Unsteady Aerodynamical Forces by Interference of Two Bluff Bodies Moving Closely *

(On Unstable Phenomenon of Automobile Running
at High Speed)

By Manabu SANO **, Taro NAGAHISA ***
and Toshiki KOBAYASHI ****

It is a familiar phenomenon that a small car may be attracted toward a large one when the small one is passed by the large one. It is the purpose of this study to clarify this attraction phenomenon from an aerodynamical point of view. The unsteady aerodynamical forces generated by an interference of two bluff bodies moving closely are measured by the wind-tunnel-balance. And changes of the yawing moment, the lift and the drag are determined at different speeds, different spacings between the two bodies and different body scales. Moreover, equations of motion for the vehicle are numerically solved by using experimental results with the unsteady aerodynamical forces. The behavior of the vehicle in this unstable situation is discussed for different handling characteristics.

Key Words: Automobile, Aerodynamics, Bluff Body, Unsteady Aerodynamical Force.

1. Introduction

Recently, opportunities of high speed cruising have been increasing more and more as a result of the highway extension and the power-up in the performance of the car. Unsteady aerodynamical forces ⁽¹⁾ bring the car in high speed cruising into an unstable situation. These unsteady aerodynamical forces are classified into two kinds. One is generated when the velocity and the direction of the natural wind change under the effects of weather and topography, and the other when two cars interfere with each other, that is, passing or being passed ^{(2),(3)}. The former is called the aerodynamical force due to the lateral wind and many studies on it have been reported ^{(4),(5)}. On the other hand, only a few studies have been reported with regard to the unstable phenomenon when one running car is passed by another running car ⁽⁶⁾.

It is a familiar phenomenon that a small car may be attracted toward a large one when the small one is passed by the large one. It is the purpose of this study to clarify this attraction phenomenon from

an aerodynamical point of view. The unsteady aerodynamical forces due to the interference of two bluff bodies moving closely are measured by the wind-tunnel-balance. Concretely, changes in the yawing moment, the lift and the drag are determined at different speeds, different spacings between two bodies and different body scales. Moreover, equations of motion for the automobile are numerically solved by using experimental results with the unsteady aerodynamical forces. The behavior of the vehicle in this unstable situation is discussed for different handling characteristics.

2. Measurements of Unsteady Aerodynamical Forces

2.1 Experimental apparatus and procedure

Pneumatic wind tunnel balances ^{(7),(8)} are used in measurements of the yawing moment, the lift and the drag. There are three balances, and they are used as the drag balance, the first lift-balance and the second lift-balance, respectively. Output pressure is recorded by an XY recorder through semi conductor type pressure transducers and direct current amplifiers.

Table 1 Dimensions of models

Body	L x W x H m
Small	0.08 x 0.03 x 0.03
Middle	0.12 x 0.045 x 0.045
Large	0.16 x 0.06 x 0.06

* Received 6th May, 1982.

** Lecturer, Faculty of Engineering, Kanazawa University, 2-40-20, Kodatsuno, Kanazawa, 920.

*** Associate Professor, Kanazawa University.

**** Nippon Denso Co., Ltd., Nishio, Aichi, 445.

The following bodies are used in this experiment: a medium Japanese car is assumed as a passed body; and a bus, a micro bus and a medium car are assumed as passing bodies. These are modeled by cubic bodies of about one-fiftieth scale of prototypes, respectively. They are manufactured of acrylic resin. Dimensions of models are shown in Table 1. The passed small model can be revolved about an axis which runs through bearings mounted in centers of the upper and the lower faces. Piano wires are connected at edges of the model to suspend the model from the first and second lift-balances. The axis of the model is connected with the drag-balance by a support. A plate, which corresponds to a ground, consists of an acrylic plate. Flaps mounted below this ground plate are used for the boundary layer suction. A guide slit is cut along the centerline of the plate, so that the passing model can be moved straight by the transverse apparatus mounted below the ground plate. The experimental set-up is schematically shown in Fig.1, as viewed from the back-side of the ground plate. The ground plate must be set vertical when the yawing moment is measured, while it must be set horizontal and turned over when the lift is measured.

In the present experiments, the passed body is semi-fixed in the wind tunnel and the passing body is moved in parallel to it, simulating passing duration and the yawing moment, the lift and the drag are measured. A small model is used as the passed body, and large, middle and small models are used as passing bodies. Experimental conditions are as follows: lateral spacings between the two bodies ΔY are 10, 20 mm, wind velocities V (corresponding to running speeds) are

Fig.1 Experimental apparatus

Fig.2 Positional relation of two bodies

36.8, 27.8, 22.2, 16.7, 11.1 m/s, the difference in speeds between the two bodies is a constant as $\Delta V = 0.7$ mm/s. Another small passed model is manufactured for measurements of pressure distributions. Pressure distributions on the side and upper faces of the model are measured by pressure transducers.

Positional relation of the two bodies in the passing and duration is shown in Fig.2. Passing is made continuous by the transverse apparatus. At first, the passing body is moved from a start point where the front surface of the passing body is located 40 mm leeward to the rear surface of the passed body. The passing is completed when the rear surface of the passing model reaches a position of 80 mm windward to the frontal surface of the passed model.

As a preliminary experiment, the lift coefficient C_L and the drag coefficient C_D are measured for the three scale models as a whole. The results are shown in Fig.3. The lift and drag coefficients are almost fixed except in the range of low Reynolds numbers. Therefore, it is considered that the similarity is satisfied in this experimental range.

2.2 Experimental results

The relation between the yawing moment coefficient C_M and the nondimensionalized position of the passing model is shown in Fig.4 for the case that the passing model is large, and $V = 36.8$ m/s, $\Delta Y = 10$ mm. The moment of clockwise direction,

Fig.3 C_L and C_D for a single body Fig.4 Yawing moment C_M for passed model

by which the front of the passed body is attracted to the passing body, corresponds to the positive yawing moment.

Pressure distributions on the open and interfered side surfaces of the passed small model are shown in Fig.5. A side surface of the small model facing the large model is called the interfered side and the opposite surface the open side for the convenience of interpretation. In this figure, surface pressure on the open side of the passed body does not show a remarkable change. In the region $0 \leq X/L \leq 0.5$, the value of C_H increases since the surface pressure on the interfered side increases and it becomes higher than that on the open side as the large model approaches. And at the position $X/L=0.5$, where the passing body catches up with the passed body, the yawing moment coefficient shows a positive peak value. As the two bodies come parallel to each other, it shows negative values because the velocity of the flow between the two bodies increases and the surface pressure on the interfered side of the paralleled part decreases to a negative value. Meanwhile, the pressure on the unparallel part of the small model is so high that the rear part of the small model is attracted to the large one. As a result, the value of C_H decreases rapidly and it becomes negative. As the passing body moves forward and the paralleled part increases, the absolute value of C_H shows a maximum at $X/L=1.1$ since the zone of the negative pressure on the interfered surface increases. Hence, the rear part of the small body is attracted strongly to the large one. As the two bodies are nearly parallel, the value of C_H begins to increase since the frontal positive zone of the small body decreases. At $X/L=1.5$, pressure distributions on the interfered and open sides become similar, and the value of C_H becomes nearly zero. At $X/L=1.7$, the yawing moment coefficient C_H shows a positive peak again since the absolute value of the negative pressure on the interfered side at the frontal part of the small model increases continuously. Until $X/L=3.5$ after that, the value of C_H decreases because the absolute value of the negative pressure on the interfered side becomes smaller under the influence of both the frontal flow separation region and the positive pressure region of the

Fig.5 Pressure distributions on side surface of passed model

large scale model. Conversely, if the influence of the negative pressure on the open side becomes larger than that on the interfered side, the value of C_H becomes negative and decreases continuously. At $X/L=3.5$, where the passing completes, once the value of C_H increases since the absolute value of the negative pressure on the interfered side decreases. As the large model moves forward, the influence becomes gradually small. The pressure distribution becomes similar to that of a single body and the value of C_H asymptotes to zero.

Thus, it is concluded that the attraction phenomenon is most remarkable when the frontal surface of the large model comes to the position $X/L=1.1$, which is slightly forward to the center of the small model, and the absolute value of C_H shows a maximum. Then, an unstable condition is expected because the rear part of the small model is attracted strongly by the large one.

The influence of the lateral spacing between the two bodies on the yawing moment is shown in Fig.6. In the case of $\Delta Y=20\text{mm}$, the yawing moment change is qualitatively similar to that of $\Delta Y=10\text{mm}$. As a whole, the change of C_H becomes small, but the difference at the negative peak becomes remarkable. Although the figure is not shown in this paper, similar tendencies are recognized in the cases of the passing models being middle and small sizes. That is, the attraction phenomenon in the rear part of the passed small body is attenuated as the spacing becomes larger. However, the change of C_H becomes totally smaller as the passed body becomes smaller.

Fig.6 Influence of spacing on C_H

Fig.7 Lift coefficient C_L for passed model

The change of the lift coefficient C_L in the passed small model is shown in Fig.7 for the case that the passing model is the large one, $V = 36.8 \text{ m/s}$, and the spacing $\Delta Y = 10 \text{ mm}$. The change of the pressure distribution on the upper surface of the passed small model is shown in Fig.8. The absolute value of the negative pressure on the upper surface in the frontal part of the small model is greater than that in the rear part so that it is considered that the frontal part of the passed model is more liable to lift up than the rear part. As the large model approaches, the value of C_L becomes also large because the absolute value of the negative pressure on the upper surface of the small model becomes large. The absolute value of the negative pressure as well as the value of C_L becomes maximum when the large model is located at a position $X/L = 1.1$, which is a little forward to the center of the small model. After that, the value of C_L decreases as the absolute value of the negative pressure decreases. It becomes almost constant after the completion of passing and asymptotes to the value of a single body. When the two bodies are parallel, the value of C_L becomes relatively large. If these results are applied to the actual behavior of the car, it is expected that the road holding of the vehicle becomes worse and the running condition of the car turns unstable. The influence of the spacing is shown in Fig.9. For $\Delta Y = 20 \text{ mm}$, the value of C_L shows a maximum at the earlier position $X/L = 1.0$ than for $\Delta Y = 10 \text{ mm}$. Generally, the change of C_L becomes small for $\Delta Y = 20 \text{ mm}$.

The change of the drag coefficient C_D

Fig.8 Pressure distributions on upper surface of passed model

Fig.9 Influence of spacing on C_L

for the passed small model is shown in Fig.10 for the case that the passing model is large, $V = 36.8 \text{ m/s}$, and $\Delta Y = 10 \text{ mm}$. At first, the value of C_D becomes rapidly large as the large model approaches. When the large one reaches the rear surface of the small one, the value of C_D shows a maximum. The reason that the flow separation around the small model is promoted by a pressure rise on the rear surface of the small one as the large one approaches. If the two bodies begin to be parallel, the value of C_D decreases since the pressure drops due to the contraction of the wake of the small model. When the large model passes the frontal surface of the small one, the velocity around the model decreases. Then, the value of C_D decreases further and may asymptote to that of a single body.

Thus, it is clear that the value of C_D becomes considerably large while the two bodies are parallel. Although there is no figure, the value of C_D becomes relatively small as the passing model becomes small. The influence of the spacing on C_D is shown in Fig.11. The value of C_D increases slightly as the spacing becomes large.

3. Behavior of Vehicle under Unsteady Aerodynamical Forces

3.1 Equations of motion for behavior of vehicle

In chapter 2, the yawing moment, the lift and the drag are measured as the unsteady aerodynamical forces generated by the interference of two rectangular parallelepipeds moving closely and the attraction phenomenon is explained qualitatively by taking pressure distributions into con-

Fig.10 Drag coefficient C_D for passed model

Fig.11 Influence of spacing on C_D

sideration. In this chapter, assuming that the aerodynamical similarity is satisfied, the behavior of the vehicle is numerically analysed by taking the handling characteristics into consideration when these unsteady aerodynamical forces acts on the prototype of the vehicle. Substituting the values of the yawing moment and the lateral force, which are obtained in the previous chapter, into equations of motion for the vehicle, the lateral displacement and the yawing angle can be obtained. It is considered that the measured results for unsteady aerodynamical forces are applicable to the numerical analysis for the prototype of the vehicle, since it is clear from experiments on a single body that they are not influenced by the Reynolds number.

A running vehicle can move freely in the horizontal plane by the driver's handling. However, it is very hard to project the dynamical performance precisely when a disturbance works on the vehicle. In this chapter, the motion of the vehicle is simplified under the following assumptions. (a) Handling wheel of the vehicle is fixed. (b) The motion of the vehicle is restricted to the horizontal plane. Only the lateral shift and the yawing are considered. (c) Both passing and passed vehicles are assumed to be running straight at constant speeds. (d) The vehicles have wheels of the same performances. (e) Difference in speeds ΔV is either 10km/h, or 20km/h.

At first, equations of motion are introduced by using coordinates shown in Fig.12. Nomenclature used for the present analysis are as follows:

- C_f : cornering force exerted on frontal wheel
- C_M : yawing moment coefficient = $M/(1/2)\rho S V^2$
- C_r : cornering force exerted on rear wheel
- C_Y : lateral force coefficient = $Y/(1/2)\rho S V^2$
- I : yaw inertial moment of vehicle
- K_f : cornering power of frontal wheel

Fig.12 Coordinates and nomenclature

- l : wheel base
- l_f : distance between center of gravity and axis of frontal wheel
- l_n : distance between NSP and center of gravity
- l_r : distance between center of gravity and axis of rear wheel
- M : yawing moment
- m : mass of vehicle
- S : frontal area of vehicle
- SM: static margin = l_n/l
 $= -(l_f K_f - l_r K_r) / (l(K_f + K_r))$
- t : time
- V : running speed
- Y : lateral force
- y : lateral displacement in center of gravity from x-axis
- β_f : slip angle of front tire
- β_r : slip angle of rear tire
- γ : angle between x-axis and lateral displacement
- δ : steer angle
- ΔL : passing zone
- Δt : necessary time for passing
- ΔV : difference of speeds
- θ : yawing angle
- ρ : air density.

When the vehicle moves on a straight road, $|\gamma| \ll 1$, $|\theta| \ll 1$, $|\delta| \ll 1$ are necessary conditions. But in this study, the running situation is slightly different from a simple straight running since the yawing angle θ can be varied widely. Considering that there are no differences between performances of the left and the right wheels and directions of C_f and C_r correspond to the y-axis (as initial condition), equations of motion are given by Eqs. (1), (2) ⁽⁹⁾

$$m d^2 y / dt^2 = 2C_f + 2C_r \quad (1)$$

$$I d^2 \theta / dt^2 = 2l_f C_f - 2l_r C_r \quad (2)$$

Referring to Fig.12, C_f and C_r are written in terms of lateral slip angles β_f and β_r as follows:

$$C_f = -K_f \beta_f \\ = K_f \left(\delta + \theta - \frac{1}{V} \frac{dy}{dt} - \frac{l_f}{V} \frac{d\theta}{dt} \right) \quad (3)$$

$$C_r = -K_r \beta_r \\ = K_r \left(\theta - \frac{1}{V} \frac{dy}{dt} + \frac{l_r}{V} \frac{d\theta}{dt} \right) \quad (4)$$

According to the previous assumptions, $\delta = 0$, $K = K_f = K_r$. Substituting Eqs. (3), (4) into Eqs. (1), (2), and arranging for the lateral force and the yawing moment and nondimensionalizing these equations for simplicity, final equations of motion are given by Eqs. (5), (6), where the positive direction of the lateral force is taken opposite to the passing vehicle. The positive direction of the yawing moment is counterclockwise, which is different from that in the experiment. The following nondimensional variables are used. $y' = y/l$, $t' = t/\Delta t = t\Delta V/\Delta L$, $\theta' = K\Delta t\theta/mV$, $K' = K\Delta t/mV$, $l_f' = l_f/l$, $l_r' = l_r/l$, $V' = V\Delta t/l$, $I' = I/m l^2$, $Y' = \Delta t Y/mV = \Delta t \rho S V C_Y / 2m$, $N' = \Delta t M/mV l = \Delta t \rho S V C_M / 2m$.

$$\frac{d^2 y'}{dt'^2} + 4K' \frac{dy'}{dt'} + 2(l'_f - l'_r) \frac{d\theta'}{dt'} - 4V'\theta' = V'Y' \dots\dots\dots (5)$$

$$2K'(l'_f - l'_r) \frac{dy'}{dt'} + \frac{I'}{K'} \frac{d^2 \theta'}{dt'^2} + 2(l_f'^2 + l_r'^2) \times \frac{d\theta'}{dt'} - 2V'(l'_f - l'_r)\theta' = V'M' \dots\dots\dots (6)$$

3.2 Calculating method

Calculations are restricted to the case where the speed $V = 133 \text{ km/h}$ (corresponding to 36.8 m/s in wind-tunnel tests), the spacing $\Delta Y = 0.5 \text{ m}$ (10mm in wind-tunnel tests). Calculations are performed under the following three conditions: (1) Large, middle and small vehicles are used as passing ones. (2) Handlings of the vehicle are understeer (US), neutral steer (NS) and oversteer (OS). Values of the static margin specifying the handling characteristics are 0.03, 0, -0.03, respectively. (3) Differences of speeds are $\Delta V = 10, 20 \text{ km/h}$.

The calculating procedure is shown in Fig.13. Measured data for Y' and M' are approximated as a continuous function by the Fourier analysis. The Runge-Kutta method is used as the numerical method for solving Eqs. (5), (6).

3.3 Calculating results and considerations

Changes in the lateral displacement y' and the yaw angle θ' for various handling characteristics are shown in Figs.14 and 15 for the case that the passing vehicle is a large one, and $\Delta V = 10 \text{ km/h}$. Figure 14 shows the change of y' in the range of small t' . In the figure, y' decreases as the large vehicle approaches, and shows a minimum at the position $t' \approx 0.08$ ($X/L \approx 0.4$) just before catching up with the small one. This minimum value of y' is attributed to the effect of the negative lateral force. At this position, the vehicle is attracted by

the passing one most strongly. After that, y' turns to increase since the effect of the positive lateral force increases. If the two vehicles begin to be parallel, y'

Fig.14 Lateral displacement with handling characteristics (small range of t')

Fig.15 Lateral displacement and yaw angle with handling characteristics

Fig.13 Calculating procedure

increases further. After the completion of passing, the value of y' increases monotonously since the motion of the vehicle becomes steady.

Next, the change of θ is shown in Fig.15. The value of θ decreases gradually since the yawing moment decreases as the large vehicle approaches. It shows a minimum at $t' \approx 0.14$. After that, the value of θ increases rapidly since the yawing moment increases. And it shows a maximum at $t' \approx 0.34$. As the yawing moment decreases and becomes negative, θ begins to decrease and shows a minimum at $t' \approx 0.52$. Following it, θ increases smoothly and shows a maximum at $t' \approx 1.0$. At this point, the rear part of the small vehicle is attracted most strongly by the large one. After that, θ decreases and settles to a constant value since $t' \approx 1.3$ (in the case of understeer).

Even if the handling is neutral steer, changes in y' and θ are little different from those of the understeer. Generally, changes in y' and θ become large. When the handling is oversteer, changes in y' and θ become larger than those of the neutral steer. In the value of y' , there are both a maximum and a minimum in the small range of t' values. In the value of θ , there appear as maximum values.

It is then concluded that y' shows a minimum just before the large vehicle catches up with the small one irrespective of handling characteristics. The time-lag to the steady state is $t' \approx 1.3$ in the case of understeer, $t' \approx 1.6$ in the neutral steer and $t' \approx 2.6$ in the oversteer. θ shows a minimum when the large vehicle begins to parallel the small one and the time-lag to the steady state shows also a similar tendency as that of y' qualitatively. Hence, if the vehicles meet in passing, the vehicle of the understeer does not show such a sharp response as the vehicle of the other handling characteristics, and changes in y' and θ are small comparatively. It is clear from changes in y' and θ that vehicles of the neutral steer and the oversteer show sharp responses in passing. Therefore, the vehicle of the smaller static margin (oversteer) is liable to be affected by passing. And the time-lag to the steady state becomes longer since its effect persists longer.

Changes in y' and θ between different sizes of vehicles are shown in Figs.16 and 17 for the case that the handling is understeer and $\Delta V = 10 \text{ km/h}$. Changes in y' and θ show similar qualitative tendencies independently of sizes of passing vehicles. The larger the vehicle size is, the longer the time-lag to the minimum in y' becomes. In both y' and θ , the time-lag to the steady state increases as the size of the vehicle becomes large. Therefore, it is clear that the effect on the passed vehicle becomes large and it persists longer as the size of the passing one becomes larger. Although there is no figure, similar qualitative results can be also obtained for cases of different handling characteristics and differences of

speeds.

Next, behaviors of the vehicle for various differences of speeds are discussed. Discussions on this calculation are made only from a qualitative point of

Fig.16 Lateral displacement with passing vehicle sizes (small range of t')

Fig.17 Lateral displacement and yaw angle with passing vehicle sizes

view. It is considered that there is a slight difference from the actual attraction phenomenon because the value of ΔV in experiments is very small. Changes in y' and θ for various ΔV are shown in Figs.18 and 19 for the case that the handling is understeer and the passing vehicle is the large one. Changes in y' and θ for $\Delta V = 20\text{km/h}$ become smaller than those for $\Delta V =$

Fig.18 Lateral displacement with differences of speeds (small range of t')

Fig.19 Lateral displacement and yaw angle with differences of speeds

10km/h. And the time-lag to the steady state for $\Delta V = 20\text{km/h}$ becomes considerably longer than that for $\Delta V = 10\text{km/h}$. Although there are no figures, these qualitative tendencies are similarly shown for various handling characteristics and sizes of vehicles.

4. Conclusions

Results in this study are summarized as follows :

- (1) The attraction phenomenon occurs most remarkably at the position where the passing model is paralleled to the proximity of the center of the passed small body. At this time, the rear part of the passed small model is attracted most strongly by the passing one and the passed one falls into a very unstable situation.
- (2) When the passing model is paralleled to the passed one, C_L and C_D become considerably large and the road holding of the vehicle becomes poor.
- (3) If the spacing between the two bodies is narrower and the passing model is larger, the attraction phenomenon occurs more remarkably and C_D and C_L are also strongly affected by it.
- (4) Even if running vehicles meet in two different passings with same conditions, their behaviors are different depending on their handling characteristics. It is clear that the vehicle with a smaller static margin (oversteer) responds more sharply to the external disturbances.
- (5) The larger the passing vehicle size is, the larger the effect on the passed one is and the longer it persists.
- (6) It is necessary to consider both the displacement in the center of gravity of the passed vehicle and the revolution about the center of gravity for analyzing the attraction phenomena.

Finally, authors wish to express their thanks to M.Takano, T.Hayashi, M.Segawa, S.Hounoki and H.Hayashi for their helpful assistances in experiments.

References

- (1) Muto, S., Jidoshiya-Kenkyu (JARI Tech. Rep.), (in Japanese), Vol.1, No.1, (1979-1), 8.
- (2) Beauvais, F.N., SAE Paper, No.700037, (1970).
- (3) Heffele, R.K., SAE Paper, No.730235, (1973).
- (4) Iguchi, M. and Imaizumi, H., Prepr. of Jpn. Soc. Mech. Eng., (in Japanese), No.182, (1967-10), 101.
- (5) Brown, G.J., SAE Paper, No.730234, (1973).
- (6) Romberg, G.F., SAE Paper, No.710213, (1971).
- (7) Tsukahara, T., Science of Machine, (in Japanese), Vol.10, No.7, (1958-7), 849.
- (8) Tsukahara, T., Science of Machine, (in Japanese), Vol.10, No.8, (1958-8), 991.
- (9) Wong, J.Y., Theory of Ground Vehicle, (1978), 210, John Wiley & Sons.