Turbulence effects on the aerodynamic forces acting on railway vehicles by means of wind tunnel experimental study

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Abstract

The present research work is based on an experimental campaign of wind tunnel tests aimed at investigating the crosswind aerodynamic of a lightweight railway vehicle. The performed tests allow to measure the aerodynamic forces on the vehicles for different wind exposures and over a wide range of Reynolds number. In particular the aerodynamic admittance functions are computed for different wind conditions by varying the turbulence intensity indexes and the integral length scales of the simulated wind flow; the final aim of the paper is to validate a numerical model which is able to reproduce the equivalent forces exerted on the vehicle in presence of turbulent flow conditions.

1 Introduction

In the last decades the investigation of the dynamic behavior of railway vehicles under cross winds was performed by means of full scale tests, wind tunnel tests and CFD simulations. Objective of this type of research was to identify the key parameters which govern the wind-train interaction and to define a common methodology to handle the problem. The most well-established approach requires the identification of the aerodynamic coefficients under simplified testing conditions, followed by a numerical investigation on the aspects which are not considered in the previous analysis. As an example, wind tunnel tests are normally performed on still models in smooth flow conditions and considering a simple infrastructure scenario (flat-ground or single track ballast and rails); therefore, numerical models are required to correctly reproduce the relative velocity between train and infrastructure, the wind turbulence characteristics and the different infrastructure scenarios. The validation of these numerical models requires in first place an experimental investigation, for this reason many wind tunnel tests are performed focusing on these aspects: moving model test rigs allow to study the influence of the wind-train relative velocity (Baker 2002, Bocciolone et al. 2008), while the effects of the wind turbulence are investigated by means of atmospheric boundary layer simulations; other experimental campaign focus on the vehicle different aerodynamic behavior when considering infrastructure scenario like embankments or viaducts (Suzuki et al., 2003, Bocciolone et al., 2008, Cheli et al. 2010). As for the present paper, the effects of turbulence on the aerodynamic forces, both in terms of mean value and frequency content were investigated. For that purpose, a wind tunnel test campaign was performed in the Politecnico di Milano wind tunnel on a 1:15 scale model of the MLA Riyadh (see Figure 1), a lightweight rail convoy. The tests have allowed both the measurement of the mean aerodynamic force coefficients and the evaluation of the aerodynamic admittance function, that is the adjusting function which corrects the values of the forces given by the steady theory, taking into account the effective turbulent wind speed distribution (which depends on space and time) (Sterling et al. 2009, Coleman and Baker 1994, Baker 1991). Aim of the paper is to study the effect of the turbulence on the non-stationary aerodynamic forces on the basis of the experimental evidence.
2 Experimental set up

Tests have been performed in the high-speed test section (4x4m) in very low turbulence conditions ($I_u=0.1\%$) and in the boundary layer test section (14x4m) both in smooth flow and in turbulent flow regimes. In the boundary layer test section Atmospheric Boundary Layer (ABL) simulations have been carried out using passive turbulence generators placed at the beginning of the test chamber (see Figure 1), while the smooth flow conditions were obtained with empty test room (with a natural turbulence level of about $I_u=2\%$). Three different levels of turbulence have been simulated during the experimental campaign (‘low turbulence’, ‘mean turbulence’, ‘high turbulence’) and their properties have been characterized in terms of mean wind speed vertical profile, turbulence intensity ($I_u$) and integral length scales ($L_u$); Table 1 reports these quantities for the reference height corresponding to the vehicle mid-height. The model of the convoy is composed by two symmetrical vehicles (vehicle length: $L=0.88m$) which are instrumented to measure both aerodynamic forces and surface pressures and it has been tested with a flat ground scenario (without ballast and rails).

![Figure 1: 1:15 scale model of the Mla Riyadh vehicle in the boundary layer test section](image)

<table>
<thead>
<tr>
<th>Smooth turbulence</th>
<th>Low turbulence</th>
<th>Mean turbulence</th>
<th>High turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_m$ [m/s]</td>
<td>$I_u$ [%]</td>
<td>$L_u$ [m]</td>
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</tr>
<tr>
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<td>2</td>
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<td>8</td>
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<tr>
<td>8</td>
<td>28.2</td>
<td>1.6</td>
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</tr>
</tbody>
</table>

Table 1: Characteristics of the generated wind flow in the boundary layer test section.

3 Experimental test results

The tests in the high-speed test section have been carried out in order to determine the mean force coefficients (CEN standard) of the considered vehicle in conditions of smooth turbulence with different Reynolds numbers, while the tests in the boundary layer test section have been performed with different simulations of boundary layer in order to evaluate both the mean aerodynamic coefficients and the aerodynamic admittance functions.

3.1 Mean aerodynamic coefficients

In Figure 2 the lateral force ($C_{fy}$) and rolling moment ($C_{Mx}$) coefficients are plotted as a function of the wind angle of exposure for different turbulence levels. The dashed line describes the behavior of the coefficients measured in the high-speed (HS) test section in smooth flow conditions, the solid lines regard the same measurement in the boundary layer (BL) test section, both for smooth flow and turbulent flow conditions. The coefficients are computed with respect to the wind speed measured at the vehicle mid-height. It is possible to notice that the two force coefficients have the same trend, which means that the application point of the lateral force is, for each exposure and wind turbulence
level, at the same height (approx. 60% of the reference height of 3m used for the moment coefficient). Considering the BL tests, it comes out that the force coefficients are higher when the turbulence level is increased: such a behavior has already been observed (Bocciolone et al., 2008) and can be explained by the interaction mechanism between the vortexes present in the incident flow (whose size is related to the integral length scale) and the ones shed in the wake of the vehicle (Robinson 1987).

3.2 Aerodynamic admittance functions

The admittance function is defined as the ratio between the PSD of the aerodynamic force acting on a vehicle subjected to turbulent wind $S_{FF}(f)$ and the corresponding PSD of the aerodynamic force evaluated through the steady theory $S_{FF,stad}(f)$ (Simiu and Scanlan 1986). Considering that the expression of the PSD of the stationary aerodynamic force is:

$$S_{FF,stad}(f) = \frac{1}{4} \rho^2 A^2 C_{Fi}^2 \frac{S_{U^2}(f)}{S_{U^2}\rho^2 C_{Fi}^2}$$

where $\rho$ is the air density, $A$ is the reference area, $C_{Fi}$ is the static aerodynamic coefficient and $S_{U^2}(f)$ is the PSD of the square wind velocity, then the admittance function assumes the following expression:

$$H(f) = \frac{S_{FF}(f)}{S_{FF,stad}(f)} = \frac{4S_{FF}(f)}{\rho^2 A^2 C_{Fi}^2 \frac{S_{U^2}(f)}{S_{U^2}\rho^2 C_{Fi}^2}}$$

From this expression it is clear that the experimental evaluation of the admittance function can be obtained through wind tunnel tests, by measuring both the wind speed $u(t)$ and the aerodynamic force/moment. The PSD of these quantities, $S_{FF}(f)$ and $S_{U^2}(f)$, are computed on 10 minutes-long time histories. In Figure 3a are reported the lateral force aerodynamic admittance functions for an exposure of $\beta_w=30^\circ$ for three different turbulence levels ($L/\delta_u=0.55$, $L/\delta_u=0.99$ and $L/\delta_u=1.36$). The aerodynamic admittance are plotted as a function of the non-dimensional frequency $f^* = f \cdot L_u / U_m$. As it is possible to notice, as the integral length scale of the wind increases (from the blue curve to the red one), the curve remains closer to the unitary value for a wide range of non-dimensional frequencies: in fact the spatial correlation of the wind velocity is higher, so the steady-theory approximates better the interaction force. Figure 3b shows the lateral force aerodynamic admittance functions for different wind exposures ($\beta_w=30^\circ$, $\beta_w=45^\circ$ and $\beta_w=60^\circ$), in high turbulence conditions ($L/\delta_u=0.55$). The comparison highlights that an increase in the angle of exposure results in a more evident detachment from the steady-theory approximation. A more in-depth investigation will
be presented with the support of the numerical model already validated for the computation of the non-stationary aerodynamic forces (Cheli and Tomasini, 2012).

![Image of Figure 3](image-url)

Figure 3: Lateral force aerodynamic admittance functions a) for different turbulence levels and b) for different exposures.

### 4 Conclusions

A wind tunnel experimental campaign was performed in order to study the aerodynamic behavior of a lightweight railway vehicle. The main focus of the analysis was to investigate the dependency of the wind-train interaction forces on the incoming flow turbulence, considering both the mean force coefficients and the aerodynamic admittance functions. A numerical model of the aerodynamic admittance function, developed in a previous work (Cheli and Tomasini 2012) will be employed as a support for a better comprehension of the experimental results.

### References


