The effect of tail roof-angle on the unsteady wake structure and slipstream of high-speed trains

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Abstract

The effect of varying the roof-angle of the tail of a generic high-speed train on the unsteady wake structure and corresponding slipstream is investigated. The wind-tunnel experiment utilised a 1/10 scale model, which corresponds to a Reynolds number of 7.2×10^5.

1. Introduction

The induced flow known as 'slipstream' caused by a high-speed train's (HST's) movement can be hazardous to commuters at platforms, track-side workers and infrastructure. As such a HST's slipstream performance is regulated in Europe [1]. Peak slipstream velocities - up to 150km/h - occur in the wake of a HST [2]. These peaks are caused by the dynamics of the wake structure of HST's, specifically the spanwise oscillation of a counter-rotating pair of trailing vortices interacting with vortex shedding occurring at the sides of the HST [3, 4].

2. Experimental methodology

A 1/10 scale model of a generic HST geometry, based on a ICE3 HST - a high-speed train in operation throughout Germany - was used in the wind-tunnel experiment. The generic geometry shared the nose geometry and cross-sectional profile of the ICE3, however, the tail had fixed radii of 0.375H (150mm) for the roof and tail tip, 0.125H side of the tail tip and and side pillars with roof angles of 20, 30, 50, 70, 90^o tested (Fig 1).

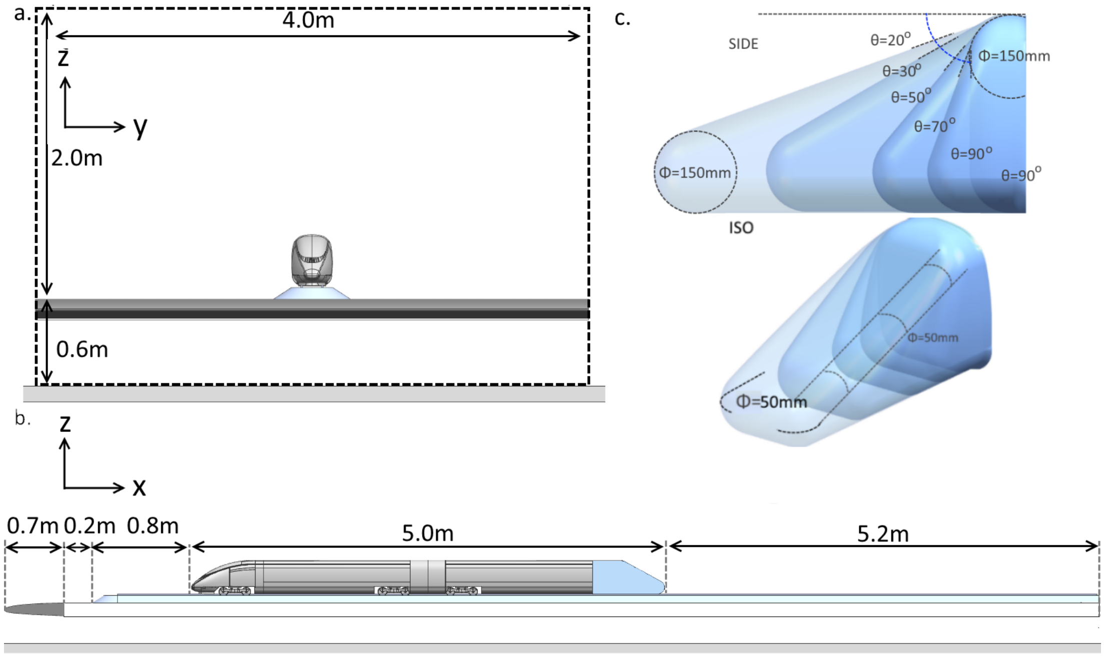

Figure 1: a), b) Experimental set-up in the 3/4 open-jet test-section of the wind-tunnel. c) The generic HST tail.

The model measured 5×0.3×0.4m (L×W×H), with a cross-sectional area of 0.115m^2. The experiment was performed in Monash University's large 3/4 open-jet wind tunnel, (12×2×4m: L×W×H) resulting in a blockage ratio of 2%. The Reynolds number based on the freestream velocity, $u_\infty = 35m/s$, and model width was 7.2×10^5. The tunnel was fitted with a splitter plane to reduce the effect of the wind tunnel boundary layer. The model had 4 sets of bogies with no inter-carriage gaps, and was mounted above a 1/10 scale single track ballast and rail (STBR).

The results presented are from measurements obtained using a 4-hole dynamic pressure 'cobra' probe and a spanwise array of 17 total-pressure probes connected to a dynamic pressure measurement system. The cobra probe and total pressure probes had frequency responses up to $2000Hz$ and $300Hz$ respectively.

3. Results and discussion

Time-averaged wake structure

The time-averaged wakes of the 20, 50 and 90^o tail geometries characterised by cobra-probe measurements in the yz plane at $x = 6H$ are presented in Fig 2. These three geometries are representative of the differences over the entire range of roof angles tested. The induced streamwise (u) velocity field, a measure of the peak velocity, $\sqrt{u^2+v^2+w^2}+2\sigma_{uvw}$, vectors of $v,\ w$ velocity, streamwise vorticity, ω_x, and vortex identifiers Γ_1 and $\Gamma_2 = 2/\pi$ are each presented.

These results clearly identify the presence of a streamwise vortex for the geometries with lower roof angles. The 20^o geometry has a distinct streamwise vortex (one of a pair) identified in the $v,\ w$ velocity vectors, streamwise vorticity, ω_x, and the vortex identifiers Γ_1 and Γ_2. The 50^o geometry has a weaker streamwise vortex.

In contrast, the 90^o geometry has significantly larger slipstream velocities in its wake (equal or exceeding the train speed) than the smaller roof angle geometries. However, these high slipstream velocities remain directly behind the vehicle, thus presenting significantly lower risk to safety and damage to infrastructure. Importantly, no coherent streamwise vortices exist in the wake for this geometry.

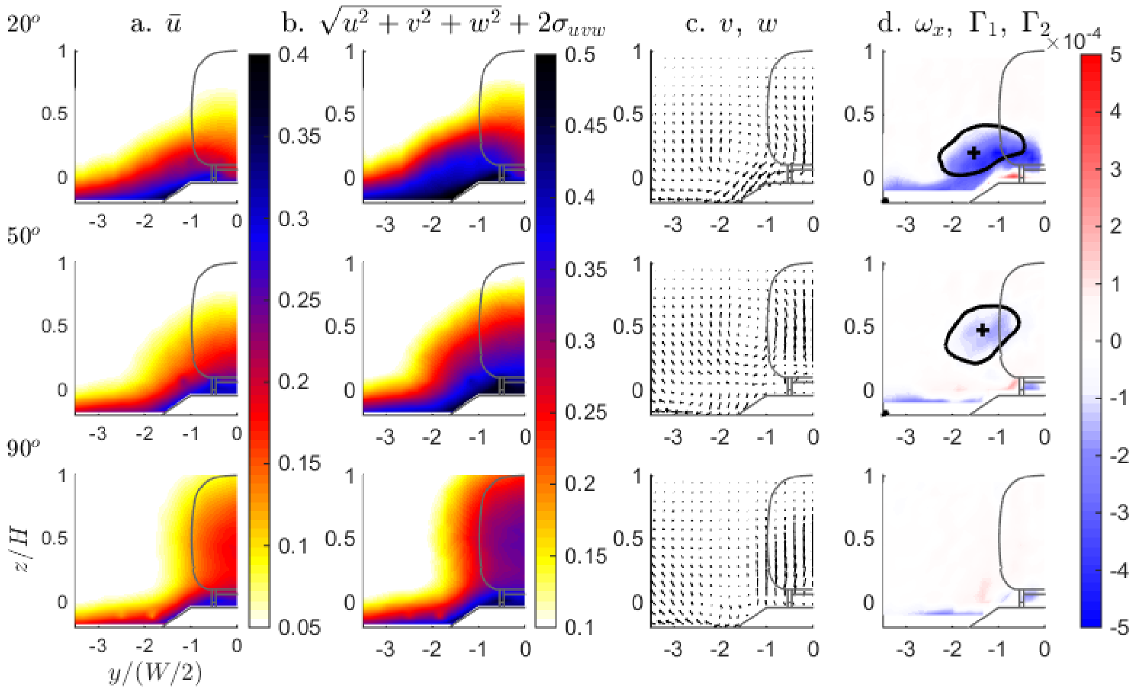

Figure 2: Time-averaged wake topology of each tail geometry at yz plane at $x = 6H$.

Surface flow visualisation performed using ink identified large-scale separation occurring for large roof angles which reduced the coherence of the pair of streamwise vortices (Fig 3). This agrees with findings by Muld et al.[4] and Morel [5] who have also found the wake of HST being dominated by a pair of streamwise vortices or large-scale separation.

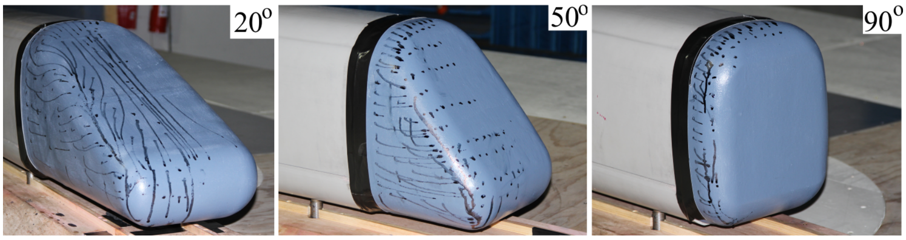

Figure 3: Surface flow visualisation over the three tail geometries.

Unsteady wake structure

Analysis of individual cobra probe measurements identified a dominant frequency, normalized by the freestream velocity and width of the model, of $St_W = 0.2$ in the regions of high fluctuating velocities. The periodicity in the flow is the proposed cause of the high variability, and corresponding peak slipstream velocities visible in Fig 2b.

Spanwise slices of total pressure filtered with a single-pole, Butterworth lowpass filter of $St_W < 0.7$, and measured at $z = 0.2H$ are presented in Fig 3 for the three representative tail geometries. The spanwise oscillations in transient pressure, presented as the coefficient of pressure, C_P, are visible in all configurations, however significant differences exist.

The 20^o and 50^o geometries have very wide regions showing strong oscillations of total pressure relative to the larger roof-angle geometries. For the 20^o geometry in particular, two regions of low total pressure visibly oscillate. These results are explained by the vortex shedding off the sides of the HST interacting with the streamwise vortices as identified in the wake of an ICE3 HST [3]. The interaction of these two wake features also result in a total pressure oscillation in the spanwise direction closer to the tail of the model.

For the 90^o roof-angle geometry, a weaker oscillation of the total pressure in the wake is also visible. Again, this is expected to be caused by vortex shedding occurring off the sides of the HST, however, there are no streamwise vortices in the wake of this geometry to interact with. The total pressure in the wake does not oscillate as widely as for 90^o roof angle geometry, due to the absence of the streamwise vortices that move the wake outwards. The spanwise oscillation also takes longer to develop downstream for these large roof-angle geometries, with clear oscillations only occurring in the wake at $x = 3H$ and $x = 6H$, but not at $x = 1H$.

The period of the oscillation in of total pressure in the wake is $tV/L \approx 5$ which corresponds to a frequency of $St_W \approx 0.2$ as measured by the cobra-probe.

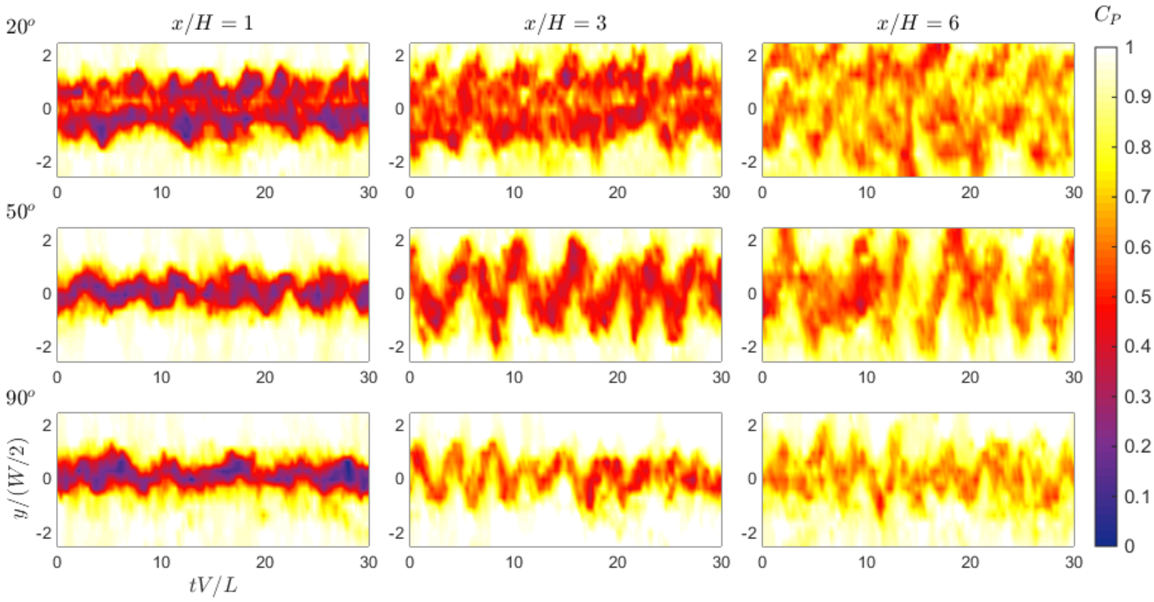

Figure 4: Transient total pressure, C_P, measured at $x = 1, 3, 6H$, $z = 0.2H$ for the three tail geometries.

4. Conclusions

The interaction between a pair of counter-rotating vortices trailing a HST interacting with vortex shedding occurring at the sides has been associated to the largest instantaneous slipstream velocities a HST induces [3]. This interaction is removed through large-scale separation off the roof, preventing the formation of the trailing vortex pair. The insight from this study provides an opportunity to better optimize a HST's geometry to reduce slipstream risk. Possible avenues for further research would be to examine ways to suppress vortex shedding to reduce the spanwise fluctuations of the wake. Alternatively, reducing the coherence of the streamwise vortices such as forcing large-scale separation as shown in these results, reduces slipstream but would also likely increase the pressure drag on the vehicle.

5. References

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