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A Prediction Model for Lateral Force Coefficients of a Train Car in Turbulent Flows

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Abstract

In this study, a new method was discussed to predict lateral force coefficients of train car in turbulent flow. Firstly, wind tunnel tests were carried out to measure wind speeds, turbulence intensities, aerodynamic coefficients of train car and wind pressures around car-body in uniform flow and in turbulent flow. These results clarify the aerodynamic characteristics of train car in both two kinds of flows and also show their differences. In addition, a prediction model was built to predict lateral force coefficients in turbulent flow from the results obtained in uniform flow wind tunnel test. In the modeling, four factors which include the vertical profiles of wind speeds, the energies of winds, the instantaneous wind direction and the wind pressures around car-body are considered. These four factors are considered as the main reason that causes the distinction of lateral force coefficients in uniform flow and in turbulent flow. Finally, compared with the measured lateral force coefficient in turbulent flow from wind tunnel tests, the predicted values obtained from this model shows good agreement with the measured ones. The determination coefficient between them is 0.993 and the root mean squared error is 0.044.

Introduction

Aerodynamic force acting on train cars caused by strong winds is one of main causes of derailment of train cars. Therefore, evaluation of the aerodynamic force is important issue for safety of train operation. Aerodynamic forces which affect overturning of train cars mainly are lateral force, lift force and rolling moment around car-body. Whole aerodynamic force is calculated as rolling moment around wheel/rail contact point on leeward from these three forces (e.g., EN14067-6 [1] which is the European standard to evaluate safety of railway against cross wind and Hibino et al. [2]). Aerodynamic forces are calculated from aerodynamic coefficients which are measured by wind tunnel tests, the air density, the wind speed and the side area of car-body. Aerodynamic coefficients are determined by many factors, such as air flow conditions, shapes of train and the type of structure under tracks and so on. Regarding air flow conditions, Suzuki et al. [3] clarified that aerodynamic coefficients in turbulent flow are different largely from those in turbulent flow. In addition, air flow condition changes from hour to hour according to running speed of train so that natural winds have turbulent flow and winds induced by running train have uniform flow. For example, when a train car is stopping, the relative wind acting on the car-body is just natural wind and the relative wind has turbulent flow. On the other hand, when a train car is running at high speed, the relative wind almost depends on the wind induced by the running train and the relative wind speed has almost uniform flow. Misu & Ishihara [4] proposed a method to predict aerodynamic coefficients when train is running from those in uniform flow and in turbulent flow. Their method make it possible to evaluate aerodynamic force close to actual condition. However, both aerodynamic coefficient in uniform flow and that in turbulent flow are needed in their method.

If prediction of aerodynamic coefficients when train is running can be possible from only aerodynamic coefficient in uniform flow, wind resistant performance of train car can be evaluated reasonably. In particular, the lateral force is the largest element of the whole aerodynamic force and its contribution ratio is about 80% of the whole aerodynamic force in the case of Japanese commuter type train. Therefore, in this study, a new method was discussed to predict lateral force coefficients of train car in turbulent flow. Firstly, wind tunnel tests were conducted and wind speeds, turbulent intensities, aerodynamic forces and wind pressures were measured. Then, the differences of the results between in uniform flow and in turbulent flow were also found and clarified. At last, a prediction model to predict the lateral force coefficients in turbulent flow from those results in uniform flow was built.

Wind tunnel tests

Wind tunnel tests were carried out referring Misu & Ishihara [4]. Additionally, the air flows on structures and wind pressures around car-body were also measured in this study.

The width of wind tunnel used in this study is 1.5 meters, the height is 1.8 meters and the length is 11 meters. The deviation of mean wind speed is $\pm 1\%$, and the turbulence intensity is less than 0.5%. Both the uniform flow and the turbulent flow (Power low $\alpha = 1/7$) are considered, and they are measured by a hot-wire anemometer (X-type prove, Dantec). The aerodynamic forces and the wind pressures are measured by a six components balance (Nissho-Electric) which is set under the turn table and by multi-channel pressure sensors (Melon Technos) respectively. The measured parameters are evaluated as mean values and those evaluation time is about one minute.

Figure 1 shows the outline of train car model. The car type is commuter type. The reduced scale of the model is 1/40. In figure 1, the pressure measurement point positions on each cross section are shown. There are two cars in the model, the leading car and the rear car. The measurement equipment is mounted only on the leading car. The train cars are fixed to three kinds of structures that are flat, bridge (1 meter girder high) and embankment (5 meters high). The wind attack angles are set from 10 degree to 170 degree with an interval of 20 degree. Figure 2 shows one case where the infrastructure is bridge and the wind attack angle is 90 degree.

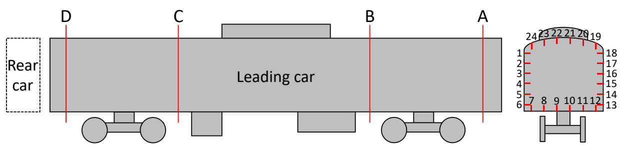

Figure 1. The outline of train car model. (Wind pressures of cross sections A, B, C and D are measured, and measurement points at each cross section arrange from No.1 to No.24.)

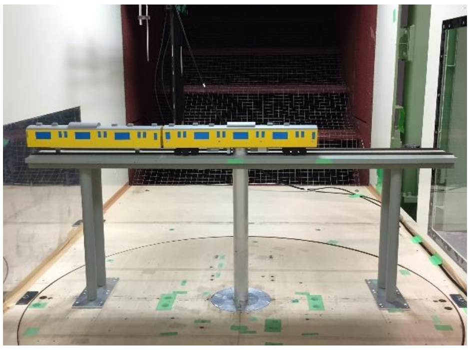

Figure 2. An example of the outlook of measurement. (The structure is bridge, its girder height is 1.0m, and the wind attack angle is 90 degrees.)

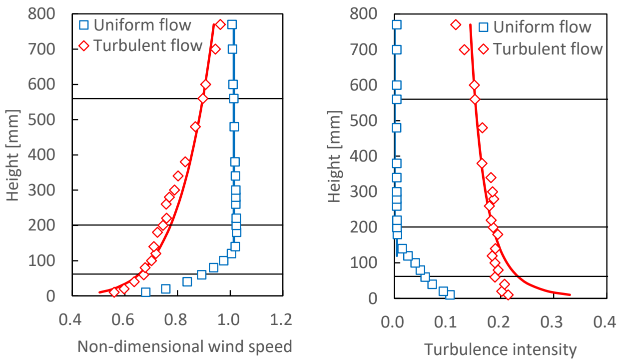

Figure 3. The vertical profiles of mean wind speeds and turbulence intensities. (The black line is the height of car-body center on bridge (560mm).)

Figure 3 describes the vertical profiles of both mean wind speeds and turbulence intensities on the turn table center without structures and train cars. Mean wind speeds are nondimensionalized by dividing the mean wind speed at the place where the pito tube is installed (3.35m ahead from the turn table center at the wind direction and 770mm high from the base). The black straight lines identify the height of car-body center on bridge (560mm high). Wind speeds in uniform flow are almost the same above 200mm high while the turbulence intensities are almost zero. In turbulent flow, wind speeds and turbulence intensities are following the line of power low $\alpha = 1/7$.

The lateral force coefficients $C_S(\psi)$ are calculated by equation (1), where F_S is the lateral force, ψ is the wind attack angle, ρ is the air density, u is the wind speed at the height of car-body center, A is the side area of car-body.

$$C_S(\psi) = \frac{F_S(\psi)}{1/2\rho u^2 A} \tag{1}$$

Figure 4 and figure 5 describe the lateral force coefficients of train car in uniform flow and in turbulent flow respectively. The measurements are carried out on three different structures which are flat, bridge and embankment. The lateral force coefficients in turbulent flow are slightly smaller than those in uniform flow. The lateral force coefficients of train car on embankment in uniform flow have peaks at the wind attack angle of 50 degree and of 130 degree, while this phenomenon does not happen in turbulent flow. The values of the lateral force coefficients on bridge have a little difference compared with those in Reference [4]. The reason is that the wind speeds u used in equation (1) are different. In reference [4], wind speeds u are calculated by the ratio of wind speeds at the height of 770mm on the turn table center to those at the height of car-body center on the turn table center. However, in this study, wind speeds u are the value that wind speeds at the place of pito tube are divided by those at the height of car-body center on the turn table center.

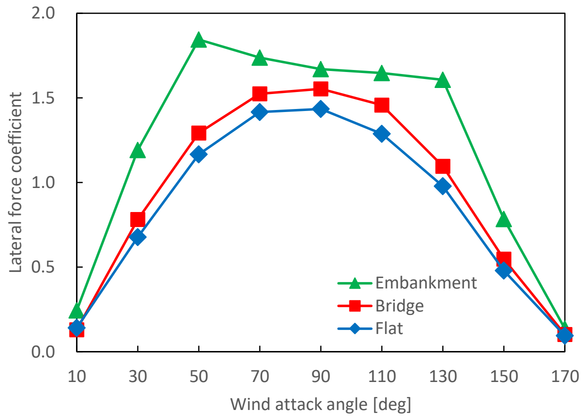

Figure 4. The lateral force coefficients in uniform flow. (The structure under trains contains flat, bridge and embankment.)

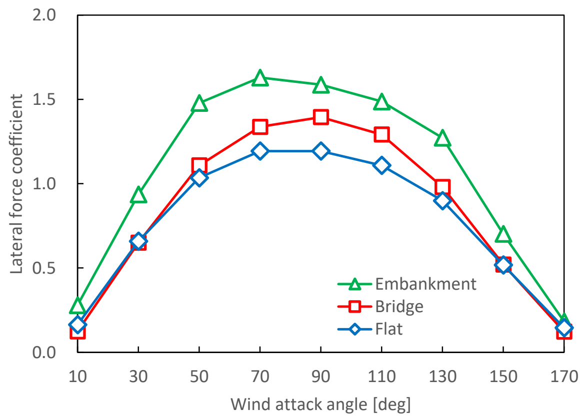

Figure 5. The lateral force coefficients in the turbulent flow. (The structure under trains contains flat, bridge and embankment.)

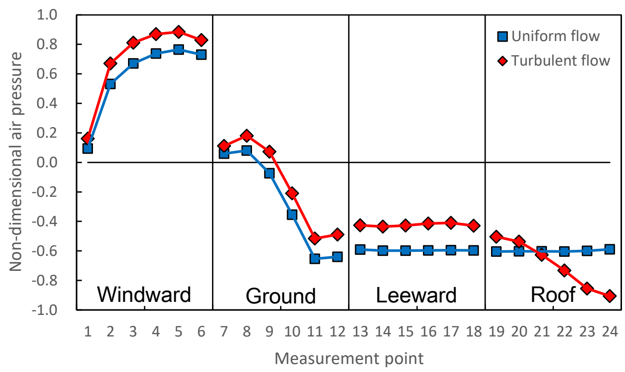

Figure 6. An example of the distribution of wind pressures around car-body. (The structure is bridge. The wind attack angle is 90 degree. The cross section is section B in figure 1. The measurement points correspond to those in figure 1. The wind pressures are nondimensionalized by the dynamic pressure at the height of car-body center.)

Wind pressures are measured at four cross sections and every cross section has 24 measurement points (six measurement points in one side). Figure 6 shows an example of the distribution of wind pressures measured from section B in figure 1. The structure is bridge, and the wind attack angle is 90 degree. The measurement point distribution showed in figure 1. Wind pressures are nondimensionalized by dividing the dynamic pressure at the height of car-body center. Wind pressures on the windward side in turbulent flow are larger than those in uniform flow. On the other hand, absolute values of wind pressures on the leeward side in turbulent flow are smaller than those in uniform flow. The wind pressures on the ground side and on the roof side are not discussed here so that they do not affect lateral forces.

Prediction model

The model to predict lateral force coefficients in turbulent flow $C_{S,t}(\psi)$ from those in uniform flow $C_{S,s}(\psi)$ is constructed considering the differences of aerodynamic characteristics of train car in both flows. There are four factors in this model and it can be written as equation (2).

$$C_{S,t}(\psi) = f_z f_I f_\psi f_p C_{S,s}(\psi) \tag{2}$$

The first term f_z represents the difference of the vertical profiles of wind speeds. Figure 7 (a) shows an image of vertical profiles of wind speeds nondimensionalized by wind speeds at the height of car-body center. Liu and Ishihara [5] proposed a method to predict aerodynamic forces that exert on structures considering vertical profile of wind speeds. Based on their proposal, the lateral force in turbulent flow $F_{S,t}$ is calculated from equation (3), where u_s and u_t are wind speeds in uniform flow and in turbulent flow respectively.

$$F_{S,t} =$$

$$\frac{1}{2} f_z f_I f_\psi f_p C_{S,s} \rho u_s^2 l (h_u - h_d) = \frac{1}{2} f_I f_\psi f_p C_{S,s} \rho l \int_{h_d}^{h_u} u_t^2(z) dz \tag{3}$$

From equation (3), the factor f_z is derived as equation (4).

$$f_z = \frac{\int_{h_d}^{h_u} u_t^2(z) dz}{u_s^2 (h_u - h_d)} \tag{4}$$

The second term is the factor f_I which shows the difference of wind energies. In uniform flow, instantaneous wind speed is almost equal to mean wind speed and its turbulence can be neglected. While in turbulent flow, instantaneous wind speed is not the same as mean wind speed. Mean values of the square of wind speeds in uniform flow and in turbulent flow are described as equation (5) and equation (6) respectively. Where $\bar{u}$ is the mean wind speed, and u', v' w' mean the fluctuations of instantaneous wind speed in longitudinal direction, lateral direction and vertical direction respectively.

$$\overline{u_s^2} = \bar{u}^2 \tag{5}$$

$$\overline{u_t^2} = \bar{u}^2 + \overline{u'^2} + \overline{v'^2} + \overline{w'^2} \tag{6}$$

The term f_I can be written as equation (7).

$$f_I = \frac{\overline{u_t^2}}{\overline{u_s^2}} = 1 + \frac{\overline{u'^2}}{\bar{u}^2} + \frac{\overline{v'^2}}{\bar{u}^2} + \frac{\overline{w'^2}}{\bar{u}^2} \tag{7}$$

In equation (7), $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{w'^2}$ are equal to their variances σ_u^2, σ_v^2 and σ_w^2, so that $\overline{u'}$, $\overline{v'}$ and $\overline{w'}$ are equal to zero. Therefore, equation (7) is rewritten as equation (8), where I_u, I_v and I_w are the turbulence intensities in longitudinal direction, lateral direction and vertical direction respectively.

$$f_I = 1 + I_u^2 + I_v^2 + I_w^2 \tag{8}$$

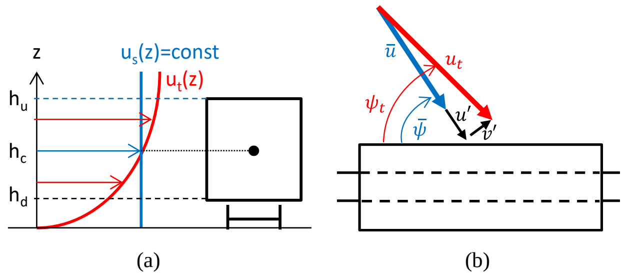

Figure 7. (a) An images of vertical profiles of wind speeds nondimensionalized by those at the height of car-body center, (b) An image of wind speed and wind direction that exerts on the side area of car-body.

The third one f_ψ indicates the distinction of instantaneous wind direction. Izawa, Kikuchi and Suzuki [6] mentioned a difference between instantaneous wind direction and mean wind direction in turbulent flow as a factor of differences of lateral force coefficient between in uniform flow and in turbulent flow. Figure 7 (b) shows an image of instantaneous wind speed and instantaneous wind direction exerting on the side area of car-body. In the figure, the mean wind speed is $\bar{u}$ and the mean wind attack angle is $\bar{\psi}$. The fluctuations of instantaneous wind speed in longitudinal direction is u' and that in lateral direction is v'. The instantaneous wind attack angle ψ_t is written as equation (9).

$$\psi_t = \bar{\psi} + \arctan\left(\frac{v'}{\bar{u} + u'}\right) \tag{9}$$

It is assumed that u' and v' have normal distribution, so their mean values are zero and standard deviations are σ_u and σ_v respectively (Hereinafter, $N(0, \sigma_u)$ and $N(0, \sigma_v)$). The factor f_ψ is calculated from the expectation value of lateral force coefficient corresponding with the instantaneous wind attack angles $E[C_{S,s}(\psi_t)]$. $E[C_{S,s}(\psi_t)]$ which can be written as equation (10).

$$E[C_{S,s}(\psi_t)] = \int_{-\infty}^{\infty} Prob[v' = j; N(0, \sigma_v)]$$

$$\int_{-\infty}^{\infty} Prob[u' = i; N(0, \sigma_u)] \cdot C_{S,s}\left\{\bar{\psi} + \arctan\left(\frac{j}{\bar{u} + i}\right)\right\} di dj \tag{10}$$

The derivation of f_ψ is shown as equation (11).

$$f_\psi = \frac{E[C_{S,s}(\psi_t)]}{C_{S,s}(\bar{\psi})} \tag{11}$$

The fourth parameter f_p means the difference of wind pressures around car-body. Lateral force acting on car-body is the summation of wind pressures on the windward side and on leeward side. Therefore, the lateral force coefficients $C_{S,s}(\psi)$ are written by those of windward side $C_{S,s,w}(\psi)$ and of leeward side $C_{S,s,l}(\psi)$ as equation (12).

$$C_{S,s}(\psi) = C_{S,s,w}(\psi) - C_{S,s,l}(\psi) \tag{12}$$

There are a great number of studies on the distribution of wind pressure exerting on square prism (e.g., Lee [7]). The results of measurements of wind pressures in this study shows the same tendency of those studies. Based on these results, the ratio $C_{S,s,w}(90){:}C_{S,s,l}(90)$ is set as 0.4:0.6. The characteristic of $C_{S,s,w}(\psi)$ regarding to wind attack angle is set as equation (13) and $C_{S,s,l}(\psi)$ is written as equation (14).

$$C_{S,s,w}(\psi) = 0.4 \sin\psi \, C_{S,s}(\psi) \tag{13}$$

$$C_{S,s,l}(\psi) = -(1 - 0.4 \sin\psi) C_{S,s}(\psi) \tag{14}$$

The relationship of lateral force coefficients of the windward side in uniform flow and in turbulent flow can be showed as equation (15) considering the factors f_z, f_I and f_ψ.

$$C_{S,t,w}(\psi) = f_z f_I f_\psi C_{S,s,w}(\psi) \tag{15}$$

The relationship of lateral force coefficients of the leeward side in uniform flow and in turbulent flow is defined as the function of turbulence intensity in the longitudinal direction and can be shown as equation (16), where I_u is based on the measurement results.

$$C_{S,t,l}(\psi) = (1 - 1.5 I_u) f_z f_I f_\psi C_{S,s,l}(\psi) \tag{16}$$

The lateral force coefficient $C_{S,t}(\psi)$ is described as equation (17).

$$C_{S,t}(\psi) = C_{S,t,w}(\psi) - C_{S,t,l}(\psi) \tag{17}$$

Substituting equation (13), (14), (15) and (16) into equation (17), rewritten as equation (18).

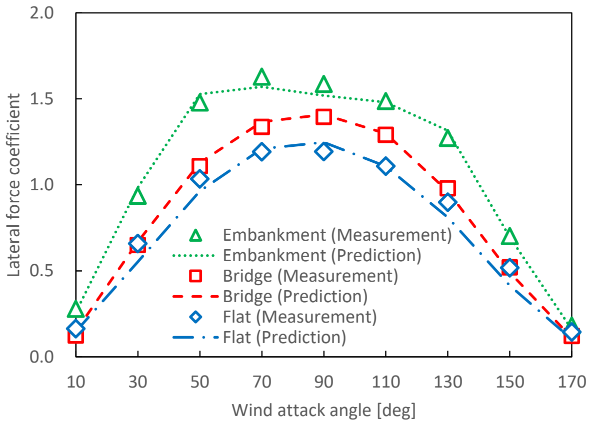

Figure 8. The measured and the predicted lateral force coefficients. The symbols are the measured values and the lines are the predicted values.

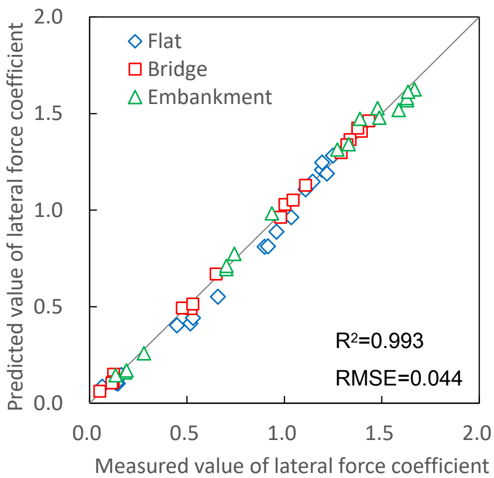

Figure 9. Relationship between the measured lateral force coefficients and the predicted ones. The straight line is the line of $y = x$.

$$C_{S,t}(\psi) = \{0.4\sin\psi + (1 - 0.4\sin\psi)(1 - 1.5I_u)\}f_z f_I f_\psi C_{S,s}(\psi) \quad (18)$$

The factor f_p is calculated as equation (19) from equation (2) and equation (18).

$$f_p = 0.4\sin\psi + (1 - 0.4\sin\psi)(1 - 1.5I_u) \quad (19)$$

Results of the prediction of lateral force coefficients

The predictions of lateral force coefficients in turbulent flow can be carried out by using the results of uniform flow wind tunnel tests and the constructed model. At the same time, it can also consider different kinds of structures under tracks and every wind attack angles. Parameters inputted to the model are different for each case. As an example, the values of factors inputted to the model are $f_z = 1.0$, $f_I = 1.037$, $f_\psi = 0.990$ and $f_p = 0.883$ when the structure under tracks is bridge and the wind attack angle is 90 degree. The values of f_I, f_ψ and f_p are calculated from the results of measurements of the air flow at the height of car-body center.

Figure 8 shows the measured and the predicted lateral force coefficients respectively. The symbols are the measured values and the lines are the predicted values. From this figure, the predicted values show good agreement with the measured ones for different structures under tracks and every wind attack angle.

The prediction error is evaluated comparing the predicted values with the measured ones. Figure 9 shows the relationship between the measured lateral force coefficients and the predicted ones. The straight line is the line of $y = x$. The symbols are on near the line of $y = x$. The determination coefficient R^2 is 0.993, and the root mean squared error is 0.044. From these results, it means that the constructed model is suitable. Moreover, the prediction error should be considered when the overturning resistances of train car are evaluated. In next step, critical wind speed of overturning will be evaluated using these results.

Conclusions

In this study, wind tunnel tests were carried out and a prediction model was constructed to predict lateral force coefficients of train car in turbulent flow from those results in uniform flow. The conclusions of this study are as follows.

1. Wind tunnel tests were conducted to measure the wind speeds, the turbulence intensities, the aerodynamic coefficients and the wind pressures around car-body. These results clarified the aerodynamic characteristics of train car and also showed the differences between in uniform flow and in turbulent flow.
2. In the modeling, four factors including vertical profile of wind speed, wind energy, instantaneous wind direction and wind pressure around car-body are considered. The constructed model make it possible to predict lateral force coefficients in turbulent flow from the results obtained in uniform flow.
3. The lateral force coefficients predicted by this model show good agreement with those measured in wind tunnel tests for different kinds of structures and every wind attack angle. The determination coefficient between them is 0.993 and the root mean squared error is 0.044.

Acknowledgments

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