

A FRAMEWORK FOR THE ANALYSIS OF THE COUPLED AERODYNAMIC-DYNAMIC RESPONSE OF A VEHICLE: AN OPENFOAM APPROACH

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Introduction

In Formula 1 competitions, the sensitivity of aerodynamic loads to the ride height variation on a lap became a matter of increasing concern with the 2022 revision of the regulations. Since the first track tests, it became clear that all cars suffered from a severe bouncing at high speeds. This phenomenon, commonly referred to as *porpoising*, stems from the coupling of the ground effect aerodynamics with the suspension system. As the car reaches top speed, and the downforce increases, the ride height decreases progressively. At a critical height, the flow under the floor stalls and the downforce is suddenly lost. The suspension springs then raise the car until the downforce is recovered and the cycle repeats. None of the F1 teams was able to anticipate porpoising, neither in numerical simulations nor in wind tunnel experiments, but only observed it in first track tests. Despite the evidence, the physics of porpoising is still not fully understood today. To understand and predict porpoising, we need a multi-physics framework coupling the aerodynamics of the vehicle to its dynamics, and possibly accounting for structural deformation.

This work aims to fulfill this need by presenting a preliminary computational framework based on a rigid vehicle model.

Method

The computational framework couples OpenFOAM [1] with a vehicle dynamics model exported as a Functional Mock-up Unit (FMU). The coupling is handled using preCICE [2], an open-source library for partitioned multi-physics simulations that enables black-box coupling between PDE-based solvers.

One of the most critical aspects of unsteady CFD simulations is the deformation of the mesh around the moving body. OpenFOAM provides different morphing methods, but all fall short when dealing with large vertical oscillations of the car near the ground. To overcome this limitation, together with the aim of providing an industrial-sized, efficient and robust framework, a custom motion solver is developed taking advantage of a commercial morpher based on Radial Basis Functions (RBF). RBF Morph [3, 4] is used in a preprocessing phase to compute the maximum prescribed node displacement. The computational framework specifies the kinematic chain through linear superimposition of the car modes. This flexible approach allows to replicate both the longitudinal and lateral motion of the car. In OpenFOAM, at each time iteration, the mesh nodes are linearly moved along the pre-computed trajectory, according to a step computed with the FMU. Figure 1 illustrates the workflow. Note that the framework is modular. Therefore, it can potentially accommodate any solver to flexibly change the level of fidelity in the describing the physics of the problem.

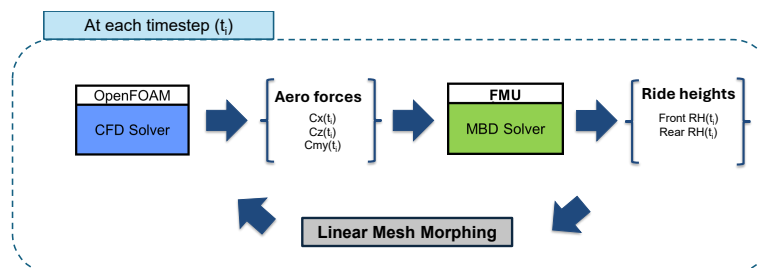


Figure 1: Workflow of the coupled computational framework.

Preliminary Results

The Windsor body is selected as the use case to test the framework. This simple car geometry is widely used in automotive aerodynamics as a popular benchmark. The Windsor body features the main flow phenomena observed in road vehicles

while avoiding excessive geometric complexity [5, 6]. In addition, extensive experimental data are available for validation. The flow field is computed by solving the unsteady incompressible Reynolds-Averaged Navier–Stokes (RANS) equations, using the open-source CFD software OpenFOAM. Turbulence effects are modelled using the $k-\omega$ SST model, which is widely used in automotive aerodynamics due to its ability to accurately predict flow separation.

The vehicle dynamics is represented by a two-degree-of-freedom half-car model. The vehicle body is modelled as a rigid body with mass m and pitch moment of inertia I_y , allowing vertical (heave) and pitching motions about the center of gravity. The body is connected to the ground through front and rear linear spring–damper suspension systems, see Fig. 2. Preliminary results show that the proposed framework is both suitable and effective for reproducing the investigated phenomenon. As shown in Fig. 3 at low ride heights and for certain suspension damping values, the aerodynamic forces couple with the suspension system, leading to oscillatory behaviour. Depending on the suspension stiffness, these oscillations may either decay or develop into sustained sinusoidal motion.

The planned work consists of a deeper analysis of the unsteady aerodynamics, targeting also different geometries.

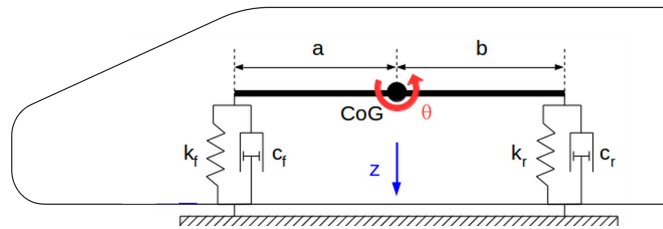


Figure 2: Half car two-degree-of-freedom model.

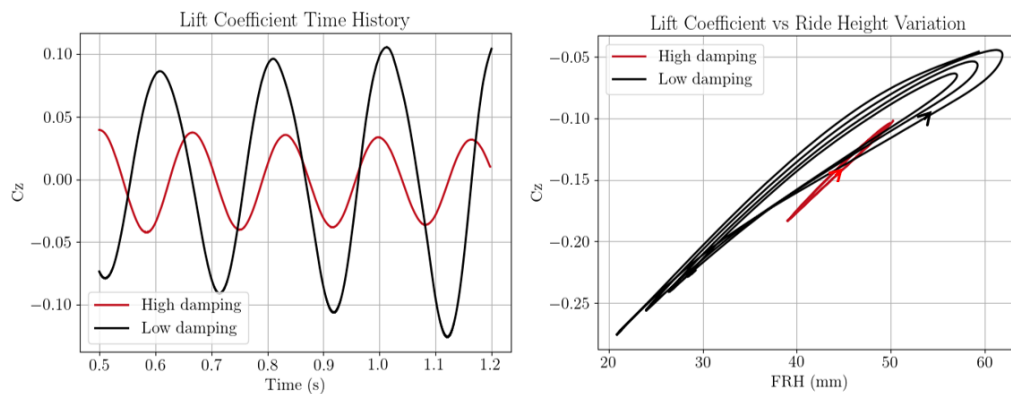


Figure 3: Lift coefficient variation with respect to time (left) and front ride height (right).

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