Applications of asymptotic-preserving (AP) methods to plasma dynamics simulations at realistic dimensionless parameters

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Over the past decade the numerical treatment of singularly perturbed problems has advanced significantly with the advent of asymptotic-preserving (AP) techniques [1]. For problems characterized by a small parameter ε, AP schemes are designed to work accurately in both the limit when the parameter is of order unity and when it approaches zero. AP schemes rely on a suitably constructed implicit part to assure the correct asymptotic behavior, thereby overcoming the limitations of a generic fully implicit or semi-implicit scheme.

In this work, we present two applications of AP methods to the context of plasma physics.

The first application concerns the strongly anisotropic transport of a scalar, such as temperature, in magnetic island geometry. Here the small parameter ε is the ratio of the perpendicular to the parallel transport coefficient. A suitable AP method is constructed which works on a uniform grid, with both open and closed field lines, without requiring alignment of the grid to the magnetic field. The strength of the method is demonstrated for values of the small parameter as low as $\varepsilon=10^{-10}$, in the case of both static and rotating magnetic islands [2].

As a second application, we have considered reduced resistive MHD system (RMHD) in two dimensions. Numerical simulations of RMHD are notoriously challenging because of the disparate time-scales, encompassing the Alfvén wave period and the resistive diffusion time, and because of the formation of thin internal layers, especially in the nonlinear phase. Upon suitable rescaling of the original equations, the small parameter ε turns out to be the inverse of the square of the Lundquist number S, $\varepsilon = S^{-2}$. The new scheme is specifically designed to study the long time scale dynamics with large time steps on the resistive time scale.
The tearing mode evolution and the formation of a magnetic island are considered as a test case. One finds that the scheme is able to reproduce efficiently the three regimes of the island dynamics, linear, Rutherford growth and saturation, with good agreement with known analytical results [3] for this problem. The scheme is shown to work well at $\varepsilon = 10^{-16}$ (Lundquist number $S=10^8$), with the quality of the simulation depending essentially on the resolution necessary to treat the small visco-resistive layer occurring around the separatrix [4].
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