Roll – Yaw Coupled Dynamic Modeling For Vehicle Stability Enhancement

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1. ABSTRACT :

Vehicle stability under dynamic driving conditions is significantly influenced by the interaction between roll and This paper presents a roll–yaw coupled dynamic model for analyzing vehicle stability under steering inputs. Traditional vehicle models neglect roll dynamics, leading to inaccurate predictions of instability. A mathematical model incorporating lateral, yaw, and roll motions is developed using Newton–Euler equations. MATLAB and Simulink simulations are performed to analyze system behavior. The results show that the coupled model exhibits increased oscillatory response compared to the uncoupled model, highlighting the importance of roll dynamics in vehicle stability analysis.

- **KEYWORDS :**

Vehicle Dynamics, Roll Motion, Yaw Stability, Simulink, MATLAB Simulation, Vehicle Control.

2. INTRODUCTION :

Vehicle stability is a critical factor in automotive safety and performance. During dynamic maneuvers such as cornering and lane changes, vehicles experience coupled interactions between lateral, yaw, and roll motions. Conventional models, such as the bicycle model, often neglect roll dynamics, resulting in inaccurate predictions of vehicle behavior.

Roll motion significantly affects load transfer between wheels, altering tire forces and influencing yaw stability. Therefore, it is essential to develop a coupled dynamic model that captures these interactions. This paper presents a roll–yaw coupled model and evaluates its performance using MATLAB and Simulink simulations.

3. MATHEMATICAL MODLING :

The vehicle is modled as a three-degree-of-freedom system consisting of a lateral velocity, yaw rate, and roll motion.

- **LATERAL EQUATION :**

$$\dot{v} = \frac{C_f\left(\delta - \frac{v+ar}{u}\right) + C_r\left(-\frac{v-br}{u}\right)}{m} - ur \qquad Equation(\ 1)$$

- **YAW EQUATION :**

$$\dot{r} = \frac{aC_f\left(\delta - \frac{v+ar}{u}\right) - bC_r\left(-\frac{v-br}{u}\right)}{I_z} \qquad Equation(\ 2)$$

- **ROLL EQUATION :**

$$\ddot{\phi} = \frac{h\left[C_f\left(\delta - \frac{v+ar}{u}\right) + C_r\left(-\frac{v-br}{u}\right)\right] - C_\phi \phi - K_\phi \phi}{I_x} \qquad Equation(\ 3)$$

- **TIRE FORCES :**

Let:

$x1 = v, x2 = r, x3 = \phi, x4 = \dot{\phi}$

Then:

$$x_1 = \frac{F_{yf}+F_{yr}}{m} - ux_2 \qquad Equation(\ 4.1)$$

$$x_2 = \frac{aF_{yf}-bF_{yr}}{I_z}$$

Equation(4.2)

$$\dot{x}_3 = x_4 \qquad \text{Equation(4.3)}$$

$$\dot{x}_4 = \frac{h(Fyf+Fyr) - C\phi x4 - K\phi x3}{Ix} \qquad \text{Equation(4.4)}$$

- VARIABLE DEFINITION :

m - Vehicle mass
u - Forward velocity v - Lateral velocity r - Yaw rate
ϕ - Roll angle
Cf, Cr - Cornering stiffness a, b - CG distances
h - CG height Iz - Yaw inertia Ix - Roll inertia
K ϕ - Roll stiffness C ϕ - Roll damping δ - Steering angle

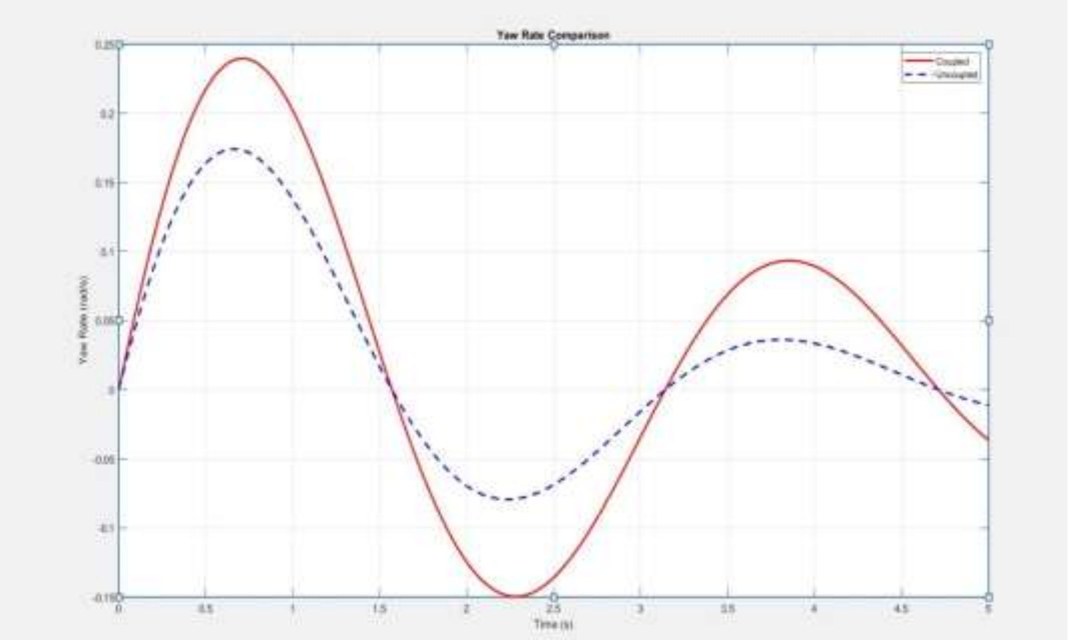
4. SIMULINK MODEL ARCHITECTURE DESCRIPTION :

MATLAB simulations are performed to evaluate the dynamic response of the system. The model is simulated for both coupled and uncoupled cases. In the uncoupled model, roll effects are neglected to analyze their impact on system stability.

[1] Yaw Rate Response Analysis : fig(1) shows "Yaw Rate Comparison" between coupled and uncoupled system.
The yaw rate response comparison illustrates the effect of roll coupling on yaw dynamics.
Observations:

- The coupled model (solid red curve) exhibits higher peak yaw rate, approximately 0.24 rad/s
- The uncoupled model (dashed blue curve) shows lower peak response, approximately 0.17 rad/s
- Oscillatory behavior is more pronounced in the coupled system
- Coupled response shows slower damping characteristics

Interpretation:
The increased yaw rate in the coupled model occurs due to interaction between roll motion and lateral tire force redistribution. Roll dynamics modify load transfer across tires, which affects cornering stiffness and amplifies yaw response.
This confirms that neglecting roll dynamics underestimates actual vehicle yaw behavior.



(Figure 1)

[2] **Roll Angle Response Analysis :** fig(2) shows “ROLL ANGLE VS TIME(in seconds)” graph of coupled system.

The roll angle response demonstrates body roll behavior under steering excitation.

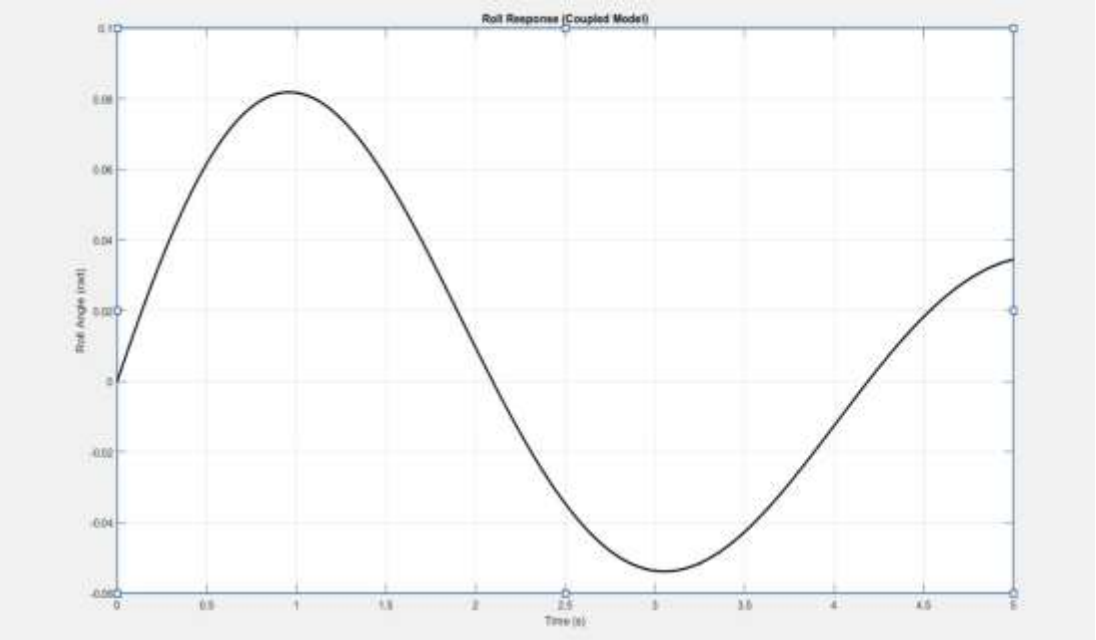
Observations:

- Maximum roll angle reaches approximately 0.082 rad
- Minimum roll angle reaches approximately −0.055 rad
- Oscillatory roll motion gradually decays
- The system remains stable without divergence

Interpretation:

The damped oscillatory roll response indicates sufficient suspension damping and roll stiffness for stability. The transient roll behavior confirms energy dissipation through damping mechanisms.

This validates the coupled roll dynamics formulation and confirms realistic suspension behavior.



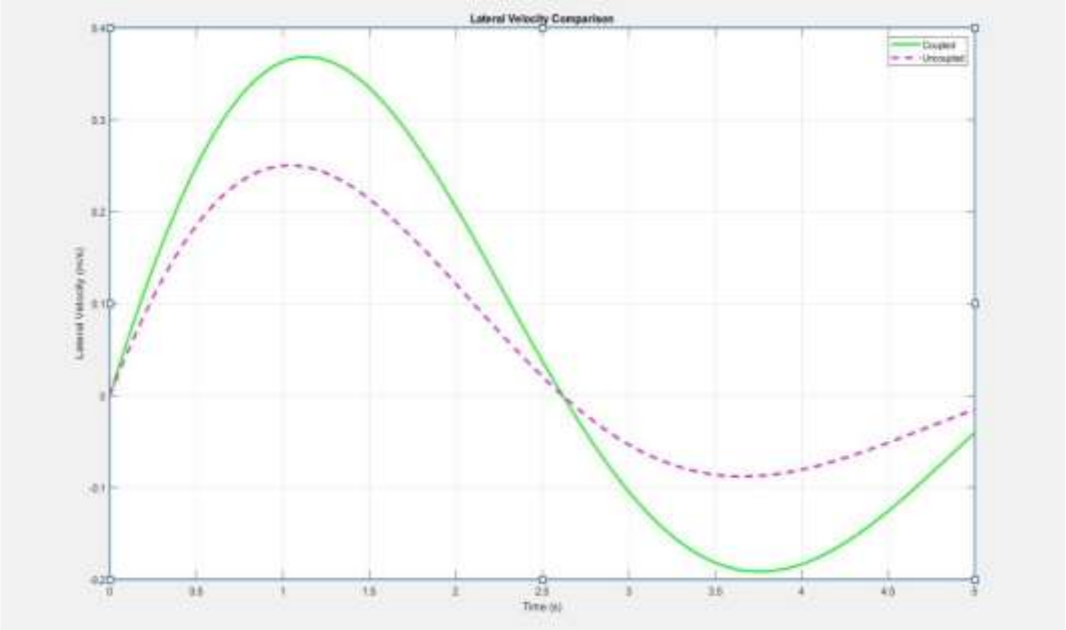
(Figure 2)

[3] **Lateral Velocity Response Analysis :** fig(3) **“**Lateral velocity Comparison Between Coupled and Uncoupled Models”
The lateral velocity response demonstrates significant influence of coupling effects.

Observations:

- Coupled model reaches a peak lateral velocity of approximately 0.37 m/s
- Uncoupled model peaks at approximately 0.25 m/s
- Coupled response exhibits larger oscillations and slower decay
- Uncoupled response stabilizes faster

Interpretation:
The stronger lateral oscillation in the coupled model is caused by body roll interaction, which alters tire-road contact forces and produces dynamic lateral force variations.
This indicates that roll dynamics significantly influence lateral stability and must be considered for accurate vehicle handling prediction.



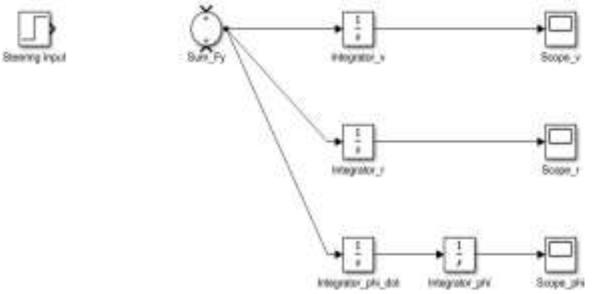
(Figure 3)

[4] **Simulink Model of Coupled Vehicle Dynamic :** fig(4) shows Simulink model of coupled vehicle dynamics.

The developed Simulink model represents the coupled lateral-roll vehicle dynamic system. The steering input is applied as external excitation to the summation block, where the lateral force response is computed. The system output is distributed into three dynamic channels:

- Lateral velocity response (v) through Integrator _ v
- Yaw rate response (r) through Integrator _ r
- Roll motion response (ϕ) through two cascaded integrators representing roll rate and roll angle

Each output is monitored using scope blocks for real-time response visualization. The model captures the interaction between lateral, yaw, and roll motions, enabling analysis of coupling effects on vehicle stability and transient response.
This structure validates the mathematical model and demonstrates the interdependency of vehicle body motions during steering excitation.



(figure 5)

5. RESULTS AND DISCUSSION :

The simulation results show that the coupled model exhibits higher oscillations in yaw rate compared to the uncoupled model. This is due to the influence of roll dynamics on tire force distribution. The roll angle response confirms the presence of load transfer effects, which are absent in the uncoupled model.

Furthermore, the lateral velocity response indicates reduced stability in the coupled system under steering input. These results demonstrate that neglecting roll dynamics can lead to inaccurate predictions of vehicle behavior.

The simulation results clearly show that coupling between lateral and roll dynamics significantly affects vehicle response characteristics.

Key findings include:

- Increased yaw rate amplitude
- Higher lateral velocity oscillations
- Additional roll-induced transient effects
- Reduced damping compared to uncoupled model

The coupled model provides a more realistic representation of vehicle dynamics and is therefore more suitable for advanced stability control design and handling analysis.

6. COMPARISON SECTION :

A comparison between coupled and uncoupled models reveals that the uncoupled model provides a smoother response but fails to capture real-world instability effects. The coupled model, although more complex, offers a more realistic representation of vehicle dynamics.

7. FUTURE SCOPE :

The future scope of integrated roll-yaw coupled dynamic modeling for vehicle stability enhancement is heavily focused on real-time, AI-driven, and multi-actuator coordination, particularly for electric and autonomous vehicles.

Key future research and development areas include:

- **AI-Driven Predictive Control:** Moving beyond traditional reactive systems to use Machine Learning (e.g., Reinforcement Learning) and Artificial Intelligence for predictive, real-time safety management.

- **EV-Specific Optimization:** Developing specialized stability models for Electric Vehicles (EVs) that account for unique torque vectoring capabilities and different center-of-gravity (CG) characteristics.

- **Multi-Actuator Coordinated Control:** Integrating braking, steering, and active suspension systems simultaneously to manage rollover (roll) and skidding (yaw) in a single, unified framework.

- **Real-Time Computational Efficiency:** Using simplified 3D dynamics (e.g., 3-DoF or 4-DoF models) with high accuracy to ensure quick, real-time implementation.

- **Intelligent Traffic Integration:** Developing systems that utilize V2X (Vehicle-to- Everything) communication to anticipate hazards and adjust stability parameters based on upcoming road geometry or traffic data. of body text

8. CONCLUSION :

This paper presents a roll–yaw coupled dynamic model for vehicle stability analysis. The results highlight the significant influence of roll dynamics on yaw response and overall stability. The coupled model provides improved accuracy compared to traditional models. Future work may include nonlinear tire modeling and control system design for stability enhancement.

The simulation results verify that lateral-roll coupling has a substantial influence on vehicle dynamic behavior. The coupled model predicts higher oscillatory response and more realistic transient characteristics compared to the uncoupled model, highlighting the importance of considering roll dynamics in vehicle stability analysis and control system design.

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