車幅の狭い傾斜車両の横転限界を向上させる

ジャイロモーメントを用いた安定制御

Stability Control with Gyro Moment to Improve Rollover Resistance of Narrow Tilting Vehicle

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要 旨

本研究では、回転体によるジャイロモーメントを利用し、急操舵による車両のロール方向の不安定を解消し、横転限界を向上させることを目的とする。マルチボディダイナミクスソフトウェアを用い、傾斜機能を有する超小型モビリティ車両のモデルを構築し、シミュレーションで急旋回の際に車両の姿勢と横転限界に対するジャイロ効果を検証した。シミュレーションの結果分析により、車輪浮き現象を検証し、回転体によるジャイロモーメントを用いた安定制御で、車両の横転限界を向上することを検討した。

Abstract

The objective of this work is to address the instability (inverse torque) caused by the tilt actuator in a narrow tilting vehicle by counterbalance it with a stability control system with gyro moment. A four-wheel narrow tilting vehicle was modeled in a multibody dynamics software to conduct a vehicle motion simulation with sharp steers, in order to investigate the gyro effects on the vehicle lateral acceleration (rollover resistance). From the results of the simulation, the inner tire displacements from ground and wheel loads were determined to analyze the vehicle stability. It was proven by the simulation that the stability control system with gyro moment had improved the rollover resistance of the narrow tilting vehicle.

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1. Motivation and Objective

Narrow vehicles have gained considerable interest in recent years due to the convenience in size and flexible maneuverability. The narrow body provides the capability in passing narrow path and also without the requirements of large parking space. However, narrow vehicles are likely to have low stability against rollover during hard cornering (So and Karnopp, 1997). To overcome this shortage, vehicle tilting (Karnopp, 2002) is often applied to improve the vehicle rollover resistance (Hac, 2002).

However, based on a tilt controlled vehicle constructed in our prior development, we had observed that when the tilt actuator activated during sharp curves or a turning operation performed suddenly, the lateral acceleration (\(a_{lat}\)) increased and the inverse torque of the tilt actuator lifted up the inside wheels temporarily and caused instability. To address this problem, we propose an approach to provide gyro moment to the tilting vehicle during hard cornering, in order to counter the lateral acceleration to improve the rollover resistance of the vehicle (Fig. 1). The rollover resistance of the vehicle is the maximum

![Fig 1 Proposal to apply gyro moment during hard cornering to improve the rollover resistance of the vehicle.](image-url)
lateral acceleration the vehicle can withstand before the vehicle rollovers.

2. Approach – Stability Control with Gyro Moment

The concept behind this approach is the gyroscopic effect, where a spinning wheel or disc is used to maintain the orientation based on the principles of angular momentum (Balo and Parent, 2003). A control moment gyroscope (Lappas, et al., 2005) device is designed with the control of the gimbal that tilts the angular momentum of the spinning disc along the yaw axis of the vehicle in order to generate a gyroscopic torque (Beznos, et al., 1998) along the roll axis of the vehicle. In this work, a gyro device was implemented in a tilting vehicle with active control to apply its gyro moment to counterbalance the lateral acceleration for stability control. Refer to Fig. 2, the added gyro effect to the vehicle moment balance equation can be expressed in Eq. (1).

\[ m a_{lat} h_{eg} = mg \frac{d}{2} + \tau_{gyro} \]  

(1)

To investigate this concept, we had developed an active stability control system (Fig. 3) to apply gyro moment onto a narrow tilting vehicle during hard cornering. Based on a simple two-wheel vehicle model in (Huang, 2014), when the vehicle was taking a cornering, the lateral acceleration acting on the vehicle can be expressed in Eq. (2) based on the (driver input) vehicle steer angle \(\delta\), vehicle speed \(V\), and the vehicle geometry. From Fig. 2, the optimum vehicle tilt angle \(\phi_d\) can be obtained by balancing the force of the lateral acceleration and the gravitational force as in Eq. (3). The equation can be expressed in terms of vehicle steer angle and vehicle speed as in Eq. (4) for the tilt angle calculation in the stability control system.

To counterbalance the inverse torque of the tilt actuator, the vehicle tilt angle was then being input into the stability control system to calculate the required gyro angular velocity, in order to control the gimbal control motor to generate the needed gyro moment. The gyro moment acted against the moment of the vehicle lateral acceleration to improve the vehicle rollover resistance.

\[ a_{lat} = V \frac{l}{l} \frac{\delta}{\delta} + V \frac{l}{l} \frac{\delta}{\delta} + \frac{V^2}{l} \frac{\delta}{\delta} \]  

(2)

\[ \phi_d = \tan^{-1} \frac{a_{lat}}{g} \]  

(3)

\[ \phi_d = \tan^{-1} \left( \frac{V \frac{l}{g l} \delta + V \frac{l}{g l} \delta + \frac{V^2}{g l} \delta \delta} \right) \]  

(4)

3. Modeling for Simulation

A computational model of a four-wheel narrow tilting vehicle was constructed in Multibody Dynamics (MBD) software ADAMS as shown in Fig. 3. The specifications of the vehicle are summarized in Table 1. A gyro device was located at the

![Fig. 2 Lateral acceleration of the tilting vehicle.](image1)

![Fig. 3 Block diagram of the stability control system with gyro moment.](image2)
middle of the vehicle to apply gyro moment in the roll axis. The specifications of the gyro device are summarized in Table 2.

4. Simulation Setup

The objective of the simulation is to investigate on the gyro effect of the active stability control system to improve the rollover resistance of the narrow tilting vehicle. A vehicle motion trajectory as in Fig. 4 was designed to simulate sharp steers (blue dotted circle) in avoiding frontal obstacle. Figure 5 illustrates the actual vehicle steer angle and steer angular velocity during sharp steers. The simulation conditions are tabulated in Table 3. The simulation was repeated without gyro for steer angle from 1 to 15 degree (with 1 degree increment) to identify the critical steer angle when the first vehicle rollover happened (to determine the rollover resistance).

Table 1 Specifications of the four-wheel narrow tilting vehicle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelbase (l)</td>
<td>1850 mm</td>
</tr>
<tr>
<td>Track (d)</td>
<td>500 mm</td>
</tr>
<tr>
<td>Height of the Center of Gravity (hcg)</td>
<td>600 mm</td>
</tr>
<tr>
<td>Length</td>
<td>2500 mm</td>
</tr>
<tr>
<td>Width</td>
<td>600 mm</td>
</tr>
<tr>
<td>Height</td>
<td>1490 mm</td>
</tr>
<tr>
<td>Total Mass (m)</td>
<td>390 kg</td>
</tr>
<tr>
<td>Tire</td>
<td>125/80R13</td>
</tr>
</tbody>
</table>

Table 2 Specifications of the gyro device.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Mass Percentage over Vehicle</td>
<td>4%</td>
</tr>
<tr>
<td>Rotation Speed</td>
<td>10,000 rpm</td>
</tr>
</tbody>
</table>

Fig. 3 Model of the four-wheel narrow tilting vehicle with gyro device.

Fig. 4 Vehicle motion trajectory with sharp steers.
The simulation was then conducted with the stability control system with gyro at the critical steer angle for the comparison of vehicle stability. Refer to the vehicle operation plot in Fig. 6, when the vehicle was undergoing sharp steers, the tilt control was activated to tilt the vehicle accordingly. The gimbal control of the gyro device was designed to be triggered with a slight delay according to the response time (0.62 s in this case) of the tilting device, in order to optimize the response timing in counterbalancing the vehicle rolling stability.

Table 3 Simulation conditions of the four-wheel narrow tilting vehicle.

<table>
<thead>
<tr>
<th>Motion Trajectory</th>
<th>Sharp Steer (Fig. 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Speed</td>
<td>36 km/h (10 m/s)</td>
</tr>
<tr>
<td>Steer Angle</td>
<td>1-15 degree</td>
</tr>
<tr>
<td>Tilting Angle</td>
<td>25 degree (max.)</td>
</tr>
</tbody>
</table>

The simulation was then conducted with the stability control system with gyro at the critical steer angle for the comparison of vehicle stability. Refer to the vehicle operation plot in Fig. 6, when the vehicle was undergoing sharp steers, the tilt control was activated to tilt the vehicle accordingly. The gimbal control of the gyro device was designed to be triggered with a slight delay according to the response time (0.62 s in this case) of the tilting device, in order to optimize the response timing in counterbalancing the vehicle rolling stability.

5. Results and Discussion

From the simulation results, the critical steer angle (when the first vehicle rollover happened without gyro) was 12 degree. The simulation results of the vehicle inner tire displacement from ground and inner wheel loads with and without gyro at critical steer angle (12 degree) were plotted as in Fig. 7 and Fig. 8. In Fig. 7, it is observed that the inner tire displacement from ground is relatively small (wheels are near to the ground) for vehicle with gyro, while vehicle without gyro experiences large displacement (overturn). Similarly in Fig. 8, the vehicle inner wheel loads has become zero (wheels are lifting from the ground) during sharp steers but is able to recover (the wheel loads) for vehicle with gyro, while vehicle without gyro failed to recover.

Both the tire displacement and wheel load results have proven...
that the stability control system with gyro had effectively protected the vehicle from being rollover. During the sharp steers (green dotted circle in Fig. 7 and 8), the lateral acceleration had caused the inner wheels to rise from the ground and resulted vehicle instability. However, when the stability control system activated vehicle tilting from the vehicle steer input, it triggered the gyro device to generate gyro moment. The gyro moment “pressed down” the inner side of the vehicle and recovered the vehicle stability.

The vehicle steer angle and steer angular velocity as in Fig. 5 were input into Eq. (2) to calculate the vehicle lateral acceleration with gyro (12 degree) and without gyro (11 degree). The calculated results were plotted in Fig. 9. Based on the simulation without gyro, the maximum lateral acceleration (rollover resistance) can be achieved is the peak value of the pink curve (11 degree). By adding gyro into the control system, the vehicle can achieve higher peak value in the blue curve (12 degree) without rollover. Hence, our proposal was proven by the simulation that the stability control system with gyro moment had improved the rollover resistance of the narrow tilting vehicle.

6. Conclusion

The objective of this work is to address the instability (inverse torque) caused by the tilt actuator in a narrow tilting vehicle by counterbalance it with a stability control system with gyro moment. A four-wheel narrow tilting vehicle was modeled in a multibody dynamics software to conduct a vehicle motion simulation with sharp steers, in order to investigate the gyro
effects on the vehicle lateral acceleration (rollover resistance). The results of the simulation can be summarized as follows:

- The critical steer angle when the first vehicle rollover happened without gyro was 12 degree.
- At critical steer angle, the inner tire displacement from ground was relatively small (wheels were near to the ground) for vehicle with gyro, while vehicle without gyro experienced large displacement (overturn).
- Also, the vehicle inner wheel loads had become zero (wheels were lifting from the ground) during sharp steers but was able to recover (the wheel loads) for vehicle with gyro, while vehicle without gyro failed to recover.
- By adding gyro into the control system, the vehicle had achieved higher lateral acceleration value (12 degree) then vehicle without gyro at the maximum steer angle (11 degree) without rollover.

Hence, our proposal was proven by the simulation that the stability control system with gyro moment had improved the rollover resistance of the narrow tilting vehicle.

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References