Letter

Low-Speed Control Experiment of Motorcycles Using SPACAR Model

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The main stream of development of autonomous driving technology (ADT) is for four-wheel motor vehicles. ADT for motorcycles has received scant attention. The motorcycle stability tends to diminish when being driven at extremely low speed. This study addresses how a motorcycle should be stabilized under low-speed driving. To obtain a linearized motorcycle model without skidding, we introduce a model based on SPACAR, a finite element method computation program. Moreover, velocity-dependent gain-scheduling LQR is applied. The experimental results demonstrate stabilized driving responses at 1.5 km/h, which is slower than a person's typical walking speed.

Keywords : low-speed driving, motorcycle, optimal control, SPACAR, unstable system

1. Introduction

Autonomous driving technology has mainly focused on four-wheeled vehicles, and research to improve the safety of two-wheeled vehicles has been limited so far. When a motorcycle runs at a low speed, upright stability is lost. If the rider loses balance as a result of encountering small bumps or uneven road surfaces, or if the motorcycle stops when it is tilted, the body of the motorcycle will fall. Various mechanisms have been proposed in previous studies to achieve the above goals; however, most of them entail modifying the structure of motorcycles [1][2].

This study discusses a control method that can be implemented without significant changes to the motorcycle structure. When a motorcycle decelerates, it is important to be able to decelerate safely while maintaining an upright position. Especially, the stability at speed of 2.0–5.0 km/h is important to secure riders. We have shown that a model derived by using SPACAR, a finite element method program, is reasonable for modeling low-speed deceleration of a motorcycle and we have already demonstrated its effectiveness through numerical simulations [3]. However, its experimental investigation has not been addressed yet. This letter shows the experiment and demonstrates that the system can be stabilized even at an extremely low speed of 1.5 km/h.

2. Motorcycle Model

In the past, the design of motorcycles was often based on the method presented by Sharp [4]. However, this is a mathematical model for evaluating stability at high speed and is not suitable for the control system design in this study. To consider the behavior at extremely low speeds, it is necessary to assume that the tires do not skid [3]. Figure 1 (a) shows a typical bicycle model, the Whipple bicycle model (WBM) [5], $\beta(t)$ is the steering angle, $\chi_f(t)$ and $\chi_r(t)$ are the rotation angles of the front and rear wheels,

respectively, $\phi(t)$ is the roll angle, $x(t)$ and $y(t)$ are the positions of the vehicle body, and $\psi(t)$ is the yaw angle. The tires are subjected to nonholonomic constraints. This constraint allows the tires to have velocity degrees of freedom in the direction of travel and rotation, but there are no degrees of freedom in the lateral direction. In general, a model with four rigid bodies connected by three pin joints has nine degrees of freedom; however, because both wheels are constrained to the ground, they lose two degrees of freedom and so seven degrees of freedom remain. In addition, four of the variables are velocity-constrained owing to the nonholonomic constraints, resulting in a velocity degree of freedom of three. The above conditions are modeled in SPACAR, which is a finite element method program [6]. Its model is represented as shown in Fig. 1 (b). In SPACAR, specifying constrained degrees of freedom is possible, and the coordinates of elements can be chosen as independent variables. The significance of adopting SPACAR is that, by using this function, a reasonable model without skidding can be formed. Sharp's model cannot derive such a model. In this study, $\chi_r(t)$, $\beta(t)$, and $\phi(t)$ were defined as variables with degrees of freedom in terms of dynamics, and $\chi_f(t)$, $x(t)$, $y(t)$, and $\psi(t)$ were specified as variables with degrees of freedom in terms of the kinematics. For more details on SPACAR, readers may refer to the literature [6].

For the WBM, SPACAR can derive the following linearized equations of motion when traveling at a steady speed [5]:

$$M\ddot{q}(t) + [\dot{x}(t)C_1]\dot{q}(t) + [K_0 + \dot{x}^2(t)K_2]q(t) = f(t), \quad \cdots\cdots \quad (1)$$
$$q(t) = [\phi(t) \ \beta(t)]^{\mathrm{T}},$$

where $\dot{x}(t)$ is the speed of the motorcycle, and $f(t)$ is the external force vector. From (1), the linear state equation for feedback control can be obtained in the same manner as Ref. (3).

3. Experiments

The experimental system used in this study is shown in Fig. 2. Its parameters necessary for using SPACAR are identified as listed in Table 1. A vehicle modified from the MT03 motorcycle manufactured by Yamaha Motor Co., Ltd., was used. The front and rear wheels were placed on separate rollers. When the rear wheel is controlled to rotate at a specified angular velocity, the

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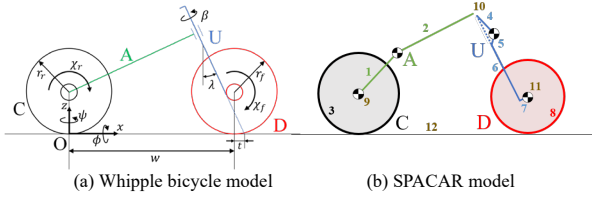** Yamaha Motor Co., Ltd., 2500 Shingai, Iwata 438-8501, Japan

(a) Whipple bicycle model   (b) SPACAR model

Fig. 1. Bicycle models.

Fig. 2. Experimental system.
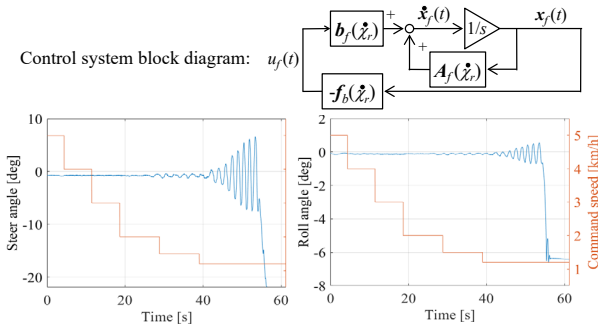
Fig. 3. Experimental responses (red lines: command speed).

Table 1. Experimental bicycle parameters.

Parameter	Symbol	Value
Wheel base	w [m]	1.3889
Trail	t [m]	0.0936
Steer axis tilt	λ [rad]	25.5°
Wheel radius	r_r, r_f [m]	0.3005, 0.285
Mass	m_A [kg]	95.436
	m_U [kg]	18.0
	m_C [kg]	18.0
	m_D [kg]	14.664
		Position centers of m_A and m_U [m] are [0.6485 0.5444] and [1.1987 0.7158].
Inertia tensor	[kg m^2]	$J_A = \begin{bmatrix} 0.3990 & -3.7523 & 3.2381 \\ -3.7523 & 28.899 & 0.1833 \\ 3.2381 & 0.1833 & 23.72 \end{bmatrix}$ $J_U = \begin{bmatrix} 1.3107 & 0.0018 & -0.3380 \\ 0.0018 & 1.3000 & 0 \\ -0.3380 & 0 & 0.3630 \end{bmatrix}$ $J_C = \begin{bmatrix} 0.3990 & 0 & 0 \\ 0 & 0.5910 & 0 \\ 0 & 0 & 0.3990 \end{bmatrix}$ $J_D = \begin{bmatrix} 0.2190 & 0 & 0 \\ 0 & 0.4100 & 0 \\ 0 & 0 & 0.2190 \end{bmatrix}$

An improvement of the gain-scheduled LQR in Ref. (3) with the weights: $\boldsymbol{Q}(\dot{\chi}_r) = (\dot{\chi}_r / 5) \cdot \mathrm{diag}\begin{bmatrix} 100 & 1.0 \times 10^6 & 100 & 1.0 \times 10^6 \end{bmatrix}$ for the states and $r = 1$ for the input, is applied. This method uses velocity-dependent LQ state feedback gains obtained from the above weights and model (2), which were obtained according to the running speed. Figure 3 shows its block diagram and the experimental responses. The stabilization is maintained up to 1.5 km/h which is slower than a person's typical walking speed.

4. Conclusion

This letter focused on a motorcycle model using SPACAR. Through experiments with an actual motorcycle, we confirmed that the model can stabilize it even at an extremely low speed. The stability issue at speed less than 1.5 km/h is a future subject.

front wheel, which is linked to the rear wheel by a belt, also rotates at the same angular velocity. The vehicle can move freely within the frame from −0.1 to 0.1 m to the left and right, and it also has a degree of freedom for the yaw angle. In addition, auxiliary wheels are attached to prevent a sudden collision with the upper part of the frame and the ground when the roll angle reaches ~7°. Power steering was implemented on the steering axis, and the steering input torque $\tau_{Handle}(t)$ was applied by a control method. It should be noted that the torque limiter was set to 50 Nm, and the experiments stopped automatically when the absolute value of the steering input torque exceeded this limit.

An IMU was attached to the center of the motorcycle to measure the roll and pitch angles. The motor of the steering axis was connected to an encoder that can measure the angle and angular velocity of the steering. Because the experiments were conducted indoors and the measurement accuracy of $y(t)$ and $\psi(t)$ were degraded, the state equations were reconstructed as follows:

$$\dot{\boldsymbol{x}}_f(t) = \boldsymbol{A}_f \boldsymbol{x}_f(t) + \boldsymbol{b}_f u_f(t), \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

$$\boldsymbol{x}_f(t) = \begin{bmatrix} \beta(t) & \phi(t) & \dot{\beta}(t) & \dot{\phi}(t) \end{bmatrix}^T, \quad u_f(t) = \tau_{Handle}(t).$$

The system consists of four state variables: $\beta(t)$, $\phi(t)$, $\dot{\beta}(t)$, and $\dot{\phi}(t)$, but it does not include displacement and yaw angle. In addition, because the measured values exhibited oscillatory responses resulting from the influence of unstructured uncertainties of higher order modes that were not included in the model to be controlled, signals passed through a second-order Butterworth-type low-pass filter with a cutoff frequency of 10.0 Hz were applied to the feedback control. MicroAutoBox, a real-time control computer (dSPACE GmbH), realizes feedback control with a sampling period of 1.0 ms.

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