DYNAMIC ANALYSIS OF A STATIC AND ROLLING TIRE AT HIGHER FREQUENCY

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Understanding the dynamic response of a static and rolling tire is important for understanding noise generation from tires at different rolling conditions. If acoustic noise from trapped air during the road/tire interaction becomes limited due to the absence of a tread pattern in a smooth tire, the main source of noise is from the structure. For structural noise, the radial displacement becomes dominant at lower frequencies and decays quickly at higher frequency and the displacement for the radial and transverse directions is not similar at low and high frequencies. At higher frequencies, the local deformations and internal structure of the tire becomes important. So, to predict the correct behaviour of the tire, the viscoelastic properties of rubber need to be considered above a certain frequency threshold. The evaluation was performed in the frequency domain. These dynamic responses also depend on the motion of the tire. As the tire motion changes, the Eigen frequency changes due to the centrifugal and Coriolis effects of rotational motion. To understand the nature of the dynamic response of a static and rolling tire, we performed computations for two different tire models. The first model entails all the main features of a tire except a specific tread pattern. In contrast, the second model contains only one single block and the rest of tire is smooth. For the smooth tire, the dynamic response of the contact node (road/tire interaction location) and side node of the static and rolling tire were recorded at high frequencies. For the single block model, we performed a transient analysis to understand the noise generation mechanism for a single block by studying the kinematic behaviour of the block during contact and detachment from the drum surface and found that the deformed zone squeezes the air out of the block during each revolution which generates the noise.

Keywords: Eigen frequency, structural noise, steady state rolling, hyperelasticity, viscoelastic

1. Introduction

Traffic noise has reduced significantly by decreasing noise level generated from vehicle. Still there exists a big challenge to reduce noise radiated from tire/road interaction. As the vehicle rolls, tire noise transmits through the powertrain system to the interior of vehicle. To reduce intensity of noise, there should be clear understanding on noise generation mechanisms. Based on origin, sources of tire/road noise can be divided into two main categories: structural-borne noise and acoustic noise [1]. The source of structural-borne noise is the contact forces acting during the tire/road interaction. The reason for acoustic noise is the resonance of air in tire grooves during each revolution through tire/road interaction. If specific tread pattern is not included in the tire model, the source of tire noise will be only restricted to structural noise. Now the behaviour of the structural noise depends on complex structure of the tire and the forces acting on the structure. As the tire rolls, structural waves [2] propagates though the tire at different frequency. These waves can be defined as membrane, longitudinal and rotational wave depending on propagation behaviour. At low frequency, external tension becomes dominant whereas bending becomes important at the medium frequency. Lateral deformation and internal structures becomes dominant at higher frequency. As the frequency range gets higher, the local deformation of tire becomes important and the response is not similar at low and
higher frequency range. Most of the previous study have performed analysis on structural noise at lower frequency range [3] and avoid the complex dynamic response of tire at higher frequency. The exterior sound radiation due to the structural vibrations becomes significant below 1000 Hz and shows distinct modal behaviour at this frequency range. The frequency range for this air-borne noise is generally above 1000 Hz [4]. The air borne noise is complex phenomenon, which is out of scope of current analysis. For this reason, the current paper consider the effects of high frequency structural noise only (200–700 Hz).

The dynamic response of current structure of tire is complex due to nonlinear material behaviour. Especially the hyperelastic and viscoelastic nature of rubber components have made the analysis intricate. The damping of the tire rubber increases with increasing frequency and effects the stiffness. As the shear modulus is function of time and both the hyperelastic and viscoelastic models are inter-dependent, it is necessary to use the appropriate hyperplastic and time dependent viscoelastic model to obtain proper response of tire at different frequency range. To reduce the complexity of structure, ring or plate/shell shape analytical models [5]-[6] have been used earlier. These simplifications have reduced the computational effort but limited structural response of real tire. To predict the accurate response of the tire, a finite element model is required that can incorporate correct material behaviour and forces developed during tire rotation. This detailed finite element model is also necessary to study dynamic response of a tire at different frequency through Eigen value analysis. The Eigen value analysis is required to understand the dynamic response of the tire at different frequency range. But the response of dynamic analysis is not similar for static and rolling tire. The Eigen frequency changes with the rotation of tire due to centrifugal and Coriolis force. So one of the objective of current analysis is to study and compare the dynamic response of a static and rolling tire at higher frequency. The analysis has been performed through the Eigen value study [7]. Static analysis of the tire has been performed before dynamic study. Then a forced excitation has been utilized to obtain the response of static tire for a frequency range defined by Eigen frequency. Direct solution has been used to calculate linearized response of a system at harmonic excitation. Natural frequency of the tire has been extracted prior to such analysis. The projection of dynamic equilibrium equations into selected modes reduces computational cost. For rolling motion of a deformable body, Arbitrary Lagrangian Eulerian (ALE) description has been used for current analysis [8]. This optimal approach is known as mixed Eulerian- Lagrangian method in which the rigid body rotation is described in Eulerian (spatial) manner and the deformation is described in Lagrangian manner. Modeling rolling motion of a deformable body, in contact with a surface is difficult for Lagrangian analysis. Because the reference frame is in motion and for observer, the problem becomes transient. But if we are able to attach the reference frame to the axle of rolling tire, the motion of any particle of tire will be fixed with respect to the observer on axle but will only move with deformation of tire. Thus, ALE removes the time-dependency of the problem and fine mesh can be employed only at the region of interest. This approach ease the complexity of the problem and saves computational time.

In the second analysis, a smooth tire with a single block has been used for transient analysis. The single block tire rotates against a rotating drum. As the tire rotates, the block meets rotating surface of drum and loses the contact during rotation. Noise generated at the empty spaces near the block at each revolution. As there is a brief contact and detachment occurs during tire/drum interaction, kinematic change takes place at the elements and nodes near the single block during noise generation. The objective of the analysis is to obtain the kinematic response of those corner elements during noise generation at each revolution. The result of the analysis will help us to understand noise generation mechanism near the tread pattern.

The current paper is organized as follows: first, the finite element model for the two analyses and the computational methods for the structural analysis have been described. The methods for static and steady state rolling analyses of tire have been illustrated in second. Then the dynamic response of static and rolling tire have been analysed and compared. The kinematic behaviour of single block tire during the transient analysis is explained in the second part of the paper. At the end, final remarks are given in the conclusions.
2. Finite element model of tire

The models for the analysis have been generated by using finite element package (Abaqus). An axisymmetric model was created with bilinear elements. Then a partial three-dimensional model was generated by revolving the axisymmetric model about the rotational symmetry axis. The full three-dimensional model was generated by reflecting the partial three-dimensional model. All the elements used for the analysis are hybrid in nature. Hybrid element is suitable for large deformation and can prevent shear and volume locking. The construction of FE model constitutes all the features of real tire. The only difference between the model and real tire is the absence of specific tread pattern. The tread and sidewalls are made of rubber, and the belts and carcass are constructed from fiber-reinforced rubber composites. Modelling the correct material behaviour is important for accurate analysis. Especially the behaviour of rubber. The shear modulus of rubber is time dependent property and also affected by frequency. Therefore, care should be taken to model the hyperelastic and viscoelastic nature of rubber. Hyperelastic material is defined in terms of strain potential energy stored in per unit volume of original configuration. For current analysis, the reduced polynomial Yeoh model has been used for hyperelastic model and Prony series have been used for viscoelastic model.

3. Static and steady state rolling analysis of tire

Prior to dynamic analysis, static and steady state rolling of the tire were performed for current study. In static analysis, the tire was inflated with a pressure of 200 kPa and a vertical load of 3.4 kN was applied to the full three-dimensional model. The contact between road and tire was modelled as hard contact and penalty method was used to approximate hard pressure-overclosure behaviour. During the static analysis, the friction between road and tire was considered zero. The deformation of partial and full tire is shown in figure 2. Arbitrary Lagrangian method has been used for steady state analysis. This method converts a time dependent problem into spatial dependent problem. During the analysis, the rigid body rotation is described as Eulerian manner and deformation of tire as Lagrangian manner. In the steady state rolling the frictional co-efficient was not zero and inertia effects were included during the study. The centrifugal and Coriolis acceleration due to rotational motion of the tire were also included in the analysis. The purpose of the steady state analysis was to obtain free rolling equilibrium solutions of a 175 SR14 tire traveling at a ground velocity of 60.0 km/hr.
4. Dynamic analysis of static and rolling tire

Steady-state dynamic analysis is the procedure to determine steady state dynamic response of a system subjected to harmonic excitation. Dynamic response of the system is recorded at a range of frequency. In the subspace based dynamic analysis, steady-state dynamic equations are projected on a subspace of selected modes of the undamped system. One of the requirement for such analysis is the extraction of Eigen frequency within the frequency domain of interest. Once the Eigen frequency is obtained from the analysis, the systems of equations are excited with at those frequencies in the frequency domain. In the subspace-based steady-state dynamic analysis, the static deformed tire was excited with a vertical load of 200 N. The dynamic response of the system was observed between 100 to 700 Hz. The dynamic response of the tire was recorded at two points. The first point was chosen at the road/tire interaction point and the second point was located on lateral side of tire. The vertical displacement ($U_3$) of the road node is shown in figure 3. The plot shows the effect of frequency on vertical displacement from 100 to 650 Hz. At the lower frequency (less than 200Hz), the initial displacement was very high. But as the frequency range increases, the vertical or radial displacements dies with increasing frequency. The results also conforms to analytical result from Larsson et al [9]. For side node, the nature of displacement (figure 4) is different from road node. Although the initial nature of displacement is similar high values for $U_2$ and $U_3$ at the initial stage, the fluctuation of displacement does not completely dies out like radial displacement of road point. The plot shows a second big surge around 350 Hz and fluctuations are frequent than the previous range up to 300Hz. After 350 Hz, the value of displacement decrease again with the increasing frequency. Now for fluctuation along the road direction ($U_1$), the displacement does not show higher magnitude at the initial stage and the maximum value was found between 300 Hz to 400 Hz. The magnitude of displacement of $U_1$ is small compared to other direction. From the dynamic response, it can be concluded that the radial displacement dies out for static tire with higher frequency range whereas secondary surge of fluctuation of displacement can be observed for the side node at higher frequency range.
The dynamic response of a rolling tire was also performed for a tire with rolling velocity of 60 km/hr. The Eigen frequency for rolling tire is different from static tire due to presence of rolling motion. As the tire rolls, centrifugal and Coriolis force have to be included in the analysis. Static and steady state rolling analysis was performed prior to dynamic analysis. After calculating the Eigen frequency, the rolling tire was excited with similar vertical load and the response was obtained at Eigen frequency between 200 Hz to 700 Hz. The nature of displacement is different for rolling from static tire. In contrast to static tire, the displacement does not show higher frequency at the initial stage. Almost nothing happens between 200 to 300 Hz and 400 to 500 Hz. These are the zones where the fluctuations of displacement very small in magnitude. Except for these two quite zones, the displacement fluctuates sharply for side node. The first surge takes place between 300~400 Hz and the second surge occurs between 500~600 Hz. The magnitude of displacement is almost similar for all the direction. Displacement for side node (point located at lateral side of tire) is shown in figure 5. In contrast to static analysis, the displacement was small in magnitude for dynamic analysis of rolling
tire. From the dynamic response, it can be concluded that displacement is comparatively small for rolling tire but almost similar in nature and magnitude for all the direction.

![Graphs](image)

**Figure 5:** (a) Vertical ($U_3$) (b) lateral ($U_2$) and (c) road side ($U_1$) displacement for rolling tire.

### 5. Kinematic analysis of the second model

To understand the noise generation mechanism from tread pattern, a partial three-dimensional tire model was generated with a single block. The tire was initially in contact against a rotating drum. The drum was modelled as discrete rigid body. The tire and drum assembly is shown in figure 6. The drum rotates opposite to the tire motion. A static analysis of tire has been performed by inflating the tire with 200-kPa air pressure. A load was applied to the tire to make initial contact with drum surface. As the load was applied, tire deformed against the rigid drum and the tire deformed. The tire was rotated with prescribed rotational motion. As the tire rotates, sliding motion takes place between rigid drum and a deformable tire. For the contact mechanism, surface-to-surface contact was made between the drum and tire. Contact was enforced in an averaged sense over both the surfaces. Surface to surface contact predicts the stress more accurately than node to surface contact model and reduce surface
penetration. The normal contact behavior was modeled as hard contact. To achieve hard contact condition “Penalty method” was used.

![Finite element model](image)

Figure 6: The finite element model for (a) tire/drum assembly (b) single block tire.

As the tire rotates, the single block meets the drum and then loses the contact. This process continues for each rotation and noise generates during the detachment of block surface from rotating drum. Our objective is to analyse the kinematic condition of the elements of the single block during the noise generation stage. Noise generation occurs during short period of contact and detachment of block surface from the rotating drum. It will be insightful, if the deformation of the block and stress level can be observed during that short period. Figure 7 shows sequence of figures of single block sliding against rotating drum. The first sequence (a) captures the deformation of single block at the moment of leaving the contact. In the second sequence (b), one-corner node of the blocks has lost the contact and the stress has developed in the corner. The other corner of the block still in contact with drum surface. In the third sequence, both the corners of the block has lost the contact and stress has developed at the both corner points during stretching of the block.

![Sequence of figures](image)

Figure 7: (a) Block in contact with drum (b) left corner node moving (c) block detached from drum surface.

The time vs stress plot will provide the detail of how the stress is evolving with time at the corner nodes of single block. The peak stress value in figure 8 shows the transition from contact to no contact of first corner node of single block during rotation. This stress transition occurs during noise generation at each revolution. As the stress is developed, the two empty block near the single block stretched and contracted due to stress generation as shown by the previous figure. The trapped air inside those empty blocks are forced to leave the tread space during each revolution. As the process is harmonic, pumping of the air continues with each rotation and generates noise and the intensity of noise increase with increasing rolling velocity.
6. Conclusions

Static and steady state rolling analyses have been performed along with dynamic analysis of a tire. The dynamic response of the tire was recorded for a static and rolling tire between 200 Hz to 700 Hz. The results show a difference in dynamic response for static and rolling tire at particular rolling condition. From the dynamic response of static tire, it can be concluded that the radial displacement dies out for static tire at higher frequency range whereas secondary surge of fluctuation of displacement can be observed for the side node at higher frequency. In contrast to static tire, displacement does not show higher fluctuations at the initial stage for rolling tire. The results show two distinct high fluctuating displacement zones for side nodes. For the second analysis, the results shows deformation and stress developed near the single block of a tire. The deformed zone squeezes the air out of the block during each revolution and generates the noise. Results obtained in the study will be helpful to understand steady state rolling motion and dynamic response of a tire at higher frequency range.

REFERENCES