技術論文

Support Effects of the Haptic Throttle Grip by the Friction Circle on the Driving Wheel

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要旨

ライダーに対する運転支援システムの開発を目的として、モーターを接続することで操作反力を可変としたスロットルグリップを作製し、触覚・力覚を通して減速要求の情報を伝達することができるシステムを構築した。この情報伝達のための基本的な考え方として、タイヤの限界摩擦力を全方位でプロットしてつなげるとできる円(摩擦円)を使用した。これに対してエンジンから出力される駆動力と旋回によって発生する横力との合力が摩擦円の大きさに近づいた場合、それ以上駆動力を上げるとスリップする可能性があると判定して、このスロットルグリップの操作反力を増すことで減速要求を提示することとした。本システムを搭載した試験車両にて走行試験を行った結果、全てのテストライダーがこの操作反力の増加を試験車両からの減速要求として感じることができ、さらに駆動力と横力の合力が摩擦円を越えないように操作を導く運転支援効果があることが分かった。

Abstract

Recently, there have been many reports about development of Human Machine Interface (HMI) which used a visual or auditory display to improve driver assist. For a motorcycle, it is suitable to use a haptic display for rider assist, since there are many disturbances in open-air situation such as sunshine and surrounding noise. Therefore, a test vehicle based on a large motorcycle equipped with the haptic throttle grip that is connected to a motor by gear, an original ECU to control the motor, and a lean angle sensor to calculate the lateral force of the motorcycle was developed. To inform surplus driving force warning, the throttle grip, a haptic display outputs additional return torque estimated by the friction circle and ellipse with the lateral force of the motorcycle. One of the purposes of this torque is that it informs the rider to decelerate when the motorcycle state of movement is around the limit of tire grip, and another purpose is that it leads to return the throttle grip to decelerate. For both purposes, the intuitive signal which adds return torque was selected to avoid misunderstanding. As the result of riding tests, all of the riders were able to recognize the signal and understood the request from the motorcycle. It became clear that this system was able to offer the information of surplus driving force warning, and to support the throttle grip operation.

1 INTRODUCTION

There are many HMI inside the cabin on production automobiles, such as meters, indictors and navigation system with audio assist. There are also many reports on haptic devices, which were tested with modified production automobiles or a simulator such as a haptic gas pedal to make deceleration [1]-[5] and a haptic steering wheel to inform lane departing with vibration or with additional steering torque [6]-[8]. These reports clearly state that the drivers can perceive the haptic signals and there are few disturbances to communicate on the channel between the driver and the car. Therefore, a haptic display was considered to match to motorcycle than applying a visual or auditory display.

To make a haptic device on a motorcycle, it is the most reasonable to use hand and throttle grip as a communication interface between the rider and the motorcycle from the following reasons. The rider's hand and the throttle grip are always in contact while riding, and there are many sensory receptors on a hand than the other parts of the body. But haptic displays have less information than visual or auditory displays. Therefore, as a haptic display, letting the throttle grip output only intuitive information to avoid misunderstanding. To use an intuitive signal is important for perception and usability from HMI point of view [9]. In addition, it became more difficult for the riders to operate the throttle grip of large displacement motorcycles like super sport models, due to increasing of engine torque year by year with technology innovation. To improve throttle grip controllability around the limit of tire grip, it is necessary to add some of function.

In order to satisfy two purposes mentioned previously, the haptic throttle grip equipped with a motor which is connected by the gear was developed; it is able to add the return torque to communicate between the rider and the motorcycle, and to improve the throttle grip controllability. In this paper, the detail of the haptic system on the motorcycle and its riding test results are reported.

2 HAPTIC SYSTEM

Haptic Throttle Grip

Figure 1 shows the haptic throttle grip which is used in this research. It consists of a throttle grip with a return spring to close itself, a gear, a one-way clutch, and a motor. This throttle grip is connected to the motor by the gear and the one-way clutch, it can output haptic signals to the rider by controlling the motor.

The one-way clutch is set between the motor and the gear, and the motor can only add torque to closing direction of the throttle grip for a safety reason. Therefore, even if the motor is locked due to breakdown, the rider can close the throttle grip to decelerate.

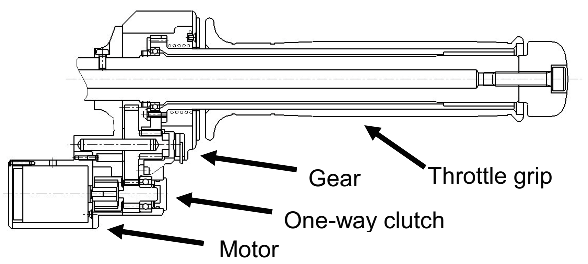


Figure 1 Haptic throttle grip

Test Vehicle

The haptic system is constructed with the haptic throttle grip, an original sensor to calculate the lean angle of the motorcycle, and an original ECU to control the motor of the haptic throttle grip. Figure 2 shows our company's large displacement motorcycle (equipped with the system), and the location of its components parts.

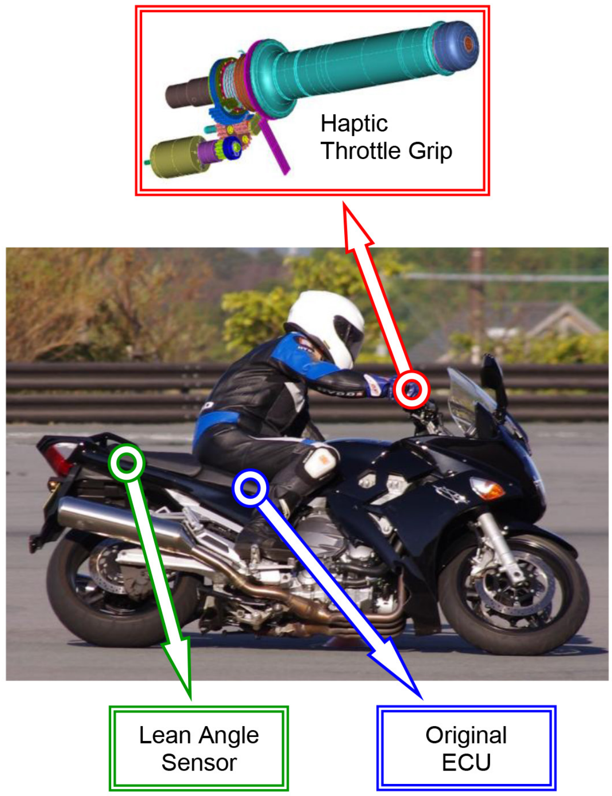


Figure 2 Test vehicle and parts

In addition to these parts, a permission switch and a mode switch are equipped. The permission switch allows the rider to activate or deactivate the control, and the mode switch allows the rider to change the level of additional return torque in five steps while riding. It is effective to use these switches for the development of the system. A logger is also equipped to the motorcycle to log data such as throttle grip position named accelerator position, engine speed, gear position, lean angle, vehicle speed, and additional return torque of haptic throttle grip. It became easy to analyze test results and to develop the system by using this system.

Friction Circle & Ellipse

One of the purposes of this system is to inform the rider to decelerate when surplus engine torque is at the edge of tire grip. The theory of friction circle is used to estimate the surplus engine torque. Figure 3 shows the image of friction circle, ellipse, and the forces on the driving wheel.

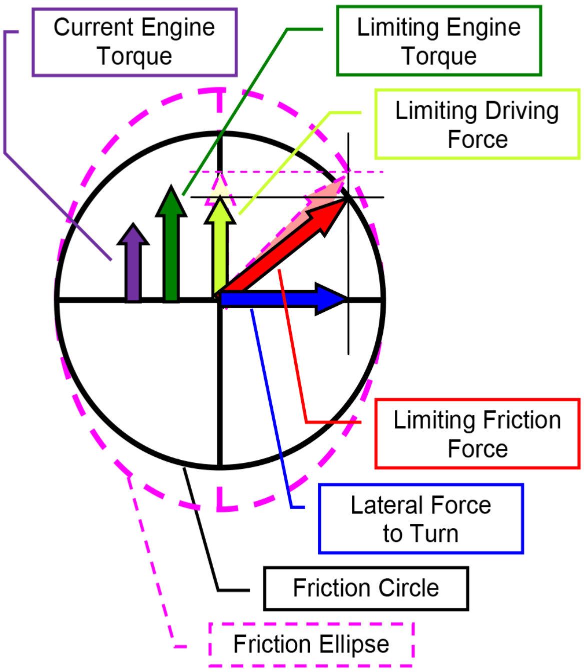


Figure 3 Image of friction circle & ellipse

As a premise, if the total force on the driving wheel does not exceed the friction circle, the wheel will not lose the tire grip. There are two forces on the driving wheel; lateral force and driving force. The lateral force is calculated from the acceleration which is created by turning movement of the motorcycle, the limiting friction force is calculated with the lateral force and the friction circle, and the limiting driving force is calculated as a longitudinal component of the limiting friction force.

In the software of this system, all data are calculated based on the engine torque, since the additional return torque is estimated from the quantity of the difference of the limiting engine torque and the current engine torque. For this, first the current engine torque must be calculated from the engine speed and throttle valve position, and the limiting engine torque must be calculated from the limiting driving force and the reduction gear ratio each gear positions. If the difference becomes small, it means that the total of friction forces on the driving wheel is becoming close to the friction circle. In this condition, there is a possibility of slipping down with losing the tire grip. Therefore, it informs the rider to decelerate by increasing the return torque of the haptic throttle grip.

In different research of our company shows the friction circle of a same test motorcycle is estimated that the longitudinal axis is about 8% bigger than the lateral axis. From this, the haptic system control is made with the friction ellipse of dashed line in addition to the friction circle in figure 3.

Based Torque Control

This haptic throttle grip is equipped with a motor to make haptic signals. Rotating the motor by the throttle grip creates counter electromotive force: V_{emf} (1) and inertia torque: T (2) of the rotor. These forces give negative influences in operation of the throttle grip, such as becoming heavy or a delay. These forces are calculated with the following equations in order to compensate.

$$V_{emf} = K_t \frac{d\theta_1}{dt} \quad (1)$$

$$T = J_1 \frac{d^2\theta_1}{dt^2} + J_2 \frac{d^2\theta_2}{dt^2} \quad (2)$$

$$V_I = \frac{R}{K_t} T \quad (3)$$

K_t : Motor Constant
J_1 : Moment of Inertia of the Rotor
J_2 : Moment of Inertia of the Gear
θ_1 : Rotating Angle of the Rotor
θ_2 : Rotating Angle of the Gear
R : Electric Resistance of the Motor
V_I : Voltage equivalent to inertia torque

The total voltage of Vemf and V_I is added to reverse direction in which they are generated by the motor. As the result, it can neutralize the negative influences, and the haptic throttle grip can offer natural feeling equivalent to a production motorcycle.

Additional Torque Control

Proportional Control

Figure 4 shows the relation between the additional return torque of the proportional control and the difference between the limiting engine torque and the current engine torque. The difference of the limiting engine torque is estimated from the friction circle or ellipse minus the current engine torque which is indicated in the solid line, the additional return torque is proportional to the difference which is indicated in dashed line. If the difference comes bigger than the margin or when the current engine torque is negative, the system outputs no additional return torque on the throttle grip. In this situation, there is no wheel spin coming from the acceleration, and therefore, it is not necessary to inform any caution. If the difference comes smaller than the margin and when the current engine torque is plus, the system adds some return torque on the throttle grip to inform only the surplus engine torque. The point where the margin is same as the difference is the control starting point, the torque is estimated from there with the proportional coefficient: a/margin. The limit of return torque is provided to prevent harder throttle grip operation for the rider. This strategy is presented in (4). From this strategy, the rider can perceive the modulation and is led to decelerate to create the margin.

$$ART = (CET + Margin - LET) \times PC \qquad (4)$$

ART : Additional Return Torque
CET : Current Engine Torque
LET : Limiting Engine Torque
PC : Proportional Coefficient

Figure 5 shows the example of return torque character of a conventional throttle grip and the proportional control. The conventional throttle grip is linked to the throttle body by the wire, and it has the base character which is indicated with the parallelogram of solid line by operating the throttle grip. This base character consists of the slope which is made by the return spring and the hysteresis which is made from the friction of the wire and others. To add the additional return torque to the base character, the proportional control character is formed in dashed line.

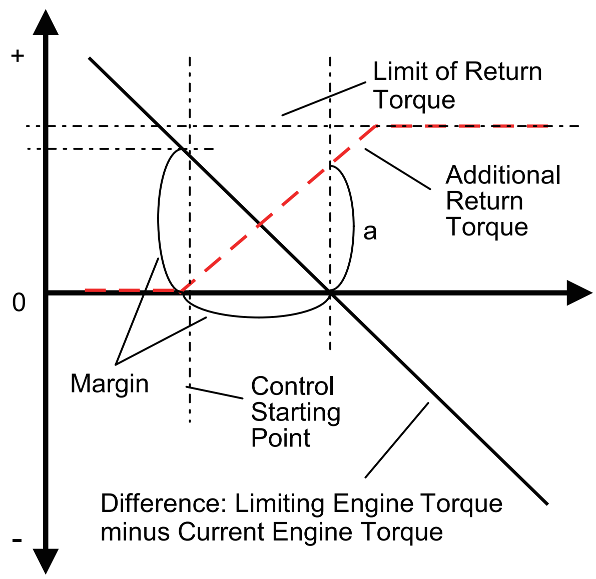


Figure 4 Relation between driving forces and additional return torque of proportional control

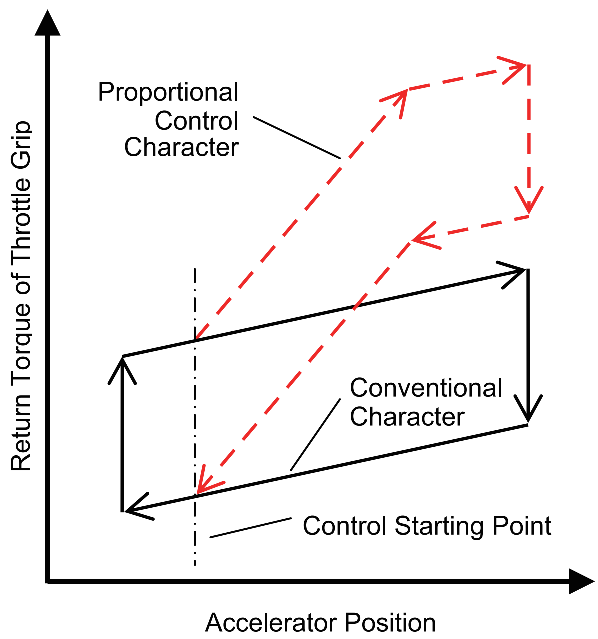


Figure 5 Return torque character of throttle grip

Differential Control

The proportional control has the functions that communicate to the rider and leads to decelerate at the edge of tire grip. Addition to the function of the proportional control, the differential control is prepared to restrain acceleration at the edge of grip, outputs the additional return torque for operation of opening the throttle grip. This control is based on the Weber-Fechner law which states that human sense is proportional logarithm of input stimulation. In addition, there are some sensory receptors which react modulation, therefore it is thought that the differential control which makes the perceptible modulation of return torque on the throttle grip is useful.

Figure 6 shows return torque character of differential control. Dashed line indicates the accelerator position, dotted line indicates accelerator speed which is the speed of operating the throttle grip, and solid line indicates the additional return torque of the differential control. This strategy becomes active when the difference is smaller than the margin in figure 4 and also when the current engine torque is plus. This additional return torque is proportional to the accelerator speed. When the speed is positive, the torque is estimated to multiply it by a constant coefficient. If the speed is smaller than 0, the torque is reduced to 0 with a time constant. The purpose of this strategy is to make the rider perceive acceleration operation of the throttle grip around the limit of tire grip, and is not to perceive keeping or deceleration operation. Even if the rider operates the throttle grip intermittently, like repeating opening and keeping, the rider can perceive the return torque on every opening operation with this strategy.

Furthermore, the PD control which is the total of the proportional control and the differential control is made to let the rider perceive the torque in every situation. These controls are tested with the test vehicle, and its results are shown in the next section.

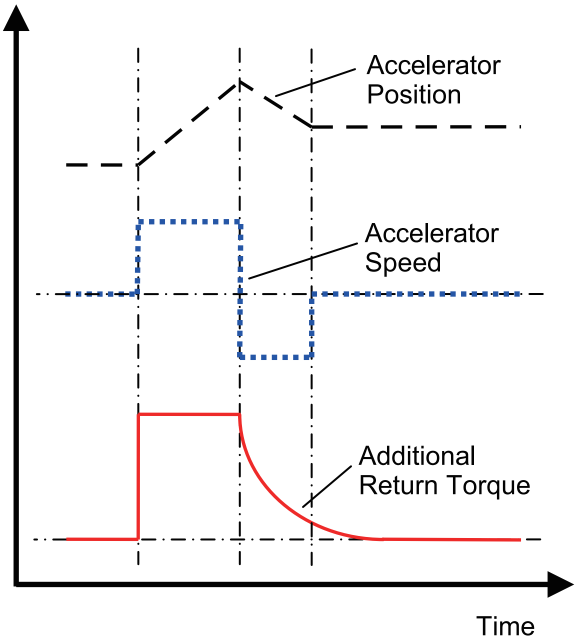


Figure 6 Return torque character of differential control

3 RIDING TESTS

All of the following riding tests had been held in closed circuits and the riding tests were done by the engineers for developing the strategy.

Proportional Control Tests

Figure 7 and 8 shows the time series data of riding tests. The horizontal axis indicates time and the vertical axis indicates each measure; the data indicate lean angle, velocity of the motorcycle, throttle valve position, additional return torque on the throttle grip, limiting engine torque and current engine torque from the top respectively. The additional return torque is limited to 70cN*m for a restriction of the system in these tests. Both of the data were taken at the same series of two tight turns.

The proportional coefficient which was used in the test of figure 7 is 30cN*m/20N*m as a small gain, which means the additional return torque against the engine torque conversion of driving force. The bottom graph of figure 7 shows the current engine torque comes over the limiting engine torque.

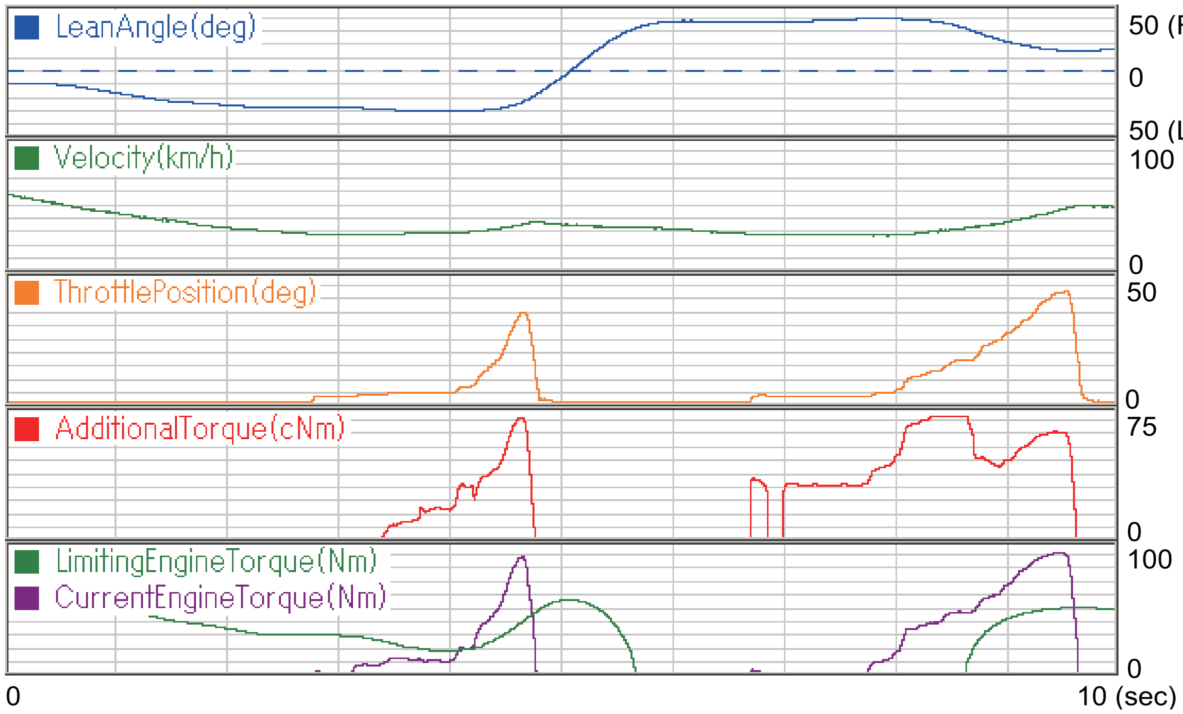


Figure 7　Time series data of proportional control with SMALL gain

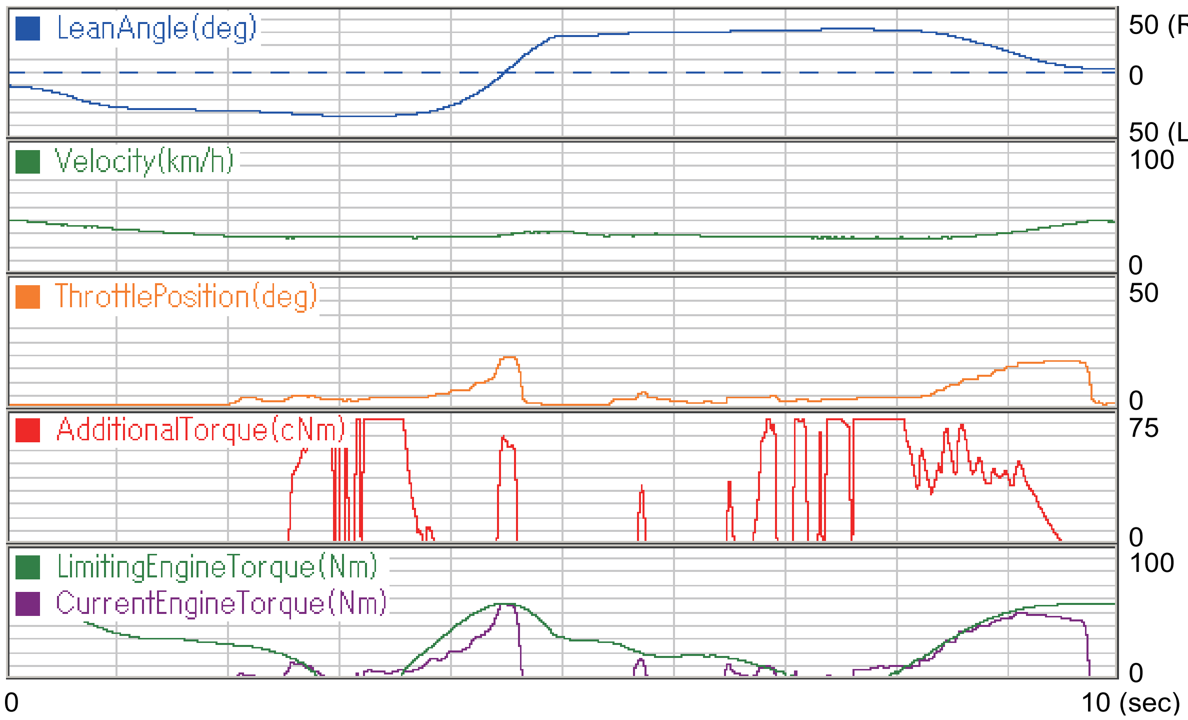


Figure 8　Time series data of proportional control with BIG gain

From this, it finds that the additional return torque does not give the rider enough information about the surplus engine torque. In this case, there was no wheel spin since the real coefficient of friction, μ_R, was higher than the μ_c which was used as a radius of friction circle. The test riders pointed out that there was no negative influence on operation of the throttle grip but they could not perceive the torque well as a warning signal. The data and their comments indicated matched matter, increasing the additional return torque to the signal as a warning method was needed.

Figure 8 shows the data with the proportional coefficient 60cN*m/10N*m which is 4 times bigger than the small one. With this setting, the tests riders could perceive the limit of tire grip easily with rapid increase of the additional return torque. On the bottom graph of figure 8, the current engine torque does not come over the limiting engine torque, and increases along with the limiting engine torque from 8 to 9 seconds. This shows the rider can perceive the limit. But there were some comments that it was difficult to operate the throttle grip since it was too heavy to operate input what they required. It is obvious that degree of the throttle position with the big gain is less than the small gain in figure 7 which agrees with the comments.

From both data, the best gain value for the riders is set between small and big one. As the result of the balance between capability of transmitting the information and the controllability, the best one became 60cN*m/20N*m.

Differential Control Tests

Figure 9 shows the time series data of the differential control with the same format as figure 7 and 8. To easily understand the character of the strategy, some of the data is added and exchanged. The data indicate lean angle, velocity of the motorcycle and gear position, accelerator position which indicates the degree of the throttle grip, additional return torque on the throttle grip, limiting engine torque and current engine torque respectively from the top. Also in this case, the current engine torque comes over the limiting engine torque but there was no wheel spin.

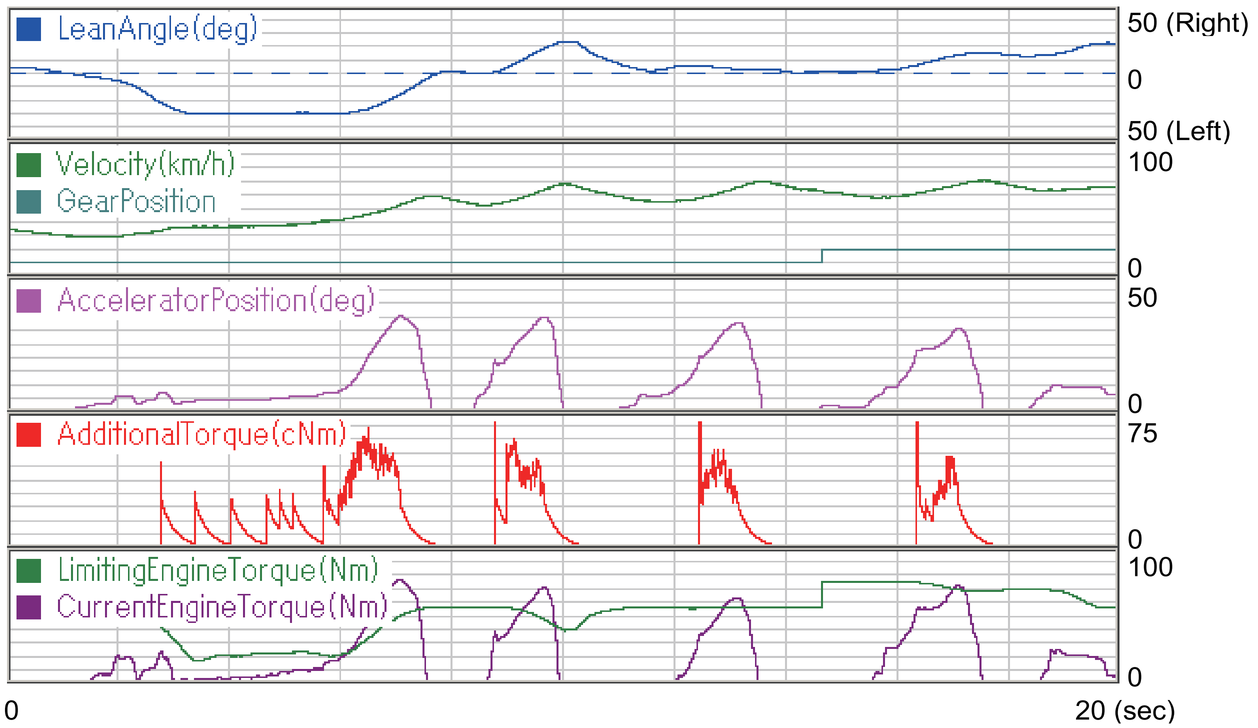


Figure 9 Time series data of differential control

On this strategy, the additional return torque is estimated from the differential of time variation of accelerator position. If the differential is positive, the torque calculated to multiply the differential by a gain is added to the throttle grip. Moreover, when the current engine torque comes close to the limiting engine torque, and the current engine torque which added the margin comes over the limiting engine torque as shown in the figure. Step change of the limiting engine torque comes from the gear position change, which uses the gear ratio to convert to the limiting engine torque from the limiting driving force. If the differential becomes under 0, the torque is reduced with a time constant to 0.

The settings which are used in figure 9 are as follows; the gain is 1cN*m/(deg/sec), the time constant is 300ms, the maximum additional return torque is 70cN*m, and the margin is same as figure 7. The result of riding tests shows that the strategy had high capability of transmitting the information with quick acceleration and could control it. But there is less capability of transmitting the information than the proportional control with slow acceleration, since the additional return torque becomes less than the torque of the proportional control.

PD Control Tests

Friction Circle

Both positive and weak points were found from the test results of two controls. The positive point was all of the riders were able to recognize the signal and understood the request from the motorcycle. The weak point on the proportional control is that, it is difficult to increase the gain for keeping operativity. And for the differential control, it is difficult to perceive the signals with slow acceleration. Therefore, the PD control was made to compensate these weak points which enabled both of the two controls to control at the same time.

Figure 10 shows the friction circles plotted with the μ value converted from the running state of the motorcycle, with the throttle grip controlled by the PD control with friction circles. The shading dots indicate the amount of the additional return torque, and the darker dots shows more torque than the lighter dots. For the coefficients of friction: μ_c, 0.5 and 0.6 are selected as the typical values of wet and dry condition. Since this control enables both controls at the same time, the additional return torque became too large. Therefore, each gain of the proportional and the differential control are reduced to 40cN*m/20N*m and 0.6cN*m/(deg/sec), and the maximum additional return torque is limited to 70cN*m.

The results of these data shows that the running states of the motorcycle are in the selected friction circles, since the rider can limit the degree of the throttle grip position. Left circle is a riding data without the control and it shows that the dots are scattered and has bigger circle than others. The other circles are rounded shape and from the result of the additional return torque. From these shapes, this system can transmit the information of the tire grip limit to the rider, and from the comments of test riders there are the ability of throttle grip operation assist for turning and accelerating. In addition, this system is found useful for helping the rider to perceive the position of the running state of the motorcycle in friction circle, which was difficult for the riders.

Moreover, the circles controlled by the system are wider to the lateral direction. This is because this system does not transmit any information when the rider keeps the throttle grip closed, and creates big lateral force over the friction circles during a turn, which results the system to output big additional return torque when the rider opens the throttle grip at the running state.

Friction Ellipse

Figure 11 shows the friction ellipse which is the same format as figure 10. The coefficient of longitudinal friction is μ_{cx} and the coefficient of lateral friction is μ_{cy}. This longitudinal axis of a friction circle on the driving wheel of the motorcycle is 8% longer than this lateral axis. From the result of the research, these values on the center circle are 0.54 and 0.5, and on the right circle are 0.648 and 0.6.

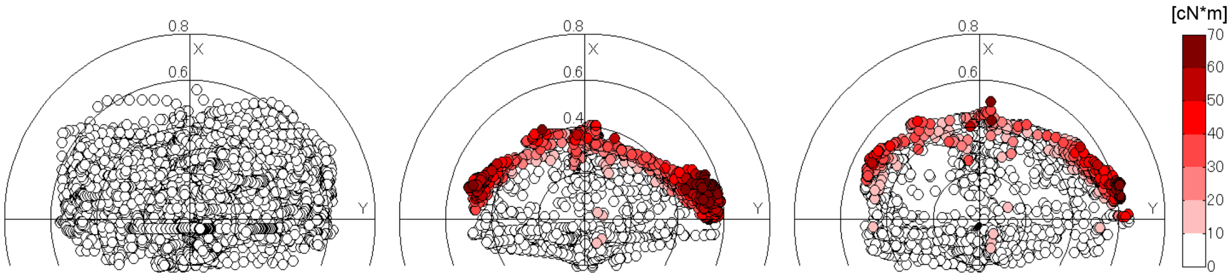


Figure 10 Plots of running state on friction circles. Left: without control, Center: PD control with friction circle of $\mu_c = 0.5$, Right: PD control with friction circle of $\mu_c = 0.6$.

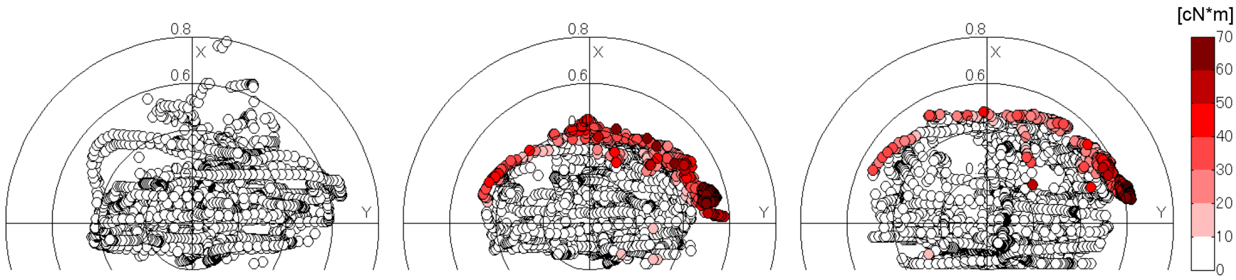


Figure 11 Plots of running state on friction ellipse. Left: without control, Center: PD control with friction ellipse of $\mu_{cx} = 0.54$ and $\mu_{cy} = 0.5$, Right: PD control with friction ellipse of $\mu_{cx} = 0.648$ and $\mu_{cy} = 0.6$, (μ_{cx}: longitudinal axis, μ_{cy}: lateral axis).

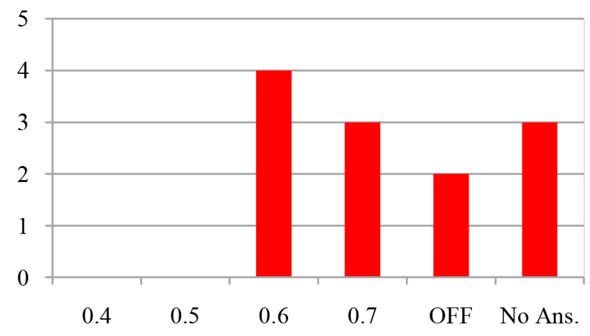
Comparing with the shapes of friction circles figure 10, the shapes of the running state of friction ellipses are a little longer on the longitudinal axis. From the comments of the riders, friction ellipse has better feeling than friction circle, since the coefficient of friction of the ellipse is close to the real coefficient. The riders can perceive the difference clearly, in spite of not being so big on their feeling. Therefore, they can accept the PD control of the friction ellipse without an unnatural feeling.

4 EVALUATION TESTS

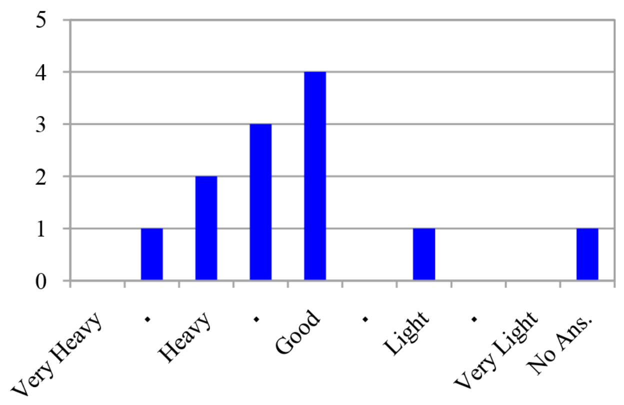
Twelve test riders evaluated the system with the PD control of friction circle on our test course in dry condition. The contents of the tests had been explained to all of the test riders prior to the tests, and they were asked to fill out the questionnaires of this system after the tests. Thus the results are with the informed consent.

The gain settings are the same as the test of PD control of friction circle, the maximum additional return torque is increased to 100cN*m in order to check the upper limit. The riders can choose the coefficients of friction: μ_c from 0.4 to 0.7 in steps of 0.1 by the mode switch while test riding. The following are the questionnaire results of the evaluation test of this system.

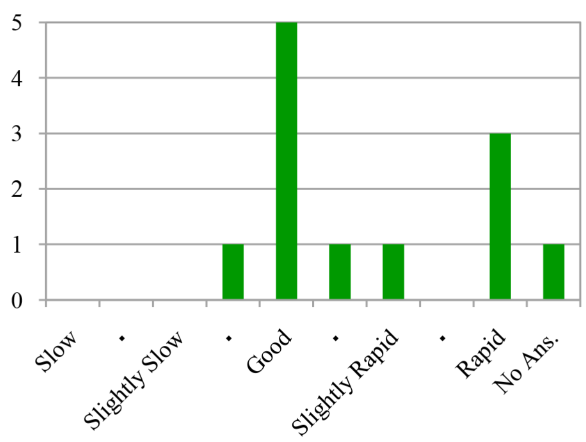
Figure 12 (a) indicates the favorite μ_c which is prepared in the mode switch. Most of the riders selected 0.6 or 0.7 for μ_c, which are the value assumed for dry condition. From the result, the differences between the timing of the control intervention and the feeling of the riders are small, and the unnatural feeling from the intervention is restrained. There are the other opinions that it needs higher μ_c since the intervention timing is a little bit early, and it was difficult to select only one μ_c since several μ_c are wanted according to the road condition.
Figure 12 (b) indicates the feeling of quantity of the additional return torque. "Good" was selected the most, half of the riders chose answers heavier than the best.



(a) Favorite μ_c



(b) Quantity of additional return torque



(c) Fluctuation speed of additional return torque

Figure 12　Questionnaire results of riding tests

From the results, the maximum additional return torque for the evaluation tests is a little higher than they want, and therefore, the maximum value is valid around 70cN*m, or needs adjustment of the gain settings for reducing the overall torque.

Figure 12 (c) indicates the feeling of the fluctuation speed of the additional return torque. This question also has the most number of "Good", and half of the riders chose answers rapider than the best. From this result, adjustments of the gain settings are needed to fit with the feeling of riders, by reducing the torque of the differential control which depends on the operation speed of the throttle grip and the torque of the proportional control from a changing direction or a quick turn.

Besides the questionnaire, there were it was got some comments from the riders. All of them were able to understand the purpose of this system, the gaps of the coefficient of friction between the mode switch were just proper, and they were able to perceive them, and use properly. Thus, it is possible to communicating with the system by force sense using intuitive information. But one of the rider commented that this system should not have the intervention on an operation system, and needs to improve to be more natural.

5 SUMMARY/CONCLUSIONS

Recently, there have been many reports about development of HMI which used a visual or auditory display to improve driver assist. A haptic display which has few disturbances was thought to suit for motorcycle even if it has less quantity of information than a visual or auditory one. The test vehicle, which has the haptic throttle grip as a haptic HMI and the logic which transmit the surplus engine torque information with friction circle was made, and the data was collected from the riding tests. The following states the conclusions.

This haptic system can transmit the limit of tire grip on the driving wheel or the surplus engine torque to the rider using a haptic signal of force sense. This system has an effect as a riding support system since this intuitive haptic signal intervening to the operation system feels like an operation support. Using the PD control from the results of the riding tests is valid for the control strategy for an operation support system of throttle grip. It is suitable to limit the maximum additional return torque 70cN*m for riders. The PD control with friction ellipse has better feeling for riders than with friction circle, and therefore, it is good to use friction ellipse for this system in the future.

Imaginary coefficients of friction decided by development engineers are used in this system, therefore, to estimate the real value is one of theme to be considered in the future. Some of riders had unnatural feelings which were made by the quantity and timing of the additional return torque. Adjustment of the gains of both controls to improve the system will also be considered. And last, improving the strategy of this system will be considered since this system cannot transmit any information when only the lateral force becomes big beyond the friction circle at acceleration. In spite of improvements to be considered, this system can transmit the information and support the rider.

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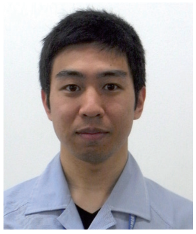

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