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Vibrational response analysis of tires using a three-dimensional flexible ring-based model

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ABSTRACT

Tire vibration characteristics influence noise, vibration, and harshness. Hence, there have been many investigations of the dynamic responses of tires. In this paper, we present new formulations for the prediction of tire tread vibrations below 150 Hz using a three-dimensional flexible ring-based model. The ring represents the tread including the belt, and the springs represent the tire sidewall stiffness. The equations of motion for lateral, longitudinal, and radial vibration on the tread are derived based on the assumption of inextensional deformation. Many of the associated numerical parameters are identified from experimental tests. Unlike most studies of flexible ring models, which mainly discussed radial and circumferential vibration, this study presents steady response functions concerning not only radial and circumferential but also lateral vibration using the three-dimensional flexible ring-based model. The results of impact tests described confirm the theoretical findings. The results show reasonable agreement with the predictions.

1. Introduction

One way to achieve improved noise, vibration, and harshness (NVH) performance in passenger cars is to reduce the input to the vehicle body [1]. Only the car tires contact the road surface in many automotive models, and tire vibration transmits energy to the vehicle body through the axle. The vibration characteristics strongly influence the level of road noise, as tire vibrations caused by road roughness transmit vibrations to the spindle and suspension system, finally appearing as interior noise. Thus, modeling tire dynamics is important for the prediction of NVH performance. Earlier studies presented an analysis of the NVH performance including the tires, suspension systems, etc. [2–4]. The demands for tire dynamics models to be computationally cheap and physically realistic are increasing in general vehicle simulations. Complex physically based models such as FE models are better suited to examining the effects of changing physical parameters such as the material stiffness and the details of the tire structure, facilitating the analysis of vibration behavior in detail [5–8]. It is necessary to obtain the details of the tire structure and material parameters available when building an FE model; however, this information is generally secret. On the other hand, to achieve the imposed demands, low-degree-of-freedom models such as the rigid ring model [5], the plate wave model [9], and the flexible ring model have received considerable attention. These models' parameters can be identified from experimental data. In particular, the flexible ring model is simple, comprehensive, and accurate, and has been most frequently adopted [10]. The presented flexible ring models are almost two-dimensional, ring-based structural models that express the tire tread (including the belts) as a thin circular ring and the tire

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sidewall as springs. Clark and Tielking derived the equation of motion for this model, including the effect of rotation [11,12]. Soedel and Huang presented a derivation of the equation of motion, including the initial tension due to the centrifugal force, and the general solution for the forced vibration of the rotating rings [13–15]. Studies of mode shape changes caused by road contact and rolling conditions have been presented [10,16–19]. Additionally, a transient response analysis [20,21] as well as modeling of the coupled vibrations between tire structures and cavity acoustic modes [22] have been performed. There have been earlier studies of three-dimensional (3D) ring-based structural models. Lecomte et al. derived a motion equation for radial and circumferential vibrations including arc modeling of sidewalls [23]. Additionally, an analytical method utilizing the natural frequency of the radial modes, including the lateral cross-section deformation, has been presented [24]. These studies, as previously stated, focused mainly on radial and circumferential vibration. In the case of coupled vibration between the tires and the suspension, lateral vibration is also important [3,4]. An earlier study considered lateral vibration using the flexible ring model with a finite element analysis [25]; however, no study has derived a motion equation for 3D vibration behavior using a flexible ring.

Thus, in this paper, we construct a 3D ring-based model with damping for tires and derive formulas for their steady-state responses, including lateral vibration. Our early studies presented a 3D flexible ring model without damping and a natural frequency formula derived by the law of conservation of mechanical energy [26]. This model consisted of a thin cylindrical shell ring and springs, designated as the tire tread and sidewall, respectively. First, we constructed a 3D ring-based model including the damping characteristics and derived the equations of motion for 3D vibration. The model proposed in this study is similar to the model proposed earlier by Matsubara et al. [26]. In addition to the previously proposed model, the damping characteristics are added in our constructed model for the derivation of the steady-state response function. Second, the formulas for the steady-state response function and frequency response functions (FRFs) are derived for the case of an input to the tread. Finally, we present an identification method for the model parameters from the modal parameters and FRFs from an experimental modal analysis. The analytical FRF data agree well with the experimental data.

2. Three-dimensional flexible ring model

Fig. 1(a)–(d) illustrate the proposed model. The following tire model assumes non-loaded and non-rolling conditions. The proposed tire model is a 3D flexible ring model in which a thin cylindrical shell ring, springs, and a cylinder represent the tire tread including the belt, sidewall, and wheel, respectively (Fig. 1(a)). Unlike most proposed ring models, this model uses two springs to express the lateral, circumferential, and radial stiffnesses of the sidewall. The springs connect the edges of the tire tread to the edges of the wheel. The cylinder is a rigid body owing to its high stiffness relative to the tire and because it is fixed in space. Fig. 1(b) show the location of the tread-ring element described using a cylindrical coordinate system (y, θ, r), in which $r = R$ is considered the neutral plane of the tread ring, and the vibrational displacement of an arbitrary point on the neural plane with respect to (y, θ, r) is (u, v, w) in Fig. 1(c). The parameters of the presented model, shown in Fig. 1(d), are as follows: for the tread ring, the radius is R, thickness b, width $2l$, bending stiffness EI, which is a function of the second moment of area I and the modulus of longitudinal elasticity E, Poisson's ratio υ, tension S_0, and mass density ρ; for the sidewall, the lateral, circumferential, and radial sidewall stiffness values are K_y, K_θ, and K_r, respectively. In this paper, it is necessary to consider the damping properties for a derivation of the motion equation. The dynamic properties are most described in terms of the complex stiffness related to the force of restitution as EI, S_0, K_y, K_θ, and K_r. The structural damping model is expressed as [27]

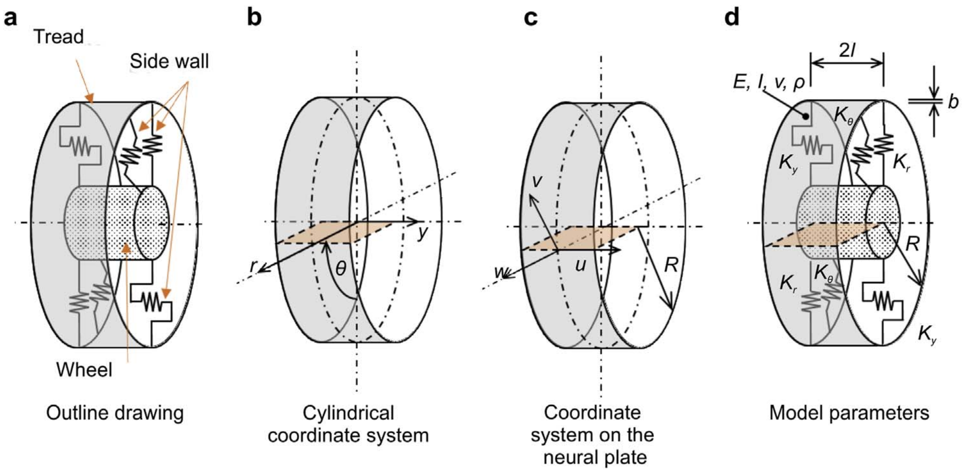

Fig. 1. A three-dimensional flexible ring-based model for the tire.