

## ZEUS-3D 2-D Gallery #6: The Orszag-Tang Magnetic Vortex



The Orszag-Tang magnetic vortex (1998, J. Fluid Mech., 90, 129) has become a standard 2-D test problem for MHD codes. Shown above from left to right are: (i) density with velocity vectors superposed; (ii) the normal component of the vorticity,  $\omega_{\perp}$ ; (iii) the velocity divergence,  $\nabla \cdot \vec{v}$ , useful for mapping out shocks; (iv) magnetic pressure ( $p_B$ ) with magnetic field lines superposed; and (v) the total energy density,  $e_{\rm T}$ . Links to the respective animations are provided below each image.

The simulation was done on a  $256 \times 256$  Cartesian grid with periodic boundary conditions using CMoC, FIT (*Finely Interleaved Transport*) using the conservative total energy equation, artificial viscosity qcon=1 and qlin=0.1, second order (van Leer) interpolation (iord=2), and Courant number courno=0.75.

In developing FIT (trnvrsn=1), this test problem was instrumental in determining what density had to be used in evaluating the *emfs*. In using Legacy transport (trnvrsn=0), which lacks consistency when the primitive variables are updated, there was often a battle to suppress unwanted behaviour in various test problems which occasionally led to seemingly arbitrary algorithmic design. In particular, when the old MoC algorithm was introduced into ZEUS-2D by Stone & Norman (1992, ApJS), the *emfs* had to be evaluated using the density *before* the transport step, lest unwanted oscillations be excited in test problems such as this. Indeed, the original MoC was a combined Eulerian-Lagrangian algorithm with the Lorentz force update being the only portion done in a Lagrangian frame of reference for similar reasons.

In hindsight, this was because of the coarseness of the operator splitting in ZEUS at the time, and the sequence in which certain operations were performed. While I didn't realise it then, the development of CMoC (Clarke, 1996, ApJ) where I was able to make the MHD algorithm fully Eulerian was the beginning of the resequencing of the operator splitting in ZEUS that ultimately led to FIT. More recently when the benefit of consistently using updated primitive variables was appreciated (see the 2-D advection page for a discussion), the requirement of using the pre-transport density disappeared. In fact, the O-T problem was the first test problem I found to be sensitive to what density was used in computing the *emfs*. Once the main principle of FIT was adopted, namely that velocity and magnetic field be updated as soon and often as they can be, the O-T vortex made it clear that the density had to be fully updated as well.

Finally, looking carefully at the  $\nabla \cdot \vec{v}$  and  $\omega_{\perp}$  animations, one can see one very brief time in each where highly localised low-level oscillations are triggered, then disappear. Whether these are glimmers of the "shear instability" discussed on the Kelvin-Kelmholtz instability page is unclear. First, the shear instability was very prominent in animations of *primitive* variables such as the density; here it is only apparent and only very briefly in variables constructed from *differences* of primitive variables, which poses a very stringent test on the numerics. At this point, I am not particularly concerned with these oscillations.