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Energy-Transmissibility-Based Transient Response Analysis of Vehicle Dynamics

Toru Yamazaki[1)] **Atsushi Kosegawa**[2)] **Yudai Araki**[1)]

1) Kanagawa University
3-27-1 Kanagawa Rokkakubashi, Yokohama, Kanagawa, 221-8686 (E-mail:toru@kanagawa-u.ac.jp)
2) Graduate School of Kanagawa University
3-27-1 Kanagawa Rokkakubashi, Yokohama, Kanagawa, 221-8686

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In recent years, mechanical systems such as vehicles are required to simultaneously satisfy multiple performances like handling stability, ride comfort, NVH, and collision safety. To manage these efficiently from the early design stages, this study extends a previously proposed energy transmissibility model from steady-state to transient vehicle dynamics.

In Chapter 2, a transient formulation is first derived for a two-degree-of-freedom coupled vibration system so that the first-peak behavior can be interpreted in terms of energy input, transfer, and dissipation. To handle time-varying elements, we utilize an arithmetic mean approximation for coupling terms, translating them into a linear combination of energy with a few time-invariant coefficients.

In Chapter 4, this formulation is applied to vehicle dynamics. By using a quasi-steady assumption for the slip angle ($\dot{\beta} \approx 0$), the planar-roll coupled motion is reduced to a two-degree-of-freedom system primarily represented by yaw and roll motions. The derived equations representing the power balance are shown below:

$$\begin{Bmatrix} P_\psi \\ P_\phi \end{Bmatrix} = \frac{d}{dt}\begin{Bmatrix} E_{\psi k} \\ E_{\phi k} + E_{\phi p} \end{Bmatrix} + \mathbf{D}\begin{Bmatrix} E_{\psi k} \\ E_{\phi k} \end{Bmatrix} + \mathbf{T}_{\mathrm{k}}\begin{Bmatrix} E_{\psi k} \\ E_{\phi k} \end{Bmatrix} + \mathbf{T}_{\mathrm{p}}\begin{Bmatrix} E_{\psi p} \\ E_{\phi p} \end{Bmatrix} \quad (1)$$

$$\mathbf{D} = \begin{bmatrix} \frac{2\bar{a}_{22}}{I_z} & 0 \\ 0 & \frac{2\bar{a}_{33}}{I_x} \end{bmatrix} = \begin{bmatrix} \eta_\psi & 0 \\ 0 & \eta_\phi \end{bmatrix} \quad (2)$$

$$\mathbf{T}_{\mathrm{k}} = \begin{bmatrix} \frac{\bar{a}_{32}}{\sqrt{I_z I_x}} & \frac{\bar{a}_{32}}{\sqrt{I_z I_x}} \\ \frac{\bar{a}_{23}}{\sqrt{I_z I_x}} & \frac{\bar{a}_{23}}{\sqrt{I_z I_x}} \end{bmatrix} = \begin{bmatrix} \eta_{\phi\psi} & \eta_{\phi\psi} \\ \eta_{\psi\phi} & \eta_{\psi\phi} \end{bmatrix}, \quad \mathbf{T}_{\mathrm{p}} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \quad (3)$$

Here, as introduced in Chapter 2, the fundamental concept of transient energy transfer can be understood through the basic two-degree-of-freedom vibration system shown in Fig A. By applying this concept and a quasi-steady assumption to the vehicle dynamics, the complex planar-roll coupled motion can be simplified into a two-degree-of-freedom system with nonsymmetric damper connections, as illustrated in Fig C.

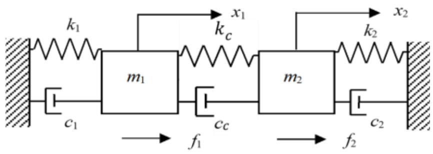

Fig.A Two-DOF system with grounded springs / dampers and coupling spring / damper

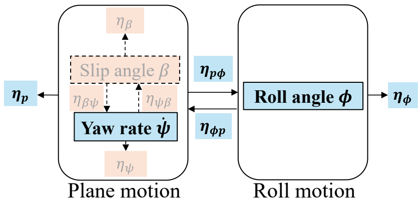

Fig.B Energy transfer path through the steering response

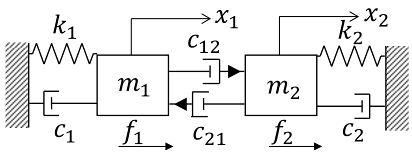

Fig.C Two-degree-of-freedom vibration system with nonsymmetric damper connections

In the equations above, $\eta_{\psi\phi}$ represents the energy transfer characteristic from the planar side to the roll side, and $\eta_{\phi\psi}$ represents the transfer characteristic from the roll side to the planar side. Additionally, η_ψ and η_ϕ represent the dissipation characteristics of the yaw motion and roll motion, respectively. The overall energy transfer path connecting these motions is depicted in the energy block diagram in Fig B.

As an example of response differences caused by design changes, the effect of vehicle mass change is examined. From the perspective of the energy transmissibility model, when the vehicle mass is increased from 1500 kg to 1700 kg , the transfer characteristic from the planar side to the roll side ($\eta_{\psi\phi}$) increases by approximately 14%, and the yaw dissipation characteristic (η_ψ) increases by about 6%. These simultaneous increases in both the transfer and dissipation characteristics indicate that the input energy is less retained as yaw motion and flows more easily into the roll motion. This clearly explains why the vehicle mass increase leads to a decrease in the yaw response and an increase in the roll response.

From the above findings, it has been demonstrated that the proposed model provides a compact and physically interpretable description of dominant transfer paths and first-peak trends. The decrease in yaw response and increase in roll response can be quantitatively explained as a change in transient energy distribution from planar motion to roll motion.