Optimal Control Experiment of Self-Standable Motorcycle MOTOROiD

Mitsuo Tsuchiya1†, Susumu Hara2, Koki Nakagami2, Nao Tsurumi1 and Tetsuya Kimura1

1Advanced Technology Center, Yamaha Motor Co., Ltd., Iwata, Shizuoka, Japan
(Tel: +81-538-32-4398; E-mail: tsuchiyamit@yamaha-motor.co.jp)
2Department of Aerospace Engineering, Nagoya University, Nagoya, Aichi, Japan
(Tel: +81-52-789-4416; E-mail: haras@nuae.nagoya-u.ac.jp)

Abstract: This study involves the experimental verification of the control system of a novel motorcycle, named “MOTOROiD,” possessing a self-stabilizing mechanism. The motorcycle possesses a novel rotary axis, referred to as the active mass center control system (AMCES), which can vary the position of the total center of gravity. This ensures stability during low-speed driving and realizes autonomous straightening from the parked mode. A mathematical controlled object model was prepared, comprising the original motorcycle and a minor feedback control loop aimed at maintaining the minimum stability in waiting mode. For improving robustness, an outer feedback controller was designed, based on the frequency-shaped LQ control theory for the controlled object model. The experimental investigation of such a feedback control problem has not yet been addressed. This work presents an actual implementation of the LQ optimal feedback controller for a MOTOROiD. The efficacy of this controller has been experimentally verified.

Keywords: Robust control, Optimal control, Frequency-shaped LQ control, Stabilizing, Motorcycle

1. INTRODUCTION

In order to design a mobility system in the future that is suitable for our rapidly aging society, it is imperative to improve not only four-wheeled motor vehicles but also motorcycles. Among the various operation conditions, the low-speed driving mode is the most unstable mode for motorcycles. Moreover, autonomous straightening from the parked mode is also a critical issue. This prompted Yamaha Motor Co., Ltd. to release MOTOROiD in 2017, a motorcycle with a self-stabilizing mechanism [1]. MOTOROiD has a novel rotary axis, active mass center control system (AMCES), and it can vary the position of the total center of gravity.

To achieve this mechanism, mathematical modeling has been performed [2], and numerical analysis has been conducted based on the use of a two-degree-of-freedom optimal control system [3]. To prevent the high-order uncertainties, the specifications of the controller have been determined using the frequency-shaped LQ control theory. The effectiveness of the controller has verified via numerical simulations. However, experimental verification of the effectiveness has not been performed thus far.

Accordingly, this study investigates the LQ-based feedback control system of MOTOROiD. A simple stabilizing control problem under a torque disturbance is selected as an example, and the effectiveness of this system is verified experimentally.

2. MOTOROiD AND AMCES

This section summarizes the specifications of MOTOROiD and its AMCES.
MOTOROiD (Fig. 1) is a proof-of-concept experimental electric motorcycle aimed to enable new forms of personal mobility [1]. Its center of gravity is adjustable according to the measurement status of the
sensors. This enables it to achieve independence from its kickstand and stand upright from the parked mode without assistance. In the parked mode, MOTOROiD is settled using the kickstand.

AMCES (Fig. 2) controls and stabilizes the chassis of two-wheeled electric motorcycles. Via active control over the chassis, it is possible to constantly maintain the optimal state of operation of the vehicle. Control over the motorcycle attitude is achieved by the rotating parts, such as the battery, swingarm, and rear wheel, around the AMCES axis that runs through the center of the vehicle to control its center of gravity. The AMCES axis also serves as a joint connecting the parts marked in red (Q1) and blue (Q2), as illustrated in Fig. 2. During rotation, the battery at the front of Q2 moves either to the right or the left, thereby acting as a counterweight that enables the machine to maintain balance and remain upright at standstill. The intersection point of the AMCES axis and the ground is also the grounding point of the rear wheel. Therefore, the grounding point of the

---

**Fig.4 Disturbance torque and responses for identification.**

**Fig.5 Frequency responses from the disturbance torque to each angle.**
rear wheel is always fixed, even when the AMCES axis is rotated. The inner frame unit area rotates around the AMCES axis via electronic control.

The modeling schematic is depicted in Fig. 3. The details of the mathematical model used as a controlled object for MOTOROiD are presented in the references [2, 3]. They indicate the linearized model for the LQ control design.

3. EXPERIMENTAL INVESTIGATION

3.1 System modeling with minor feedback loop
The simulation-based investigation [2, 3] conducted considers the modeling and control method during the feedback control period. However, the real MOTOROiD requires a minor feedback loop to stabilize it not only in the control mode but also the waiting mode. Subsequently, the single-input linearized controlled object without any minor feedback control model is defined as

\[
\dot{x}(t) = A_n x(t) + b_n u(t)
\]

(1)

where \(q_1(t)\) and \(q_2(t)\) are the angles in Fig. 3, and \(u(t)\) is the control input. Here, the minor feedback control gain vector \(k_w\) was chosen via trial and error by stabilizing the vehicle during the waiting mode. The linearized model, including the minor feedback control, was defined as follows:

\[
\dot{x}_f(t) = A_f x_f(t) + b_f u_f(t)
\]

(2)

where \(A_p = A_n - b_n k_w\) and \(b_p = b_n\). Hereafter, the system equation (2) is referred to as the controlled object model in this paper.

In order to identify the elements in \(A_p\) and \(b_p\), the ARX model in MATLAB is applied to the MOTOROiD under M-sequence APRBS signal [4] disturbance torque for \(u(t) = u_d(t)\), as shown at the top figure of Fig. 4. Figure 4 also illustrates the comparison between the responses of the models (angles \(q_1\) and \(q_2\) in Fig. 3 and their time derivative values) and their corresponding real measurement data. This result shows that the identification of model (2) is achieved sufficiently. The minor feedback control is sufficient for the stabilization in waiting mode but insufficient for the robustness required during actual driving. Subsequently, we designed an outer feedback control loop based on the LQ control theory for the linearized model (2) because the sensors of MOTOROiD enabled us to realize the state feedback control easily. This in turn made it easy to determine the robust control characteristics [5]. However, the frequency responses from the disturbance torque to each angle \(q_1\) and \(q_2\) indicated the influences of high frequency unmodeled dynamics of over 10 Hz, as shown in Fig. 5.

3.2 Application of the frequency-shaped LQ control
The frequency-shaped LQ (FSLQ) control method [6] is applied after the high-frequency uncertainties shown in Fig. 5 are accounted for. In the FSLQ control method, the second order Butterworth low-pass characteristic, whose cut-off frequency is set to 10 Hz on the control input, is applied. Its dynamic characteristics are determined by the following state equation:

\[
\dot{x}_f(t) = A_f x_f(t) + b_f u_f(t)
\]

\[
u_f(t) = c_f x_f(t)
\]

\[
A_f = \begin{bmatrix} 0 & 1 \\ -\omega_f^2 & -2\zeta_f\omega_f \end{bmatrix}, \quad b_f = \begin{bmatrix} 0 \\ \omega_f^2 \end{bmatrix}, \quad c_f = [1 \ 0],
\]

where \(\omega_f\) and \(\zeta_f\) are the cut-off frequency (10 Hz) and the damping ratio \(1/\sqrt{2}\) : Butterworth type, respectively. Subsequently, the feedback control system obtained by the LQ control feedback gain vector \([k_p, k]\) for the augmented system is represented as follows:

\[
\dot{x}_a(t) = A_x x_a(t) + b_x u_a(t)
\]

\[
A_x = \begin{bmatrix} A_f & b_f c_f \\ 0 & A_f \end{bmatrix}, \quad b_a = \begin{bmatrix} 0 \\ b_f \\ b_f \end{bmatrix}
\]

\[
u_a(t) = -k x_a(t) - k x_f(t).
\]

The weighting coefficients \(Q\) and \(r\) in the LQ control theory are

\[
Q = \text{diag}[5000 \ 2500 \ 95 \ 0 \ 0 \ 0], \quad r = 1. \quad (5)
\]

The block diagram of the FSLQ control is presented in Fig. 6.

3.3 Experimental results
The results of the simple feedback control stabilizing experiments are summarized in Fig. 7. In all the experiments, the disturbance torque, whose maximum value is 250 Nm as shown at the top figure of Fig. 7, is applied. The bottom figure \(w(W)\) represents the electric power of the control input. Figure 7 comprises four cases: (i) minor feedback control only; (ii) LQ control w/o frequency-shaping (weighting coefficients: \(Q = \text{diag}[5000 \ 2500 \ 95 \ 0\] and \(r = 1\)); (iii) FSLQ based on \((5)\); (iv) FSLQ \((Q = \text{diag}[17600 \ 8800 \ 100 \ 0 \ 0 \ 0\] and \(r = 1\)).

![Fig.6 Block diagram of FSLQ control system.](image-url)
Case (iv) corresponds to the high gain feedback version of FSLQ control.

The experimental results show that cases (i) and (ii) exhibit insufficient robustness and high frequency chattering, respectively. On the contrary, cases (iii) and (iv) exhibit the robust responses and effectiveness of the proposed FSLQ. Moreover, the power spectral densities (PSDs) of responses in Fig. 8 verify the efficacy of the frequency-shaping. Cases (iii) and (iv) exhibit a decrease in PSDs in comparison to that of the original LQ control case (ii) in frequencies of 10 Hz or higher. This prevents high-frequency chattering. Moreover, the PSD of the electric power indicates that the high gain FSLQ control in case (iv) is effective in reducing battery consumption. This can be concluded because case (iv) realizes the lowest electric power in all frequency domains.

Fig.7 Comparison of feedback control experiment results.

Fig.8 Power spectral densities of responses.
4. CONCLUSION

This study involves the experimental verification of concepts presented in the authors’ previous papers on the control system of a novel motorcycle with a self-stabilizing mechanism, named “MOTOROiD.” The effectiveness of the combination of inner and outer feedback control loops and the outer feedback controller design, based on the frequency-shaped LQ control theory, was verified experimentally.

Future investigations can focus on experimental verification of low-speed driving stabilization, robustness improvement for ground uncertainties, and parameter variations depending on the presence of driver.

The authors thank Mr. Eiichirou Tsujii for his effort and significant contribution to the MOTOROiD project.

REFERENCES


