

Tire Sensors for the Measurement of Slip Angle and Friction Coefficient and Their Use in Stability Control Systems

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ABSTRACT

Intelligent tires are envisioned to be an important part of the future vehicle control systems and the three dimensional wireless MEMS accelerometers embedded inside the tire stand out as a promising candidate for the development of intelligent tires. The first part of the paper focuses on accelerometer based tire sensors for the estimation of slip angle and tire/road friction coefficient. We use a simple tire finite element model to generate lateral, tangential and radial tire accelerations for a fixed load and slip angle. The profiles are validated by using experimental data. The simulated acceleration profiles are used for the estimation of slip angle and tire/road friction coefficient. We present the estimation algorithms, promising simulative results and output sensitivities studies focused on the effects of changes in normal load, tire pressure and vehicle velocity. The second part of the paper focuses on the integration of the accelerometer based tire sensors into the vehicle control systems. The benefits of tire sensors coupled with a control system are quantified using computer simulations and their contributions to the overall performance of the control system are discussed.

INTRODUCTION

Direct measurement of tire variables using wireless sensors embedded inside the tire is a challenging objective that could potentially open a new era in the design of vehicle control systems. Existing control systems have limited information regarding the tire deformations, traction forces and road surface condition. Intelligent tire technology could potentially eliminate some of the vehicle sensors and provide accurate, reliable and real-time information about magnitudes, directions and limits of forces for each tire.

Tire slips and the tire-road friction coefficient quantifies an upper bound on the lateral and longitudinal forces that a tire can achieve [1, 2]. Accurate and real-time estimation of these tire variables would therefore be very useful to avoid tire saturation during an emergency maneuver. Early warning systems can benefit from these estimations to inform drivers about the diminishing road traction abilities when the vehicle hits a slippery road surface or when the driver makes excessive steering. This information can be used in a predictive control framework in order to design more reliable lateral and longitudinal control systems for active safety systems.

Techniques proposed for the tire slip, traction force and friction coefficient estimations in the literature mostly depend on the vehicle sensors such as engine torque sensor, throttle position sensor, steering angle sensor, wheel speed sensor, yaw rate sensor, GPS receiver, strain gauges, steering torque, etc. Type and number of sensors may change depending on the vehicle. The indirect techniques used in the existing control systems are generally known as “observer based techniques”, since the tire slip and traction force observers are designed based on the vehicle models and the measured vehicle states. The main goal of these observers is to identify the slip-force curve that corresponds to the current operating condition of the tire and thereby estimate the current limit of the traction force, i.e. the tire-road friction coefficient [3, 4, 5].

A primary disadvantage of observer based techniques is that they do not work under steady state driving conditions, i.e. when the vehicle speed is constant and the steering wheel angle is close to zero. A minimum acceleration/deceleration or steering of the vehicle is required for tire-road friction coefficient parameter to converge to its correct value. Since

the vehicle is not likely to always be accelerating/decelerating or cornering, this means that the friction coefficient cannot be continuously updated. A secondary disadvantage is that the slip and force observers are usually based on lateral/longitudinal vehicle models whose outputs are mispredicted during extreme combined maneuvers. This is due to the fact that tire slip and force conditions change quickly and significantly during extreme maneuvers and often faster than the convergence rate required by the estimation algorithms. Also, noise and accuracy of each sensor used in the estimation algorithms increase during extreme maneuvers [4]. Accelerometer based tire sensors could overcome all these issues by measuring the slip variables directly from the tire.

Despite the widely accepted benefits of intelligent tires, only a few sensor prototypes based on various technologies have been proposed in the literature such as surface acoustic wave sensor [6], capacitive sensor [7], hall-effect sensor [8], magnetic tire sidewall deflection sensor [9, 10, 11], optical sensor [12], yet none of these technologies have been commercialized. Further information on the pros and cons of these sensors can be found in [13]. Strain sensors attached to the inner-liner of the tire are generally not recommended due to a number of facts including: (1) large differences between the sensor and rubber surfaces is likely to disturb the strain measurements, (2) large deformations can cause detachment of the sensors over a long period of service, (3) strain based sensors are excessively susceptible to the vibrations coming from the roadway which are difficult to isolate, (4) measurements need to be continuously compensated for temperature changes [7].

Among the existing sensor prototypes, the 3D wireless MEMS accelerometers are beneficial in several aspects. First, the wireless sensors can be mounted on the inner surface of the tire without any connection with the wheel rim. This is a great advantage facilitating the mass production and maintenance. Second, the acceleration signal profiles can simply be converted into deflection profiles through double-integration. Third, the obtained tire deflection profiles can be associated with the unknown tire variables through the existing tire models in the literature which would eventually bridges the gap between the sensor development efforts and the mature theory in tire modeling. In addition to these technical advantages the 3D MEMS accelerometers are also inexpensive which guarantees the economic feasibility of a final product.

Accelerometer based tire sensors have been proposed for the estimation of normal tire forces and slip ratios in the literature in [14] and [15]. This paper investigates the use of accelerometer based tire sensors for the estimation of tire slip angle and the tire-road friction coefficient. The lateral acceleration and deflection profiles measured by the embedded accelerometers throughout the circumference of the tire are simulated with the help of finite element software

and compared with the actual measurements taken from a tire testing machine for verification. Algorithms introduced in [13] and [16] are used to estimate the slip angle and tire-road friction coefficients. Simulations are repeated under various loading conditions in order to understand how sensitive is the accelerometer measurements to the changes in the operating conditions as the tire roles and travels along the roadway. Finally, the potential contributions of a tire sensor is discussed and demonstrated.

ACCELEROMETER BASED TIRE SENSOR

Accelerometers measure the accelerations observed from an inertial coordinate frame and expressed in the accelerometers' body coordinate frame. In the current setup, a 3D MEMS accelerometer is attached to the inner-liner of the tire and measures tangential, lateral and radial accelerations in the x, y and z directions of its body coordinate frame, respectively. The accelerometer location and its body coordinate frame are presented in [figure 1-a](#). The tangential, lateral and radial directions of the tire deformations are presented in [figure 1-b](#). 3D MEMS accelerometers can also measure the gravitational acceleration.

Next we consider the simple rolling motion of a rigid tire with a constant translational velocity ([figure 2-a](#)) in order to describe the qualitative behavior of the accelerations occurring in a tire. In a rolling motion of a rigid tire, the accelerometer attached to the inner-liner rotates and moves forward along with the tire body. The z direction of the accelerometer measures the centripetal acceleration plus the radial component of the gravitational acceleration (which can be neglected at high angular velocities). The x and y direction of the accelerometer measures the tangential component of the gravitational acceleration and zero, respectively. Once the accelerometer reaches to the contact point, i.e. the instantaneous center of rotation, accelerometer does not move for a moment and the whole wheel body rolls over it. In other words, accelerometer measures only the full gravitational acceleration in the z direction and zero in the x and y directions. Rigid tires do not deform in any direction and thus their acceleration profiles cannot be used in the estimation of tire variables. Due to this fact rolling of a rigid tire is neither simulated nor used in the estimation algorithms.

Accelerations occurring inside a rubber tire rotating at a constant speed as shown in [figure 2-b](#) have more complicated character compared to the accelerations of the simple case described above due to the tire deformations. When a normal force is applied, the circular shape of the tire periphery is distorted by the reaction forces acting through the contact surface in the opposite direction. The tire radius enlarges and peaks close to the tire-road contact surface, and then decreases inside the contact surface and reaches its minimum value (called the loaded tire radius) at the contact center. The

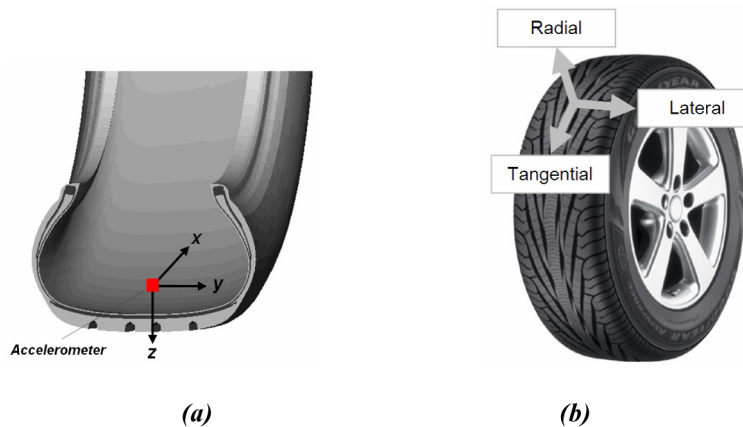


Figure 1. (a) Accelerometer Location and Body Coordinate Frame (b) Tire Coordinate Frame

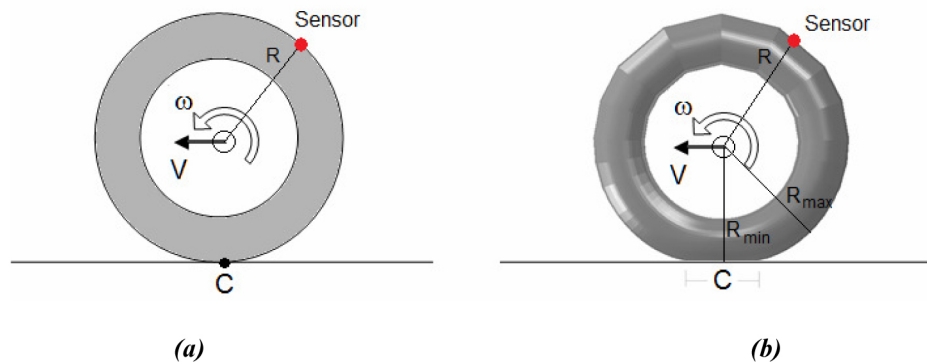


Figure 2. Rolling (a) Rigid Tire and (b) Rubber Tire

changes in tire radius effect the centrifugal acceleration in the radial direction. In other words, the distorted circular shape of the deformed tire causes a directional change in the tangential velocity and creates additional accelerations in both radial and tangential directions.

Further, the normal force acting on the tire creates a contact surface rather than a contact line and the instantaneous center of rotation turns into an instantaneous track which stays stand-still as the whole tire body rolls over. The measured accelerations throughout the instantaneous track are very close to zero in all three directions. However, minor accelerations inside the contact surface are still possible due to the sliding or slipping of tire depending on the force equilibrium between the elastic and friction forces. In the following section, the finite element model of the tire is constructed and the accelerations measured inside a rubber tire are simulated in the computer environment.

FINITE ELEMENT ANALYSIS

Finite element simulations facilitate the interpretation of the accelerometer measurements and help the development of the tire sensor along with the tire tests. Finite element analysis of

a radial tire in rotational and translational motion is executed in ABAQUS/CAE program [17, 18, 19].

Tires are made of rubber material and reinforced by body plies, steel belts and beads as shown in [figure 3-a](#). It is possible to construct finite element models at different levels of complexity and detail for various design purposes such as road traction analysis, vibration and acoustics design of tires, hydroplaning, etc. However, a simplified finite element model is constructed for this work in order to simulate the measurements of an accelerometer attached to the inner-liner of the tire as presented in [figure 3-b](#). A passenger car tire with the size of 215/60R16 is used in the simulations. The tire model is composed of the tire body which is made of rubber material, two layers of belts which are made of steel, beads which are made of steel cords and inner-liner which is made of a hardened rubber material. Material types used for each tire component and the constitutive model parameters of these materials are presented in [table 1](#).

The constitutive model used for the rubber material is a combination of the hyperelastic and the viscoelastic models. The *polynomial* and *prony series* constants defining the hyperelastic and viscoelastic characteristics of the tire

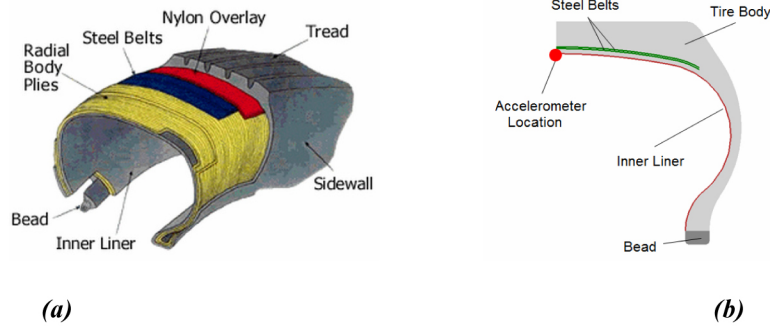


Figure 3. (a) Actual Radial Tire Structure (b) Components of Simplified Tire Model

Table 1. Material Types and Constitutive Model Parameters

Components	Material Type	Constitutive Model	Model Parameters	
Inner-Liner	Fiber-Reinforced Rubber Composite	Linear Elastic Model	Young's Modulus	9.90E+09
			Poisson's Ratio	0.3
Belt	Steel	Linear Elastic Model	Young's Modulus	1.70E+11
			Poisson's Ratio	0.3
Tire Body	Rubber	Hyperelastic Model (Polynomial)	C10	5.00E+05
			C01	0
			D1	0
		Viscoelastic Model (Prony Series)	g_i	0.3
			k_i	0
			τ_i	0.1
Bead	N/A	Rigid	N/A	N/A

material, respectively, are given in the table. Viscoelastic property of the rubber material is closely related to the *tire rolling resistance* which explains the asymmetric shape of the in-tire acceleration profiles. Energy dissipation due to viscoelasticity causes a difference in the compression and tension forces at the leading and trailing sides of the tire [20], respectively, which influences the acceleration profiles significantly.

Two layers of steel belt and the inner-liner are embedded inside the rubber tire body. This means that the coincident nodal points of tire body and the embedded component are constrained to move together as the tire deforms. The tire beads are defined as a rigid part and their distances to the wheel center are fixed. Threads and grooves on the outer surface of the tire are neglected for simplicity.

Different types of elements are used based on the geometry and mechanical behavior of the tire components. CGAX3H and CGAX4H are generalized triangular and quadrilateral axisymmetric hybrid plate/shell elements with twist defined in ABAQUS. These elements are designed for incompressible materials and employed for the modeling of rubber tire body. The reinforcements such as inner-liner and belts utilize the

SFMGAX1 element type which is a generalized surface element with twist and can carry embedded rebar layers.

In order to take advantage of the symmetric geometry of the tire and decrease the computational cost of simulations, special methods available in the simulation software are used. Finite element model of the tire is constructed in three main steps by using the *Symmetric Model Generation* method; (1) 2D half section sketch, (2) 3D revolve and (3) 3D reflection as depicted in [figure 4-a](#), [4-b](#) and [4-c](#), respectively. The 2D tire half cross-section sketched and meshed on the X-Y plane is first revolved about Y axis and then reflected with respect to X-Z plane to obtain a full 3D model of the tire. Note that the mesh density is reduced in the upper half of the tire, since the upper half of the tire experience less deformation compared to the lower half of the tire. This modification also eliminates redundant computations and speeds up the simulations. The three consecutive loading steps of the tire simulation are (1) inflation, (2) application of normal load and (3) application of slip angle on a rolling tire. Results of each loading simulations are transferred to the next simulation step by using the *Symmetric Result Transfer* method.

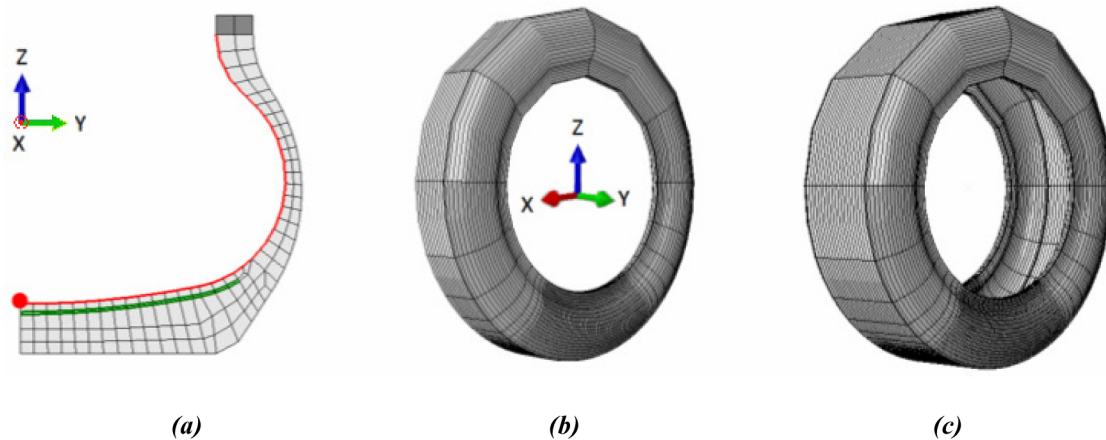


Figure 4. (a) 2D Half Section Model (b) 3D Half Tire Model (c) 3D Full Tire Model

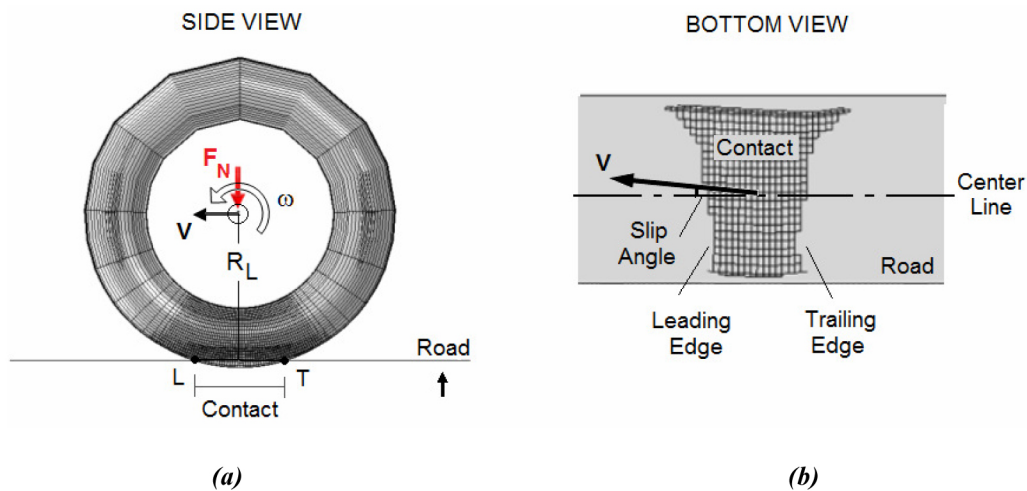


Figure 5. Tire Deformations due to (a) Normal Force and (b) Slip Angle

Tire pressure is first applied to the inner-liner of the 2D half section model, and then the simulation results are transferred and extended to the full tire model in the revolving and reflection modeling steps. The unloaded radius of the tire reaches from 332mm to 335 mm after inflation with a tire pressure of 200 [kPa].

For the application of normal load as shown in [figure 5-a](#), the rigid road surface is moved up towards the wheel center first. The deformed tire obtained from this preliminary simulation step is then used as the initial state for the optimization of the vertical distance between the road surface and the wheel center while achieving the desired normal force. The desired normal force of 3800N, for example, is obtained at a vertical distance, i.e. at a loaded tire radius, of 317mm. During the application of normal force, the friction coefficient is set to zero in order to converge faster to the optimum solution which is approximately the same as the solutions of the non-zero friction case.

Angular velocity of the tire that corresponds to the zero driving torque is obtained by executing another preliminary simulation. Zero driving torque implies that the angular-velocity of the tire is almost equal to the translational-velocity of the tire and thus the slip ratio of the tire is very close to zero. This enables us to simulate the pure lateral slip case in which the tire free-rolls on the roadway in the longitudinal direction. Slip angles are introduced by changing the direction and calculating the lateral and longitudinal components of the velocity vector. Thus, a small amount of slip ratio is inevitable when a slip angle is introduced. Lateral deformation of the tire inside the contact surface is shown from a bottom view in [figure 5-b](#). These lateral deflections due to the slip angle are the steady state tire deformations and do not include any transient behaviour.