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## APPLICATION AND VALIDATION OF DIRECT NUMERICAL SIMULATION FOR ICF IMPLOSION STABILITY ANALYSIS

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We have recently been applying a powerful computational tool, direct numerical simulation (DNS), to evaluate the stability of imploding inertial confinement fusion (ICF) capsules designed for the National Ignition Facility. In DNS, we explicitly calculate the evolution of realistic surface perturbations far into their nonlinear regimes, using a 2D Lagrangian radiation-hydrodynamics code. Because the mesh may become greatly distorted during the calculation, requiring frequent application of an automatic rezoner, and because we use a 2D code to represent 3D perturbations whose nonlinear behavior is shape-dependent, we have been seeking to assess the accuracy of DNS in as many regimes as possible. For this purpose, we have conducted experimental campaigns to observe the instability of radiatively driven imploding cylinders, deuterated-shell spherical capsules, and radiatively accelerated flat foils perturbed on the unheated surface ("feedout" experiments). We have compared DNS calculations to data from these experiments, and to theoretical predictions for incompressible Rayleigh-Taylor instability, with satisfactory agreement. Thus we are gradually accumulating confidence in the validity of DNS as applied to ICF.

### 1 Introduction

Large-memory vector-processor computers have in recent years made it practical to compute the evolution of multimode perturbations in inertial confinement fusion (ICF) capsule implosions throughout the duration of the implosion. Flexible automatic rezoning techniques<sup>1</sup> have enabled the use of 2D Lagrangian radiation-hydrodynamics codes such as LASNEX<sup>2</sup> for this purpose. A typical multimode surface-displacement perturbation, for example, can be followed computationally as it passes from an initial linear stage to an extremely nonlinear late stage, characterized by mode interactions, strong vorticity, and a large departure of the flow field from its unperturbed state. We use the term direct numerical simulation (DNS) to denote the process of

calculating the implosion of capsules and the development of such multimode nonlinear perturbations.<sup>4</sup>

Many DNS calculations have been performed<sup>3,4</sup> to evaluate the stability of capsules designed for the National Ignition Facility (NIF)<sup>5</sup> and similar facilities. DNS has allowed us to: set quantitative limits on the roughness of shell surfaces that is permissible if NIF capsules are to ignite; determine that capsules with expected levels of surface roughness are more sensitive to radiation drive time variations than are idealized 1D capsules; compare the relative hydrodynamic stability of shells with different ablator materials; and demonstrate the coupling of radiation drive asymmetry with surface perturbations.

Because of our increasing reliance on DNS for assessing the stability of NIF capsules, it is crucial that we have confidence in its accuracy.<sup>6</sup> We must try to validate DNS in as many regimes as possible, by comparing the results of DNS to experimental data and exact theoretical solutions, to identify the regimes of validity of the technique. In this article we shall describe briefly several ongoing efforts to carry out such validation, and describe some improvements to the computational technique of DNS.

## 2 Experimental Comparisons

### 2.1 Deuterated-shell implosions

An extensive series of experiments has been conducted over several years at Lawrence Livermore National Laboratory's Nova laser, to investigate the growth of perturbations in capsule implosions.<sup>6,7</sup> In the most recent experiments, hundreds of small pits are deliberately introduced into the ablator surface of the capsule during the fabrication process, as a controlled initial perturbation whose subsequent evolution may be diagnosed. We have recently applied DNS to the modeling of one class of perturbed-aborator experiments,

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<sup>4</sup>In the fluid mechanics community, DNS refers strictly to calculations in which the viscous dissipation scale is resolved. Calculations which do not resolve such a small scale, but instead employ a model of the small-scale flow below the grid resolution, are called large eddy simulations (LES). Our calculations more nearly resemble LES calculations, but use an artificial viscosity instead of a subgrid turbulence model. We prefer to avoid these fine distinctions in the context of ICF, and use the term "DNS" in a loose sense to apply to our simulations.

<sup>6</sup>Accuracy may be compromised by, for example, the severe distortion of the Lagrangian mesh for implosions with relatively large initial perturbations. Typically it is necessary in such situations to perform frequent rezoning of physical quantities to a more nearly orthogonal mesh. Furthermore, accuracy may be compromised by the fact that real perturbations are 3-dimensional, whereas in our calculations we must (so far) represent them as 2-dimensional.

in which the capsule contains hydrogen gas instead of deuterium gas, and a deuterated polystyrene (CD) shell instead of the usual polystyrene.<sup>8</sup> Thus in these implosions the fusion processes occur in the compressed CD shell rather than in the gaseous core, permitting an assessment of thermodynamic processes coupling the core and the shell. DNS has been successful in accounting for the observed variation of neutron yield with imposed surface roughness, including the relatively sudden fall-off in yield due to shell breakup, when the surface roughness exceeds 0.5  $\mu\text{m}$  RMS. The observed width of the neutron spectrum is also explained by Doppler broadening resulting from bulk motion of falling Rayleigh-Taylor (RT) "spikes" of deuterated polystyrene, with velocity of order  $10^7$  cm/s, during burn.

### *2.2 Perturbed cylindrical implosions; "feedout" experiment*

Two other experiment campaigns of particular value for DNS validation are the cylindrical implosion experiments<sup>9,10</sup> and the "feedout" experiments being performed at Nova. In the former, a cylindrical shell ablator composed of polystyrene and monobromostyrene is fabricated with a single-mode azimuthal surface perturbation (typically  $m=10$  or  $m=14$ ). The growth of the perturbation during the x-ray-driven implosion of the cylinder is imaged with an x-ray backlighter. Images of the perturbation have been compared directly with the predictions of DNS, with satisfactory agreement.

The feedout experiment addresses the seeding of ablative Rayleigh-Taylor (ART) instability at the ablation surface of a planar foil by a perturbation initially present on the cold side of the foil. This process is analogous to the seeding of ART by perturbations on the DT ice surface in NIF capsules. In both cases, Richtmyer-Meshkov (RM) instability occurs when a shock traverses the perturbed surface, and the subsequent RM flow field carries a perturbation of all physical variables back to the ablation surface, where the perturbation may be rapidly amplified. Initial experiments show reasonable agreement with computational predictions.

## **3 Theoretical Comparisons**

### *3.1 Linear phase of incompressible RT instability*

We have studied the accuracy of LASNEX calculations of planar incompressible RT instability for small-amplitude perturbations. In this case, the exact growth rate is known from theory. Calculations were performed with large internal energy, so the sound speed  $c$  is very high and the flow is nearly incompressible. For a perturbation with wavelength  $\lambda$  and gravity  $g$ , the con-

compressibility parameter  $M^2 \equiv g\lambda/c^2 \simeq 0.006$ . Our study examined the effect of mesh refinement on the accuracy of computed growth rates, for several values of the Atwood number  $A$ , where  $A \equiv (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ , and  $\rho_2$  and  $\rho_1$  are the densities in the upper and lower fluids, respectively. Calculations were done with  $A = 1/3, 5/6$ , and  $49/51$  and with the number of mesh cells per wavelength  $N$  between 10 and 80. Various amounts of linear artificial viscosity were used. We found that for  $A \geq 5/6$ , the computed linear growth rate was within 5% of the theoretical value provided  $N \geq 20$ . For smaller Atwood numbers, the convergence with mesh refinement was not so rapid. For  $A = 1/3$ , it was required that  $N \geq 35$  to give a computed growth rate within 5% of theoretical.

### 3.2 Late-stage bubble rise in incompressible RT instability

After the RT instability becomes nonlinear, the bubble eventually rises with constant velocity  $V_\infty$ . A simple analysis leads to  $V_\infty = \alpha \sqrt{2Ag\lambda/(1+A)}$ , where  $0.2 \leq \alpha \leq 0.3$ . Layzer<sup>11</sup> found  $\alpha \simeq 0.2303$  for a 2D bubble when  $A = 1$ . We have begun a computational study of the constant-velocity bubble, as a test of the rezoning capability of the code. To date, we have results for  $A = 1/3$  and  $N = 56$ , using several different prescriptions for the extent of rezoning. We find that the bubble velocity approaches within about 5% of the value of  $V_\infty$  obtained using Layzer's value of  $\alpha$ , at about the time that an extrapolation of the linear-stage bubble velocity reaches this value. The bubble velocity then decreases slightly (for a period of about one time unit  $\sqrt{\lambda/2\pi g}$ ), and then increases slowly again. There is no exact time-dependent theory of the bubble rise for  $A < 1$ , but the approximate agreement with  $V_\infty$  in this case is satisfactory.

## 4 Improvements to Numerical Technique

We have made progress in understanding the limits of the numerical technique used for DNS, and thereby increased our confidence in its results. Continued experimentation with numerical procedures has led to improvements in the accuracy and efficiency of the rezoning technique. An "anti-bow" capability is being tested, which is an efficient way to identify mesh cells that require rezoning. The use of graded remapping, where various parts of the mesh are allowed to approach farther or nearer the full Brackbill-Saltzman mesh solution, as necessary, has improved accuracy. Mesh refinement studies of full DNS capsule implosion calculations are leading to an understanding of zoning requirements.

We have also identified a surprising effect of mesh "hourglass" oscillations.

Such oscillations are one of the normal numerical modes of a finite-difference mesh, which preserve cell volume even as edge lengths oscillate in a correlated way. Such oscillations do no work on the fluid directly. Nevertheless, we have observed that such oscillations may be triggered by a physical perturbation, whose growth is then enhanced in some way by the presence of the hourglass oscillations, perhaps related to the effect of radiation flux. Thus it is crucial to prevent the occurrence of the hourglass oscillations. We have found several ways of doing so, including refining the radial mesh and rezoning the oscillating cells. Employing an "anti-hourglass" mesh stiffening algorithm may also prove useful.

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