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A Fundamental Interpretation of the Coupling Structure Between Steering Systems and Vehicle Dynamics

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Vehicle response to steering input is determined by the dynamic interaction between the steering system and vehicle lateral motion. Lateral forces generated at the front tyres produce restoring moments about the kingpin, inherently coupling steering dynamics with vehicle motion. With the widespread adoption of Electric Power Steering (EPS), the steering system has evolved from a purely mechanical mechanism into a controlled dynamic system. Although steering–vehicle coupling has been extensively discussed, how this coupling appears as a structural property in the equations of motion has not been sufficiently organized.

This study examines the coupling structure between the steering system and vehicle dynamics from a coefficient-based viewpoint. Focusing on the restoring moment acting on the front steering system, the coupled equations of motion are reformulated to clarify how vehicle motion influences steering dynamics. A low-frequency perspective is adopted, since vehicle stability and steering feel are governed by coupled low-frequency modes.

Vehicle-speed-sweep pole maps show that the dominant low-frequency least stable poles are identical between a two-degree-of-freedom steering model and a reduced one-degree-of-freedom representation. As vehicle speed increases, these poles exhibit a characteristic transition in which the natural frequency remains nearly constant while damping decreases. This tendency appears consistently over a wide range of steering system parameters and EPS control settings. Although the coupling effect is not always evident from the diagonal structure of the equations of motion, examination of the characteristic equation reveals that the restoring moment originating from front tyre lateral forces constitutes the essential coupling term between steering dynamics and vehicle motion.

The restoring moment acting on the steering system can be approximated in the low-frequency region as an equivalent stiffness and an equivalent damping. By expressing the influence of vehicle motion in this form, the effects of steering system properties, EPS control, and vehicle dynamics can be treated using the same set of stiffness and damping elements. The equivalent stiffness increases with vehicle speed, while the equivalent damping decreases and becomes negative at higher speeds. These equivalent quantities do not represent physical steering system parameters but provide a unified representation that enables systematic interpretation of the coupled effects of steering control and vehicle motion on steering dynamics.

From a structural viewpoint, EPS control does not modify the fundamental coupling between steering systems and vehicle dynamics. Instead, control terms act as compensatory elements superimposed on the inherent coupling induced by the restoring moment. Velocity-dependent control offsets negative equivalent damping at higher speeds. The proposed interpretation provides a systematic framework for understanding steering–vehicle interaction and clarifies the role and limitation of steering control as compensation within an inherent coupling structure.

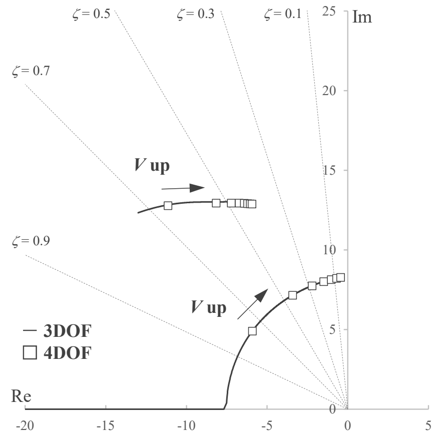

Fig.2 Pole Map Comparison between 4 and 3DOF Models

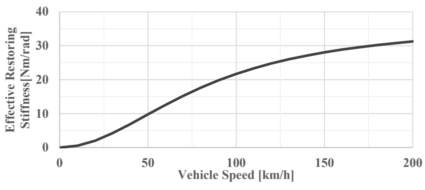

Fig.8 Speed-Dependent Effective Restoring Stiffness

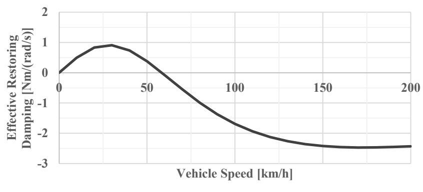

Fig.9 Speed-Dependent Effective Restoring Damping

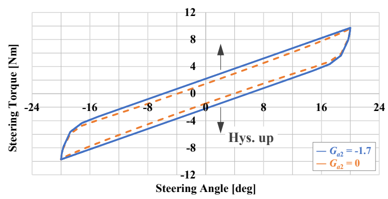

Fig.11 Damping Compensation Effect on Steering Torque Hysteresis

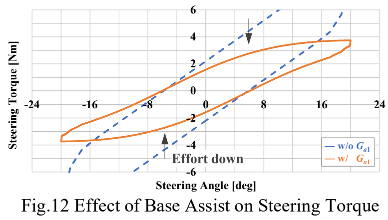

Fig.12 Effect of Base Assist on Steering Torque Hysteresis

$$2\frac{\xi}{n_s}\frac{Y_f}{\theta_s}(s) \approx (K_v + C_v s) \quad (14)$$

$$K_v = \frac{2\xi}{n_s} G_{\theta_s}^{Y_f}(0) = \frac{2\xi}{n_s}\frac{ml_r}{2l} G_{\theta_h}^{\ddot{y}}(0) \quad C_v = \frac{2\xi}{n_s} G_{\theta_s}^{Y_f}(0)\left(T_{Y_{f1}} - 2\frac{\zeta}{\omega_n}\right)$$

$$I_h'\ddot{\theta}_h + C_h''\dot{\theta}_h + K_h''\theta_h + F_h'(\theta_h) = T_h \quad (5)'$$

$$I_h' = I_h + \frac{I_s}{1+G_{a1}} \qquad C_h'' = C_h + \frac{C_s + C_v - G_{a2}}{1+G_{a1}}$$

$$K_h'' = \frac{K_v - G_{a3}}{1+G_{a1}} \qquad F_h' = F_h(\theta_h) + \frac{F_s(\theta_h)}{1+G_{a1}}$$