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Wind tunnel tests to obtain train aerodynamic drag coefficients: Reynolds number and ground simulation effects

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Summary

An assessment is made of the effect of different types of ground simulation on wind tunnel measurements of the aerodynamic drag of trains, together with an assessment of Reynolds number effects which must be considered when extrapolating from model scale to full scale values. Drag coefficients are considered for two train types, the French TGV001 and the British HST. It is shown that the errors involved in extrapolating values of drag coefficient from model scale to full scale are significantly greater than possible errors caused by inadequate ground simulation. These extrapolation errors seem to be due to significant three-dimensionality in the train boundary layers, and it is suggested that these effects warrant further research.

1. Introduction

There are two main reasons for wishing to obtain values of train aerodynamic drag coefficient from wind tunnel tests: firstly to assess the effects of various drag reduction techniques and secondly to provide an input to a train resistance equation for journey time calculation etc. While for the first requirement absolute accuracy of the drag coefficient measurements is not needed (since relative drag values are of interest), for the second requirement fairly accurate absolute values are needed. This paper considers the adequacy of wind tunnel tests in providing such accurate full scale drag coefficient data. Such wind tunnel tests are by no means straightforward — the high length-to-height ratio implies either large tunnel blockage (and the use of blockage corrections) or small scales (with the need to correct to full scale Reynolds numbers). Also, the way in which the ground should be simulated in wind tunnel tests is not clear: are static ground plane tests adequate or should more complex moving ground plane or image model tests be used? These points will be addressed in what follows.

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2. Theoretical background

The aerodynamic drag coefficient of a train C_D, is given by:

$$C_D = D/1/2\rho AV^2 \qquad (1)$$

where D is the drag force in zero cross-wind, V is the train velocity, A is a reference frontal area and ρ is the density of air. As an approximation one may write the following expression for C_D, which assumes a two-dimensional flat plate analogy for skin friction drag

$$C_D = \alpha + \beta \log(\mathrm{Re})^{\gamma} \qquad (2)$$

where Re is a Reynolds number based on train speed and length, α is the pressure drag (independent of Reynolds number) and the term $\beta \log(\mathrm{Re})^{\gamma}$ represents skin friction drag [1]. It is the second term that makes model scale values of C_D difficult to relate to full scale values since its value can vary significantly over the Reynolds number range between model and full scale, particularly for high speed passenger trains. Now there are two possible ways of correcting model scale data to full scale. Firstly, it could be assumed that eqn. (2) is directly applicable and the results can be plotted in the C_D–log(Re) plane and then simply extrapolated to full scale values. Secondly, boundary layer measurements at model and full scale could be used to assess the skin friction component of the drag coefficient at all scales. Drag measurements at model scale would then enable the pressure drag independent of Reynolds number to be calculated from eqn. (2). If this is taken to be the same at full scale and at model scale, a further application of eqn. (2) should enable the full scale value of C_D to be calculated. Both these methods will be used in what follows.

3. Experimental data

The two sets of experimental data that were used were as follows.

(a) Full scale and 1/20 model scale data for the French (SNCF) TGV001 train in two configurations: two power cars and one intermediate trailing car (2+1) and two power cars and three intermediate trailing cars (2+3). Model tests were carried out with the models above a static ground plane, above a moving ground plane, and using the image model technique of ground simulation. Full scale tests were carried out using the well established coasting technique. Full details of test techniques are given in ref. 2.

(b) Full scale, 1/40 scale and 1/76 scale data for the British (BR) HST in the configuration of two power cars and eight trailing cars (2+8). Model tests were carried out with the models above a static ground plane at 1/76 and 1/40 scales; above a moving ground plane at 1/40 scale, and using the image model technique at 1/76 scale. Full scale tests were again carried out using the coasting technique. The sources of these data are described in ref. 1.

4. Experimental results and discussion

Figure 1 shows a plot of the drag coefficient against scale Reynolds number for the HST and TGV tests. C_D is defined by eqn. (1) with $A = 9.12\ m^2$ full scale for the HST and 7.88 m^2 full scale for the TGV. The scale Reynolds number is the ratio of the test Reynolds number to the full scale Reynolds number at a train speed of 30 m s^{-1}. This figure shows several interesting features. Let us consider the relationship between the image model results and the results with the model mounted above a static ground plane. For both the

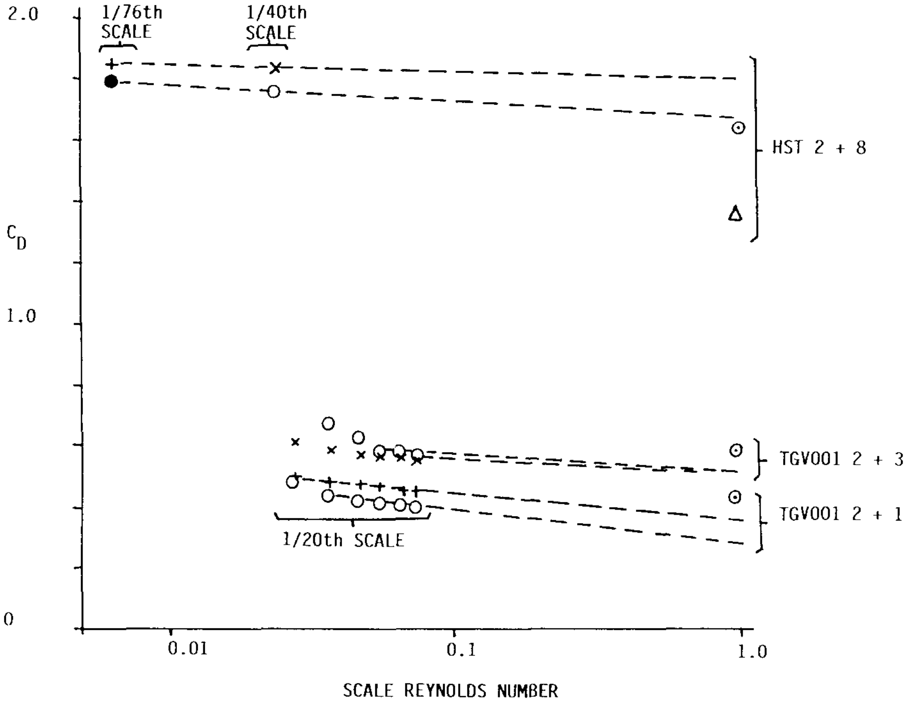

Fig. 1. Variation in drag with Reynolds number: ⊙ full scale, ○ static ground with leading edge suction, ● static ground without suction, + image model, × moving ground, - - graphical extrapolation of model results, △ extrapolation of model results using skin friction measurements.

1/76 scale HST results and the 1/20 scale TGV001 (2+1) results, values for C_D for the image results lie above the values for the static ground plane result, by about 3% for the HST and about 11% for the TGV. This is to be expected for two reasons. Firstly, since in the static ground tests the models are immersed in a ground board boundary layer, the average velocity experienced by the train models will be less than the free stream velocity that is used in the non-dimensionalization of measured drag. Thus even if the true drag coefficients in the two types of test were identical, non-dimensionalization would result in a lower calculated value of C_D for the static ground tests. Secondly, because the average velocity around the train is lower in the static ground tests, the model skin friction will also be lower, which will again result in lower values of drag coefficient for these tests.

In contrast to this fairly well defined trend, if the results for moving ground and static ground tests are compared, they can be seen to be somewhat contradictory. For the 1/40 scale HST tests, C_D for the moving ground tests lies above C_D for the static ground tests by about 4%. For the 1/20 scale TGV001 (2+3) the reverse is true, with a 3% decrease in C_D (at least at the higher values of Reynolds number). Thus it can be seen that the various types of simulation affect the values of C_D measured in wind tunnel tests by up to about 10%. Now the extrapolation of these results to full scale Reynolds number will be considered.

Firstly we consider the results for the static ground tests for the HST at 1/76 and 1/40 scales. When extrapolated to full scale (assuming a logarithmic variation of C_D with Reynolds number), they produce a value of C_D which differs from the measured full scale value by about 2%. If the 1/76 scale image tests and the 1/40 scale moving ground tests are similarly extrapolated, the result differs from the full scale value by about 10%. For the TGV001 (2+1) results, an extrapolation of the static ground results produces results which differ from full scale values by 33%, and a similar extrapolation for the moving ground results produces a 17% difference. Extrapolation of the results for TGV001 (2+3) is somewhat difficult as these results do not lie on a straight line in the experimental plane. The increase in the magnitude of the gradient of the drag coefficient versus Reynolds number curve at low values of Reynolds numbers suggests that the model boundary layer was not turbulent over the whole vehicle. However, extrapolating both moving and static ground results for the higher Reynolds numbers to full scale produces results which differ from the full scale values by 12%. Guiheu [2] claims excellent agreement between full scale and model scale results. Clearly, this conclusion can only be arrived at by ignoring the variation of C_D with Reynolds number.

Now, by using the second extrapolation method outlined in Section 2 (i.e. the measurement of skin friction drag by boundary layer measurements at all scales, and the assumption of constant pressure drag at all scales), it is possible to extrapolate values of C_D from model scale to full scale. The results are again shown in Fig. 1 for the HST. It can be seen that the full scale drag coefficient is substantially underpredicted by 16%.

Thus it would seem that errors involved in extrapolating model scale values to full scale conditions are significantly greater than those associated with differing ground simulations. The model tests themselves are probably reliable to within, say, ±3%, while the full scale tests should have error bounds of around ±10%. So it would seem that extrapolating errors from model scale to full scale are significant, even when full scale experimental error is considered.

The question then arises as to why such extrapolations are inadequate. The reasons are to be found partly in the HST boundary layer measurements reported by Brockie [1], and summarized in Fig. 2. Values of boundary layer momentum thickness θ are plotted against the position on the train. TC1, TC2 etc. indicate the positions of the centres of trailing coaches 1, 2 etc. These positions are 21.8 m apart at full scale. The Reynolds numbers for these tests are as indicated in Fig. 1. Results for both train side and roof boundary layers are given. Also shown are boundary layer calculations using an integral method of proven accuracy for two-dimensional flows [3]. It can be seen that the calculation method overpredicts train side values of θ, and underpredicts train roof values. This suggests flow three-dimensionality, with the flow diverging up the train sides and converging on the train roof centre-line. In view of this,

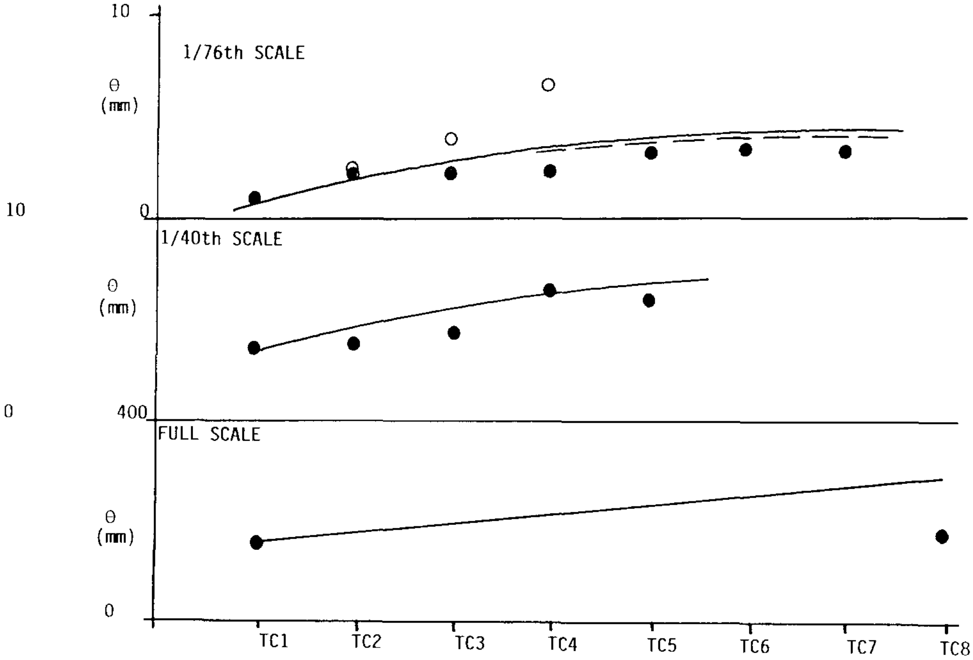

Fig. 2. Boundary layer measurements for the HST: ● train side measurements, ○ train roof measurements, — grain side calculations, - - train roof calculations.

the failure of extrapolation techniques, which are essentially based on the assumption of a log–linear relationship between drag coefficient and Reynolds number (i.e. a two-dimensional flat plate analogy), is perhaps not surprising.

5. Conclusions

From what has been said the following conclusions can be drawn.

(a) Different types of wind tunnel ground simulation produce differences of up to approximately 10% in model values of train drag coefficient.

(b) Extrapolation of model scale results to full scale can produce values of C_D which differ from full scale values by up to about 30%.

(c) The determination of a reliable means of extrapolation of model scale results to full scale seems to be more important than the determination of the best type of wind tunnel ground simulation.

(d) Since the failure of extrapolation methods seems to be due to severe boundary layer three-dimensionality, three-dimensional boundary layer calculation methods suitable for calculating train skin friction drag should be developed.

References

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