Active Front Independent Steering System and its Control for Road Vehicle with Understeer Characteristics


Abstract—Active steering systems improve vehicle handling by controlling the steer angle of the wheels depending on speed. Such controls, however, have limitations as they do not attempt to utilize tires’ force generating potential. The present study proposes Active Independent Front Steering (AIFS) technique with independent control for each front wheel such that the tire workload for each steered wheel is equalized. A simple control scheme has been developed for a vehicle with understeering handling characteristics which applies the corrective input primarily to the outer wheel. The results show that proposed concept of AIFS can provide performances equal to that of a conventional active steering system while tire work loads are balanced to maximize the performance limits.

Keywords—Active independent steering, tire workload, understeer vehicle, Vehicle handling.

I. INTRODUCTION

The concept of Active Front Steering (AFS) system has been around since the 90’s. It has gained new momentum with the advancement of sensors and control systems. Conventional AFS system [1, 2] modifies the driver command steering input by a corrective steering angle in order to realize a target response for that command at any forward speed. The correction is however made to both the steered wheels that are designed to closely follow Ackerman steering geometry. Such control strategy can provide adequate performance at low speed maneuvers [3, 4] until the dynamic load shift from the inner to the outer wheel become significant [5]. During a high lateral acceleration maneuver, the inner tire with less normal load can generate significantly less cornering force than the outer tire with much higher normal load. The AFS induced correction to both wheel will therefore tend to saturate the inner tire while the outer tire capacity remain unexploited [6]. In order to maximize the performance potentials of AFS, it is necessary that different corrections are introduced for the inner and outer wheels [5, 6]. Such a control strategy would require an independently controllable steering system, referred to here as Active Independent Front Steering (AIFS). Furthermore, criteria must be established to quantify the ability of tire to generate further force or determine their saturation limit. The concept of tire workload [7, 8] defined as the ratio of normal load to resultant tire force can be an effective measure for implementation of the AIFS system. The present investigation is carried out to evaluate the concept of AIFS with a control strategy applicable to a vehicle with understeer characteristics. A simple Proportional Integral (PI) controller is utilized to generate corrective steering for the inner and outer wheels such that the target is realized while attempt is made to equalize the tire workloads of both the tires. Simulation results generated for AIFS for a rounded step and sinusoidal lane change maneuvers are compared with those of AFS and uncontrolled systems to illustrate the effectiveness of the proposed concept.

II. SYSTEM MODEL

A. Vehicle System

Handling study of conventional AFS system will typically employ a bicycle model of road vehicle without regard to lateral load shift or tire’s saturation limit. To examine the proposed AIFS, it is essential to develop a 4-wheel vehicle handling model that includes tire non-linearity and vehicle roll dynamics. Using the vehicle coordinate system shown in Fig.1, the normal forces for each of the tires are:

Front, Right wheel: \( F_{zR} = W_t - \frac{m_x h_{cg}}{2L} + \frac{m_y h_{cg} c}{2T_t L} \)

Front, Left wheel: \( F_{zL} = W_t - \frac{m_x h_{cg}}{2L} - \frac{m_y h_{cg} c}{2T_t L} \) (1)

Rear, Right wheel: \( F_{zR} = W_t + \frac{m_x h_{cg}}{2L} + \frac{m_y h_{cg} b}{2T_t L} \)

Rear, Left wheel: \( F_{zL} = W_t + \frac{m_x h_{cg}}{2L} - \frac{m_y h_{cg} b}{2T_t L} \)

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For simplicity, the handling model is considered to be a 3DOF (longitudinal-\(x\), lateral-\(y\), and yaw-\(\Omega\)) model as shown in Fig. 2.

The tire lateral forces (\(F_y\)) and aligning moments (\(M_i\)) are computed from well-established non-linear Pacejka’s Magic Formula [9] tire model. The coefficients of the magic formula used are those corresponding to a medium size car tire provided in [9] and the slip angles for each of the four tires are computed from [10]:

\[
\alpha_{f,R} = \delta_L - \tan^{-1}\left[ \frac{b \cdot \Omega + V_y}{V_x + T_j \cdot \Omega} \right]; \quad \alpha_{r,R} = \tan^{-1}\left[ \frac{c \cdot \Omega - V_y}{V_x + T_j \cdot \Omega} \right]
\]

Detailed derivations for the vehicle and tire model are presented in [5]. In this investigation, a tire’s ability to generate handling or cornering force is defined by tire workload defined as:

\[
\text{Tire work-load} = \sqrt{F_y^2 + F_x^2} \cdot \mu \cdot F_z
\]

For coefficient of friction \(\mu = 1\), the tire workload approaching 0.9 is considered to be the saturation limit for a tire when its ability to generate further force is diminished.

### B. Control System

Pro-Ackerman steering geometry is desirable for passenger vehicles to minimize tire scrub and related noise and wear. On the other hand, anti-Ackerman ratio as used in race cars [11] has its merits where the tire capable of developing higher lateral force is allowed to do so. The control strategy proposed in this investigation utilizes Ackerman steering geometry with active independent front steering (AIFS) control. The control strategy will also allow anti-Ackerman ratio for high speeds when necessary to realize the reference yaw-rate, while optimizing the tire work-load.

In order to realize a target response at any speed, an understeer vehicle’s steering angle must be increased with speed. Furthermore the corrective steering angle should be primarily added to the outer wheel with lower workload. In the event the inner tire reaches saturation or the tire workload approaches unity, the angle for the inner tire should be reduced while that of the outer increased further. The initial results presented in this paper are obtained for corrective angle to the outer wheel only in order to demonstrate the effectiveness of AIFS system. The controller thus must identify the outer wheel prior to any corrective action taken. A general AIFS control strategy is presented in Fig. 3 and the present investigation considers only an understeer vehicle.
In this case, the corrective angle will be added to the outer wheel based on the error between reference and actual measured yaw rate:

$$\Delta \Omega = \Omega_{\text{ref}} - \Omega_{\text{act}} \quad (5)$$

where the reference yaw rate can be calculated from vehicle and operating parameters of a neutrally steered vehicle as:

$$\Omega_{\text{ref}} = \frac{V}{R_{\text{ref}}} = \frac{V}{L} \cdot \tan(\delta_{st}) \quad (6)$$

A corrective steering angle factor is then obtained using a steering gain factor:

$$\Delta \delta_{st} = K_{st} \cdot \Delta \Omega \quad (7)$$

Finally, the actively controlled AIFS steering correction command for the outer wheel is established using:

$$\delta_c = k_1 \Delta \delta_{st} + k_2 \int \Delta \delta_{st} \quad (8)$$

For the present investigation the gains are established by trial and error and are kept constant. It must be pointed out that for an optimal AIFS system, the gains must also be established in an adaptive manner along with different correction command for the inner and outer wheels.

III. Simulation Results

Due to interdependency between, vehicle and tire models and control system, it was necessary to formulate a closed loop simulation scheme as illustrated in Fig. 4, where $\delta_{st}$ is the controller corrected steering input for the inner and outer wheels.

The parameters used for the simulation of vehicle-controller system are presented in Table I. A turning simulation is carried out for driver steering command of 0.1 radians (5.73 degrees) in the form of rounded step input over a period of 2.0 seconds. Simulations are carried out for conventional AFS, where the correction is added to both wheels without altering the steering geometry, and AIFS where the correction is added to the outer wheel only. The results in terms of vehicle yaw velocity for a constant forward velocity of 15 m/s (54 km/h) are shown in Fig. 5.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Magnitude and Unit</th>
</tr>
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<tbody>
<tr>
<td>$m$</td>
<td>mass of the vehicle</td>
<td>1530 Kg</td>
</tr>
<tr>
<td>$I_z$</td>
<td>moment of inertia about z axis</td>
<td>3500 Kg.m$^2$</td>
</tr>
<tr>
<td>$L$</td>
<td>Wheel base</td>
<td>2.8 m</td>
</tr>
<tr>
<td>$b$</td>
<td>Distance of CG from front axle</td>
<td>1.3 m</td>
</tr>
<tr>
<td>$c$</td>
<td>Distance of CG from rear axle</td>
<td>1.5 m</td>
</tr>
<tr>
<td>$h_{cg}$</td>
<td>Height of CG from ground</td>
<td>0.4 m</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Half Track Width - front axle</td>
<td>0.7 m</td>
</tr>
<tr>
<td>$T_r$</td>
<td>Half Track Width - rear axle</td>
<td>0.7 m</td>
</tr>
<tr>
<td>$k_1$</td>
<td>Controller proportional gain</td>
<td>4.0</td>
</tr>
<tr>
<td>$k_2$</td>
<td>Controller integral gain</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The results show that as expected for an understeer vehicle, the steady state yaw rate will be lower than the reference or ideal if uncontrolled. Hence the control system will require adding to the steering command in order to realize the target response. The results in Fig. 5 show that both AFS and AIFS can equally realize the target response while AIFS correction is done for the outer wheel only. The wheel steer angles generated by the controller that lead to these responses are shown in Fig. 6.
The results show that the AIFS correction was achieved by increasing the outer (right) wheel steer angle alone to 8 degrees, while for AFS both the the inner and outer were increased above 7 degrees. The AFS by design maintained the Ackerman steering ratio and the increase was necessary to realize the target at this speed. However, due to lack of normal load on the inner (left) wheel, the workload on the inner wheel of AFS system was the highest as shown in Fig. 7. These results showing workload for each tire during the maneuver indicate that the inner of AFS has reached saturation while that of the outer wheel is the lowest. On the other hand, for AIFS, the workload of both tires is close to each other. With independent controllability of AIFS system, it is possible for the controller to reduce the steer angle of the inner (left) wheel while increase that of the outer (right) wheel further to realize the target. And in doing so, the workload will be equalized. This will leave each of the tires a reserve to develop further cornering or braking force without any of the tires reaching saturation.

In order to examine the performance of the proposed concept in a lane change maneuver, next set of results are generated for a sinusoidal steering input of peak to peak magnitude 0.03 rad (1.72 degrees) over a period of 2\(\pi\) sec. The simulations are carried out for a fairly high constant forward velocity of 25 m/sec. (90 km/h). The target, ideal or the reference yaw rate for the vehicle is defined by equation (6) corresponding to a neutrally steered vehicle configuration.

Similar to step input response, the AIFS realized the target response in lane change by modifying the steer angle of the outer wheel alone. However, for a sinusoidal input or a lane change maneuver, the right wheel is the outer wheel only for half the cycle after which the left wheel will become the outer wheel. The steering angles generated by the AFS and AIFS in order to realize the responses in Fig. 8 are shown in Fig. 9. The results show that steering angle for AFS was increased from driver command of 1.72 degrees peak to peak while the increase was applied to both the left and right wheels. The AIFS realized the same target response by applying totally different strategy where the corrective angle was applied to the right wheel for first half of the cycle while the left being the inner wheel was kept at the level of driver command. For the second half of the cycle, the right wheel was brought back to the level of driver command while the required increase in the cornering force was realized by the increase in the steering angle of the left wheel. The results presented in Fig. 9 further indicate that the switching between the inner and outer wheel takes place prior to reaching the half cycle. It is attributed to the attempt of controller to maintain target yaw rate and the point during the cycle where no correction is required to realize the target.

The performance measure in terms of tire work load of left and right wheels of AFS and AIFS systems for the lane change
maneuver is presented in Fig. 10. Although the tire work load is low for this maneuver, it presents a comparative analysis for the two active steering systems considered. Although the steering angle of both left and right wheels of AFS system is very similar (Fig. 9), there is a 30% difference between the peak tire workloads of the two wheels as shown in Fig. 10. For the proposed AIFS system, the tire workloads of both wheels remain close to each other throughout the cycle. These results clearly show that in a severe lane change maneuver, one of the wheels of AFS will approach saturation while the other will have the least work load. For the same maneuver, the AIFS will yield lower workload and hence will be able to handle more severe maneuver than the AFS system.

**Fig. 10 Tire workload for a lane change maneuver**

**IV. CONCLUSION**

The concept of AIFS with appropriate controller can be designed for an understeer vehicle to realize target response to a handling command similar to conventional AFS system. AIFS can however, enhance the performance limits of AFS by increasing the tire’s capability as it tends to equalize the workloads of the tires. In contrast to an understeer vehicle, an oversteer vehicle will require a more complex control strategy as the steer angle must be reduced with speed to realize target.

**REFERENCES**


