AN EFFICIENT METHOD FOR HYPERSONIC LAMINAR–TURBULENT TRANSITION PREDICTION

Allocation: Innovation and Exploration/140 Knh
PI: Oliver M. F. Browne[1]
Collaborator: Christoph Brehm[1]

[1]University of Kentucky

EXECUTIVE SUMMARY

A thorough understanding of the laminar–turbulent transition process of high-speed boundary layers is of paramount importance when designing supersonic or hypersonic vehicles. These high-speed vehicles are among the most difficult and challenging to design owing to significant aerothermal loads experienced on the vehicle during the transition to turbulence. An accurate prediction of the boundary-layer state can help reduce design margins and, ultimately, guide the development of novel, innovative, high-speed vehicles.

In this project, the research team has developed and validated a new efficient stability and transition prediction method for hypersonic boundary layers; namely, the AMR–WPT (adaptive mesh refinement wavepacket tracking) method, which was up to 10 times more efficient when compared with static mesh approaches. The AMR–WPT method was validated against conventional stability and transition methods (LST—linear stability theory, DNS—direct numerical simulation, etc.).

RESEARCH CHALLENGE

Conducting numerical transition prediction investigations for complex geometries is either generally too computationally expensive (*e.g.*, DNS) or unable to capture all flow physics (*e.g.*, nonlinear receptivity, nonlinear instability mechanisms, nonlinear breakdown, and the like). The latter is due to the assumptions that these conventional methods rely upon (*e.g.*, LST—linear and parallel flow assumption; parabolized stability equations—mostly linear, although they can be weakly nonlinear, etc.) The AMR–WPT method attempts to capture all flow physics as DNS can but also to be competitive with LST in terms of computational efficiency.

In many cases, the instabilities in high-speed boundary layers are convectively unstable and appear as localized convecting wavepackets. This inherent nature of the wavepacket can be exploited with AMR, which can be employed to track the wavepacket as it convects downstream and ultimately reduce the number of grid points that are required for the simulation.

METHODS & CODES

The governing equations of the AMR–WPT method are the disturbance flow formulation of the 3D compressible Navier–Stokes equations. This formulation decomposes the flow state vector and fluxes in the Navier–Stokes equations into steady base flow (or mean flow) components and unsteady disturbance components. From the disturbance flow equations, the higher-order terms can either be dropped to solve the linear disturbance flow equations or included to solve for the nonlinear disturbance flow equations—this research considered both. The base flow terms are computed by interpolating from a base flow solution on a base flow mesh.

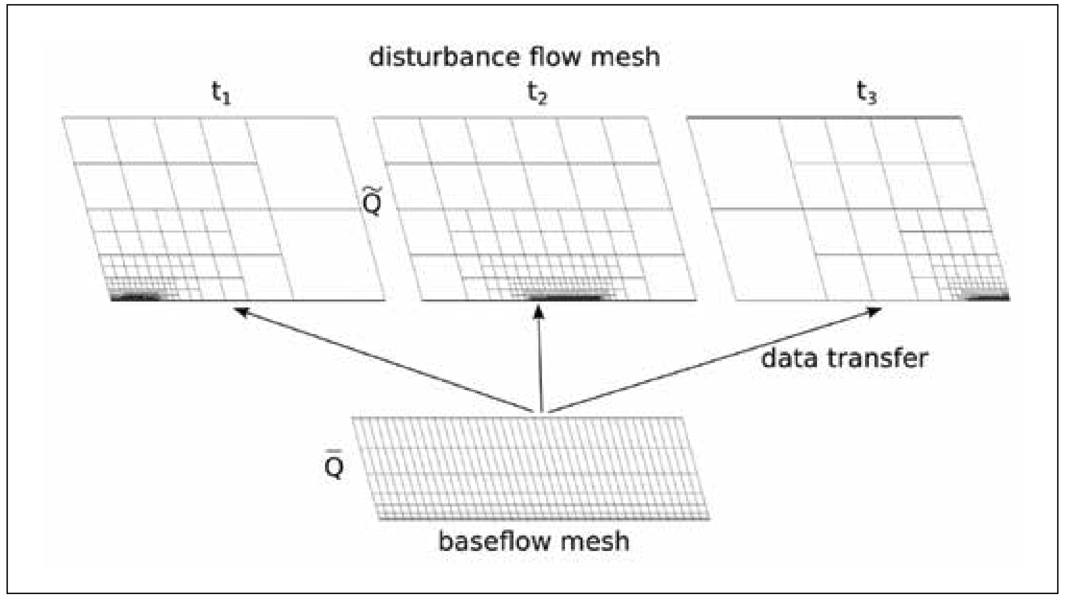

Figure 1: Overview of overset mesh approach for AMR–WPT method (adjusted from [1]).

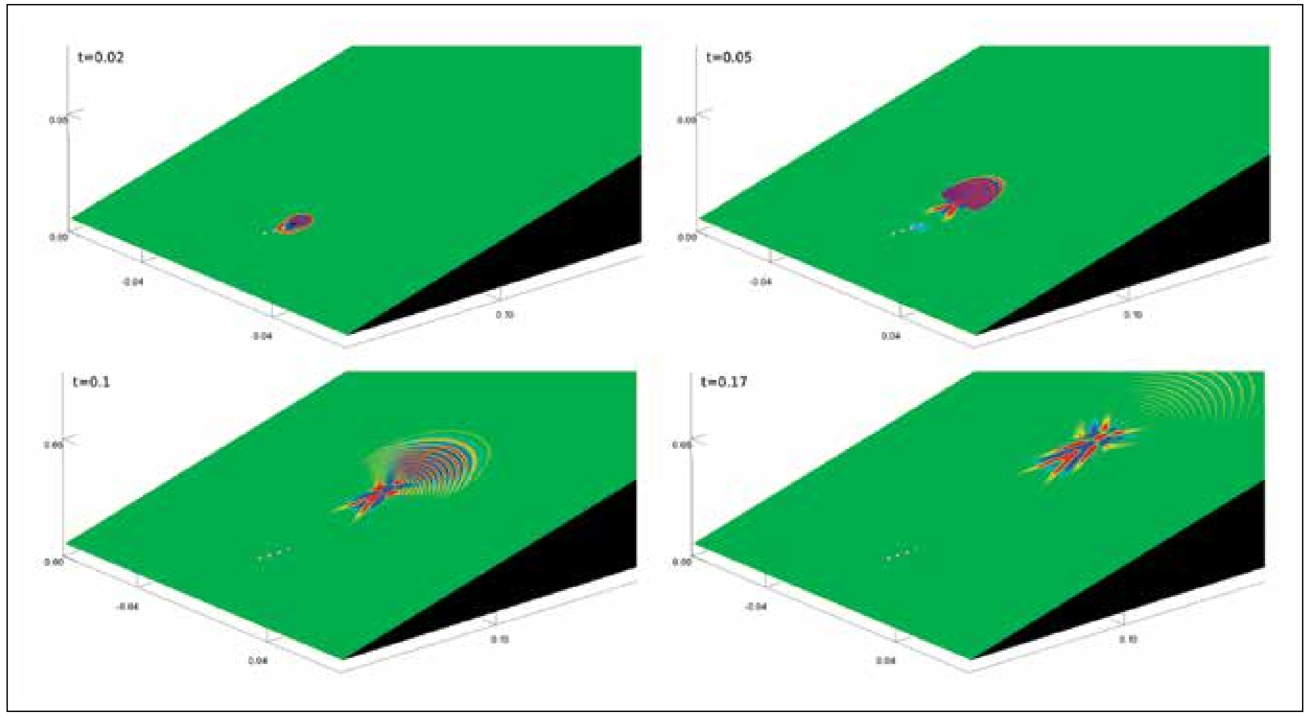

Figure 2: Instantaneous visualization of particulate trajectory and collision (contour showing pressure disturbance) with 3D M = 4 14° straight wedge at four time instances (adjusted from [3]).

The disturbance is introduced into the flow field via wall forcing (blowing/section) [1,4], which subsequently develops into a wavepacket. Disturbance generation via particulate collision was also investigated [3]. At predefined intervals, a refinement/derefinement step is performed to redistribute the grid points to track the wavepacket as it convects downstream (Fig. 1).

The AMR is handled by the external library PARAMESH [5]. Higher-order prolongation and restriction operators are employed for transferring the information between different refinement levels in the block-structured Cartesian mesh. Dynamic load balancing and Morton ordering is used to redistribute the loads among the different processors after each refinement/derefinement step is performed.

RESULTS & IMPACT

The AMR–WPT method has been validated against a number of test cases including: (1) a 2D M = 5.35 (M is Mach number) flat-plate boundary layer [1,2]; (2) an axisymmetric M = 10 7° straight cone [1,2]; (3) a 3D M = 5.35 flat-plate boundary layer [4]; and (4) a 3D M = 4 14° straight wedge [3]. Fig. 2 shows an example of the AMR–WPT method for a particulate collision.

The AMR algorithms were able to successfully track the wavepackets in all cases and significantly reduce the number of grid points that were required when compared with static mesh methods. In static mesh approaches, the computational cost scales with the size of the domain whereas with the AMR–WPT method the cost scales with the size of the wavepacket. Different criteria were tested to determine the most appropriate parameter(s) for tracking the wavepackets (*i.e.*, refining/derefining the mesh). This ultimately comes down to a compromise between efficiency and accuracy [1–4]. The next step will be to examine more complex geometries.

WHY BLUE WATERS

The Blue Waters supercomputer and its staff were essential for this research. The large amount of computational resources and storage facilities available on the system played a considerable part in enabling this research to move forward at the pace it did. The expertise of the project staff allowed the research team to maximize the efficiency of its code and parallelization capacity on the Blue Waters system.

PUBLICATIONS & DATA SETS

O. M. F. Browne, S. M. A. Al Hasnine, and C. Brehm, "Towards modeling and simulation of particulate interactions with high-speed transitional boundary-layer flows," presented at the AIAA Conf., Dallas, TX, U.S.A., 2019.

O. M. F. Browne, A. P. Haas, H. F. Fasel, and C. Brehm, "An efficient nonlinear wavepacket tracking method for hypersonic boundary-layer flows," under consideration, 2019.