技 術 論 文

Investigation of the behavior of three-wheel vehicles when they pass over a low μ road surface

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要旨

近年、高い安定性と2輪車並の運動性能から前2輪、後1輪の3輪キャンバ車両が普及しつつある。我々はこのような車両をLeaning Multi Wheel 車両(以下LMW 車両)と呼び、研究と開発を進めている。LMW 車両は様々な特徴を持つが、その中の一つとして旋回中に前輪片輪が路面摩擦係数の低い箇所を通過しても安定して走行可能な点があげられる。ただ、なぜそのような特性になるか調査はできておらず、車両理解の観点からも理論的に現象を明らかにすることが求められている。そこで、本報告では計測とシミュレーションによりLMW 車両が旋回中に低μ路を通過した際の挙動に注目して検討を行う。初めに確認のため、実機での計測を実施した。その結果、車両姿勢の変化が小さいことと、もう一方の前輪が減った横力を補うようにタイヤ力を発生していることを確認した。次に要因調査を行うため、機構解析上で検討を行った。その結果、解析上でも実機と同様の現象を確認することができた。以上の検討を通じて現象を明らかにすることにより、LMW 車両が持つ旋回安定性の一因を示すことができた。

Abstract

In recent years three-wheel camber vehicles, with two wheels in the front and a single rear wheel, have been growing in popularity. We call this kind of vehicle A “Leaning Multi Wheel category Vehicle” (hereinafter referred to as a “LMWV”). A LMWV has various characteristics, but one of them stands out in particular. When a LMWV is cornering, if one of the front wheels passes over a section of road surface with a low friction coefficient, there is very little disturbance to the vehicle’s behavior and can continue to be driven as normal. However, there has been no investigation into why these vehicles have this particular characteristic. Consequently, in this paper an investigation was carried out in order to determine the behavior of a LMWV in this situation. First, measurements were taken using an actual vehicle to confirm the situation described above. As a result, it was confirmed that there is only a small change in the vehicle’s posture and also that the other front tire generates tire force that appears to compensate for the decrease in lateral force. Next, a multibody dynamics analysis was carried out. The results of this simulation indicated that the cause of this phenomenon is the steering turns toward the inside of the corner and the other front tire develops a slip angle which in turn generates a lateral force. The investigation and analysis described above clarified this phenomenon and demonstrated one of the factors that gives a LMWV its cornering stability.

1 INTRODUCTION

If we take a look back at the evolution of personal mobility, there is a long history of various vehicles being proposed all around the world. In recent years there has been an increase in the number of three-wheel vehicles, particularly in Europe, that have two wheels in the front, a single wheel in the rear, and that feature large camber angles. These vehicles possess a mechanism that is different from both automobiles and motorcycles, but they keep stability and motorcycle-like handling. We call this kind of vehicle a "Leaning Multi Wheel category Vehicle" (hereinafter referred to as a "LMWV") and have been pursuing their development as well as investigating their characteristics[1][2][3]. LMWV are known to possess a number of characteristics[4], but the riders of these vehicles have indicated that one noteworthy characteristic is the vehicle's stability when cornering. One concrete example that has been reported was the case where one of the front wheels passed over a low μ road surface, such as a wet manhole cover, while the vehicle was cornering. Despite these conditions, the vehicle remains stable throughout the turn and can continue to be driven as normal because of little roll angle change. However, there has not been a thorough examination of this particular characteristic and so there is a need for a theoretical study from the standpoint of understanding these vehicles better. In addition, there are very few other examples of research into these types of vehicles, so this is another factor that is preventing a better understanding of LMWV.

Therefore, in this paper an investigation was carried out to examine the phenomenon that occurs when one of the front wheels of a LMWV passes over a low μ road surface during cornering. The purpose of this investigation is to determine the factors that contribute to the turning stability of these vehicles. First, measurements were taken using an actual vehicle during the situation where one of the front wheels passes over a low μ road surface during cornering to confirm the phenomenon. Next, a multibody dynamics analysis was carried out by simulating the same situation to investigate the cause of the abovementioned phenomenon. This paper reports the results and new knowledge that were obtained from these analyses and examinations.

2 ACTUAL MEASUREMENT TEST

First, an actual measurement test was carried out to investigate and confirm this phenomenon. Fig.1 shows the LMWV with 155 cm^3 of displacement that was used for the test. Table 1 lists the vehicle specifications. Furthermore, in this paper, in order to focus on the vehi-cle characteristics, theoretically, when the vehicle is cornering, the examination was carried out using a geometry in which the difference in the left and right wheel steering angles was 0 degrees at the time of roll. The vehicle was equipped with an inertial GPS sensor, a steering torque sensor, and tire six-component force meter wheels on the left and right front wheels. Please see the references for more details about the measuring instruments[5]. The coordinate system uses the ISO coordinate system, as shown in Fig.2 and the origin point is located in the center of the right and left Fr.tire road contact point. It is a right-handed orthogonal coordinate system and the axis of rotation is positive in the direction of the right-hand screw. Fig.3 shows the tire force coordinate system. The origin point is located in the each Fr.tire road contact point and the coordinate axes follow along the road surface. α in Fig.3 indicates the direction of slip angle.

Fig.1 External Appearance of LMWV

Table 1 Vehicle Specifications

Vehicle spec					
Wheelbase	1350	mm	Overall length	1980	mm
Caster angle	20	deg	Trail	67	mm
Curb weight	165	kg	Engine displacement	155	cm^3
Fr tire	90/80-14M/C	-	Max power	11.1	kW
Rr tire	130/70-13M/C	-	Max torque	14.4	Nm

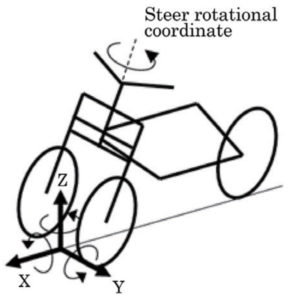

Fig.2 Coordinate system

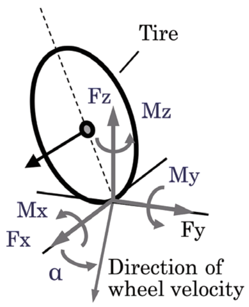

Fig.3 Tire Force Coordinate System

Outriggers were attached to the vehicle during measurement in consideration of the rider's safety. Fig. 4 shows the external appearance of the test vehicle. A smooth, steel plate (670×670×2.5mm) in a wet state was prepared to be the low μ road surface. A skid resistance tester was used to take measurements in advance and as a result it was confirmed that the BPN(British Pendulum Number) was 13.9. The test was then conducted on a circular test course with a radius of 30 meters. The vehicle was driven counterclock-wise around the course in a steady state circular turn and only the right front wheel passed over the low μ road surface. Rider always keeps a steady circular turn. The vehicle velocity was a constant 30 km/h. Fig.5 shows the roll angle measurement results. All measurement data was passed through a 10 Hz low pass filter. The area where one wheel passed over low μ road surface was determined from the tire force measure-ment data. The roll angle changed by approximately 1 degree when one of the front wheels passed over the low μ road surface. This amount of fluctuation in the roll angle is small in respect to that found during a steady state circular turn and so it was concluded that the vehicle was maintaining its stability. This result matched the comments received from the vehicle's riders. Next, as a distinguishing characteristic of the data measured by using the tire six-component force meter, Fig.6 shows lateral force measurement data which is shown as Fy in Fig. 3 from the front tires. The graph indicates that when one of the front tires passed over the low μ road surface, as the lateral force of the tire on the low friction surface decreased, the other tire appeared to compensate for it. Next, Fig.7 shows the steer angle result. The result shows the steering angle changed on the inside of turn. Consequently, this verification testing and the actual measurement data that was obtained made it possible to confirm that this phenomenon, which occurs when only one of the front wheels of the LMWV passes over a low μ road surface while cornering, does in fact exist.

Fig.4 External View of the Test Vehicle

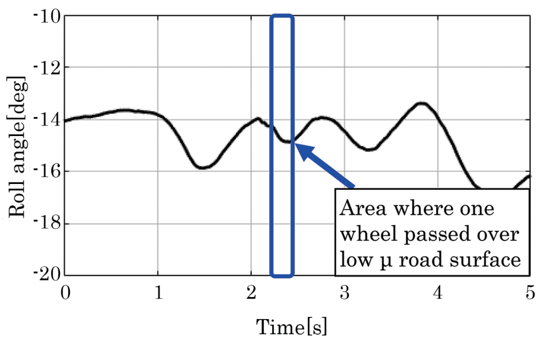

Fig.5 Roll Angle Measurement Data at Left Turn

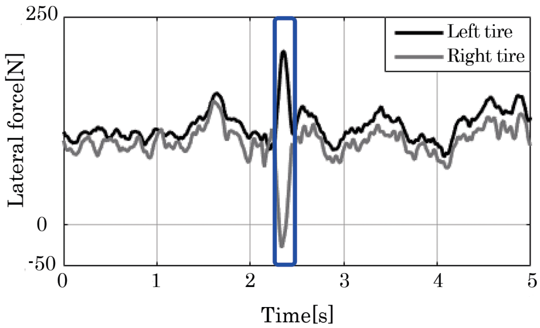

Fig.6 Tire Lateral Force Measurement Data

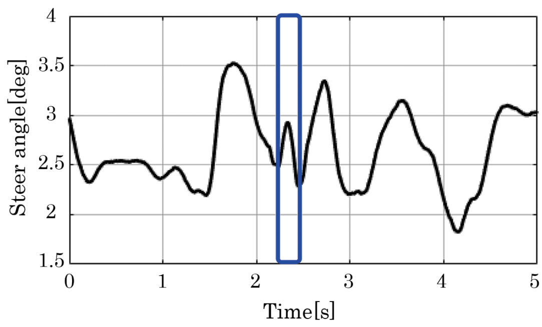

Fig.7 Steer Angle Measurement Data

3 SIMULATION

3-1. SIMULATION MODEL

There is a limit to the number of items that can be measured using the actual vehicle, so this phenomenon was investigated further by using a simulation. A simulation model of the same vehicle used in the actual measurement test was created for this investigation. The analysis software that was used was SimMechanics. The simulation model of the vehicle was composed of 20 rigid bodies, 18 revolute joints, and two prismatic joints for the left and right front suspension. In addition, non-linear springs and dampers were established for the left and right front forks and the rear suspension, while torsion springs corresponding to rubber bushings were established in rear arm and engine rotation axis. The rider was coupled to the main frame as a rigid body. The main frame of the vehicle possesses six degrees-of-freedom as a reference point, but the other portions of the simulation model, the rotation of the left and right front wheels and of the rear wheel, the rotation of the front lean mechanism, the elasticity of the left and right front suspension, the rotation of the handle bars, the rotation of the rear arm, and the rotation of the engine all possess 15 degrees-of-freedom. The Magic Formula model was used as the tire model. Each rigid element has mass property, moment of inertia, and coordinates at connecting points, and the springs and dampers have the values for the physical properties. Figs.8,9 and 10 show the simulation model in more detail.

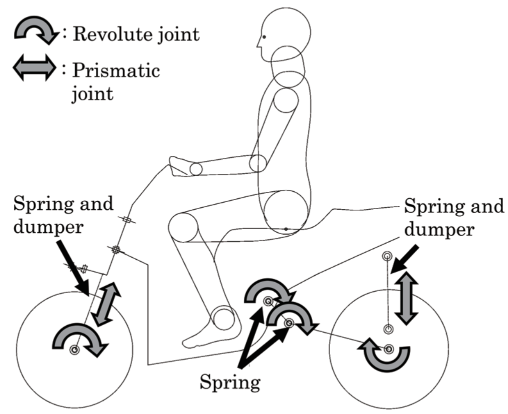

Fig.8 LMWV Simulation Model

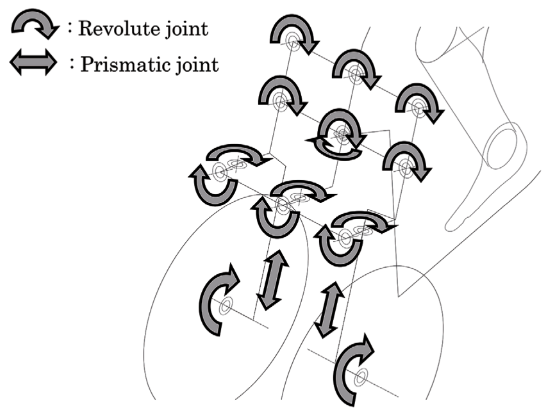

Fig.9 Lean Mechanism of the Simulation Model

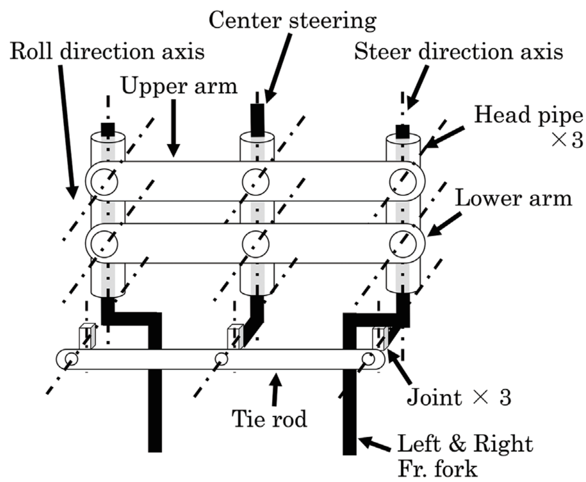

Fig.10 Detailed Drawing of the Lean Mechanism

3-2. RIDER CONTROL MODEL

A simulation of the vehicle being driven was carried out by having a maneuvering model control the vehicle model in the state described in the previous section. In the maneuvering model the drive torque of the rear wheel, τ_d, and the steering torque, τ_s, were found from the following equations.

$$\begin{aligned} \tau_d &= -K_{p1}(v - v_{ref}) \\ \tau_s &= -K_{p2}\left(\varphi - \varphi_{ref}\right) - K_{d2}\dot{\varphi} \end{aligned} \quad (1)$$

Where,
τ_d = drive torque
τ_s = steering torque
v = vehicle velocity
φ = roll angle
K = gain

In other words, proportional (and differential) control was carried out so that the velocity and roll angle would approach the target velocity, v_{ref}, and the target roll angle, φ_{ref}. In this paper, this rider model was used to conduct the investigation[6].

3-3. VERIFICATION OF THE MODEL

Prior to using the simulation to investigate the phenomenon, the simulation results were compared to the actual measurement data as a means of validating the suitability of the analysis model. The comparison was made when the vehicle was in a steady state circular turn in order to confirm the basic characteristics. The turning conditions for both the actual vehicle and the analysis were a radius of 30 meters, a vehicle velocity of 30 km/h and the target roll angle of 14.3 degrees. Furthermore, weights equivalent to the measurement instruments on the vehicle were added to the analysis model for the purpose of this comparison. All measure-ment data was passed through a 10 Hz low pass filter. Fig.11 shows the comparison results for the roll angle, steering torque, vertical force of the left front tire, and the lateral force. There is some fluctuation in the actual measurement data, but the figure shows that in all of these cases the simulation data largely corresponds to the measurement data. Consequently, the suitability of the simulation model was able to be confirmed from these results.

3-4. ANALYSIS OF VEHICLE BEHAVIOR

The vehicle model was used to carry out an analysis of the vehicle behavior when one of the front wheels passes over a low μ road surface. The target velocity was a constant 30 km/h. The vehicle would run straight forward for 10 seconds after the start of the simulation and then run in a steady state circular turn with a radius of 30 meters in a counterclockwise direction at the target roll angle of 14.3 degrees. Next, the situation where one of the front wheels passes over a low μ road surface while the vehicle is running in this constant turn was simulated. Once the turning stabilized after 20 seconds from the start of the simulation, the tire friction coefficient parameter was reduced to a friction coefficient equivalent to the one obtained from the actual vehicle meas-

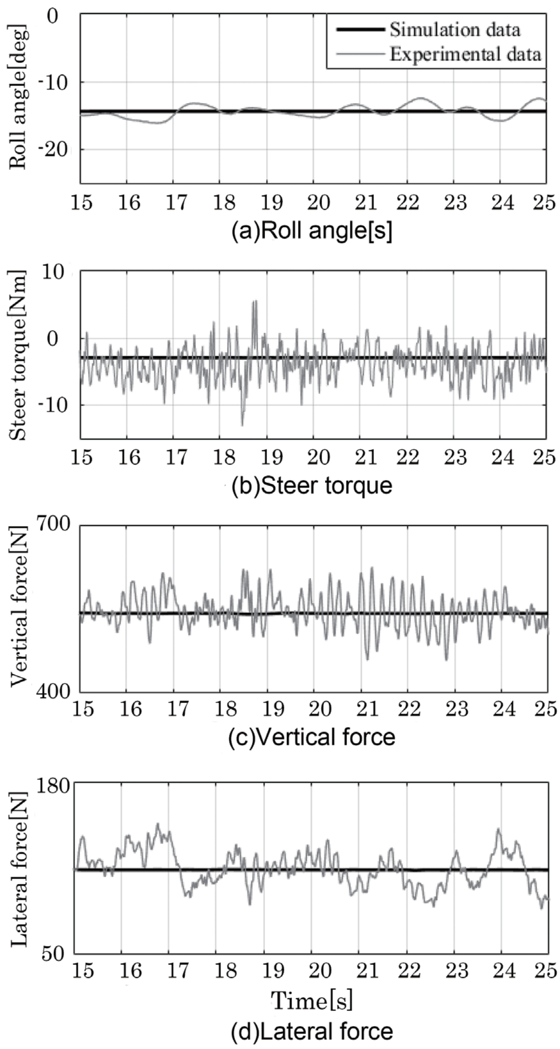

Fig.11 Comparison of the Simulation Data to the Actual Measurement Data

urement test, for 0.2 seconds on the front right wheel only (the wheel on the outside of the left turn). It is said that 1/100th of the BPN value has a correlation with the friction coefficient, so in this case the friction coefficient (μ_y) of the low μ road surface was set to 0.14 by changing lateral friction parameter in Magic Formula model.

The conditions described here were used to simulate and analyze the vehicle behavior. Fig.12 shows the analysis results. The results in this figure indicate that the change in the roll angle was small, approximately 0.4 degree, the same as in the results obtained from the actual measurements.

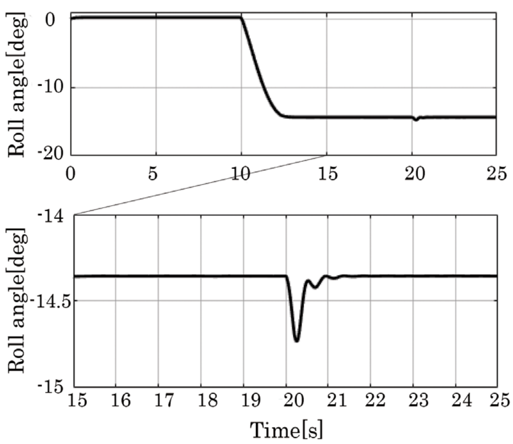

Fig.12 Roll Angle when the Friction Coefficient of One Wheel Changes

Fig.13 shows the left and right front tire forces obtained from the vehicle simulation. Focus on the vehicle behavior starting from the 20-second mark. The lateral force of the right tire tended to decrease when μ_y was reduced. In response to this, the lateral force of the left tire tended to increase. Consequently, a phenomenon in which the other tire (not passing over the low μ road surface) appears to compensate for the decrease in lateral force caused by the reduction in the friction coefficient was observed. Although some fluctuation in the vertical force can also be seen after the tire passed over the low μ road surface, the amount of change during the pass is very small and no other movements were seen that appears to show a difference in load on the left and right tires. In order for the tire to generate the lateral force to compensate for the shortfall of the other tire, for the most part, this would require changes in the tire vertical force, roll angle, and tire slip angle. In this case, there is little change in the tire vertical force and the roll angle, so the examination continued with a greater focus on the tire slip angle. Fig.14 shows the tire slip angle and steering angle. Slip angle direction is shown in Fig.3. These results show that the front tires have a positive slip angle when the vehicle is turning, but that these change to negative direction at the same time that the friction coefficient of the right tire changes. In other words, the change in the slip angles of the front tires causes the generation of a cornering force on the inside of the turn and so the tire lateral force increases. The steering angle also increases on the inside of the turn at the same time that the friction coefficient of the tire changes. This indicates that the slip angle of the front tires has changed. In this way, the front tires develop a slip angle at the same time that the friction coefficient of one of the front tires decreases and this in turn compensates for the decline in lateral force. The result of steer angle also shows that the same trend can be recognized on steer angle measurement data in Fig.7. This indicates the rider control model works almost same as the steer control of actual rider in this situation.

As a means of comparison, Fig.15 shows the results when the μ_y of both the front tires becomes 0.14 for 0.2 seconds after the 20-second mark of the simulation. The analysis actually stops in this case because of a very large change in the vehicle posture. However, in comparison to the results obtained when the tire friction coefficient is changed for only one front tire, it is obvious that there is a much larger change in the vehicle posture. As a result of this investigation, it is thought that when the friction coefficient of a single front tire declines, the other front tire generates a lateral force and this restrains the change in the vehicle posture.

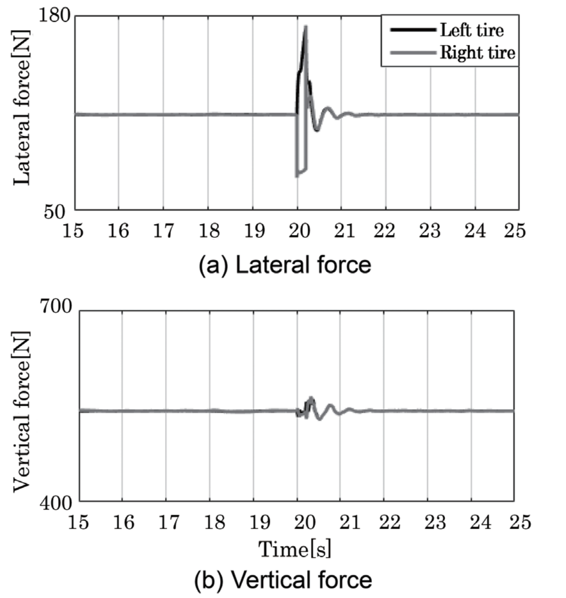

Fig.13 Tire Force when Friction Coefficient of One Tire Changes

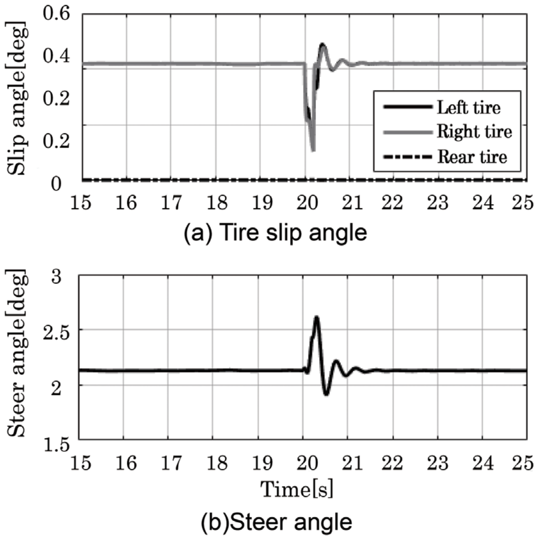

Fig.14 Tire slip Angle and Steering Angle when Friction Coefficient of One Tire Changes

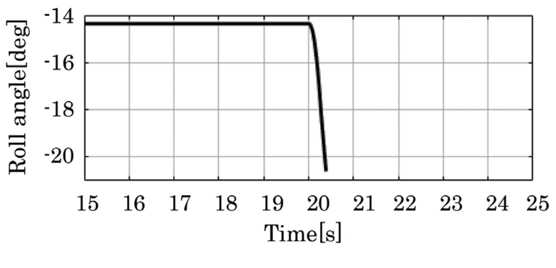

Fig.15 Roll Angle when Friction Coefficient of Both Front Tires Changes

3-5. EFFECT OF THE OTHER FR.TIRE PASSES OVER A LOW μ ROAD SURFACE

Next, Fig.16 shows the results of a simulation using the same conditions described above, except that this time it was only the front left wheel (the wheel on the inside of the left turn) that had its μ_y changed to 0.14. In the same fashion as when the outside front tire's μ_y was decreased, the change in the roll angle was small and the front tire appears to generate a lateral force to compensate for the decrease in the lateral force of the other front tire. This result demonstrated that the same result was obtained no matter which of the front tires suffers a sudden decrease in its friction coefficient.

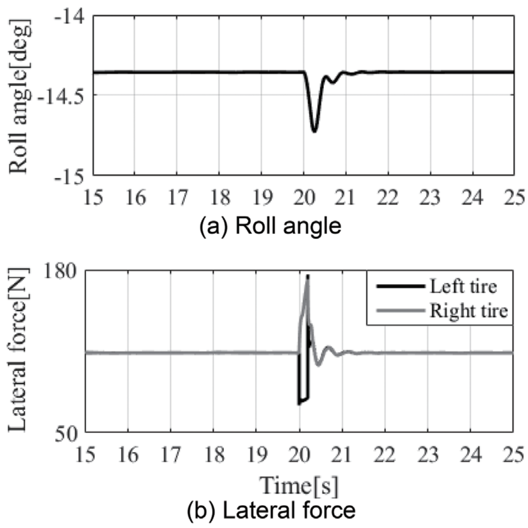

Fig.16 Analysis Results when the Friction Coefficient of the Inside Tire Changes

3-6. EFFECT OF THE LARGE ROLL ANGLE CONDITION

All of the investigations described above were carried out under conditions in which the roll angle was about 14.3 deg. Therefore, the roll angle was changed to 30 deg by increasing vehicle velocity and another analysis was run in order to confirm whether or not the same phenomenon would occur under the conditions. Fig.17 shows these analysis results. The results confirm that both the roll angle and tire lateral force show the same tendencies under these conditions as they did in the analysis results obtained when the roll angle was 30 deg.

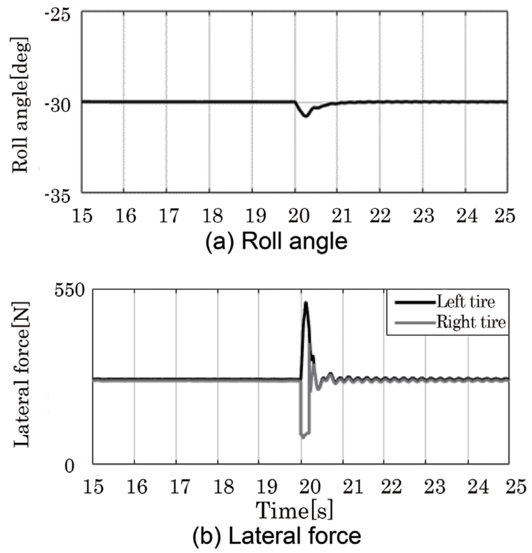

Fig.17 Analysis Results When the Roll Angle was Changed

3-7. EFFECT OF THE RIDER CONTROL MODEL

In the simulations and analysis described in this paper up to now the phenomenon that occurs when one front wheel of a LMWV passes over a low μ road surface while cornering has been investigated. However, these analysis results included steering torque control that simulated a rider. It is conceivable that in reality the rider would react too slowly and there would be no steering intervention. Consequently, the simulation was carried out again, except that this time steering torque control was not applied to reach the target roll angle when one of the front wheels passed over the low μ road surface so that the effect this has on the vehicle behavior could be isolated. Specifically, a constant steering torque of -2.9 Nm was added instead of the steering torque control of the target roll angle starting from 17 seconds after the simulation began. This constant value is the average steering torque from the simulation analysis that was obtained under the following conditions: a steady state circular turn at a target roll angle of 14.3 degrees and a vehicle velocity of 30 km/h. Under these conditions it was possible to examine the behavior of the vehicle when the friction coefficient decreased and there was no steering toque control to reach the target roll angle. A simulation was run in which only the front right tire of the vehicle had its μ_y reduced to 0.14 for 0.2 seconds under the conditions described above. Figs.18 and 19 show these simulation results. The steer rotational coordinate in Fig.2 is used as steer torque coordinate. The results in Fig.18 indicate that the steering torque of the rider model does not change when the friction coefficient of one of the front tires decreases. This means that it is possible to carry out this examination of the vehicle behavior even when the steering torque is constant. Furthermore, the results in Fig.19 indicate that the vehicle is still running stably, even though the change in the roll angle has increased. The results also demonstrate that the tire lateral force, slip angle, and steering angle have the same tendencies as in the case where target roll angle control was applied. It is thought that this suggests that even when the steering torque is held constant, the front tire slip angle and steering angle are changing and this causes the steering to turn toward the inside of the corner due to the torque from the vehicle body side. This in turn causes the front tire slip angle to change and a force is generated to compensate for the amount of decrease in the lateral force. In other words, it can be said that LMWV possess characteristics that reduce the steering control load on the rider that is necessary to stabilize the vehicle posture. These results confirmed that, regardless of rider control, a tire force is generated that compensates for the decrease in lateral force when one front wheel passes over a low μ road surface and this suppresses the change in the vehicle's posture.

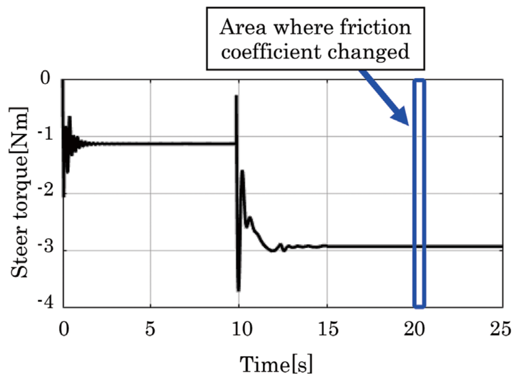

Fig.18 Steering Torque during Analysis

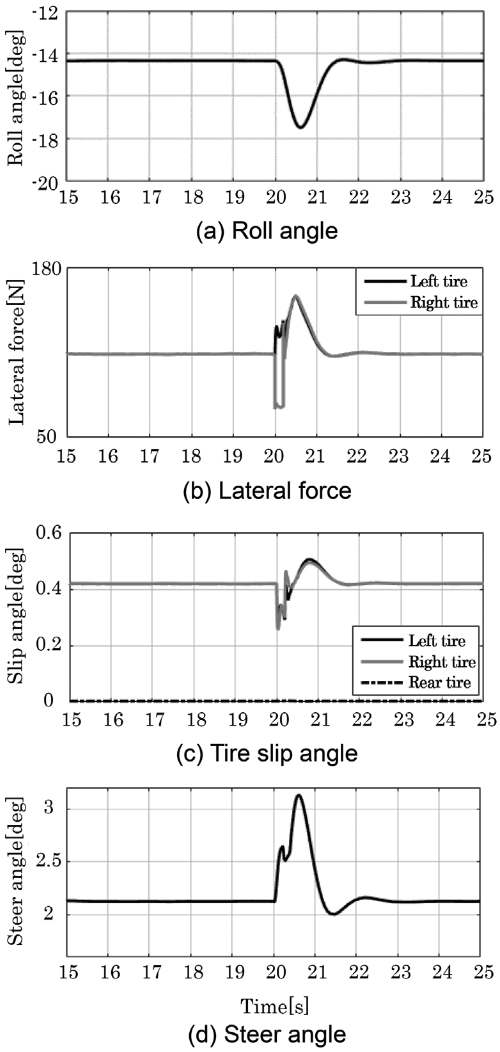

Fig.19 Analysis Results with No Steering Torque Control

4 SUMMARY

The following conclusions about LMWV were able to be drawn from the analysis and examinations that were carried out using actual measurement tests and simulation models.

1. Measurements were taken using an actual LMWV when one of the vehicle's front wheels passes over a low μ road surface while the vehicle is cornering and rider keeps a steady state turn. The measurement results clearly indicated that in reality the change in the vehicle posture under these conditions is very small and the decrease in lateral force on one front tire when it passes over the low μ road surface is compensated for by the other front tire.

2. A simulation of a LMWV was created to confirm the existence and cause of this phenomenon by the vehicle behavior when one of the vehicle's front wheels passes over a low μ road surface while the vehicle is cornering. The simulation results were analyzed and it was shown that the change in the vehicle posture was also small when the friction coefficient of one front tire of the LMWV decreased. The results clearly indicated that when the slip angle of one front tire changes, the other front tire compensates for the decrease in lateral force. In addition, further analysis of the simulation vehicle was also carried out under conditions in which the target roll angle control of the rider model was removed. This confirmed that the same phenomenon also occurred regardless of rider control.

3. The investigation described above was able to show one of the main causes that contributes to the stability of LMWV during cornering.

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