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Using singular systems analysis to characterise the flow in the wake of a model passenger vehicle

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Abstract

As the time-dependent fluid dynamics of wakes becomes important in industrial applications such as vehicle design, so techniques need to be found that enable these dynamics to be characterised. Whilst laser Doppler anemometry and particle image velocimetry are becoming widespread in their application, they are not necessarily suitable for this application due to their low rate of data capture when air is the working fluid. In this paper, a methodology that has already been applied successfully to low Reynolds number flows is applied to a turbulent wake. This involves the use of hot-wire anemometry to capture a large number of time series of velocity throughout the wake of a model road passenger vehicle. These time series are then analysed by a mathematical analysis tool known as singular systems analysis, which enables the low-frequency components of a noisy signal to be determined. This is done in the framework of non-linear dynamical systems theory so that the underlying dynamics of the wake can be determined. From this it is possible to characterise those areas of the wake where coherent dynamical structures are present and to explore the mechanism responsible for the oscillation of the wake. The paper reviews the background to singular systems analysis systems analysis and describes the application of the technique to the characterisation of the dynamics of the wake of a model vehicle placed in an open jet wind tunnel. Results are presented for three cross-flow planes in the wake where the structure of the wake is revealed in a new light. In particular, it is clear that the traditional picture of the vortex core appear to be present around the periphery of the vortex and in other areas where shear is apparent in the mean flow. The analysis technique allows the motion of these to be tracked downstream through the wake, whereas simpler analysis techniques do not allow such tracking to be carried out.

Keywords: Wakes; Hot-wire anemometry; Vehicle aerodynamics; Unsteady flow; Non-linear dynamics

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1. Introduction

1.1. Background

At present there is a trend for road passenger vehicles to become lighter and more streamlined in an attempt to reduce fuel consumption and so increase the efficiency of such vehicles, as well as to assist in materials recycling [1–3]. These changes in vehicle design have a negative consequence in that future vehicles might well be more susceptible to any aerodynamic forcing of the vehicle body due to oscillations of the vehicle wake. Because of this, there is now an increased interest in the prediction of the dynamic stability of a vehicle at an early stage in the design process.

As the low-frequency oscillation of the vehicle wake can affect the stability of the driver–vehicle combination, a more detailed understanding of the oscillatory nature of a wake is necessary, if appropriate design decisions are to be made. Traditionally, information on the flow behaviour in the wake has been gathered using some form of anemometry, usually using either laser Doppler anemometry (LDA) [4] or hot-wire anemometry (HWA) [5], to obtain time series of the flow velocity in the wake. Recently, particle image velocimetry (PIV) [6] has also become available and has been used to look at vehicle wakes [7].

Unfortunately, previous work has often assumed that the flow in the wake behind a vehicle is steady or quasi-steady. It is from this assumption that the traditional picture of a vehicle wake with two contra-rotating vortices emerges [8]. Following close behind a road vehicle in the rain enables the wake motion to be made visible, as spray coming off the vehicle moves through the wake. In these circumstances the wake is seen to have a large time-dependent component demonstrating that the idealised model of two vortices which are steady in time is not true. Recent PIV studies [7] have confirmed this by showing large-scale vortical structures distributed throughout the wake that not only move with time but are also created and destroyed as time evolves.

Determining the dynamics of the wake using either LDA or PIV methods is difficult at present, however. For example, LDA methods measure the velocity of particles in the flow as they pass in a random way through the measurement volume. This means that the time series generated is not evenly spaced in time and can also have a poor frequency resolution due to the low sampling rate, typically around 200 Hz for flows involving air. Equally the time resolution of PIV is normally very poor, around 15 Hz. Hence, there is still a place for HWA techniques, which have frequency resolution in the kilohertz range, to provide a means of determining the dynamics of the wake.

Work has been going on for some time using singular systems analysis (SSA) to analyse the wake of the flow behind a cylinder at low Reynolds numbers, both before and after transition of the wake from laminar to turbulent flow. This work [9–11] has shown that the flow structure of the wake is quite clearly made visible from the data obtained with SSA, and also that the dynamics of the flow can be determined by careful analysis of the time-series data.