Detail design (DD), front end (FE), back end (BE) design of non-tactical deployable 20 GWh (17.20841 kilo ton TNT) plane wave lens configuration fusion device

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Short Report

Keywords: Integration, charge, explosive, parts, method

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Abstract

A simple plane wave lens, using an inert central plastic wave shaper, has been designed. An experiment was done with a 4 in diam, zeroth order design. An iterative technique that uses measured time deviations to connect the next wave shape was developed. Two identical versions of the first iterated shape were fired. Arrival time deviations in these first iterates fell within 50 ns bonds. With greater care and further iterations, lenses bound by 10 ns deviations seem possible. An advanced and novel integration method is applied. It is shown that this technique bears significant advantage over prior methods and is meritorious.

Keywords: Integration, charge, explosive, parts, method
1. Introduction

Current explosive lens, although successful has problems. They tend to be expensive. Required rigid tolerances and concomitant machining costs account for much of the expense. Complex explosive formulations make uniform production difficult. Most explosive lens operate by transforming the spherical wave from a single detector to a plane wave by using a central explosive, with a slow detonation velocity, bounded by a sheath of explosive with a faster detonation velocity. For a certain sheath angle, the fast detonation velocity of outer explosive, expanding on spherical front, induces a flat wave in the central explosive that is moving at its detonation velocity. Using an explosive for the central part of lens is an advantage because the detonation velocity, \( D \), is not diminished by attenuations coming from rear of the lens. The faster external explosive usually overdrives the internal explosive. This again, should result in constant \( D \), because the tangent Chapman – Jouget condition implies a relatively slowly varying \( D \) for relatively wide pressure excursions. A slow detonation velocity for the inner explosive. A slow detonation velocity for the inner explosive results in a wide aspect for the lens (\( D_{in} / D_{out} = \cos \theta \)), where \( \theta \) is the half angle of outer sheath). This allows the use of minimum amount of high – detonation velocity (and usually more energetic) explosive, which is an advantage. Baratol, a TNT / Ba (NO\(_3\))\(_2\) mixture served this purpose. Admirably in the old P-xx lenses. It is now deemed a hazardous waste because of barium content. Currently, a mixture of TNT / CaCO\(_3\) / microballoons / talc is replacing Baratol.

Another way of delaying the central dome of spherical wave is to use an air gap. A donor explosive accelerates the metal plate. The shaped metal runs through the lands simultaneously on a flat acceptor explosive. Because of large difference between the free surface velocity of the metal and detonation velocity in explosive, tolerances in shapes and positioning of the components of the lens are extremely tight. The design for a lens we present here is directed towards simplicity and economy. We present the results of preliminary design and experiments.

Basic Idea

Our idea for a lens is shown in Fig 1. We use an inert material instead of an explosive for the central wave shaping mechanism. All of the complicated machining is concentrated in the curved surface of part B. Once a shape has been finally determined, this part could be fabricated by molding a suitable plastic. A final bit of machining would probably be required to make the shape true.
Fig. 1: Schematic of lens. A – accepter explosive, B – plastic wave shaper, C – donor explosive, D – Detonator, E – Detonator support and lid for explosive, F – plastic cylinder to hold in explosive.

For the donor explosive, we envision a material that can be poured or pressed into the lens and, in this process, conforms to the shape of part B. Liquid TNT could be poured into the donor explosive cavity. A plastic capable of withstanding this temperature and chemical environment is doubtless available. One should try to match thermal expansions of explosive and plastic. This is presumably an easy job since they are “similar” organic materials. Freezing of the liquid TNT should be by thermal conduction through the flat face of part B. The practicality of this needs to be investigated. In a lens of this type, where precise timing depends on constant material properties, it is important to choose materials that lend themselves to tight specifications. An explosive with a single chemical component such as TNT (almost a single component) has an advantage in this respect. Some of most consistent, modern, and pelletized explosives with their excellent pressing properties, are also candidates for the donor explosive. Simple design for preliminary experiments dictated a cylinder for part F. Much of the upper explosive in the outer run is probably unnecessary. A cone, or some other shape that minimizes the upper explosive is packed. For our preliminary experiments we used compositions C – 4 for the donor explosive and PMMA (poly methylmethacrylates - Flexiglas) for the plastic parts. A thin layer of PBX 9501 was used as an accepter. The detonation wave in the accepter transmitted a shock through a thin layer of Al. Arrival times over the face of lens were recorded by flash gaps on the other side of Al. The preliminary design used a simple lens formula and ray tracing with constant velocities for the media. An iterative procedure is then used to correct the shape of part B, using measured time deviations from planarity. In this later procedure, everything is kept fixed except for the position of the interface between the donor explosive and part B.
Initial design and results

The radius of curvature of central part of the wave shaping plastic can be obtained from simple lens approximation (see fig 2). This approximation is valid for a small region about the optic axis where the sagittae of the arc, \( x \), is adequately given by \( y^2 / 2R \). The spherical wave from a point detonation a distance \( P \) away from the interface arrives at the interface at \( t_1 \). At a time \( \Delta t \) later, the wave at the edge of the shown arc contacts the interface. We have

\[
\frac{(Z_p - Z_R)}{D} = \frac{(Z_R - Z_Q)}{U_s}
\]

Lens formula from above

\[
(PD)^{-1} + (QU_s)^{-1} = \left(\frac{U^{-1} - D^{-1}}{s}\right)/R
\]

(2)

To get a flat wave

\[ Q = \infty \]

In (2)

\[
R_L = \frac{U^{-1} - D^{-1}}{(PD)^{-1} + (PU_s)^{-1}}
\]

\[
R_L = \frac{U_s^{-1} - D^{-1}}{(PD)^{-1} + \infty}
\]

\[
R_L = (PD)(U_s^{-1} - D^{-1})
\]

\[
R_L = P(DU_s^{-1} - DD^{-1})
\]

\[
R_L = P(DU_s^{-1} - D)
\]

\[
R_L = P\left(\frac{D}{U_s} - 1\right)
\]
Fig. 2: Simple lens approximation for central part of lens.

Lens shape may also be calculations by other means e.g.

1. Volume with washer method
   (a) Revolving around x axis or y axis
   (b) Revolving around other axes

2. Volume of a solid of revolution method

We concentrate on a 4-in diam lens, the equivalent of a P – 40, with P = 3in. This is probably more explosive than is necessary on the topic of axis and is a parameter to investigate in a more general study. Properties of composition C – 4 explosives are not that well known. Initially, we choose D = 8.0 mm / μs for the composition C – 4 detonations velocity, and \( U_s = 6.5 \text{ mm / μs} \) for the shock velocity in PMMA resulting from the C-4 / PMMA interaction. This gives \( R_L = 0.692 \text{ in} \), a discouraging small radius of curvature. However, it only applies to a small region near the optic axis. To get a better idea of our lens shape, we need to go to a ray tracing approximation (see Fig 3).

At \( t = 0 \), spherical wave has just touched the plastic surface

At time \( t \),

\[
R(t) = P + Dt
\]

\[
\Delta y = U_s t
\]

\[
X^2 + (P + \Delta y)^2 = R^2
\]

\[
t = \frac{\Delta y}{U_s}
\]

Hence from (3) and (4) and

\[
x^2 + (P + \Delta y)^2 = R^2
\]
\[ x^2 + (P + \Delta y) = \left( \frac{P + D \Delta y}{U_s} \right)^2 \]

\[ R = P + Dt \]

\[ R = P + D \Delta y \frac{U}{U_s} \]

We then have

\[ \frac{\Delta y}{P} \frac{P}{U_s} + 1 = \left( 1 + \frac{D + U_s x}{D - U_s P} \right)^2 - 1 \]

For small \( x \), \( \Delta y \approx \frac{1}{u} x^2 / (P(D - u)) \). The radius of curvature is \( P(D-U)/U_s \), agreeing with the simple lens approximation. For large \( x \), \( D \approx s x, s = \left( \frac{u_s}{D - u_s} \right) \). The lens tends towards a cone, not the sphere of the simple lens approximation. For our initial numbers, \( s = 1.394 \). Figure 4 shows computed shapes using Eq (1). For our experiment we choose \( P = 3.0 \) in. A value of 2.0 in. and possibly 1.5 in would probably have been a safe choice.

Shock velocity in the plastic is not constant. Due to finite thickness of the donor explosive, the shock wave gradually attenuates on the optic axis after it enters the plastic. As the detonation wave moves farther on the radius of plastic lens, the interaction between the explosive and plastic changes from normal incidence towards tangential incidence. Both of these effects cause the real wave to lag behind the calculated flat wave position. A real detonator has finite size. We do not have an ideal point detonation. We account for this by positioning the front surface of detonator 3/8 in. (10 mm) nearer the plastic lens rather than at the 0-mm position of point detonation. This number was chosen somewhat arbitrarily. One could do better by considering the actual shape of a detonator and its internal construction.

Because of perturbation and uncertainty in the properties of C–4 explosives, we need data from an experiment. Figure 5 gives our exact initial configuration. We do not expect success on first try.
Fig – 4: Plastic lens shapes at varying explosive thicknesses from a point detonation. Note that the vertical scale is compressed by about a third.

Fig – 5: An explode view of our first design

Seven slits, spaced 0.5-in apart, recorded the arrival of the shock on the surface of aluminum. Fig – 6 shows the streak – camera record obtained. The axial symmetry of the lens is evident. The slit plate was not quite centered on the lens, evidenced by the pattern of peak lags from the traces down in Fig 7. This affects the side traces but has a slight negligible effect on the central face. The resulting time lags for
various regions of the lens are shown in Fig 7. The radius location of a time lag is obtained from the image magnification.

Fig – 6: Streak camera record, lens 1. Seven traces, 0.5 in. apart, record light from the flash gaps above the aluminum surface. If the record had not been swept in the x direction (0.48 mm / µm), the traces would all have fallen on the dotted lines. The x – displacement of the traces, from the dotted lines, yields the time – lags for the wave arrived. The spacing between the dotted line (1.313 mm / 0.5 in) gives the magnification for the image, 0.1034 (±1)

Fig – 7: Lens 1 time lag

The radical location of a time – lag is obtained from the image magnification. The film may have been slightly tilted; there were not any good streaks to align the time axis on the film. The effect of this single error (cos θ type) on our results is negligible.
We had a time differential of 0.80 μs. The lag was probably due to the expected attenuation caused by Taylor wave and, in part, to our uncertainty for the value of $DU_s/(D - U_s)$. Our guess for this value is 34.7 mm / μs. On a more positive note, the traces are very smooth. The scatter about a given trace is ~20 ns. If we want to control the lag time, $\delta t$, by moving the interface, $\delta y$, the velocity $\delta y / \delta t \approx DU_s / (D - U_s)$ is pertinent. The value 34 mm / μs implies a tolerance of 1.5 mm / 50 ns. That is, for a relatively low tolerance, we have a tight control on timing. The lag measured in the first experiment implies we have to “scalp” our lens by an inch. This greatly improves our aspect ratio and will ultimately allow use of less donor explosive.

The edge of the donor explosive is a sharp-edged cone pointing towards the acceptor through 0.25 in of plastic. At this point, a side rarefaction starts working inward toward the center, relieving the wave and causing a lag in time. This influence is clearly shown in Fig 6 and 7. The influence extends inward to a radius of 1.6 and 1.7 in. (definitely). At 45° rule, for loss due to unsupported plastic run, seems to be in effect. If we want a full 2 – in radius of flat wave, we would clearly have to extend the explosive radius to 2 in + thickness of plastic run.

**Design two and results**

We pay more attention to the equation of state of composition C (C – 4) and PMMA. We have³ for C – 4.

\[
\rho_0 = 1.66 \text{ g/cm}^3, D = 8.37 \text{ mm/μs, and } P_{CJ} = 25.7 \text{ GPa (calc.)}
\]

We fit a simple $\gamma$-law EOS (4) to the parameters,

\[
\gamma G = \frac{\rho_0 D^2}{P_{CJ}} - 2 = 2.5251 \text{ and } q = - \frac{D^2}{2 \gamma G (\gamma G + 2)} = -3.0656 \text{ J/mg}
\]

The M – 6 fit is used for the EOS of PMMA

\[
\rho_0 = 1.186 \text{ g/cm}^3, u_s = 2.598 + 1.516 u_p \text{ mm/μs }, \gamma G = 1.5
\]

We used this data and the ray tracing code MACRAME to calculate the ID behavior of lens along its central axis. Results are shown in Figs. 8 – 11. The time lag measured in the experiments can be attributed to the lag produced by the decaying wave in the PMMA. The inert, mock = explosive Hugoniot gave the initial pressure in the explosive as 140 kbar. This was sufficient to insure prompt initiation, with a run to detonation of <0.1 mm. in the PBX 9501 acceptor. The ability of plastic at state B to initiate the acceptor is an important consideration in lens design. This ensures a uniform pressure wave is transmitted into the adjacent material.
Fig 8: MACRAME (a 1D, wave-approximation hydrocode) waves and interface along lens axis (the “optical” axis). The Taylor wave emanating from point detonation is truncated to the portion that controls the lens behavior. The decay of shock as it travels through the plastic leads to an arrival time at the acceptor explosive 0.834 µs later than the arrival of non-decaying wave. We use mock explosive (a Hugoniot curve of an inert chemical match to PBX 9501, $\rho_0 = 1.87 \text{ g/cm}^3$, $u_s = 2.71 + 1.61 u_p$, $\gamma G = 1.5$) for two reasons. First, the initial pressure in the mock Hugoniot let us judge the likelihood of and run to detonation of the accepter explosive. Second MACRAME at the moment does not correctly handle an explosive that has been shocked to a weak detonation.
Fig 9: MACRAME $P - u_p$ interactions. The C – 4 explosives, at its C – J point, interacts with PMMA to produce state A. As the wavelets in the explosive Taylor wave catches up to the lead shock in the PMMA, its strength decays to state B. The state interacts with the mock – explosive Hugoniot to get state C.
Figure 10: Lead characteristic pressures. Pressures along the lead shock down the central axis of the lens are shown. States A, B, and C in the $P - u_p$ diagram are indicated. In the actual lens, state C rapidly grows to a detonation in the acceptor explosive.
Fig 11: Lead characteristics particle velocities.

Clearly, if we had allowed for the lag in the plastic, we would have achieved a much better 0\textsuperscript{th} order lens. We need an iterative method to go from measured time lags, $\delta t$, to corrections in the explosive/plastic interface location, $\delta y$. We use the ray tracing approximation. In Fig 3, we let $y_o$ be the thickness of the lens at the center (i.e., the position where we want wave to be flat). Then, if at a radius $x$, we increase $\Delta y$, $\Delta y_{i+1} = \Delta y_i + \delta y$, the change in arrival time (an earlier arrival) will be given by

$$
\delta t = \frac{R(\Delta y)}{D} + \frac{y_o - \delta y}{u_s} - \frac{R(\Delta y + \delta y)}{D} - \frac{y_o - \Delta y - \delta y}{u_s}
$$

To first order in $\delta y$ we have

$$
\delta t = \delta y \left( \frac{1}{u_s} \cos \theta \right) \text{ and } \cos \theta = \frac{(P + \Delta y)}{R} \left( \frac{1}{\Delta y} \right)
$$

The $(1/u_s - \cos \theta/D)$ factor in Eq. (2) varies from 39 ns / mm; on the ‘optic axis’ to 47 ns / mm out at the edge of our particular lens.
A spline fit to the $\delta t$ shown in figure 7 was mapped to $\delta y$ via Eq. (2). The corrected lens shape is shown in Fig. 12. A quadratic fit to this result seems adequate. The machining specifications for the new lens is shown in Fig 13.

Two lenses were fabricated with the new shape and fired. Streak – camera results are shown in Fig. 14. We did not get the middle slit centered over the lens and the slits were slightly tilted with respect to the streaking direction; however, this is not critical to the analysis. Time offsets can be measured relative to the dotted lines added to the figure.

Fig. 12. New lens shape, first iteration.
In this particular iteration of the shape, the outer sharp wedge of explosive still produces a circle of earliest arrival that is readily apparent in the traces. Presumably, in a final iteration, this early arrival will be lost or ambiguous. Figure 15 shows the same records with the $x_G$ axis changed to time. Relative times along a trace are meaningful.

Figure 16 shows the t-offsets from a base, the dotted lines in Fig. 15. Lens 3 seems more evolved in the center than lens 2, but both have a characteristic “M” shape. In both cases, the arrival time spread is about 50 ns. The character of the deviation follows the character of deviation of our polynomial approximation, from the first calculated iterative shape. This is probably fortuitous because of the large size of our iterative first step. It does suggest that we ought to use a spline to represent our $y$–shape rather than a low order polynomial.

In Fig. 17, we plot the widespread traces (giving a 3D effect), from lens 3. The axial symmetry of the deviation from simultaneous arrival is apparent. The outer portion of the retained trace is the early arrival from sharp wedge of explosive at the outer portion of the lens. (Actually, rarefactions have cut into this wave and moved it in along the 45° line from the wedge tip). There is a circular region of lagging arrival and then, in the center, a dome of early arrival. We should have followed the precise spline for $\Delta y_0 + \delta y$ in Figure 12 for our machining specifications in Fig 13. (This has to be fortuitous for such a large, first – iterative step).
Fig 14: Trace readings from new lens shape, (a) lens 2, (b) lens 3. The recording system is the same used for lens 1 (see Fig 6)
Fig 15: Trace times vs $y_G$, (a) lens 2, (b) lens 3
Lens 2, t offsets
**Fig 16:** Times relative to outer early circle, (a) lens 2, (b) lens 3

Lens 3, t offsets

\[ t \text{ (\mu s)} \]

\[ yG \text{ (mm)} \]
Calculations

We have approximated the full two-dimensional behavior of the lens by picking particular 1D ray paths. A full 2D calculation of our last iteration is appropriate at this point. We use a 2D Eulerian code for the task. The calculated setup is shown in Fig. 18. Pressure contours are shown in Fig. 19, when the wave has advanced about a quarter of the way into the mock explosive (HE) layer. One can tell them from this figure that a fairly flat wave has been achieved. A better idea of the wave shape calculated by the 2D code can be obtained by plotting the PMMA / Mock – HE interface pressure. Figure 20 shows two times that closely follow the entry of wave into the mock high explosive (HE). This still does not give precise, sharp shock wave arrival time. Refinement in the code is required and is sought further from 2D calculation of about 100 kbar < 1D code ≈ 150 kbar.

**Fig 17:** Displaced t – offsets from lens 3
Fig 18: Setup for calculating iteration for lens showing plastic containing wall, plastic wave shaper, and a layer of acceptor mock explosive (HE)

Fig 19: Pressure contours 16.5037 µs after the point detonation.
Fig 20: Pressure at the interface between the lens and the (mock) accepter explosive

Fig 21: Pressure contours 16.3564 µs after the point detonation.
**Discussion and Conclusion**

With an aim to develop and perfect a reliable and economical plane wave, this iteration is stopped at this stage. Lens yielded from present iteration is quite simple for many applications. Iteration to this point, removes time leads and lags in an adequate manner. Adding controls, a coarse and fine knob is obtained. Fine tuning encompasses iteration and is success because of large value of phase velocity.

\[
\frac{\delta y_{\text{interface}}}{\delta t} = \frac{U_s D}{(D - u_s)}
\]

With relatively low tolerances (less adjustments) on $\delta y$, still $\delta t$ of $10 - 20$ ns is obtained. That is, very high changes in time are obtained by mere slight, or no adjustment on displacement. Function of coarse knob is to keep rest of lens constant. Fanatical quality control may be required to take full advantage of fine tuning. Complete engineering related to back side of lens may result in wave shaping and minimization of fluctuations in lens. This aspect still needs to be explored. Few advantages and disadvantages of present lens are described here.
**Advantages**

1. All of free form fabrication is done on inert material of plastic lens
2. A mold is made for production runs of plastic lens which minimizes machining to just truing up final shape by fine machining.
3. Lens is essentially free from metal, hence there is no shrapnel.
4. Smooth wave is obtained without any small perturbations.
5. Smoothness of wave arrival combined with fine tuning capability gives a wave arrival flat to 10 ns. Smoothness to this level is a function of reproducibility in back design.

**Disadvantages**

1. Back condition changes affect wave arrival
2. Flat part of lens may produce a shock which is considerably weaker than fully explosive lens. An acceptor pad of readily detonated HE could be required as second component of lens to counter this. This may be eliminated by careful initial design and mold making and machining.
3. Such lens (one with accepter pad) is heavy than fully explosive lens and is avoided.
4. Present fully explosive lens serves as disadvantage towards further research and development as further fine tuning and redesign of fabrication methods may give even better design which is fully explored here.

**Prescription for designing the lens**

Steps to achieve present lens with given shape, choice of explosive and choice of plastic are enlisted here.

1. A complete back design is performed.
2. Select an optimized explosive plastic combination.
3. Decide upon method of manufacture, press, pour or pack.
4. Select and design shape which give maximum output from back surface of explosive.
5. Devise method of attachment of detonator.
6. Design any mechanical components for holding explosive and lens.
7. Decide upon fabrication processes and their easiness.
8. Determine attachment and design assemblies to achieve the same.
9. An optimized lens which may deliver a flat wave to a circle of radius $x_o$ is shown in below figure 19
10. Using constitutive equations, initial value of $D$, initial interaction between explosive and plastic is calculated and value of $u_s$ is obtained.
11. Pick the P dimension to be small enough to have enough strength in shock coming out of bottom to promptly initiate acceptor explosive.
12. Calculate shape 1 using equation 1 such that point Q has an x sufficiently greater than $x_o$. Use $x_Q = x_o + w$, where w is dimension chosen large enough for mechanical stability.
13. Using some hydrocode, calculate the lag, $\delta t_{op}$, on the optic axis due to Taylor release wave in the explosive. This is done to correct shape 1.
This gives 0th order lens. This paves the way for 2 dimensional calculations of this behavior. This will lead to fabrication and testing of lens. Subsequent lenses have shapes corrected by Eq (2) which now has iterative form

\[ \delta y_{t+1} = \delta t u_s D / (D - u_s \cos \theta) \]

Fig 19: Schematic of lens design \( y_0 = \Delta_y(x_Q) + w \)

**Design three and results**

1. Volume of solid of revolution
2. Washer and disks
3. Cylindrical shells
4. Volume of solids with known cross sections

Same results may be achieved from integration method applied.

**Conclusion**

Fusion devices may be designed by many ways, various methods are described. Integration methods applied are proposed to be superior.
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