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A Computational Fluid Dynamics Study on the Relative Motion Effects for High Speed Train Crosswind Assessment

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Abstract

The effect of the relative motion between a train and the surrounding infrastructure may result in critical scenarios where the infrastructure has a significant effect on the atmospheric wind. This paper analyses using a computational dynamics approach the variation of the aerodynamic force coefficients on the leading vehicle of a high speed train due to the relative motion between the train and the infrastructure. A limited increase (below 10%) in force coefficients are calculated and a small decrease (below 7%) is observed in the characteristic wind curve computation.

Keywords: high speed train, aerodynamics, crosswind, computational fluid dynamics, ANSYS Fluent.

1 Introduction

Crosswind is a critical issue in high speed train aerodynamics. The aerodynamic forces increase with the square of the relative wind speed, and increase almost linearly with the increase of crosswind angle of attack (at least for the lower wind incidence angles). When the atmospheric wind interacts with the railway infrastructure there can be an influence on the relative flow that is impinging on the train. Possible interactions between the wind and the infrastructure may be seen when wind-break fences are installed along the track or when the train is running in a cutting: the wind speed is considerably reduced, and the overturning risk is significantly lower. When the track is positioned at a higher level than the ground level in general the wind blows with a speed higher than the undisturbed one over the track and the vehicle overturning risk is greater: this happens for instance for the embankment scenario.

The assessment of crosswind risk is generally performed through experimental wind tunnel tests, using scaled models placed on the track. Wind tunnel tests are in general performed by fixing the train model on a balance and measuring the aerodynamic forces acting on the vehicle. The wind yaw angle is changed by rotating the train and the entire infrastructure with respect to the incoming wind: wind tunnel tests are performed considering the relative wind perceived by the train. The relative motion between train and infrastructure is neglected and the relative angle of attack of the air on the train and the wind on the infrastructure is not taken into account. The relative motion may have an influence on the aerodynamic forces experienced by the train.

Some work has already been done by measuring crosswind effects on moving models in wind tunnels (Bocciolone et al. [6]): in this case the issues are related to the difficulties in the measurement of the forces on a moving model in the very short measurement time and on the very low Reynolds' numbers that it is possible to achieve. A moving train test rig has been prepared for the assessment of crosswind effects on trains where the train speeds are higher and at 30° to the flat ground scenario (Dorigatti et al. [7]). In this paper the authors found that the only effect of the train motion is on the pressure distribution on the nose but there are not significant differences in terms of aerodynamic forces.

On the embankment scenario, when the wind is blowing perpendicular to the track and no train is present, the wind close to the ground is deflected upwards in order to flow over the track and then runs downwards on the leeward side of the embankment. On the top of the embankment, the wind profile is different from the wind profile measured on the ground and, in particular, it is accelerated, especially at low heights. The modifications of the wind profile depend on the shape of the embankment (angle of the embankment sides) and on the height of the embankment. In this paper the TSI standard [5] 6 meter-high embankment will be considered.

In this paper the effect of motion for the definition of the aerodynamic coefficients of a train running on a standard 6 meter-high embankment are investigated using a numerical approach. In particular Reynolds-Averaged Navier-Stokes equations will be solved using commercial software to calculate the flow around the train. Forces and pressure distributions around the ETR500 high speed train will be analyzed when considering a still train and a moving train condition. High speed trains travel at a typical speed of *300km/h*, while for a strong crosswind condition (considering a wind speed of *30m/s* that is blowing perpendicular to the track) at an angle of attack of about *20°* can be considered for the generation of the aerodynamic forces. A range of relative angles of attack up to 30° is considered.

2 Numerical model

The numerical model of the ETR500 Italian high speed train has been implemented in the commercial software Ansys Fluent. The model reproduces a 1:15 scaled model of the train, using the same size that was used during wind tunnel tests: the numerical model on a Single-Track Ballast and Rail (STBR) scenario will be validated against experimental wind tunnel tests.

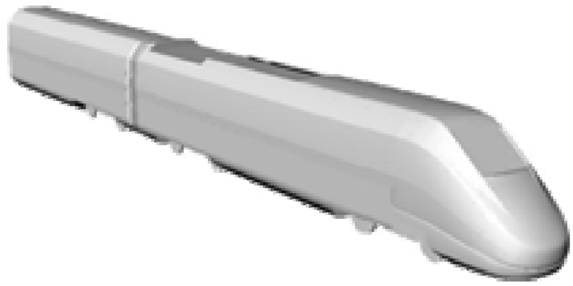


Figure 1: Geometry of the ETR500 train used for the CFD analysis.

The geometry of the train (reported in Figure 1) reproduces the ETR500 leading vehicle and one third of the first trailer car as can be seen in Figure 2. The length of the leading vehicle is *L=1.4m*. The domain has a nearly square shape, as can be seen in Figure 2, with a longitudinal size of *21L*, a width of *19L* and a height of *4.5L*. The train nose is directed to the right. This setup allows to realize only one mesh of the domain and change the train yaw angle by defining the suitable wind incoming direction.

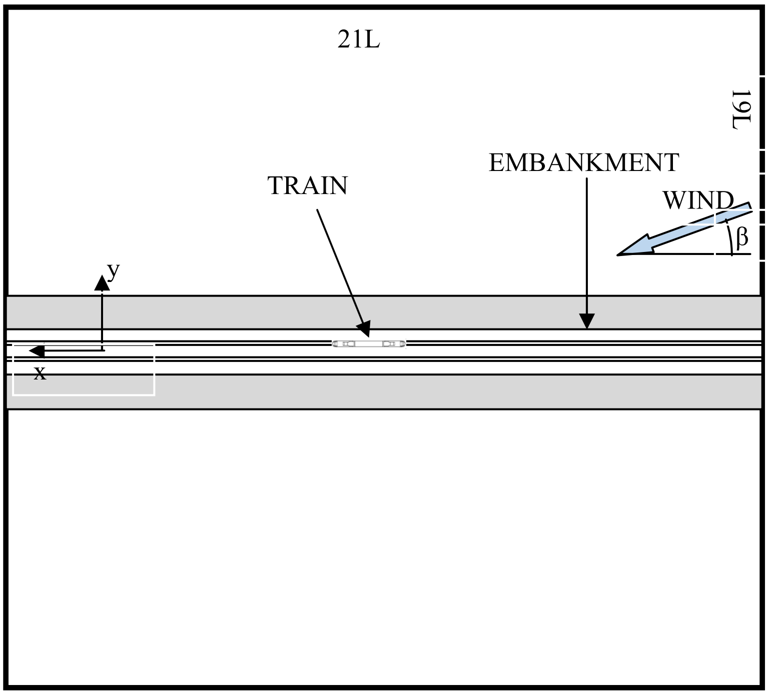
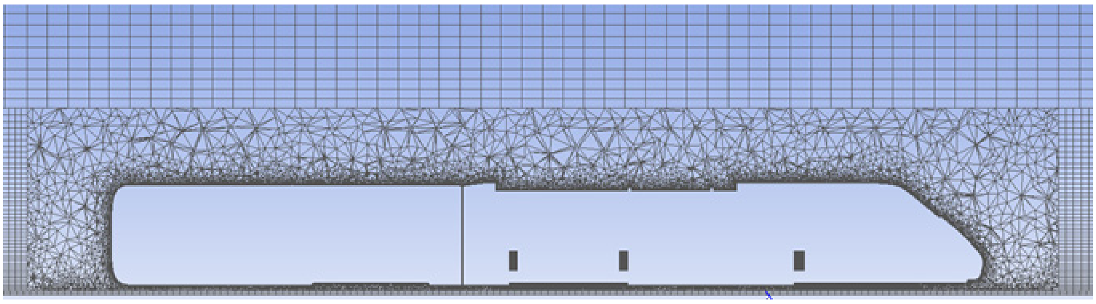
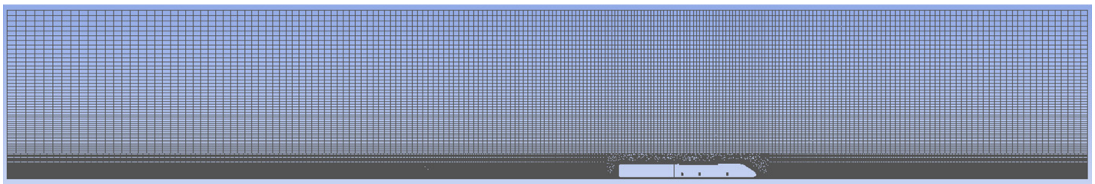


Figure 2: Geometry of the domain used for the CFD analysis.

The mesh of the domain is realized using a mixed structured-unstructured approach: the mesh close to the complex train surface is realized using an unstructured approach (see Figure 3-a) that allows a better quality and flow reproduction of complex geometries; a structured mesh approach (see Figure 3-b) is used where the domain is more regular (this allows to have a higher mesh quality and also to use fewer elements to describe the same volume).



(a)



(b)

Figure 3: Details of the mesh adopted for the CFD analysis. (a) unstructured mesh around the train and (b) structured mesh in the rest of the domain.

Steady state RANS equations are solved using a *k-ω SST* [1] turbulence closure model with a 3rd order discretization scheme. Boundary conditions are defined differently depending if the train movement with respect to the ground is taken into account.

When the train is considered still the boundary conditions are defined as follows: the train, the ballast and rail, the embankment and the ground are modelled as no-slip walls, the top face of the domain is defined as a slip wall, the incoming wind is defined as a constant wind profile coming from the direction defined by the wind incidence angle β defined in Figure 2 on the face from where the wind in entering the domain, while on the faces where the air is leaving the domain the pressure is imposed.

When the train motion is considered a different set of boundary conditions is defined on the domain using different reference frames: the train is moving with constant speed, therefore it is possible to define an absolute reference frame that is fixed with the ground and a moving reference frame that is fixed to the train. Considering the entire mesh as fixed to the train moving reference frame, a non-slip wall condition on the train is defined on the relative reference frame. All other boundary conditions are defined on the absolute reference frame, defining the non-slip wall condition on the ground, the track and the infrastructure. The crosswind condition is realized defining a train speed and a wind speed perpendicular to the track that results in the desired relative wind incidence angle.

Relative air-train speed is equal for the still and moving train conditions, in order to have the same Reynolds' number.

Analysing what happens to the incoming flow on the track when considering a still model or a moving model it is possible to see at the wind profiles in Figure 4.

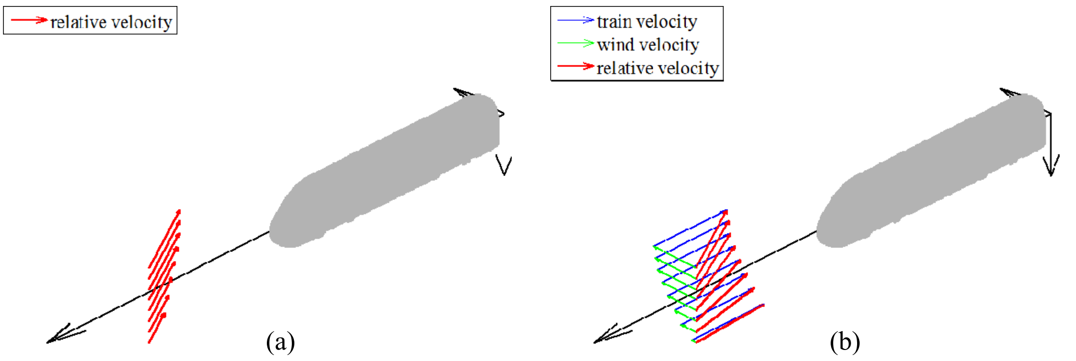


Figure 4: Details of the air flow incoming in different conditions: (a) the train is considered still (b) train-infrastructure relative motion is considered.

The incoming flow is different in the two cases: when a still train is considered the incoming wind incidence angle is constant with height, while when the train is considered moving the wind angle changes with height. The wind speed profile also shows significant differences: the still train profile has a null wind speed on the ground, developing a wind profile on the ground; the moving train encounters a wind speed on the bottom that is equal to the speed of the vehicle, and the crosswind air speed is added on the vehicle block profile.

3 Results

The results of crosswind on the high speed train are presented in terms of force coefficients reported according to CEN standards [4] using the reference system reported in Figure 5 and pressure coefficient distribution on some train sections.

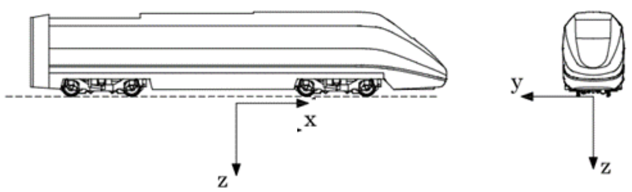


Figure 5: Reference system for the definition of the aerodynamic forces on the train.

The aerodynamic force coefficient C_{Fi} and the aerodynamic moment coefficient C_{Mi} are defined as:

$$C_{Fi} = \frac{F_i}{\frac{1}{2}\rho V^2 S} \qquad C_{Mi} = \frac{M_i}{\frac{1}{2}\rho V^2 Sh} \qquad (1)$$

where, F_i is the force along the i-th axis, M_i is the moment along the i-th axis, ρ is the air density, V is the relative wind speed, $S=10m^2$ the train frontal area and $h=3m$ the reference length according to CEN standards [4].
The pressure coefficients are computed as:

$$C_P = \frac{p - p_0}{\frac{1}{2}\rho V^2} \tag{2}$$

where p is the local pressure and p_0 is the reference pressure.

Pressure distributions are reported for some sections of the train identified as shown in Figure 6.

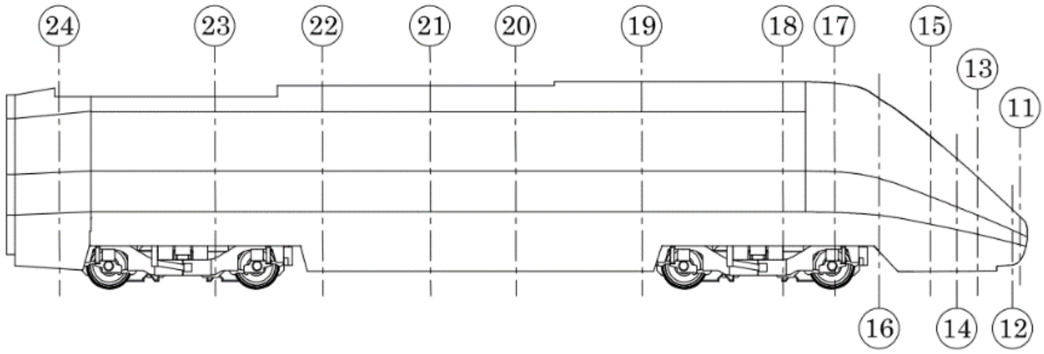


Figure 6: Identification of the sections on the ETR500 leading vehicle

The numerical model is compared against experimental wind tunnel tests performed in the Politecnico di Milano wind tunnel (Bocciolone et al. [6]) on the STBR scenario. The validated numerical model is then used for the assessment of the crosswind coefficients on the embankment scenario when the train is still and moving.

3.1 Validation of the numerical model

The validation of the numerical model is performed by comparing the lateral force coefficient C_{Fy} and the rolling moment coefficient C_{Mx} for the wind tunnel tests and the CFD model: these coefficients are the mainly responsible for the train overturning risk. High speed trains travel at a typical speed of *300km/h*, while for a strong crosswind condition (considering a wind speed of *30m/s* blowing perpendicular to the track) an angle of attack of about *20°* can be considered for the generation of the aerodynamic forces. The wind incidence angles range that is considered is $0° < \beta < 30°$ since this range is the most common for high speed trains.

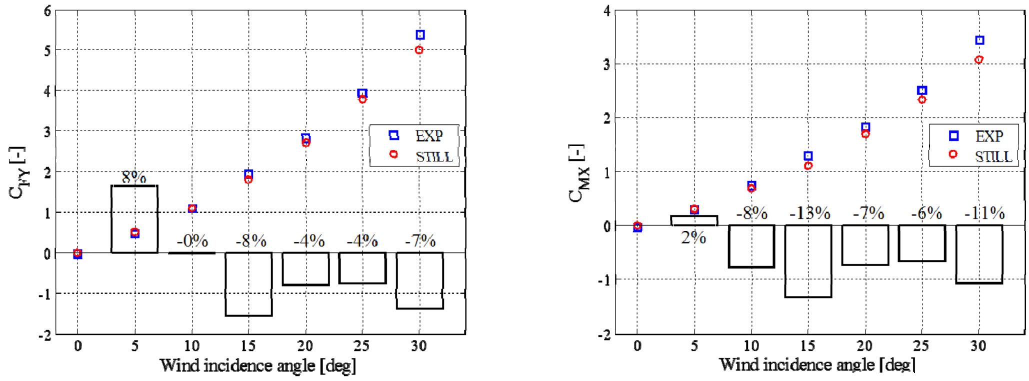


Figure 7: Aerodynamic forces and moments on the train for the STBR scenario: comparison between experimental wind tunnel tests and numerical model

The differences between experimental and numerical data for the lateral force coefficients are lower than 10% for the entire range considered. In general the CFD model tends to under estimate the aerodynamic force and moment coefficients, but this difference is defined as limited by CEN standards [4] and the numerical model can be considered validated.

3.2 Results on embankment scenario

In this case the coefficients are reported for positive and negative angles of attack since the train may be running on the windward ($\beta > 0$) or on the leeward track (see Figure 2).

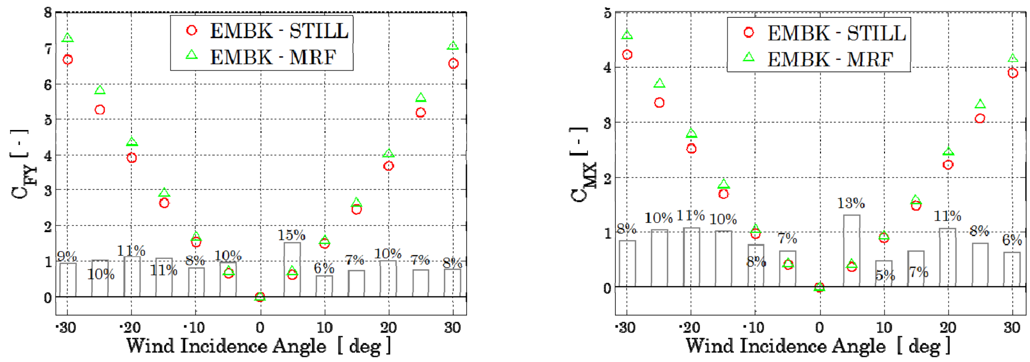


Figure 8: Aerodynamic forces and moments on the train for the embankment scenario: comparison between still and moving train condition

Considering the case of the train on the embankment scenario it is possible to note that the force and moment coefficients are larger than for the STBR case. An explanation for this phenomenon can be imputed to the larger wind speed that is expected on the track due to the flow acceleration on the top of the infrastructure (Baker [3]). The wind speed becomes larger than the reference wind speed therefore the aerodynamic forces are expected to become larger. Looking to the relative wind incidence angle also the angle of attack at the train height is larger than the reference wind incidence angle. Both the observations lead to larger forces and moments acting on the train as can be seen by comparing the coefficients reported in Figure 7 and Figure 8.

Considering the still and the moving train coefficients on the embankment (reported in Figure 8), it is possible to see that the train has larger crosswind coefficients when the relative motion between train and infrastructure is considered than when the still train condition is reproduced. When the train is running on the windward track the increase in the aerodynamic forces for the moving train is generally lower than when the train is running on the leeward track. In general when the train is moving the increase in the forces and moments is around 10%.

Looking to the pressure distribution on a train section it is possible to justify the increase in the aerodynamic coefficients. The calculations on the moving train show higher pressure coefficients on the leeward side for a section that is located on the front part of the leading vehicle (Figure 9 - left), increasing the lateral force and the rolling moment. For a section that corresponds to the central part of the leading vehicle (Figure 9 - right) the moving train shows higher pressure values on the higher part of the train section with respect to the still train condition. Differences in the lower part of the section may give minor contributions to force coefficient variations.

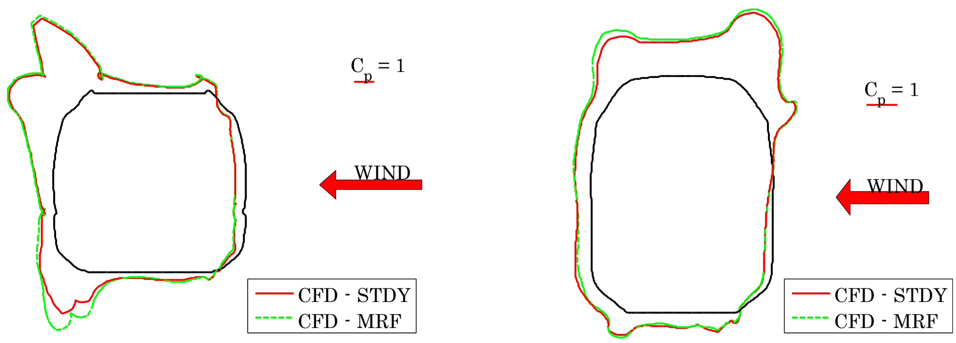


Figure 9: Pressure coefficient distribution on two train sections: section 15 (left) and section 19 (right)

The analysis of crosswind aerodynamic coefficients leads to a general increase of the values, but the overturning risk increase may be assessed only considering the Characteristic Wind Curve (CWC). The CWCs are computed according to TSI standards [5] using the dynamic method based on the ‘Chinese Hat’ wind speed profile. The variation in the CWC computed using the train aerodynamic coefficients with the still train and the moving train are reported in Figure 10. It is possible to see that the variation in the aerodynamic coefficients results in a reduction of the critical wind speed in the order of less than *7%*.

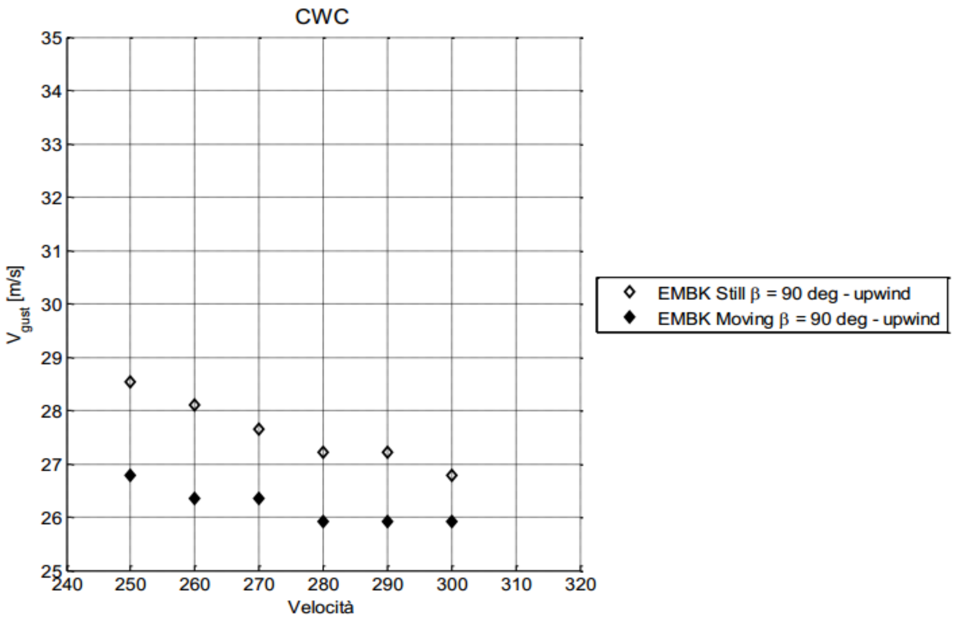


Figure 10: Characteristic wind curve calculation for the ETR500 train on a *6m* high embankment using the still and moving aerodynamic coefficients

3 Conclusions

A numerical model for the calculation of the aerodynamic forces on a high speed train has been implemented using a commercial software. The effect of relative motion between the train and the embankment infrastructure has been investigated, observing in general that the moving train experiences higher aerodynamic forces than a still train. The differences between the still and the moving coefficients are more evident when the train is running on the leeward track than on the windward one and the difference is in the order of 10%.

In conclusion, aerodynamic coefficients obtained from still model on embankment are not conservative with respect to the moving model and the CWC obtained with the moving coefficients is lower (more critical) than the corresponding CWC calculated with the static coefficients of about 7%.

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