講演番号	211

Design and Implementation of a Tire Force Estimation Model Based on the Extended Kalman Filter - Second Report -

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KEY WORDS: **Vehicle dynamics,** Tire, Dynamic model, Kalman filter, Optimization algorithm (B1)

This study presents an extended Kalman filter (EKF)-based tire force estimation model with a focus on a systematic and statistically grounded determination of the process noise covariance Q and measurement noise covariance R. A four-wheel vehicle dynamics model incorporating suspension compliance, steering characteristics, and a combined tire model is employed to estimate longitudinal, lateral, and vertical tire forces using only standard onboard sensors.

The vehicle model considers longitudinal, lateral, and vertical dynamics, including load transfer and roll motion. Tire forces are calculated using a combined tire model with friction similarity, enabling consistent representation of nonlinear behavior under combined slip conditions. Vehicle speed derived from wheel speed sensors and wheel rotational speeds are used as EKF observations, allowing real-time implementation without dedicated force sensors.

Although the EKF framework was previously reported, practical tuning of Q and R remained a major challenge, especially for reduced-order models with unavoidable model mismatch. To address this issue, two statistical criteria are introduced: a consistency check (P-test) based on ±3σ covariance bounds, and a chi-square test (S-test) based on innovation statistics (Fig.1). By jointly constraining both the ratio and the sum of Q and R, indeterminacy in noise scaling and allocation is avoided. Optimal parameters are identified using multi-objective Bayesian optimization and robustness is examined using DEBAS.

Vehicle experiments using a rear-wheel-drive test vehicle demonstrated up to a 50% reduction in longitudinal tire force estimation errors, particularly in high-force regions critical for vehicle control (Fig.2, Fig.3).

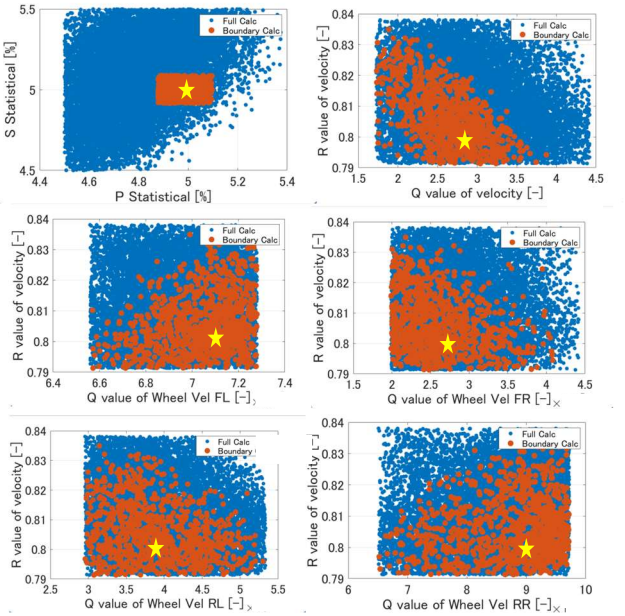


Fig.1 A Robust Parameter Determination Method Using DEBAS

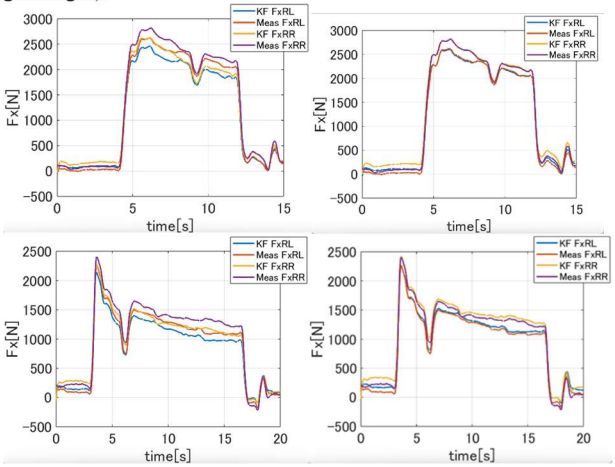
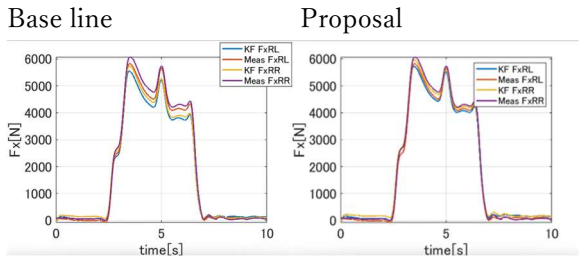


Fig.2 Comparison of Fx Estimation Accuracy Across Different Methods



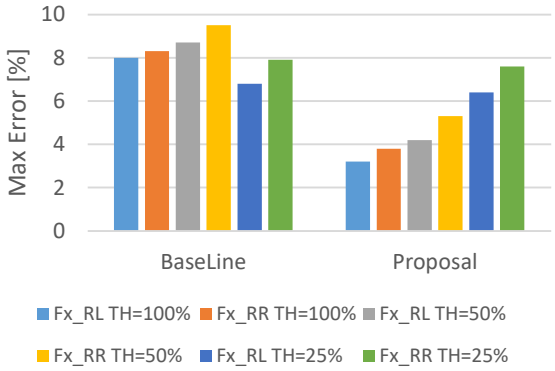


Fig.3 Results of slalom drivin