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Road-Adaptive Control Using Haptic Steer-by-Wire

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With the rapid advancement of vehicle electrification and autonomous driving technologies, Steer-by-Wire (SBW) systems have attracted significant attention as a next-generation steering technology. By eliminating the mechanical linkage between the steering wheel and the front tires, SBW enhances design flexibility and vehicle dynamics. However, the physical isolation from road reaction forces prevents drivers from perceiving tire–road interaction, including grip limits. Consequently, on low-friction roads, the sudden loss of steering resistance can induce dangerous excessive steering. Conventional force-feedback approaches either rely on predefined torque maps, which cannot adapt to sudden physical changes in road conditions, or employ physical torque sensors, which suffer from high cost and noise limitations. To address these issues, this study proposes a torque-sensorless bilateral control framework for SBW using a Disturbance Observer (DOB) and a Reaction Torque Observer (RTOB). The proposed system aims to achieve both steering feel through torque scaling and enhanced safety through a novel slip-adaptive variable damping control.

To restore realistic road feedback without torque sensors, a robust acceleration control system is constructed by applying DOBs to both the steering (leader) and actuation (follower) motors. The RTOB estimates the actual road reaction force based on the motor current and angular measurements, while compensating for internal friction. A four-channel bilateral control architecture is implemented to ensure both position synchronization and compliance with the law of action and reaction. Furthermore, to reduce the driver's steering effort, a torque scaling function is introduced. By applying a scaling factor α , the force equilibrium is defined as $\alpha\,\tau_l \;+\tau_f \;=\;0$, which allows the system to provide power assist purely through control parameters without altering the mechanical gear ratio.

To enhance safety on low-friction road surfaces, a variable damping control system based on slip detection is proposed. This system uses the reaction torque obtained during driving on high-friction road surfaces as a reference and monitors the deviation between this reference and the actual reaction torque estimated by the RTOB. When tires slip occurs and the reaction torque decreases, the deviation increases. The system then immediately applies active viscous damping to the steering wheel. This artificial "heaviness" serves as haptic guidance, intuitively warning the driver of slip and physically suppressing excessive steering inputs.

The experiment was conducted using a small SBW test vehicle equipped with a direct-drive motor. To evaluate safety interventions, low-friction tape was applied to the tires to simulate different road surface conditions.

First, the force feedback transparency and torque scaling performance of the bilateral control system were evaluated on a high-friction road surface. The results confirmed that, under conditions of $\alpha = 2.0$, the driver's steering torque was effectively reduced to half of the actual road reaction force while maintaining the transparency of force feedback.

Next, the system behavior was compared when a virtual steering torque was applied to the steering wheel such that the steering angle tracked 35 degrees 6 seconds after startup. Fig.1 shows the angular response when the proposed variable damping control is activated, while Fig.2 presents the corresponding torque response. Through variable damping control, the system instantly detected the decrease in road reaction force and applied a braking torque to the steering wheel. This intervention suppressed excessive steering input, significantly reduced overshoot, and resulted in the steering angle converging toward the target angle.

In conclusion, this study developed a torque-sensorless bilateral control system for SBW vehicles. Experimental results demonstrated that the proposed system provides transparency in force feedback, while the variable damping control adaptively increases steering resistance during tire slip. This approach stabilizes steering behavior and prevents excessive steering on low-friction roads, thereby providing an effective solution for enhancing both driving comfort and active safety in next-generation steering systems.

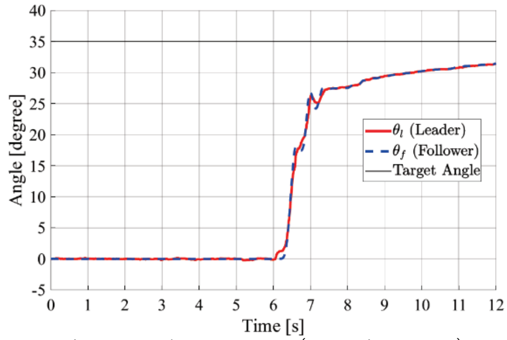

Fig.1 Angular response（Damping：ON）

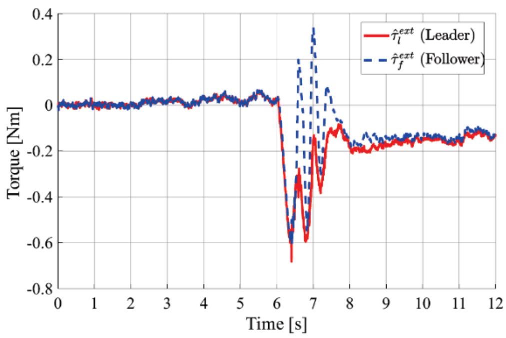

Fig.2 Torque response（Damping：ON）

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