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Preventing the Rollover Phenomenon of the Vehicle by Using the Hydraulic Stabilizer Bar Controlled by a Two-input Fuzzy Controller

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ABSTRACT When the vehicle is traveling at high speed and suddenly steers, a rollover phenomenon may occur. The main cause of this phenomenon is the appearance of a centrifugal force, which is proportional to the mass and the square of the velocity. In order to limit this situation, the method of using the hydraulic stabilizer bar (active stabilizer bar) has been proposed. The performance of the hydraulic stabilizer bar is highly dependent on the control method, which has been designed to ensure the stabilizer bar's operation. Previous research often only used simple dynamics models and conventional linear control methods. Therefore, the performance of the stabilizer bar is not guaranteed. At the same time, the factors affecting the movement of a vehicle are not mentioned. This will cause inaccuracies. This research used a spatial dynamics model combined with a non-linear double-track dynamics model, which fully describes the effects of vehicle oscillations. Besides, the two-input Fuzzy control method is also proposed. This is a completely novel model, and it is not like the previous models that have been used to study the stabilizer bar. The results of this research show that if the vehicle uses the hydraulic stabilizer bar controlled by a two-input Fuzzy controller, the values of the roll angle and roll index have been reduced. As a result, stability and safety have been significantly improved. The achievements of this research will be the basis for the development of other intelligent control methods in the future.

INDEX TERMS Active stabilizer bar, Fuzzy control, Hydraulic actuator, Vehicle dynamics.

I. INTRODUCTION

The stability and safety of the vehicle when traveling on the road is one of the most important issues. As a result, safety standards and regulations of the vehicle are increasingly being raised. Nowadays, automotive manufacturers face these problems frequently. When the vehicle is moving on the road, many situations can occur, which can affect the stability of the vehicle. In particular, when the vehicle is traveling at high speed and the driver suddenly steers, the vehicle can be rolled over. The rollover phenomenon is caused by the effect of centrifugal force, which is produced when the vehicle steers. This force is proportional to the mass of the vehicle and the square of the velocity. Therefore, if the vehicle moves at a higher speed, the instability will be greater. If the vehicle is tilted, the load on both sides of the wheel will change. At the same time, the vertical force F_{zij} at each wheel will also tend to change. According to [1], if the vertical force at the wheel approaches zero, the roll angle of the vehicle will reach the maximum limitation, φ_{max}. Therefore, the rollover phenomenon may occur. These accidents often have extremely serious consequences for both passengers and goods in the vehicle.

In order to overcome this problem, several suggestions have been made. First, the dimensional parameters of the vehicle need to be optimized. In fact, if the mass and height of the vehicle's center of gravity are too large, and the track width is too small, the vehicle can be easily rolled over. However, if the vehicle's mass is reduced, the carrying capacity of the vehicle will not be guaranteed. Besides, the size parameters have been standardized according to regulations, so it is difficult to change these parameters. Therefore, this measure has little feasibility. Second, the driver's controllability is extremely important. The driver should avoid sudden steering with a large steering angle, and should not steer at high speed. Many unexpected situations occur on the road, and the driver can’t fully control them. A third solution has been suggested, which is to use the stabilizer bar. Today, on most vehicles, the stabilizer bar has been equipped to ensure stability when traveling on the road [2]. The stabilizer bar, also known as the anti-roll bar has been widely used all over the world. It includes three types: mechanical stabilizer bar, hydraulic stabilizer bar, and electronic stabilizer bar [3]. The mechanical stabilizer bar has a simple structure, and it is made of an elastic steel bar with a circular cross-section. Besides, its durability is very high, and it can be easily used on many vehicles today [4]. However, the effect of the mechanical stabilizer bar is not good. In many dangerous cases, it can't guarantee the vehicle's safety. Therefore, the active stabilizer bar (hydraulic, electronic) is proposed to replace the mechanical stabilizer bar (passive). At present, the hydraulic stabilizer bar is used more than the electronic stabilizer bar. Because its price is better than the others. The hydraulic stabilizer bar consists of a hydraulic motor and two lever-arms that attach to the wheel hub. This bar works by the displacement of the servo valves located inside the hydraulic actuator. The displacement of the servo valve depends on the current signal provided by the controller. The hydraulic stabilizer bar can produce more impact force F_A than the conventional mechanical stabilizer bar. Therefore, the stability and safety of the vehicle can be ensured if the vehicle uses this type of bar.

In recent years, many pieces of research on the rollover phenomenon have been published. According to [5], centrifugal force is the main cause of this phenomenon. In addition, if the wheel enters locations with large excitation, this phenomenon may also occur. However, its frequency is quite low [6]. According to Tuan and Thang, if the vertical force at the wheel approaches zero, the wheel will be separated from the road surface [7]. Then, the displacement of the unsprung mass and the roll angle also reach their maximum value [8]. For an infinitesimal moment, the rollover phenomenon can occur. In addition to using parameters such as the roll angle φ, the vertical force at the wheel F_z, and the displacement of the unsprung mass ξ to evaluate the rollover phenomenon, many researchers have also used the concept of the Roll Index (RI). In [9], Ataei et al. introduced the concept of the static roll index, which is expressed through the Static Stability Factor (SSF). This factor is used when the vehicle is parked on a lateral ramp, and it depends only on the dimensional parameters of the vehicle. When the vehicle travels on the road, many factors affect it, such as speed, steering angle, etc. Therefore, this factor is not suitable for determining the vehicle's stability. As an alternative to the Static Stability Factor, the Dynamic Roll Index has been proposed. In [10], Rajamani et al. introduced the concept of the Dynamic Roll Index (RI). This index is a complex function. It depends on the difference in vertical forces at the wheels F_{zij}. Based on this idea, Phanomchoeng et al. analyzed the Roll Index (RI) as a function that depends on the sprung mass m, the lateral acceleration a_y, and the height of the center of gravity h_φ [11]. According to Treetipsounthorn and Phanomchoeng [12], the value of the Roll Index (RI) ranges from -1 to +1. If its absolute value $|RI| = 1$, the vehicle will be rolled over. Recently, Dengler et al. made their announcement on the application of this index. According to [13], these authors used a neural network to predict the rollover phenomenon through the Roll Index. Besides, the Roll Index is also used on a variety of vehicles, such as buses [14], electric vehicles [15], etc. The models used in these papers are similar. Besides, there are many other methods used to predict the rollover phenomenon that have also been published [16-21].

$$R = \frac{F_{z1} - F_{z2}}{F_{z1} + F_{z2}} \quad (1)$$

As stated above, the use of the stabilizer bar is necessary. In fact, popular vehicles are only equipped with the mechanical stabilizer bar [22]. According to Kelkar et al., its specific shape and installation location will depend on the vehicle type and the different uses [23]. When the mechanical stabilizer bar is used, the vehicle's stability can be improved, which has been demonstrated through the research of Shi and Wang [24]. However, in special cases, the mechanical stabilizer bar is not able to guarantee safety for passengers and cargoes. To overcome this drawback, the active stabilizer bar is suggested. The effectiveness of the active stabilizer bar is highly dependent on its control method. Several researchers have presented linear control methods for hydraulic stabilizer bars. In [25], Yim et al. introduced the LQ algorithm to control this model. Similarly, this method was used again in the study of Varga et al. In [26], these authors have optimized the cost function of the controller so that its value is minimal. In [27], Zulkarnain et al. used a Gaussian filter for the system, so the controller becomes LQG. Muniandy et al. also proposed using a PI-PD controller for the hydraulic stabilizer bar [28]. Based on this view, Nguyen has shown the efficiency of the PID controller, which is used to control the operation of the stabilizer bar in his paper [29]. Besides, many other linear control methods have also been introduced [30-32]. In general, these methods all have their distinct effects. However, the vehicle is a complex nonlinear system. If only the conventional linear control method is used, the performance of the stabilizer bar is not guaranteed. Besides the traditional control methods, many modern control methods have been used for the hydraulic stabilizer bar model. In [33], Zulkarnain et al. combined the use of LQG (Linear Quadratic Gaussian) and CNF (Composite Non-linear Feedback Controller) control methods. Its performance is better than using only the LQG control method. In addition, the Sliding Mode Control method (SMC) has also been proposed to be used for the stabilizer bar. This was pointed out in the paper by Zhang et al. [34]. Furthermore, Xing et al. also published their work on hierarchical control algorithms, which are used to control

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the active stabilizer bar [35]. For complex objects, intelligent control methods are the appropriate choice. In [36], Marzbanrad et al. came up with the idea of using the Fuzzy control method for the active stabilizer bar. However, the controller designed in their paper is quite simple, and the authors do not mention the use of a hydraulic actuator. Similar to the above content, the paper by Yan et al. also modeled the use of a Fuzzy controller for the stabilizer bar [37]. According to the content of the paper, the Load Transfer Ratio (LTR) has been reduced quite a lot. But this paper also does not mention the influence of the actuator on the system. In [38-40], the authors also gave the idea of using the Fuzzy control method to adjust the parameters of the PID controller for the stabilizer bar. Its effect is also very positive. However, the performance of the actuator has not been demonstrated.

The above researches usually only use a half dynamics model combined with a linear single-track dynamics model to simulate the vehicle's motion. In addition, a description of the effect of a hydraulic actuator is lacking. With the aim of continuing to improve and develop the model based on the available views, this paper focuses on establishing a vehicle dynamics model and control method for the active stabilizer bar. In this research, a model of spatial dynamics is used, which can fully describe the factors affecting the vehicle's oscillation. Besides, the non-linear double-track dynamics model is combined with the model of spatial dynamics to describe the vehicle's motion most accurately. The hydraulic actuator has been analyzed and simulated clearly in this paper. The research proposed the use of a two-input Fuzzy controller to control the operation of the stabilizer bar. In general, the model and control method in this paper are completely novel and unique. They are very different from previous researches. This paper consists of four sections. In the first section, rollover problems are introduced. Research on the stabilizer bar has also been clearly analyzed. In the second section, the dynamics model of the vehicle and the dynamics model of the hydraulic actuator have been established. Besides, the control algorithm has been proposed. The results of the simulation are shown in the third section. These results will be compared with some results of other papers. In the last section, the contents and results of the paper will be briefly summarized. Additionally, some future proposals will be pointed out.

II. MATERIAL AND METHOD

A. VEHICLE DYNAMICS MODEL

The previous researches often only used a half dynamics model combined with a linear single-track dynamics model. In this paper, a spatial dynamics model that fully describes the effects of the vehicle is used (FIGURE 1). Besides, a non-linear double-track dynamics model is combined to describe the motion of the vehicle.

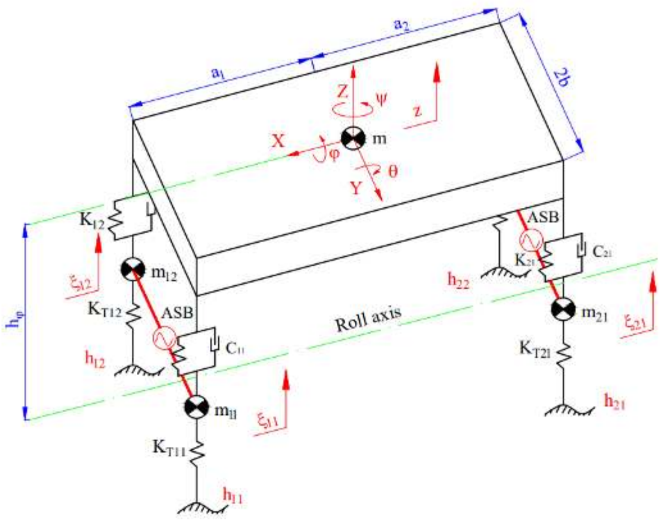

FIGURE 1. Spatial dynamics model.

Separation of the sprung mass and the unsprung mass. Equations that describe the oscillation of the sprung mass are given as follows:

$$m\ddot{z} = \sum_{i,j=1}^{2} F_{Cij} + F_{Kij} \tag{2}$$

$$\left(I_x + mh_\varphi^2\right)\ddot{\varphi} = \sum_{i,j=1}^{2}\left[(-1)^{j-1}\left(F_{Cij} + F_{Kij}\right)b_i\right] + \left(g\sin\varphi + a_y\cos\varphi\right)mh_\varphi \tag{3}$$

$$\left(I_y + mh_\theta^2\right)\ddot{\theta} = \sum_{i,j=1}^{2}(-1)^{i-1}\left(F_{Cij} + F_{Kij}\right)a_i \tag{4}$$

For the sprung mass, vertical displacements are corresponding to their positions:

$$m_{ij}\ddot{\xi}_{ij} = F_{KTij} - F_{Cij} - F_{Kij} + (-1)^j F_{Ai} \quad i, j = \overline{1,2} \tag{5}$$

The lateral acceleration causes the body to tilt. This value appears when the driver steers. Therefore, a non-linear double-track dynamics model is used to determine the lateral acceleration of the vehicle. The diagram of the model is presented as shown in FIGURE 2. At this time, the vehicle will perform three movements corresponding to three directions: longitudinal, lateral, and yaw [41].

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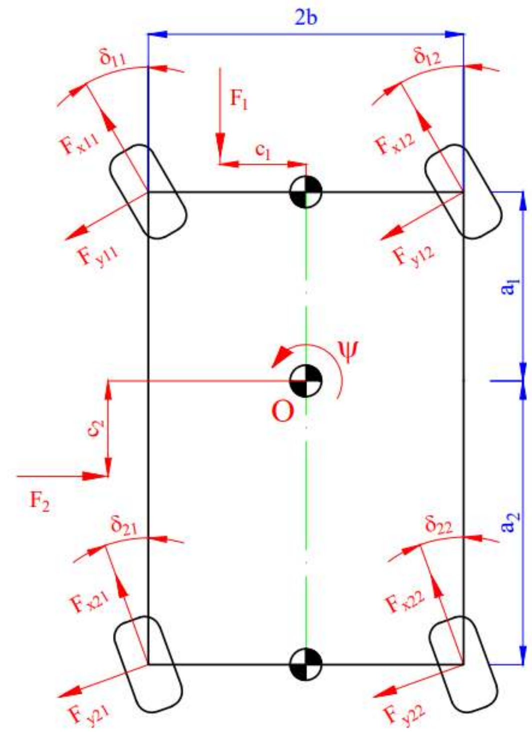

FIGURE 2. **Non-linear double-track dynamics model.**

$$M\left[\dot{v}_x - \left(\dot{\alpha}+\dot{\psi}\right)v_y\right] = \sum_{i,j=1}^{2}\left(F_{xij}\cos\delta_{ij} - F_{yij}\sin\delta_{ij}\right) - F_1 \quad (6)$$

$$M\left[\dot{v}_y + \left(\dot{\alpha}+\dot{\psi}\right)v_x\right] = \sum_{i,j=1}^{2}\left(F_{xij}\sin\delta_{ij} + F_{yij}\cos\delta_{ij}\right) - F_2 \quad (7)$$

$$I_z\ddot{\psi} = \sum_{i,j=1}^{2}\begin{bmatrix}(-1)^j\left(F_{xij}\cos\delta_{ij} - F_{yij}\sin\delta_{ij}\right)b_i \\ +(-1)^{i+1}\left(F_{xij}\sin\delta_{ij} + F_{yij}\cos\delta_{ij}\right)a_i \\ +F_i c_i - M_{zij}\end{bmatrix} \quad (8)$$

If the forces at the wheels are determined, the equations above can be efficiently calculated. There are many methods used to determine the longitudinal force F_x, the lateral force F_y, and the moment M_z at the wheels. In this paper, the Pacejka tire model is used based on the reference parameters [42].

$$F_x = D_x\sin\left(C_x\arctan\begin{bmatrix}B_x(1-E_x)(s_x+S_{hx}) \\ +E_x\arctan\left\{B_x(s_x+S_{hx})\right\}\end{bmatrix}\right)+S_{vx} \quad (9)$$

$$F_y = D_y\sin\left(C_y\arctan\begin{bmatrix}B_y(1-E_y)(\alpha+S_{hy}) \\ +E_y\arctan\left\{B_y(\alpha+S_{hy})\right\}\end{bmatrix}\right)+S_{vy} \quad (10)$$

$$M_z = D_z\sin\left(C_z\arctan\begin{bmatrix}B_z(1-E_z)(\alpha+S_{hz}) \\ +E_z\arctan\left\{B_z(\alpha+S_{hz})\right\}\end{bmatrix}\right)+S_{vz} \quad (11)$$

B. ACTUATOR DYNAMICS MODEL

In this research, a hydraulic actuator is used to generate the impact force that acts on the sprung mass of the vehicle. This actuator is a hydraulic motor controlled based on the opening and closing of the servo valves (FIGURE 3). The valves inside a hydraulic motor are controlled by a control signal, which is generated from the controller.

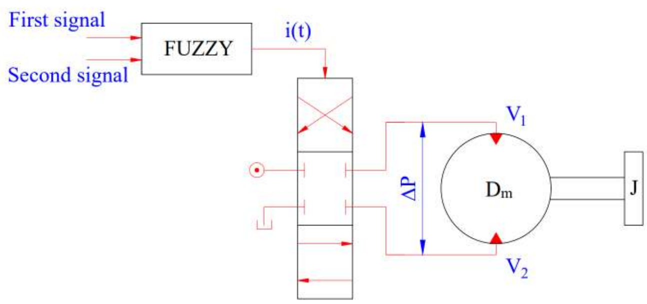

FIGURE 3. **Schematic of the hydraulic motor and servo valve.**

When a current signal is supplied, the servo valves will shift. The relationship between them is shown through (12):

$$\dot{X}_v\tau + X_v - K_v i\left(t\right) = 0 \quad (12)$$

If the servo valve is open, hydraulic oil will flow from the reservoir into the motor. The flow of the fluid depends on the displacement of the servo valve.

$$\Delta Q = K_{qi}X_v - K_c\Delta P \quad (13)$$

Besides, the flow of the liquid can also be defined as (14):

$$\Delta Q = D_m\dot{\theta}_m + C_m\Delta P + \frac{V_t}{4\beta_e}\Delta\dot{P} \quad (14)$$

From (13) and (14), the relationship between the servo valve's displacement, the motor shaft's rotation angle, and the fluid pressure's change is shown as in (15):

$$K_{qi}X_v = D_m\dot{\theta}_m + K_{ce}\Delta P + \frac{V_t}{4\beta_e}\Delta\dot{P} \quad (15)$$

During operation, friction will appear. Therefore, the torque generated on the motor shaft must overcome their resisting moments.

$$D_m\Delta P = J_a\ddot{\theta}_m + B_m\dot{\theta}_m + T_r \quad (16)$$

Based on the dynamics model of the actuator that was established, if the current signal i(t) is known, other parameters of the hydraulic motor can be calculated easily.

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C. DESIGNING THE CONTROLLER

There are many methods used to control the operation of the system. These methods have their distinctive features. In this research, a two-input Fuzzy control method is proposed. Because the vehicle is a very complex system. Also, it travels on many terrains with constantly changing conditions. Therefore, linear control methods cannot guarantee the stability of the system. So, the intelligent control method, which can change according to the input parameters, is suitable in this situation. The schematic of the system is shown in FIGURE 4. Different from the conventional Fuzzy controllers, which have only a single input parameter, this Fuzzy controller has two input parameters, including the roll angle and the displacement of the unsprung mass. These are two warning signals of the rollover phenomenon. If only one signal is used as the input parameter of the controller, the operation process of the controller will be inaccurate. If both signals are used, the operation process will be more stable. These parameters can be measured by sensors that are mounted on the vehicle. Through the controller, a current signal i(t) is supplied to the actuator. After that, the hydraulic actuator will generate the impact force F_A, which acts on the unsprung mass.

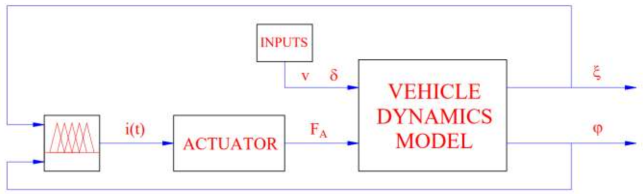

FIGURE 4. Schematic of the system.

The input parameters of the controller will be fuzzified through the membership function (FIGURE 5). This function is determined based on the following rule:

$$\mu(\zeta) = \begin{cases} 1, \zeta < \zeta_{min} \\ \dfrac{\zeta_i - \zeta}{\zeta_i - \zeta_{i-1}}, \zeta_{i-1} < \zeta < \zeta_i \\ 1, \zeta > \zeta_{max} \end{cases} \quad (17)$$

Where: $\zeta(t) = \{\varphi(t); \xi(t)\}$

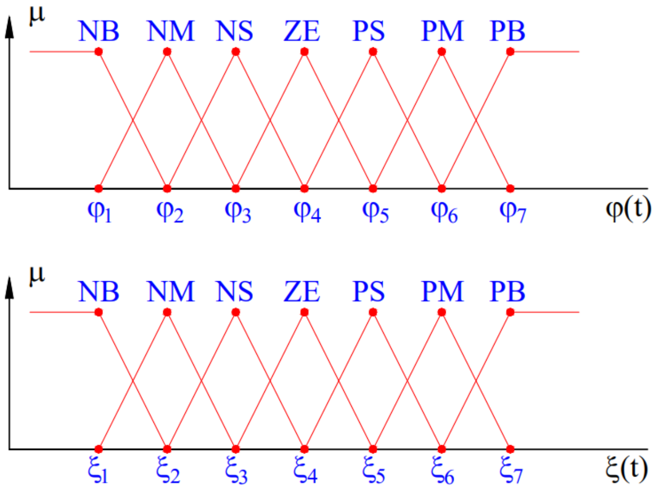

FIGURE 5. Membership function of the Fuzzy controller.

The output signal is determined based on the control rules of the controller. The control law proposal is extremely important. The output signal must match the input signal. If the output signal is too large, the vehicle may oscillate. On the contrary, if the output signal is too small, stability and safety will not be guaranteed. In addition, because the controller has two input parameters, the output signal needs to be selected precisely and optimally. The control law is selected based on actual experience and simulation process, which has been done many times before. The Fuzzy control law is given as shown in TABLE I and FIGURE 6.

TABLE I
FUZZY RULES.

	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NM	NS	NS	ZE
NM	NB	NM	NM	NS	NS	ZE	PS
NS	NM	NM	NS	NS	ZE	PS	PS
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NS	NS	ZE	PS	PS	PM	PM
PM	NM	ZE	PS	PS	PM	PM	PB
PB	ZE	PS	PS	PM	PM	PB	PB

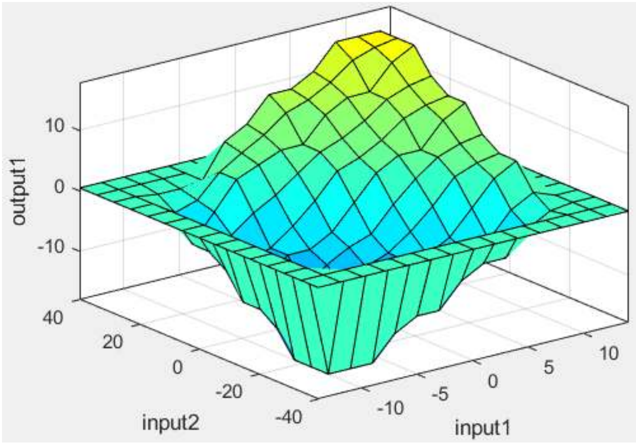

FIGURE 6. Fuzzy rule surface.

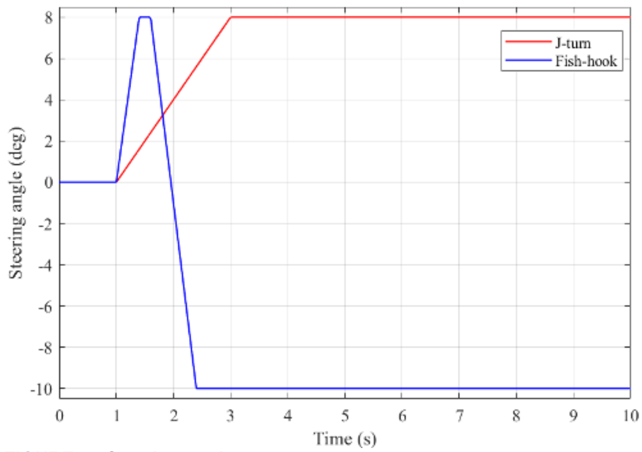

FIGURE 7. Steering angle.

III. RESULTS AND DISCUSSIONS

A. PARAMETERS OF THE SIMULATION PROCESS

Simulation is conducted when the vehicle steers with two types: J-turn and Fishhook (FIGURE 7). For each type of steering, the vehicle's speed will be changed to three different levels: $v = \{v_1, v_2, v_3\}$. The results of the simulation process are evaluated based on the following situations:

+ Vehicle uses the active stabilizer bar controlled by a Fuzzy controller

+ Vehicle uses the mechanical stabilizer bar

+ Vehicle does not use the stabilizer bar

The reference parameters, which used in this paper are given in TABLE II.

TABLE II
SIMULATION PAREMETERS.

Symbol	Description	Value	Unit
m	Sprung mass	1780	kg
m_{ij}	Unsprung mass	48	kg
h_φ	Distance from center of gravity to roll axis	0.61	m
t_{wi}	Half of the track width front/rear axle	0.730/0.725	m
a_i	Distance from center of gravity to front/rear axle	1.15/1.55	m
I_x	Moment of inertia of the x-axis	685	kgm^2
I_y	Moment of inertia of the y-axis	2485	kgm^2
I_z	Moment of inertia of the z-axis	2450	kgm^2
τ	Time constant	0.004	s
K_v	Servo valve gain	0.025	m/A
K_{qi}	Valve flow gain coefficient	0.02	m^2/s
K_{ce}	Total flow pressure coefficient	4×10^{-11}	m^5/Ns
V_t	Total volume of trapped oil	1×10^{-3}	m^3
β_e	Effective bulk modulus of the oil	6×10^{6}	N/m^2
D_m	Flow per revolution	1.6×10^{-5}	m^3/rad
B_m	Viscous friction coefficient	11	Nms/rad
J_a	Moment of inertia of the hydraulic motor	3	kgm^2

B. J-turn steering

The J-turn steering type is usually used when the vehicle enters a roundabout. With this type of steering, the value of the steering angle δ is usually not too large. Besides, the steering acceleration is stable. Therefore, the level of danger, in this case, is usually not high.

v_1 = 60 (km/h)

FIGURE 8 shows the change in the roll angle over time. When the vehicle is moving at an average speed, $v_1 = 60$ (km/h), the maximum value of the roll angle is 7.14^0 if the vehicle does not use the stabilizer bar. In addition, if the mechanical stabilizer bar is used, this value drops slightly, to only 6.41^0. Besides, the active stabilizer bar controlled by the Fuzzy controller can further reduce this value. In fact, this value only reaches 5.77^0, which is about 1.37^0 smaller than the first situation.

The roll angle of the vehicle has not been able to fully assess the effect of the rollover phenomenon. Therefore, the Roll Index (RI) is used to indicate this sign. The value of this index has been shown in the graph in FIGURE 9. Its maximum value is 0.76, 0.46, and 0.25 respectively, corresponding to the three situations mentioned above.

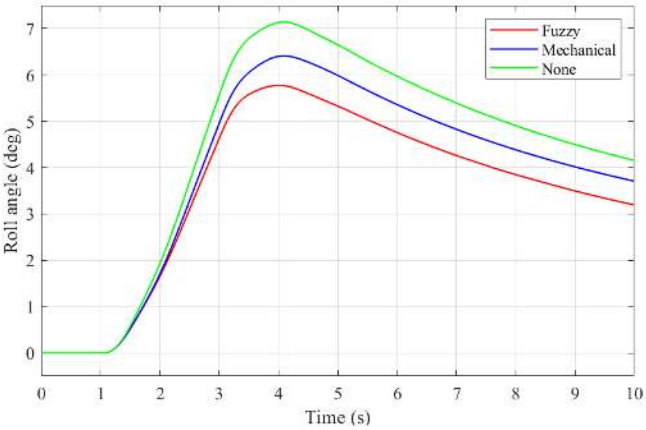

FIGURE 8. Roll angle.

In the condition of the vehicle moving at medium speed, the roll angle, and the Roll Index when the vehicle doesn't use the stabilizer bar are quite high. However, it has not yet reached the dangerous threshold where a rollover phenomenon can occur. If the vehicle's speed increases, this phenomenon can be alarmed.

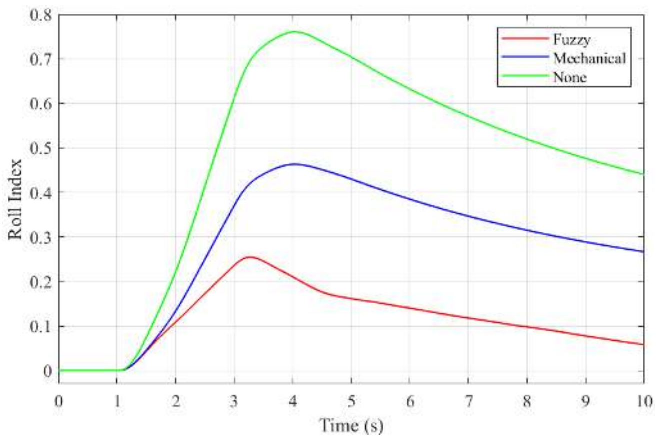

FIGURE 9. Roll Index.

v_2 = 75 (km/h)

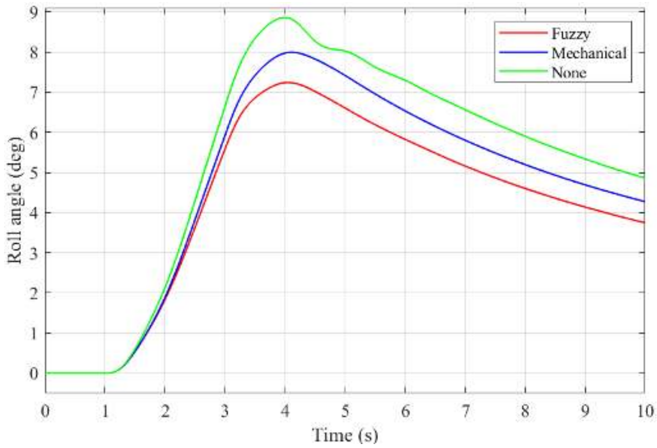

FIGURE 10. Roll angle.

As the vehicle's speed increased, $v_2 = 75$ (km/h), the value of the roll angle changed rapidly (FIGURE 10). Its maximum value can reach 8.86^0, 7.99^0, and 7.24^0 respectively for 3 simulation situations. The biggest difference between them is up to 1.62^0, which is quite a large value.

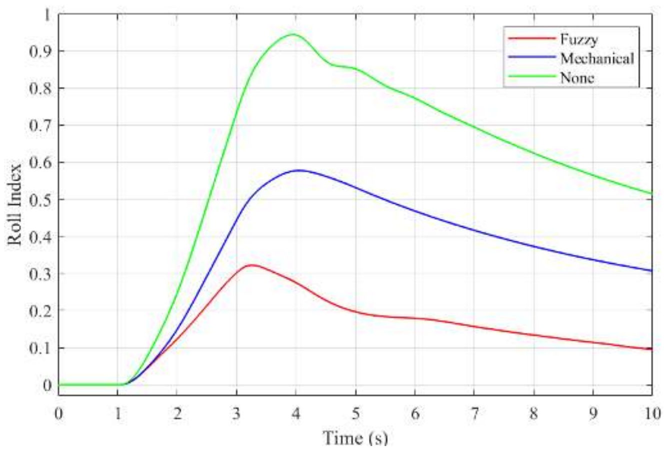

FIGURE 11. Roll Index.

If the roll angle increases, the difference in the vertical force between the two wheels on the same axle will also increase. As a result, the value of the Roll Index will also increase, which means that the risk of a rollover will be higher. Based on FIGURE 11, the Roll Index of the vehicle that doesn't use the stabilizer bar reached 0.94. This is a very large value, which indicates that a rollover phenomenon may occur soon. Meanwhile, if the vehicle uses the stabilizer bar, this value is only 0.58 (mechanical stabilizer bar) and 0.32 (active stabilizer bar). The effect of the stabilizer bar is extremely positive.

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v_3 = 90 (km/h)

As the speed of the vehicle continuously increases, if the vehicle does not use the stabilizer bar, the rollover phenomenon will occur. At high speed, v_3 = 90 (km/h), this occurs at time t = 3.27 (s). Meanwhile, the vehicle can still move stably if it is equipped with the stabilizer bar. The difference in the value of the roll angle now reaches about 0.79^0 (FIGURE 12), which is not a very large number. However, compared with other research [27, 29], the control algorithm proposed in this paper can greatly reduce the roll angle. Furthermore, the Roll Index falls significantly.

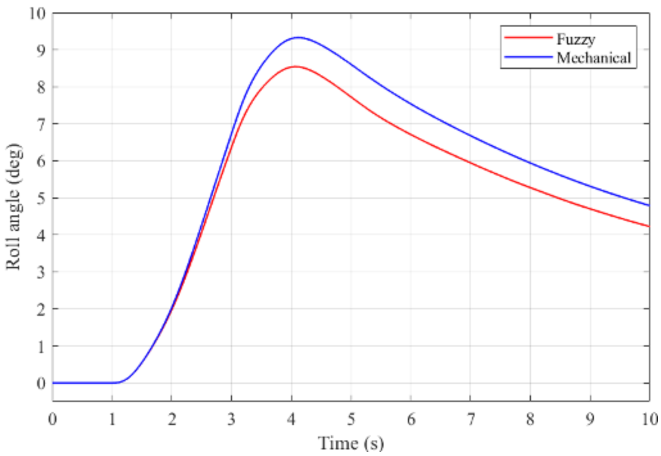

FIGURE 12. Roll angle.

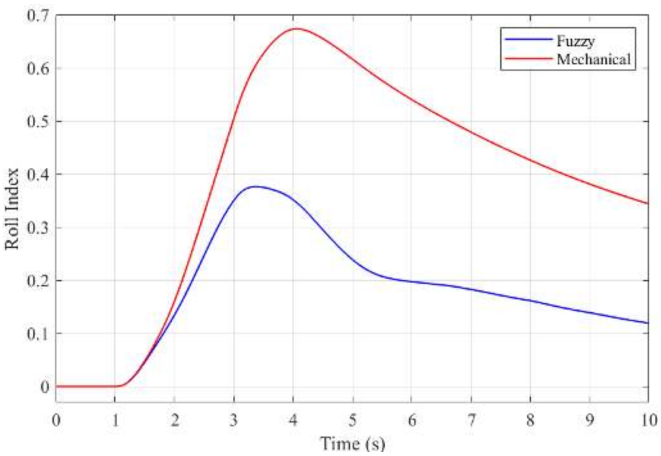

FIGURE 13. Roll Index.

Although the difference in the maximum value of the roll angle in this condition is less than 0.8^0, however, the difference in the Roll Index is very large. FIGURE 13 shows that when the vehicle uses the mechanical stabilizer bar, the Roll Index can be as high as 0.67. Also, under the same motion condition, if the active stabilizer bar is controlled by a Fuzzy controller, this value drops sharply, to only 0.38. As a result, the active stabilizer bar can provide a more stable and safer than just using the passive stabilizer bar or not using the stabilizer bar. Besides, the Fuzzy controller which has been designed in the paper has proved its very positive effect.

C. Fish-hook steering

In fact, Fish-hook steering often causes more danger to the vehicle than J-turn steering. This type of steering is usually used when the vehicle is avoiding an emergency obstacle. Many rollover accidents have occurred when the driver used this type of steering. Therefore, it is necessary to simulate and evaluate the performance of the active stabilizer bar in this case.

v_1 = 60 (km/h)

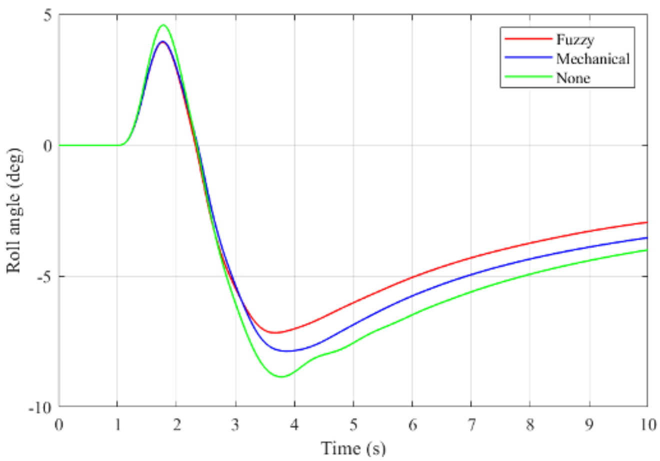

FIGURE 14. Roll angle.

Although the vehicle is only traveling at an average speed, v_1 = 60 (km/h), the danger is demonstrated by the graphs in FIGURE 14 and FIGURE 15. In the first phase, because the steering angle is not large, the maximum value of the roll angle is also quite small. At the same time, the Roll Index of all three situations is also very small, so no danger is presented. In contrast, the danger was clearly demonstrated in the second phase. Because the steering angle and steering acceleration are very large, therefore, the roll angle has also increased rapidly. Its maximum value can be up to 8.85^0, 7.86^0, and 7.16^0 respectively. Besides, the Roll Index of the first situation (the vehicle does not use the stabilizer bar) is very high, about 0.94. This shows that the rollover phenomenon can happen at any time. In another way, the Roll Index of the other two situations only reached 0.57 and 0.44. It shows that if the vehicle uses the stabilizer bar, the safety of the vehicle can be better guaranteed.

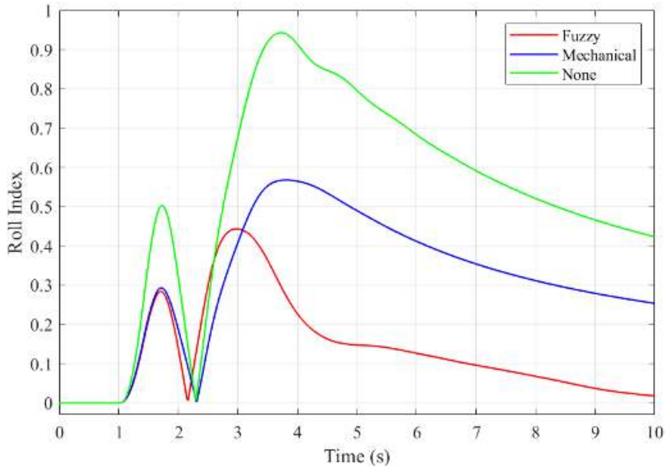

FIGURE 15. Roll Index.

v_2 = 75 (km/h)

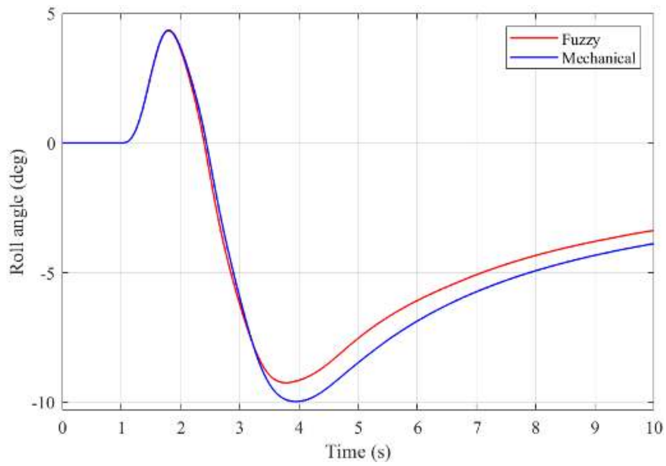

FIGURE 16. Roll Index.

If the vehicle's speed increases, v_2 = 75 (km/h), a rollover phenomenon will occur at time t = 3.2 (s), corresponding to the situation where the vehicle does not have the stabilizer bar. The maximum value of the roll angle of the vehicle reached 9.97^0 and 9.24^0 respectively for the other two situations (FIGURE 16). In addition, the Roll Index, which is used to warn of the occurrence of a rollover, is also shown in FIGURE 17. In the second phase, the maximum Roll Index of the vehicle using the mechanical stabilizer bar reached 0.72. Meanwhile, this value corresponds to the situation where the vehicle using the hydraulic stabilizer bar controlled by the Fuzzy method is only 0.58. Obviously, the hydraulic stabilizer bar has many advantages over the conventional mechanical stabilizer bar.

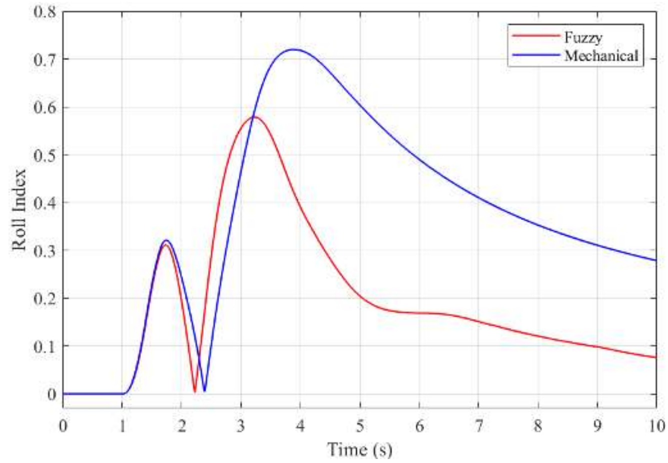

FIGURE 17. Roll Index.

v_3 = 90 (km/h)

In the final case, the vehicle moves at a very high speed, v_3 = 90 (km/h). The roll angle reaches very largely, 11.87^0 and 10.94^0 respectively (FIGURE 18). Based on FIGURE 19, the vehicle's Roll Index has also increased rapidly. According to this graph, if the vehicle uses only the passive stabilizer bar, the Roll Index reaches 0.86. In fact, this is a very high and dangerous threshold. Meanwhile, the active stabilizer bar can reduce this to 0.67. In fact, the control method proposed in this research can provide high stability. In many dangerous cases, it can still ensure the safety of the vehicle. Besides, this is an intelligent control method, and it is suitable for complex non-linear systems. However, if the vehicle only uses linear control methods such as HC [20], LQG [24], or PID [29], the vehicle's stability cannot be guaranteed.

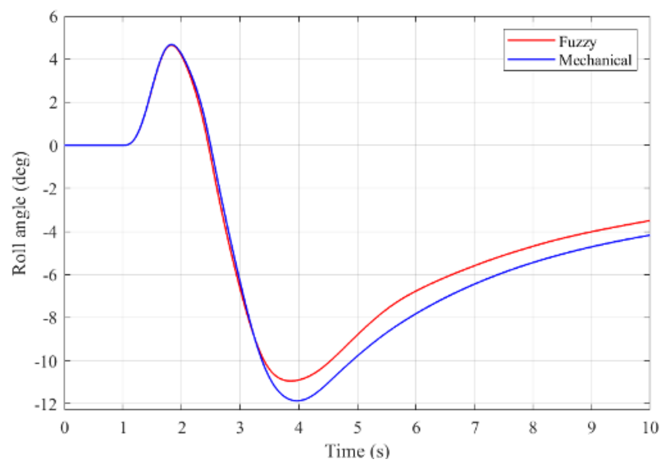

FIGURE 18. Roll angle.

Through the simulation process, the values of roll angle and Roll Index have been demonstrated by the graphs as above. According to this result, if the vehicle's speed is increased (either the steering angle increases or the steering acceleration increases, etc.), the values of the roll angle and Roll Index also increase accordingly. In particular, in dangerous situations, if the vehicle does not use the stabilizer bar, a rollover phenomenon may occur.

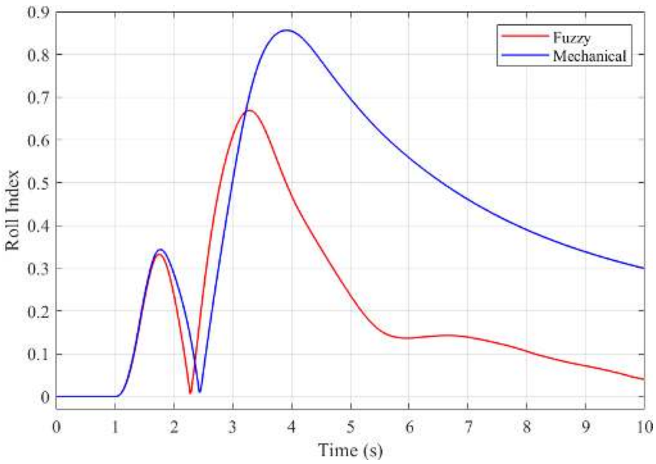

FIGURE 19. Roll Index.

The hydraulic stabilizer bar, which is controlled by the Fuzzy controller, can help the vehicle improve safety and stability when traveling. Under dangerous conditions, the hydraulic stabilizer bar can give full play to its performance compared to the conventional mechanical stabilizer bar. Besides, the two-input Fuzzy controller has also shown its outstanding efficiency in simulation cases. Therefore, using the hydraulic stabilizer bar and the Fuzzy control method are recommended.

IV. CONCLUSIONS

When the vehicle moves on the road, many dangerous factors cause the vehicle to fall into an unstable state. In particular, if the driver steers sharply at high speed, the vehicle can be rolled over. The consequences of this problem are particularly severe, causing great damage to passengers and cargo. Therefore, it is necessary to take measures to limit this situation. The method of using the stabilizer bar is one of the very effective solutions, and it has been applied to many vehicles today. However, the mechanical stabilizer bar (passive) is not able to fully meet the requirements set forth for the stability and safety of the vehicle. Therefore, the hydraulic stabilizer (active) is suggested to be used to replace the conventional mechanical stabilizer bar. In fact, the hydraulic stabilizer bar has been equipped on some high-end vehicles.

This research focuses on simulating and controlling the operation of the hydraulic stabilizer bar to improve the stability and safety of the vehicle when traveling on the road. In this research, the model of spatial dynamics combined with the model of nonlinear double-track dynamics has been established. Besides, the dynamics model of the actuator has also been introduced. The two-input Fuzzy control method is shown in this paper. Its control law is formed based on practical experience. With the above simulation conditions, the results of the paper show that:

+ If the vehicle's speed is large, the roll angle and the Roll Index will be large.

+ If the steering angle or steering acceleration is large, the roll angle and the Roll Index will be large.

+ When the vehicle is equipped with the hydraulic stabilizer bar, these values are greatly reduced. Even in dangerous situations (Fish-hook steering at high speed), the hydraulic stabilizer bar still ensures the stable and safe operation of the vehicle.

The model and method used in this paper are completely novel and original. It has inherited and developed many previous models and methods. Its results have been clearly demonstrated. However, this research only simulates the operation of the system. The experimental process needs to be conducted to verify the effectiveness of the designed controller. In the future, the two-input Fuzzy control method can be combined with Practice Swarm Optimization algorithms (PSO) to optimize the system's performance.

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