

Development of Brake-by-Wire System for Super Sport Motorcycles

Yutaka NISHIKAWA*
Shinji TAKAYANAGI*

Takehiko NANRI*
Kazuhiko TANI*

Kazuya TAKENOUCHI*
Syuichi FUKAYA*

ABSTRACT

Honda has developed a variety of innovative motorcycle brake technologies. Super sport motorcycles, CBR600/1000RR, have a unique combination of short wheel bases and center of gravity locations as vehicle characteristics, and the possibility towards pitching under hard braking has prevented conventional ABS from being used in these motorcycles. In addition, the characteristics of mechanical combined brake systems (CBS) make it challenging to adapt them for sport riding. Therefore, a new brake-by-wire system has been developed in which brake input is detected by a hydraulic sensor and the brake hydraulic pressure is varied by a power unit. A newly developed stroke simulator has enabled the achievement of an operation feeling similar to that of a conventional brake. In addition, the precise control of hydraulic pressure achieved by this system has enabled pitching to be controlled and made ABS/CBS compatible with sport riding.

The new system represents a first for super sport motorcycles, and has been employed in the 2009 model year CBR600/1000RR.

1. Introduction

To enhance motorcycle braking performance, Honda has offered anti-lock braking systems (ABS), combined braking systems (CBS), or combined braking systems with ABS (Combined ABS) on much of its on-road motorcycle lineup with engine sizes 250cm³ and greater^{(1), (2)}. However, the following issues have been encountered in attempting to use these systems in super sport motorcycles, CBR600/1000RR:

- (1) Super sport motorcycles have short wheel bases, increasing the possibility for some degree of pitching during high rates of deceleration, such as those that characterize ABS⁽³⁾.
- (2) Conventional CBS distributes braking force by varying the braking force on the front and rear wheels by means of mechanical valves. As a result, the front-rear braking force distribution pattern cannot be changed.
- (3) The necessity of having to make super sport motorcycles compact and lightweight and to concentrate their mass means that there is a minimal margin of space for additional equipments in the body.

- (4) The use of special CBS components such as dual channel calipers and secondary master cylinder increases the unsprung mass of the motorcycles.

In order to address these issues, a brake-by-wire system was developed that detects the brake input force by means of hydraulic sensors and applies completely independent control to the front and rear wheel braking force.

This paper will provide an overview of the new braking system, which is offered in the 2009 model year CBR600/1000RR.

2. Development Goals

The following targets were established for the development of a brake-by-wire system for super sport motorcycles:

- (1) Achievement of a balance between a high level of deceleration during ABS operation and motorcycle stability
- (2) CBS characteristics that did not impede sports riding
- (3) Appropriate size to enable fitting on a super sports motorcycle

* Motorcycle R&D Center

- (4) No significant increase in unsprung mass due to the employment of conventional brake calipers
- (5) No sense of discomfort in brake feeling in comparison to conventional brakes
- (6) Guaranteed brake operation in the event of system failure

3. Components

Figure 1 shows a schematic of the system when activated. Table 1 defines the codes used in the diagram in Fig. 1. This chapter will discuss the individual components of the system.

3.1. ECU

The electronic control unit (ECU) is the central element in the control system of the new brake system. The ECU processes signals from the wheel speed sensors (Section 3.6.) and pressure sensors (Section 3.3.) in its internal CPU, and controls the solenoid (electromagnetic) valves and motors, and conducts system diagnoses.

3.2. Power Units

The power units adjust brake pressures in response to control signals from the ECU. Figure 2 shows the basic configuration of the power unit and the initial set position of the power piston. When the power piston moves upward from this set position, the pressure on the brake caliper increases. The pressure decreases as the power piston returns to its set position. The motors and power pistons have been positioned in parallel configurations in

Table 1 Codes used in diagram of brake-by-wire system

Codes	Meanings
SNOM	Solenoid valve, normal open, master cylinder
SNCS	Solenoid valve, normal close, simulator
SNCP	Solenoid valve, normal close, power unit
PMC	Pressure sensor (master cylinder)
PFS	Pressure sensor (fail safe)
PCC	Pressure sensor (brake caliper cylinder)
VOW1	One-way valve
VOW2	One-way valve
SWSF	Front wheel speed sensor
SWSR	Rear wheel speed sensor
SymF	Front brake stroke simulator
SymR	Rear brake stroke simulator
MCF	Front brake master cylinder
MCR	Rear brake master cylinder
LWG	Warning lamp
Batt	Battery
ECU	Electronic control unit
M	Motor

order to reduce the size of the power units. Ball screws have been employed to efficiently convert the rotation of the motors into linear motion of the power pistons.

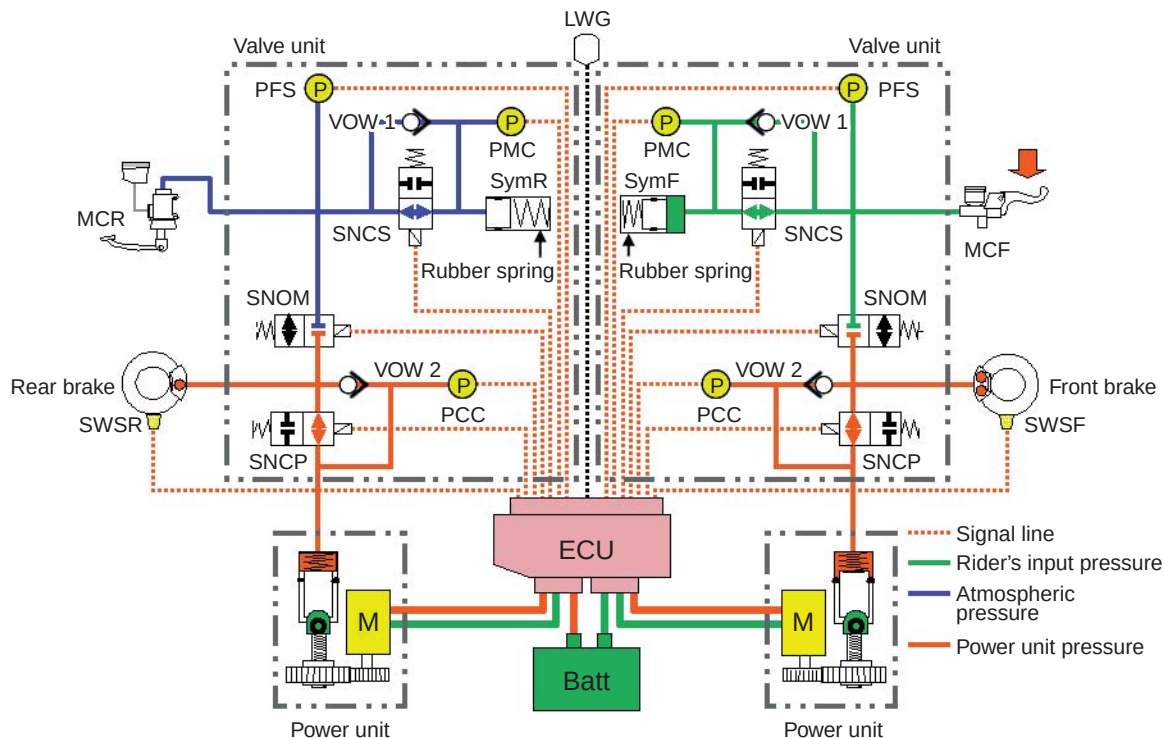


Fig. 1 Diagram of brake by wire system (Activated)

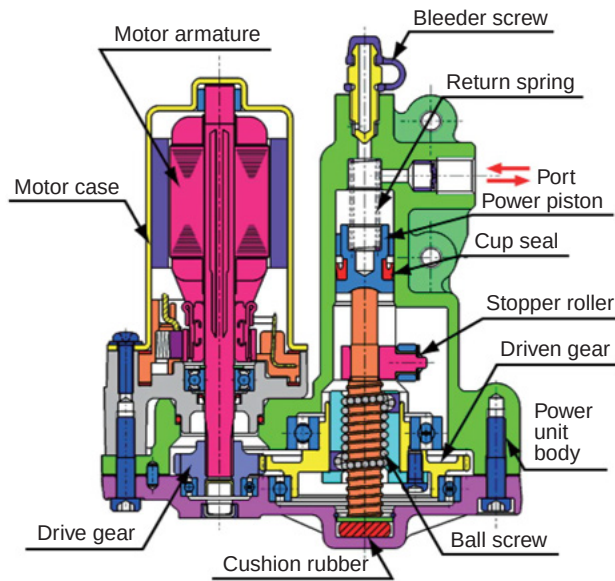


Fig. 2 Power unit

3.3. Pressure Sensors

Pressure sensors are employed to detect brake hydraulic pressure. Pressure is normally detected as the degree of strain on the pressure-detection section of the sensor. The resolution of the sensors is therefore higher the higher the degree of strain in relation to pressure, but a higher degree of strain reduces the pressure resistance of the detection section of the sensor. During motorcycle operation, there are occasions on which a high instantaneous hydraulic pressure is generated. However, pressure sensors have not previously balanced high resolution with high pressure resistance.

In the developed system, all forms of brake control are based on the input pressure, making it vital to attempt to prevent inaccuracies in pressure detection. High pressure resistance sensors (PFS) and high-resolution sensors (PMC) were therefore positioned upstream and downstream, respectively, of the SNCS solenoid valves, enabling the system to self-diagnose inaccuracies by comparing pressure measurements from the sensors. In addition, the SNCS valves close when a high input pressure exceeding a preset value is generated in order to protect the high-resolution sensors on the input side. High pressure resistance sensors, with a level of pressure resistance equivalent to that of the brake calipers, have been positioned upstream of the SNCS valves.

The high-resolution sensors that detect the brake caliper hydraulic pressure (PCC) have identical specifications to the input-side PMC sensors, and have been positioned downstream of the SNCP for the same reasons. The output pressure sensors (PCC) are able to self-diagnose inaccuracies by monitoring pressure in relation to the operating state of the motor.

3.4. Stroke Simulator

The stroke simulators reproduce the reaction force produced when the rider operates the brake lever or the brake pedal. The rider operates the brakes while feeling the reaction force generated by lever operation and the braking force. The difference of the slight reaction force transmitted to the rider's hand or foot is important in the braking control during a turning. In order to enable response to subtle operation of the brakes by the rider, it is therefore necessary for brake systems to generate a reaction force in response to input. Figure 3 shows a cross-sectional view of the stroke simulator section of a valve unit (Section 3.5.). The stroke simulators are positioned downstream of the SNCS solenoid valves, and are therefore connected to the master cylinders when the valves are open. When the rider operates the master cylinders, the pressure generated passes through the SNCS valves and acts on the simulator pistons. The load characteristic of the rubber springs that are fitted to the pistons is set to be identical to a normal brake operation feeling. In order to enable reproduction of an operation feeling even closer to that of an actual motorcycle, two rubber springs with two different load characteristics have been employed per piston in the developed system (Fig. 4).

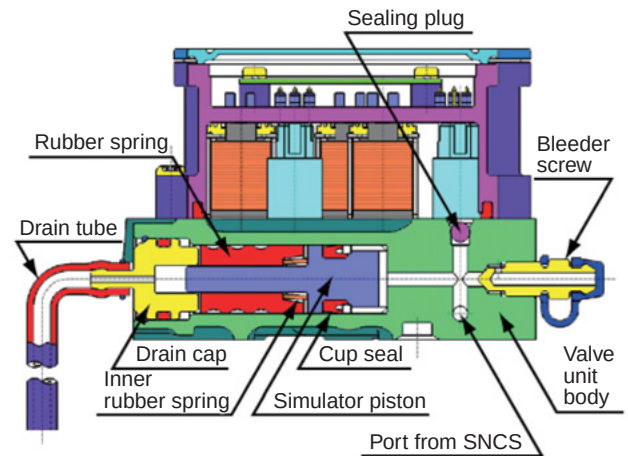


Fig. 3 Valve unit

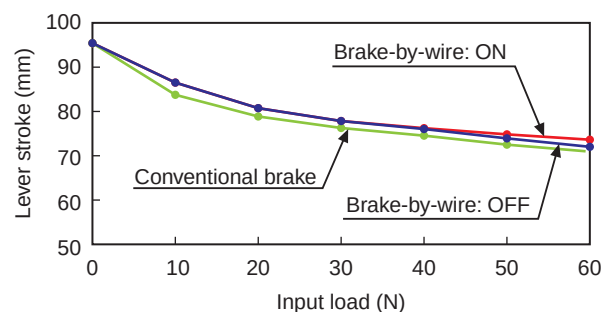


Fig. 4 Load deformation characteristics of stroke simulator

3.5. Valve Units

Solenoid valves, pressure sensors, and stroke simulators are built into the valve units. The solenoid valves are opened and closed by current from electromagnetic coils. Two types of valves are employed: Normal open valves, which close when current flows to them, and normal closed valves, which open when current flows. The solenoid valves operate in response to signals from the ECU, connecting and disconnecting the master cylinders, brake calipers, power units, and stroke simulators.

3.6. Wheel Speed Sensors

The wheel speed sensors (SWSF and SWSR) use hall elements (magneto-electric transducers) to detect the rotation of pulsar rings manufactured by punching slits in thin, circular steel sheets. This type of wheel speed sensor is widely used in the ABS systems of current production motorcycles.

4. Mounting in Actual Motorcycle

Hydraulic brake systems for motorcycles are made up of a master cylinder that generates hydraulic pressure when the rider operates the brake levers (or brake pedal), brake calipers that convert the hydraulic pressure into braking force, and brake hoses that connect these components. Figure 5 shows the layout of the developed system in an actual motorcycle.

The developed system adds an ECU, power units, valve units, and wheel speed sensors to a conventional hydraulic brake system. Due to the concentration of mass in a super sport motorcycle, there is a minimal margin of space in the body of the vehicle.

To enable the new system to be easily mounted in an actual motorcycle, it was divided into a number of smaller units.

The power units and the valve units are connected

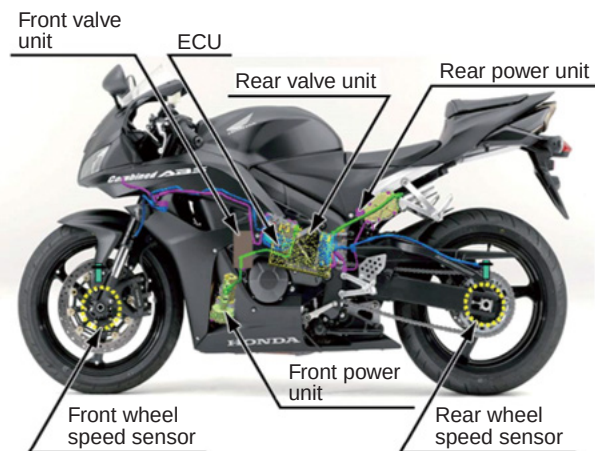


Fig. 5 Layout of brake-by-wire system

between the master cylinders and brake calipers, and the units are electrically connected to the ECU by signal lines. The system does not require pipes to connect the front and rear brakes, dual channel calipers or secondary master cylinder similar to a conventional mechanical CBS, and enables CBS to be realized using standard brake calipers. Other than the wheel speed sensors, the system does not increase the unsprung mass of the motorcycle, and thus enables the high level of dynamic performance required from a super sport motorcycle to be maintained.

5. Operation of Brake-by-Wire System

5.1. System in Deactivated State

The system diagram in Fig. 6 shows the system when it is deactivated. When the motorcycle is stopped, the master cylinders on the front wheel side (MCF) and the rear wheel side (MCR) are connected to their respective brake calipers via the normal open solenoid valves (SNOM). Due to their normal closed configuration, the solenoid valves (SNCS) that connect the master cylinders to the stroke simulators and the solenoid valves (SNCP) that connect the brake calipers to the power units are closed at this time. If the rider operates the brakes in this state, the hydraulic pressure acts directly on the brake calipers through the pathway shown in green in Fig. 6. The rider is therefore able to operate the brakes like a conventional system.

5.2. System in Activated State

The brake system goes into stand-by mode when the speed of the motorcycle exceeds 6 km/h. In this state, the SNCS solenoid valves open, and the PMC high-resolution pressure sensors are able to detect input pressure. When the input hydraulic pressure exceeds a preset level after the brake lever operation by the rider, the system enters by-wire mode (Fig. 1). The SNOM solenoid valves close the pathways from the master cylinders to the brake calipers, and at the same time the input pressure from the rider's brake operation is transmitted to the simulator piston of the SymF stroke simulator via the SNCS solenoid valve. The ECU calculates the required brake caliper pressure from the input pressure and the rate of pressure increase. As the motor rotates, the ball screws raise the power pistons, and brake hydraulic pressure is generated. The hydraulic pressure generated in the power units on the front wheel side is transmitted to the brake calipers via the SNCP solenoid valves, and braking force acts on the wheels. When the brake lever is operated, the ECU applies CBS control to the rear wheel brake power unit in order to produce the optimum braking force in relation to the brake caliper pressure on the front wheel. The system functions in the same manner when the brake pedal is operated. If the slip ratio of the wheels exceeds a preset value, the ECU puts the motor into reverse, the power pistons are lowered and brake pressure is reduced,

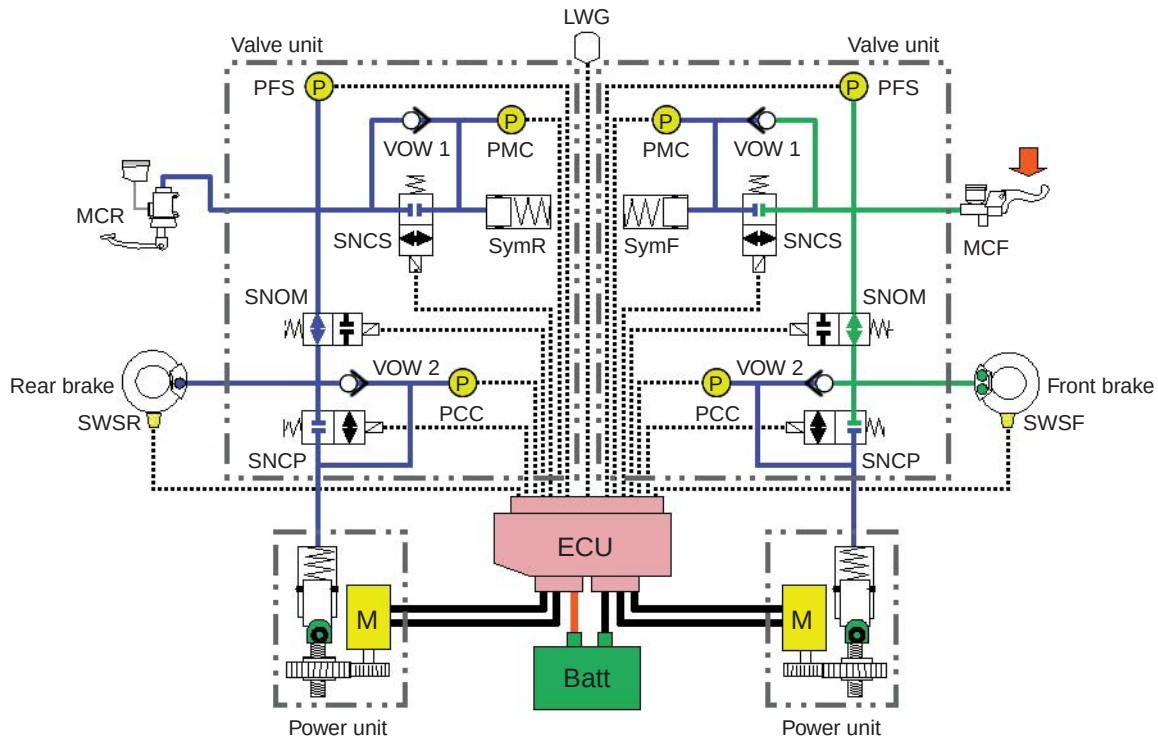


Fig. 6 Diagram of brake-by-wire system (Deactivated)

and the ECU controls brake pressures by ABS to keep an appropriate slip ratio.

5.3. System Failure

When the ignition switch is ON, the ECU constantly conducts self-diagnosis, irrespective of whether the system is activated or deactivated. In the event of a system failure during operation, the ECU will disconnect the power from the solenoid valves and the motors. The internal springs in the solenoid valves will induce them to return to their original positions, enabling normal braking pathways to be maintained.

6. Effect of Use of Brake-by-Wire

6.1. Setting Braking Force Distribution in CBS

Figure 7 shows a conceptual image of CBS control by hand operated combined brake. The figures on the left show front and rear wheel braking force distribution patterns, and the figures on the right show the changes over time in the braking force on the rear wheel from when the brakes are applied, to their release, resulting from these patterns. Figure 7(a) shows a conventional CBS, and Fig. 7(b) shows the brake-by-wire system.

Because in conventional CBS the front and rear wheel braking force distribution patterns are the same for application and release of the brakes, when the hand operated combined brake is released there is a temporary increase in the hydraulic pressure in the rear wheel brakes.

This could result in an instantaneous brake drag on the rear wheel. This peculiar character disturbed sport riding. By contrast, in the brake-by-wire system, the braking force distribution between the front and rear wheels is independent and can be freely set, and therefore there is no increase in rear wheel hydraulic pressure when the hand operated combined brake is released.

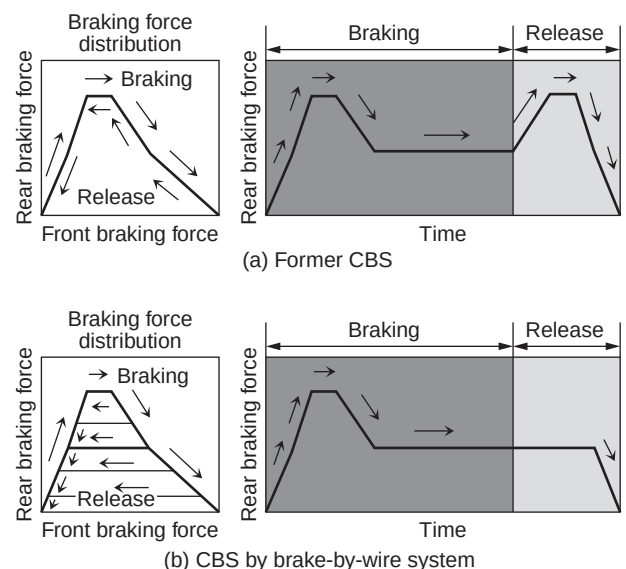


Fig. 7 Braking force distribution pattern of CBS

Table 2 Test conditions

	Brake-by-wire system	Brake operation	Brake control system		
			ABS	Combined brake	Pitching control
Test 1	Deactivated	Conventional brake (hand and foot)	Deactivated	Deactivated	Deactivated
Test 2	Activated	Hand-operated combined brake	Activated	Activated	Deactivated
Test 3	Activated	Hand-operated combined brake	Activated	Activated	Activated

6.2. Pitching Control

Super sport motorcycles can experience pitching which in some circumstances may result in the rear wheel lifting off the ground in the high deceleration range. The operation of ABS at an appropriate timing is able to help prevent this pitching. However, conventional ABS which is responded by deceleration has not been able to be used for this purpose because the slip ratio does not increase in response to the speed of the brake input or the change in the front and rear wheel loads.

The new system controls pitching by predicting the occurrence of pitching from the brake input pressure and the rate of pressure increase, and operating with optimum timing of the ABS⁽³⁾.

The effectiveness of this pitching control was verified in tests conducted using a super sport motorcycle fitted with the system under the test conditions shown in Table 2. Table 3 shows the main specifications of the motorcycle used in the tests. Figure 8 shows an example of results when pitching control was deactivated. There is a 0.8 G deceleration immediately following the application of the brakes, but this is directly followed by a high degree of pitching, and the rider releases the brakes.

Figure 9 shows an example of results when pitching

Table 3 Specifications of test motorcycle

Items		Test motorcycle
Brake system	—	Brake-by-wire
Wheelbase	L (m)	1.372
Curb mass	M (kg)	185.6
Height of C.G.	H (m)	0.681
Distance between C.G. and rear axle	X (m)	0.663
Distributed load of motorcycle with one rider	Front (N)	1 235
	Rear (N)	1 321
Pitching factor	(L-X)/H	1.04
Engine displacement	V (cm ³)	599

control was activated. The ECU predicts pitching from the pressure rise rate of the front wheel brake input, and rapidly increases the front wheel brake caliper pressure. This result in ABS operation of the front brake, and even at its maximum, the pitching is controlled to around 5 deg. Given that the pitching that occurs when conventional brakes are used is around 6 deg, the pitching control in the new system can be judged to be effective.

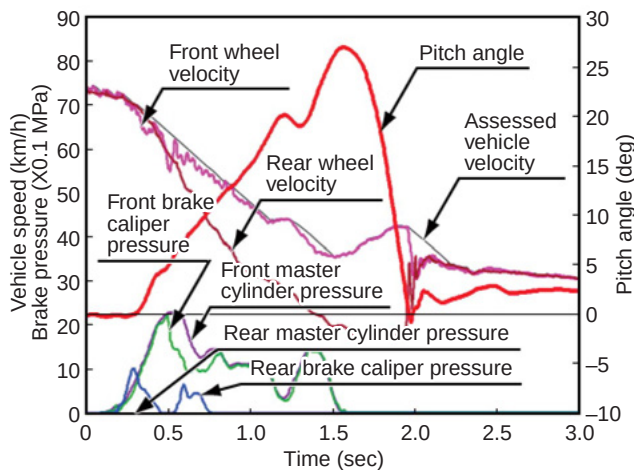


Fig. 8 Example of time history data (Pitching control deactivated)

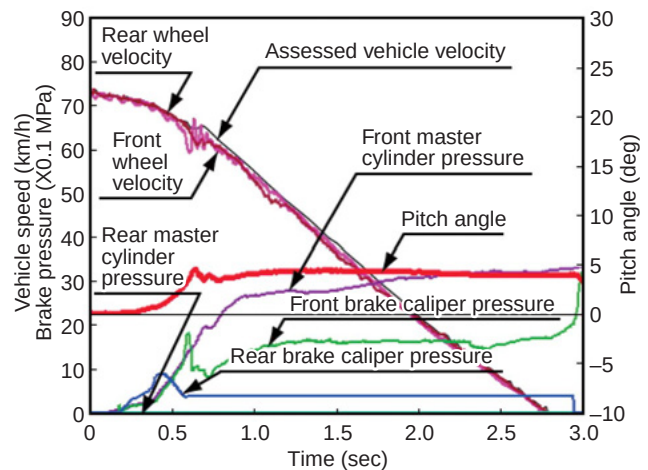


Fig. 9 Example of time history data (Pitching control activated)

7. Conclusion

A brake-by-wire system has been developed for super sport motorcycles. The following results were obtained:

- (1) Pitching control has reconciled a high rate of deceleration with rear wheel lift during ABS operation.
- (2) The new system reconciles sport riding and the use of CBS.
- (3) A brake-by-wire system able to be fitted in a super sport motorcycle has been developed.
- (4) Increase in unsprung mass has been limited to a level that does not affect operation or stability.
- (5) A newly developed stroke simulator has enabled the achievement of an operation feeling similar to that of a normal brake system.
- (6) The brake operation has been guaranteed in the event of power-off and system failure.

References

- (1) Nishimoto, Y., Tani, K.: Present and Future for Motorcycle Brake System, JSAE Symposium, 20054590, No. 05-05, p. 41-46 (2005)
- (2) Tsuchida, T., Nishimoto, Y., Thiem, M.: Advanced Brake Systems for Powered Two Wheelers: CBS, ABS and Future Directions, 4th International Motorcycle Conference, p. 379-396 (2002)
- (3) Nishikawa, Y., Nanri, T., Takenouchi, K., Takayanagi, S., Tani, K., Fukaya, S.: Experimental Study of Pitching Control of Large Motorcycle with Short Wheelbase Using a Brake-by-Wire System, 7th International Motorcycle Conference (2008)

■ Author ■



Yutaka NISHIKAWA



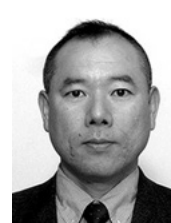
Takehiko NANRI



Kazuya TAKENOUCHI



Shinji TAKAYANAGI



Kazuhiko TANI



Syuichi FUKAYA