

Development of a Tubeless Tire Pressure Monitoring System for Motorcycles

Masayoshi ORITA*

Tomoyuki HARADA*

Toshio YAMAGIWA*

ABSTRACT

A tire air pressure monitoring system for motorcycles was developed. The system informs a rider of low air pressure or an air leak in the tire. High monitoring accuracy was obtained by compensating for the temperature of the air pressure, by measuring air pressure in the tire, by changes in pressure and temperature during running, and by the lowering of air pressure in the case of a flat tire. An air leak is judged by the speed of the air leak converted from an air pressure change and temperature change. The adjustment of the unbalanced revolution of wheels was minimized by mounting a separated tire valve and sensor. Indication of the air pressure and an alarm is for enhancing the rider's recognition during running.

1. Introduction

The recent trend toward larger motorcycle tire sizes and a prevalence toward low-profile tire designs has made it increasingly difficult for the rider to sense underinflated tires or tire air leakage while riding. For safety reasons, it is important for the rider to be aware of any such reduction in air pressure. Thus, a tire air pressure monitoring system for motorcycles has been developed. The system informs the rider of sudden air leaks brought on by tire punctures and helps prevent poor fuel economy caused by driving on underinflated tires by detecting a drop in tire air pressure and notifying the rider of this condition. A tire air pressure monitoring system detects tire air leakage in one of two ways: either by indirect detection, in which the system uses an anti-lock brake system speed detector to detect any differences in the rotation speed of the front and rear tires when a significant leak occurs, or by direct detection, where changes are detected in the tire pressure inside the tire. The indirect detection method is less reliable as there are only two tires for which it is able to draw comparative readings. For this reason, the direct method for detecting changes in tire pressure has been adopted. To accurately detect tire air leakage the system must be able to detect and compensate for the relationship between tire air pressure and temperature changes to determine the cause of the change in tire pressure.

The system also needs to be able to determine the tire temperature allowable limit since increases in tire temperature, due to underinflation, are a leading cause of tire failures. The system must also have an interface display suitable for motorcycles to effectively notify the rider of tire pressure abnormalities. While there are currently tire pressure monitoring systems used in automobiles, this newly

developed technology is the world's first motorcycle tire air pressure monitoring system.

2. Targeted Development Goals and Related Issues

In developing a tire air pressure monitoring system for motorcycles, the unique characteristics of motorcycle tires and driving conditions were reviewed and considered before the development targets and topic areas were defined. The developmental goals were to:

- (1) Build a system that can detect changes in tire air pressure and temperature while the motorcycle is being ridden and that can accurately inform the rider of tire pressure changes that can possibly lead to tire failure.
- (2) Study the relationship between tire damage and temperature changes that occur when the motorcycle is being operated with low tire pressure and have a set temperature at which the system can predict the possible occurrence of a tire failure.
- (3) Develop a communication system that incorporates a stable line of transmission within the legal regulations established in Japan, which has adopted the lowest field intensity in the world. The system must also be reliable enough to prevent erroneous data transmission.
- (4) Develop a display system that enables the rider to discern failure conditions and system errors.
- (5) Develop a sensor that incorporates intelligent assembly design.
- (6) Develop a system that preserves battery life from the time of production to the point of sales, in order to provide a transmitter life period of 10 years.

* Asaka R&D Center

3. Analysis of Tire Air Temperature and Air Pressure by Tire Fault Forecasting

To predict tire fault conditions, the relationship between the tire air pressure and the temperature inside the tire was analyzed, and then to what degree these apply to the tire failure was determined. Sudden changes in tire pressure brought on by punctures were also analyzed and the possibility of prediction and precognition of tire failures were discussed.

3.1. Tire Temperature at Tire Damage Occurrence

Continued driving on low inflated tires causes tire chipping and leads to tire damage. An endurance test was

conducted while driving on a test drum to record the tire surface temperature and the temperature inside the tire until damage occurred. Air pressures of 50 kPa, 100 kPa, 150 kPa, 200 kPa and 280 kPa were initially set while the tires were still cold. The tire rotation speed was gradually increased from 170 km/h to 280 km/h. Figures 1 and 2 show the respective tire surface temperature conditions recorded with a thermograph.

At low tire air pressure conditions, the left-right block on the tire tread pattern showed an increase in temperature and chipping. Tire air pressure was then set relatively high at 200 kPa, and driven at high speed yielding a high surface temperature at the center part of the tire tread leading to chipping. Figure 3 shows the relationship between the tire air pressure and tire tread surface temperature, tire sidewall

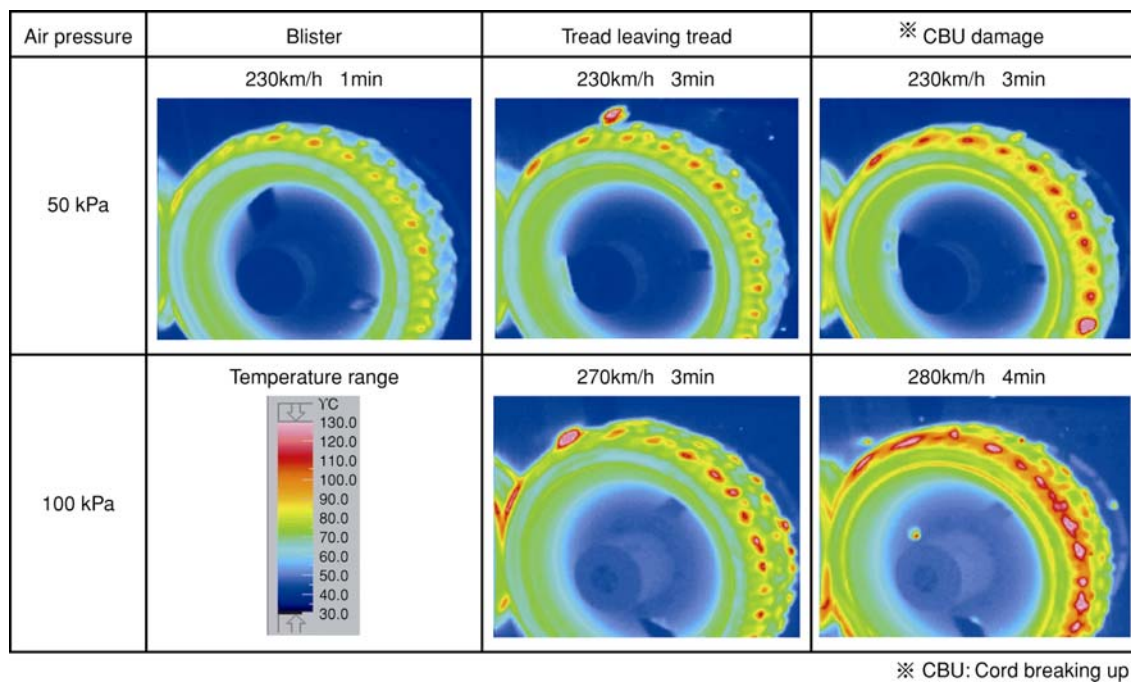


Fig. 1 Temperature images of tire surface: Air pressure 50, 100 kPa

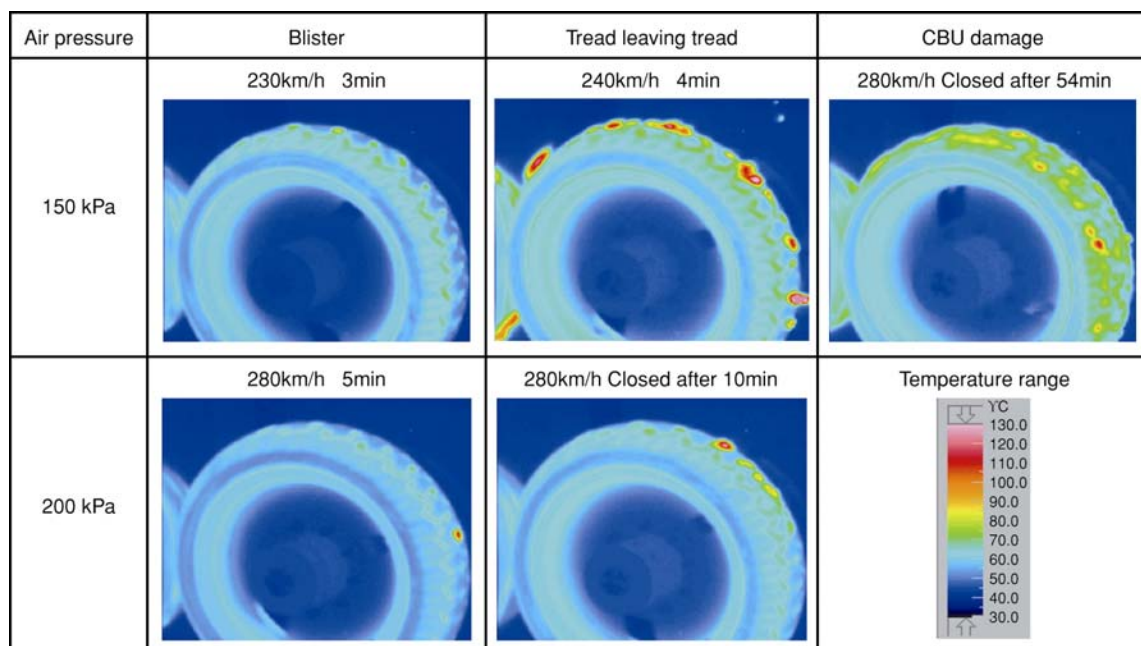


Fig. 2 Temperature images of tire surface: Air pressure 150, 200 kPa

surface temperature, and the temperature inside the tire. These all showed tire failure in the end. The tread surface temperature and the air temperature inside the tire showed a correlation but there was considerable difference in the tread surface temperature and sidewall surface temperature. The higher the tire pressure, the greater the discrepancy became. Furthermore, the lower the tire pressure, the higher the sidewall deflection, which generated more heat and higher air temperature inside the tire. Figure 4 graphically shows a relationship between the air temperature inside the tire and the tire pressure as a parameter. This revealed that the lower the tire pressure, the greater the heat generated from tire flex and the prevalence of chipping and bursting. Figure 5 shows the relationship between the temperature inside the tire and the drum rotation speed, as well as the resulting tire failures. From this, it has been learned that the higher the rotation speed, the easier it becomes for tire failures to occur. Figure 6 shows the relationship between the air temperature inside the tire and the running distance, as well as the resulting tire failures. This has shown that as the temperature inside the tire increases, tire failures tend to occur more readily. Also, the running distance at which the tires can maintain normal conditions tends to decrease at high temperatures.

These three graphs show that tire failures occur more readily with high tire temperature, lower tire pressure and at higher running speeds. Additionally, as conditions like loading force are increased, there is a greater likelihood of tire failures resulting from sudden tire temperature increases. As Figures 4, 5 and 6 clearly demonstrate, the majority of bursting and chipping faults occur in temperature conditions

greater than 100 °C. Consequentially, the system temperature warning buzzer has been set at 100 °C. The temperature warning buzzer has a second function to indicate tire failures caused by the tire being driven on low air pressure. Tire deflection caused by over loading and driving beyond the permissible speed range also may cause the tire temperature to increase. The implementation of a temperature warning device has enabled greater accuracy in tire failure identification.

3.2. Verification of Air Leak Speed at Puncture Occurrence

Tire damage frequently occurs as a result of continued running on low air pressure brought on by natural air leakage in rubber tires and by punctures that occur when a foreign object pierces the tire. Most cases of sudden tire pressure deflation occur when an object which has pierced a tire on a local street, suddenly comes out of the tire while travelling at high speed. To detect this occurrence, testing was repeated in which a tire was pierced with a $\varnothing$ 2.8 nail and the test drum speed set to a speed range of 0 ~ 120 km. The tire was run over the test drum as the speed was gradually increased. Figure 7 shows the measurements of air leakage that occurred in the drum test.

For safety, it is important that the rider be notified of any such air pressure leakage. To satisfy this requirement, the system's air pressure measurement interval was set to 7.5 seconds. In the experiment, the nail came out of the tire by centrifugal force causing the tire pressure monitor buzzer

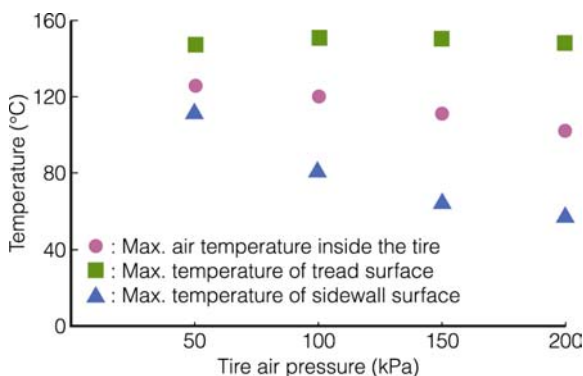


Fig. 3 Relation between temperature of each part of tire and air pressure in tire

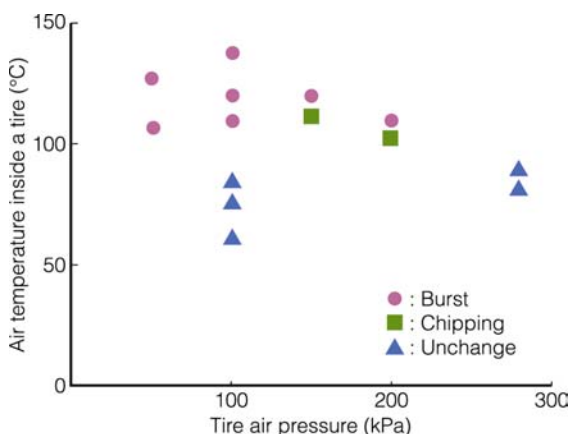


Fig. 4 Relation between air temperature and air pressure in tire at failures

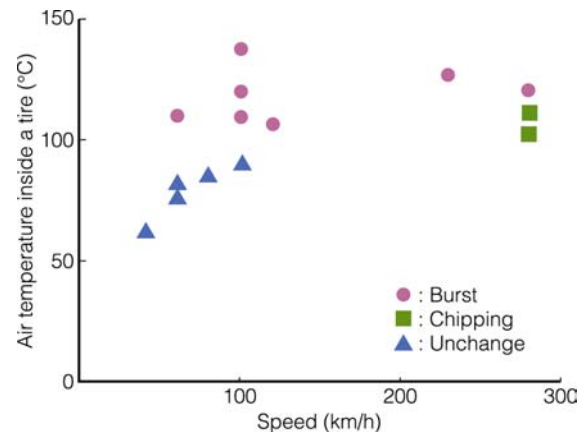


Fig. 5 Relation between air temperature in tire and drum rotation speed at failures

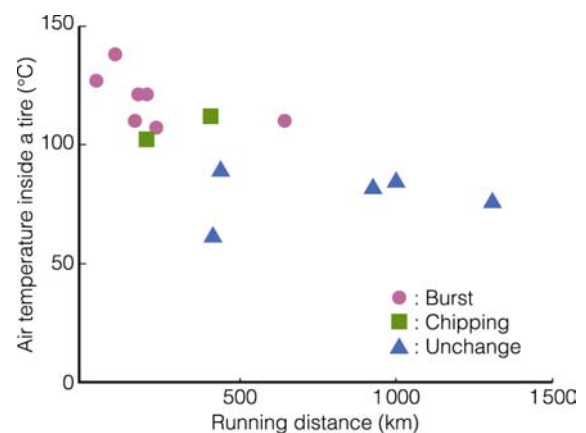


Fig. 6 Relation between air temperature in tire and running distance at failures

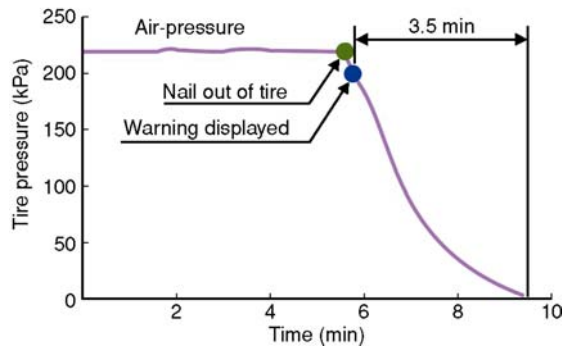


Fig. 7 Result of air leakage by drum test

to sound. It took the air pressure 3 minutes and 30 seconds to drop to zero thereby providing a greater opportunity for the rider to determine an accurate measurement.

3.3. Increasing Detection Accuracy by Temperature Correction

The newly developed air pressure monitoring system works by detecting air leakage according to changes in air pressure. To further increase the level of detection accuracy, the system must also be able to correct for changes in tire air pressure according to temperature changes. Figure 8 shows the changes in air pressure over a period of elapsed time without the application of any temperature correction. As the graph shows, the temperature tends to rise as the air pressure decreases. From this, it can be judged that it becomes increasingly important to adjust changes in temperature with temperature correction as the air pressure decreases. Figures 9 and 10 show the relationship between the changes in measured air pressure according to the temperature inside the tire, and the corrected air pressure following temperature correction. Air pressure adjusted according to temperature can be expressed in the following formula.

$$P = P_x - (T_x - 30) \quad (1)$$

P: Corrected air pressure (kPa)

Px: Measured air pressure (kPa)

Tx: Measure temperature (°C) (for conditions where temperatures are greater than 30 °C.)

Formula 1 expresses how air leakage is detected. However, since the formula has been devised for temperatures above 30 °C, temperature correction does not apply to temperature conditions below 30 °C. This is because in low cold temperature conditions, the system misjudges the lower temperature for the standard air pressure and inaccurately concludes the result to be air leakage.

3.4. Increasing Detection Accuracy by Atmospheric Pressure Correction

Prescribed air pressure inside the tire is regulated by relative atmospheric pressure and gauge pressure. As the altitude changes, the air pressure also changes resulting in a variance in tire air pressure even though there is no air leakage. As the altitude increases from 0 m to 3,000 m, the gauged air pressure reading decreases by 30 kPa. This loss represents a 15% reduction in the prescribed standard air pressure setting of 200 kPa and has a large influence on the detection accuracy. Generally, air pressure is regulated according to pressure gauge readings. Once the tire pressure has been adjusted at a high altitude and the motorcycle

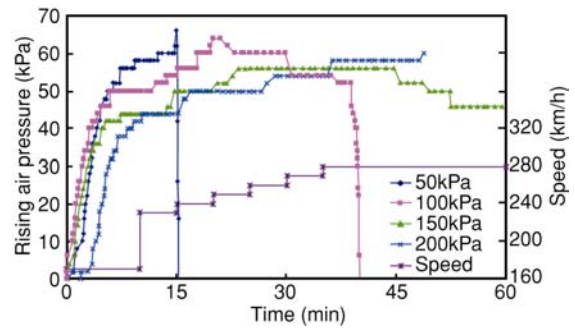


Fig. 8 Relation between air pressure rise and elapsed time during running

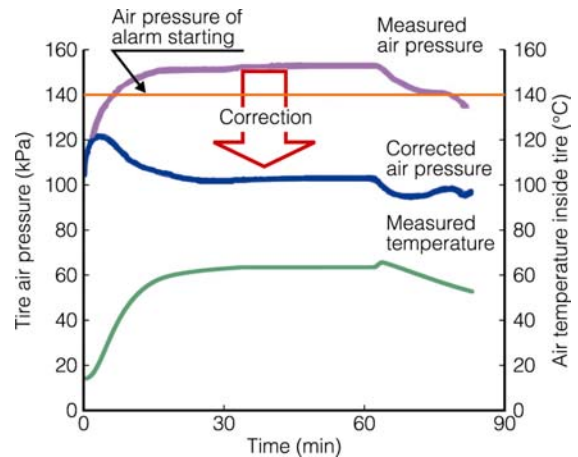


Fig. 9 Example of air temperature rise in tire

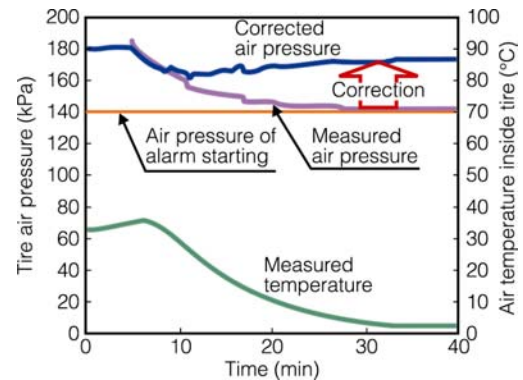


Fig. 10 Example of air temperature decline in tire

descends to a lower altitude, the surrounding atmospheric pressure increases causing the tire air pressure to decrease. Adopting a pressure sensor in the air pressure monitoring system will only measure the absolute pressure but does not measure the difference in atmospheric pressure. There is a concern that as the difference in the absolute pressure measured by the sensor and adjusted gauged tire pressure at high altitude increases, the air pressure monitoring system will increasingly be unable to detect air leakage and low air pressure tire conditions. On the other hand, tires that have had air pressure set at low altitudes show a gauge pressure increase as they move to higher altitudes. Conversely, riders living at high altitudes experience decreases in tire air pressure as they move to lower altitudes. Therefore, effective atmospheric correction will increase the accuracy of the air pressure warning system to respond as the motorcycle moves to higher or lower altitudes.

4. System Configuration

Figure 11 shows the configuration and layout of the air pressure monitoring system. The system is divided into a transmitter, a receiver, and a display unit. The transmitter is fitted to the wheel rim inside the tire and is located on both the front and rear tires. The pressure inside the tire and the temperature are measured in intervals of 7.5 seconds. The measured data is transmitted as radio signals. The signals are transmitted once every 6 minutes if no abnormalities are detected. If a pressure leak occurs, the system detects the leak and transmits the data every 7.5 seconds.

The receiver receives the radio signals from the transmitter, analyzes the data and sends the tire air pressure and temperature information to the display unit. If any abnormality is detected, the receiver sends a warning signal to the display unit as well.

The display unit informs the rider of the current tire condition. To assist the rider in recognizing abnormalities, the system sounds a warning buzzer and displays the information on the display panel. Figure 12 shows the mounting position of the transmitter with air pressure sensor.

Current air pressure sensor transmitters used in automobiles typically consist of a combined valve and sensor transmitter assembly unit. However, air pressure sensor transmitters for motorcycles are designed with separate valve and sensor units. Since motorcycle wheel rims are shaped differently from that of automobiles, the air valves are mounted in different directions. On automobiles, the air

valves are usually mounted horizontally while they are mounted vertically on motorcycles. The sensor transmitter is mounted on the inside of the tire wheel and is built separately from the valve. This is to avoid any wheel imbalance caused by the weight of the transmitter. The transmitter mounting is positioned as required to cancel this imbalance. The transmitter is shaped so as to facilitate tire removal and mounting and is mounted on the inside rim opposite the valve. This also allows for less additional weight for wheel balancing. Figure 13 shows the mounting position of the transmitter on the tire wheel.

The sensor transmitter consists of a sensor unit with a semiconductor pressure sensor and a thermo sensor; a circuit unit which determines the air pressure status based on the measured air pressure and temperature conditions and then transmits this data from the built-in antenna; and a small button-shape lithium battery. The circuit unit uses a low frequency radio wave setting of 315 MHz that is applied to keyless entry systems used on automobiles designed for the Japanese market. Transmission signals for each transmitter are allocated unique ID numbers to enable identification of each transmitter. The sensor transmitter achieves reliable durability by adopting a potting processed circuit capable of handling the severe vibration, acceleration, high temperature and humidity conditions, and a power enhanced exclusive lithium battery. Figure 14 shows the configuration of the transmitter with sensor and Table 1 lists the transmitter specifications. The receiver has the same functions and design configuration as the above mentioned keyless entry

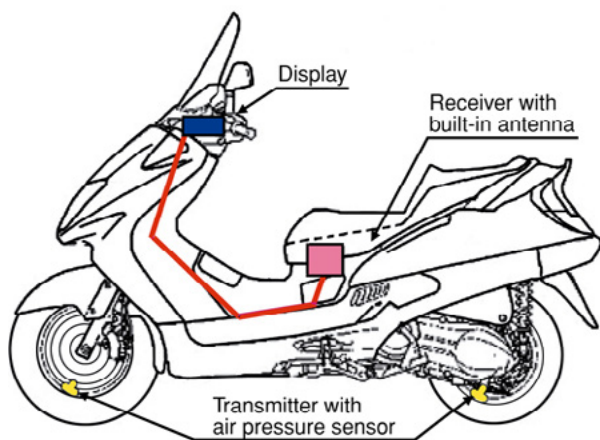


Fig. 11 Configuration of monitoring system of tire air pressure

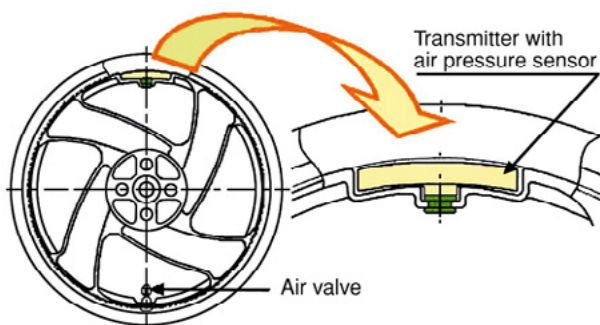


Fig. 12 Mounting location of transmitter with air pressure sensor

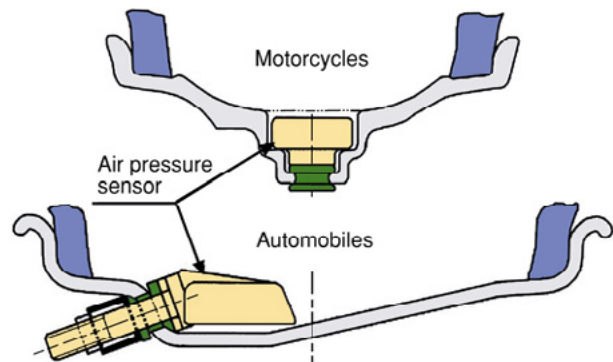


Fig. 13 Comparison of section shape motorcycle's wheel and automobile's wheel

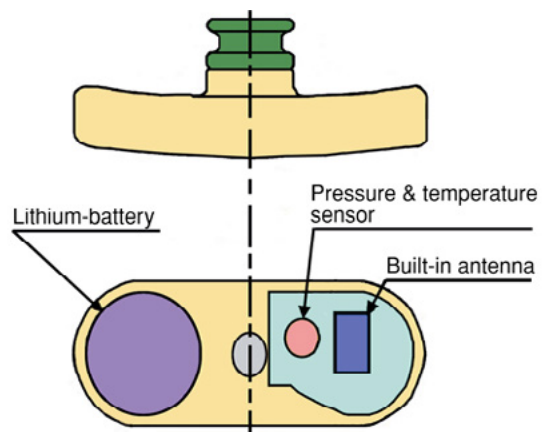


Fig. 14 Configuration of transmitter with air pressure sensor

system. The receiver receives data relating to tire air pressure and temperature from the transmitter and judges whether air leakage, low pressure or abnormal temperatures exist then sends the data to the display unit. Figure 15 shows the receiver unit configuration and Table 2 lists the receiver specifications.

Table 1 Specifications of transmitter with air pressure sensor

Items	Specifications
Mass	50 grams
Pressure sensing element	Semiconductor pressure sensor
Pressure sensing range	0 - 500 kPa
Pressure sensing accuracy	$\pm 2\%$
Temperature measuring range	- 40 ~ 120 °C
Temperature measuring accuracy	$\pm 8\text{ }^{\circ}\text{C}$
Transmitting frequency	314.98 MHz
Modulation formula	FM modulation
Power supply	Coin shaped lithium battery

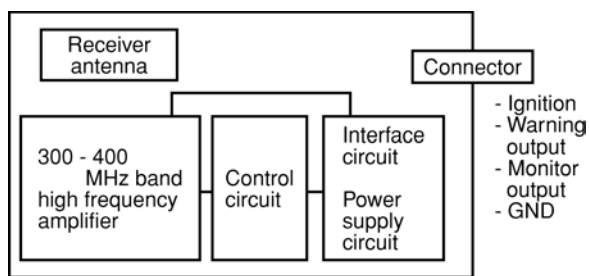


Fig. 15 Configuration of receiver

Table 2 Specifications of receiver

Items	Specifications
Receiving band	300 kHz
Receiving sensitivity	3 dB μ V
Mass	60 grams
Antenna	Built-in type
Power source	In-vehicle battery

5. Differences in Field Intensity According to Radio Law and Systemic Variation

Figure 16 shows the allowable ranges of transmitter field intensity defined by respective radio laws in Japan, USA, and Europe. As shown in the figure, Japan imposes the most stringent standard level set at 54 dB μ V/m, the lowest intensity level shown in the comparison.

Existing automobile specifications applied in the USA and Europe position the respective antennas close to the transmitter unit. On the other hand, this system receives radio waves transmitted from the individual units mounted on the front and rear wheels with antenna integrated into one receiver. This configuration sets the receiver at a considerable distance from the transmitter resulting in a weakening of receiver field intensity. This system applies a unique ID to each transmitter and uses FSK type wave transmission. The receiver's single built-in antenna enables reliable transmission even in weak field intensity settings and conforms to domestic radio law standards.

6. Warning System

6.1. Warning Fundamentals

American automobile regulations set by the National Highway Traffic Safety Administration (NHTSA) have

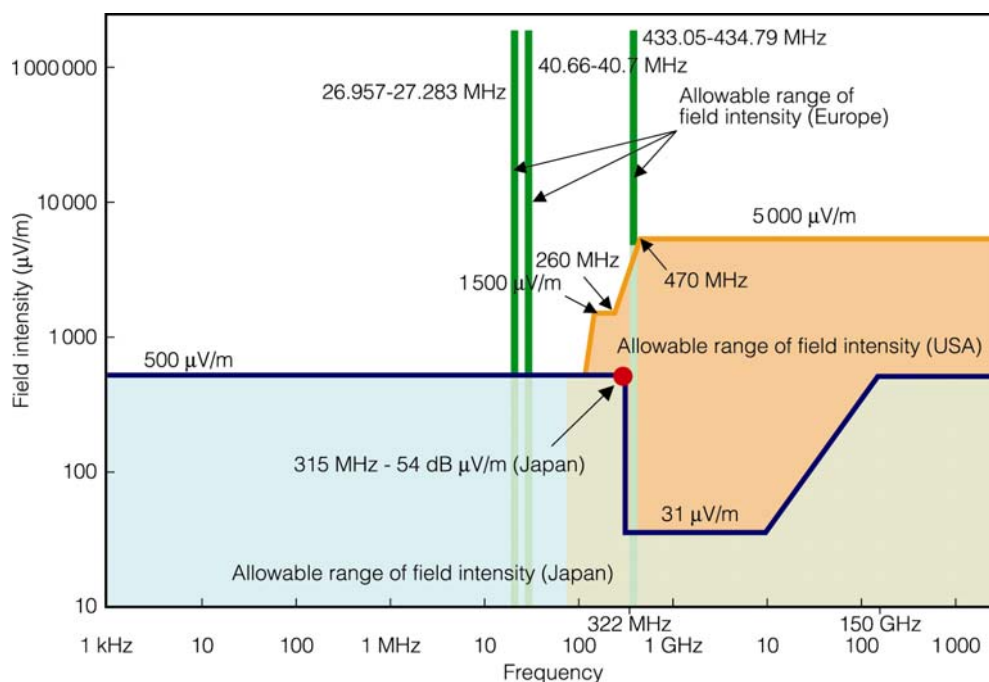


Fig. 16 Radio Laws in Japan, USA, and Europe

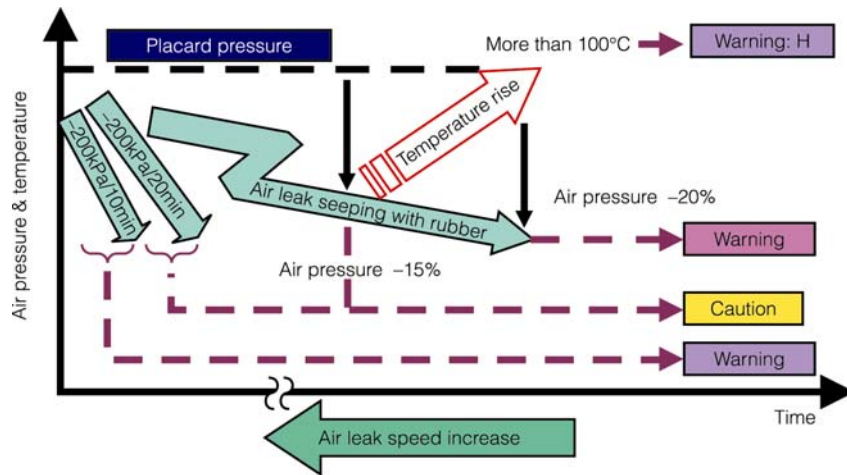


Fig. 17 Operation flow of alarm system

specified warning setting levels to respond when the air pressure level falls by -25% , or -30% below the specified air pressure in cold conditions. The new air pressure monitoring system has set the following warning specifications for detecting abnormal conditions.

(1) Caution Warning

- When the tire air pressure drops from 200 kPa to 0 kPa within a 20 minute period in cold conditions
- When the tire air pressure drops 15% below the specified pressure level in cold conditions

(2) Warning Alert

- When the tire air pressure drops from 200 kPa to 0 kPa within a 10 minute period in cold conditions
- When the tire air pressure drops 20% below the specified pressure level in cold conditions
- When the tire air temperature is greater than 100°C

Figure 17 shows the operation flow of the alarm system developed for the new tire air pressure monitoring system.



Fig. 18 Alarm indicator

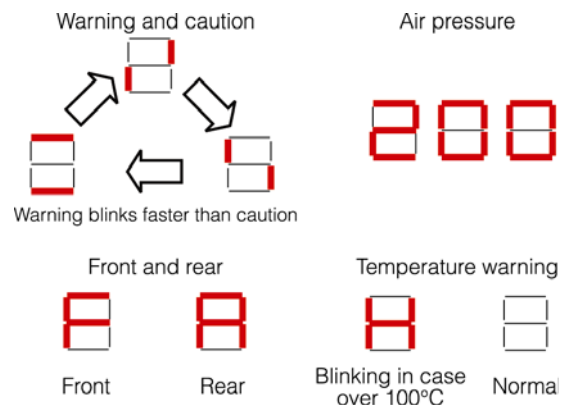


Fig. 19 Indication form

6.2. Rider Display

The method of displaying abnormal status information to the rider is an important element in the design. The system display must be easy to read to enable immediate rider response at infrequent occurrences of abnormal conditions. Figures 18 and 19 show the display setting when detecting abnormal conditions. When a warning or caution condition is displayed, the system also sounds a buzzer to ensure rider is aware of the displayed warning. The buzzer indicates the degree of urgency by changing the buzzer sound interval.

6.3. System Diagnostics and Warnings

The newly developed air pressure monitoring system includes system error diagnostic functions for better reliability. Displaying the location of the system error helps the rider discern the exact nature of the system error and has been designed to enhance tire failure warnings. Table 3 lists the display information for the system error occurrences.

Table 3 Indication of system error

Failure modes	Indications
ID failure	FE00 or RE00
Status failure	FE01 or RE01
Receiver counter failure	FE02 or RE02
Receiver system failure	E03
Transmitter battery voltage failure	FBAT or RBAT

F: Front tire R: Rear tire

7. Trigger Device for Improved Battery Life

The life of the battery on the air pressure monitoring system transmitter maintains stable battery voltage and will continue to transmit data until the vital voltage level is

depleted. To ensure a longer battery life, it is important to ensure that the battery is not tapped until the date of purchase. A trigger device with an ON/OFF battery transmission control setting has been incorporated to ensure the longest battery life possible. Table 4 lists the required conditions for the ON/OFF settings on the trigger device for controlling radio wave transmission from initial factory stock

Table 4 Management for transmitting radiowave in physical distribution

		Manufacturer		Factory				Carrier	Dealer	
Process flow		Delivery	Assemble	ID registration	Inspection	Stoppage	Shipment	Distribution	Stock	Delivery
State of radiowave	Transmission ON	—	—	○	○	—	—	—	—	○
	Transmission OFF	○	○	—	—	○	○	○	○	—
Trigger device		Unrequired		Required			Unrequired			

to the point of delivery. The device has also been designed to enable dealers to set the transmission ON by increasing tire air pressure temporarily.

8. Efficiency of Tire Air Pressure Monitoring System

According to the NHTSA's recent announcement regarding tire pressure monitoring specifications, the following negative conditions have been observed when tire air pressure drops below the prescribed level. As the following list indicates, there is a reduction in safety, a decrease in wear longevity and a reduction in fuel economy.

- (1) Reduction in Safety
 - Tire failures by increased bending of tire sidewalls and increased air temperature inside the tire
 - Reduction in handling performance resulting from reduced horizontal traction
 - Increase in breaking distance on wet roads (Data Source: Goodyear)
- (2) Decrease in Wear Longevity
 - Reduction in tire wear longevity by 1.78% for every 1 psi drop in tire pressure (Data Source: Goodyear)
- (3) Reduction in Fuel Economy
 - Poor fuel economy resulting from increased driving resistance.

A report released in 1978 indicates that there is a 1% reduction in fuel economy for every 3.3% drop in tire pressure.

Data recently released by Goodyear indicates that there is a 1% reduction in fuel economy for every 2.96% drop in tire pressure

The purpose behind the proposed legal requirement in America for the air pressure monitor is to prevent tire failures caused by driving on low pressure tires.

According to estimations released by the NHTSA, by fitting tire air pressure monitoring systems (direct monitoring types) to automobiles in the US, there would be 8,722 fewer injuries and 124 fewer deaths a year. The motorcycle tire air pressure monitoring system is expected to bring effective results in reducing the number of road injuries and deaths as well.

9. Conclusion

The newly developed motorcycle tire air pressure monitoring system has achieved effective tire failure forecasting and preventative functionality and more accurate monitoring capability in a systematized mode of delivery.

- (1) The tire air pressure monitoring system is reliable and has brought increased accuracy in detecting low tire pressure and air leakage through temperature correction.

- (2) The system responds to sudden air leakage due to tire puncture by reducing the time required to measure changes in air pressure conditions.
- (3) In addition to temperature monitoring, the system has also achieved dual forecasting functionality.
- (4) The system offers system diagnostic functionality by analyzing abnormalities such as decreases in battery voltage and error occurrences in system functions.
- (5) The system satisfies low radio wave field intensity regulations prescribed in Japan and adopts a transmitting system that does not require a separate antenna.
- (6) The system achieves the decrease in balancing weight used in wheel balancement and a conventional tire assembly by adopting two separate structures of transmitter and tire valve.
- (7) The system achieves a battery life of 10 years by adopting an ON/OFF sensor transmission control function and regulating the interval of data transmission.

10. Acknowledgments

The authors would like to express their deep appreciation and gratitude to everyone at Pacific Industrial Co., Ltd., Denso Corporation, Bridgestone Corporation and Inoue Rubber Co., Ltd. for their support and assistance in helping make the development of the motorcycle air pressure monitoring system a success.

References

- (1) U.S.DOT/NHTSA: Federal Motor Vehicle Safety standards: Tire Pressure Monitoring Systems; Controls and Displays: Docket No. NHTSA 2000-8572-28 (2000)

■ Authors ■



Masayoshi ORITA



Tomoyuki HARADA



Toshio YAMAGIWA