

A Scalable Numerical Method for Simulating Flows Around High-Speed Train Under Crosswind Conditions

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Abstract. This paper presents a parallel Newton-Krylov-Schwarz method for the numerical simulation of unsteady flows at high Reynolds number around a high-speed train under crosswind. With a realistic train geometry, a realistic Reynolds number, and a realistic wind speed, this is a very challenging computational problem. Because of the limited parallel scalability, commercial CFD software is not suitable for supercomputers with a large number of processors. We develop a Newton-Krylov-Schwarz based fully implicit method, and the corresponding parallel software, for the 3D unsteady incompressible Navier-Stokes equations discretized with a stabilized finite element method on very fine unstructured meshes. We test the algorithm and software for flows passing a train modeled after China's high-speed train CRH380B, and we also compare our results with results obtained from commercial CFD software. Our algorithm shows very good parallel scalability on a supercomputer with over one thousand processors.

AMS subject classifications: 76D05, 76F65, 65M55, 65Y05

Key words: Three-dimensional unsteady incompressible flows, high-speed train, crosswind, full Navier-Stokes equations, Newton-Krylov-Schwarz algorithm, parallel computing.

1 Introduction

In recent years, high-speed trains with characteristics of high-speed, high-efficiency and low-energy consumption have been rapidly developed. When the wind is strong, trains

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experience certain aerodynamic phenomena such as increased drag and lift, reduced stability and raised level of acoustic noise. Unfortunately, the increase of speed often enhances these negative effects, and some of which may result in accidents if they are not controlled correctly. Several train accidents caused by crosswind were reported in [6,22]. Crosswind is one of the main threats that impact passenger's comfort and/or vehicle's safety in high-speed train transportation. Therefore, it is both important and necessary to carefully study the aerodynamic performance of trains under crosswind conditions.

Experimental techniques and commercial software based numerical simulations are the two main tools in the train industry since analytical techniques are only applicable for a few limited cases. Experimental investigations are usually expensive and subject to the restrictions of design cycle, special boundary conditions and Reynolds numbers, and sometimes become not applicable or even impossible for high-speed trains. Numerical simulations are used more often and now become an important engineering tool, especially in the early design stages.

Historically, numerical simulations of crosswind around a train are inherited from a simple model, the Ahmed body [1], which includes most of the flow features in a real vehicle. Khier et al. [16] first use Reynolds averaged Navier-Stokes (RANS) equations combined with the $k-\epsilon$ turbulence model to study the flow structures around a simplified train under crosswind. In recent years, researchers have applied other techniques in solving this problem numerically. The majority of these simulations are to apply some kind of statistical techniques to reduce the computational cost. RANS [9], large eddy simulation (LES) [10,11] and detached eddy simulation (DES) [7,17] are the three main approaches. All of these approaches can successfully obtain the flow structures relatively accurately. However, with the speed of trains increasing, certain design problems neglected at low speed are raised, more detailed computations are needed for the operational safety of a high-speed train. In this paper, we solve the full Navier-Stokes equations numerically without any further simplifications, on a very fine mesh of size $10^{-3}m$ in order to capture the subtle features and obtain sufficiently accurate solutions. Due to the limitation of computer memory and processing speed, this method is usually considered as a research tool rather than an engineering tool. In the past few years, the full Navier-Stokes equations have been successfully used to the low Reynolds number cases, but high Reynolds number flows implies a wide instantaneous range of scales, and high computing cost. Thanks to the recent development of large scale parallel computers with a large number of processors, the computational capability is improved significantly. This makes it possible to use full Navier-Stokes for engineering problems like the aerodynamics of a high-speed train. Correspondingly, the parallel scalability becomes an important indicator of a good numerical algorithm.

In this work, we present a scalable parallel Newton-Krylov-Schwarz (NKS) method for the full unsteady incompressible Navier-Stokes equations describing the flows around high-speed train under crosswind. Generally speaking, the NKS method is suitable for solving large, sparse nonlinear systems and has been widely applied in various problems [4, 5, 13, 14, 20]. In our algorithm, a fully implicit backward difference scheme is