Wind Tunnel Test Study for the Influence of Reynolds Number on the Aerodynamic Performance of High-speed Trains

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ABSTRACT

The low temperature variable Reynolds number wind tunnel test for a high-speed train model (EMU) with a leading car and half of middle car is done to study the aerodynamic performance of high-speed trains in the Reynolds number range between $10^6$ and $10^7$, and the conformity test is performed with a scaled ICE3 model. The test results show that the drag of the leading car decreases almost monotonically with increasing yaw angle, while the side and lift force increases with increasing yaw angle. The $C_m_{lex}$, which is the most important parameter with respect to cross-wind stability, also increases with increasing yaw angle. The drag force coefficient ($C_{fx}$) of the leading car decreases with higher Reynolds number for yaw angles of $0^\circ$. The $C_{fx}$ drops about 0.03 when the Reynolds number is raised from 1 million to 10 million. The lift force coefficient decreases with higher Reynolds numbers.

KEYWORDS: Reynolds number, wind tunnel test, aerodynamic performance, high-speed train.

1 INTRODUCTION

As a large slenderness ratio vehicle, high-speed trains operating in dense atmosphere close to the ground. The flow field characteristic around the train is affected by the viscous air seriously\cite{1}. If we take the width of high-speed train as the characteristic length, the Reynolds number is $10^7$. Because of the ground test conditions, the Reynolds number of conventional wind tunnel test is only about $10^6$. 


Compared to aircraft, there is a relative motion between the ground and the high-speed train, and the ground moving cannot be simulated in most of wind tunnel tests. Although methods like suction floor can be used to eliminate the boundary layer effect of static ground, but the results have not yet been quantitative evaluation. After analysis the wind tunnel test results with the wind speed changes from a critical range, the aerodynamic performance is considered change little that when the wind speed critical value \(^{[2-4]}\), which is known as the "self-simulation zone", and this is the test criteria followed by the wind tunnel test. However, the highest Reynolds number for the wind tunnel test with different wind speeds only reached \(10^6\), so the aerodynamic performance of the high-speed train between \(10^6\) and \(10^7\) has not yet been confirmed. Reynolds number effect is discussed by numerical simulation method \(^{[5]}\) but the lack of wind tunnel test demonstration. In this paper, the low temperature variable Reynolds number wind tunnel test is done to study the aerodynamic performance of high-speed trains in the Reynolds number range between \(10^6\) and \(10^7\), which may provide the quantitative evaluation of the aerodynamic performance of high-speed trains.

2 WIND TUNNEL SETUP

2.1 Wind Tunnel Setup

The measurements are carried out in the DNW Cryogenic wind tunnel (KKK) in Cologne Germany. KKK is a closed circuit low speed tunnel. To achieve high Reynolds numbers, the gas temperature in the tunnel circuit can be lowered down to 100 K by injecting liquid nitrogen. The Reynolds number can be thus increased by a factor of 5.5 while the drive power remains constant. Due to the possibility of independent variation of the gas temperature and flow velocity, the influence of the Mach number and Reynolds number on the aerodynamic characteristics can be investigated separately.

The model access lock and the model conditioning room both have individual temperature control systems provided by nitrogen and dry air injection and enforced heating. In this manner they can also be used as independent cryogenic (pre-) test facilities.

The measurements are performed using an internal 6-component balance. This is a cold balance. It can work from ambient to cryogenic conditions. A temperature compensated electronic pressure scanning system (PSI) was used for pressure measurements.

Past investigations using hotwire probes have shown that the turbulence intensity in the free stream flow was between 0.05% and 0.4% depending of the Mach (from 0.1 to 0.3) and Reynolds number (from \(0.5\times10^6\) and \(7\times10^6\)) for temperatures between 100 and 285K. These measurements were performed in the center of the wind tunnel with an array of 4 hotwires.
The velocity distribution in the test section is measured using a 5-hole probe rake. The rake is equipped with 15 probes. The distance between the probes is 25mm. A block profile is presented for the wind tunnel (Figure 1).

2.2 Ground Simulation

According to the standard EN 14067:2010, the model is installed on a 3.1 × 1.3 × 0.03m splitter plate located 185 mm above the wind tunnel floor in order to be outside of the wind tunnel boundary layer. This setup allows a fresh boundary layer on the splitter plate which is small enough compared to the model height.

The simulation of the flow between a stationary train model and ground in a wind tunnel is difficult, because in a wind tunnel the model and the ground undergo the same wind velocity, while in reality a train runs over a rail. To simplify the train test in a wind tunnel, En14067-6:2010 has defined three ground configurations: flat ground, single track and ballast, and embankment of 6 m height.

For the flat ground configuration (Figure 2), the simulation of the ballast and rails is omitted, thus the unrealistic effect of the rail is eliminated. This configuration is a better compromise. The flat ground configuration is chosen for this investigation.
2.3 Model Setup

The wind tunnel measurements are performed with 1:15 scaled train model. The model is shown in Figure 3.

The model is composed of a leading car and a downstream body. The downstream body is one half of the middle car. Its end is smoothed with an elliptical surface. The model is equipped with three bogies, two driving bogies and one towing bogie. The leading car is fixed to the splitter plate via an internal six-component balance. There is a gap between the leading car and the downstream body to prevent any contact between the measured car and downstream body during the measurements. The bogie is simplified, but preserves its aerodynamic characteristics.

![Wind tunnel model EMU.](image)

Figure 3. Wind tunnel model EMU.

3. WIND TUNNEL TEST INSTRUMENTATION

3.1 Reynolds Number

The measurements are performed at different Reynolds numbers in order to investigate the Reynolds number independency. For the model the Reynolds number is defined by:

\[ R_e = \frac{ud_0}{v} \quad (1) \]

With \( U \) the tunnel velocity in the test section, \( v \) the kinematic viscosity and \( d_0 \) the characteristic length of 0.27m for a 1:15 scale model.

3.2 Air density

The air density \( \rho = p/(RT) \) is calculated from the average measured temperature \( T \) and the static pressure \( p \) for each test using the ideal gas law with an specific gas constant \( R \) of 297 J/(kg\cdotK). The temperature \( T \) is measured using a temperature sensor in the test section and the static pressure \( p \) is measured using a Prandtl probe in the test section.
3.3 Coordinate system

The coordinate system defined in En14067-1:2010 is used in this paper, as shown in Figure 4.

![Figure 4. Aerodynamic force and moment reference system.](image)

3.4 Benchmark test

The wind tunnel has been qualified for rolling stock test according to EN147067-6. The conformity test is performed with a 1:25 scaled ICE3 model at Re of 1 million and temperature of 200K. Any changes made to the tunnel, including new test set-ups, shall be compared with these data for verification. The measured test results for the reference model C_{mx,lee} shall be compared with the conformity data to determine whether the wind tunnel tests are giving results which are within the required tolerances. The target tolerances have been found to be $\varepsilon_{\text{max}} = 15\%$ and $\varepsilon_{\text{mean}} = 10\%$ for the relevant yaw angles.

Because the test model has a scale factor of 1:15, a new test set-up is designed and constructed. A new 1:15 scaled ICE3 model (Figure 5) is also manufactured to verify the test set-up.

![Figure 5. Benchmark model ICE3.](image)

Before the test model began, this 1:15 scaled reference model was tested. The results were shown in Figure 6. In these diagrams the current test results are compared to the data set from EN147067-6 which was acquired with a 1:7 scaled...
model at Re of 2.3 million and the conformity test data set which is used to qualify the KKK for the cross wind assessment. It can be seen that the three force and moment components as well as the rolling moment around the leeward rail of the three tests match well, especially the side force, rolling and yawing. The difference in drag and lift is relatively large. This is because drag and lift are sensitive to the clearance between the ground and the vehicle underfloor. The ground boundary layer thickness at the model reference point does not correspond to the model scale, so the effective clearance under the vehicle floor is not the same for the three tests.

Figure 6. Comparison of the current test results with the EN14067-6 and the conformity test.

The deviation to the reference value is defined as:

\[ \varepsilon = \frac{C_{\text{mlee, test}} - C_{\text{mlee, refer}}}{C_{\text{mlee, refer}}} \]  

(2)

The result is listed in Table 1. The maximal deviation is 8.8%, smaller than the required 15% and the mean deviation is 7.2%, smaller than the required 10%. So the test setup is verified.
TABLE 1. DEVIATION OF THE $C_{\text{MX, Lee}}$ OF THE CURRENT TEST TO THE CONFORMITY TEST.

<table>
<thead>
<tr>
<th>Yaw Angle [$^\circ$]</th>
<th>$C_{\text{mxLee}}$ Current Test</th>
<th>$C_{\text{mxLee}}$ Conformity</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.56</td>
<td>0.60</td>
<td>7.70</td>
</tr>
<tr>
<td>20</td>
<td>1.57</td>
<td>1.72</td>
<td>8.81</td>
</tr>
<tr>
<td>30</td>
<td>2.95</td>
<td>3.11</td>
<td>5.05</td>
</tr>
<tr>
<td>max</td>
<td>/</td>
<td>/</td>
<td>8.81</td>
</tr>
<tr>
<td>mean</td>
<td>/</td>
<td>/</td>
<td>7.19</td>
</tr>
</tbody>
</table>

4 DATA ANALYSIS

4.1 Aerodynamic force coefficients

Figure 7 shows the coefficients of EMU at a Reynolds number of 1 million. The drag of the EMU leading car decreases almost monotonically with increasing yaw angle. This is due to the low pressure formed in the nose region. The higher the yaw angle, the higher the flow velocity around the nose and thus a stronger suction force acts on the vehicle. For the ICE3 the drag increases with the yaw angle up to 22°, then decreases. The drag of the EMU is smaller than ICE3.

![Graphs showing coefficients of EMU at various yaw angles.](image)

Figure 7. Coefficients of EUM at $Ma=0.16$, $T=294K$ and $Re=1$ million.

The side force increases with increasing yaw angle. The side force of EMU at 30° is 8% smaller than that of the ICE3. EMU leading car generates a down force at yaw angles up to 4°, afterwards it generates a lift.
The lift increases with increasing yaw angle. At yaw angles larger than 12°, EMU has more lift than ICE3. It is interesting to note that the point of application of the side force does not change much with the yaw angle. It increases from 0.48L_{ref} to 0.50L_{ref} above the top of the rail.

The rolling moment of EMU at 30° is 13% smaller than that of the ICE3. The most important parameter with respect to cross-wind stability is C_{mx,Lee}. It increases with increasing yaw angle. This moment of EMU1 at 30° is 7% smaller than that of ICE3. It indicates better cross-wind stability.

4.2 Reynolds number effect on coefficients

The Reynolds number effect of EMU at yaw angle of 0° is shown in Figure 8. The drag drops about 0.03 when the Reynolds number is raised from 1 million to 10 million. This phenomenon is consistent with the boundary theory. The drag consists of skin friction and pressure drag. The pressure drag does not change much with the Reynolds number for small yaw angles. The skin friction decreases with higher Reynolds number.

![Figure 8. Reynolds number effects of EMU at yaw angles (0°).](image)

The lift decreases with higher Reynolds numbers, though the change is small. At yaw angle of zero the down force is reduced by about 0.03 when the Reynolds number is raised from 1 million to 10 million.

5 CONCLUSIONS

The low temperature variable Reynolds number wind tunnel test for a high-speed train model (EMU) with a leading car and half of middle car is done to study the aerodynamic performance of high-speed trains in the Reynolds number range between $10^6$ and $10^7$. The test results are as follows:

1. Due to the low pressure formed in the nose region, the drag force coefficient of the EMU leading car decreases almost monotonically with increasing yaw angle. While the drag force coefficient decreases with higher Reynolds number for yaw angles up to 0°.
(2) The side and lift force coefficient increase with increasing yaw angle. The side force of EMU at 30° is 8% smaller than that of the ICE3. EMU leading car generates a down force at yaw angles up to 4°, afterwards it generates a lift. The lift force coefficient increases with higher Reynolds numbers, though the change is small.

REFERENCES