

# Modeling of Transient Aerodynamic Forces based on Crosswind Test

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## ABSTRACT

The aerodynamic stability of energy-saving, lightweight, and low-drag vehicles is reduced by crosswind disturbances. In particular, crosswinds cause unsteady motion in vehicles with low-drag body shapes due to aerodynamic yaw moment. To verify fluctuations in the unsteady aerodynamic forces of a vehicle, a direct measurement method of these forces in a crosswind test was established using inertial force and tire load data. The former uses an inertia sensor comprised of a gyro, acceleration sensor, and GPS sensor, and the latter uses a wheel force sensor. Noise in the measurement data caused by the natural frequency of the tires was reduced using a spectral subtraction method. It was confirmed that aerodynamic data measured in the crosswind test corresponded to wind tunnel test data. Numerical expressions were defined to model the unsteady aerodynamic forces in a crosswind. Crosswind tests were conducted under various conditions consisting of different wind patterns and test vehicle yawing motions, to identify the model parameters in the numerical expressions by multiple linear regression analysis. The analysis results showed that dynamic aerodynamic forces can be expressed as a function of yaw rate, side slip angle, the derivative of the relative wind angle, and the relative wind angle, i.e. aerodynamic side slip angle. The transient state in a crosswind can be estimated by the proposed transient aerodynamic model more accurately than the previous static aerodynamic model. Furthermore, it was found that the dynamic aerodynamic force increases yaw rate due to crosswind disturbance, thereby deteriorating the stability of road vehicles.

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## 1. INTRODUCTION

In recent years, the development of lightweight and low-drag vehicles to help achieve a more energy-efficient society is attracting attention. However, the aerodynamic shapes of low-drag vehicle bodies [1] and the lower weight of these vehicles are known as factors that reduce stability in crosswinds. Body shapes that are designed to reduce drag are generally streamlined, which leads to increases in certain aerodynamic forces (yaw moment). In addition, it is also known that aerodynamic forces in a crosswind do not have static characteristics that change in proportion to the relative wind angle. Recent reports have highlighted unsteady aerodynamic forces that occur due to sudden changes in the wind, such as at tunnel exits [2, 3, 4].

Previous research into the detection of unsteady aerodynamic forces in crosswinds has included wind tunnel tests [5, 6, 7, 8, 9, 10] and the estimation of aerodynamic forces by the numerical integration of surface pressures measured at discrete points in actual vehicles [11]. However, there have been no reports describing direct measurement methods using actual vehicles.

In addition, the modeling of unsteady aerodynamic forces has focused on dynamic components that accompany the rate of vehicle attitude change while driving [12]. Here, Kawakami et al. reported a modeling method for dynamic aerodynamic forces assuming incorporation into vehicle equations of motion [13]. However, this model is limited to the linear region and does not consider external factors such as crosswinds.

The research described in this paper focused on lateral force and yaw moment as the aerodynamic forces when driving in a crosswind. This research developed a method of measuring these aerodynamic forces, and then constructed a filtering method to appropriately extract the fluctuating forces from the measured values. Subsequently, the correlation between the measured aerodynamic forces and vehicle motion, crosswinds, and the like was analyzed. A model was then created to estimate the fluctuating aerodynamic forces in a crosswind. Finally, this paper discusses the effects of dynamic aerodynamic forces on vehicle motion.

## 2. AERODYNAMIC FORCE MEASUREMENT METHOD

### 2.1. Measurement Principle and Test Method

When driven, aerodynamic forces, inertial force due to motion, and tire load balance out and act in concert on the vehicle. Equation of motion (1) can be obtained based on the definitions shown in Fig. 1. Here, the four-wheel total of the lateral tire load and yaw moment are defined as  $F_T$  and  $M_T$ , the vehicle speed, lateral velocity, and yaw angular velocity are defined as  $U$ ,  $v$ , and  $r$ , side slip angle and relative wind angle are defined as  $\beta$  and  $\beta_w$ , the lateral aerodynamic forces and yaw moment are defined as  $F_S$  and  $M_Y$ , and the vehicle mass and yaw moment of inertia are defined as  $m$  and  $I$ , respectively.

$$\begin{cases} m(\dot{v} + Ur) = F_T + F_S \\ I\dot{r} = M_T + M_Y \end{cases} \quad (1)$$

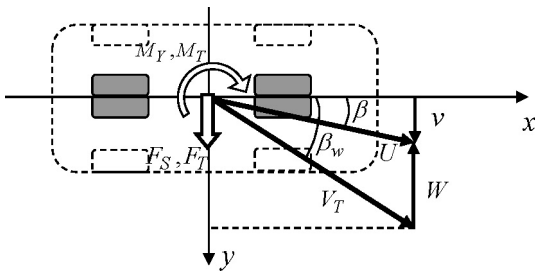


Figure 1. Coordinate system.

The vehicle mass and yaw moment of inertia were measured in advance in bench tests. As shown in Fig. 2, inertia and wheel force sensors were installed at each wheel and the aerodynamic forces were reverse calculated from the difference in each measured value.

Aerodynamic forces were measured in a crosswind test by driving a vehicle straight on at a constant speed in front of a crosswind generator that applies a wind at a constant velocity. To provide a comparison with wind tunnel tests based on the relative wind angle, this test was carried out at different vehicle speed and wind velocity conditions.

Two types of experimental test vehicles were adopted to examine aerodynamic characteristics. Test vehicle (A) had a unique body shape in order to achieve low drag performance such as a highly streamlined body, fully flat under-floor, side skirts to cover rear wheels, and the like. The attached flow around the streamlined body causes extreme aerodynamic instability [1]. Test vehicle (B) had an ordinary body shape like a commercially available compact hatchback. The flow separation at the front and the rear corner reduces the aerodynamic instability [1].

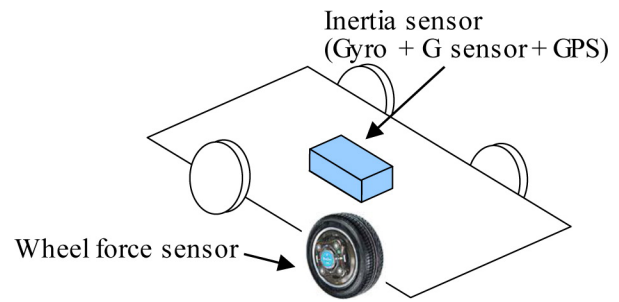


Figure 2. Instrument system.

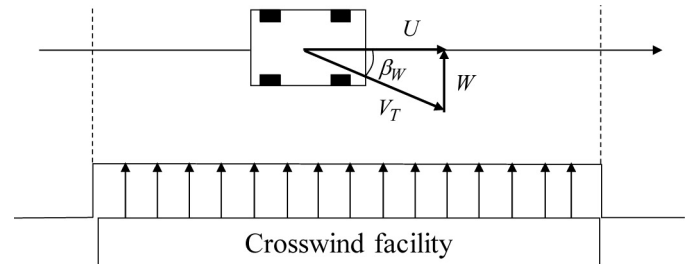


Figure 3. Crosswind test.

### 2.2. Post-Test Processing of Measured Data

Figure 4 shows an example of the measured data and converted aerodynamic force coefficient. The aerodynamic forces were expressed as a non-dimensional number using Equation (2). Here,  $\rho$  is the air density,  $V_T$  is the air speed,  $S$  is the frontal projected area of the vehicle,  $L$  is the wheelbase, and  $a_s$  is the lateral acceleration. In addition, for time  $t$ , zero-time was set as the moment at which the front edge of the vehicle reached the crosswind range, and expressed as the non-dimensional number  $T (=t \cdot U/L_A)$ , where  $L_A$  is the total length).

$$C_S = \frac{F_S}{1/2 \rho V_T^2 S}, \quad C_Y = \frac{M_{YC}}{1/2 \rho V_T^2 SL} \quad (2)$$

In addition, unless otherwise stated in this paper,  $C_Y$  is the non-dimensional number of  $M_{YC}$  i.e., the yaw moment around the wheel center. The relationship with the yaw moment around the center of gravity  $M_Y$  described above is as follows.

$$M_{YC} = M_Y + l_C F_S \quad (3)$$

See Fig. 5 for the details of  $l_C$ .

Since the data immediately after measurement includes noise, a filtering process is required to extract the true values. Setting the cutoff frequency is the main issue for most commonly used low pass filters (LPF).

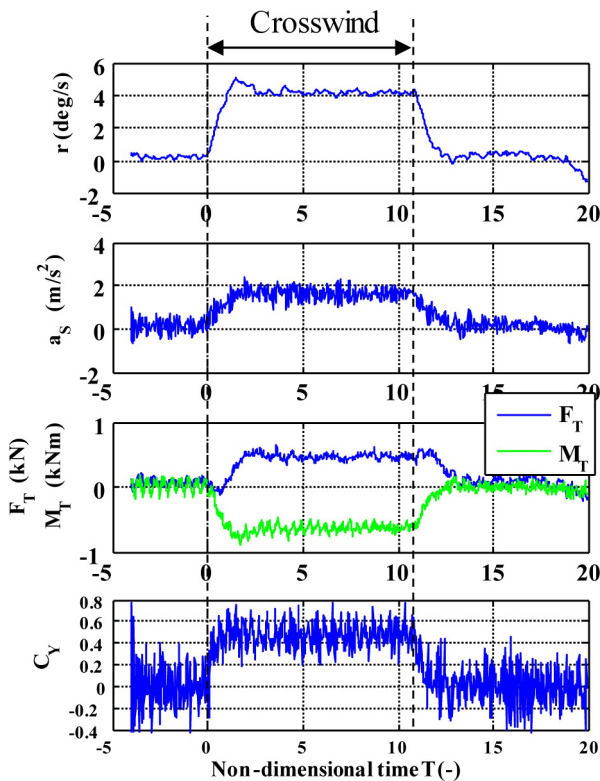


Figure 4. Crosswind test data.

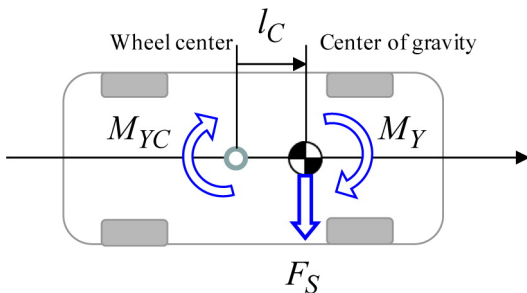


Figure 5. Definition of yaw moment.

Figure 6 shows the results of the frequency analysis. Since the characteristics with and without crosswinds above 10 Hz share the same trends, this indicates that the natural vibration frequency of the vehicle is applied to the entire data. Therefore, regarding the data without crosswind as noise, a method to subtract this from the crosswind data in the frequency range was applied (this is called the spectral subtraction (SS) method [14]) and compared with a method using an LPF. Figure 7 shows the results. Although some noise remained after the application of the SS method, enough noise was eliminated to allow simple estimation of the true aerodynamic force value. In contrast, when the LPF cutoff frequency was examined, it was found that the frequency capable of maintaining the same quality as the SS method was 5 Hz (Fig. 7). Therefore, a 5 Hz LPF was applied to the test data.

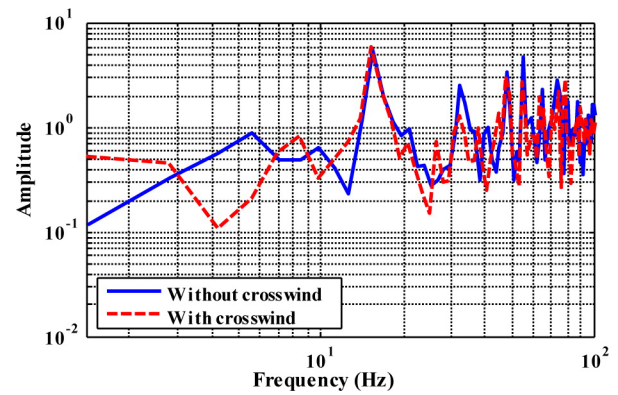
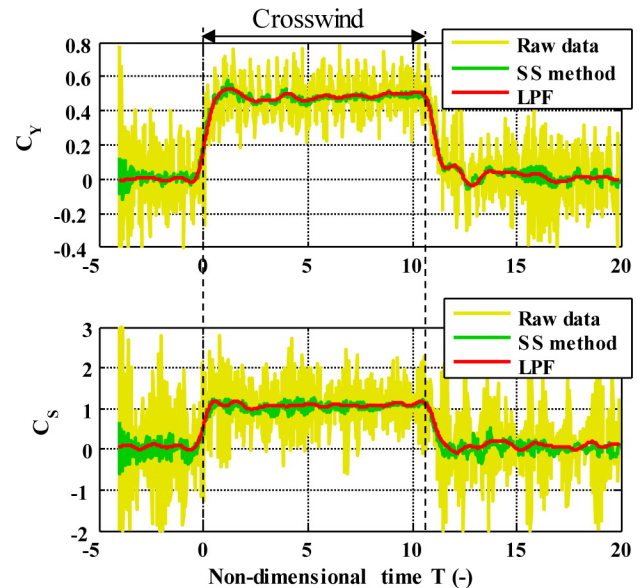
Figure 6. Fast Fourier transform (FFT) results of  $C_Y$ .

Figure 7. Comparison between two filtering methods.

### 2.3. Comparison with Wind Tunnel Results

To confirm the validity of this measurement method, the results were compared with the results of a full scale wind tunnel test (Test section size: W5m, H3m, and L20m, Turbulence intensity: less than 0.2%, Wind speed distribution: less than 0.4%). The wind tunnel test was carried out using the actual vehicles and the wind velocity was set to 30 m/s. The aerodynamic forces were measured at each fixed yaw angle which was between 0 and 30 degrees (Fig. 8). Measurements were performed without the attachment of a moving belt or other device to simulate the under-floor boundary layer.

The results of the crosswind test were calculated as the average in the range of steady vehicle motion ( $T=3$  to 10 in Fig. 4). The vehicle speed was between 80 and 120 km/h and the crosswind velocity was between 5 and 20 m/s. The relative wind angle range was between approximately 8 and 36°.

It is possible that differences between the wind tunnel results and the aerodynamic forces generated during driving might be caused by simulation of the under-floor boundary layer. Therefore, the aerodynamic characteristics including the dynamic characteristics described below were measured for the wind tunnel results. Therefore, although a simple comparison between the two tests does not necessarily guarantee validity, both tests yielded similar trends. Consequently, it was concluded that the good repeatability between the two results indicates that this measurement method is valid.

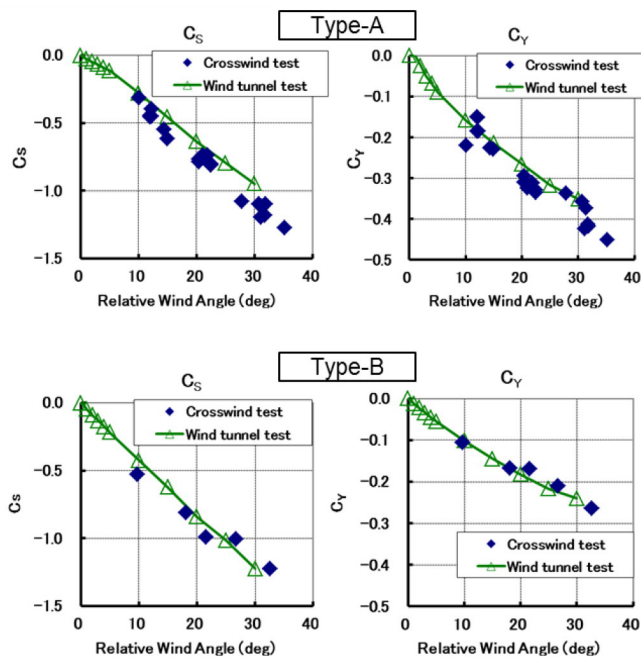


Figure 8. Comparison of results in crosswind and wind tunnel tests.

### 3. MODELING OF UNSTEADY AERODYNAMIC FORCES

#### 3.1. Modeling Method

The modeling flow was as follows.

1. Definition of numerical expressions for aerodynamic forces
2. Acquisition of aerodynamic forces data by a crosswind test
3. Identification by the statistical multiple regression analysis method

When defining the numerical expressions, the following known dynamic characteristics were regarded as the state variables linked to aerodynamic forces in addition to the static relative wind angle characteristic: relative wind angular velocity, slip angle, and yaw angular velocity. Numerical expressions for the relationships of the changes in aerodynamic forces were defined using these characteristics. In addition, to apply multiple regression analysis, variables that are unique to the vehicle and must be identified from the measurement data were set as characteristic variables and summarized as polynomial expressions.

In a crosswind test using actual vehicles, an arbitrary wind velocity distribution can be set by adopting individual settings for the crosswind generation fans. This allows the effect of changes in the relative wind angle to be studied and also allows the dynamic state created by steering operations to be changed easily. In contrast, it is difficult to set deliberate test conditions such as yaw angular velocity and slip angle in a crosswind test. Differences between the actual and intended test conditions or changes linked to various motion-related state variables can occur.

Therefore, multiple regression analysis capable of identifying multiple characteristic variables from results combining various conditions was adopted. Since the statistical multiple regression analysis method enables the quantitative verification of model significance and suitability, this method is also capable of reducing the possibility that an inappropriate model will be derived due to error included in the test data.

#### 3.2. Definition of Numerical Expressions for Aerodynamic Forces

First, the following section discusses the aerodynamic yaw moment.

The forces generated by changes in the relative air flow angle in the yaw direction in accordance with the crosswind and vehicle motion (called the “relative angle” below) were considered. The aerodynamic coefficient is defined as  $C_{Y\beta_w}$ . As shown in Equation (4), this includes the conventional relative wind angle function and a new slip angle function  $C_{Y\beta}$ . This is an additional force generated by vehicle motion. It was added since it has a different generation principle to the relative wind angle (for example, it is susceptible to complex under-floor flows).

In addition, the yaw moment is also a function of the air speed  $V_T$ . However, this can be converted into functions for the relative wind angle ( $\beta_w \approx W/U$ ) and the slip angle ( $\beta \approx v/U$ ) by the transformation described in Equation (5). Equation (6) is obtained by substituting Equations (4) and (5) into Equation (2), considering that  $\beta_w \gg \beta$  and  $C_{Y\beta_w} \gg C_{Y\beta}$ .

$$M_Y = 1/2 \rho V_T^2 S L (C_{Y\beta_w} + C_{Y\beta}) \quad (4)$$

$$\begin{aligned} V_T^2 &= \{U^2 + (W + v)^2\} \\ &\approx U^2 (1 + \beta_w^2 + 2\beta\beta_w + \beta^2) \end{aligned} \quad (5)$$

$$C_Y = C_{Y\beta_w} + 2 \frac{U^2}{V_T^2} \beta_w \beta C_{Y\beta_w} + C_{Y\beta} \quad (6)$$

The equations above only target the relative wind angle and the slip angle. However, this research also introduced the relative angles ( $\beta_r$  and  $\beta_G$ ) caused by the yaw angular velocity and relative wind angular velocity, considering the research performed by Kawakami et al. [13].