DEVELOPMENT OF TIRE PRESSURE MONITORING SYSTEM USING WHEEL-SPEED SENSOR SIGNAL

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Abstract

It is difficult for today's motorists to detect a loss of tire pressure since a gradual tire pressure loss occurring on four wheels at the same time (natural leak) accounts for a large proportion of the tire pressure loss incident.

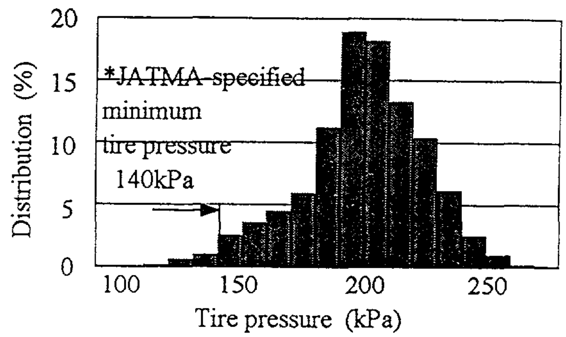
To help overcome this difficulty, we have developed a tire pressure monitoring system using the wheel-speed sensor signal of the ABS system. The monitoring system is low in cost and is capable of detecting the simultaneous air pressure loss on four wheels.

Background to R&D Effort

It seems that today's motorists are paying less and less attention to tires since the improved performance of tires has reduced the natural tire pressure loss and consequently reduced the incidence of puncture.

Nonetheless, there is a natural loss of tire pressure at around 5-10 kPa/month. With an additional tire pressure change caused by the change in ambient temperature (approx. 10 kPa/10℃), the driver may experience low tire pressure without knowing it.

Fig. 1 shows the results of the survey on the tire pressure of the cars parked at the employee's parking lot of our affiliated company. 4.4% of these cars had the tire pressure of 140 kPa or less, and about 64% of which (or 2.8% of the cars surveyed) had nearly the same tire pressure for four wheels (natural leak). On the other hand, 0.2% of total cars surveyed had the tire pressure difference of 50kPa or more among four wheels.



*JATMA : The Japan Automobile Tire Manufacturers' Association, INC.

Fig. 1 Results of Survey on Distribution of Tire Pressure

Table 1 shows the number of on-site services by Japan Automobile Federation (JAF) for tire trouble.

JAF made about 3,800 on-site services per week or about 200,000 services when simply translated into yearly terms on general roads and expressways.

Table 1 Causes for Calling the JAF Rescue Service (Weekly Basis)

Cause of trouble	General roads		Expressways	
	Number of cases	% total	Number of cases	% total
Tire	2783	3.64	1069	11.75
Fuel shortage	970	1.27	732	8.05
Locked-in key	25316	33.09	415	4.56
Traffic accident	4532	5.92	533	5.86
Battery	18012	23.55	703	7.73

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Since long-range driving of a car with under-inflated tires will lead to deterioration in stability, controllability and fuel economy, acceleration of tire wear and tire burst, a number of tire pressure loss detection systems have been commercialized in the recent years.

One such system consists of a pressure sensor mounted inside the tire to directly measure the tire pressure.

It is highly accurate but has yet to be popularized due to its high cost. The recently-commercialized monitoring system that uses the tire revolution difference data transmitted by the wheel-speed sensor of ABS (which is similar to our system) has succeeded in reducing the cost, but it can not detect the simultaneous loss of tire pressure on four wheels (natural leak) since the system is based on relative determination of the conditions of four tires.

Principle of Detection

Fig. 2 shows the power spectrum density (PSD) of the wheel-speed sensor signal at the standard air pressure (200 kPa) and the low air pressure (100 kPa).

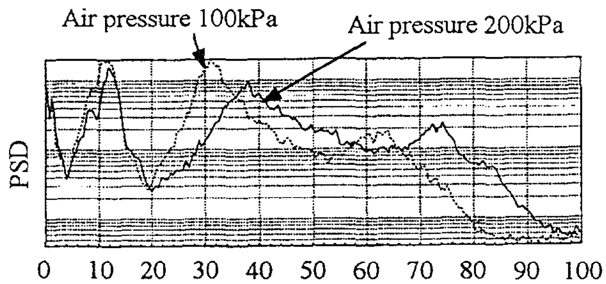

Fig. 2 PSD of Wheel-Speed Sensor Signal

As the air pressure changes, the peak frequency in the frequency band of 30 to 40 Hz varies. This variation is probably due to the coupled vibration of tire and suspension since this frequency band nearly overlaps with the longitudinal acceleration.

If the variation in resonance frequency is detected, a change in the tire pressure can be detected. However, a significant volume of data will be required to obtain stable results, and this means greater workload on the on-board electronic control unit (ECU) which will limit the cost reduction effort.

Fig. 3 shows the relationship between the spring constant in the direction of the rotation of the tire and the tire pressure as determined in the hammering test of an individual tire. The chart shows that the spring constant almost changes in proportion to the tire pressure.

A tire model can be constructed on the basis of these results, and by using this model, the amount of variation of the torsional spring.

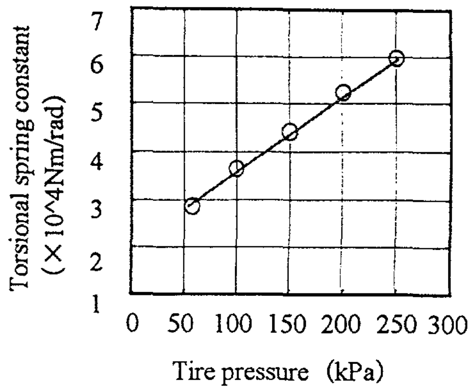

Fig. 3 Relationship between Torsional Spring Constant and Air Pressure of Tire

Tire Model

Fig. 4 indicates the tire model used for our system.

In this model, J1 is the moment of inertia on the rim side, J2 is the moment of inertia on the belt side, K is the torsional spring constant of the tire, D is the equivalent viscous damping coefficient of the tire, $\omega 1$ is the rotational speed on the rim side (detectable), $\omega 2$ is the rotational speed on the belt side, θs is the torsional angle and Td is the road surface disturbance.

The equation of state for this diagram is shown below:

$$\begin{cases} J1\,\dot{\omega}1 = -K(\theta 1 - \theta 2) - D(\omega 1 - \omega 2) \\ J2\,\dot{\omega}2 = K(\theta 1 - \theta 2) + D(\omega 1 - \omega 2) - Td \\ \theta s = \theta 1 - \theta 2 \end{cases} \quad (1)$$

The variation of the spring constant K in this equation from the standard value is estimated by the external disturbance observer and the least-squares method.

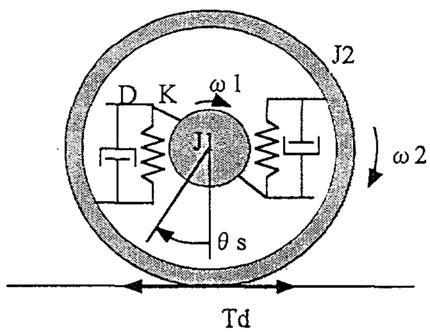

Fig. 4 Tire Model

The block diagram of the estimation procedure is shown in Fig. 5. In this diagram, the pre-filter is a band path filter that separates the resonance component from the wheel-speed sensor signal.

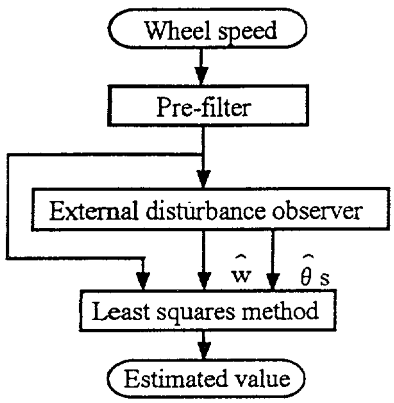

Fig. 5 Block Diagram of Air Pressure Estimation Method

Estimation of External Disturbance

When the tire pressure changes, and the torsional spring constant K and the equivalent viscous damping coefficient D change as shown in Equation (2),

$$K \rightarrow K+\Delta K \quad D \rightarrow D+\Delta D \tag{2}$$

the equation of state for the tire becomes equivalent to the condition in which the external disturbance, as shown in Equation (4), is applied to the normal condition, as shown in Equation (3).

$$\begin{bmatrix} \dot{\omega}1 \\ \dot{\omega}2 \\ \theta s \end{bmatrix} = \begin{bmatrix} -D/J1 & D/J1 & -K/J1 \\ D/J2 & -D/J2 & K/J2 \\ 1 & -1 & 0 \end{bmatrix} \begin{bmatrix} \omega 1 \\ \omega 2 \\ \theta s \end{bmatrix} + \begin{bmatrix} 0 \\ -1/J2 \\ 0 \end{bmatrix} Td \tag{3}$$

$$w = \begin{bmatrix} 0 \\ -1/J2 \\ 0 \end{bmatrix} Td + \begin{bmatrix} -(\Delta K/J1)\theta s-(\Delta D/J1)\theta' s \\ (\Delta K/J2)\theta s + (\Delta D/J2)\theta' s \\ 0 \end{bmatrix} \tag{4}$$

Since only the data on $\omega 1$ can be obtained, $\omega 2$ which secondary factor is expressed in Equation (5) is estimated.

$$w2/J2=-(Td/J2)+(\Delta K/J2)\theta s+(\Delta D/J2)\theta s \tag{5}$$

When this external disturbance is included in the equation of state equation for the system to construct an observer of the least order, the estimated external disturbance can be expressed as Equation (6).

$$\begin{aligned} \hat{w}2 &= -Td+\Delta K \hat{\theta} s+\Delta D \hat{\dot{\theta}} s \\ &= [\Delta K \quad \Delta D] \begin{bmatrix} \hat{\theta} s \\ \hat{\dot{\theta}} s \end{bmatrix} - Td \end{aligned} \tag{6}$$

Consequently, variations ΔK and ΔD are estimated by using the least-squares method.

Improvement in Detection Accuracy

In this section, the problems and the countermeasures related with the use of the estimated (variation of) spring constant under the above algorithm on the actual vehicle, and part of the compensation logic, which has taken into consideration the use environment, will be introduced.

1. Separation of Uniformity Noise

The estimated value was found to vary at high vehicle speeds and at a certain vehicle speed. This variation was caused by the variation component of the rotational period, appearing in the form of a variation in the wheel speed under the influence of the uniformity of tire and sensor rotor, being added to the coupled vibration of tire and suspension.

Since the problem lay in the oscillation of the rotational rotational period of the tire, it was separated by learning compensation of the periodic component. Fig. 6 shows the results of the countermeasure.

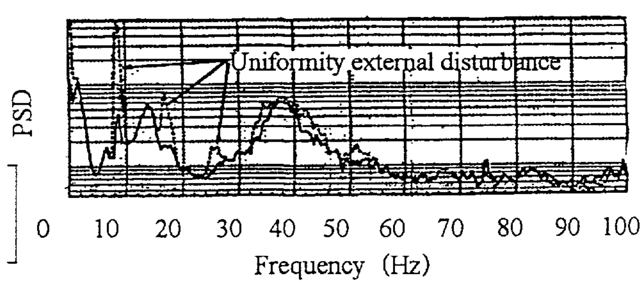

Fig. 6 PSD after Separation of Tire Uniformity

2. Compensation for Outside Air Temperature

Changes in the rubber hardness of the tire according to the temperature are shown in Fig. 7. Since the changes in the rubber hardness of the tire affect the spring constant in a certain temperature range, the estimated spring constant was compensated for by taking into consideration the temperature data.

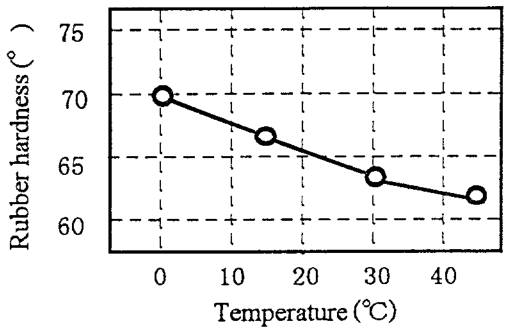

Fig. 7 Changes in Rubber Hardness According to Temperature

System Configuration

Fig. 8 shows the system configuration and Fig. 9 shows the parts layout diagram. This system consists of a wheel-speed sensor that detects the rotational speed of four wheels, a temperature sensor that collects temperature data, a set switch that makes the system learn the initial setting for the timing of tire replacement, a computer that calculates to estimate the tire pressure based on the above signal and send outputs to the warning lamp, and a warning lamp in the meter that indicates the tire pressure loss.

If the computer is shared with other systems, the set switch and the warning lamp will be the only parts designed exclusively for this system.

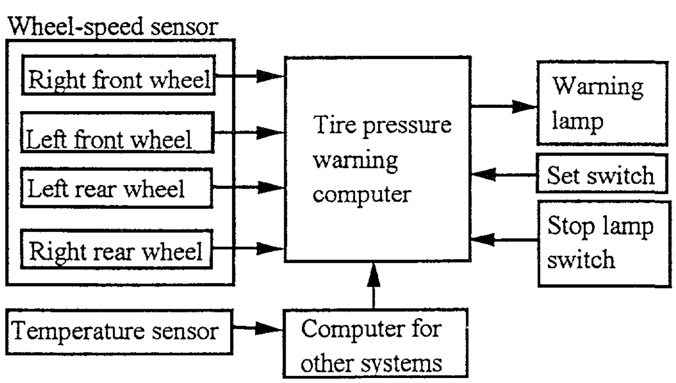

Fig. 8 System Configuration

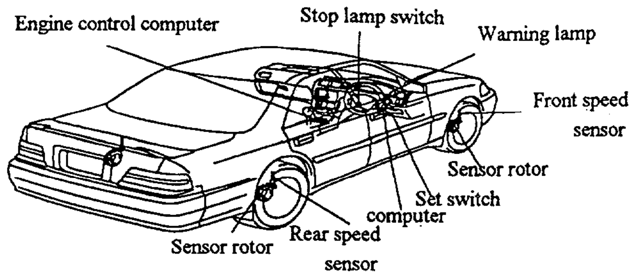

Fig. 9 Parts Layout Diagram

The design of the warning lamp is the one being applied to ISO (Fig. 10).

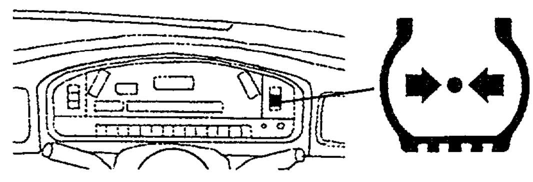

Fig. 10 Example of Warning Lamp

System Performance on Actual Vehicles

Fig. 11 shows the results of the evaluation of a vehicle equipped with this system.

The test vehicle had the following specifications:

- Rear-wheel-drive vehicle
- 3.0-liter natural aspiration engine
- A/T
- Tire size: 205/65R15

The computer-output values of the test vehicle driven on the test course were evaluated at three levels of tire pressure.

It was found that the computer-output value fell as the tire pressure fell.

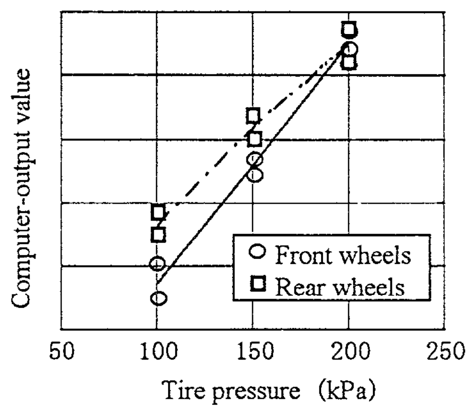

Fig. 11 FR Vehicle Road-Test Results (on Test Course)

Fig. 12 shows the results of the evaluation of another vehicle equipped with this system conducted outside the company.

The test vehicle had the following specifications:

- Front-wheel-drive vehicle
- 1.6-liter natural aspiration engine
- A/T
- Tire size: 185/65R14

Although the variation in the estimated value slightly increased for the general road driving because of variations in road surface conditions and running conditions, the system was confirmed to show adequate performance in practical uses with the addition of the above compensation logic.

In this system, the estimated value is updated every 60 seconds. In the event of a puncture caused by nail or other foreign objects on the tire, the time required for reduction in the tire pressure to the JATMA-specified minimum pressure of 140 kPa will be about 30 minutes, if the standard pressure is set at 200 kPa. Thus, the estimation time is considered to be practically sufficient.

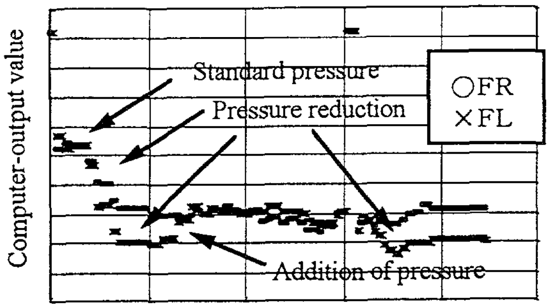

Fig. 12 FF Vehicle Exterior Road Test Results (approximately 2-hour driving)

Conclusion

- By focusing on the correlation between the tire pressure and the spring constant of the tire, a system in which the variation in the spring constant of the tire was estimated on the basis of the wheel-speed sensor signal for each wheel by using the external disturbance observer.
- The system was developed at a low cost by using the existing wheel-speed sensor for ABS, and designed to detect the tire pressure loss of a single wheel as well as the simultaneous tire pressure loss on four wheels.

Finally, the authors wish to express a renewed feeling of gratitude to numerous people concerned in the development effort for their cooperation.

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