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S. T. Weir, E. A. Chandler, B. T. Goodwin

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Rayleigh-Taylor Instability Growth Experiments in a Cylindrically Convergent Geometry

S.T. Weir, E.A. Chandler, and B.T. Goodwin
Lawrence Livermore National Laboratory
University of California, P.O. Box 808
Livermore, CA 94550

Abstract: Convergent geometry Rayleigh-Taylor experiments have been performed with a 122-point detonation initiation system on cylinders having sinusoidal perturbations on the outer surface ranging from mode-6 to mode-36. Experiments were performed with various perturbation mode numbers, perturbation amplitudes, and ring accelerations. Feedthrough perturbation growth on the inner surface was observed in several experiments, and in one experiment the feedthrough perturbation underwent a phase inversion. These experimental results were found to be in good agreement with linear, small-amplitude analysis of feedthrough growth in an incompressible, cylindrically convergent geometry.

1. Introduction

The gelatin cylinder technique1 has many features which make it a very attractive method for studying Rayleigh-Taylor instabilities. Precise control can be exercised over the gelatin strength, the driving pressure, and the initial perturbations. In addition, by using high-speed framing cameras, it is possible to obtain high-resolution images of the entire implosion history and to examine in detail all stages of the instability growth and cylinder collapse.

A number of interesting topics can be studied with this technique, including the rate of turbulent mix development in a convergent geometry, the mode-mode coupling of RT unstable modes in the weakly non-linear regime, and the feedthrough growth of perturbations on the inner surface of the cylinder. This last topic is of special interest to members of the intertial confinement fusion (ICF) community, since the feedthrough growth of instabilities is an important ICF capsule design concern. In our most recent experiments, we have chosen to focus on the observation and analysis of feedthrough growth in a cylindrically convergent geometry.

2. Experimental

In the previous set of experiments, we utilized up to 12 exploding bridge wires (EBWs) to initiate the detonation of the oxygen-acetylene driving gas. However, with this small number of initiation points, detonation front interactions between adjacent EBWs were significant, and this seeded large localized perturbations on the cylinder. In our latest series of experiments, we eliminated these large pressure-induced perturbations by using a 122-point EBW system. With this new initiation system, we are able to systematically study the RT and feedthrough growth rates for various initial perturbation wavelengths and amplitudes.

Our apparatus is essentially the same as that used in our previous experiments2, except for the introduction of the 122-point EBW system. The gelatin rings were formed using water with a 6% concentration of gelatin (Kind and Knox Company, 225 Bloom gelatin). The rings were fabricated by an in-place casting technique. Judging by the surface finish of the Plexiglas parts used to cast the gelatin, we estimate that the surface roughness of the gelatin ring is <12 μm, which is much less than typical imposed perturbation amplitudes of about 1 mm. Gelation was performed at a temperature of 7 °C for at least 12 hours.

Optical diagnostics included two high-speed framing cameras (Cordin, Model 6 and Model 121). Illumination was provided by back-lighting the gelatin ring with a high-intensity xenon flashbulb, and control electronics were programmed so that the high-speed cameras were properly synchronized to the xenon flash and the firing of the EBWs.

3. Experiments Performed

In our experiments we fabricated small sinusoidal perturbations in the azimuthal direction in order to seed Rayleigh-Taylor instability growth. These sinusoidal perturbations are characterized by two parameters: the initial amplitude A and the mode number m_θ (Figure 1). In addition, we varied the ring thickness ΔR, which has the effect of varying the acceleration history as well as varying the amplitude of the perturbations which feed through to the inner surface of the ring. No perturbations were fabricated on either the outer or inner interfaces in the axial (z) direction. A summary of the experiments performed is listed in Table I.

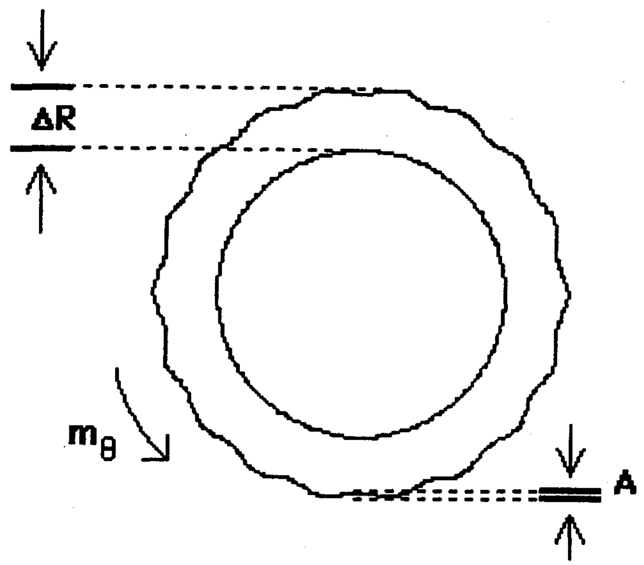

Figure 1. Figure 1. Gelatin Ring Geometry

We analyzed the growth of the fundamental mode and of the first four harmonics of the fundamental for both the Rayleigh-Taylor growth on the outer surface of each ring and, for those experiments which showed measureable feedthrough growth, the feedthrough growth on the inner surface. The growth rates were determined by digitizing the framing image records, tracing the gas-gelatin interface boundaries for the inner and outer ring surfaces, and then Fourier analyzing these boundaries.

In a planar, thin-wall geometry, the amplitude of a feedthrough perturbation is related to the amplitude of the associated RT perturbation by an attenuation factor of $\exp(-k\Delta R)$. In our experiments, $k\Delta R_o$ ranges from 1.1 to 9.8. We observe measurable feedthrough amplitudes only in the three experiments where $k\Delta R_o$ is less than 1.7 (GELB-4, GELB-7, and GELB-11).

Experiment	Mode Number	Initial Amplitude (mm)	Initial ΔR (cm)
GELB-1	36	0.5	0.5
GELB-4	18	0.5	0.5
GELB-5	36	0.5	1.0
GELB-7	6	1.0	1.0
GELB-10	36	1.0	1.5
GELB-11	6	1.0	1.5
GELB-14	18	0.5	1.0
GELB-15	12	1.0	1.5
GELB-16	36	0.2	1.0
GELB-17	18	0.5	1.5
GELB-18	36	0.1	1.0

Table 1. Summary of Gelatin Ring Experiments

In the other experiments, the inner surfaces of the rings showed no feedthrough perturbations to within the resolution of our system ($\approx$0.1 mm).

A mode number 6 experiment (GELB-11) is shown in Figure 2. In this experiment the Rayleigh-Taylor instability growth on the outer surface of the ring is clearly seen to feed through to the inner surface, imprinting a mode number 6 perturbation. At 540 μsec, the feedthrough perturbation is in-phase with the outer perturbation, i.e., the peaks of the inner feedthrough perturbation correspond to peaks in the outer perturbation. The development of the feedthrough perturbation is interesting. At a later time of 675 μsec, the feedthrough perturbation has reduced to nearly zero amplitude. Finally, at 729 μsec, the feedthrough perturbation is seen to be present again, but with an opposite phase.

Feedthrough growth was also observed in two other experiments (GELB-4, GELB-7), but in these experiments the feedthrough growth remained in-phase with the RT perturbation within the time period of observation.

4. Analysis

For the long wavelength mode-6 experiments, both the RT and the feedthrough perturbations remain in the linear growth stage throughout the experiment, and so it is possible to apply small amplitude analysis to compute both the RT and feedthrough growth rates. First, we determined the acceleration history of the cylinder using Lagrangian analysis and taking into account the potential energies due to the expanding gas outside the cylinder, the gas inside the cylinder, and the elastic energy of the cylinder itself. Gamma-law equations-of-state were used to describe the detonation product gases outside the cylinder and the air inside the cylinder. Good agreement between experimental and calculated ring motions was obtained for an initial pressure of P_o=16.5 atm. Figure 3 shows the normalized accelerations at the outer cylinder surface plotted versus the instantaneous outer surface radius. Note that the accelerations decrease very rapidly as the cylinder collapses due to the convergent geometry of the ring. In other words, there is a significant "funneling" effect which affects the acceleration even at very early times. This is an important fact to note when analyzing convergent ring experiments for instability and turbulent mix growth.

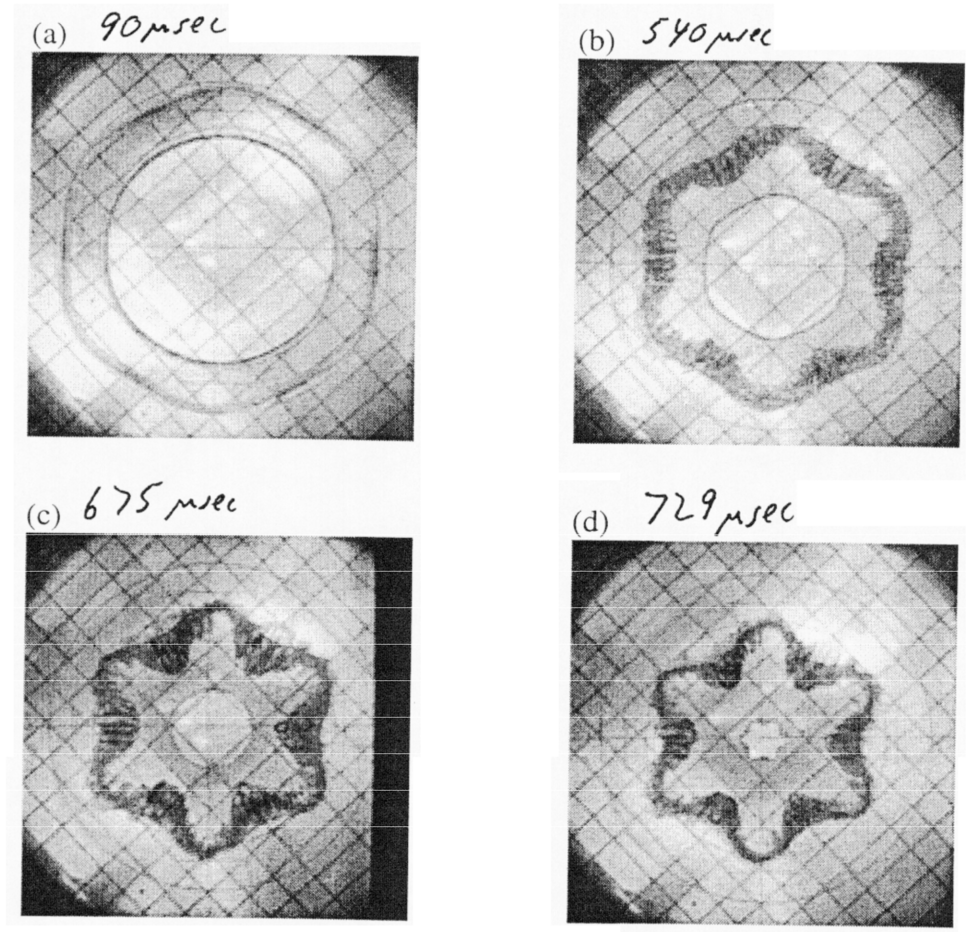

Figure 2. Figure 2. Framing Images from the GELB-11 Experiment (perturbation amplitude = 1 mm, m_θ= 6, and ΔR=1.5 cm)

Simulations based on a P_o=16.5 atm were also performed for rings with initial radial thicknesses of 0.5 cm and 1.0 cm. These simulations were also found to be in excellent agreement with experimental data. Initial t=0 accelerations were $8.85\text{x}10^6$ cm/sec^2 for a ΔR=1.5 cm ring, $1.40\text{x}10^7$ cm/sec^2 for a 1.0 cm ring, and $2.96\text{x}10^7$ cm/sec^2 for a 0.5 cm ring.

We also derived the linear-stage perturbation evolution equations for an incompressible cylinder undergoing a radial implosion. This cylindrical geometry derivation proceeds along essentially the same path used by Plesset3 and Mikaelian4 to study spherically imploding shells. The small amplitude analysis resulted in two, coupled, 2^{nd} order differential equations in a(t) and b(t), the amplitudes of the outer and inner perturbations, respectively. The equations can be presented in the form

$$G_{11}(t) \cdot a''(t) + G_{12}(t) \cdot a'(t) + G_{13}(t) \cdot a(t) + G_{14}(t) \cdot b''(t) + G_{15}(t) \cdot b'(t) + G_{16}(t) \cdot b(t) = 0 \quad (1)$$

$$G_{21}(t) \cdot a''(t) + G_{22}(t) \cdot a'(t) + G_{23}(t) \cdot a(t) + G_{24}(t) \cdot b''(t) + G_{25}(t) \cdot b'(t) + G_{26}(t) \cdot b(t) = 0 \quad (2)$$

where the G_{ij} are functions of the outer cylinder radius $r_o(t)$ and the mode number m_θ. By numerically solving these coupled differential equations, we were able to accurately predict the

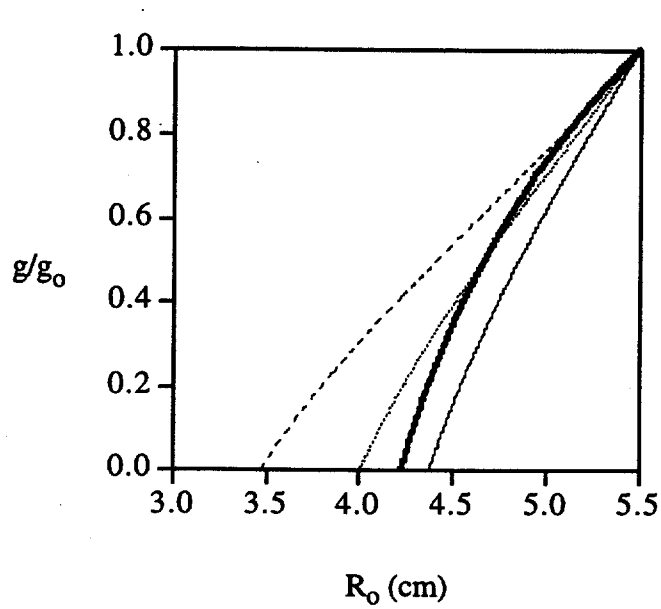

Figure 3. Figure 3. Normalized accelerations of the outer cylinder surface vs. outer radius. Thin solid line: 1.5 cm thick ring. Thin dotted line: 1.0 cm thick ring. Thin dashed line: 0.5 cm thick ring. Thick solid line: 1.5 cm thick ring with outer gas pressure fixed at 15.5 atm and inner gas pressure fixed at 0 atm.

growth of both the outer perturbations as well as the inner, feedthrough perturbations for our mode-6 experiments. In particular, these equations predict the development of the feedthrough phase inversion at about the time actually observed in the GELB-11 experiment5.

5. Conclusion

The latest set of experiments shows that we can eliminate the effect of shock perturbations on the gelatin cylinder with a 122-point initiation system. Furthermore, by using an in-place casting technique, we can fabricate precise initial cylinder surface perturbations. Recent experiments have focused on studying feedthrough growth, and interesting behavior such as a feedthrough phase inversion has been observed. Although this phase inversion behavior cannot be explained by the standard, first-order Exp(-kΔR) attenuation factor, we can accurately predict this and other feedthrough behavior using linear, small amplitude analysis. Future experiments will focus on the issues of mode-mode coupling and turbulent mix development.

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University of California • Livermore, California 94551