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Author(s):	Ramsey, Scott D.
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Summary of Results for Converging Shock Wave Problems

Scott D. Ramsey, XCP-8

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The purpose of this note is to provide a brief overview of an attempt to simulate a Guderley-like imploding shock problem in xRAGE. Prior to this study, the following have been completed with respect to the Guderley problem itself:

- A canonical definition for use with ASC codes has been proposed (LA-UR-11-02765).
- 1D simulations with spherical symmetry on uniform grids have been performed, with associated spatial convergence analysis. The xRAGE code showed near 1st order convergence for this problem in the initial studies (LA-UR-10-06435).
- A version of the Guderley problem as been added to the xRAGE regression test suite.

More recently, a large number of simulations have been performed for the Guderley problem (and a similar problem) using xRAGE's (v. 1009.02) AMR capability.

1D Results

With 1D spherical symmetry, AMR can easily be brought to bear on the Guderley problem itself, as only a few additional flags need to be set in input decks used for previous spatial convergence studies.

AMR flag	Meaning	Setting
norecon	If false, enable AMR	False
numlev	Number of allowed AMR levels	10 (1D), 5 (2D)
pctdiv	Relative adjacent cell pressure threshold to mark for AMR	0.001

Table 1: xRAGE flags used to enable AMR.

There are additional settings that control the AMR package in different ways (e.g., different refinement criteria, number of allowed refinement levels, etc.), and these have yet to be investigated. The flags appearing in Table 1 were used for all xRAGE simulations including AMR.

The 1D spherical Guderley problem is initialized in a $\gamma = 1.4$ gas over $r = (0,3)$ with a shock located at $r = 1$, so that it hits the origin at $t = 1.0$ and reflects out into the gas for $t > 1.0$. All subsequent analysis is performed over $r = (0,2)$ so as to ignore the presence of spurious, boundary-driven rarefaction waves.

Selected 1D spherical results with and without AMR are shown in Figs. 1 and 2.

Figure 1: Refinement level for 1D spherical AMR Guderley calculation at a sequence of times.

Figure 2: “Eyeball” comparison of uniform-grid and AMR Guderley density solutions at $t = 0.5$ (converging flow, left) and $t = 1.5$ (diverging flow, right).

The Surrogate Guderley Problem

A purely numerical “surrogate Guderley problem” that closely replicates the 1D spherical Guderley results has been developed for use with 2D geometries. Even though this new problem does not have an exact solution, it is used to ease the challenge of initializing the inherently 1D spherical Guderley solution on a square grid.

The surrogate Guderley problem (SGP) is essentially a “spherical shock tube” problem. The SGP consists of two concentric spherical regions in a $\gamma = 1.4$ gas with constant properties, as outlined in Table 2.

	Inner region	Outer region
Inner spherical radius (cm)	0.0	4.0
Outer spherical radius (cm)	4.0	10.0
Initial density (g/cm ³)	1.0	6.0
Initial SIE (erg/g)	0.0	0.06
Initial velocity (cm/s)	0.0	0.0

Table 2: Surrogate Guderley problem setup.

The SGP simulates the shock jump conditions for the true Guderley problem as closely as possible at initialization, except for the velocity. As the flow evolves, a strong shock forms at $r = 4.0$ at $t = 0.0$ and moves inward through the inner region, hitting the origin at approximately $t = 14.1$ s. A Guderley solution can be fit with arbitrary precision to the SGP solution in the neighborhood of the shock for a wide variety of times.

To simplify matters, results will be presented for the SGP only at $t = 14$ s (converging flow) and 15 s (diverging flow), where the shock is located in the interval $r = (0,1)$, which will also be used as the analysis domain. Additional results are available for other times.

Figure 3: Guderley fit to SGP density results at $t = 14$ and 15 in 1D spherical symmetry.

Since the SGP does not have an exact solution, any spatial convergence analysis using for reference the results of the problem on a super-fine grid represents a calculation verification analysis. The results of such analysis are presented in Table 3.

Variable	$t = 14.0$ (converging flow)	$t = 15.0$ (diverging flow)
Density	1.2	1.3
Velocity	1.2	1.1
Pressure	1.3	1.1
SIE	1.3	1.3

Table 3: L1-norm spatial convergence rates for 1D spherical SGP over $r = (0,1)$ with 500/1,000/2,000 zones.

Reference solution: SGP with 10,000 zones over $r = (0,1)$.

Like the Guderley problem, the SGP can also be run with AMR settings enabled. The results of these calculations closely resemble those seen in Fig. 2, and will be omitted here for the sake of brevity.

2D (r,z) Results

The SGP is straightforward to initialize in 2D (r,z) geometry, as a circular boundary separating the inner and outer regions can be overlaid onto a uniform square grid. Since the boundary passes within a large number of computational zones, this initialization of course introduces symmetry perturbations into the resulting shock structure – one late time ($t = 14$ and 15 s) effect of which is seen in Fig. 4.

Figure 4: SGP SIE results at $t = 14$ (left) and 15 (right) on 100×100 uniform cells over $r = (0,1)$ (horizontal axis) and $z = (0,1)$ (vertical axis).

Enabling AMR for the 2D problem results in refinement in the neighborhood of the circular boundary before any time steps are taken, as shown in Fig. 5. The refinement appears to better resolve the shock. At later times ($t = 14$ and 15), Fig. 6 shows a lingering high degree of refinement surrounding the shock.

Figure 5: AMR level vs. cell center at $t = 0$, based on 40×40 initial zones over $r = (0,10)$ and $z = (0,10)$.

Figure 6: AMR level vs. cell center at $t = 14$ (left) and 15 (right), based on Fig. 5 initialization.

SIE results at $t = 14$ and 15 are shown in Fig. 7; post-bounce asymmetry has not been visibly improved.

Figure 7: SGP SIE results at $t = 14$ (left) and 15 (right) on AMR grid over $r = (0,1)$ and $z = (0,1)$.

An attempt was made to quantify the differences between the 2D uniform-grid and AMR simulations using L1-norm spatial convergence rates (Table 4).

Time (s)	Variable	25/50/100 Uniform	25/50/100 AMR
14 (converging flow)	Density	1.1	0.7
	Velocity	0.7	-0.1
	Pressure	0.9	0.4
	SIE	0.9	-0.3
15 (diverging flow)	Density	1.1	-0.2
	Velocity	0.9	-0.2
	Pressure	1.1	-0.4
	SIE	0.7	-0.1

Table 4: L1-norm spatial convergence rates for SGP over $r = (0,1)$ and $z = (0,1)$. “25/50/100” refers to initial number of computational zones over each of $r = (0,1)$ and $z = (0,1)$ at initialization.

In light of the poor (and of dubious meaning) convergence rate results for the AMR problem, L1-norm error (Table 5) vs. a high resolution 1D SGP calculation for the two problems, now with comparable run times, was also examined. At the time of this writing it is unclear as to whether or not the time budget for the AMR problem is being dominated by refinement effects outside of the $r = (0,1)$ and $z = (0,1)$ analysis domain.

Time (s)		50x50 AMR	216x216 Uniform
14 (converging flow)	Wall clock time (hr)	1.15	1.16
	# cells on (0,1) square	23,065	46,656
	L1 Density	3.00e-1	1.41e-1
	L1 Velocity	1.14e-2	2.08e-3
	L1 Pressure	2.74e-2	6.43e-3
	L1 SIE	3.99e-3	6.64e-4
15 (diverging flow)	Wall clock time (hr)	1.24	1.27
	# cells on (0,1) square	122,837	46,656
	L1 Density	3.59e-1	3.39e-1
	L1 Velocity	9.48e-4	8.62e-4
	L1 Pressure	1.88e-2	1.39e-2
	L1 SIE	6.01e-4	9.48e-4

Table 5: Wall clock time (yellowrail 256 procs), number of computational zones over $r = (0,1)$ and $z = (0,1)$, and associated L1 error norms for each flow variable. “50x50” and “216x216” refer to number of zones over $r = (0,1)$ and $z = (0,1)$ at initialization; the uniform zoning was chosen to enable a match of the AMR wall clock time as closely as possible.

Summary

An investigation of converging shock problems in conjunction with the use of AMR tools and/or 2D geometry has been initiated, and it appears that a more rigorous exploration of underlying settings and result analysis methods is warranted.

When done, it may also prove useful to explore additional test problems, including at least one that does not contain shocks. The ultimate goal of this effort is to examine the same problems using more than one ASC code.