The University of Alabama at Birmingham

School of Engineering

Department of Mechanical Engineering

in collaboration with

Center for Advanced Automotive Technology

Wheel Force Transducer



***Prepared By:***

**Vehicle and Robotics Engineering Laboratory**

**[](http://www.uab.edu/engineering/home)Mechanical Engineering Department**

**School of Engineering**

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**Vladimir V. Vantsevich**

**Professor and VREL Director**

**Jesse R. Paldan**

**Research Assistant**

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## Objective

1. Understand the design of a rotating wheel transducer
2. Understand the process of measuring wheel rotational kinematics parameters using the wheel transducer
3. Calculate the wheel torque and tire’s rolling radius using experimental data from the wheel transducer

### WHEEL FORCE MEASURING AND DATA ACQUISITION SYSTEM

#### Overview of the Wheel Force Transducer’s Construction

A wheel transducer, also called a rotating wheel dynamometer, is a sensor device for measuring forces and torques on a wheel. This wheel force measuring system (Fig. 1.1) consists of one to four wheel force sensors, a control unit, and a computer for control and data acquisition.



Figure 1.: Wheel Force Sensor

The system is powered from a separate 12V DC car battery. The three force components (x, y, and z axis) are measured by quartz force sensors. These have outputs in the form of electrical charges, which are converted into voltages by charge amplifiers in the wheel electronics on the wheel. The angular position of the wheel is determined by an electromagnetic angle encoder, and a built-in analog calculator then transforms the rotating coordinate system of the wheel force sensor into a stationary coordinate system relative to the car body using the output from the angle encoder. The same calculator derives the three components of the moment from the force signals. The signals are transmitted by slip rings to the stationary part of the wheel force sensor and to the control unit.

In the wheel transducer (Fig. 1.2), the force is introduced from the tire through the rim to the center flange, which is sandwiched between the two outer flanges, enclosing eight three-component force sensors. The sensors are preloaded in pairs by a high-strength bolt. The outer flanges are bolted together, passing through the bore of the center flange and transmit the force via the hub adapter to the standard hub of the car. This triple flange design with two sensors in a push-pull arrangement offers the advantage that the unit is insensitive to temperature changes.

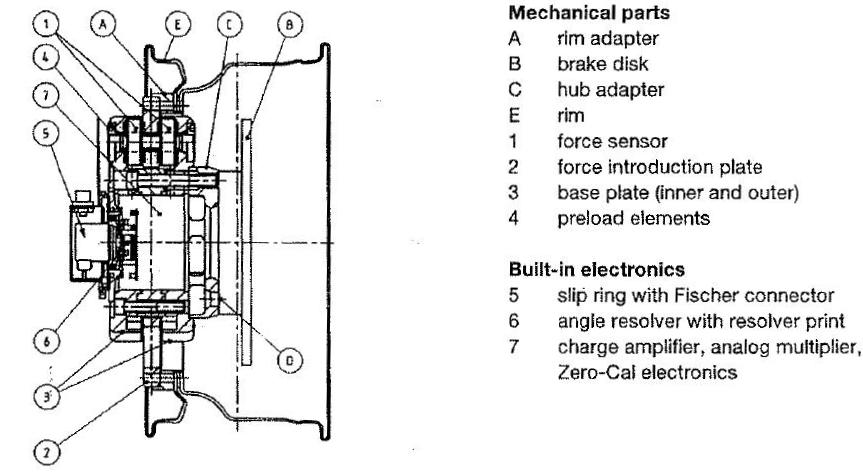


Figure 1.: Wheel Transducer side view

The center bore of the wheel force sensor contains the electronics, which consists of charge amplifiers, an angle encoder, an analog calculator for coordinate transformation, and slip rings for signal transmission.

A holding arm attached to the body keeps the stationary part of the angular encoder steady to define the reference point for the angular position of the wheel. It also holds the stationary part of the slip ring assembly and carries the cables. The wheel force sensor outputs directly the following signals:

* Force components Fx, Fy, Fz;
* Moment components Mx, My, Mz;
* Sine and cosine of the angular position of the wheel.

Rim adapters are used to attach rims of various sizes and offsets and make it possible to exchange already inflated and balanced tire/rim-base assemblies quickly. Hub adapters can be designed to accommodate for four to eight screw fixations. The hub adapter is fastened to the hub before the dynamometer is attached to it. Rim and hub adapters are matched to give the desired in- or outset. The standard rim of the vehicle is therefore replaced by the assembly, which consists of (Fig. 1.3):

* Hub adapter
* Wheel force sensor electronics
* Rim adapter
* Rim components

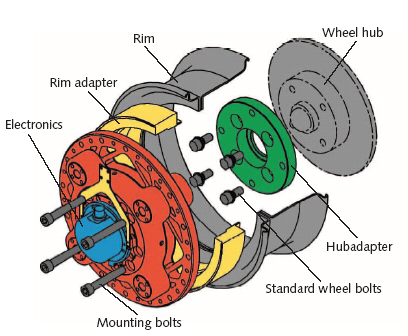


Figure 1.: Exploded view

The force is introduced from the tire through the rim to the center flange and transmitted via the hub adapter to the standard hub of the car. Data acquisition speed is limited to 250k samples/sec (no sample and hold). At a speed of 1,500 rpm (approximating 180 km/h) data can be acquired from all four dynamometers every 1.2°, generating 0.5MB/sec. of data. The samples of one dynamometer are all within 0.3°.

#### Wheel Transducer Force/Moment Calculations

The transducer calculates forces and moments on the wheel using the output of four sensors spaced around the transducer. Each sensor measures a force acting upon its x, y, and z axes. Therefore, there are 12 force components in total (, , and ). Each of these forces is measured in a frame of reference centered on the sensor, which rotate continuously with the wheel. To obtain useful data, they are transformed inside the sensor from this coordinate system (, , ) into a new frame of reference (X, Y, Z) which is fixed to the wheel and does not rotate. The following calculations explain this process. Force is the force in the longitudinal direction, the lateral force, and the force in the vertical direction. Figure (1.4) depicts the sensors spaced around the wheel, their force components, and the X, Y, and Z forces which need to be calculated. Angle α is the rotation angle of the wheel.

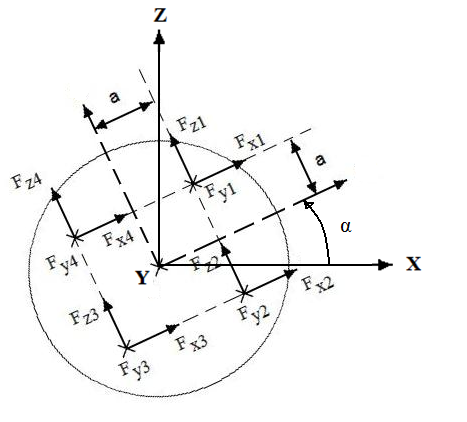


Figure 1.: Wheel Transducer force sensors

By adding forces which act along the same axis, we get

(1.1)

(1.2)

(1.3)

(1.4)

The following equations then transform the force components which rotate with the wheel into the coordinate system (X,Y,Z) which does not rotate:

(1.5)

(1.6)

(1.7)

The X, Y, and Z axis moments are also computed using the same force components (Refer to Fig. 1.5).

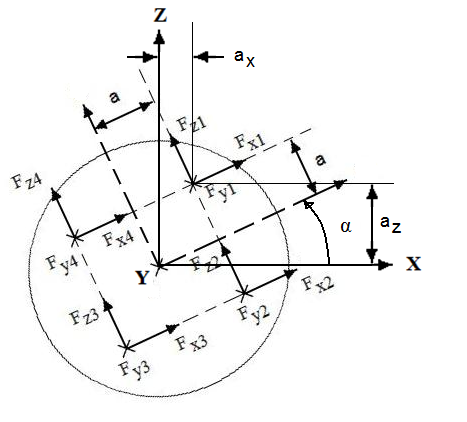


Figure 1.5: Moment computation diagram

(1.8)

(1.9)

(1.10)

Distances and are calculated with

(1.11)

(1.12)

where is the rotation angle in radians. is the distance between the center of each sensor and the center axis of the wheel in the x and z directions. This distance is 8 cm.

Note that these moments are measured in the counter-clockwise direction. Axis X points toward the front of the vehicle. The driving torque applied to the wheel is the moment about axis Y. However, a positive torque would act in the clockwise direction. Therefore, to obtain the wheel torque the moment should be have the opposite sign:

(1.13)

### Tire Kinematic and Force Parameters

#### 2.1 Mathematical Relationship between Tire Kinematic and Force Parameters

In many respects, features of the pneumatic wheel rolling process are connected with tire deformations. In this connection, it is expedient to give definitions to various radii of the wheel through which it is convenient to highlight an influence of the tire deformations on wheel kinematics and dynamics.

Traditionally, the static loaded radius  of a wheel is the shortest distance from the center of the stationary wheel loaded with the normal load  up to a basic surface

 (2.1)

where the free wheel radius  is equal to half of the outside diameter of the unloaded tire measured along the middle racing wheel path;  is the normal deflection of the tire or of the tire and soil for deformable surfaces.

The shortest distance from the center of a rolling wheel up to the road or up to the action line of the horizontal ground reaction when moving on a soil presents the dynamic radius, , of the wheel (Fig. 2.1).

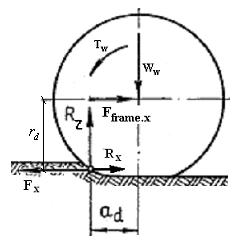


Figure 2.1: Drive mode. Free-body diagram

The radii  and  actually differ from each other a little bit due to the longitudinal tire deflection when the wheel is in motion (joint tire and soil longitudinal deflections on soils). However, one can assume that  for many practical computations. Based on the Coulomb approach to friction, the dynamic radius has been in use for many years to link forces and moments applied to a wheel (see references [1, 2], and Fig. 2.1):

 (2.2)

here,  is the wheel torque;  is the circumferential force;  is the rolling resistance force;  is the force that acts from the vehicle onto the wheel;  and  are the normal load and ground reaction. It should be noticed that the force  is equal to the wheel net tractive force , which is the resultant of the two forces in the tire-road/soil patch:

 (2.3)

The actual forward speed  of a wheel rolling in a rectilinear motion divided by the angular wheel speed, , gives neither the static radius, , nor dynamic radius, . This new radius has been named as the rolling wheel radius, and it is an important wheel parameter, which links the translational and rotational wheel velocities:

(2.4)

The rolling radius can be determined experimentally by measuring the wheel travel, , and the number of wheel revolutions, , that the wheel does moving from position 1 to position 2 under the action of the wheel torque (see Fig. 2.2):

(2.5)

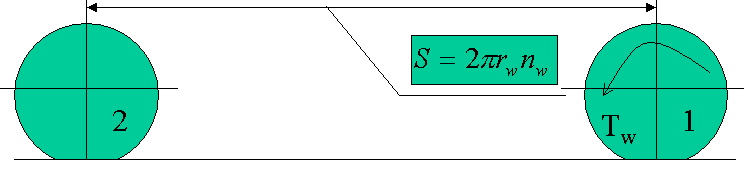


Fig. 2.2. Wheel rolling from position 1 to position 2

From Equation (2.5), the instantaneous value of the rolling radius can then be computed at any moment of time by knowing the change in 1) the wheel travel and 2) the number of revolutions that have occurred between the current moment of time and a previous time :

(2.6)

With a continuous measurement of the wheel’s angular travel , the number of revolutions can be computed with

(2.7)

To capture a signal for the linear travel distance, , a 5th wheel sensor can be used. Figure 2.3 shows this type of sensor attached to a vehicle. The 5th wheel is used to accurately measure the linear travel and velocity. Using from the wheel transducer and from the 5th wheel in Equation 2.6, the rolling radius can be computed.



Figure 2.3: 5th wheel sensor

The rolling radius of a wheel is not a constant. If a pushing force, which is equal to , is applied to the center of the wheel instead of the torque , the radius  will receive a different value. The same wheel will make a different number of revolutions, , when it covers the same travel under the action of the force . It takes place due to the change in the longitudinal deflection of the tire (or joint longitudinal deflection of the tire and soil on deformable surfaces of motion).

Hence, the actual value of the rolling radius strongly depends on combinations of forces and moments acting on a wheel. There are five major combinations of the longitudinal forces and the wheel moments that give five wheel modes [3, 4]: driven 1, neutral 2, free 3, drive 4, and braking 5 modes (see Fig. 2.4).

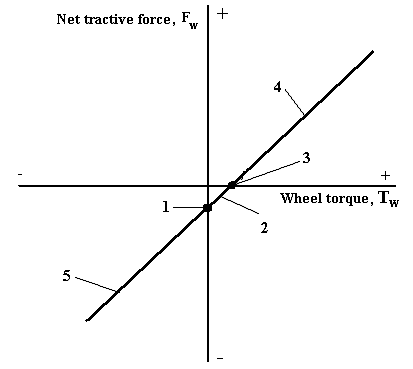


Figure 2.4: Five power-loading modes

As has been noticed above, the net tractive force, , becomes the pushing force  for the part of the vertical axis below zero in Fig. 2.4.

With this comes one important fact: the rolling radius is not only the relationship between the translational and rotational wheel velocities as it comes from Equations (2.4) and (2.5). This radius also links the tire kinematics with some force parameters of the tire. Different wheel modes from Fig. 2.4 are distinguished from each other by different values of the rolling radius. Moreover, whereas the driven and free modes have one value of the radius each,  and , the drive mode, the neutral mode, and the braking mode have the totalities of the rolling radius values, which engender various moments applied to a wheel.

When the wheel torque increases, the tire (and soil) receive bigger longitudinal deflections. At higher torques, all the points in the tire-surface patch may start moving relative to the surface of motion. In these conditions, the wheel does a bigger number of revolutions  on the same travel , and the rolling radius  decreases, respectively (see Fig. 2.2 and Equation (2.5)). Generally, the rolling radius  fluctuates from its value in the driven mode, , to zero when the wheel torque changes from zero in the driven mode to a higher value of  in the drive mode:

, when  (2.8)

Due to the described process, the values of the rolling radius  within this range of  determine locations of the instantaneous center of zero velocity (see point B in Fig. 2.5), which moves along the vertical axis of the wheel between the points given by the value of  and the rotation center of the wheel (see points A and C in Fig. 2.5).

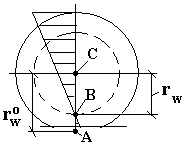


Figure 2.5: Instantaneous center of zero velocity

When the wheel torque  changes, the rolling radius  also changes due to both the tire longitudinal deflections (or joint tire and soil deflections on soft grounds) and relative motion between the tire and road/soil in the tire-road/soil patch. This change in the rolling radius may be defined as the tire slip coefficient:

 (2.9)

Mathematically, the above functional relation of the rolling radius  (same as the slip coefficient ) and the wheel torque  may be either linear or non-linear one depending on the tire and surface mechanical properties [3, 5, 6].

Another mathematically proven way to introduce the rolling radius for linking the tire kinematic and force parameters comes from the consideration of the wheel power balance equation. Based on the power balance equation of a wheel, it was proven that the rolling radius links the wheel torque with wheel forces in the longitudinal direction. From the power balance equation, the equation of wheel force balance may be derived. For different forms of the force balance equation, the rolling radii in some of the five modes are in use [3, 4, 5, 6, 7]. One of the forms is given below [4, 6]:

 (2.10)

Since the power balance equation gives a rather general approach to determining wheel forces comparing with a free-body diagram of a wheel based on Coulomb friction approach, one could notice that the rolling radius should be used instead of the dynamic radius when studying forces and torques on a wheel (see Equations (2.2) and (2.10)).

The rolling radius is of both theoretical and practical interest. Modern vehicles very often perform with tire slip even on firm roads when the vehicle speeds up with high acceleration and faces different friction conditions for its wheels. Tire slip signifies the longitudinal deflection of the tire (tire and soil on deformable grounds) and, accordingly, change in the rolling radius. Through many experimental studies, it was found that the rolling radius is not constant and follows the changes of the wheel torque, wheel normal load and tire inflation pressure. It is clear that Equation (2.6) can provide instant values of the radii if the time interval between the two measurements, i and (i-2), is really small and close to the longitudinal relaxation time constant. The physical meaning of the time constant is the time interval, in which the tire’s (tire-soil) longitudinal deflection is being established and the tire patch reaction force is emerging or changing under the action of an external force and/or applied wheel torque. Hence, the time constant is an available time period, during which the developments of the tire-soil deflections and reactions can be identified, analyzed and a control decision can be made and executed towards improving tire performance. This can be done by agile wheel torque control and, thus, agile longitudinal tire slippage control to enhance vehicle mobility and energy efficiency. Indeed, agile control of wheel torques and tire slippages can reduce slippages of some tires by re-distributing the torque to other wheels, which are in better terrain conditions. This can be done in a pre-emptive way while the tire-soil deflections are still changing which is an indication of emerging slippages of tires. The torque re-distribution to equal slippages between the tires can minimize the power losses in tire-terrain interaction and, thus, increase vehicle energy efficiency Since the instant rolling radii change very fast in time, their instant values can be utilized in agile slippage control. An agile tire slippage control algorithm should be designed as a parallel control of the agile tire slippage components, including the instant tire rolling radii and the wheel rim’s rotational kinematic parameters [8].

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## Assignment:

Experimental data is provided which was captured from a wheel transducer and 5th wheel during a vehicle maneuver lasting 11 seconds. This data includes:

* Time,
* Force components,
* Wheel angle,
* Travel distance (from 5th wheel),

1. Using the experimental data provided from the wheel transducer, calculate and plot the wheel torque.
2. Using the experimental data provided from the wheel transducer and 5th wheel, calculate and plot the rolling radius.