VEHICLE STEERING RETURNABILITY WITH MAXIMUM STEERING WHEEL ANGLE AT LOW SPEEDS

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ABSTRACT – In this paper, an analytical model with suitable vehicle parameters, together with a multi-body model is proposed to predict steering returnability in low-speed cornering with what is expected to be adequate precision as the steering wheel moves from lock to lock. This model shows how the steering response can be interpreted in terms of vertical force, lateral force with aligning moment, and longitudinal force. The simulation results show that vertical steering rack forces increase in the restoring direction according to steering rack displacement for both the inner and outer wheels. As lateral forces due to side-slip angle are directed toward the medial plane of the vehicle in both wheels, the outer wheel pushes the steering wheel in the returning direction while the inner wheel does not. In order to improve steering returnability, it is possible to increase the total steering rack force in both road wheels through adjustments to the kingpin axis and steering angle. This approach is useful for setting up a proper suspension geometry during conceptual chassis design.

KEY WORDS : Steering returnability, Kingpin axis, Steering effort, Wheel alignment, Suspension geometry

NOMENCLATURE

τ : caster angle
σ : kingpin inclination angle
λ : spatial kingpin angle with relation to vertical direction
β : camber angle
rc : kingpin offset at ground
nc : caster trail
nr : pneumatic trail
rcw : kingpin offset at wheel center
ncw : caster offset
δ : steer angle
Mr : kingpin axis moment
Vx : longitudinal velocity

SUBSCRIPTS
fr, fl : front right, front left
o, i : outer, inner
v, l, d : vertical, lateral, driving

1. INTRODUCTION

Well-designed vehicle chassis systems require good steering performance with regard to understeer characteristics, response, feedback, on-center feel, steering torque build-up, and steering returnability. In particular, steering returnability involves two maneuvers: maximum steering wheel returnability (which happens during low-speed cornering), and on-center area returnability (which occurs during high-speed driving with a small steering wheel angle). In low-speed cornering, a driver controls the steering wheel with precision (to take the car out of the parking lot, for example), and then releases the steering wheel to make the vehicle go straight. Upon release, the steering wheel is expected to return automatically to a straight-ahead position. Therefore, it is important to design a steering returnability characteristic adequate to move the road wheels against various forms of resistance at low vehicle speeds and to provide adequate steering wheel torque during handling maneuvers in order to give the driver appropriate feedback. Steering returnability at low speeds is heavily influenced by the restoring moment that originates from the suspension and steering geometry, in contrast to the restoring moment from lateral acceleration at high speeds. Gough (1953) shows that steering geometry and frictional force influence the maximum steering wheel torque when a vehicle is stationary. Pitts and Wildig (1978) discuss the influence of steering geometry between parallel steering and full Ackerman steering with an experimental validation. Sharp and Granger (2003) devised a static tire test-rig to measure tire properties, and developed a stationary suspension model. They show that kingpin offset at the ground has a very small influence on steering wheel torque because of the small vehicle lifting effect. However, they do not discuss the turning effect or suspension geometry such as the kingpin and caster angles. Kim et al. (2007) propose a more accurate multi-body dynamic approach to estimate steering wheel torque with experimental validation, and the work includes some analysis of suspension geometry effects. Pfeffer and Harrer (2008) present a method.
that allows the steady-state steering wheel torque characteristics to be laid out analytically with respect to the steering wheel angle near the on-center area without consideration of caster trail migration for inner or outer road wheels. Schmitt (2003) introduces a steering torque simulation model that includes suspension geometry changes according to road wheel steering angle with a focus on vertical and braking forces during parking maneuvers. Cho and Lee (2004) presents a kingpin axis moment analysis and reveals the directional contribution of vertical, lateral, and longitudinal tire forces. The current increase in the use of electrical assistance like MDPS makes this subject topical, as evidenced by the increased number of studies in recent literature (Park et al., 2007). Kurishige et al. (2000) propose an electric power steering control strategy to improve steering wheel returnability. Most papers focus on steering effort rather than returnability, and there have been few studies on suspension geometry for automatic returnability.

This paper suggests an analytical method to acquire returning steering wheel torque through an alteration of the kingpin axis in the suspension geometry. Section 2 describes the characteristics of tire force and moment at low speeds. Section 3 introduces the kingpin axis moment mechanism including the kingpin axis migration on steering. Section 4 describes the analytical model simulating the restoring moment in the vertical, lateral, and longitudinal directions. The model is validated by a full vehicle simulation with geometric sensitivity results presented in Section 5.

2. TIRE FORCES AND MOMENTS AT LOW SPEEDS

Since tire force and moment have a considerable effect on a vehicle’s cornering performance, they are important factors for understanding steering returnability. The tire lateral force \( F_y \), aligning moment \( M_z \), and overturning moment \( M_x \) are generated by tire slip angle, camber angle, axle weight \( F_z \), and their coupling effects. Driving force \( F_x \), which depends on the slip ratio and axle weight, is also generated to maintain constant speed on a front-wheel-drive vehicle.

To understand the tire characteristics at low speeds, we measured tire force and moment using an MTS® flat track machine at the 1.0 deg slip angle region and at various speeds. We found that cornering stiffness at 5 km/h is 6% lower than that at high speeds, and aligning moment stiffness is 8% lower than that at high speeds. Since tire properties change considerably at low speeds, tire properties are of consequence in steering returnability. Table 1 lists the measured tire parameters; cornering stiffness in the front and rear tires was 1,354 N/deg and 1,232 N/deg respectively, and the pneumatic trail was 22.1 mm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Cornering stiffness ( C_f ), ( C_r )</td>
<td>1354, 1232 N/deg</td>
</tr>
<tr>
<td>Camber thrust coefficient ( K_f )</td>
<td>141 N/deg</td>
</tr>
<tr>
<td>Overturning coefficient ( K_o )</td>
<td>40 Nm/deg</td>
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3. KINGPIN AXIS MOMENT WITH REGARD TO STEERING RETURNABILITY

3.1. Trajectory of the Kingpin Axis

A tire connected to the suspension system through a hub bearing is steered freely around a rotating axis called the kingpin axis. In a McPherson strut system (Figure 2), the kingpin axis is defined as a vector between the strut top mounting point and the lower ball joint point at a lower control arm. On a local tire coordinate system, kingpin axis trajectories migrate on a contact patch plane as well as a wheel center plane according to the tire turning angle, even

Figure 1. Tire cornering stiffness and aligning moment stiffness according to speed.

Figure 2. McPherson strut system (front suspension).