

## Full Vehicle NVH Analysis with Rolling Tires

### Summary

In a traditional automobile noise, vibration and harshness (NVH) analysis, stationary tires are defined and subjected to vertical dynamic loading. The actual operating conditions of a tire involve rolling however, and the vibration characteristics of rolling tires are considerably different from those of stationary tires.

Abaqus offers a methodology to include the pre-loading and gyroscopic effects of rolling tires in a forced response dynamic analysis of the moving vehicle. This article closely follows SIMULIA Technology Brief TB-08-TVC-1 and illustrates the use of substructures in a typical NVH analysis for a full vehicle model with steadily rolling tires.

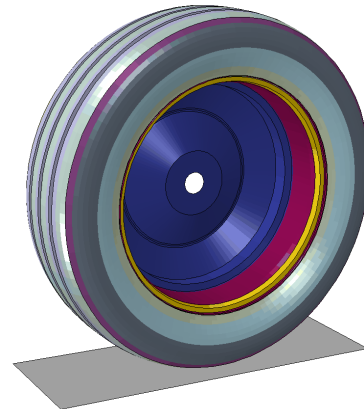
### Background

Small amplitude vibrations of a tire on the road can be treated as a linear superposition of small amplitude steady state vibrations on a highly nonlinear base state. For stationary tires, this base state is the footprint configuration of the tire. The base state contains nonlinearities arising from the load-deflection behavior of various rubber compounds, contact between the tire and the road, reinforcement behavior, etc.

In a traditional NVH analysis, the tires are stationary and subjected to vertical load. However, the vibration characteristics of rolling tires depend on the rolling velocity and are considerably different from those of stationary tires. Specifically, the rolling condition contributes loads in the fore-aft direction as well as the vertical [Ref 1].

It is common practice to employ a mixed Eulerian-Lagrangian scheme to compute the steady state rolling configuration of the tire. This methodology uses a reference frame that is attached to the axle of the rotating tire. An observer in this frame sees the tire as points that do not move, although the material of which the tire is made moves through these points. Small amplitude vibrations can then be superposed on the rolling configuration corresponding to the velocity of interest.

The dynamic substructure of a rolling tire can be created and incorporated in a full vehicle assembly, thus eliminating the need to use a fully meshed representation of the tire. With these modeling capabilities, tire manufacturers can provide automotive designers with richer, more comprehensive numeric representations of their tire's behavior – without divulging their detailed tire FE models.



### Key Abaqus Features and Benefits

- Symmetric model generation and symmetric results transfer
- A mixed Eulerian-Lagrangian scheme to compute the steady state rolling configuration of tires
- Dynamic substructures to account for pre-loading and gyroscopic effects of a rolling tire
- Subspace-based steady state dynamics for relatively inexpensive forced response prediction

The simulation presented here demonstrates the analysis methodology for including the effect of rolling tires on the vehicle forced frequency response. A dynamic substructure of a rolling tire FE model is created and assembled into a full vehicle model for NVH analysis. The automatic multi-level substructuring (AMS) eigensolver is used to extract the eigensolution of the vehicle assembly, which is then subsequently used in the steady-state dynamic analyses.

### Finite Element Analysis Approach

The model under consideration represents a typical passenger car tire. The road is modeled as an analytical rigid surface. Contact is defined between this surface and the tire. A simple Mooney-Rivlin law is used for the strain energy potential of the various rubber materials. This simulation ignores the viscoelastic nature of the rubber. The plies and belts are modeled using rebar layers embedded in the surrounding rubber matrix. Linear elastic material properties are applied to the reinforcement fibers.

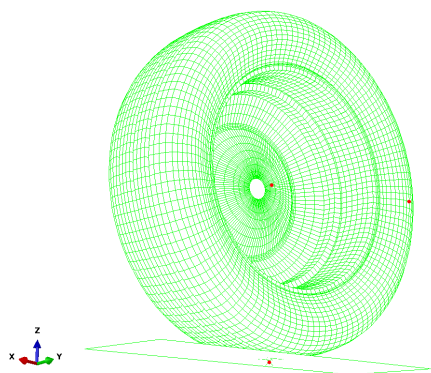


Figure 1: Substructure retained nodes

### Step 1: Rim mounting and inflation analysis

Rim mounting and inflation are carried out using an axisymmetric model of the tire cross-section to save analysis time. Axisymmetric elements with twist capture the out of plane deformation introduced by the belts.

### Step 2: Footprint loading

Symmetric model generation is used to revolve the axisymmetric cross-section into a three-dimensional model, in this case with uniform mesh density around the circumference. The results from the end of the inflation step are transferred to the three-dimensional model to act as the base state for the ensuing footprint loading simulation. The vehicle load contribution is applied as a concentrated load to the reference point of the road rigid surface.

### Step 3: Computation of the steady state rolling configuration

The static footprint configuration acts as the base state for the subsequent steady state transport analysis at the desired velocity. The steady state transport analysis accounts for the effect of inertial and frictional forces. The coefficient of friction between the road and the tire is set to 1.0. The free-rolling configuration corresponding to 50 km/h is computed. If the substructure was being developed for a stationary tire, the steady state transport analysis would not be necessary.

### Step 4: Frequency extraction of the tire

For the purposes of generating a substructure, the modes of the tire are extracted. For a stationary configuration this is done after the static footprint step, and for a dynamic configuration after the steady state rolling step. Inclusion of these modes when building the substructure provides for a better dynamic approximation. Note that the natural frequency extraction does not consider gyroscopic effects or damping. These real modes can be either the fixed- or free-interface type. In this example, the fixed-interface modes are calculated based on three retained nodes (see the rim center node, road reference node, and a tire node indicated with red dots in Figure 1).

Contact conditions from the base state are preserved in both the normal and tangential directions. Points that are slipping (equivalent shear stress greater than critical shear stress) are free to move tangential to the contact surface, while points that are sticking are kept fixed.

### Step 5: Substructure generation

The dynamic substructure is created by retaining both nodal degrees of freedom and the eigenmodes calculated from Step 4. The substructure's reduced mass, structural damping, and viscous damping matrices are calculated and stored; these are necessary to capture the dynamic properties at the usage level. It is necessary to use the unsymmetric solver so that gyroscopic effects are considered.

### Step 6: Frequency extraction of the entire vehicle

The tire substructure is imported, repositioned (translated and rotated) and used in the vehicle assembly. For the NVH analysis of the large assembly model, the AMS eigensolver can be used to efficiently extract the modes in the frequency range of interest.

### Step 7: Steady state dynamics

The forced response analysis can be performed using the mode-based steady-state dynamics procedure for the stationary tire case, or the subspace-based steady-state dynamics procedure for the rolling tire case. The subspace projection method uses the eigenmodes extracted in the preceding frequency extraction step.

## Results and Discussion

In both the tire-only model and vehicle-with-tires model, tire design affects the amount of energy channeled into the vehicle body. Both types of models are discussed separately below.

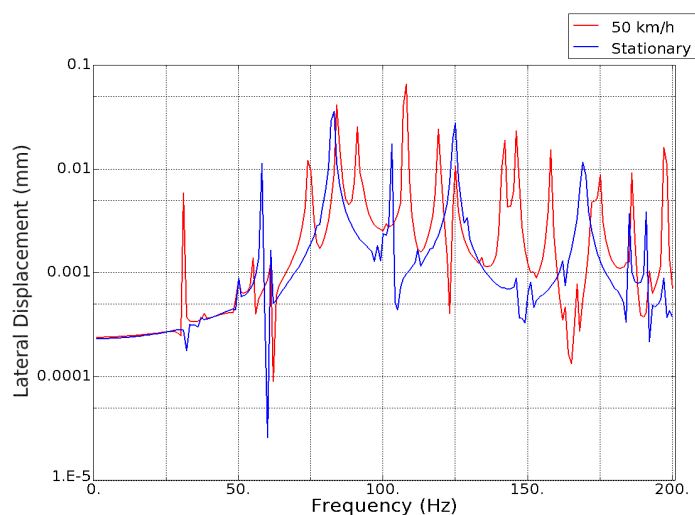


Figure 2: Undamped lateral displacement for stationary (blue) and 50 km/h rolling (red)

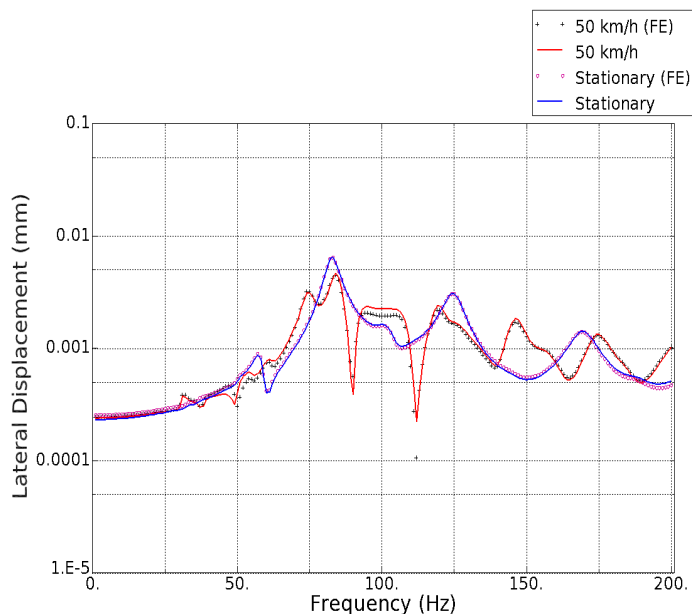


Figure 3: Damped lateral displacement for stationary (blue) and 50 km/h rolling (red)

#### Tire-only model

The stationary tire and rolling tire substructures are created based on Steps 1-5 as described above. At the substructure usage level, a fixed boundary condition is applied at the rim center node. At the road reference node, a unit harmonic load is applied in the vertical direction, while the remaining degrees of freedom are fixed. Figure 2 shows the undamped lateral displacement frequency response at the retained tire node for both a stationary tire (blue curve) and a rolling tire (red curve) with a traveling speed of 50 km/h.

The two responses highlight the mode splitting phenomena. When symmetry causes two modes to occur at the same frequency in an unloaded, stationary tire, the symmetry is broken when the footprint load is applied. This

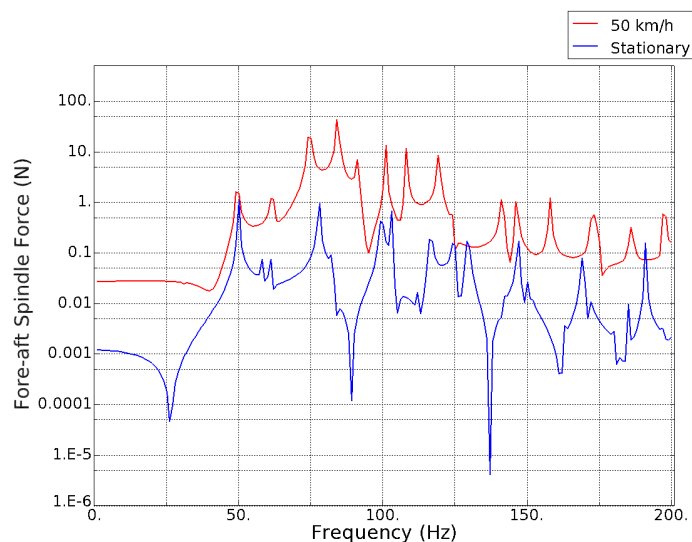


Figure 4: Fore-aft spindle force, undamped case

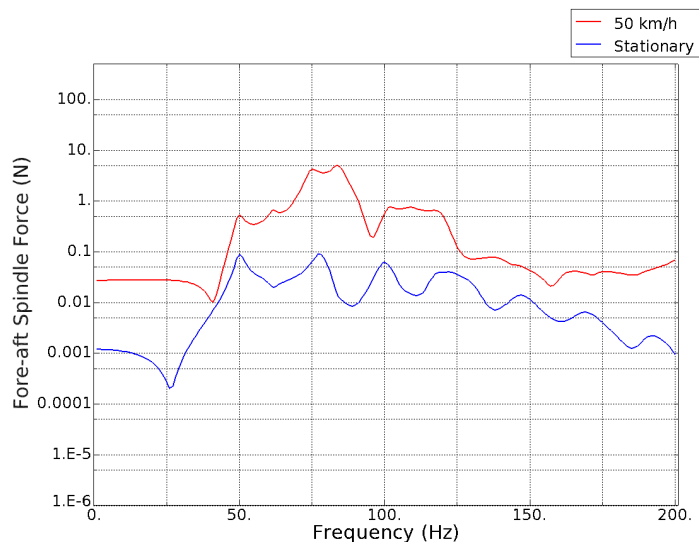


Figure 5: Fore-aft spindle force, damped case

causes the two modes to split slightly. When the tire is rolling, the gyroscopic effect further splits the two symmetry-broken modes as the tire speed increases.

The lateral displacement at the same tire node when a global structural damping factor of six percent is applied to the model is shown in Figure 3. The results based on the substructure approach are also compared against those from a fully meshed approach (labeled (FE) and marked “+”). It shows that the dynamic substructure provides a good representation of the tire FE model in either the stationary- or rolling-tire case.

In order to highlight the difference in energy transfer due to the rolling effect, the fore-aft reaction (or spindle) force at the rim center node is shown in Figures 4 and 5 for the undamped and damped cases, respectively. It is clear that the rolling effect leads to higher fore-aft spindle forces in certain frequency ranges and will therefore affect the frequency response prediction at the full-vehicle level. Changes in tire design generally play an important role in how the rolling configuration affects the amount of energy transferred from the road to the vehicle body.

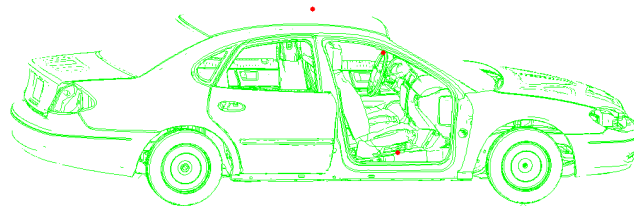


Figure 6: Floor, steering wheel, and roof output points

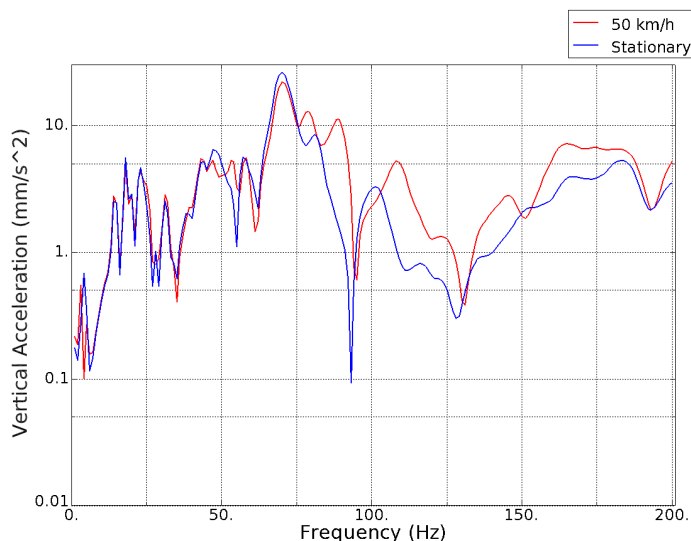


Figure 7: Acceleration response at the floor

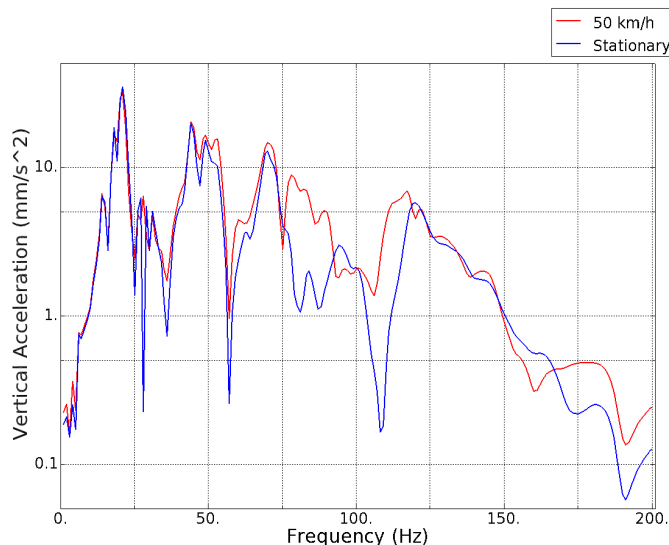


Figure 8: Acceleration response at the steering wheel

### Vehicle-with-tires model

Road asperities act as a source of excitation for tire vibrations, which produce spindle forces that act as the primary source of excitation for the vehicle. A unit harmonic load is applied to each of the four road reference nodes in the vertical direction. These loads are applied simultaneously in-phase between left and right tires and out-of-phase between front and rear tires. Mode extraction using the AMS eigensolver followed by an excitation frequency sweep from 1 to 200 Hz is performed for both the stationary- and rolling-tire cases. A global structural damping factor of six percent is applied. The acceleration frequency responses in the vertical direction at the floor and

steering wheel (highlighted in Figure 6) are shown in Figures 7 and 8 respectively.

### Conclusions

The NVH response prediction of a moving vehicle will be more realistic if the effect of the rolling tires is included. The substructure, nonlinear, and steady state dynamics functionalities of Abaqus/Standard allow for a greater understanding of how the interaction between a rolling tire and the road contribute to vehicle noise and vibration. This capability allows engineers to quantify how different tire designs transfer energy to a moving vehicle.

### References

1. Abaqus Technology Brief TB-08-TVC-1: Vibration Characteristics of Rolling Tires
2. Abaqus Technology Brief TB-07-SSD-1: Noise, Vibration, and Harshness (NVH) Analysis of a Full Vehicle Model

### Abaqus References

For additional information please see the following Abaqus 6.11 Analysis User's Manual references:

- 'Mode-based steady-state dynamic analysis,' Section 6.3.8
- 'Subspace-based steady-state dynamic analysis,' Section 6.3.9
- 'Steady-state transport analysis,' Section 6.4.1
- 'Defining substructures,' Section 10.1.2

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