

Validation and Modeling of Transient Aerodynamic Loads Acting on a Simplified Passenger Car Model in Sinusoidal Motion

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ABSTRACT

Dynamic wind-tunnel tests of a simplified passenger car model were conducted using a two-degree-of-freedom model shaker. Time-resolved aerodynamic loads were derived from a built-in six-component balance and other sensors while the model underwent sinusoidal heaving and pitching motions at frequencies up to 8 Hz. The experimental results showed that frequency-dependent gains and phase differences between the model height/angle and the aerodynamic loads are in close agreement with those predicted by large-eddy simulation (LES) using an arbitrary Lagrangian-Eulerian (ALE) method. Based on these findings, transient aerodynamic loads associated with lateral motions were also estimated by LES analysis.

Based on the above results, a full-unsteady aerodynamic load model was then derived in the form of a linear transfer function. The force and moment fluctuations associated with the vertical and lateral motions are well described by the full-unsteady aerodynamic load model. This load model integrates added mass and moment-of-inertia terms into the quasi-unsteady model that takes into account the effect of the motion rate as an equivalent change in the relative inflow angle. Vertical motion analysis of a nominal passenger car model coupled with the full-unsteady aerodynamic load model showed that the transient aerodynamic loads affect the frequency response in such a way as to reduce its resonance frequency. The added mass and moment-of-inertia terms were eventually confirmed to have little effect on the vehicle dynamics; it should, however, be mentioned that their inclusion is inevitable in the modeling of transient aerodynamic loads, which inherently involves the added mass effect.

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INTRODUCTION

Although steady aerodynamic loads are normally used for vehicle performance evaluation under static driving conditions, the use of transient aerodynamic loads associated with the vehicle motion provides a more accurate prediction of vehicle maneuverability, stability, and ride comfort. Accordingly, the analysis of transient aerodynamics is of increasing interest in the automobile industry (see, for instance, Ref. [1]).

Most of the transient studies to date have been performed experimentally and numerically for a pure yawing motion [2],

[3], [4], [5] or a yaw angle variation of the onset flow [6], [7], [8] to address gusty crosswind conditions, while only a few experimental studies have been conducted to directly measure the aerodynamic loads on a vertically moving model. Due to the practical difficulties associated with the design of a robust model shaker system and the difficulties of accurately separating inertia effects from the measurements, experimental data are often limited to the measurement of response behavior using the free vibration method [9] or the surface pressure measurement at finite, discrete points [10]. While the numerical analysis of the flow around a pitching vehicle is under intense investigation [11], [12], the recent

development of a sophisticated model shaker system has enabled reliable measurement of transient aerodynamic loads acting on a vehicle model in vertical motion [13], [14].

In this study, dynamic wind-tunnel tests of a simplified passenger car model known as the Ahmed model [15] were conducted using a two-degree-of-freedom model shaker with a built-in six-component balance. The time-resolved force and moment data acquired for sinusoidal heaving and pitching motions were compared with those predicted by large-eddy simulation (LES) [16], which was validated with a forced-oscillating circular-cylinder case [17]. In addition, transient aerodynamic loads associated with lateral motions were also estimated by LES analysis for relatively small oscillations representative of steering activities rather than the gusty crosswind situations of previous studies.

Based on the above results, a full-unsteady aerodynamic load model was then derived from the quasi-unsteady model [18] that takes into account the effect of the motion rate as an equivalent change in the relative inflow angle. Given that the load model is expressed in a linear form, its incorporation into the vehicle's equation of motion is rather straightforward. Although computing power has become quite abundant and now allows computational fluid dynamics (CFD) analysis to be applied to unsteady aerodynamic situations such as those described above for selected cases (as presented in Refs. [19] and [20], albeit in a one-way coupling manner), there still exists a need for approximation methods based on the linear formation of the aerodynamic forces and moments, which would provide a quick and efficient evaluation of the vehicle system response.

EXPERIMENTAL METHOD

Dynamic wind-tunnel tests were conducted in the 50-percent-scale automotive wind tunnel at RUAG Aviation, Switzerland. The nozzle exit area is 2.45 m in width and 1.55 m in height. The test section is 3/4 open and is equipped with a moving belt system. A compact internal model shaker was attached to the end of the model support. It consists of two hydraulic actuators, which allow independent pitching and heaving motions in the range of approximately $\pm 3^\circ$ and ± 10 mm, respectively.

A simplified passenger car model defined by Ahmed et al. [15] was chosen as the subject for this study. Two configurations were considered for the rear-end slant angle Φ : 12.5° and 25° ; the drag coefficient of the former is less sensitive to small angle variations, while the latter is just below the critical angle of 30° , at which a sudden drag breakdown occurs. The model, which weighs 15.2 kg, was made of a carbon composite material and has an optimized internal structure to provide sufficient stiffness and a low inertia. A vibration analysis estimated the eigen-frequencies of the model to be more than 86 Hz for the side plate and 180 Hz for the bottom plate.

The Ahmed model equipped with the internal model shaker is illustrated in Fig. 1. Figure 2 shows the model in its

default position ($z = 0$, $\theta = 0$), the origin of the coordinate system, the selected center of rotation for the pitch (a positive pitch angle θ is in the clockwise direction), and the moment reference point M, which is fixed in space (not relative to the moving model). The model's floor is parallel to the ground, and the ground clearance is 50 mm. The overall length, height, and width of the model are 1044 mm, 288 mm, and 389 mm, respectively, and the blockage ratio is 5.3% (including the model support). Instead of being held on short support struts from beneath, as is the standard for Ahmed models, the model is held by a model support from above through a clearance hole in the model's roof. Thus, direct comparison of the presented results with the results of other Ahmed model studies may not be straightforward (but this is not the primary goal of this study).

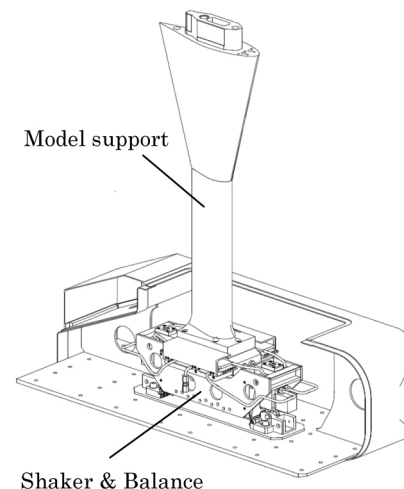
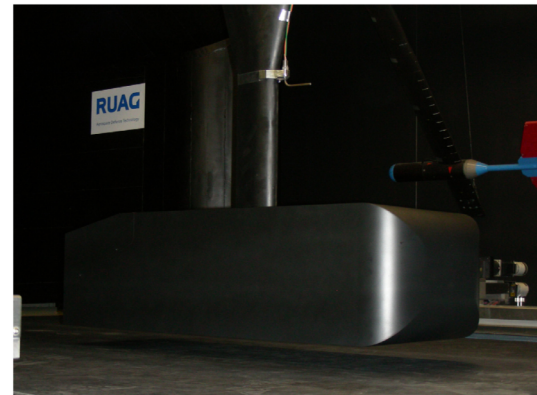


Figure 1. Ahmed model equipped with an internal model shaker.

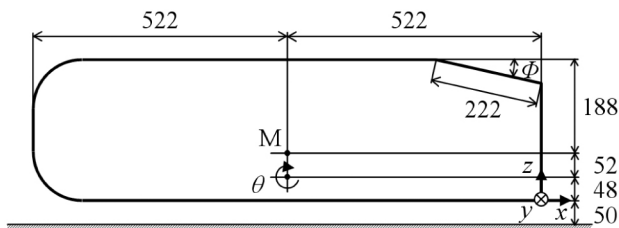


Figure 2. Coordinate system and reference points for vertical motions (unit: mm).

Preliminary CFD simulations conducted with and without the model support for the 12.5° slant-angle model under static conditions showed that the influence of the support interference on a time-averaged static pressure profile at the center plane was restricted to the upstream/downstream vicinity of the support, and the pressure profiles on the rear slant surface and elsewhere were seemingly consistent with each other. Under the effects of dynamic motion, the influence of the model support on the aerodynamic loads is non-negligible; nevertheless, it is considered to be small enough not to impact the assessment of the dynamic properties.

Transient aerodynamic forces and moments were measured with a very stiff, built-in six-component balance in the shaker. The sampling rate was set to 400 Hz, and the raw data were phase averaged over 36 to 144 motion cycles, depending on the motion frequency. The inertia compensation procedure is as follows:

1. The inertia characteristics of the model are determined by correlating the balance reading to the measurements of the model's internal accelerometers under the reference wind-off condition at a position 450 mm above the ground.
2. Under the wind-on condition, aerodynamic loads are estimated by subtracting from the balance readings the inertial loads calculated from the measured accelerations. The non-negligible inertia of the added mass is an aerodynamic effect and is taken into account in the results (not subtracted).

The motion amplitudes (denoted by the subscript *max*) were set to $z_{\max} = 8$ mm for the heaving motion and $\theta_{\max} = 0.878^\circ$ and 3.0° for the pitching motion, which well cover the possible vertical displacements of real cars with dimensions approximately four times larger than the Ahmed model under straight-ahead driving conditions. The forcing frequencies were set to $f = 2$ Hz, 4 Hz, and up to 8 Hz, depending on the motion type. Under these conditions, the deformation of the model's bottom plate (measured with a laser displacement meter) was less than 0.5 mm. The free-stream velocity U was set to 40 m/s, which yields a Reynolds number of 2.8 million based on the model length. The moving belt system was not activated unless stated otherwise.

NUMERICAL METHOD

Corresponding numerical simulations under basically the same conditions as the experiments were performed using an

in-house large-eddy simulation (LES) code extended to the arbitrary Lagrangian-Eulerian (ALE) coordinate system so that the moving boundary associated with the vehicle motions could be handled. Further details of the method are available in Refs. [16] and [17]. Numerical analyses were also conducted for lateral (sway and yaw) motions but could not be verified experimentally as this motion mode was not supported by the shaker system. Still, the results are interesting to compare with the vertical motion results and previously published results from other authors [2], [6], [21]. They also represent a first step towards the analysis of multi-degree-of-freedom vehicle dynamics.

The side-force coefficient C_Y , the rolling-moment coefficient C_{MX} , and the yawing-moment coefficient C_{MZ} acting on the vehicle model are defined in the $x'-y'-z$ model-fixed coordinate system, as defined in Fig. 3. Note that the x or x' axis is pointing upstream. The lateral motion amplitudes were, for consistency with the vertical motions, set to $y_{\max} = 8$ mm for the swaying motion and $\beta_{\max} = 0.878^\circ$ and 3.0° for the yawing motion with forcing frequencies of 4 Hz and 8 Hz, which again well cover the possible lateral motions of full-scale vehicles for steering activities. The numerical load data were phase averaged over 9 to 12 motion cycles.

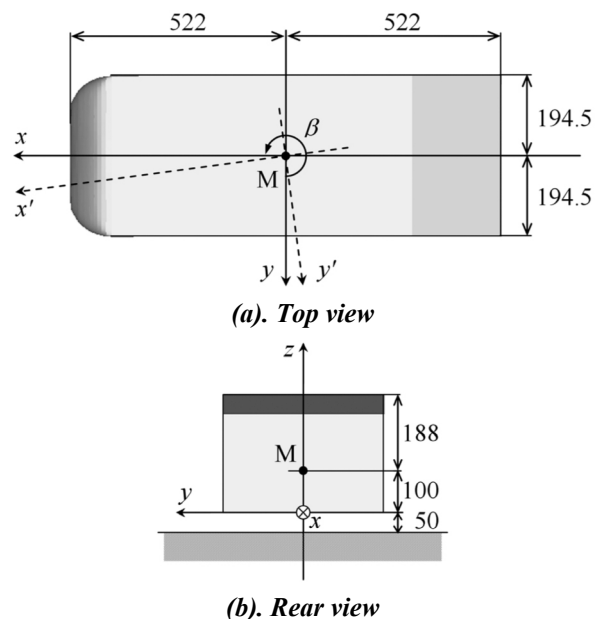


Figure 3. Coordinate system and reference point for lateral motions (unit: mm).

For the modeling of sub-grid scale (SGS) components, a mixed-time-scale SGS model was used, the advantage of which had been established for several basic flows as well as the flow around the Ahmed model [22]. Figure 4 shows the computational domain with an overlaid grid system, which consists of an inner structured grid and a background orthogonal grid. The former is subject to transformation in accordance with the vehicle motion, while the latter is fixed. The inner grid surrounding the Ahmed model is illustrated in

Fig. 5. The number of inner grid points is $215 \times 143 \times 123$, and there are $123 \times 69 \times 62$ points for the background grid. Note that a half model with a symmetry condition imposed on the center plane was used for the vertical motion analysis to reduce computational costs. The minimum grid spacing adjacent to the model is 0.05 mm for the 25° slant-angle model, as it was in Ref. [22]. Based on observations from a previous study [15], the flow was expected to remain fully attached on the slant surface except in the vicinity of the side edges for the 12.5° slant-angle model. This allowed the spatial resolution to be reduced to a computationally more economical 0.1 mm. The development of the boundary layer on the fixed ground surface was taken into account by imposing a nonslip boundary condition over the entire computational domain.

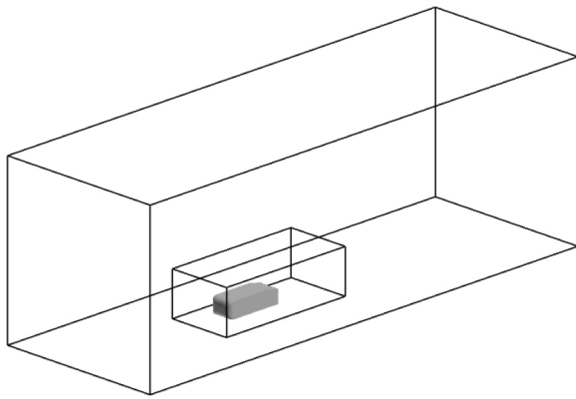


Figure 4. Computational domain with an overlaid grid system.

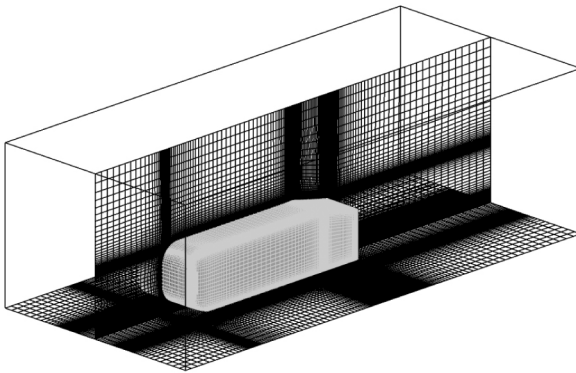


Figure 5. Inner structured grid surrounding the Ahmed model with a slant angle of 12.5° .

VEHICLE MOTION ANALYSIS

One of the focuses of this study is the modeling of the transient aerodynamic loads as a step towards the quick and efficient assessment of the vehicle's dynamic performance. A half-car suspension model with four degrees of freedom (illustrated in Fig. 6) was used to demonstrate the influence of the transient aerodynamic loads on the vehicle's dynamic

behavior when subjected to road excitation. Here, z and θ are the vertical displacement and pitch angle of the sprung mass at the center of gravity (CG), z_f and z_r are the vertical displacement of the front and rear wheels, respectively, and z_{f0} and z_{r0} are the excitations from the road surface. The specifications of the nominal passenger car model considered in this study are given in Table 1 (adapted from Kojima et al. [23]).

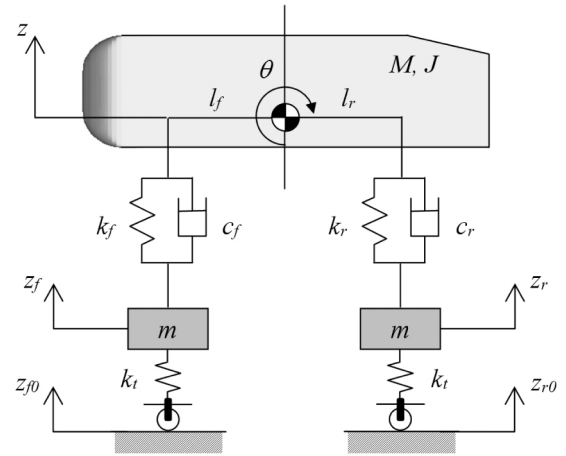


Figure 6. Half-car suspension model with four degrees of freedom.

Table 1. Specifications of the nominal passenger car model (adapted from Kojima et al. [23]).

Sprung mass: M	1200 kg
Mass moment of inertia: J	2600 kgm^2
Mass of front/rear wheel: m	40 kg
Distance from CG to front suspension: l_f	1.2 m
Distance from CG to rear suspension: l_r	1.2 m
Spring stiffness of front suspension: k_f	14000 N/m
Spring stiffness of rear suspension: k_r	12000 N/m
Damping coefficient of front suspension: c_f	1800 Ns/m
Damping coefficient of rear suspension: c_r	1500 Ns/m
Spring stiffness of tire: k_t	200000 N/m

Let the transient aerodynamic coefficient C be decomposed in the form of $C = \bar{C} + \Delta C$, where $\bar{C}$ and ΔC represent the steady component at the default position and the fluctuating component associated with the vehicle motion, respectively. The equation of motion for the vehicle body and the front/rear wheels are given by Eqs. (1), (2), (3), (4),

$$\begin{aligned}
 M\ddot{z} = & -2k_f(z + l_f\theta - z_f) - 2c_f(\dot{z} + l_f\dot{\theta} - \dot{z}_f) \\
 & - 2k_r(z - l_r\theta - z_r) - 2c_r(\dot{z} - l_r\dot{\theta} - \dot{z}_r) \\
 & + \frac{1}{2}\rho U^2 A(\bar{C}_z + \Delta C_z)
 \end{aligned} \quad (1)$$

$$J\ddot{\theta} = -2l_f k_f (z + l_f \theta - z_f) - 2l_f c_f (\dot{z} + l_f \dot{\theta} - \dot{z}_f) + 2l_r k_r (z - l_r \theta - z_r) + 2l_r c_r (\dot{z} - l_r \dot{\theta} - \dot{z}_r) + \frac{1}{2} \rho U^2 AL (\bar{C}_{MY} + \Delta C_{MY}) \quad (2)$$

$$m\ddot{z}_f = k_f (z + l_f \theta - z_f) + c_f (\dot{z} + l_f \dot{\theta} - \dot{z}_f) - k_i (z_f - z_{f0}) \quad (3)$$

$$m\ddot{z}_r = k_r (z - l_r \theta - z_r) + c_r (\dot{z} - l_r \dot{\theta} - \dot{z}_r) - k_i (z_r - z_{r0}) \quad (4)$$

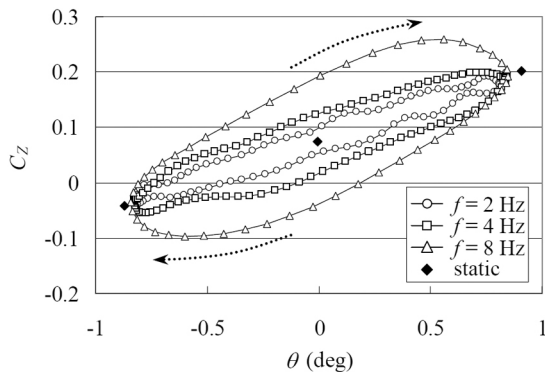
where ρ , U , A , and L represent the density of air, the driving speed, the frontal projected area, and the length of the vehicle, respectively.

RESULTS AND DISCUSSION

TRANSIENT AERODYNAMIC LOADS FOR VERTICAL MOTIONS

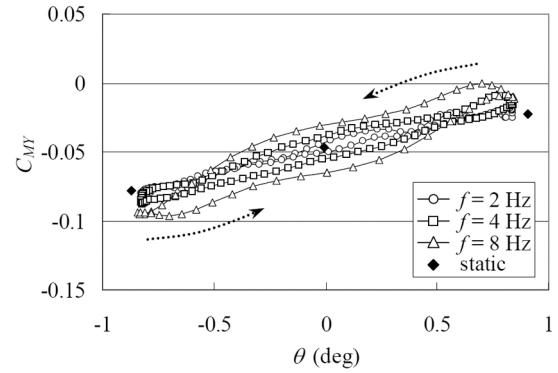
Effect of Forcing Frequency (Experimental Results)

The phase-averaged curves in Fig. 7, which resemble classical Lissajous curves (henceforth referred to as "Lissajous curves"), show the relationship between the model's pitch angle θ and the aerodynamic coefficients for the 12.5° slant-angle model subjected to a pitching motion with a motion amplitude of 0.878° . The aerodynamic coefficients measured under static conditions are also plotted (corresponding to a forcing frequency of 0 Hz). The lift coefficient C_Z and the pitching-moment coefficient C_{MY} are defined according to Eqs. (5) and (6), where A ($= 0.112 \text{ m}^2$) is the frontal projected area of the Ahmed model, and F_Z and M_Y are the aerodynamic lift force and the pitching moment, respectively.



(a). Lift coefficient

Figure 7. Lissajous curves for sinusoidal pitching motions with three different forcing frequencies ($\Phi = 12.5^\circ$, $\theta_{\max} = 0.878^\circ$).



(b). Pitching-moment coefficient

Figure 7 (cont.). Lissajous curves for sinusoidal pitching motions with three different forcing frequencies ($\Phi = 12.5^\circ$, $\theta_{\max} = 0.878^\circ$).

$$C_Z = \frac{F_Z}{\frac{1}{2} \rho U^2 A} \quad (5)$$

$$C_{MY} = \frac{M_Y}{\frac{1}{2} \rho U^2 AL} \quad (6)$$

It appears that the lift and pitching-moment coefficients plotted against the pitch angle form loops, indicating the presence of a phase shift, and moreover, the amplitudes of both coefficients tend to increase with an increase in forcing frequency; these are remarkably different from the static characteristics. Here, the Lissajous curves of the lift coefficient rotate clockwise (as indicated by the dotted arrow), whereas those of the pitching-moment coefficient rotate counterclockwise, meaning that the former is phase leading the model angle, and the latter is phase lagging.

The relationship between the model height z and the aerodynamic coefficients is shown in Fig. 8 for the 12.5° slant-angle model subjected to a heaving motion with an amplitude of 8 mm. In the same way as for the pitching motion, the lift and pitching-moment coefficients form loops due to the phase shift, and those amplitudes tend to increase with an increase in frequency. Furthermore, it should be noted that the slope of the C_Z Lissajous curve steepens with an increase in frequency, which is in contrast to the pitching results. The rotational directions of the Lissajous curves are counterclockwise for both coefficients, indicating a phase-lag property.