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Vortical Flow Structure in the Wake of an Estate Car

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Abstract. A finite volume simulation of unsteady vortical wake flow behind a square-back estate car is presented. The three-dimensional time-averaged incompressible Navier-Stokes equations are solved together with the Reynolds stress transport equations for turbulence. By virtue of the simulated surface streamlines, the physics of fluid can be extracted using the topological theory. In addition, the simulated topological singular points and lines of separation are plotted on the car surface. The vortical flow motions that developed behind the mirrors, wheels and car body are explored by means of the simulated time evolving vortex corelines. The formation and interaction of the vortex systems in the wake are examined by tracing the instantaneous streamlines in the vicinity of the simulated vortex corelines. The vortex street behind the estate car is also illustrated by the simulated streaklines. Finally the Hopf bifurcation phenomenon is revealed by the time-varying aerodynamic forces on the car.

AMS subject classifications: 65M08, 76D05

Key words: Vortical wake flow, estate car, topological theory, vortex corelines, vortex street, time-varying aerodynamic forces.

1 Introduction

Airflow around a vehicle can be physically very complex due to nonlinear nature of equations of motion. What further complicates the exterior aerodynamics is the variety of appendants on the car surface, which can strongly affect the car performance. For example, an aerodynamic designed wing mirror helps to gain 5% drag reduction for a typical diesel-engine heavy truck. The resulting fuel saving can be with an amount of 500-1000 liters a year. Besides improving fuel economy owing to drag reduction, issues such as the wind loading, handling of rain, snow and dirt around the vehicle are also crucial. Note

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that cabin ventilation, underhood thermal management and brake cooling depend also on the external aerodynamics. To meet the desired vehicle aerodynamic design requirements, there is a strong need for acquiring more information about the air flow behavior around vehicle.

In the past, wind tunnel testing is the sole source to obtain aerodynamic data around the vehicle. With the advent of increasingly faster and cheaper high-performance computers and commercially available codes for grid generation and flow visualization, the flow details around automobiles can be obtained cost-effectively by means of flow simulation. The simulated results can be correlated with test results to within 5%, while temperatures correlated to within 10%. Nowadays, the numerical simulation tool has been the daily practice in the vehicle design. Almost all the major automobile manufactures combine now the capabilities of wind tunnel testing and computational fluid dynamics techniques and put them to optimal use for obtaining a best designed vehicle shape [1–3].

The rest of this paper is organized as follows. In Section 2 working equations for incompressible viscous fluid flow, transport equations for Reynolds stresses, boundary conditions and aerodynamic force equation are described for use in external car aerodynamics. This is followed by brief descriptions of the packages Pro/Engineer [4], ICEM-CFD [5], CFX [6] and FIELDVIEW [7] for CAD, mesh generation, flow solver and visualization of simulated results, respectively, in Section 3. In Section 4, results are presented in addressing flow topology, formation of vortex corelines, and field variables such as pressure distribution, velocity vectors, streamlines, streaklines, and time-varying aerodynamic forces. Finally, conclusions are drawn in Section 5.

2 Model equations

Airflow over the investigated car schematic in Fig. 1 is unsteady and turbulent in nature. We, therefore, need to solve for the transient incompressible Navier-Stokes equations together with the Reynolds stress transport equations to account for turbulence.

Figure 1: The full model for the investigated estate car, namely, the Mitsubishi Freeca. Photograph courtesy of China Motor Car.