Semi-Active Damping Control of Vehicles Based on Negative Stiffness Suspensions

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Abstract: In order to design a suspension system with better ride comfort, the concept of negative stiffness is introduced into the suspension system by analyzing the functional characteristics of elastic elements, and the damping control algorithm is designed according to the functional characteristics of the spring suspension, simulated and analyzed using Matlab/Simulink tools, and the results are compared with the passive suspension, negative stiffness passive suspension and skyhook damping semi-active control suspension. The results show that the new proposed algorithm combined with the negative stiffness suspension can effectively improve the vehicle ride comfort.

1 INTRODUCTION

As a product of the civilization of our time, the number of automobiles has been increasing day by day since its creation in the late 19th century. According to the website of the Chinese Ministry of Public Security, the number of cars and motor vehicles in China has also been gradually increasing in recent years. In modern society, the car is not only a means of travel, but also a way of daily life in pursuit of a higher quality of life and better sensory enjoyment. Therefore, improving the comfort and safety of cars has become one of the important goals of car design in modern society (Zhang, 2021).

As one of the most important parts of a car, the suspension connects the body to the axle, and it is not only the medium for transmitting all the forces and moments between the wheels and the body, but also plays an important role in cushioning and suppressing the shock and vibration caused by the unevenness of the road. Therefore, a well-designed suspension can effectively improve the ride comfort of the car (Olugbade,2021). Scholars at home and abroad have focused more on the fault tolerance capability of the strategy in the study of semi-active suspension control strategy, while less attention has been paid to the improvement of the overall combined performance of the suspension control strategy and the suspension. In this paper, based on the previous research, we propose a negative stiffness semi-active suspension damping algorithm in combination with the vehicle suspension performance.

2 DESIGN OF NEGATIVE STIFFNESS SUSPENSION

The analysis of the spring characteristics of the vehicle suspension (Zhang, 2017) shows that the deflection of the vehicle suspension spring has two parts: one is the static deflection, which is mainly caused by the vehicle itself and the vehicle load, and the other is the dynamic deflection, which is mainly caused by the vibration. The main function of the static deflection is to support the vehicle itself and its load, and the main function of the dynamic deflection is to transmit the vibration of the unsprung part to the whole vehicle body. The expectation is that the vibration of the unsprung part will be reduced in the process of transferring it to the vehicle body, which requires that the spring stiffness of the unsprung part be as small as possible, because the smaller the spring stiffness, the more the vibration energy will be reduced. Such a spring structure can be designed with the stiffness characteristics shown in Figure 1. This ensures that the spring has a small (or even negative) stiffness (Shahadat, 2010) in the vibration region, while still having a large stiffness coefficient to carry the overall vehicle load. The spring stiffness characteristics can be obtained by connecting a spring with negative stiffness characteristics in parallel with the normal spring operating at the balance point, and the positive and negative stiffness characteristics of the spring are shown in Figure 2.

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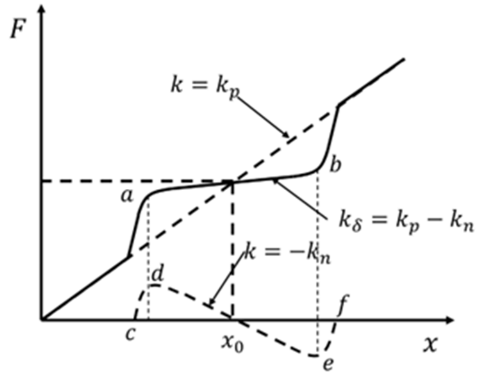

Figure 1: Negative stiffness characteristics of the suspension concept.

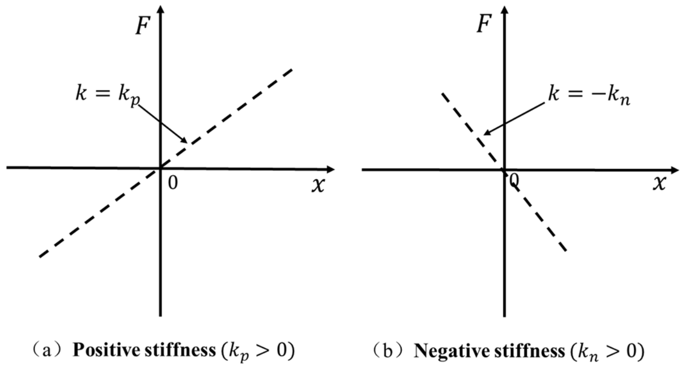

Figure 2: Spring positive and negative stiffness characteristics.

When the incremental deformation of the elastic element after the force is in the same direction as the incremental load, the stiffness is positive and the elastic element is said to have positive stiffness characteristics, as shown in Figure 2(a); on the contrary, when the incremental deformation of the elastic element after the force is in the opposite direction of the incremental load, the elastic element is said to have negative stiffness characteristics, as shown in Figure 2(b). A spring element with a small range of negative stiffness characteristics can be connected in parallel with a spring element with positive stiffness characteristics at the vibration balance point, allowing the suspension system to have a small range of negative stiffness characteristics at the vibration balance point. A steel plate spring in parallel with a membrane air spring gives us the desired negative spring stiffness characteristics, with a local negative stiffness characteristic at the design point and a load-deflection curve roughly as shown in Figure 3. In order to facilitate the analysis of the suspension vertical dynamics, we established the two-degree-of-freedom quarter-vehicle suspension model in Figure 4.

According to Newton's second law we can obtain the following set of kinetic equations:

$$\begin{cases} m_s\ddot{x}_s + g(x_s - x_u) + c_0(\dot{x}_s - \dot{x}_u) + c_{switch}\dot{x}_s = 0 \\ m_u\ddot{x}_u - g(x_s - x_u) - c_0(\dot{x}_s - \dot{x}_u) + k_t(x_u - x_r) - c_{switch}\dot{x}_s = 0 \end{cases} \tag{1}$$

Where $\boldsymbol{m_s}$ and m_u are the spring loaded mass and unsprung mass, respectively; x_s and x_u are the spring loaded displacement and unsprung displacement, respectively; k_t is the tire vertical stiffness; c_0 is the damper damping coefficient; c_{switch} is the variable switching control damping; x_r is the displacement excitation of the road surface to the wheels; $g(x)$ is the restoring force of the suspension system with negative stiffness characteristics, and the expression can be fitted according to the experimental simulation results (preconceived).

3 DESIGN OF DAMPING CONTROL ALGORITHM

3.1 Skyhook Control

The skyhook damper control algorithm was first proposed by Karnopp in the United States (Karnopp, 1974), using an imaginary dampener connected with the skyhook damper to suppress the vibration of the body. The principle is to design and install an ideal skyhook damper between the body and the sky, with the sky remaining absolutely stationary. The ideal skyhook damper can suppress the vertical motion of the body, thus making the vehicle more stable and improving the comfort of the ride and smoothness of the vehicle during the driving process.

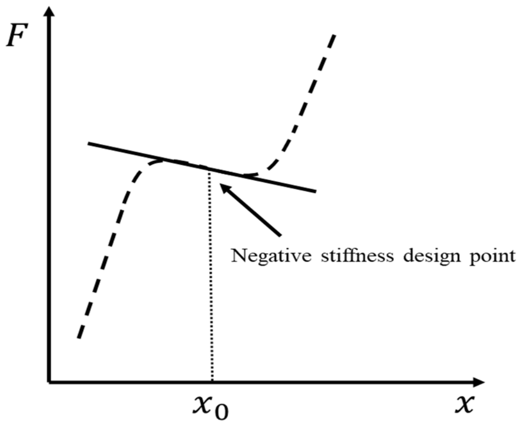

Figure 3: Spring design load-deflection curve.

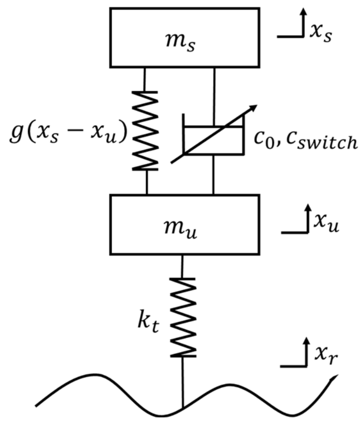

Figure 4: Vehicle suspension model.

Figure 5 shows the quarter vehicle suspension dynamics model with ideal skyhook damper damping control. where m_s and m_u are the spring loaded mass and unsprung mass, respectively; x_s and x_u are the spring loaded displacement and unsprung displacement, respectively; k_s and k_t are suspension stiffness and tire vertical stiffness, respectively; c_s is the damper damping coefficient; c_{sky} is the skyhook damper damping coefficient; and x_r is the displacement excitation of the road surface to the wheel. The kinetic equation can be expressed as

$$\begin{cases} m_s\ddot{x}_s + k_s(x_s - x_u) + c_s(\dot{x}_s - \dot{x}_u) + c_{sky}\dot{x}_s = 0 \\ m_u\ddot{x}_u - k_s(x_s - x_u) - c_s(\dot{x}_s - \dot{x}_u) + k_t(x_u - x_r) = 0 \end{cases} \tag{2}$$

In practical applications where the vehicle cannot exert this ideal force, a controllable actuator is generally used in the system to simulate the skyhook damper control force. The actuation rules for the skyhook damper damping coefficient c_{sky} are developed by measuring the relative velocity of motion of the spring loaded and unsprung masses, and the rules are as follows:

$$c_{sky} = \begin{cases} c_{\max} & , \ \dot{x}_s(\dot{x}_s - \dot{x}_u) \geq 0 \\ c_{\min} & , \ \dot{x}_s(\dot{x}_s - \dot{x}_u) < 0 \end{cases} \tag{3}$$

Where, c_{max} and $c_{\min}$ represent the maximum and minimum damping coefficients that skyhook dampers can produce, respectively.

3.2 Improved Skyhook Control

According to the mechanical properties of the damper, we can know that the damping force is always in the opposite direction of its relative motion speed and proportional to its size. The main role of the dampers in the suspension is to absorb energy to reduce the relative speed displacement changes between the body and the wheels, thus playing a role in energy consumption and attenuation of vibration. (Chen, 2010) In the process of evaluating the ride comfort and smoothness of the vehicle, we pay more attention to the magnitude of the vertical displacement, vertical velocity and vertical acceleration of the spring-loaded part of the vehicle. Skyhook damping control is designed to install an ideal skyhook damper between the body and the sky, which is essentially achieved by suppressing the vertical velocity of the vehicle body. It is based on the relationship between the car body vertical speed and the suspension speed relative to the car body speed to act. Since it takes some time for the suspension speed to change with respect to the vehicle speed, this can make the damping action behavior lag in time, which will lead to the method not better improve the ride comfort.

In this paper, the main purpose is to improve the ride comfort, and the improved canopy damping control algorithm is proposed for the negative stiffness suspension model mentioned in the previous paper. The damping adjustment is based on different speed relationship, so as to achieve the effect of suppressing the vehicle vibration and improving the vehicle ride comfort. Figure 6 shows the relationship between the body vertical velocity and the suspension vertical velocity.

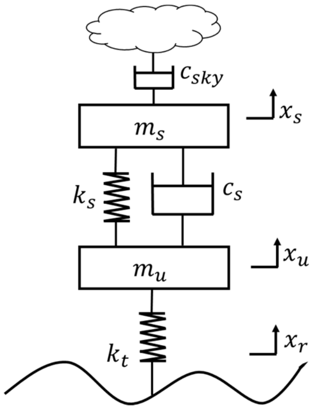

Figure 5: Vehicle suspension model.

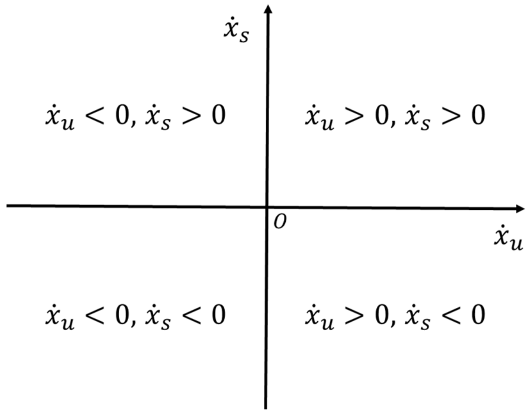

Figure 6: The relationship between the action of parameters $\dot{x}_u$ and $\dot{x}_s$.

We can discuss in two cases: the first case is when the spring-loaded velocity $\dot{x}_s$ and the unsprung velocity $\dot{x}_u$ are in the same direction (quadrant I and III in Fig. 6), at this time the car body and the suspension show the tendency to move in the same direction, which we can understand as encountering the convex block road or concave block road, since there is already a negative stiffness characteristic restoring force to prompt the suspension to act after the disturbance, considering that the restoring force will increase the dynamic travel of the suspension, the speed change difference between the suspension and the body is reduced by increasing the coefficient of the damper, so that the vibration transmitted by the suspension to the body can be reduced, which can directly reduce the speed change of the body and the travel of the body. The second case is when the spring-loaded velocity $\dot{x}_s$ is opposite to the unsprung velocity $\dot{x}_u$ (quadrant II and IV in Figure 6), when the car body and the suspension show a tendency to move in the opposite direction, which can be interpreted as the back-range condition when encountering a bumpy road or a concave road, and the difference in velocity between the suspension and the car body is reduced by reducing the damper coefficient. The speed change difference between the suspension and the car body is reduced, so that the vibration of the car body can be reduced when the suspension returns to its original state, which can also directly reduce the speed change of the car body. Considering the simplicity of the algorithm, we attribute the case of the presence of 0 to the first case. According to the above discussion, the expression of the damping coefficient in the improved skyhook control algorithm is:

$$c_{sky} = \begin{cases} c_{\max} & , \ \dot{x}_s \dot{x}_u \geq 0 \\ c_{\min} & , \ \dot{x}_s \dot{x}_u < 0 \end{cases} \quad (4)$$

Bringing equation (4) into equation (1), we can obtain a dynamics expression for the application of the improved damping control strategy on a negative stiffness suspension, and we call it new negative stiffness improved damping control strategy.

4 NEGATIVE STIFFNESS SEMI-ACTIVE SUSPENSION PERFORMANCE ANALYSIS

In order to analyze the effectiveness of the algorithm improved in this paper on the role of the designed negative stiffness suspension, this paper uses the more widely used passive suspension, skyhook semi-active control suspension as a comparison, while for better quantitative analysis, we add the negative stiffness passive suspension as a comparison. The body vibration displacement, body vibration velocity and body vibration acceleration are used as indicators for time domain analysis.

4.1 Random Pavement Excitation Response

Random pavement is the closest model to the real pavement, and the response analysis under random pavement excitation is an important method to comprehensively examine the overall performance of the suspension. (Hongbin, 2011) We use the random pavement excitation curve fitted by the finite bandwidth white noise as the input of the simulated pavement, as shown in Figure 7, and the time domain curves of each index for different control methods of different suspensions under the random pavement excitation are shown in Figures 8-10.

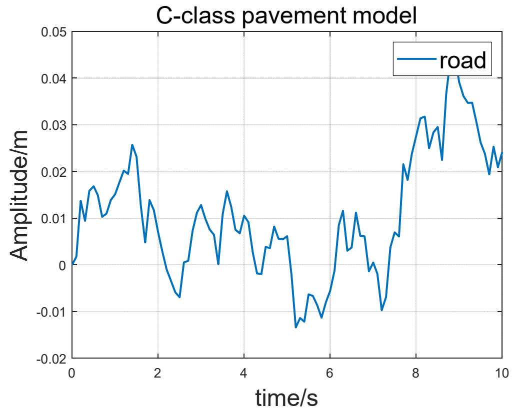

Figure 7: C-class pavement model.

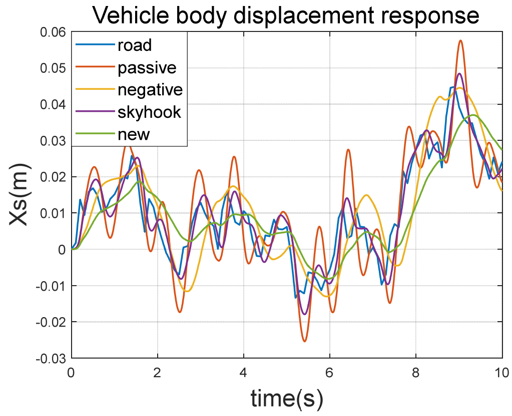

Figure 8: Vehicle body displacement response.

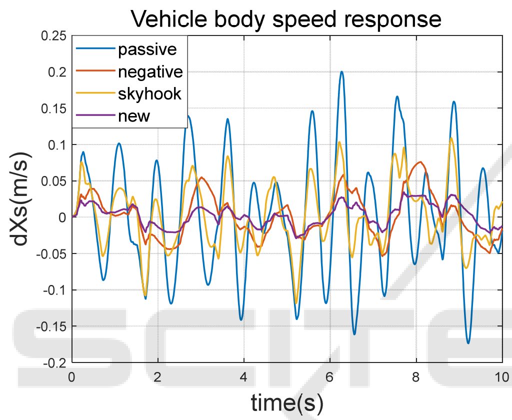

Figure 9: Vehicle body speed response.

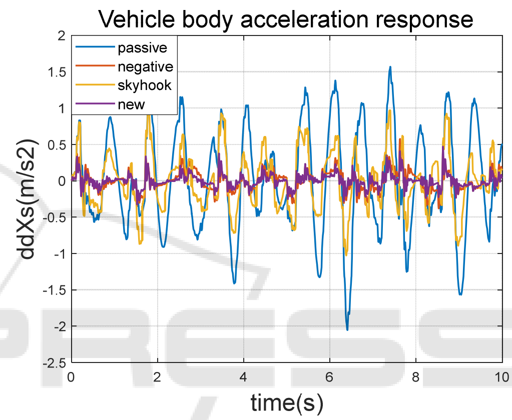

Figure 10: Vehicle body acceleration response

Table 1: Calculation results of suspension indexes.

	Amplitude(m)		Velocity(m s^{-1})		Acceleration(m s^{-2})	
Algorithm	RMS	Improve	RMS	Improve	RMS	Improve
Passive	0.0154	——	0.0851	——	0.7157	——
Negative	0.0158	-2.60%	0.0303	64.39%	0.1534	78.57%
Skyhook	0.0137	11.04%	0.0538	36.78%	0.4194	41.40%
New	0.011	28.57%	0.0157	81.55%	0.0942	86.84%

As can be seen from the figure, the improved damping control strategy combined with the negative stiffness suspension can effectively attenuate the body vibration amplitude, while the speed and acceleration of the body vibration are also effectively suppressed. In order to be able to quantitatively analyze, we calculate the root mean square (RMS) values of body vibration amplitude response, body speed response and body acceleration response indexes and the calculation results of optimization degree are shown in Table 1.

According to the data analysis in the table, we can know that different suspension control methods have different effects on body vibration amplitude, body speed and body acceleration suppression. In terms of body vibration amplitude suppression, compared with the passive suspension, the negative stiffness suspension has a slight deterioration of 2.60%, the skyhook semi-active control suspension has an 11.04% improvement, and the new improved damping control negative stiffness suspension has a 28.57% improvement. In terms of body speed suppression, compared to the passive suspension, there is a 64.39% improvement for the negative stiffness suspension, a 36.78% improvement for the skyhook semi-active control suspension, and an 81.55% improvement for the new improved damping control negative stiffness suspension. In terms of body acceleration suppression, compared to the passive suspension, the negative stiffness suspension has a 78.57% improvement, the skyhook semi-active control suspension has a 41.40% improvement, and the new improved damping control negative stiffness suspension has an 86.84% improvement. It can be seen that our proposed new improved damping controlled negative stiffness suspension system has some or greater improvement compared to other suspension systems under random road excitation.

4.2 Impact Response of Bumpy Pavement

Bump pavement is usually used for suspension impact tests, which mainly simulate road conditions such as speed bumps or potholes on the road. (Khot, 2017) We use the following equation to simulate the clod pavement excitation.

$$Z_r(t)=\begin{cases}\frac{1}{2}A[1+\cos(\omega(t-t_0)-\pi)]\ , & t_0\le t\le t_0+T \\ 0\ , & other\end{cases} \quad (5)$$

Where A is the peak height of the bump pavement, t_0 is the start time of the bump pavement (s), and T is the sine wave period (s), which is the duration of the bump pavement. The excitation curves are shown in Fig. 11, and the time domain curves of each index for different control methods of different suspensions under bump pavement excitation are shown in Figs. 12-14.

As can be seen from the figure, under the action of bump road excitation, improved damping control strategy combined with negative stiffness suspension has good performance relative to passive suspension, skyhook semi-active suspension and negative stiffness passive suspension in terms of attenuating the vibration amplitude of the body and the vibration speed of the body. However, at this time in terms of.

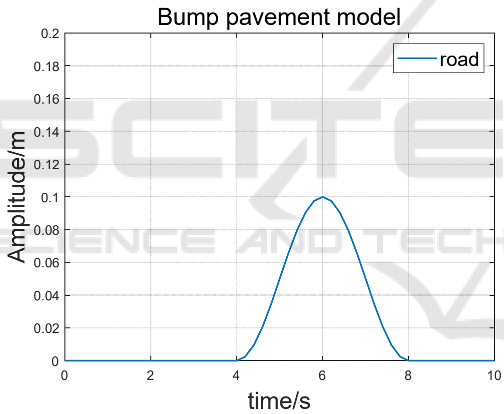

Figure 11: Bump pavement model.

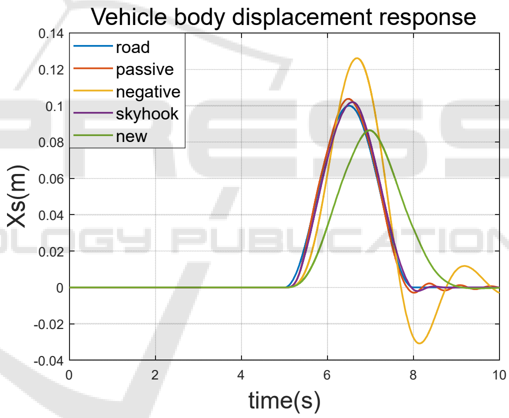

Figure 12: Vehicle body displacement response.

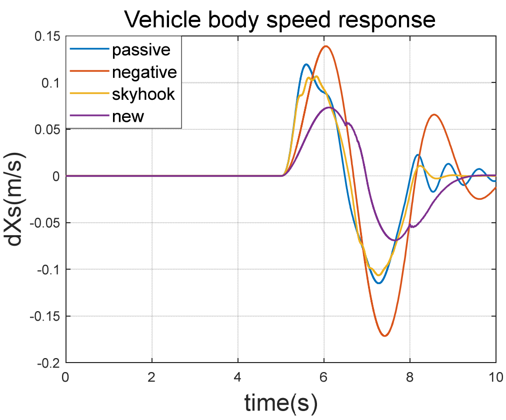

Figure 13: Vehicle body speed response.

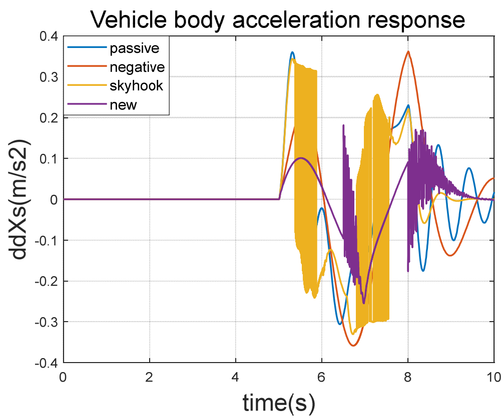

Figure 14: Vehicle body acceleration response.

body acceleration there will be high-frequency jitter vibration phenomenon, due to the high frequency, the vibration can consume most of the energy after it is transmitted to the human body through the seat, the follow-up will be dedicated to the study. This shows that the combination of improved damping control strategy and negative stiffness suspension system can provide better ride comfort and driving smoothness under the road conditions through the bumpy road

5 CONCLUSIONS

In this paper, with the main purpose of improving vehicle ride comfort, the concept of negative stiffness is introduced into the suspension system by analyzing the functional characteristics of elastic elements, and the damping control algorithm is designed according to the functional characteristics of the spring suspension, and the following conclusions are obtained after simulation and analysis:

The new improved damping control negative stiffness suspension has superior vibration suppression performance compared to other suspension systems on normal random road surfaces, effectively reducing the root mean square value of vehicle amplitude and significantly improving the comfort of the vehicle ride.

When the new improved damping control negative stiffness suspension passes through the bump road surface such as the acceleration belt or the pit, the vehicle body vibration amplitude is also obviously smaller than other suspensions, and its callback time is longer, which can better reduce the vibration energy of vehicle body vibration and improve the ride comfort.

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