generated in the hub axis, the simple projection is installed offset from the center line of the tread. The response is measured with a 5-component force meter of a tire stand. By using general testing equipment and mass-produced tires and wheels, this test can be performed on various tires. The input and response from this device have the characteristics described below.