

Method of Vehicle Dynamics Analysis by means of Equivalent Cornering Stiffness for Aerodynamic Forces and Moments

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ABSTRACT

The dynamic performance of a vehicle traveling at high speeds is affected by the aerodynamic characteristics consisting of lift on front and rear axles, side force, and yawing moment. In order to enable consideration of these aerodynamic characteristics from the early stages of the vehicle development process, it is required that the characteristics are replaced by simple development indices. The study discussed in this paper introduced the concept of equivalent cornering stiffness to analyze these aerodynamic characteristics from the viewpoint of vehicle dynamics. Using this method, it is possible to integrate four aerodynamic characteristics into two variables which are very important to vehicle dynamics. As a result, the interaction between each aerodynamic characteristic is simply expressed in the equations of motion. Moreover the aerodynamic characteristics are dealt with as the same variables which are commonly used in other chassis systems such as suspensions and tires. It can hereby simplify to allocate the various chassis characteristics including aerodynamics to fulfill the high requirements for the vehicle dynamics performance, such as minimizing running resistance in keeping with appropriate lateral dynamics.

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INTRODUCTION

The dynamic performance of a vehicle traveling at high speeds is strongly affected by aerodynamic characteristics. They are represented by three forces as drag, side force, and lift and three moments as rolling, pitching, and yawing [1]. In this paper, front and rear lift forces, which are regarded as reacting on front and rear axles, are used instead of the combination of lift force and pitching moment, as it is more popular. Here, regarding lateral dynamics of a vehicle, it should be considered that front and rear lift forces alter the tire lateral forces through the changes of the wheel loads besides side force and yawing moment which directly act on the vehicle body. These effects are considered using the response characteristic of the yaw velocity in relation to the steering angle as the standard index of dynamic performance. Figure 1 is the simulation of yaw velocity gain and its natural frequency, and it shows the contribution of each aerodynamic characteristic. C_{Lf} is the lift coefficient for the front axle, C_{Lr} is the lift coefficient for the rear axle, C_S is the side force coefficient for each one degree of the aerodynamic angle of attack, and C_{YM} is the yaw moment coefficient for each one degree of the aerodynamic angle of attack. C_{Lf} , C_{Lr} , and C_S

are evaluated for changes of ± 0.1 and C_{YM} for ± 0.02 as ordinary ranges of aerodynamic characteristics. The results demonstrate that the yaw velocity response characteristics are considerably affected by these coefficients. Some studies have been conducted to investigate the effect of these coefficients on lateral dynamics of a vehicle [2], [3]. Especially, the study [2] investigated various aerodynamic characteristics to improve lateral stability while keeping the aerodynamic drag low. It aimed to fulfill the high requirement for future low emission vehicles. However there are few analytical studies to deal with the effect from the viewpoint of interaction between each aerodynamic characteristic. In order to improve efficiency of the aerodynamics development, it is required that the characteristics intertwined each other are replaced by simple development indices [4]. The study discussed in this paper introduces the solution of conversion of aerodynamic characteristics to the important values in terms of vehicle dynamic performance.

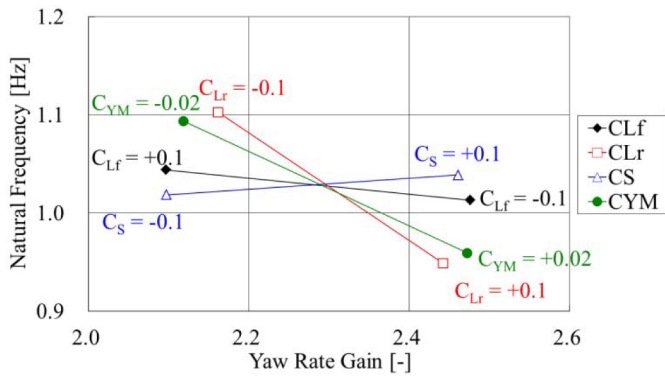


Figure 1. Yaw Velocity Response due to Aerodynamic Characteristics at 200 [km/h]

Prior to the study of the method of aerodynamic analysis, subjective evaluation tests were conducted using an actual vehicle driven at high speeds by experienced drivers. The vehicle used in the tests was a front-wheel drive five door hatchback. Table 1 shows the specifications of the vehicle. It was given different aerodynamic characteristics by combining various additional aerodynamic parts considered to have effects on aerodynamic characteristics. In other words, the differences in the evaluations can be considered to be primarily the effects of the differences in the aerodynamic characteristics imparted by each specification. Table 2 and Figure 2 show the specifications of the additional aerodynamic parts. The result of the subjective evaluation tests are shown in Table 3. The rating system is set out in Table 4.

Table 1. Specifications of the Vehicle in the Subjective Evaluation Test

Mass of the vehicle	1246 [kg]
Moment of inertia about the z-axis	2200 [kgm ²]
Wheelbase	2.63 [m]
Weight distribution of front axle	62.7 [%]
Frontal area of the vehicle	2.23 [m ²]

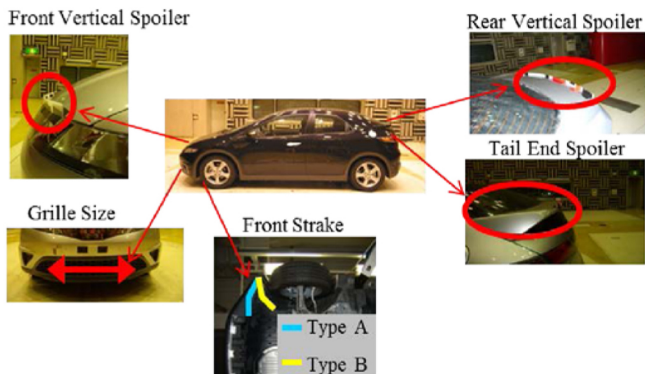


Figure 2. Pictures of the Additional Aerodynamic Parts

Table 2. Specifications of the Additional Aerodynamic Parts

Specifi- cation	Specification Substance				
	Front Vertical Spoiler	Grille Size	Front Strake	Tail End Spoiler	Rear Vertical Spoiler
A	✓	Full	type B	✓	✓
B	✓	Full	type A	✓	✓
C		Limited	type A	✓	✓
D		Limited	type A		
E		Full	type A		
F		Full	type A	✓	
G		Limited		✓	
H		Limited			✓

Table 3. Results of the Subjective Evaluation Test

Specification	Rating	Comment
A	6.0	Moves lightly in the straight line. Steering becomes lighter with angles.
B	6.5	Straight stability is better but cornering and lane change behavior is worse than E.
C	6.3	Straight stability is slightly worse than B.
D	5.8	Straight stability is very poor. It doesn't calm down in lane change.
E	6.5	More stable than D. Keeps moving after lane change.
F	6.7	More stable than E in straight line and corner entry.
G	7.0	More stable than E in straight line and during cornering. Feels to be pressed down on the ground.
H	6.0	Stability is poorer than E. Steering becomes lighter with angles.

Table 4. Rating System

Rating	Evaluation
10	Excellent
9	Very Good
8	Good
7	Acceptable
6	Marginally Acceptable
5	Border Line
4	Unacceptable
3	Poor
2	Very Poor
1	Extremely Poor

Figures 3a, 3b, 3c, 3d show the relationship between the ratings given in the subjective evaluations and the front lift coefficient, the rear lift coefficient, the side force coefficient, and the yawing moment coefficient for each aerodynamic specification, all obtained from wind tunnel tests. It would be difficult to determine a quantitative relationship between each coefficient and the rating from these results, because it is considered that the complicated interrelationship between each aerodynamic characteristic determines the vehicle behavior. Nevertheless it is therefore essential to design these aerodynamic characteristics in order to obtain appropriate vehicle behavior at high speeds. In addition, it is challenging to independently design the amount of lift on front and rear axles, side force, and yawing moment in the process of aerodynamics development, which is restricted to the exterior shape of the vehicle. For the reasons above, it is required to standardize the comprehensive evaluation of aerodynamic characteristics from the perspective of vehicle behavior at high speeds. The research discussed in this paper introduces the solution of converting each aerodynamic characteristic into equivalent cornering stiffness, a fundamental vehicle dynamic characteristic, and examines the method of expressing the contribution of aerodynamic characteristics to vehicle dynamic performance on this basis. Because the focus of the study was the small range of body sideslip angle close to the straight, the research employed a linearized bicycle model. The model diagram is shown in Figure 4 and the definitions of the variables are in the section of notation.

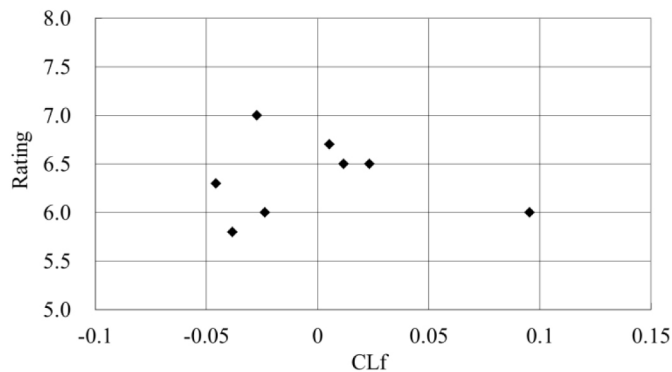


Figure 3a. Subjective Rating versus Front Lift Coefficient

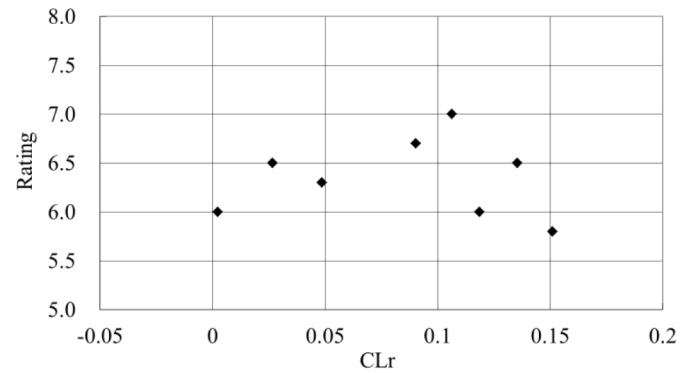


Figure 3b. Subjective Rating versus Rear Lift Coefficient

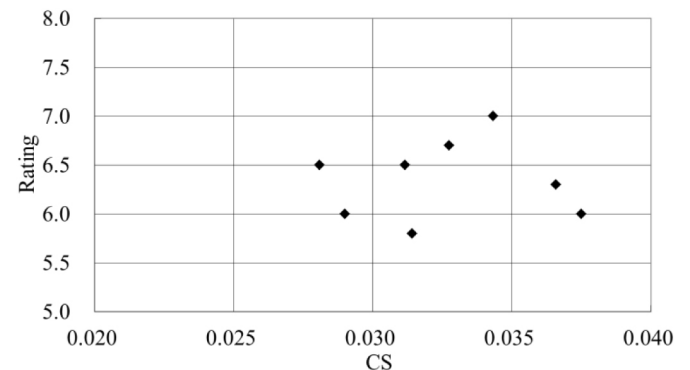


Figure 3c. Subjective Rating versus Side Force Coefficient

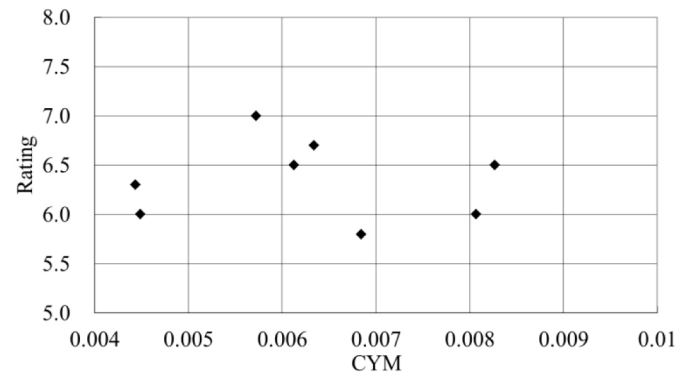


Figure 3d. Subjective Rating versus Yawing Moment Coefficient