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School of Engineering

Department of Mechanical Engineering

in Collaboration with

Center for Advanced Automotive Technology

Force Plate Transducer



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## Objective

1. Understand the design of a force plate transducer
2. Understand the process of measuring a tire’s normal load using the force plate
3. Calculate the normal load and its offset distance using data from the force plate transducer

### Force Plate Sensor Description and Calculations

#### 1.1 Measuring Forces with a Piezoelectric Sensor

A force plate transducer is a plate embedded with sensors which respond to forces applied to the plate. This allows it to act as a surface to measures forces applied from above, such as a person walking or a vehicle tire rolling over the plate. The force plate uses a piezoelectric measurement method. These sensors use the piezoelectric properties of quartz crystals to generate an electric charge when forces are applied. A quartz crystal is silicon and oxygen arranged in a crystalline structure (SiO2). The application of force to the crystal deforms its lattice structure (Fig. 1). The deformation forces its positive silicon and negative oxygen ions towards each other. The resultant shift in the center of positive and negative charge generates an electric charge on the surface of the crystal.

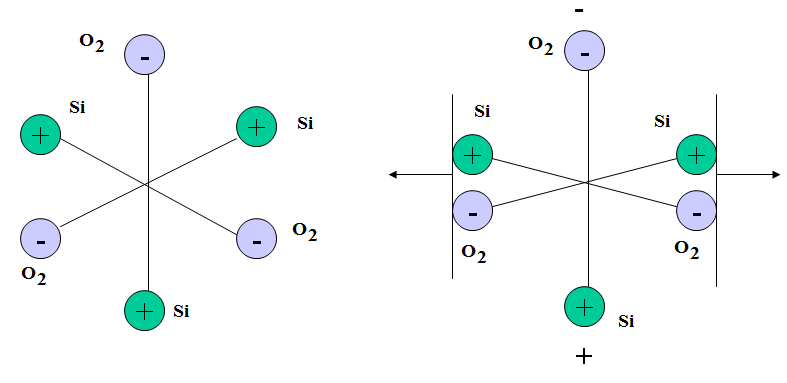


Figure 1: Quartz crystal structure in deformation

The orientation of the polar axes of the crystal with respect to the acting force determines the magnitude of the charge. Three different effects can accordingly be discerned (see Fig. 2):

* Longitudinal Effect
* Shear Effect
* Transverse Effect

The piezoelectric coefficient indicates the crystal’s degree of force sensitivity in the direction of the corresponding axis. The position of the crystal cut therefore determines the properties and the area of application for the quartz force link. Piezo-elements cut to produce a longitudinal effect are sensitive to compression forces and are therefore suitable for simple and sturdy sensors used to measure normal forces. Shear-sensitive piezo elements are used for sensors measuring shear forces, torque and strain.

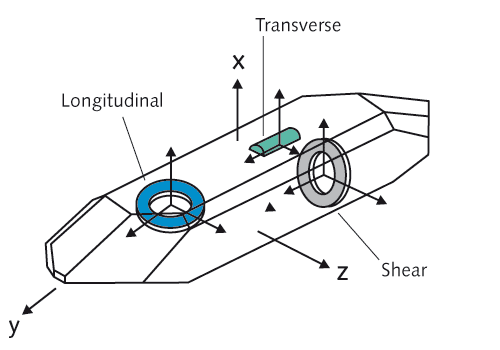


Figure 2: Orientation of effects on the quartz crystal

**Longitudinal Effect (Fig. 3)**

* The charge output occurs at the force contact surfaces and can be measured in this area.
* The magnitude of the electric charge depends only on the force applied. The dimensions of the crystal discs are immaterial.
* The only way to increase this charge is to connect several discs mechanically in series and electrically in parallel.
* If this is done, the size of the output charge is (for quartz):

(1.1)

where is the piezoelectric coefficient (–2.3 pC/N for quartz crystals), Fx is the force in the x-direction, and n is the number of crystal discs

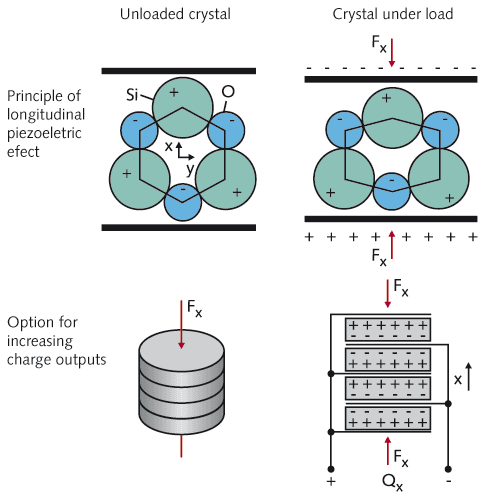


Figure 3: Longitudinal effect

**Shear Effect (Fig. 4)**

* The charge output occurs at the force contact surfaces and can be measured in this area.
* The magnitude of the electric charge depends only on the force applied. The dimensions of the crystal discs are immaterial.
* The only way to increase this charge is to connect several discs mechanically in series and electrically in parallel.
* If this is done, the size of the output charge is (for quartz):

(1.2)

where is the piezoelectric coefficient (–2.3 pC/N for quartz crystals), Fx is the force in the x-direction, and n is the number of crystal discs

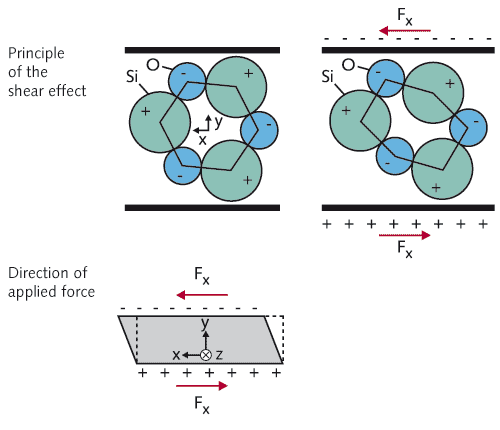


Figure 4: Shear Effect

**Transverse Effect (Fig. 5)**

* In the case of transversal effect, a force in the direction of one of the neutral axes y produces a charge on the surfaces of the corresponding polar axis x.
* In contrast to the longitudinal piezoelectric effect, the magnitude of this charge (which occurs on unloaded surfaces) is dependent on the geometrical dimensions of the piezoelectric element.
* Assuming element dimensions a and b, the charge is (for quartz):

(1.3)

where is the piezoelectric coefficient (–2.3 pC/N for quartz crystals), Fy is the force in the y-direction, b and a are dimensions of the piezoelectric element

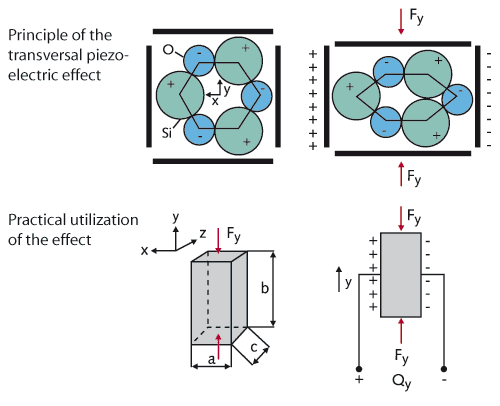


Figure 5: Transverse Effect

#### 1.2 Calculation of Resultant Forces

The force plate transducer as shown in Fig. (6) has four Piezoelectric sensors at each corner (represented by numbers 1, 2, 3 and 4). Each sensor has three pairs of quartz plates, one sensitive to pressure in the z-direction and the other two to shear in the x and y directions respectively. Thus, application of pressure ‘P’ on the force plate will give four signals for each direction proportional to forces in those directions. The forces are represented by Fx1, Fx2, Fx3, and Fx4 for the x-direction, Fy1, Fy2, Fy3, and Fy4 for the y-direction and Fz1, Fz2, Fz3, and Fz4 for the z-direction.

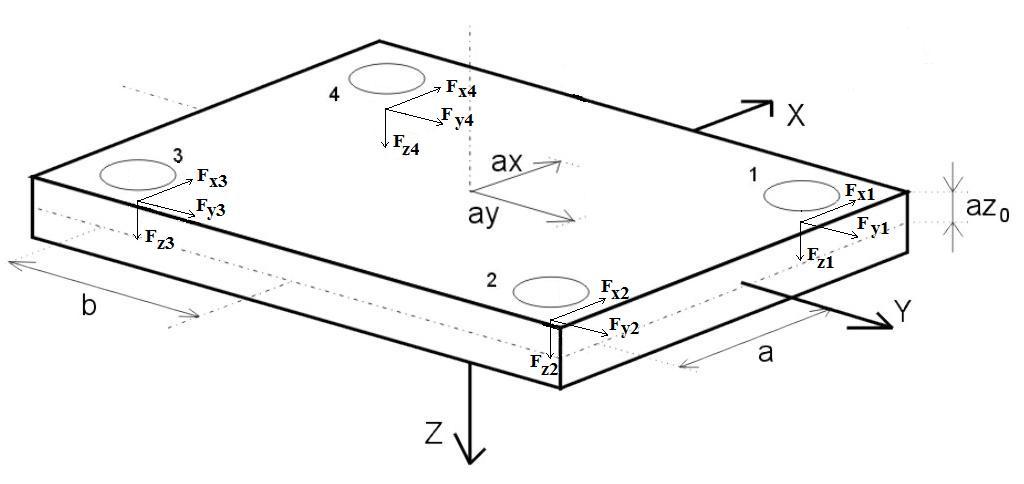


Figure 6: Force plate diagram for forces in X, Y, and Z direction

As seen from Fig. (6), and have same line of action and hence can be combined to give one signal represented by

(1.4)

Similarly, we get

(1.5)

(1.6)

(1.7)

***Resultant Forces along the Sensor Plane Axis (X, Y and Z):***

Resultant forces in each direction are obtained by summing forces in that direction:

(1.8)

(1.9)

(1.10)

The total resultant force, , is calculated using the x, y, and z components of the force with

(1.11)

***Moment about Sensor Plane Axis (X, Y and Z) and Plate Surface:***

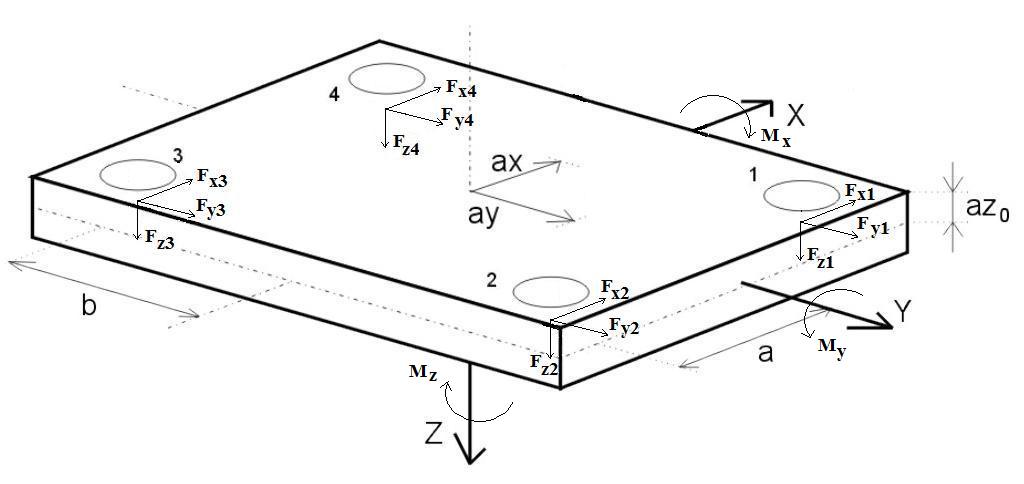
x, y, and z axis moments (see Fig. 7 for the location and orientation of the moments) are calculated using

(1.12)

(1.13)

(1.14)

where a and b are dimensions on the force plate shown in Fig. 7. The moments have a counter-clockwise orientation.



.

P

O

Figure 7: Force plate moment diagram

Moments about the Plate Surface X’ and Y’ (see Fig. 8) are calculated with

(1.15)

(1.16)

where is the vertical distance from the center of the plate to its surface. Since the z axis is positive in the downward direction, has a negative value.

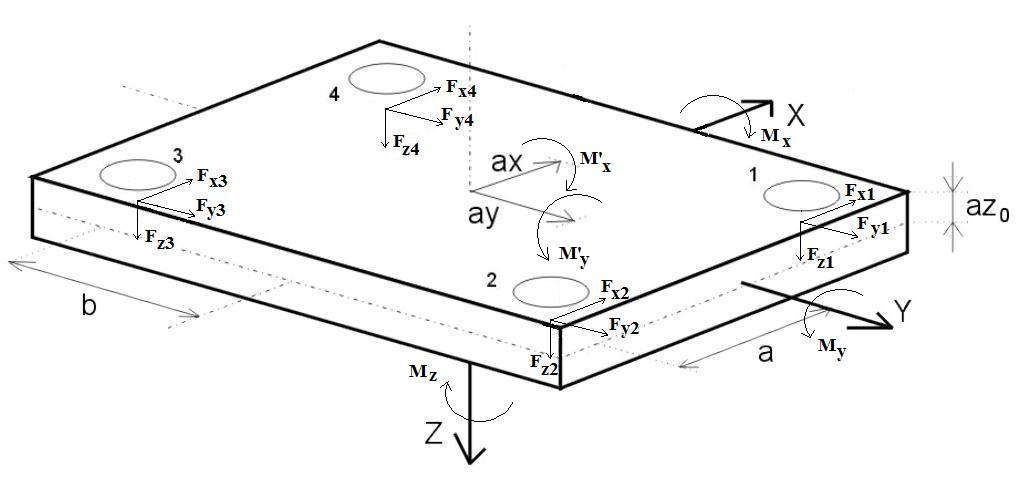


Figure 8: Moments about the plate surface

***Center of Pressure (Point ‘O’):***

The center of pressure (COP) is at distance (, ) from the force plate’s center

The moment about the COP along y-axis,

Hence,

(1.17)

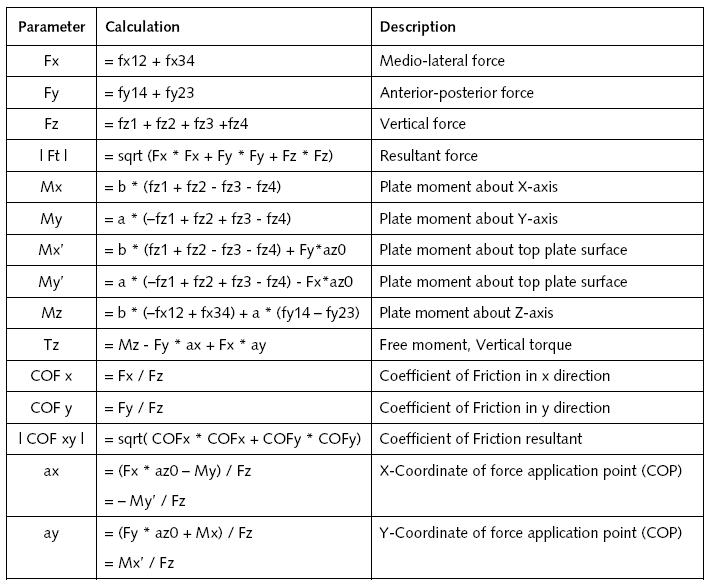
Moment about the COP along x-axis,

Hence,

(1.18)

A Summary of all calculations using the force plate is presented in Tab. 1:

Table 1: Force plate calculation summary



### Overview of the Tire’s Loading Properties

#### 2.1 Normal Reaction and Offset Distance

When a wheel is not in motion, the load is distributed symmetrically about wheel vertical axis (Fig. 9a). is the load exerted by the weight of the wheel. is the normal reaction. When the wheel is in motion, the load distribution is no longer symmetrical (Fig. 9b), resulting in an offset distance between and .

|  |  |
| --- | --- |
| (a) | (b) |

Figure 9: Load distribution under (a) an unmoving tire and (b) a moving tire [1]

Figure 10 illustrates a wheel in the driving mode (the wheel torque and the longitudinal reaction from the frame, , is not zero). For a given vehicle specification (curb weight) and pay load (total passenger and cargo weight) and similar road condition he frame force will be constant. is the rolling resistance force. is the circumferential force which results from the applied wheel torque. For a driving wheel, needs to overcome and to move the wheel. The application of the wheel torque results in a change of the longitudinal deflection of the tire (Fig. 10a), and of the tire and the soil (Fig. 10b). The tire circumference is deflected in region 1-2 (increasing from point 1 to point 2) before this region contacts the surface of motion. The longitudinal compression becomes even bigger in region 2-3-4. The tire circumference can slip in zone 3-4 in the direction that is opposite to the wheel’s motion. Under large torques, the whole region of 2-3-4 can slip relative to the surface. Finally, the longitudinal deflections of the tire are significantly less in region 4-5 than in region 1-2.

|  |  |
| --- | --- |
| Figure 2a_V4.jpg  (a) | Figure 2b_V2.jpg  (b) |

Figure 10: Illustration of longitudinal deflections of: (a.) a tire on a road; (b.) a tire-soil contact on deformable surfaces [2]

As any elastic body, the tire should deflect before it transmits a load (a force or torque). For this reason, the tire cannot move at the time moment when the wheel torque (or force) is applied. The tire should accumulate a longitudinal deflection and get “twisted” by the torque relative to the rim and the surface with the twist angle that is usually not more than 2 degrees. This “twist” process also occurs when a tire is already in motion and the applied wheel torque varies. Thus, the rim-tire set can be considered as a two-degree of freedom system with rotation of the rim and angular motion of the tire [2]. Different configurations of torque and forces exerted on the tire results in different tire-soil longitudinal deflections and different modes of a rolling tire. Figure 11 depicts a tire in the driven mode (no torque is applied to the tire).

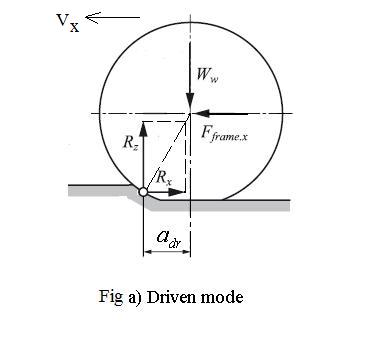
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Figure 11: Tire in the Driven Mode

The frame force is generated by the torque at the drive wheels. At a constant velocity as shown in Fig. (11), resolving the forces in the horizontal direction gives

(2.1)

Resolving the moments about the wheel center gives

(2.2)

where, is the rolling radius of the driven wheel. Solving Eq. (2.1) and Eq. (2.2) results in

(2.3)

As seen from Eq. (2.3), the offset is a function of

1. **Normal Load :** The normal load is a function of gross vehicle weight (curb weight + pay load). For a given vehicle specification (curb weight) and pay load (total passenger and cargo weight) it will be constant when the wheel is moving at a constant velocity. Acceleration in the longitudinal direction (when the vehicle speed is changing), the lateral direction (when the vehicle is in a turn), and vertical direction (when the vehicle is moving on uneven ground) causes dynamic shifting in the distribution of loads among the vehicle’s wheels.
2. **Frame Force :** The frame force is generated by the torque at the drive wheels. For a given vehicle specification (curb weight) and pay load (total passenger and cargo weight) and similar road condition it will be constant.
3. **Rolling Radius :** Rolling radius for a driven wheel is a function of normal load and tire inflation pressure.

### Distance Measurement and Data Acquisition

#### 3.1 Measuring the Wheel Center’s Location

Measuring the offset distance of the normal reaction experimentally requires 1) the location of the force and 2) the location of the wheel. The location of the force is accomplished with the force plate’s center of pressure calculation (Eq. (1.18)). To measure the location of the wheel center, a second system is needed: a combination of a laser distance sensor and 5th wheel sensor will be used. Figure 12 shows a 5th wheel sensor attached to a vehicle. The 5th wheel is used to accurately measure the linear travel and velocity.



Figure 12: 5th wheel sensor

The laser distance sensor (Fig. 13a) is attached to the wheel center. This sensor gives a distance measurement by calculating the time it takes for a reflected laser beam to return to the sensor. An obstacle (Fig. 13b) is placed along the edge of the force plate. When the wheel crosses onto the force plate, the laser beam will be interrupted by the obstacle. This will make a sudden change in the distance measurement recorded by the laser.

|  |  |
| --- | --- |
| (a) | (b) |

Figure 13: Laser sensor (a) and obstacle (b)

The result allows the precise time in which the wheel crosses the force plate to be recorded. The process of calculating the wheel center’s linear travel distance, , is as follows:

* Continuously record a travel distance with the 5th wheel sensor.
* Record the time at the moment the laser sensor detects the obstacle. This is the time value, , in which the wheel center reaches the force plate’s edge.
* Look up the distance measurement from the 5th wheel at time .
* Subtract the distance from .

(3.1)

This makes a measurement of the wheel center’s location relative to the force plate’s edge. has a value of zero when the wheel center is aligned with the edge of the force plate. increases as the wheel crosses further onto the force plate. It has negative values before the wheel reaches the plate. Now, can be compared with the center of pressure. The difference between the two is the offset of the normal reaction.

#### Data Acquisition Units

The data acquisition system used to connect the sensors to a PC for recording data is shown in Fig. 14. (1) is a junction box for connecting wheel force/torque transducers. (2) is a power inverter which provides electrical power to the system from the car’s battery. (3) is a National Instruments CompactRIO control unit. The control unit contains modules with terminals that allow multiple sensors to be connected. Data from all sensors is recorded to an attached PC.



Figure 14: Data Acquisition Unit

Figure 15a shows the complete measurement and data acquisition system for the force plate, which includes the force plate itself, junction box, and PC. The junction box (Fig. 15b) provides a direct interface between the PC’s data acquisition board and force plate with integrated charge amplifier. The charge amplifier converts the small values of the charges produced by the Piezoelectric sensors into a voltage proportional to the force.

|  |  |
| --- | --- |
| MVC-028S (a) | MVC-026S (b) |

Figure 15: Force plate (a) connected to PC and (b) junction box

# References

[1] Vantsevich, V. V., “Inverse Wheel Dynamics,” ASME Conf. Proc. 2006, 227 (2006), DOI:10.1115/IMECE2006-13787

[2] J. P. Gray, V. V. Vantsevich, J. R. Paldan, Agile Tire Slippage Dynamics for Radical Enhancement of Vehicle Mobility, Journal of Terramechanics, Volume 65, June 2016, Pages 14-37, ISSN 0022-4898.

## Assignment:

Experimental data is provided which was captured from a tire rolling over the force plate. This data includes:

* Time,
* Force components,
* Location of the wheel center,

The dimensions of the force plate are

(refer to Fig. 8 for a diagram of these dimensions on the force plate)

Full length of the force plate along the y-axis (see Fig. 16)

1. Using the experimental data provided, calculate and plot the tire’s normal reaction, .
2. Using the experimental data provided, calculate and plot the offset distance of the normal reaction, , by determining the difference between the location of the wheel center and the center of pressure recorded by the force plate.

Note: Figure (16) shows the orientation of the wheel and force plate when the test was done. The wheel moves along the plate’s y-axis. The center of pressure in the y-direction is measured from the center of the force plate. The wheel travel is recorded relative to the force plate’s edge as shown in Fig. (16).

*Rz*

*sw*

*ay*

*ly=0.6 m*

+ Direction of wheel travel

*adr*

Figure 16: Tire on force plate