LIMITATION OF THE TIRE-ROAD CONTACT

GIỚI HẠN CỦA LIÊN KẾT GIỮA LỐP VÀ MẶT ĐƯỜNG

Nguyen Dang Quy[1,*], Vo Quoc Dai[1], Pham Xuan Phuong[1], Vu Ngoc Tuan[1],
Nguyen Truong Sinh[1], Nguyen Trung Kien[1], Vu Van Tan[2]

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ABSTRACT

The paper focuses on studying dynamic vibrations in a nondimensional field using a quarter-car model and governing equations. The analysis of vibrations is conducted in the frequency response domain considering both the no-contact and in-contact states. The study explores the limits of tire-road contact phenomena and identifies a series of separation points that form the separation boundary, which divides the plane into separation and contact zones. The study examines how suspension parameters influence the separation zone, aiming to offer valuable guidance to designers in making informed choices when selecting suspension parameters. The objective is to ensure the desired tire-road interaction, which ultimately improves vehicle dynamics and safety.

Keywords: *Separation boundary, vehicle vibrations, vibration dynamics, tire-road separation, ride safety.*

TÓM TẮT

Bài báo tập trung nghiên cứu về dao động bằng phương pháp không thứ nguyên sử bằng cách dụng mô hình một phần tư và đề xuất các phương trình đặc trưng. Phân tích dao động được thực hiện trong miền đáp ứng tần số cho hai trạng thái tiếp xúc và không tiếp xúc với mặt đường. Nghiên cứu cho thấy các giới hạn của hiện tượng tiếp xúc giữa lốp xe và mặt đường và xác định một loạt các điểm tách lốp tạo thành vùng biên tách bánh, phân chia mặt phẳng thành các vùng tách bánh và tiếp xúc. Nghiên cứu xem xét cách các thông số hệ thống treo ảnh hưởng đến vùng tách bánh, nhằm cung cấp hướng dẫn cho các nhà thiết kế trong việc đưa ra các lựa chọn sáng suốt khi lựa chọn các thông số hệ thống treo. Mục tiêu là đảm bảo sự tương tác mong muốn giữa lốp xe và mặt đường, điều này sẽ cải thiện động lực học và độ an toàn của xe.

Từ khóa: *Vùng biên tách bánh, dao động phương tiện cơ giới, động lực học dao động, tách bánh, an toàn chuyển động.*

[1]Institute of Vehicle and Energy Engineering, Le Quy Don Technical University, Vietnam
[2]Faculty of Mechanical Engineering, University of Transport and Communications, Vietnam
*Email: quynd@lqdtu.edu.vn

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1. INTRODUCTION

The use of the quarter-car model is prevalent in initial and optimization investigations of vehicle ride dynamics. Despite its simplicity, this model effectively captures the essential aspects of real-world vehicle dynamics and facilitates a fundamental comprehension of the limitations associated with suspension performance. Moreover, it serves as a foundational framework for suspension design that takes into account practical experience [1, 2]. However, most quarter-car models used for studying vibrations assume tire-road contact [3]. Neglecting the consideration of tire-road separation can lead to inadequate dynamic response predictions [4]. Therefore, it is necessary to reassess vibration responses by incorporating a switching differential equation system [5]. In this study, the vehicle is simulated in both contact and no-contact states. The identification of separation points and boundaries is crucial for gaining insights into vibration behavior [6]. By understanding the impact of suspension parameters on the separation zone, designers can make informed decisions to optimize the suspension system and achieve the desired tire-road interaction, resulting in enhanced vehicle dynamics, ride comfort and improved safety [7].

The recent shift in the automotive industry towards adaptive suspensions has highlighted the necessity for the development of more precise models that can accurately represent real suspension systems. Additionally, it is crucial to address the inherent nonlinearities in actual suspension systems, which are often overlooked in traditional models. To achieve greater accuracy, these models should also consider the impact of tire-road separation. This research focuses on analyzing how vehicle suspension models respond dynamically when their tires lose contact with the road. The study will involve comparing different car suspension models in terms of their ability to predict dynamic behaviors associated with tire separation, based on analytical results. Consequently, investigating vehicle vibrations in tire separation conditions necessitates a sophisticated level of mathematical modeling to accurately forecast their dynamic responses.

2. VEHICLE MODELING

In this section, a 2-degree-of-freedom quarter-car model is presented, which includes both in-contact and no-contact states. The corresponding systems of differential equations are described. Additionally, the study introduces the concept of the separation boundary to address the limitation of tire-road separation. This boundary helps define and understand the extent to which the tire and road are separated during different operational conditions.

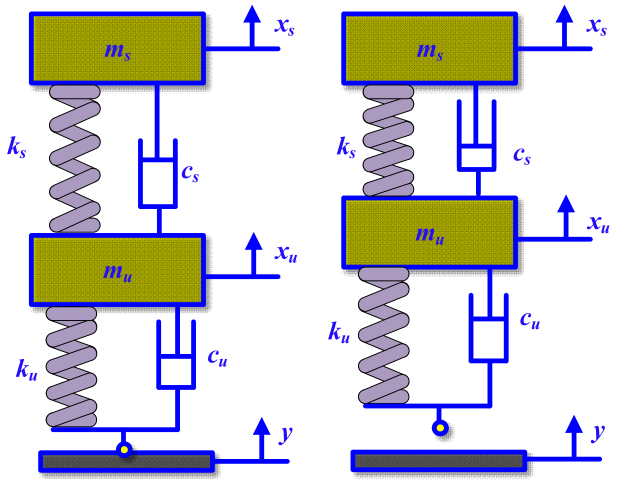

Figure 1. Model of a vehicle suspension with in-contact and free-flight states

2.1. Governing Equation System

To analysis the vertical vibration, Figure 1 describes the tire-road separation model as reference. The study will utilize a vehicle suspension system that encompasses both in-contact and no-contact states. This system will be employed to investigate the transitions between the tire and road by subjecting it to periodic excitations, specifically represented as $Y = cos\omega t$, where Y denotes the displacement and ω represents the angular frequency of the excitation.

In the nondimentional field, the equation of motion of sprung mass (the body of the vehicle) is written [8]:

$$X_s'' + 2\xi(X_s' - X_u') + (X_s - X_u) = 0 \quad (1)$$

Where, X_s is the displacement of sprung mass, and X_u is the displacement of unsprung mass.

While the motion equations of the unsprung mass (the wheel and suspension components) are divided into two situations:

For in-contact state:

$$X_u'' + 2\varepsilon\xi(X_u' - X_s') + \varepsilon(X_u - X_s) + \alpha^2(X_u - Y) = 0 \quad (2)$$

For no-contact state:

$$X_u'' + 2\varepsilon\xi(X_u' - X_s') + \varepsilon(X_u - X_s) + \alpha^2 = 0 \quad (3)$$

When the system is within the contact zone, it is governed by equations (1) and (2). However, when the separation condition is maintained, the motion of the system will adhere to equations (1) and (3).

2.2. Separation Boundary

To identify the limitation of contact between the tire and road, the study introduces a new variable namely the relative displacement $\mathbf{X_t}$:

$$\mathbf{X_t} = \mathbf{X_u} - \mathbf{Y} \quad (4)$$

This variable aims to quantify the extent of displacement between the tire and the road surface. The separation condition refers to the limit that defines the maximum allowable distance between the tire and the road surface in a suspension system. The boundary is determined by $\mathbf{X_t} = \mathbf{1}$ when the road separation occurs, separating the regions of in-contact $\mathbf{X_t} < \mathbf{1}$ and no-contact $\mathbf{X_t} > \mathbf{1}$.

The symbolic solution provides quadratic relative amplitude [8]:

$$\left|\frac{X_t}{Y_0}\right|^2 = \frac{4\xi^2 r^2(\varepsilon+1)^2 + (r^2-1)^2 + \varepsilon^2 - 2\varepsilon(r^2-1)}{Z_1^2 + Z_2^2} r^4 \quad (5)$$

Where,

$$Z_1 = r^2(r^2 - \alpha^2) + (\alpha^2 - (1+\varepsilon)r^2)$$

$$Z_2 = 2r\xi(\alpha^2 - (1+\varepsilon)r^2)$$

By considering this relative displacement, the study aims to gain insights into the constraints and boundaries of the tire-road contact during the analysis.

3. RESULTS AND DISCUSSION

In order to analyze the dynamics of tire-road separation, the researchers utilize dimensionless parameters listed in Table 1 [5]. However, for the purpose of clarity and comprehension in the figures, the examination of tire-road separation will be conducted using typical parameters. This approach allows for a more intuitive understanding of the results presented in the nondimensional parameters of Suspension.

Table 1. The suspension parameters in dimensionless

Parameter	Symbol	Value [Unit]
Stiffness ratio	α	1 - 10
Mass ratio	ε	2 - 20
Damping ratio	ξ	0 - 2
Frequency ratio	r	0 - 200
Road amplitude	Y_0	1

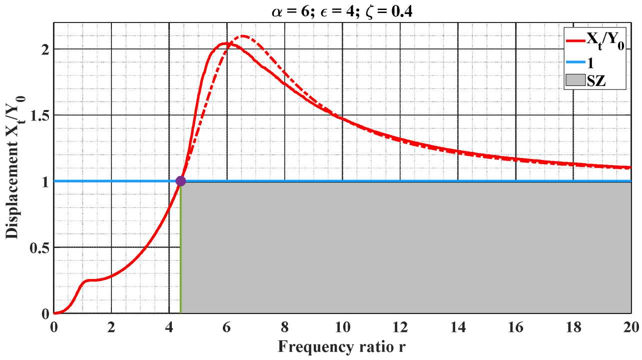

Figure 2. The relative frequency response

Figure 2 illustrates the real relative frequency response, represented by the solid curve. The frequency response comprises two axes, which include the frequency ratio representing the road excitation and the displacement, all for a specified set of suspension parameters. It is evident that the solid curve deviates substantially from the dotted curve, which assumes no separation, after reaching the position S corresponding to $r = 4.4$. Notably, once the relative displacement $\mathbf{X_t}$ reaches the horizontal line $y = 1$, the dynamic responses of the linear system become invalid. This observation signifies the presence of a limiting frequency ratio known as the separation point. Beyond this point, the no-contact zone SZ emerges, indicating that the system will be in a state of no contact with the road surface after passing this particular position.

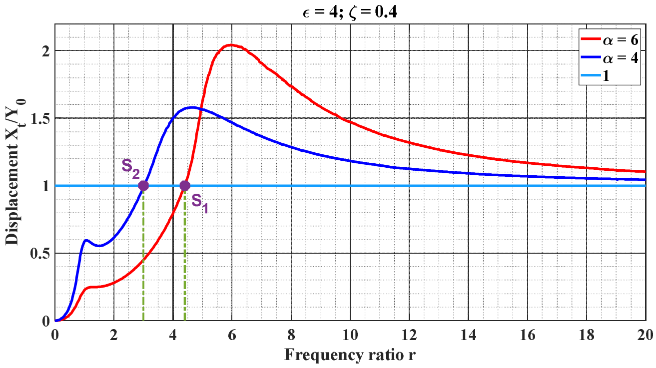

Figure 3. The relative frequency response with two separation points

Continuing with the provided input data, Figure 3 illustrates a decrease in the stiffness ratio as a means of identifying the separation point. Specifically, the separation point denoted as S_1 remains distinct from the curve with $\alpha = 6$. Another separation point, denoted as S_2, is observed when the relative displacement reaches the horizontal line $y = 1$ at $r = 3.0$. This finding indicates that the system might lose contact with the road surface at a lower frequency ratio when the stiffness ratio is low. Conversely, increasing the stiffness ratio would delay the occurrence of tire-road separation in such a scenario. By conducting simulations across a wide range of stiffness ratios, the study is able to obtain a collection of separation points known as the separation boundary.

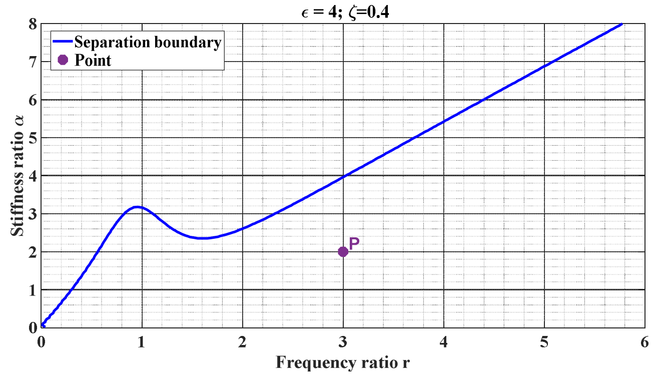

Figure 4. The separation boundary

Consider a nominal value of $\varepsilon = 4$ and a given damping ratio $\xi = 0.4$. In Figure 4, the effect of the stiffness ratio α on the no-contact zone is depicted as a continuous curve within a range of damping ratios. This curve divides the (r, α) plane into two regions. Points below the solid curve, such as $P(r = 3, \alpha = 2)$, indicate that the wheel remains in contact with the ground. On the other hand, points above the curve represent conditions where the wheel begins to separate from the surface. Hence, this curve is referred to as the separation boundary. The graph serves as a valuable tool in suggesting optimal techniques to enhance the contact capacity of vehicles by reducing the extent of the no-contact area.

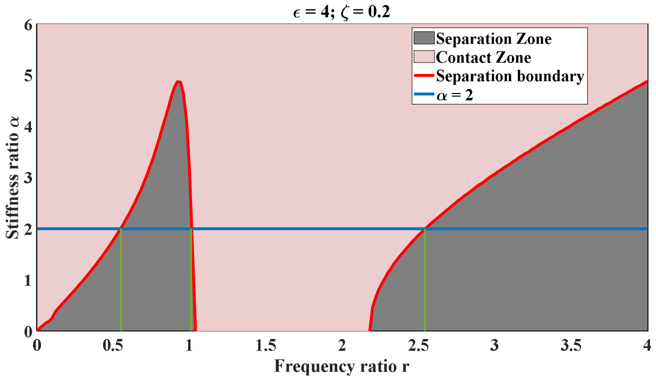

Figure 5. The separation boundary with two curves

When the damping ratio is low, such as $\xi = 0.2$, the separation boundaries in terms of the stiffness ratio α exhibit parabolic and exponential curves, as shown in Figure 5. These curves divide the (r, α) plane into the contact zone and separation zones. Any point that lies below the parabolic path or to the right of the exponential branch is considered part of the separation zones. Each separation point on the curve corresponds to a specific value of the stiffness ratio. To identify the regions where the tires are in contact with the road, a horizontal line can be drawn corresponding to a specific stiffness ratio that intersects the separation curve. For example, when $\alpha = 2$, there are three intersecting points: $r_1 = 0.6$, $r_2 = 1.0$, and $r_3 = 2.6$. These points indicate two regions: the in-contact region for $r < 0.6$ or $1.0 < r < 2.6$ and the no-contact region for $0.6 < r < 1.0$ or $r > 2.6$.

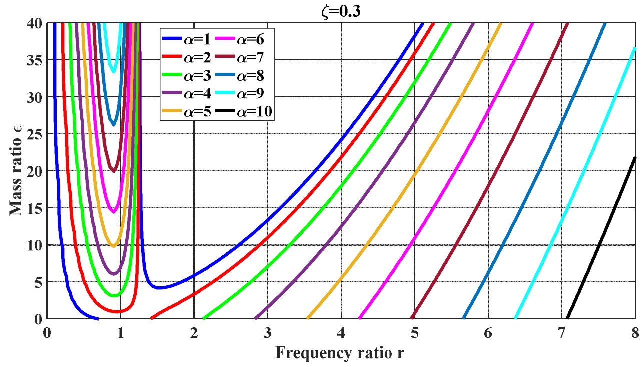

Figure 6. Series of separation boundaries

In Figure 6, the impact of the mass ratio on the separation boundary is explored while maintaining a constant damping ratio of $\xi = 0.3$. The separation boundary consists of a series of curves, and the separation zone is located above the parabolic curve and to the right of the exponential curve. In this context, it's understood that each value of the stiffness ratio corresponds to a distinct separation boundary. Consequently, at higher stiffness ratios, the contact area widens. This suggests that increasing the stiffness ratio leads to a larger region of contact between the tire and the road surface.

4. CONCLUSION

The study investigates the tire-road progress in the time and frequency responses, and identifies the separation point playing a crucial role in understanding the limitations of accuracy for linear systems. When the system operates beyond these points, the linear approximation may no longer provide accurate predictions of dynamic responses. The simulation results demonstrate that designing a suspension system with a high stiffness ratio can effectively expand the contact zone between the tire and the road surface. The limitations of tire-road contact have been identified through the observation of separation points, as indicated by the separation boundary. By utilizing the boundary information, designers can make informed decisions to ensure optimal system performance and avoid undesired tire-road separation.

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THÔNG TIN TÁC GIẢ

Nguyễn Đăng Quý[1], Võ Quốc Đại[1], Phạm Xuân Phương[1], Vũ Ngọc Tuấn[1], Nguyễn Trường Sinh[1], Nguyễn Trung Kiên[1], Vũ Văn Tấn[2]

[1]Viện Cơ khí Động lực, Trường Đại học Kỹ thuật Lê Quý Đôn

[2]Khoa Cơ khí, Trường Đại học Giao thông Vận tải