Technical Paper

Development of Tire Torque Sensor

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Received on July 18, 2014
Presented at the JSAE Annual Congress on October 13, 2011

ABSTRACT: A sensor that is capable of directly measuring tire torque has been developed to improve vehicle control. The sensing element is installed between the brake rotor and wheel, where both the drive torque and breaking torque can be measured. The easy detachment of the sensor from the brake rotor and wheel was achieved using a screw joint. The beams on the sensing element are set in parallel with the wheel’s axis of rotation and the bending strain of the beams is measured and converted to torque. The measured torque data is transmitted wirelessly. A measurement accuracy of ±5% was confirmed during the actual running of the vehicle, and the appropriate torque change was measured according to the acceleration and braking of the vehicle.

KEY WORDS: vehicle dynamics, tire and wheel, torque sensor, strain measurement, wireless measurement [B1]

1. Introduction

Various environmental, safety and comfort demands of vehicles have been increasing in recent years. In order to achieve low fuel consumption, safety, comfort, and dynamics performance at a high level, a method to optimally control energy and torque from a vehicle’s engine to its tires has been developed [2,3].

One technology to control the energy and torque focuses on controlling the drive torque and braking torque which are generated in the tire. If tire torque control technology can be realized, vehicle stability and energy recovery efficiency are expected to improve. Therefore, it is important to develop measurement technology such as a tire torque sensor to measure the tire torque directly in a tire [3,4]. Such a sensor would be effective not only as a vehicle control sensor but also as a development tool. For example, it would be useful in optimizing the drive torque and braking torque by providing feedback regarding a tire torque information, and for the analysis of torque transfer characteristics from vehicle’s engine to its tires.

However, the existing tire torque sensor relies on a wheel that is specially modified for measurement [5]. There have been adaptability problems around mounting the sensor on a different kinds of vehicles or evaluating various kinds of tires immediately.

Therefore, in this research, a tire torque sensor that is capable of directly measuring tire torque and which can be used on commercial wheels has been developed. The sensing element is installed between the brake rotor and wheel, where both the drive torque and breaking torque can be measured. The tire torque data is captured using a telemeter system.

2. Development of Sensor

2.1. Sensor Specifications

The specifications of the developed tire torque sensor are shown in Table 1. A small size front-wheel drive vehicle which has 1500cc of engine displacement and whose wheels have four screw holes was chosen as the development object. The sensor was mounted between the wheel and brake rotor where both the braking and driving torque of the tire could be measured when the vehicle was running. The thickness of the sensor was designed to be 20mm, which is the same width as a general wheel spacer so as to ensure the tire did not stick out from the vehicle body. In consideration of the use of data analysis and vehicle control when running, the target measurement range was set to ±1000Nm with a target measurement accuracy of ±5%.

Table 1  Sensor Specifications

| Object Vehicle | Mass Production Vehicle with 4Hole PCD100 Hub |
|----------------|---------------------------------------------|
| Mounting Location | Between Brake Rotor and Wheel |
| Size            | 140mm×20mm                                  |
| Measurement Range | ±1000Nm                                     |
| Measurement Accuracy | ±5% (±50Nm)                                |
| Sampling Rate   | 1kHz                                        |
| Data Transfer Method | Telemeter                                  |
| Maximum Temperature | 100 Ž                                     |

2.2. Measurement Method and Sensing Element

Regarding the method of torque measurement, the strain measurement method was adopted in consideration of the response and accuracy [6]. Three items were considered when designing the sensing element: the large quantity of strain to input torque, the margin of breaking strength, and the need for a
thickness less than 20mm. FEM analysis was examined to predict the strain and stress which would be generated on the sensing element. The shape of the torque sensing element is shown in Figure 1.

The beams on the sensing element are set in parallel with the wheel’s axis of rotation and the bending strain of the beams is measured. The eight strain gauges installed in each beam are constructed in a bridged circuit, and strain quantity calculated by the formula (1) is considered as the driving and braking torque.

To achieve the target measurement accuracy, the strain quantity was stabilized by measuring the strain of the whole region of a beam across the entire width. A measurement error due to wheel detachment were reduced by designing a high degree of stiffness in the joint between the wheel and brake rotor. Measurement errors due to different kinds of wheels have also been reduced by keeping the contact surface with a wheel within a limited area. The breaking strength was simulated with a FEM analysis. The test condition was assumed to be the highest load of the outer wheel when the vehicle was turning, and it was checked to ensure that the stress was within the tolerance level.

\[
\varepsilon_{My} = \frac{\varepsilon_1 - \varepsilon_2 + \varepsilon_3 - \varepsilon_4 + \varepsilon_5 - \varepsilon_6 + \varepsilon_7 - \varepsilon_8}{2}
\]  

(1)

2.3. Sensor Structure

The structure of the tire torque sensor including the signal processing and telemeter system is shown in Figure 2. The sensing element is fixed to the brake rotor using the existing hub bolts. The wheel is fixed to the sensing element with the other hub bolts installed in the position with the phase shifted 45 degrees from the existing hub bolts.

Wirings from a strain gauge are connected to the signal process and telemeter circuit installed in the center of the sensor. After being converted into a digital signal by the circuit, torque data is transmitted wirelessly from the transmitter antenna to the receiver antenna which is fixed to the fender. Electromagnetic induction and a battery can be used as the power supply method. In this case a battery was adopted in order to simplify the sensor. Measurement for approximately 8 hours is possible with dry cell battery.

3. Evaluation of Sensor

Evaluation of static condition, tire rotation condition and a vehicle on a chassis dynamometer was conducted to confirm the performance of the developed sensor.

3.1. Accuracy Evaluation of the Static Condition

The measurement accuracy was evaluated using the calibration apparatus shown in Figure 3. A hub assembly with the sensor was fixed to a rig. A known quantity of static load from arbitrary directions was applied to the wheel by oil pressure cylinders and the sensor output was evaluated.

3.1.1 Linearity and Gain

The linearity and gain of the sensor output when the static torque equivalent to drive torque and braking torque was applied are shown in Figure 4. In order to satisfy the ±5% of target accuracy, it was necessary to present a minimum linearity of ±5%, and it was checked that the linearity was less than ±1%. In order to satisfy the ±1% of measurement accuracy, sensor output of 213 \(\pi\) str/1000Nm or more of were required from the performance of the signal-processing circuit, and it was checked that the gain was 300 \(\pi\) str/1000 Nm.
3.1.2 Cross-Talk
The 6-component force (three forces and three torques) acts on a tire. One of the 6-component force is drive torque and braking torque (My) which is the object of measurement. Other than this force, longitudinal force (Fx), lateral force (Fy), vertical force (Fz), over-turning moment (Mx), and self-aligning torque (Mz) are also present. The sensor is required to sense just the drive torque and braking torque and not sense the other five forces. If the other forces are sensed, it is called cross-talk and considered a measurement error. The sensor output when both driving and braking torque (My) and the other forces were act on the wheel was compared with the sensor output when just the drive torque and braking torque were act on the wheel. The evaluation result of cross-talk is shown in Figure 5. The drive torque and braking torque can be measured to an accuracy of $\pm 2\%$ without cross-talk from the other forces.

Even when the same wheel was detached and a wheel with a different form of contact surface was attached, a measurement accuracy of $\pm 2\%$ was achieved as shown in Figure 6.

As a result of the above static evaluations, it was confirmed that the sensor has a target accuracy of less than $\pm 5\%$ even when considering any cross-talk error and wheel attachment error.

3.2. Evaluation of the Tire Rotation Condition
The sensor was evaluated under a tire rotation condition using the test apparatus shown in Figure 7. The purpose of this evaluation was to check the measurement accuracy under a running condition and to check the working of the telemeter system. The parts from the suspension arm to the tire were attached to the apparatus. The preload equivalent to the load from a vehicle was applied to the tire. The tire was rotated by the chassis dynamometer and an arbitrary braking torque was applied by controlling the brake oil pressure. The measurement value of the developed tire torque sensors was compared with the measurement value of a commercial wheel torque meter.

The result is shown in Figure 8. The torque fluctuation synchronized with the tire rotational period appeared at the tire torque sensor signal. It is thought that some cross-talk occurred. However, the change is less than $\pm 5\%$ of the target measurement accuracy.
The response of the sensor at the time of braking start and tire stop was equivalent to a commercial wheel torque meter. Moreover, when braking from 100 km/h was repeated, the temperature of the sensor rose to 100 °C due to the generation of heat by braking, however there was no failure of the strain gauges or telemeter system.

3.3. Evaluation on a Chassis Dynamometer

The sensor was installed in a test vehicle and a running test was carried out on a chassis dynamometer. The evaluation result of measurement accuracy is shown in Figure 9. Two tire torque sensors were installed in the right and left drive wheels, and the total value on each wheel was compared with the torque of the chassis dynamometer. The wheel speed was fixed to 50 km/h and the driving torque was changed by controlling the position of the accelerator pedal.

4. Example of Measurement

4.1. Measurement of Transient Torque

The measurement result of the transient torque change is shown in Figure 10. The torque changes according to the acceleration and braking of a vehicle, and the measurement response of the torque was good compared with the torque of a chassis dynamometer.

4.2. Torque Transmission Characteristics

An example of the torque transmission characteristics of the vehicle is shown in Figure 11. By measuring the torque of each part from the engine to the tire, it becomes possible to realize the trend of the torque transmission loss in each operating condition.

5. Conclusion

(1) A sensor that is capable of directly measuring tire torque with a telemeter system has been developed. The sensing element is installed between the brake rotor and wheel, where both the drive torque and breaking torque can be measured. The easy detachment of the sensor was achieved using a screw joint to the brake rotor and wheel.

(2) As a result of an evaluation of both the static and tire rotation conditions, the developed sensor was confirmed to measure torque within an accuracy of ±5% at a condition of 100 km/h and 100 °C.
It was presented that the sensor can be installed in a vehicle and can measure the transient change of the tire torque, and by using the developed tire torque sensor, the torque transmission characteristics of a vehicle can be measured.

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