Flow Control in High-Speed Train Applications

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Abstract. The possibility to apply passive flow control devices for the design of high-speed trains has been assessed. High-speed trains are sensitive to cross-wind as the resulting turn over moment increases with the cruising speed at a given wind speed. The study shows that there is a potential to decrease the resulting roll moment at the leeward wheel with the aid of passive flow control devices. Further studies are necessary to optimise and reduce the geometry of the flow control devices.

Key words: cross-wind stability, flow control, aerodynamic coefficients, high-speed train

1. Introduction

Various cross-wind related accidents of trains have been reported in recent years (see Figure 1). The risk of accidents is expected to increase in the future as extreme storms have been recorded more frequently in North America and are forecasted for Europe. In Europe, this topic has gained special attention since the mid nineties. National guidelines for the assessment of the crosswind limit are available today in England, Germany and France. Recent studies in Italy, Belgium and Spain have been undertaken as well and are becoming subject of national regulations.

Figure 1 Cross-wind related accident in Austria, 2002

In order to achieve maximum performance and cost-efficiency, it is necessary to construct ever lighter trains. As the weight decreases, the impact of the aerodynamic forces increases, particularly for high-speed trains which are exposed to strong cross-wind gusts.

This paper deals with the possibility to increase the cross-wind stability of a train by means of turbulence control. Wind tunnel experiments have been performed to evaluate the impact of different design variants.

2. Coordinate System and Aerodynamic Coefficients

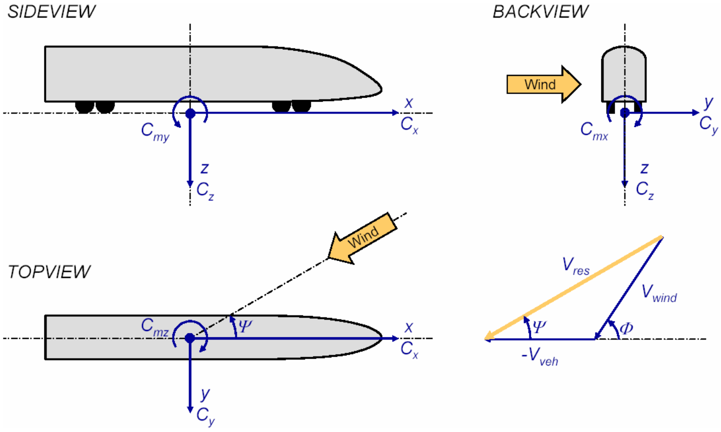

Figure 2 Definition of coordinate system and aerodynamic coefficients

Figure 2 provides an overview of the employed coordinate system.
The coefficients for the aerodynamic forces are calculated as follows:

$$c_i = \frac{F_i}{0.5 \cdot \rho \cdot U^2 \cdot A} \qquad \Big|_{i=x,y,z}$$

where F_i is the force, ρ is the air density, U denotes the approaching air speed and A represents a fixed reference area of $0.1m^2$ in the present case of a 1:10 scale model. The aerodynamic coefficients for the moments are defined as:

$$c_{mi} = \frac{M_i}{0.5 \cdot \rho \cdot U^2 \cdot A \cdot l} \qquad \Big|_{i=x,y,z}$$

where M_i is the moment and l is a fixed reference length of $0.3m$ in case of a 1:10 scale model. Accordingly a typical time scale is obtained from $T = l/U = 0.3/U$. The height of the investigated train model corresponds to approximately $h = 1.3\ l$. The respective length of the investigated car reads $L=7.5h$.

3. Flow Physics

High-speed trains exhibit many complex flow features: reverse-flow regions, cavities and stagnation points in the gangway and bogie region, laminar-turbulent transition in the nose region, turbulent boundary layer development, separation and re-attachment as well as Kàrmàn-vortex streets at the pantographs contact strip are some examples of flow phenomena observed. Nevertheless, only few basic flow features have major influence on cross-wind stability. We can restrict ourselves to a slender and smooth body near a wall as it exhibits all flow features with major impact on the forces and moments leading to over-turning and wheel de-loading of a typical high-speed train.

Basically, three different flow states can be distinguished which are dependent on the yaw angle of the flow. For yaw angles smaller than approximately 10° the flow is mainly attached (see [1]). For yaw angles between 10° and 50° strong vortical regions with conical shape are produced as can be seen in *Figure 3*. The corresponding separation lines are located at the lee-ward directed upper and lower edge of the body (see [3]). These leading edge vortices are known as "delta vortices" in the field of aerodynamics of delta wings. The corresponding pressure induced by the leading-edge vortex provides a significant vortex-lift increment at moderate to high angles of attack. The so-called delta vortices are mainly responsible for the low-pressure region on the lee-side of the body leading to a substantial increase of the lift and side force component of the train and the corresponding moments, respectively. This vortex becomes unstable and exhibits a transient behaviour for flow angles larger than approximately 40°. The instability leads finally to a break-down of the delta vortex (vortex burst) for flow angles exceeding 50°. The low-pressure region rapidly decreases as the delta vortex structure disappears.

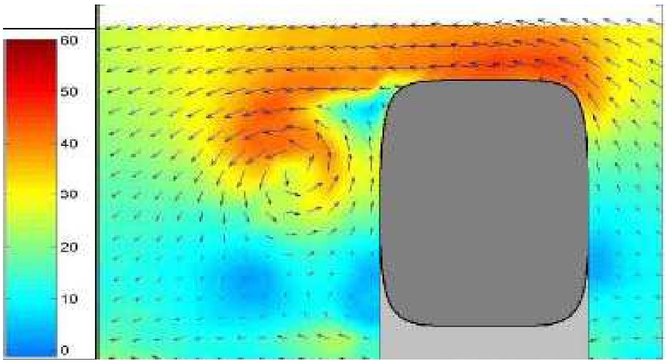

Figure 3 Mean velocity distribution at x=-0.134 and β=30°, 5-hole probe measurements

Nevertheless, with increasing yaw angle two other instability mechanisms become relevant and replace the overall dominance of the delta vortex: the Kelvin-Helmholtz 'shear layer type instability' of the separating shear layer ([4]) and a "shedding type instability" of the entire separation bubble ([5], [6]). The shear layer type instability mode can be characterized by a Strouhal number Str_Θ=0.010 to 0.012 (based on the momentum thickness, Θ at the location of separation, and on the maximum velocity, U_{max} of the inflow. The "shedding type" instability is known as Kàrmàn-vortex instability and the corresponding Strouhal number is Str_D= 0.2 (based on the height of the train and incoming flow velocity) for bodies with rectangular cross-sections. Experimental data (see [3]) show that the pressure distribution is nearly independent of the axial position in case of very high yaw angle flow (β = 60°...90°) and in regions away from the nose. This means that the governing vortex system is statistically homogeneous in the axial direction. This fact motivated Chiu [4] to use a two-dimensional panel-method for the prediction of the pressure field at yaw angles between 60° and 90°. The very high-angle problem is in fact out of problem scope of real high-speed trains. Nowadays, high-speed trains travel with maximum cruising speed of 200 km/h till 350 km/h. With a critical wind-speed between 20 m/s and 30 m/s the relevant yaw angles are approximately between 10° and 30°. Higher yaw angles can be obtained only by decreasing the train speed. However, the corresponding increase of the roll moment coefficient c_{mx} with the increase of the yaw angle does not compensate the decrease of the roll moment. The roll moment decreases with the dynamic pressure which in turn decreases with the square of the flow velocity. This is the motivation for restricting our investigation on yaw angles between 0° and 30°.

4. Experiment

An 1:10 scaled ICE3 model has been subject of various studies aiming to reduce the aerodynamic coefficients responsible for over turning of a train when exposed to cross-wind. The experiments presented here have been performed in the wind tunnel ("Großer Windkanal") of the University of Technology Berlin. The Reynolds number based on the width of the train is Re = 700000. The wind tunnel used (see Figure 2) exhibits a closed test section. The dimension of the test section is 10 x 1.4 x 2.0 m in length, height and width.

Figure 4 « Großer Windkanal » at TU Berlin and tested design variants of ICE3, left: variant 2, right: variant 1

5. Results

Figure 3 shows the roll moment at the leeward rail which is the most significant coefficient for cross-wind stability. The reference case shows the roll moment of the original ICE3. Variant 2 exhibits two separation plates at the windward side of the model and variant 1 exhibit in addition to that vortex generators at the middle line along the roof. The roll moment has been reduced by around 18% in case of variant 2. The model with additional vortex generators (variant 1) exhibits only an 8% reduction of the roll moment which indicates the inconveniency of the vortex generators placed at roof level for cross-wind stability.

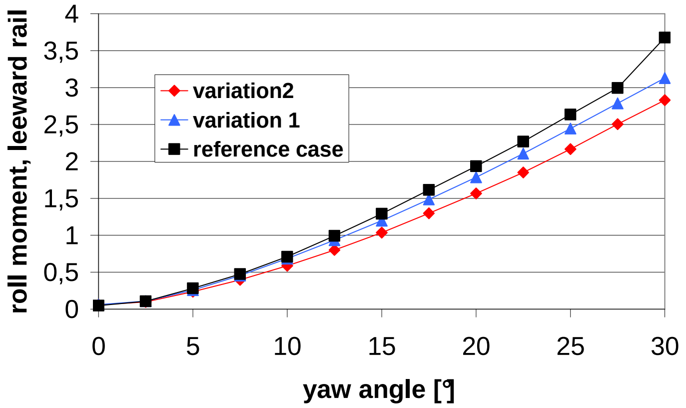

Figure 5 Roll moment at leeward rail for the original and modified ICE3

6. Conclusions

It has been demonstrated that it is possible to reduce the aerodynamic forces of high-speed trains by controlling the separation. Despite the fact that the ICE3 shows a relatively low aerodynamic force when exposed to cross-wind compared to other high-speed trains there is still potential to improve the performance.

References

1. T. Chiu, An experimental study of the flow over a train in a crosswind at large yaw angles up to 90°, J. Wind Eng. Ind. Aerodyn., 45, (1992), 47–74.
2. T. Chiu, Prediction of the aerodynamic loads on a railway train in a cross-wind at large yaw angles using an integrated two- and three-dimensional source/vortex panel method, J. Wind Eng. Ind. Aerodyn., 57, (1995), 19–39.
3. R. Legendre, H.Werle, Toward the elucidation of three-dimensional separation, Ann. Rev. Fluid Mech., 33, (2001), 129–154.
4. C. M. Ho, P. Huerre, Perturbed free shear layers, Ann. Rev. Fluid Mech., 16, (1984), 365–424.
5. L. Sigurdson, The structure and control of a turbulent reattaching flow, J. Fluid Mech., 298, (1995), 139–165.
6. A. Orellano, H. Wengle, POD analysis of coherent structures in forced turbulent flow over a fence, J. Turbulence 2, 8, (2001), 1–35.