

Tire and Road Input Modeling for Low-Frequency Road Noise Prediction

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ABSTRACT

This paper presents a modeling method for prediction of low-frequency road noise in a steady-state condition where rotating tires are excited by actual road profile undulation input.

The proposed finite element (FE) tire model contains not only additional geometric stiffness related to inflation pressure and axle load but also Coriolis force and centrifugal force effects caused by tire rotation for precise road noise simulation. Road inputs act on the nodes of each rib in the contact patch of the stationary tire model and move along them at the driving velocity. The nodes are enforced to displace in frequency domain based on the measured road profile.

Tire model accuracy was confirmed by the spindle forces on the rotating chassis drum up to 100Hz where Coriolis force effect should be considered. Full vehicle simulation results showed good agreement with the vibration measurement of front/rear suspension at two driving velocities.

INTRODUCTION

Low rolling resistance tires, which have been introduced for the reduction of fuel consumption, make it difficult to establish the road noise quality. Improvement of low frequency road noise requires modification of the whole vehicle structure, i.e. body and chassis. Therefore, low-frequency road noise is difficult to improve, especially in the later development stage, because such a modification is not easy to implement. Hence road noise simulation is necessary to predict the effect of the whole vehicle structure

modification in the early development stage even if tire is changed.

In order to predict road noise accurately, it is important to represent the transmission of road input through suspension to body [1] [2]. For the identification of road input, some methods have been presented, each with its own merit and demerit. The first method for road input estimation is proposed based on tire patch forces identified with suspension frequency response functions (FRF) measured in laboratory and suspension accelerations driving on the road [3]. The second and third methods are based on measured road surface data. In the second method, rough road profile is expressed as the set of projections of same shape, and road input is modeled as forces excited at the points of entrance and exit of tire patch with phase shift according to driving velocity and the length between the points [4]. In the third method, road profile is converted from function of space (location) to frequency-based input spectrum according to the velocity: road inputs are specified as enforced displacements in the vertical direction at each of the tire patch points, and the displacements are defined as the Power Spectral Density smoothed to logarithmic decrement function of frequency [5].

The first method is based on the measured stationary FRF, so it is difficult to consider the FRF difference between in stationary condition and in driving condition such as tire rotating effects. Although we agree the second method is valuable for tire qualification in mid-frequency road noise, it is difficult to predict actual responses in low frequency range up to 100Hz where long wavelength components are dominant in road profile. In the third method, because road profile for road noise evaluation is assumed random, this

method would be insufficient to predict the responses that are affected by input phase shifts in such low-frequency road noise caused by long wavelength components.

In this paper, FE modeling method of steady-state rolling tire is presented. Further, an input method by tire patch enforcement is developed taking into consideration the excitation effects of long wavelength components of road profile. By these methods, accurate prediction for low-frequency road noise is achieved.

TIRE FE MODELING

MODELING ITEMS

Frequency response of tire axle vibration varies depending on the operational condition. As shown in [Figure 1](#) where tire passes a hemispherical $\phi 10$ projection screwed on a chassis drum, the frequency responses of vertical spindle force are much different between the static axle loads and the driving velocities. Improved technology for tire modeling and road input is required to make it possible to take these influences into account.

The vertical axle load influences the tire deformed shape and the tire patch area, and this change the vibration characteristic and the input area of the tire. Time delay of the road input between entrance point and exit point of tire patch area is determined by driving velocity, and is equivalent to phase delay in frequency domain. Phase delays among the road inputs in tire patch area influence tire forced vibration shape.

Elastic modulus of rubber changes by the magnitude and velocity of deformation [6]. In relation to this, dynamic stiffness of tire is known to change according to the rotating velocity [7]. The change of dynamic stiffness of tire is also influenced by Coriolis force and centrifugal force [8]. Response of the tire and wheel x excited by the external force f at tire rotational angular velocity ω_r (rad/sec) is represented by the following Equation of motion:

$$M\ddot{x} + (C + \omega_r M_1)\dot{x} + (K - \omega_r^2 M_2)x = f \quad (1)$$

where M , K and C express mass matrix, stiffness matrix and viscous damping matrix based on the tire vibrational properties, respectively. The skew-symmetric matrix M_1 and symmetric matrix M_2 depend on the inertia property and rotational axis of the tire. The Coriolis force is in proportion to the velocity $\omega_r M_1 \dot{x}$ and centrifugal force is in proportion to displacement $\omega_r^2 M_2 x$.

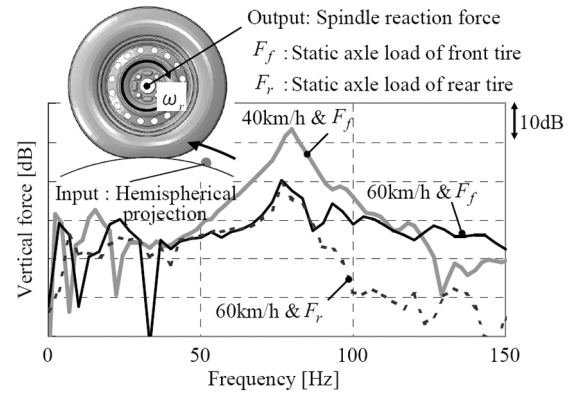


Figure 1. Spindle force under the operational condition

FINITE ELEMENT MODEL

In order to appropriately consider influence of vertical axle load, input time delay and rotational effect as shown in previous section, a proprietary modeling method of the tire was developed by finite element method. The model is constructed through the steps as follows:

1. Define static material properties [6]. Mesh with geometrical shapes based on drawing and measured data: e.g., external size, number of cord layers.
2. Inflate and impose vertical axle load with the specific toe/camber angle to exactly represent the shape of actual tire patch by non-linear static analysis.
3. Identify the elastic modulus and loss factor of the model with reference to the non-rotating measured data: e.g., modes and natural frequencies.
4. Represent the Coriolis force and centrifugal force effects on the vibration model using the steady-state transfer analysis [9].
5. Reidentify the elastic modulus to take account of the tire stiffness drop caused by rotation, with the measured frequency response of spindle forces excited by a projection screwed on a chassis drum at a specific rotating velocity.

VERIFICATION OF TIRE MODEL

[Figure 2](#) shows longitudinal and vertical spindle forces on traveling over the projection at 40km/h. The calculation results whose model is explained in the previous section are compared to the measurement. The peak frequency and level of the calculation results with rotational effects matches the measurement well. The tire model can be utilized for the prediction of low-frequency road noise. This Figure also shows that the peak level of the longitudinal force is different if Coriolis force and centrifugal force are not considered.