Development of multi-component explosive lenses for arbitrary phase velocity generation

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Abstract. The combination of explosives with different detonation velocities and lens-like geometric shaping is a well-established technique for producing phased detonation waves of a desired shape. This technique can be extended to produce nearly arbitrary detonation phase velocities for the purposes of sequentially imploding pressurized tubes, driving Mach disks or directing blast and fragmentation. This paper presents the theoretical development and experimental testing of two types of explosive lenses designed to produce either of these effects.

1. Introduction

Control of the shape of detonation waves is an essential objective in the design of a variety of precision explosive devices. While the most common application of waveshaping is the control of curvature (e.g., planarity) in shock compression devices, it can also be applied to the generation of phase velocities that, in turn, drive very strong shocks and Mach disks or that introduce anisotropy in the blast and fragment signature of an explosive device. The current study builds on the work of the Physics International Company, who first developed the variable phase velocity generating lens [1–3], and the Naval Surface Warfare Center, Corona Division, who developed explosive lenses for anisotropic blast applications [4].

A typical method of detonation wave shaping is the geometric shaping of an interface between two explosives of different detonation velocities (VOD). The behavior of this system can be understood through an analogy between geometric optics and detonation wave dynamics [5]. At the interface between the two explosives, a detonation wave in the fast explosive will initiate a detonation wave composed of an infinite number of point source detonations in the slow explosive, as shown in figure 1. Each point source expands spherically with a radial velocity vector equal to the VOD of the slow explosive. This situation is conceptually identical to a Huygens refraction and the resulting oblique detonation wave in the slow explosive will be tilted or “refracted” by an angle, \( \alpha \) that is only a function of the ratio of the detonation velocities:

\[
\alpha = \sin^{-1} \left( \frac{V_s}{V_f} \right)
\]

Evidently this optical analog is only approximative due to real effects in explosives. In real devices edge expansion losses, curvature related VOD deficits, dead-zone formation at the...
explosive-explosive interfaces and delays in the onset of sustained detonation cause deviations from the idealized Huygens construction [6]. Furthermore, aberrations in detonator initiation and placement can further disrupt real device behavior. Nevertheless, the geometric optic analog provides a useful initial design tool and can produce functional explosive devices where high precision in the wavefront geometry is not required. This paper presents the development of two types of explosive lenses based on geometric optics. The first type uses two explosive components and bulb-like contouring of the explosive-explosive interface to generate smoothly accelerating, linear phase velocities. The second type uses a circular geometry with radial variation in the explosive detonation velocity to produce an anisotropic blast and fragment signature.

2. Accelerating Explosive Lens
For the situation depicted in figure 1, an apparent or phase velocity will be observed at the base of the slow explosive that is equal to the detonation velocity of the fast explosive. This phase velocity can be increased by inclining the fast explosive relative to the base, thereby changing the oblique detonation wave's angle of interaction with the base. For a fast explosive angled by $\theta$, the phase velocity is equal to:

$$V_{ph} = \frac{V_s}{\sin (\alpha - \theta)}$$

If the angle of the fast explosive is continuously varied, the apparent VOD in the slow explosive can be smoothly increased in a programmed fashion. This design is schematically depicted in figure 2. A concave detonation wave is generated that is increasingly tilted toward the base of the slow explosive along the length of the lens. In principle, the phase velocity can be accelerated from the VOD of the slow explosive to an arbitrarily high velocity by beginning the fast explosive at the base of the slow explosive. In practice, this acceleration requires a minimum linear distance because the point sources that form the trailing edge of the phased detonation wave at velocities above the slow VOD must originate fairly far behind the point of interaction with the base. This is depicted in figure 2 where point sources originating at “A” and “C” form the tail of the oblique detonation wave at “B” and “D” respectively. The location of the interaction point can be determined by projecting a vector, rotated by $\alpha$ from tangency with the explosive interface, down to the explosive base.

The slope of the fast explosive can be straightforwardly related to the angle $\theta$ and thus the phase velocity at a given point via rearranging Eq. 2 and substituting the slope-angle relation:

$$\frac{dy}{dx_i} = -\tan \left\{ \alpha - \sin^{-1} \left( \frac{V_s}{V_{ph} (x_f)} \right) \right\}$$

Here $x_i$ is the coordinate of the lens profile and $x_f$ is the location where the point source initiated
at \((x_i, y_i)\) will first reach the base of the lens. These two quantities can be related by the vector normal to point source detonation front:

\[
x_f = x_i + y_i \tan \left\{ \alpha - \tan^{-1} \left( -\frac{dy}{dx_i} \right) \right\}
\] (4)

Substituting Eq. 4 into Eq. 3 yields an implicit differential equation that can be solved via a number of pre-packaged solvers. An important feature is that the equation must be solved backwards, starting from the point of highest phase velocity where the fast component touches the x-axis. At this point the value of \(\theta\) is known and \(x_f = x_i\). For lenses that begin at a velocity faster than the slow component VOD, the lens must be cut away at an angle equal to the angle produced by the first point source. This results in a half chevron shape, where the start of the lens profile begins above and behind where the lens first interacts with the target plane.

An experimental lens was constructed to evaluate the accuracy of the Huygens methodology. The slow component was nitromethane (NM) diluted with 30\% diethylenetriamine (DETA) by weight. The VOD was measured as 5.5 km/s in a 6.35 mm PVC tube. Increasing the dilution to 45\% only reduced the VOD to 5.2 km/s. The fast component was Primasheet 1000, which detonates at 7 km/s. The lens was fabricated by CNC routering two 6.35 mm thick PVC sheets into the desired lens profile. These slabs were then spaced by PVC side supports to have a uniform explosive thickness of 6.35 mm. The slow-fast explosive interface was sealed with a semi-rigid strip of 1.5 mm thick PVC. An MREL 1-05-10 continuous velocity gage was used to measure the velocity profile of the lens. The profile was designed to accelerate from 7 km/s to 14 km/s over 400 mm. The profile and a photograph of the charge are depicted in figure 3 while the resulting profile compared to the theoretical profile is plotted in figure 4. Overall agreement is quite good, with deviations attributed to the relative inaccuracy of the router and signal noise inherent in the continuous gage.

![Figure 3](image1.png)

**Figure 3.** Charge photograph and plot of the design geometry.

![Figure 4](image2.png)

**Figure 4.** \(x - t\) diagram for the measured trajectory of the oblique detonation wave along the target plane.

3. **Circular Anisotropic Lens**

Following the optical lens analogy, the previous device can be described as an explosive Snell lens because the transmitted detonation wave is simply bent across the explosive interface. The
second type of device tested can thus be called a circular explosive gradient-index lens since the wave shaping is accomplished by varying the detonation velocity as a function of lens radius. Here variation of the curvature of the detonation wave is produced by the continuous variation in VOD and not by changing the curvature of the explosive interfaces as in the first lens concept. If VOD is reduced with decreasing radius, a point detonation initiated at one side of the lens can be converted into a quasi-plane wave when it expands out to reach the center of the lens. Conceptually, this is possible because the faster running detonation on the outer radius will drag a continuously varying phased detonation through the incrementally slower adjacent explosive. Past the mid point of the lens, the faster parts of the detonation wave will outrun the slower components, leading to the formation of a Mach stem in the middle of the device and an intense jetting of detonation products opposite to the initiation point. This behavior is schematically depicted in figure 5.

![Figure 5. Schematic of the evolution of the detonation wave across the circular lens.](image1)

Figure 5. Schematic of the evolution of the detonation wave across the circular lens.

It is evidently very difficult to create an explosive charge with a programmed continuous variation in detonation velocity. However the art developed by Conger illustrates that the device can function with discrete variations in VOD at fixed radii [4]. Furthermore, the velocity gradient required towards the center is much less than the gradient near the outer surface. This means that the central portion of the lens can be a large, continuous zone of low-VOD explosive. Following the velocity profile designed by Conger, a planar lens was constructed based on using PBX (C4) and rubberized explosive: C4 and Primasheet 1000 for the outer layers and NM with varying degrees of DETA dilution separated by thin PVC rings for the inner layers. A charge using Primasheet 1000 as the outer layer is depicted in figure 6. Here the slowest component was a packed bed of glass particles saturated with diluted NM with an effective VOD of 5.2 km/s. It was hoped that the packed bed would be partially jetted by the Mach stem and provide a greater momentum flux in the jet. Witness plate testing and hydrocode simulations revealed that the particle bed was not appreciably entrained into the forward flow as desired, resulting in a reduced jetting effect compared to a similar charge containing just neat explosive. Nevertheless, the particle bed did detonate consistently with the optical behavior of the overall device, although the detonation wave in the central portion was 2-3 µs ahead as the VOD was not sufficiently low compared to Primasheet 1000.

To rectify these issues an improved design was constructed using a faster outer component and a heavily diluted liquid explosive for the central region. The outer diameters of the regions, the explosive composition and the nominal VOD are listed in table 1. DETA sensitization and dilution is reported on a per-mass basis.
Table 1. Details of the circular explosive lens.

| Average Diameter (mm) | VOD (km/s) | Explosive            |
|-----------------------|------------|----------------------|
| 302                   | 8          | C4                   |
| 271                   | 7          | Primasheet 1000      |
| 240                   | 6.1        | NM +5% DETA          |
| 210                   | 5.7        | NM +20% DETA         |
| 149                   | 5.2        | NM + 45% DETA        |

Behavior of this lens design is depicted in figure 7, which contains frames from EDEN hydrocode simulations showing the detonation front profile near the center of the lens as well as the formation of the detonation product jet after detonation of the outer ring is complete. Also shown are two framing camera stills of a device in operation. The first still shows the detonation front location in all but the most central layer at approximately the half way point in the charge. The second shows the emergence of the product jet near the moment of collision of the fastest portions of the detonation wave at the opposite end of the charge. Unfortunately luminosity from the jet and expanding products saturated the camera, thereby preventing further recording of the time history of the jet.

![Figure 7](image_url)

**Figure 7.** EDEN simulations showing (a) the wave front profile just after the midpoint of the charge, (b) the air blast profile. High speed photography showing (c) the detonation front curvature at the mid point of the lens, (d) the emergence of the product jet from the far edge of the lens.
4. Conclusions
The development of two different lens concepts relying on the formation of oblique/phased
detonation waves between explosive components of differing detonation velocities has been
presented. Experimental implementations of these lenses were constructed and tested, showing
qualitative and quantitative agreement with simple Huygens-based analytic models and/or
conceptual device operation.

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