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# THE MEASURE OF JET "GOODNESS"

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Shaped charge jets are usually characterized by their jet velocity and jet mass profiles. This information is presented in the form of a plot of these two variables. From these plots, designers can form a mental picture of the jet: 'it is stretching here, there is little mass in this region and therefore a small diameter here', etc. Comparisons of various designs are possible for these figures, yet it requires a subjective interpretation to decide which design may be better. Fast computational methods can easily generate hundreds of design results, thereby overwhelming the designer with too many options. We herein outline a method for reducing the jet velocity and jet mass profiles to a single value that allows the rapid screening of results.

## INTRODUCTION

During the design of a shaped charge, the designer is often faced with the problem of determining which computational design is best. The selection process is highly subjective and based on intuition and years of experience. By and large this approach has worked rather well. The use of hydrocode modeling has further reduced the unknowns and assumptions that were built into the analytical models. This improved modeling accuracy has made it possible to further refine designs that have subtle differences. This coupled with the relative maturity of shaped charge technology results in performance gains that are often measured by a few percent. These minor differences in jet characteristics increase the difficulty in selecting the better design. At the same time, due to advances in computational speed, much of the design is becoming more automated via optimization codes or parametric runs. This design methodology exacerbates the challenge to select the better design from hundreds of runs rather than a handful of designs. This introduces the need to have a single parameter that represents a measure of jet goodness, which we will refer to as д. This paper presents a method for establishing the relative 'goodness' of any jet.

There are a number of characteristics that we examine during the comparison of two charge designs. For the initial screening, we may examine the physical characteristics of

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the design: explosive and liner mass, initiator type (point, plane, ring), manufacturing complexity, etc. The various trade-offs are easy to quantify and sort. After this screening, we usually examine the estimated jet properties. The predicted jet is usually characterized by its mass and velocity distribution, much like its experimental counterpart is determined by flash x-radiography testing. Of particular interest is the tip velocity as it is critical in the determination of the early jet length and reflective of the penetration capability. The mass distribution along the velocity gradient (or jet length) can be correlated to the jet break up time, which also significantly influences the penetration capability. The velocity gradient is proportional to the strain rate, which also influences the breakup time. The mass per unit velocity also indicates the kinetic energy of the jet, which controls the hole volume within a target. Other parameters that may be examined are the flow velocity during collapse to insure the formation of a stable jet. One may also look at the collapse angle, particularly to see if there are possible interferences between the liner collapse and the forward section of the warhead. The origination of various mass elements may be tracked to maximize the working length of the liner and optimize the energy coupling between the liner and the explosive.

As the database of shaped charges has developed since World War II, it has become possible to establish criteria or working limits for some of these characteristics. At the same time, it has become feasible to analyze a target and determine the length and energy of penetrator that is required for defeat. This makes it possible to ‘reverse’ engineer the ideal jet, which then becomes the design goal. In the case of product improvements, the deficiencies of the current charge are known as well as what corrective action is required. For example, it may be adding a few grams of mass to the tail of the jet or increasing the tip velocity by 0.3 km/s. In either case, one can develop a jet velocity-mass curve that represents the improved or ideal jet.

## APPROACH

The general approach is to numerically compare the computational jet to the ideal jet. It is easy for a designer to look at a plot of two curves and decide if they match. It is more difficult for a digital computer to be programmed to do the same. If the shape of the jet mass profile were linear, it would simply be a matter of matching the slopes and intercepts. Fitting a mathematical curve, such as a higher order polynomial, to the jet velocity-mass profile, could be an approximation. However, one would have to match multiple coefficients. Taking a sufficient number of derivatives of the polynomial curve could lead to a linear formulation that could be compared; however, much of the specific shape function is lost in the process. Similarly, a least squares regression could be used to fit a best-fit line to the jet velocity-mass profile. This approach still requires the comparison of the resultant slope, intercept and correlation coefficient. Even if all three values were to match, one is still not guaranteed that the original curves match. Unfortunately, there is not a simple, unique solution to the linear approach. Another approach would be to look at the area under the curve. However, there are an infinite number of curves that will yield the same area.

Our approach is to discretize, on a mass basis, three different jet characteristics: velocity, momentum, and kinetic energy. Granted the third is a combination of the first two; however, the square factor of the velocity in the energy terms adds some uniqueness. The velocity, momentum and kinetic energy are plotted as a function of mass. Each curve is subdivided into separate mass regions, usually ten. The sub-division should reflect any specific feature that needs to be identified. Accordingly, we use smaller mass increments to resolve the jet tip. The average velocity, momentum, and kinetic energy for each increment are calculated. These values are stored in a look-up table. This table becomes the descriptor of the ideal jet. For subsequent design calculations the process is repeated in the same manner. Then the differences for each mass subdivision between the current design and the idealized jet are calculated. Each difference is squared to eliminate the possibility of positive and negative differences canceling each other. These squared differences are then summed over all the subdivisions. The square root of each of these three sums is divided by the total cumulative values of the ideal jet. The three quotients are then summed to produce a single value.

The difference between the ideal and computed tip velocity is added as a fourth distinguishing factor. This difference must be multiplied by a suitable scale factor such that its importance is properly weighted and then added to the previous single sum. This net result is л, our measure of jet goodness. We have found that the weighting factor applied to the tip velocity can promote rapid convergence to the tip velocity while still experiencing variations in the jet mass.

## EXAMPLE

This technique is illustrated through the application to an example problem. Consider the 48mm explosive diameter charge shown in Figure 1. It is a copper-lined, cylindrical charge that is point initiated. This is a non-optimized charge that produces a jet tip velocity-mass profile shown in Figure 2. However, for the purposes of this example, we assume that we desire similar jet tail properties and the jet tip velocity should be 7.6 km/s. Figure 2 also shows the mass division of the jet. The jet momentum and jet kinetic energy plots were divided similarly to develop the look-up table.

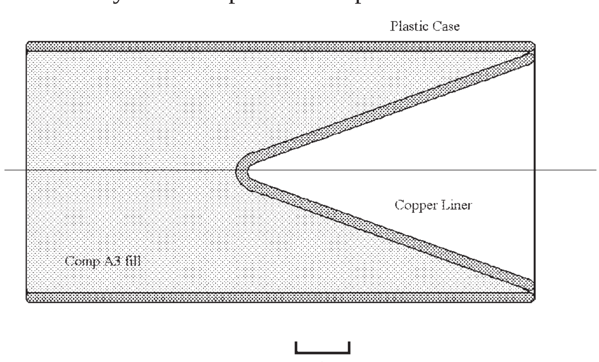


Figure 1. Configuration of shaped charge for example application of methodology.

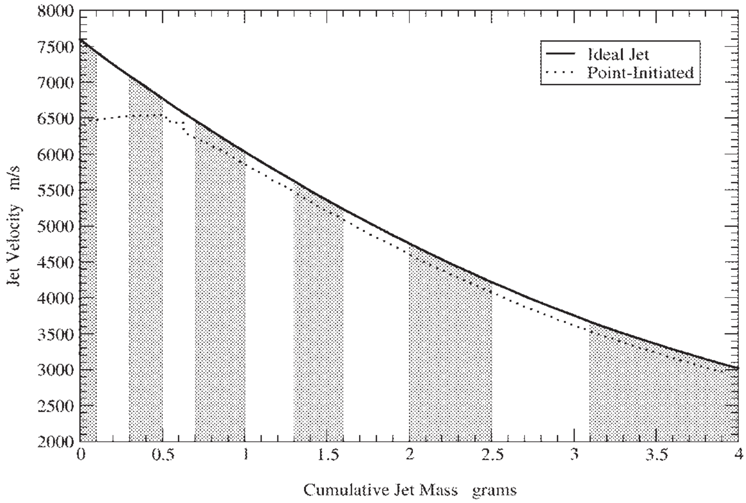


Figure 2. Comparison of the ideal jet and the original point-initiated jet. The gray and white regions show the mass sub-division of the ideal jet.

A simple design modification is to change the detonation source from point to ring initiation. The GLO software package [1] was used as the optimization driver. The figure-of-merit was the jet goodness value, д. Shown in Figure 3 are the results of this simple approach. These runs were completed using CTH running under Linux on a PC. The problem was coarsely zoned (approximately 3 cells through the liner thickness.) Typical run time is about ten minutes. This permits quick convergence to the approximate solution space. After twelve iterations, we find the ring diameter and axial location that produces a jet that matches the ideal jet. The figure-of-merit values are reported in Table 1. A more finely zoned computational model could be used to further improve the fidelity of the model and improve the agreement. Our experience has shown the GLO software package integrates well with CTH and develops reasonable solutions. We find that the д parameter converges as the jet velocity-mass curves converge.

Table 1. Optimization convergence figure-of-merit

| Design | Jet Goodness Value, Д |
|---|---|
| Point initiated | 166 |
| Iteration 1 Jet | 101 |
| Iteration 4 Jet | 57 |
| Iteration 12 Jet | 38 |

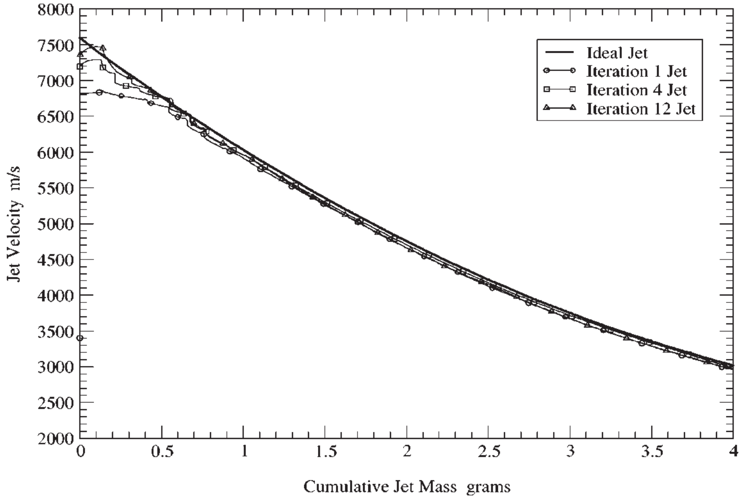


Figure 3. Shown are the converging jet velocity-mass profiles due to the optimization of the ring-initiation.

This approach has application in addition to checking for convergence. The parameter can be used to determine if a resultant jet still matches the ideal. Consider the prior example. Once the ring initiation is known, the body could be boat-tailed to reduce the explosive quantity. In this case, the figure-of-merit then becomes the explosive mass, not the jet character. We can use the д term to assure that the jet does not deviate from its character as a constraint. The GLO package also handles this type of optimization. We find that a simple boat-tail reduces the explosive mass from 221 g of the point-initiated design to 148 g of the ring-design. The д parameter remains the same for the ring-initiated charge and the boat-tailed charge, insuring that the jet velocity-mass properties are retained.

# CONCLUSION

Other researchers have used optimization routines to improve a single jet feature, such as the tip velocity. However, the rest of the jet is usually not treated. The approach described herein offers a mean of describing the entire jet velocity-mass character. The use of a single figure-of-merit to quantify the jet goodness permits the rapid comparison of a multitude of designs and facilitates the use of modern computer-aided design methodologies. This approach can be further refined via weighting factors to introduce faster convergence in optimization approaches. While the approach may not reflect high technology or advanced mathematics, it does demonstrate that a simple routine can be used to eliminate the subjective assessment of the 'goodness' of a particular design.

# REFERENCES

1. M. Murphy, *Global Local Optimizer User's Manual*, Lawrence Livermore National Laboratories, 1998.