Review Article

The Dynamic Model and Control Algorithm for the Active Suspension System

Duc Ngoc Nguyen and Tuan Anh Nguyen

Faculty of the Mechanical Engineering, Thuyloi University, Hanoi, Vietnam

Correspondence should be addressed to Duc Ngoc Nguyen; ndn@tlu.edu.vn

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Road surface roughness is the leading cause of vehicle oscillation. The suspension system is used to dampen these oscillations. The active suspension system equipped with a hydraulic actuator is more efficient than the passive one. Therefore, it is used to replace the passive suspension system. In this article, the author mentioned three dynamic models commonly used to simulate vehicle oscillations: a quarter-dynamic model, a half-dynamic model, and a fully dynamic model. Each hydraulic actuator can be considered a state variable in the dynamic model. Besides, the control algorithm for the suspension system is significant. Algorithms like PID (proportional–integral–derivative) and LQR (linear quadratic regulator) will fit the linear model. In contrast, the nonlinear model’s algorithms, such as SMC (sliding mode control), fuzzy, and ANN (artificial neural network), will perform better. Overall, vehicle oscillation can be significantly improved once an active suspension system is used. The contents analysed in this article will be the database for selecting control models and algorithms by other researchers in the future.

1. Introduction

The suspension system is a critical component of the vehicle. The suspension system controls the stability and comfort of the vehicle. The suspension system is not only equipped for cars but is also used for all vehicles, such as trains, motorcycles, airplanes, etc. A basic car suspension system structure usually has three main components: coil springs, dampers, and a lever arm [1]. The number of lever arms will depend on the specific type of suspension. For the McPherson suspension, only the lower lever arm is used (Figure 1). Some models can use multilink bars to replace the lever arm. For truck models, the coil spring is replaced by a leaf spring [2]. The above suspension system is called the passive (mechanical) suspension system [3]. The structure of a mechanical suspension is usually quite simple. However, its working efficiency is not high. Vehicle body oscillations are controlled in a completely passive way. As a result, stability and comfort can be lost if vehicle body oscillations are too great.

Researchers have recently proposed using electronic suspension systems to replace mechanical suspension systems. Electronic suspension systems have a more complex structure, and at the same time, their cost is also higher. However, the smoothness effect it brings is also more significant. There are three commonly mentioned electronic suspension systems: the air suspension system, the semi-active suspension system, and the active suspension system.

Air suspension is a rather complicated system. The air springs of the suspension system can be changed in stiffness by changing the pressure inside the chambers of the air balloon [4]. According to Yin et al., this suspension system often uses solenoid valves (ON-OFF valves) to regulate the air supply [5]. The cost of the air suspension system is usually relatively high. Therefore, it is often used for high-end cars. Another suspension system that can change the stiffness of the dampers is called a semi-active suspension system. This suspension system uses electromagnetic dampers to replace conventional linear dampers [6]. According to Yang et al., the current provided to the damper can change the
arrangement of the surrounding metal particles. Therefore, the viscosity of the liquid inside will also change [7]. A semi-active suspension system has a more straightforward structure than an air suspension system. Therefore, its cost is also lower. However, its oscillatory conditioning efficiency is also lower. Another solution has also been proposed, which is to use an active suspension system. According to Huang et al., the active suspension system has an additional hydraulic actuator [8]. The hydraulic actuator operates based on the displacement of the servo-valve [9]. The pump pressurizes the fluid before it is directed into the hydraulic cylinder. The idea of using linear pumps for hydraulic actuators was proposed by Lee et al. [10]. The active suspension system has a more complex structure than the semi-active one. However, the hydraulic actuator can generate force to act on the vehicle body, which helps reduce vehicle oscillation. Therefore, its performance will be higher. In addition, the active suspension system also helps to limit the rollover phenomenon. This was pointed out in [11] by Guan et al., but it cannot replace the function of the stabilizer bar [12]. The active suspension system is commonly used in high-end cars. In particular, electric vehicles using motor-in-wheel are also equipped with an active suspension system [13].

Thanks to the suspension system, the car’s oscillation can be improved. Many criteria have been used to evaluate the smoothness of the vehicle when moving. In [14], Lan and Xu used the criteria of vertical displacement and vertical acceleration of the sprung mass to evaluate the stability and comfort once the vehicle oscillates. Many other studies also used these values [15–17]. The maximum and average values will be considered for comparison between oscillation situations. Besides, the average value can be calculated according to the RMS (root mean square) criterion [18]. Some other studies also use DLC (dynamic load coefficient) criteria to evaluate the interaction between the wheel and the road surface when the vehicle body oscillates [19]. When using a half-dynamic or spatial dynamic model, some values, such as roll angle, pitch angle, etc., should also be considered [20]. The output values of the simulation problem can be reviewed in the time domain [21, 22] or the frequency domain [23].

An active suspension system improves vehicle ride comfort by generating impact force that is transmitted to the sprung and unsprung masses. If the value of this force is small, the system’s response is not good. This means that the car’s vibration has yet to improve much. If the impact force is large, the ride comfort can be further improved. However, a more significant impact force will cause a change in the dynamic load at the wheel. Once the value of the dynamic force at the wheel is reduced to zero, the wheel may be lifted off the road, and instability will occur. It is difficult to satisfy both conditions of smoothness and stability when studying control algorithms for active suspension.

The main content of this article is to review the models and control algorithms for the active suspension system. The article’s structure consists of three parts: introduction, control and model, and conclusion. In the first part, active suspension system ideas are introduced. The second part presents a review and analysis of control models and algorithms. In the conclusion part, several conclusions will be provided.

2. Model and Control

2.1. Vehicle Dynamic Models. Dynamic models can explain automobile oscillations. These models represent the entire vehicle structure’s simplicity. There are three typical models: the quarter-dynamic model, the half-dynamic model, and the fully dynamic model.

2.1.1. The Quarter-Dynamic Model. A quarter-dynamic model is commonly used in studies of oscillation control for suspension systems. According to Wang et al., this model includes only two masses: the sprung mass, $m_s$, and the unsprung mass, $m_u$ [24]. The suspension system is modelled as a spring and a shock absorber. The tires are also modelled similarly to the suspension system. For vehicles with an active suspension system, an actuator is located between the sprung mass and the unsprung mass (Figure 2). The equations describing the oscillations of a quarter-dynamic model are shown as follows:

$$m_s\ddot{z}_s = K(z_s - z_t) + C(\dot{z}_s - \dot{z}_t) + F_a,$$

$$m_u\ddot{z}_u = K_T(z_t - z_u) - K(z_u - z_s) - C(\dot{z}_u - \dot{z}_t) - F_a,$$

where $K$ is the stiffness of the spring, $K_T$ is the stiffness of the tire, and $C$ is the stiffness of the damper.

Overall, this model is quite simple. Therefore, it is perfectly suitable for simulating control algorithms for suspension systems. This model is also used in [25] by Chen et al. However, the authors hypothesized that the controller would generate a force to act directly on both parts of the mass. The influence of hydraulic actuators has been neglected [25, 26]. This simplifies the control problem. The problem’s accuracy is enhanced once the hydraulic actuator...
is considered in the control model (Figure 3). According to Kilicaslan, the operating principle of hydraulic actuators can be described through complex nonlinear equations [27]. These equations are presented as follows:

\[
F_a = AP_L, \\
P_L = P_1 - P_2, \\
V_t = P_L = C_v P_L - A(\dot{z}_s - \dot{z}_u), \\
Q_L = C_d x_v \mu \sqrt{\frac{1}{\rho} \left[ P_s - \text{sgn}(x_v) P_L \right]},
\]

where \( V_t \): effective volume of the hydraulic actuator, \( \beta_e \): bulk modulus of the fluid, \( C_d \): leakage constant, \( Q_L \): hydraulic load flow, \( C_d \): discharge coefficient, \( x_v \): servo valve spool displacement, and \( \rho \): fluid density.

\[
m_s \ddot{z}_c + k_f (z_{sf} - z_{uf}) + c_f (\dot{z}_{sf} - \dot{z}_{uf}) + k_r (z_{sr} - z_{ur}) + c_r (\dot{z}_{sr} - \dot{z}_{ur}) + k_t (z_{tr} - z_{ur}) = u_f + u_r, \\
I_\psi \ddot{\psi} - l_1 k_f (z_{sf} - z_{uf}) - l_1 c_f (\dot{z}_{sf} - \dot{z}_{uf}) + I_2 k_r (z_{sr} - z_{ur}) + I_2 c_r (\dot{z}_{sr} - \dot{z}_{ur}) = -I_1 u_f + I_2 u_r, \\
m_u \ddot{z}_{uf} - k_f (z_{sf} - z_{uf}) - c_f (\dot{z}_{sf} - \dot{z}_{uf}) + k_r (z_{sr} - z_{ur}) = -u_f, \\
m_u \ddot{z}_{ur} - k_r (z_{sr} - z_{ur}) - c_r (\dot{z}_{sr} - \dot{z}_{ur}) + k_t (z_{tr} - z_{ur}) = -u_r,
\]

where \( k_f \) is the stiffness of the front spring, \( k_r \) is the stiffness of the rear spring, \( k_t \) is the stiffness of the front tire, \( k_r \) is the stiffness of the rear tire, \( c_f \) is the stiffness of the front damper, \( c_r \) is the stiffness of the rear damper, \( u_f \) is the control force of the front actuator, and \( u_r \) is the control force of the rear actuator.

This model uses two actuators at the vehicle’s front and rear. Two independent controllers can control the two actuators. In some cases, these two controllers can also interact with each other. This is a complete model, but not too complicated. It is also commonly used in many vehicle oscillation simulation problems.

2.1.2. The Half-Dynamic Model. A half-dynamic model of a vehicle has four degrees of freedom (Figure 4). It can be roll model or pitch model. This model considers the influence of the vehicle’s body roll or pitch angles.

Considering the pitch model, the equations describing the oscillations of the vehicle are established based on Newton’s second law [31].

2.1.3. The Fully Dynamic Model. Another model used to describe vehicle oscillations is the fully dynamic model (spatial dynamic model). This model consists of 5 masses and 7 degrees of freedom (Figure 5). Overall, this model is quite complex. The controllers of each actuator may have signal conflicts when working. However, this model provides all the necessary elements to evaluate the vehicle’s oscillation.

The system of equations describing the oscillations of the spatial model was established by Sun et al. in [32].

The binding forces of the dynamic model are calculated more specifically in [32].

2.2. Control Algorithms. Many articles on control algorithms for suspension systems have been published. The choice of algorithms will depend on the views of the researchers. If the pavement excitations are linear, the oscillating system is considered to be a linear system. Then, algorithms like PID, LPV (linear parameter varying), LQR, etc., can be used. In [33], Liu et al. proposed using the PID algorithm for a quarter-dynamic suspension system model. If the differential stage is omitted, this algorithm has only two components, $K_P$ and $K_I$ [34]. If the integral is ideal, the PID algorithm becomes PD [35]. The parameters of the PID algorithm can be self-tuning or tuned by intelligent algorithms such as fuzzy, PSO (particle swarm optimization), GA (genetic algorithm), etc. [36–38]. This is only a SISO (single input–single output) algorithm, i.e., it can only control one object. If the number of objects to be controlled is greater, more controllers and actuators should be used [39]. However, this can cause internal effects on the system. Therefore, the better solution is to use the LQR algorithm for the multi-object system. In [40], Nguyen et al. presented the LQR control algorithm for the MIMO (multi-input–multioutput) system with the model of five state variables. This algorithm needs to use matrices describing the oscillation state of the dynamic model. Minimizing the cost function, like in equation (6), will make the system more stable [41]. A Gaussian filter is integrated to remove noise [42]. Then, it is called the LQG (Linear Quadratic Gaussian) algorithm [43]. The parameters of the control matrix can be selected empirically or by intelligent algorithms. These parameters are fixed. The LPV control algorithm can be used if variable parameters are used instead [44].

$$I_x \ddot{\varphi} - d (F_{s1} + F_{d2} + F_{a11} + F_{a12} + F_{a13} + F_{a14}) - M_{\varphi} = 0,$$


A result of using the PID algorithm to control the active suspension is shown in Figure 6. This is the change in vehicle body acceleration over simulation time. The acceleration value is maximum if the vehicle uses only a passive suspension system. This value can be reduced once the PID algorithm is used. In [33], Liu et al. used the BPNN (back propagation neural network) algorithm to determine the PID controller’s parameters. Therefore, the performance of the controller can be better improved. In [39], Nguyen compared the use of a single PID controller and a double PID controller. According to the results shown in Figure 7, the displacement of the vehicle body is significantly reduced once the double PID controller is used. However, improper selection of parameters can lead to the oscillation phase difference.

The pavement stimuli are random; therefore, the vehicle’s oscillation is nonlinear. For nonlinear systems, more complex algorithms should be used. In [45], Bai and Wang proposed using optimally robust algorithms for suspensions with uncertainties. This algorithm was established based on the combination of the LQR algorithm and the SMC algorithm. Besides, Wei et al. also showed a new method for...
the $H_{\infty}$ controller [46]. According to Wei et al., this controller is established based on solving linear and related matrices. Besides, using adaptive control algorithms for harmonic oscillations also brings high efficiency [47]. In [48], Gang proposed using a fully model’s SMC algorithm for suspension. This algorithm can also be used for half- or quarter-models [49, 50]. The SMC algorithm needs to use the higher-order derivative of the output signals, so the use of a linear model of the actuator is necessary [29]. For this algorithm, the sliding surface is an essential component, so it needs to be set up carefully [51]. The input signal from the controller can be received by sensors or cameras [52]. A drawback still exists when using the SMC algorithm, which is the phenomenon of “chattering.” This phenomenon will cause the signal to vibrate continuously [53]. Therefore, it can affect the quality of the system. A simulation result of this phenomenon is shown in Figure 8. Accordingly, the control signal oscillates continuously at a high frequency throughout the simulation time. This is not good for the system. To solve this problem, Nguyen combined the SMC algorithm and the PID algorithm to become a synthesis algorithm [54]. The SMC algorithm’s output signal will be the PID algorithm’s input signal. Therefore, the phenomenon of “chattering” has been significantly reduced. Another way to limit the phenomenon of “chattering” has also been described by Wang et al., as shown in [55]. The efficiency of the SMC algorithm is very high, which is proved by Nguyen in [54]. Displacement of the vehicle body can be up to 61.96 (mm) if the car only uses conventional mechanical suspension (Figure 9). When the PID controller controls the active suspension, this value is reduced to 23.35 (mm). This value decreases to only 7.73 (mm) once the SMC algorithm is applied. Furthermore, if the PID algorithm and the SMC algorithm are combined, the maximum displacement value of the sprung mass will not exceed 1.00 (mm). This is an ideal result. However, the design of this algorithm is also quite complicated. Sliding control algorithms can be applied to many system models, such as leg robots [56] or quadrotor UAVs [57]. The performance that this algorithm brings is outstanding. For uncertain systems, it is necessary to use composite controllers. V. Ghafari and S. Mobayen et al. propose a robust tracking nonlinear feedback controller for the system [58], which results in high efficiency. Several intelligent control algorithms have also been used to control the suspension. In [59], Ozbek et al. used the fuzzy algorithm to control the spatial model. A fuzzy algorithm allows for defining an intermediate state when the system is working. This algorithm is determined based on the membership function that has been designed before [60]. Different researchers’ points of view formulate fuzzy rules. The fuzzy algorithm can also be combined with the SMC algorithm to eliminate the “chattering” phenomenon, as shown by Shaer et al. [61]. Several algorithms using ANN have also been proposed to control the suspension system. In [62], Zhang et al. used the AFTNN (adaptive finite-time neural network) control algorithm for the suspension model with three degrees of freedom. More recently, an adaptive control algorithm using a saturated neural network has also been proposed by Wang and Li [63]. In addition, many PSO algorithms that use animal behaviour are also used for suspension systems [64–66]. These algorithms also bring high efficiency to the system. Moreover, some control algorithms for mobile robots and quadrotors should also be considered to control the active suspension [67–70].
Table 1 shows a comparison of the different ways to control an active suspension system.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Objects of application</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>Applicable to linear systems with only a single input and output.</td>
<td>The design process is simple, low-cost, and widely used in industry. It is necessary to choose the parameters appropriately.</td>
</tr>
<tr>
<td>LQR/LQG</td>
<td>Applicable to linear systems with multiple inputs and outputs.</td>
<td>The design process is simple; however, it is necessary to use a matrix of oscillations instead of the usual system of differential equations.</td>
</tr>
<tr>
<td>SMC</td>
<td>Applicable to complex nonlinear systems.</td>
<td>High stability and good performance. It is necessary to use the signal of the higher-order derivative while the “chattering” phenomenon can occur. The design process is very complex.</td>
</tr>
<tr>
<td>Robust, adaptive</td>
<td>Applicable to complex nonlinear systems.</td>
<td>Good responsiveness to the continuous change of input parameters. The design process is complicated.</td>
</tr>
<tr>
<td>Fuzzy, ANN, PSO, etc.</td>
<td>Applicable to multiple complex systems.</td>
<td>Well-adapted to the continuous change of input parameters. The design of algorithms is challenging and depends a lot on the designer’s point of view.</td>
</tr>
<tr>
<td>Combination methods</td>
<td>Applicable to multiple complex systems.</td>
<td>High stability and good adaptability. The combination process is very difficult, and there may be conflicts between the component algorithms.</td>
</tr>
</tbody>
</table>

Table 1 shows a comparison of the different ways to control an active suspension system.

3. Conclusions

The suspension system plays an essential role in ensuring the stability and comfort of the vehicle. The structure of the passive suspension system has only three basic components, so it cannot meet the requirements for smoothness in motion. Therefore, an active suspension system replaces a conventional passive suspension system. The hydraulic actuator is a component that may be found in the active suspension system. The operation of this actuator is determined by whether or not the servo valves are open or closed. It can exert force on both the sprung and unsprung mass of the vehicle, which helps to lessen oscillation. However, the structure of the active suspension system will be more complicated than that of the passive suspension system.

This article introduces and reviews models and control algorithms for the active suspension system. From the author’s point of view, three dynamic models are used to simulate vehicle oscillations: the quarter, the half, and the spatial. Among them, the quarter model is quite commonly used. The hydraulic actuator is also considered a state variable of the dynamic model. Control algorithms such as PID, LQR, and LPV may apply if the system oscillation is considered linear. These algorithms are quite simple. However, the response is good only in a few specific cases. In contrast, more complex algorithms such as robust control, adaptive control, SMC, Fuzzy, ANN, etc., can be suitable for nonlinear systems at all times. The choice of algorithms is entirely up to each researcher’s point of view.

The input of the simulation problem is the stimuli from the road surface; the output usually includes the values of displacement, acceleration, and roll angle of the vehicle body. These values can be evaluated according to RMS, DLC, maximum value, etc. Overall, when active suspension is used, ride comfort and stability can improve. The contribution of this article can make it easier for researchers to choose more suitable control models and algorithms. Today,
several challenges related to controlling issues for the active suspension system still exist. For example, if the ride comfort is improved, the interaction between the wheels and the road surface may be negatively affected. Conversely, if the wheels are controlled to increase road holding, smoothness and comfort can be lost. Both of the above factors are very important for the suspension system, and it is not easy to satisfy them simultaneously.

4. Future Recommendation

In the future, the suspension system on cars will be further developed to be more robust. The suspension system control algorithms need to satisfy ride comfort and road-holding requirements. To do this, combining many complex nonlinear algorithms or using intelligent algorithms is necessary. Besides, it is necessary to carry out experiments to evaluate the actual effectiveness of the controllers for the car suspension system. Another solution is to use many independent controllers for many different purposes.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

References


[54] D. N. Nguyen and T. A. Nguyen, “A novel hybrid control algorithm sliding mode-PID for the active suspension system...