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FURTHER DEVELOPMENT OF THE JET SUITE CAPABILITY: APPLICATION OF OPTIMISATION TECHNIQUES FOR ADVANCED WARHEAD DESIGN

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Analytic models of shaped charge jet formation, break-up and target penetration are becoming ever faster to run with the advent of increasing computational power. The challenge of using these models to search for a design that optimises a prescribed performance measure poses an infinite range of combinations to be tested. This paper presents the results of a research study that uses a standard QinetiQ shaped charge, the K4, as a baseline charge. An optimisation study is performed in which up to fourteen geometric and material design parameters are varied subject to various design constraints. Contrasting optimisation methods are employed first to maximise the speed of the tip of the coherent portion of the jet, then to maximise the kinetic energy of the jet and finally to maximise the penetration into a semi-infinite RHA target. It is concluded that stochastic and evolutionary methods appear to offer the most success and promise for advanced weapon optimisation methods including material and geometry selection.

INTRODUCTION

Analytic models that describe weapon performance against a range of targets have an important role in both the weapon design process and as part of lethality/vulnerability assessment. The JET Suite [1-4] is one such model, developed by QinetiQ over a number of years to predict shaped charge jet characteristics and their penetration performance.

The inherent speed of analytic models, compared with hydrocode simulations, implies that a large design space can be rapidly explored. This in turn suggests that they could be successfully exploited as part of an optimisation process that matches a weapon to the target, against a number of given system-engineering constraints. Moreover, some of the lessons on integration of codes in the optimisation process are cheaper to learn while using analytical codes rather than more complex codes such as hydrocodes.

This paper presents the results of a research study to investigate the use of the JET Suite as part of an optimisation study for shaped charges. The Options design exploration system [5] has been used to investigate a wide range of optimisation techniques.

The QinetiQ standard research K4 shaped charge has been used as the baseline charge design. The optimisation study has been performed using between five and fourteen geometric and material design characteristics constrained within a range of design criteria.

The direct optimisation method has been employed in the study and to date over two million design iterations have been performed. Both inherent jet characteristics, e.g. jet kinetic energy, and performance characteristics, e.g. jet penetration, have been employed as objective functions for the optimisation process. Their relative merits are reviewed and discussed.

Optimisation techniques using stochastic methods, gradient based methods, mathematical programming methods, heuristic approaches and evolutionary approaches were investigated and have been demonstrated. The results of these studies are presented and discussed. It is concluded that whilst analytic methods have some limitations, and the heuristic and stochastic methods are quite successful, it is the stochastic and evolutionary methods that show the most success and promise for advanced weapon optimisation methods using analytic models in terms of material and geometry selection.

THE JET SUITE

The JET Suite comprises a fully integrated set of programs for modelling shaped charge jet phenomena. It offers the means to make predictions of the performance of a jet entirely from first principles. The jet model created may then be used to make penetration predictions into monolithic or laminated targets. Data is passed from program to program in files of specified format. This modular approach offers considerable flexibility in the manipulation of data and has greatly facilitated the installation of the JET programs as subroutines called by the Options design exploration system as described below.

The functions performed by the main programs of the theoretical branch are:

- **JETFORM** - Theoretical prediction of the formation of the shaped charge jet in its unbroken state from charge properties. The program includes an algorithm determining which portions of the jet are formed in a coherent state, an important feature for designers.
- **JETBREAK** - Prediction based on an empirical model of the times and locations of the breaks in the jet, and hence of the entire motion history of the jet. The assumption is made that the fronts and backs of the individual particles travel at constant velocity, with values within the particle determined by linear interpolation.
- **JETPEN** - Prediction of penetration by the jet, treating each particle individually prior to and after break-up. The program models the off-axis motion of the jet particles, thereby achieving realistic penetration stand-off curves. A treatment of compressibility effects has recently been incorporated in this code, allowing predictions to be made for non-metallic materials, such as water, plastics, concrete and soil. Target components can be made of a single material or be laminated. Air gaps between components can be treated.

The programs of the theoretical branch typically run in seconds, allowing the user to explore the effects of parameter variations very rapidly. This feature and their modular design have greatly facilitated their inclusion in other software.

THE OPTIONS DESIGN EXPLORATION SYSTEM

The Options Design Exploration System is a suite of software that provides the user with a comprehensive selection of optimisation algorithms, including the following well-known algorithms applied in this study:

- The Simplex Method
- Simulated Annealing
- Genetic Algorithm
- Evolutionary Programming
- Bit Climbing Algorithm
- Design of Experiments Algorithm
- Adaptive Random Search
- Method of Successive Linear Approximation
- Random Exploration with Shrinkage
- Dynamic Hill Climbing Algorithm
- Hook and Jeeves Direct Search
- Repeated Application of 1-D Fibonacci Search

The user's software can be run by Options or called as a subroutine, to be repeatedly used in the search for the desired optimal value.

THE K4 CHARGE

The K4 charge is a standard QinetiQ research shaped charge warhead with a conical copper liner and aluminium casing. The charge has a central initiation method and uses EDC1S explosive. The characteristics of the K4 are given in Table I and Table II

Each of the studies conducted has used this charge data as a basis, with different choices of the parameters varied within a finite multi-dimensional range that was considered physically realistic, based on our previous experience. In two of the studies the choice of materials for the liner and casing was allowed to vary.

MAXIMISATION OF THE COHERENT JET TIP SPEED

The first study conducted addressed the maximisation of the speed of that part of the jet formed coherently, as predicted by the program JETFORM. There were several reasons for this. First, jet tip speed is of great interest physically, since, as a broad rule of thumb, the higher it is the more the jet stretches and the more it penetrates. Another basis for this choice was that this quantity could be automatically obtained from the JETFORM output. This is also a parameter that can in principle be extracted from hydrocode simulations of jet formation. Finally, JETFORM runs fast (less than a second to form a jet for the K4 design), so that it could be called very many times by the optimisation process.

TABLE I. Ranges of independent continuous variables and basic K4 charge characteristics

Parameter	Dimensions	Lower Bound	Upper Bound	K4 Charge
Explosive height above cone	mm	30	60	44.49
Height of cone	mm	50	90	68.98
Half angle of cone	°	15	45	22.5
Truncation of cone	%	0.0	12.0	0.0
Casing thickness	mm	2	10	3.0
Liner thickness (apex)	mm	0.5	3.0	0.9525
Liner thickness (base)	mm	0.5	3.0	0.9525
Barrier radius	mm	1.0	10.0	0.0
Barrier height	mm	1.0	5.0	0.0

The first set of studies used a simple optimisation test harness which calls the JETFORM DLL (dynamic linked library) directly, passing to it the desired design parameters of the jet shaped charge. The maximum coherent jet tip speed is then simply extracted from an output file. It is now that an optimising algorithm can be applied and the parameters for the next jet shaped charge can be generated.

Table I gives the ranges of those charge characteristic parameters treated as independent continuous variables. The only significant departure from the K4 design is the use of a wave-shaper barrier, with dimensions of height and radius required by JETFORM.

Several of the design variables are linked according to selection of material and/or explosive. Hence, design variations are achieved by varying the choice of material, rather than through continuous variation of the dependent parameters (such as the density of the material, its Gurney constant, etc.). Table II defines the independent materials and the associated dependent variables.

The remaining independent input values define discrete elements of the charge design, namely one of four initiation options, and, one of two cone geometry options.

Preliminary explorations of the sensitivities of the maximum coherent speed to the parameters were made. We plotted velocity values, by first varying one, and then two, parameters. In each case the speed increased or decreased, with no turning points in the middle of the range considered. The simplex and simulated annealing algorithms [6] were coded into the test harness and then run. In both these cases the search was confined to the case of barrier initiation and constant

TABLE II. Independent material choices and associated dependent parameters and basic K4 charge characteristics

Independent Material Choice	Dependent Parameters	K4 Charge
Explosive	Detonation velocity Gurney energy Density Detonation pressure	8430 m/s 4.0434 MJ/kg 1800.0 kg/m^3 32.0 Gpa
Liner material	Bulk sound speed Density Index of density ratio in Murnaghan Equation of State	3921.67 m/s 8960 kg/m^3 4.999
Casing material	Density	2700 kg/ m^3

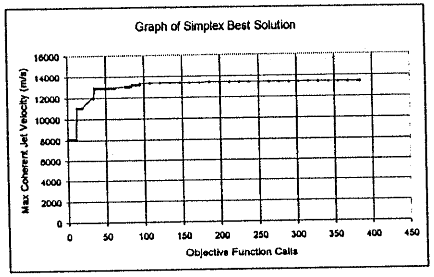

FIGURE 1. Simplex method best solutions.

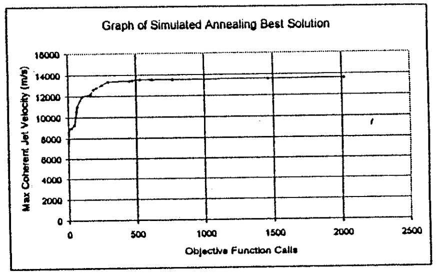

FIGURE 2. Simulated annealing best solutions.

liner thickness. A plot of the best solutions that the simplex method found is shown in Figure 1, with the corresponding maximum found to be 13417 m/s after 290 iterations. The corresponding plot for the simulated annealing algorithm is shown in Figure 2, with the corresponding maximum found to be 13628 m/s, i.e. some 211 m/s faster, after 2018 JETFORM executions.

The corresponding optimal design included the selection of an initiation method, the explosive, and the liner and casing materials. The independent continuous parameters ended at either the minimum or maximum of their bound values.

The fact that the parameters are at the bounds of the ranges is expected in view of the absence of turning points observed in the preliminary plotting. The feasibility study test harness, in conjunction with JET, had thus been used successfully to design a charge with optimal maximum coherent jet tip speed. This included the choice of component material types and the initiation method. The number of iterations to home in on the maximum was not excessive. However, the maximum velocity problem clearly leads to the solution where the liner material is the lightest available and other parameters are at their bounds. No realistic design constraints were applied, such as physical size, weight etc. Nevertheless, we were encouraged by these results to apply the method to more realistic objective functions. The first of these we considered was the total kinetic energy of the jet.

MAXIMISATION OF THE JET KINETIC ENERGY

Following the initial demonstration of the feasibility of applying optimisation algorithms to charge design, JETFORM was then integrated into the Options design exploration system. Options includes a wide range of facilities for design exploration, as well as containing many optimisation algorithms already coded. The Options package deals with JETFORM like a subroutine, therefore all necessary input and output variables were set and extracted relatively easily. Validation tests between the integrated JETFORM within Options and the test harness were performed.

It was considered that an objective function of maximum jet kinetic energy might be a better measure of charge performance and might also provide a function easily extractable from hydrocode runs. The key results of the runs performed on the integrated JETFORM within Options are shown in Table III.

Table III. Results of maximisation of jet kinetic energy.

Algorithm	Energy kJ	No. of iterations
Simulated Annealing	1404	150000
Genetic Algorithm	1226	40000
Evolutionary Programming	1366	75000
Bit Climbing Algorithm	1225	3000
Design of Experiments Algorithm	556	4000
Successive Linear Approximation	1383	297
Random Exploration with Shrinkage	949	7218

Figures 3-5 show the results for the Simulated Annealing, Genetic Algorithm, and Successive Linear Approximation algorithms, respectively. The latter is much the quickest to reach a maximum, but it cannot treat the discrete variables. The Simulated Annealing and Genetic Algorithm methods automatically chose the explosive, and the liner and casing materials, the initiation method, and the amount of tapering. The Evolutionary Programming algorithm selected a different casing material, but otherwise made identical choices.

It was pleasing that the algorithms functioned effectively in generating improvements on the performance of the basic K4 jet. However, while jet kinetic energy is an important quantity, it was naturally of interest to see if the methods could be applied to that quantity usually considered the most desirable to maximise, namely the penetration.

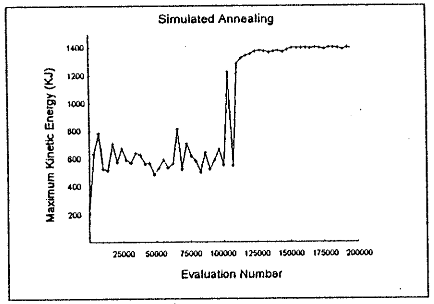

FIGURE 3. Simulated annealing results.

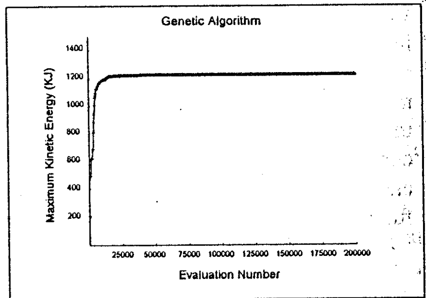

FIGURE 4. Genetic algorithm results.

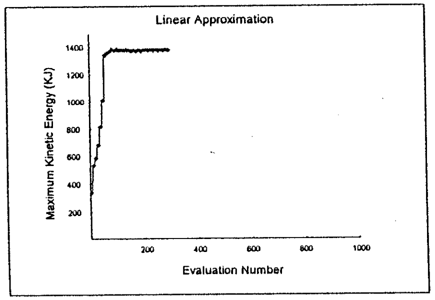

FIGURE 5. Linear approximation results.

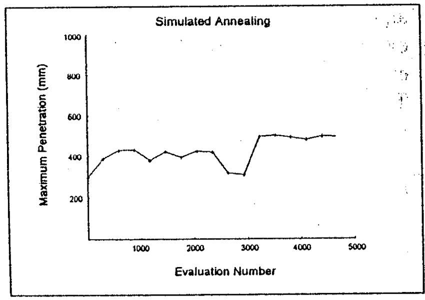

FIGURE 6. SA method, penetration results.

MAXIMISATION OF PENETRATION

To investigate the maximisation of the penetration achieved by the jet into a semi-infinite Rolled Homogeneous Armour (RHA) target it was necessary to include the jet break-up code JETBREAK and the penetration program JETPEN as additional subroutines within the Options design exploration system. Repeated iterations of the entire theoretical arm of the JET Suite could then be made automatically. The modularity of the JET Suite rendered this a reasonably straightforward programming task and the low run times of all three programs made the study feasible. We have, however, encountered some difficulties associated with the use of the finite time-step in JETFORM and with the decision logic in JETPEN, which can result in the generation of what appear to be clearly defined local maxima. These local solutions can fool some optimisation algorithms into reaching the conclusion that a global maximum has been found.

The inclusion of JETPEN added the standoff distance to the parameters that could be optimised. The successful optimisation of standoff showed the ability to optimise variables at different stages of the analytical models simulation process.

We imposed the realistic constraint that the overall charge volume remained fixed and this time confined the search to the parameters used in the standard K4. We thus were in effect seeking a realistic upgrade to the K4. It should be noted that the optimisation algorithms were not started at the K4 design but in the middle of the bounds for each parameter. This explains why the linear approximation terminated at a lower penetration than the K4 charge. The Simulated Annealing (SA), Genetic Algorithm, and Evolutionary Programming methods have the happy characteristic that they are capable of extending the search beyond local maxima that can trap other methods. They predicted maximum penetrations up to 76.5% above the standard value for the K4 and the predictions of the other methods. Table IV shows the results, while Figure 6 shows the results for the SA Method.

It is interesting to note that the Simulated Annealing algorithm will allow the consideration of apparently inferior solutions while exploring the charge design space. For the reasons given above it is apparent that the stochastic and evolutionary methods are far superior for this particular application. The close agreement between the maximum penetration predictions for the Simulated Annealing and Genetic Algorithms is particularly pleasing.

Table IV. Results of maximisation of jet penetration.

Optimisation Algorithm	Maximum penetration (mm)	No. of iterations
QinetiQ K4 baseline charge design	287.0	-
Random Exploration with Shrinkage	435.4	5213
Adaptive Random Search (Stochastic)	419.3	376
Dynamic Hill Climb Algorithm	454.0	1067
Method of Successive Linear Approx.	126.6	98
Bit Climbing Algorithm	443.8	977
Hook and Jeeves Direct Search	383.3	680 (approx)
Simplex Method (Heuristic)	358.0	879
1-D Fibonacci Search (Heuristic)	449.8	313
Evolutionary Programming	441.6	5000
Simulated Annealing (Stochastic)	506.2	5000
Genetic Algorithm (Evolutionary)	506.6	5000

DISCUSSION

It is has been shown possible to use one or more JET Suite programs within the Options design exploration system to provide the objective function for the optimisation process. In particular optimisation of the maximum coherent jet tip speed and kinetic energy as evaluated by JETFORM has been accomplished before addressing the optimisation of the penetration into a target using the entire theoretical arm of the JET Suite, namely JETFORM, JETBREAK, and JETPEN.

In each case the Simulated Annealing Method has achieved the best, or very close to the best, result, although this has been at a high price in the number of evaluations performed. The low run times associated with the JET Suite programs have made the use of this method perfectly feasible within typical concept design project time-scales of a few weeks. Other algorithms can home in much faster on the optimum, but this typically requires the correct choices of discrete variables and materials already to have been made. Other algorithms can also get trapped on local optima. Probably the most efficient approach would be to apply the simulated annealing method first and then, when the presence of a local maximum is detected, use the faster algorithms to home in on this quickly.

It is apparent that stochastic and evolutionary methods appear to offer the most success and promise for advanced weapon optimisation methods including material and geometry selection. As with any tool, such methods must always be applied with care, since the mathematics will at times make selections that are not practical. The reason for this is that no mathematical constraint reflecting the practical limitations has been imposed. Nonetheless the methods can highlight automatically combinations of materials and geometries that a designer may not have chanced upon using traditional methods.

When considering the results of this research it should be noted that the penetration predictions have been derived based on certain assumptions regarding the magnitude of the lateral drift. It is left to validate the results against experiment.

It remains to exploit this knowledge in the creation of new warhead designs.

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NEUTRALISATION OF AP-MINES WITH ND: YAG LASER

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Trinitrotoluene (TNT) is the most common explosive used in antipersonnel-mines. To neutralise mines without any detonation a deflagration of the explosive has to be initiated. In this paper interaction between pulsed laser radiation in the UV-range and bare TNT and interaction between cw Nd:YAG laser radiation and bare and wrapped TNT are investigated. The results are compared with theoretical predictions. With pulsed ArF excimer laser emission of $215 \cdot 10^6$ kW/m^2 intensity the predicted TNT ablation is achieved. Wrapping the TNT into an absorbing material leads to the desired burning process under Nd:YAG irradiation.

INTRODUCTION

In approximately 70 countries of the world [1] landmines have become a problem and a daily threat. Mines and other unexploded ordnance (UXO) that are mostly triggered accidentally are killing or injuring more than 2000 civilians per month worldwide. There exist a broad range of different types of antipersonnel-mines (AP-mines) but mostly trinitrotoluene (TNT) is used as explosive charge. Different methods to destroy detected AP-mines are available but all these methods are dangerous because the deminers have to work near or even in contact with the mines. Laser neutralisation of detected mines offer the possibility to work from safe distance. Additionally it could be possible to destroy the mines without any detonation. To investigate the most suitable laser system the interaction of laser and TNT is first treated theoretically. Several articles [2-5] where the conditions to reach ignition of the explosive are estimated are available. There are two possible ignition mechanism, a thermal mechanism in which intense local heating by the laser radiation causes the rate of chemical reactions within the explosive and an impact mechanism in which the chemical reactions are accelerated by a strong laser generated shock wave in the material. In this letter the main focus is on the thermal ignition because in the demining process a deflagration of the explosive is desired.