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A proposition for new vehicle dynamic performance index †

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Abstract

Current vehicle dynamic performance indices seem to be insufficient to represent the fundamental of vehicle dynamic performance because they are easily influenced by tuning elements such as springs. In this paper, suspension geometry is discussed as the basis of vehicle ride and handling performance. To analyze the characteristics of the suspension geometry, the screw theory is introduced. The screw axes surface, which is generated by continuous vehicle body motion, is the pure geometric property of the suspensions, and the shape of the surface is not influenced by tuning elements. Therefore, the shape of the screw axes surface can be regarded as the "genome" of vehicle performance. The gradients of screw parameters with respect to body lateral acceleration are proposed for new vehicle dynamic performance, and their correlation to vehicle performance is validated by full vehicle dynamic analysis.

Keywords: Vehicle dynamics; Screw theory; Screw axes surface; Vehicle dynamic performance index; Suspension geometry

1. Introduction

Much effort has been devoted by worldwide automotive engineers to develop a method or index to evaluate the dynamic performance of vehicles. As a result, there exist a number of vehicle dynamic performance indices. Performance indices, such as understeer gradient, critical speed, and static margin, are widely used to design the basic cornering characteristics of vehicles. For the transient state, yaw rate, natural frequency, yaw rate damping, and phase delay are the typical performance indices for evaluating vehicle performance.

However, all these performance indices are likely to be changed by tuning parameters such as tire, spring, damper, and stabilizer bar properties. In other words, existing vehicle performance indices seem to be insufficient to fully represent fundamental vehicle performance.

Therefore, a fundamental question emerges:

"Is there anything that can be referred as the 'Seed', or the 'DNA' of fundamental vehicle performance?"

Correspondingly, the goal of this paper is to propose new vehicle dynamics performance indices by defining the basis of vehicle performance and by determining the design parameters that can represent fundamental vehicle performance.

2. Suspension geometry as the foundation of vehicle performance

As a matter of fact, vehicle performance is determined not only by suspension geometry but also by body structure, powertrain, and other tuning elements. However, the term "vehicle performance" in this paper refers only to the ride and handling performance in order to focus on the suspension geometric characteristics. The term "suspension geometry" refers to the wheel trajectory characteristics which are determined by the kinematic configuration of suspension and steering mechanism, and by the properties of bushings in the joints.

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Assume that there exists a vehicle with bad suspension geometry, for example, with a potential magnitude of 10. If the potential of the suspension geometry is poor, the overall performance of the vehicle cannot exceed the limit of geometry potential, even with excellent tuning.

What is worse is that the overall vehicle performance can be impaired below the geometry potential with poor tuning. However, if the vehicle has good geometry potential, for example, a magnitude of 20, the vehicle will exert good performance up to 20 or even greater magnitude; even with bad tuning, therefore, the vehicle will at least demonstrate marginal performance.

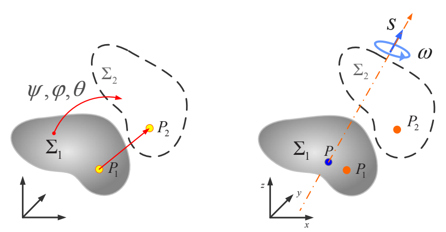
In other words, the potential of vehicle dynamic performance is determined by suspension geometry, and therefore, suspension geometry can be regarded as the basis of vehicle dynamic performance.

3. The screw theory

There are a number of methods to describe a motion of a body in space, such as Euler angles. The screw theory is one of these methods, and it was originally proposed by Sir Robert Stawell Ball in 1876[1]. As shown in Fig.1, the screw theory is a way to express displacement, velocity, forces, and torques in space, combining both rotational element about the screw axis and translational element along the axis.

The screw theory can provide a powerful way to analyze motion in space because it describes motion with the concept of the instantaneous center in a plane. The instantaneous center is the pure geometric property of a mechanism, and therefore, the motion can be intuitively and easily characterized by the instantaneous center.

Fig. 2(a) shows a four-bar mechanism in a plane. When link AB rotates about the A_0 point, the displacement of link A_1B_1, A_2B_2, and A_nB_n can be described by multiplication of the displacement matrix,



(a) By Euler angles (b) By Screw theory

Fig. 1. Spatial displacement of a body.

denoted by $[D_{12}]$, $[D_{1n}]$, and so on. The displacement matrix is defined by the following equation [2]. During the displacement, the loci of the instantaneous center of link A_1B_1 generate *curve 1*. *curve 2* can be computed by multiplying the inverse displacement matrix to *curve 1*.

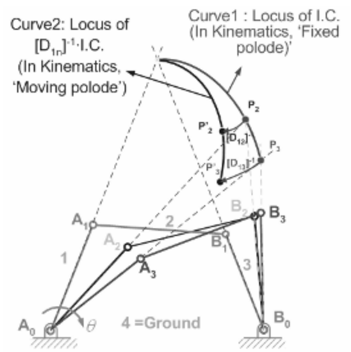
$$[D_{1n}] = \left[\begin{array}{ccc|c} & R & & \begin{array}{c} su_x + x_1 - (r_{11}x_1 + r_{12}y_1 + r_{13}z_1) \\ su_y + y_1 - (r_{21}x_1 + r_{22}y_1 + r_{23}z_1) \\ su_z + z_1 - (r_{31}x_1 + r_{32}y_1 + r_{33}z_1) \end{array} \\ \hline 0 & 0 & 0 & 1 \end{array}\right] \quad (1)$$

where $\hat{u}(u_x, u_y, u_z)$: Direction vector of the screw axis
$P(p_x, p_y, p_z)$: Any point on the screw axis
s, φ: The translation, rotation about the screw axis

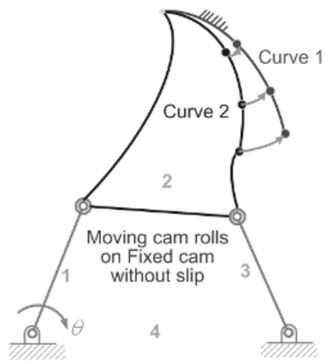
$$[R] = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$$

$$= \begin{bmatrix} u_x^2 V\varphi + C\varphi & u_x u_y V\varphi - u_z S\varphi & u_x u_z V\varphi + u_y S\varphi \\ u_x u_y V\varphi + u_z S\varphi & u_y^2 V\varphi + C\varphi & u_y u_z V\varphi - u_x S\varphi \\ u_x u_z V\varphi - u_y S\varphi & u_y u_z V\varphi + u_x S\varphi & u_z^2 V\varphi + C\varphi \end{bmatrix}$$

$$S\varphi = \sin\varphi,\ C\varphi = \cos\varphi,\ V\varphi = 1 - \cos\varphi$$



(a) The four-bar mechanism



(b) Equivalent cam system

Fig. 2. The four-bar mechanism and its equivalent cam system.

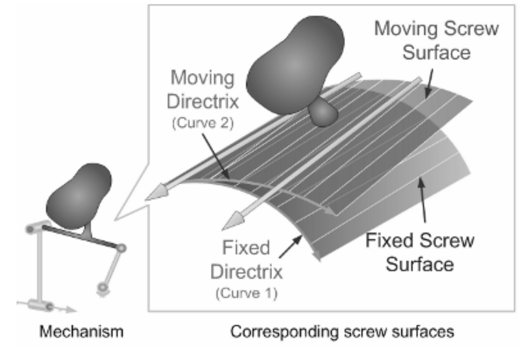


Fig. 3. Spatial mechanism and equivalent screw surfaces.

As shown in Fig. 2(b), the displacement of link A_1B_1 can be described by a rolling motion of *curve 2* on *curve 1* without slip. *curve2* belongs to a rigid body, which includes link A_1B_1[3].

In kinematics, curves 1 and 2 in Fig. 2(a) are referred to as “Fixed polode” and “Moving polode,” respectively. In the same manner, bodies 2 and 5 in Fig. 2(b) could be referred to as “moving cam,” and “fixed cam.”

If the instantaneous center is expanded to space, it becomes the instantaneous screw axis. As shown in Fig. 3, the continuous motion of a body in space now generates fixed screw surfaces.

Once a fixed screw axes surface is found, the moving screw axes surface can easily be calculated by simply multiplying the inverse displacement matrix to the moving screw axes surface.

Now, the motion in space can be described by the rolling of the moving screw axes surface belonging to the body, on the fixed screw axes surface. Therefore, if the shapes of the surfaces are investigated, the motion characteristics of the body can be understood intuitively. Note that the contact between the surfaces is one-to-one line contact.

4. Screw axes surface of the vehicle

If the idea of screw axes surfaces is simply applied to the vehicle system, it can be said that ‘the motion of the vehicle can be described by the rolling of the moving screw axis on a fixed screw axis maintaining line contact, without slip.” The fixed screw axes surfaces are generated by four-corner suspension mechanisms of vehicle. It should be emphasized that the screw axes surface is a pure geometric property of the suspension mechanism.

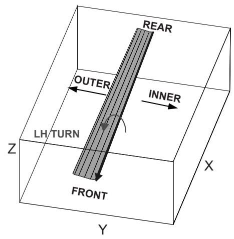
To analyze the fixed and moving screw axes surfaces of the vehicle, a kinematic model for the full vehicle is required. Unfortunately, the vehicle system is not fully kinematic because it has compliant elements such as springs, bushes, tires, and even the flexibility of its body structure. Therefore, the finite screw axis and corresponding finite screw axes surfaces need to be introduced to consider the compliant characteristics of the vehicle. In this paper, a quasi-static full vehicle roll model is established to simulate the cornering motion of a vehicle, and develop the corresponding screw axes and surfaces. The analysis

Table 1. Full vehicle models for quasi-static roll analysis.

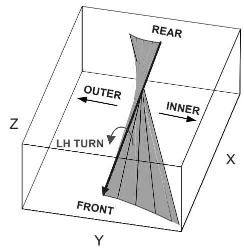
Model	Front suspension	Rear suspension
1	McPherson	Double wishbone
2	Double wishbone	Double wishbone
3	Double wishbone	McPherson

Table 2. The influence of tuning elements on the shape.

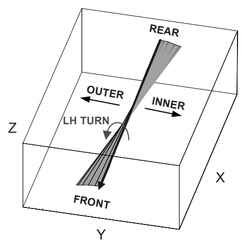
Case	Parameter change	Shape of surface
1	Bush stiffness is increased by 10 times	Shape pattern is not changed
2	Front spring stiffness is increased by 1.5 times to raise roll stiffness	Not changed
3	Suspension geometry is changed by applying steering rack stroke of 10mm	Not changed
4	Initial toe angle is increased by 3 times	Not changed



(a) Model 1



(b) Model 2



(c) Model 3

Fig. 4. Quasi-static analysis result (Screw axes surfaces).

is carried out by applying quasi-static lateral force in the body center of gravity, while lateral displacement of the body is restrained by certain tire forces.

To investigate if the screw axes surface can represent the fundamental of suspension characteristics, and to determine the correlation between screw axis and vehicle performance, three vehicle models of different suspension combinations are introduced. The combinations are summarized in Table 1.

Fig. 4 shows the results of the quasi-static cornering analyses of three different models. As can be seen from Fig. 4, each suspension combination shows distinct shape of the screw axes surface. Therefore, it may be concluded that the screw axes surface can represent the fundamental suspension geometry characteristics, which can be referred to as the "DNA" of vehicle performance. To investigate and confirm that the shape of the screw axes surfaces is not affected by tuning elements, quasi-static cornering analysis with variation of the properties of the tuning elements is carried out.

The change in tuning parameters and the corresponding change in shape of the screw axes surfaces are summarized in Table 2.

The analyses results show that the shapes of the screw axes surfaces are not affected by the changes in tuning parameters. Therefore, they can be regarded as the "genome" of suspension geometry.

5. Screw parameter method

Since P can be any point on the axis, Body C.G. coordinate is used for p_x. To quantify the shape of the screw axes surface, the gradients of screw axis parameters with respect to a body lateral acceleration of 0.5G are introduced.

The correlation between screw parameters and vehicle performance is investigated using full vehicle dynamic analysis. The result of the dynamic analysis shows that the gradients of the screw axis parameters have a strong bond with vehicle dynamic performance. The correlation between the parameters and vehicle dynamic performance is summarized in Table 3.

Table 3. Correlation of screw parameters.

Screw parameter	Correlation with vehicle motion
$\partial y / \partial F_y$	Vertical migration of Body C.G. (lift up/down), Roll stiffness
$\partial z / \partial F_y$	• Lateral migration of body C.G. • Roll moment
$\partial u_y / \partial F_y$	• Body pitch
$\partial u_z / \partial F_y$	• Body yaw
$\partial S / \partial F_y$	• Cornering rapidness

6. Conclusion

In this paper, the fundamentals of vehicle performance, especially of ride and handling performance, are discussed. Current vehicle performance indices could be insufficient to represent fundamental vehicle performance since they are easily influenced by tuning parameters such as springs and bushes. Meanwhile, the geometry of suspension can be regarded as the basis of vehicle performance because it determines the potential of vehicle performance.

To investigate and evaluate the characteristics of suspension geometry, the screw axis theory is introduced. Continuous migration of the finite screw axis during vehicle roll motion forms the screw axes surface, which is a pure geometric property of vehicle suspensions. The shape of the screw surface is unique according to suspension geometry, and it is not changed by tuning elements. Therefore, the shape of the screw axes surface can represent the fundamental characteristics of suspension geometry, which is the basis of vehicle performance.

To quantify the shape of each screw axes surface, the gradient of the screw axis parameters is proposed as a new vehicle performance index.

Validation via multibody dynamics simulation using ADAMS/Car confirms that vehicle dynamic performance can efficiently be predicted by the indices proposed. The application of the screw axes surface and corresponding screw parameters is not for vehicle systems alone but for all other systems as well.

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