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Theoretical Modelling of Shaped Charges in the Last Two Decades (1990-2010): A Review

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Abstract: Shaped charges are used for the penetration of targets in all three dimensions of warfare – land, air and naval. With fillings of high explosives compositions inside, they generate a thin high velocity metal jet, which can perforate the targets. Shaped charges can penetrate tanks with thick armour protection, they can destroy bunkers, they can destroy aircraft and are also useful for attacking ships or submarines. Although shaped charges have a very long history since the Second World War, theoretical modelling efforts started with the steady state theory of Birkhoff in 1948. This theory was modified by the non-steady state theory known as the PER theory of shaped charges. Later, several contributions from experimental evidence were incorporated in the theoretical formulations, and the mathematical models were refined by including the virtual origin, and physical qualities of the jet breakup time, defragmentation into particulates time, the diameter of the metal jet, wave amplitude etc. To review the development of theoretical modelling of shaped charges, three stages are defined. The first is the development until 1990, when the theory of shaped charges was fully developed and penetration predictions with fairly good accuracy were possible. The second stage reviews work carried out in the last decade of the 20th century. During this period good experiments were planned, parametric study was carried out and the results incorporated in the mathematical model of shaped charges. The third stage is all work done in the 21st century (2000-2010), when the tools for advanced diagnostics, new fabrication and inspection, as well as new liner materials were incorporated. The anomalies obtained were resolved by further refinements in the developed theoretical models. The unexplored areas of the theoretical modelling of shaped charges are also enumerated in this paper.

Keywords: copper liner, high explosives, jet formation, shaped charges, target penetration

Introduction

Shaped charges (SC) are cylindrical explosive charges with a hollow cavity at one end and a detonator at the other. They are also called “hollow charges” or appear as explosively formed projectiles (EFP). The shape of the hollow cavity may be conical, hemi-spherical or tulip-shaped, and the cavity is usually lined with a metallic liner made of copper, steel, aluminum, etc. Detonation of the explosive charge creates intense, focused, localized forces and shock waves. They are directed towards the metallic liner, which is accelerated under the high detonation pressure (200-300 kbar) of the explosive at a very high strain rate (104-107 /s). As a result, the liner material collapses in the form of a jet, whose tip may attain a velocity in excess of 10 km/s and the rearward tail, called a “slug”, can attain a velocity up to a maximum of 2 km/s. The velocity gradient along the length of the jet leads to stretching of the jet, which ultimately fractures the jet due to severe elongation, if uninterrupted. This is called the Munroe effect, the Von Foerster effect or the Neumann effect.

If this elongating jet is directed towards a metallic plate, a deep cavity is formed in the plate. Due to the high velocity of the jet, the stagnation pressure exceeds the strength of any known material and can easily penetrate even the hardest material. The strength of the target material has no significance and only the density of this material is taken into account to calculate the penetration depth. Although, shaped charges were used during the Second World War, theoretical modelling and performance prediction approach started much later, in the form of a steady state, hydrodynamic theory by Birkhoff [1], later supplemented with the non-steady hydrodynamic theory by Pugh, Eichelberger and Rostoker [2].

There are several aspects concerning shaped charges: the explosive, the material and fabrication of the liner, metallurgical considerations, the strength of materials, hydrodynamics, the jet formation, interaction and penetration, etc. However, the present article reviews only the theoretical modelling efforts, with some experimental facts being considered for supplementing the theoretical achievements. The development of shaped charges and theoretical predictions made before 1990 are compiled in the book by Walter and Zukas [3]. Later developments are chronologically described in the present article in two parts: new areas which have evolved (i) between 1990 and 2000, and (ii) since 2000.

Status until 1990

Common terms used in the theoretical modelling of shaped charges are enumerated in Figure 1. Due to ease of fabrication, sufficiency of performance and easy analysis, the liners used in shaped charges are fabricated from copper in conical shapes. The main parameter of the shaped charge is the charge diameter (D) and many other dimensional and performance parameters are generally expressed in terms of this parameter. The charge length, standoff distance of the target from the face of the shaped charge, penetration, etc have been described as multiples of the shaped charge diameter. The explosives used are characterized by the Gurney Constant, the velocity of detonation and the detonation pressure. The liner material is described in the theoretical modelling by its density, dynamic strength and thickness. A casing of steel or aluminum may be used, so as to ensure confinement of the explosive charge, otherwise shaped charges are also fabricated as unconfined charges. The geometry of the lined cavity is characterized by the apex angle, which is a very significant factor for the performance assessment of the shaped charge. Tremendous efforts were made in the area of theoretical modelling of shaped charges before 1990 and the classical hydrodynamic theory for prediction of performance of shaped charges was well understood and the results invariably matched the experimental observations.

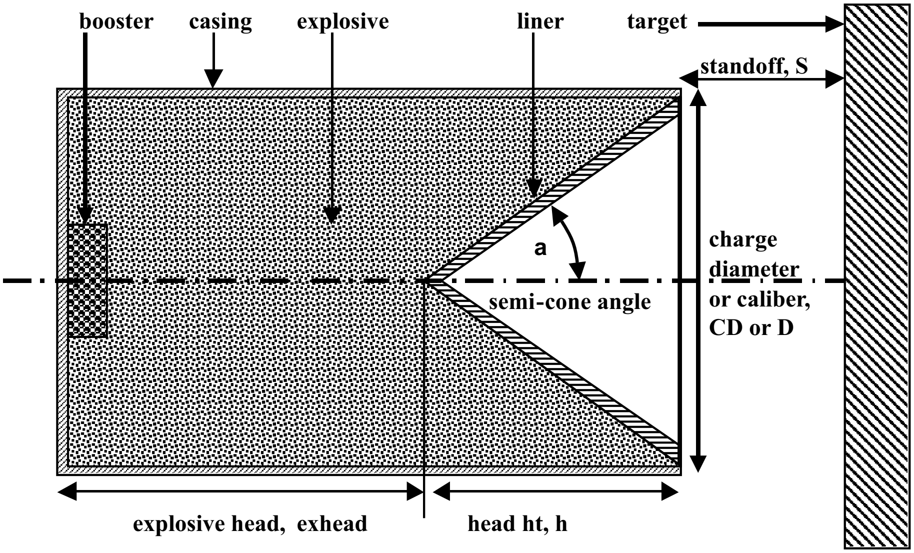

Figure 1. Nomenclature of terms used in shaped charges.

The hydrodynamic theory developed earlier as the PER theory [2], was validated by experiments and the effect of the strength of the target material in the assessment of the penetration depth in the target was highlighted by Eichelberger [4]. Steel, aluminum and lead were considered as target materials and it was found that the static strength of these materials was not sufficient for the estimation of penetration. Dynamic strength of these materials was coined and it was observed that the ratio of dynamic strength to static strength varies for different materials. For steel it is around 1, while for aluminum it is 4-5. Gradually the hydrodynamic theory gained in importance, with minor modifications based on experimental observations, and the sequence of events during the detonation of a shaped charge was divided into the following steps: (i) initiation of the charge, (ii) arrival of the detonation wave at the liner, (iii) collapse of the liner along the axis, (iv) jet formation, stretching and particulation, (v) interaction of the metallic jet with the target, and (vi) assessment of penetration.

Although several papers are cited in the book by Walter and Zukas [3], isolated work carried out in different parts of the world were published in the form of many reports and papers, validating or modelling any single important aspect of shaped charges. In the US Army Military Command Pamphlet (AMCP), the steps for detailed design of shaped charge warheads are enumerated [5]. If the dimensions are in inches, then the copper cone diameter (*D*) is related empirically to the thickness of the armour plate (T) to be penetrated by the relation, D = (T + 2) / 5. For short standoff distances, the liner may be made of copper, aluminum, steel, zinc, lead or glass, in order of their penetration ability. The most ductile alloy of a specific material always gives higher penetration. If the steel target is fixed, then the copper liner gives the maximum penetration at a standoff of 1-3 charge diameters (CD), while the aluminum liner gives the maximum penetration at a standoff of 5-7 CD. This means that the liner material should be copper if the maximum penetration is desired at a short standoff. For aircraft as the target, the best liner material is aluminum because a low density target receives the highest penetration with a low density liner. It is also stated in the design process, that the cone apex angle is generally between 40° and 60°. A liner with a smaller cone apex angle also gives penetration at a smaller standoff distances. However, manufacturing the liner with a small cone apex angle is a challenge. The optimum liner wall thickness is also in the range of 2-4% of the CD.

A generalized analytical approach to shaped charge warhead design is presented in a report by Behrmann [6]. This report refers to the practical aspect of the warhead design. The process starts with a given target to be defeated by the shaped charge. The existing jet penetration theory is applied and the warhead is designed. The report describes the utility of non-steady state theory for the jet formation and the one-dimensional. finite difference, continuum mechanics formulation to calculate the complete jet formation parameters for any generalized axis-symmetric shaped charge. Many new concepts are also analyzed, like the jet stability, bifurcation on the axis, shear gradient, viscosity, shock, incipient vaporization, surface tension, etc. The report also describes several experimental findings. The liner velocity is not found to be constant and the acceleration is discontinuous. As the liner radius is increased, the velocity gradient through the liner at the time of collapse is reduced. Several empirical relations are also discussed.

Perez [7] reported experimental observations and tried to explain the shaped charge effects using a computer code, called HOCC. It was explained that the complete shaped charge effect has many intermediate phenomena, like diameter of the charge, lengthening of the metallic liner, velocity of detonation of the explosive used, the booster or initiator location, etc. It was also stated, that unfortunately it was difficult to isolate these effects. The PIESES code handled these aspects to some extent, but more complexities and jet coherence calculations were difficult to carry out without manual intervention. Compared to that, the simplicity of the HOCC code was explained. Complete mapping of the liner collapse and parametric variations were plotted and explained in the report.

In another report [8], the PER theory is modified slightly for prediction matching to the experimental results and for making the theory more versatile for different formulations. A number of advantages of the developed code are put forth in this report. The input of geometrical parameters and coefficients to the program in a functional form makes it easy to use. The output can be compared directly with the experimental results. The computer run time is short and the parametric study can be facilitated in the software. The Defernoux equation is used for the deflection angle and the coefficients 'K' and 'ϕ_o' are simulated as a polynomial equation in 'γ' (the deflection angle between normal to the detonation wave and tangent to the liner). For a typical example, the jet velocity is found to increase monotonically with the jet particle position and proper matching of the experimental and theoretical results is also depicted.

In the BRL report [9], radiographs taken during jet formation of the shaped charge are studied and some preliminary calculations are made regarding stability of the jet. In another study [10], two aspects of shaped charges are considered – the first is the jet breakup and the second is the broken jet penetration. The jet breakup is studied from the stability approach, where a one-dimensional stability theory for stretching plastic jets is presented. The stress-strain capabilities of the materials are incorporated in the stability criteria of the jet for their coherency. It is observed that if the stretching rate is decreased, the rate of disturbance growth increases. However, if the ratio of the flow stress to the density is increased, the rate of disturbance growth also increases. In jet penetration, also after fragmentation, the penetration continues and the impact of high velocity particles at the base of the penetrated hole make it deeper.

The penetration of a target by a shaped charge jet can be simulated as a penetration of a target by a long rod. Most of the penetration codes also rely on a rod penetration model for the shaped charge performance. The rod penetration model uses Bernoulli's equation in the Lagrangian coordinate system. The variable jet length poses another mapping exercise, where each element on the liner surface is mapped onto the jet axis by suitable transformation. A one-dimensional rod penetration model is described in report [11] and a computer code for the same is also developed. A full program listing, test cases, parametric studies and relevant curves are available for rod penetration in this report. Various projectile materials, such as aluminum, gold, magnesium, tin and lead are considered, and their penetration in the aluminum (7075-T6) target for different impact velocities is monitored and listed.

By the 1980s, the theory and prediction for shaped charges were so refined that a manual for shaped charge design was published in 1982 [12]. This design manual included all the principles of Birkhoff and PER. The mechanism up to penetration was studied and the experimental evidence was also quoted in support of the validity of the developed formulations. The report highlights several governing parameters for shaped charge design by real examples and some new areas to be explored are identified. Among others proposed in the report, the most significant is the research on fluted liners.

In a report from the US Army Ballistic Research Laboratory [13], quantitative support for the assumption that jet curvature is the major cause for non-ideal jet penetration is established, after analysis of a component of the jet velocity normal to the axis of symmetry of the charge for each jet particle. This non-ideal velocity component is the drift velocity which is used in a computer simulation of the penetration process. The computer code, referred to as PENJET, was employed to generate penetration-standoff curves using the data from the specific round. This curve depicts the penetration-standoff performance for a single round as if it could be shot repeatedly at a variety of standoffs. The curve could then be compared with the actual datum for the round.

The tandem shaped charge emerged in the 1970s, where two shaped charges – a precursor and the main charge – are placed in tandem and initiated one after another to acheive a longer penetration. As per a patent filed in 1973 [14], enhancement in penetration from a shaped charge warhead was described by providing a follow-through charge in the jet-hole created by the initial shaped charge. The invention used two shaped charges (Figure 2A), one behind the other, in a single warhead, with the rear charge (also called the initial charge) initiated first. The front charge (the secondary charge) had a central opening called the aperture, through which the jet from the rear charge is passed. However the slug from the rear charge is restricted by the aperture diameter and this initiates the front shaped charge. The front charge is filled with an explosive that gives a higher jet velocity. This augmented the jet from the initial charge and the penetration performance is improved. In the inceptive design [15], initiation of the main charge is realized by a clipper element in the precursor and not by a separate initiation mechanism with a time delay. Using flash x-ray it was found that a sub-optimal design results in unwanted incidents, like the tip of the main charge jet hitting the tail of the precursor jet, non-uniform initiation of the main charge, etc. A tandem shaped charge warhead is described in patent [16], where the main aims were an improvement in performance, reduction in weight of the warhead and neutralization of the active armour on tanks. A sketch of the proposed warhead is presented in Figure 2B, where the forward charge is smaller in size and is made of an explosive filling to give a target impact speed of the generated core in the range of 1000-1500 m/s. The rear secondary charge was initiated after a delay time of 50-300 μs. The delay time is provided for neutralization of the active protection system of the tank, sequential action of the rear charge after action of front charge and reduction in the interaction of the jets from the two charges. The shape and material of construction of the liner were also enumerated as claims of the patent. As per another United States patent from Israeli researchers [17], the section between front and rear charges was modified and an X-section was introduced to divert gases and debris from the front charge from affecting the rear charge. The sketch of the warhead design is reproduced as Figure 2C, where the connector between both the shaped charges in an X-shape was designed to guard as well as shield the rear main charge. It deflects gases produced from the front charge away from the line of the main charge.

Overall, the theory of shaped charges, their design, their modelling, experimental validation, 1D software development, hydrodynamic 2D software validation and prediction of penetration by several empirical equations were perfected by 1990. The principles for shaped charge design were fully understood by this time. Although several papers were published before 1990, the book by Walter and Zukas gave complete coverage of them . The modelling of shaped charges entered a new phase in 1990, with other considerations forming the major part of the development and modelling simulation.

Developments during 1990-2000

Shaped charges were analyzed with renewed interest during this period. Several important conclusions were derived from experiments and the incorporation of these concepts into the theory of shaped charge modelling became prime concerns. Diverse papers on the specific diagnostic tools for shaped charge studies were explored during this period. 450 kV flash x-ray radiographs were used to study shaped charges of different calibres (30, 60 and 90 mm) in one of the papers [18].

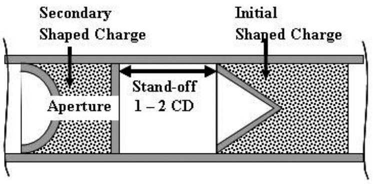

Figure 2A. TSCW Patented in 1973

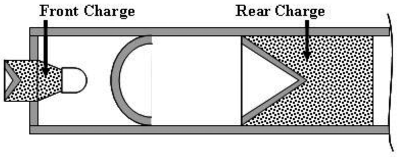

Figure 2B. TSCW Patented in 1987

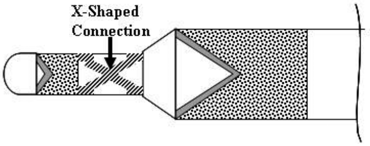

Figure 2C. TSCW Patented in 1989

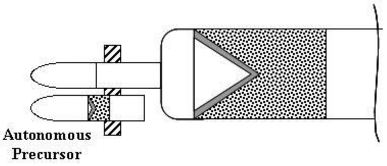

Figure 2D. TSCW Patented in 2000

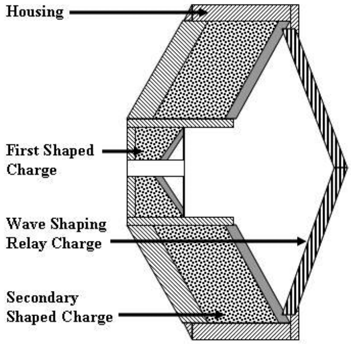

Figure 2E. TSCW Patented in 2010

Figure 2. Evolution of Tandem Shaped Charge Warheads (TSCW).

The compendium of work carried out until 1993 is available in a concise form in an AIAA publication [19]. It contains separate chapters on the shaped charge mechanism, the jet formation, the experimental evidence and the penetration of targets. The theoretical aspects of shaped charges for modelling purposes are well defined in this book. In the paper [20], the 1D and 2D computer codes for shaped charges were analyzed and a new 3D code was proposed to be a better alternative for predicting the performance of shaped charges. In another paper [21], a new model for shaped charge jet break-up is devised after analysis of the fragments of the shaped charge jet and their characteristics are compared against the ones predicted by the break-up proposed by Pfeffer, Hirsch, Chou und Haugstad. As the predictions provided by these models are not completely satisfactory, the break-up process was analyzed in order to develop a new break-up model which provides a better estimation of the break-up time and the accumulated length of the jet. This model makes use of one parameter, the fragment shape index, which can be determined experimentally. This parameter characterizes the type of jet break-up (ductile or brittle) and is hence indicative of the jet quality.

The use of copper-tungsten alloys for shaped charge liners leads to an improvement of jet penetration into a homogeneous steel target [22]. In comparison with copper jets, the penetration depth can be increased by a factor 1.3 due to the enhancement in the density and the break-up time for the copper-tungsten liner. Copper-tungsten shaped charge jets and the break-up phenomena were investigated by flash radiography. The effects of the copper-tungsten jets for both rotation and standoff performance were also examined.

A well-characterized shaped charge was used to study the influence of asymmetrical initiation on the jet [23]. An experimental study yielded flash radiographs of the jets from charges fired with the initiation point offset by 2, 4, 6, 8 and 10 mm, respectively, from the central axis. The axial and lateral velocities of the jet particles were determined from these sets of radiographs. Since it is possible to map particle velocities in the jet on to those regions of the liner where they originated, simulated sets of axial and lateral jet velocities were readily generated. Agreement between theory and experiment is sufficiently close to suggest that the approximation is useful and can assist in understanding the jet dynamics of asymmetrically initiated shaped charges.

A paper [24] indicates a density deficit of at least 6.5% as one of the unexplained effects of a shaped charge jet. Density deficit is present in the stretching, unparticulated shaped charge jet, after all known sources of error are evaluated and all contributing factors (e.g. heating due to plastic work) are considered. It is suggested that a “vacancy avalanche” mechanism, which is operating only during the highest strain-rate interval, preceding particulation, can generate the high transient vacancy concentrations required to explain the observed density deficit.

Under research highlights [25], the largest shaped charge in the world is illustrated. In early 1997, Lawrence Livermore successfully tested a shaped charge that penetrated 3.4 meters of high-strength armour steel. The largest diameter, precision shaped charge ever built produced a jet of molybdenum that travelled several meters through the air before making its way through successive blocks of steel. The team performed simulations using CALE (C-language-based Arbitrary Lagrangian-Eulerian), a two dimensional hydrodynamic code developed at Livermore. Livermore scientists used a variety of complementary diagnostic tools during the experiments with shaped charges. The tools were X-radiography, the rotating-mirror framing camera, a kind of motion picture camera, which can shoot millions of frames in a second etc. The newest tool was the image-converter (IC) camera, which was developed at Livermore in the mid-1980s. With exposure times of just 15 to 20 nanoseconds (up to ten times shorter than those of the framing camera) and a band pass filter mounted on the camera to exclude extraneous light, the IC camera supplied the first truly higher solution images of the formation and early flight of a shaped-charge jet.

Alistair Doig [26] reviewed various criteria for material selection of the shaped charge liner. The copper liner is well suited for shaped charge purposes and the selection of any new material for the liner needs a thorough consideration of ductility, strength and density. The anomaly of treating the jet as an incompressible fluid, despite it acting as a solid, is explained in the article. Because of its better ductility, copper cones with a finer grain size perform better than those with larger grains, partially because of the higher strength of copper with finer grain size. Graphite cones, and even ceramic cones with zero ductility, have shown significant penetration into steel targets. There is confusion in the selection of liner materials for shaped charge applications because accurate dynamic properties of any new proposed liner material are neither easily available nor determined. The mathematical modellers, therefore, often fit their output to the results of firing trials (cross-calibration to reality) by adjusting some of the materials' coefficients. Event fitting is necessary, but it does not allow the models to be used for predictions. Using the measured dynamic properties of materials would enable the mathematical modeller to enter the era of true prediction, and the instrumented Drop Tower can help in this area.

Davidson et al. [27] changed the shape of the liner for optimization of the performance of a well-perforator. The objective of the optimization was to increase the jet energy and penetration as much as possible within the limitations of the same outer dimensions of the perforator body and restricting the explosive mass to 39 g. The strategy was to replace the conical liner with a bell-shaped one of variable thickness, similar to ones that have shown significant gains in performance in prior studies. The outcome was an improved design that produced a jet with 10% more kinetic energy than before, with much of the increase at the back of the jet, where it was most effective in increasing the penetration depth. The penetration into the concrete target of the designed shaped charge increased by 28% from that of a reference charge. The hydrodynamic computer program AUTODYN 2D and its thin-shell jetting option, and the analytical penetration analysis program JEPETA, were used to evaluate the baseline design and candidate alternative designs.

Manfred Held [28] investigated the effect of shaped charge jets on glass armour. 115 mm shaped charges were fired at constant built-in standoffs of 3 calibres against glass targets, covered on both sides with steel plate, from 0 to 60 NATO angles. The residual jet tip velocities and the disturbed jet regions have been analyzed from double flash X-ray pictures of the residual jet behind the target. Surprisingly, under small angles the tip regions, and under large angles the residual jet velocity regions, have been more disturbed. This can be explained by the fact that under small angles the closure effect of glass is efficient, but is not so effective at large angles. The cover plates of the glass sandwich are effective as bulging armour. From the measurements of the penetration time and the jet fan, the limiting jet velocities for definite penetration can be enumerated and defined. The response time of the armour interaction with the jet, or induction time for the same, can be calculated from the measured values.

Research carried out in Japan in the direction of shaped charge modelling is presented in paper [29], where jet formation and impact on targets is simulated by the AUTODYN-2D computer code for a conical liner of aluminum. The decreased effect of the jet mass during travel to the target is investigated. The effect of the density and shape of the jet on the size of the crater formed on the target are also simulated. The investigation is useful for the calibration of the jet mass and jet velocity, because it is difficult to gain accurate information on them by experimental measurements. These numerical results are discussed along with a comparison with the corresponding experimental results for variation in the jet shape, the crater shape, the jet mass and the jet velocity.

An interesting observation is described [30] when steel targets were shot at with shaped charges whose liners were made of aluminum and magnesium. The jet velocities ranged from 5 to 7 mm/µs. Behind the steel target, a large behind armour blast (BAB) – effect occurred. In order to gain a better understanding of the physical phenomena responsible for this strong BAB effect, hypervelocity impact tests with conventional spherical projectiles were carried out. These tests were conducted on a two stage, light gas gun using Al and Mg projectiles at the same impact velocity as in the shaped charge tests. The target consisted of a thin steel plate, followed by a thin aluminum witness plate. The first tests showed comparable BAB effects. The experimental test set-up, results and interpretation of the results are reported in the paper.

In the area of tandem shaped charge warheads, performance improvements were attempted [31] to counter advancements in the tank protection domain. The development of active armour necessitated onboard adjustments of ignition delay and angle of attack on active targets. Four distance measuring optical (laser diodes) means with their own transmitting and receiving units, were incorporated on the body of the warhead, so that the momentary angle and ignition delay can be adjusted for optimum performance. The calculations for different combinations of measured mean distances by different sensors were presented in the patent and the method for estimation of the stand-off distance for activation of the warhead is discussed. In another patent [32], precursor charges of either kinetic energy or chemical energy (shaped charge) projectiles were made autonomous and attachable (Figure 2D) without affecting the overall length of the warhead.

During the last decade of the 20th century, theoretical modelling has gained in importance and several new theories have been proposed. Experimental observations through flash x-ray were used effectively for understanding the particle velocity and the jet break-up time. Asymmetric initiation was investigated and experimental observations were simulated using different hydro codes. Several new hydro codes for specific purpose were also developed. Studies were carried out in which the copper liner was replaced with copper-tungsten, molybdenum, aluminum, magnesium, graphite and ceramic materials. The target materials investigated included steel, glass and lead.

Developments during 2000-2010

Theory became further refined and most of the modelling work was concentrated on matching experimental results using empirical formulations. The diagnostic tools matured during this period and experiments were planned with greater precision and variation of parameters, which was not possible earlier due to constraints of measurement accuracy. The cut-off velocity of a shaped charge jet was investigated and a model was developed for the limiting velocity U_{min} in paper [33]. Another paper [34] also described a limiting velocity below which target strength cannot be neglected. The limiting velocity is dependent on the target hardness and density. For the high-hardness aluminum and titanium alloys used in this paper, the limiting velocity is around 3.0 km/s. Penetration into the aluminum and titanium alloys by portions of the jet with velocities below 3 km/s was studied experimentally; the depths of penetration were found to be significantly smaller compared to the hydrodynamic predictions. This deviation has been attributed to the target strength effect. A preliminary experimental study [35] to understand the penetration effectiveness of titanium against shaped charge jets was investigated in detail. Shaped charge jets formed from 100-mm charge diameter, 42° apex cone angle, conical shaped charge liners fabricated from tantalum were directed towards titanium targets. This work represents the first study of hypervelocity, high density jet penetration into titanium alloys.

In another paper [36], various potential degradation mechanisms for the penetration process of shaped charge jets were investigated. The mechanisms addressed were: particle shape effects, particle separation, the extent of necking, the deposition of jet material and the effects of collisions of the particles with the crater wall. The study consisted primarily of hydro code simulations using the DERA Eulerian code cAst-Euler. In each case the effects of one or more copper particles impacting upon a semi-infinite Rolled Homogeneous Armour target are modelled. It is concluded from the study that particle shape and impact speed can be significant factors contributing to penetration degradation. Collisions at the side of the crater and tumbling of the particles are also likely to be adverse factors.

Oleg V. Svirsky [37] investigated jet penetration. The problem of reducing the jet penetration capability upon its interaction with a finite-thickness target, due to the erosion of the front region of the jet having perforated through the target, was considered. The experimental examination and the mathematical modelling of the process were performed; semi-empirical formulae were obtained. The calculation techniques are shown to allow the description of interaction processes with satisfactory accuracy.

Boeka et al. [38] described a method for the assessment of the cut-off velocity or minimum velocity for the application of hydrodynamic theory. Every shaped charge jet has a last particle that contributes to the penetration depth. Estimating the speed of this particle, or "cutoff" velocity of the jet, is a key factor in predicting penetration performance for a given shaped charge. Direct comparison between particles in flight and their individual contributions to the penetration depth are made. The importance of local hole shape ("scalloping") is discussed, and a simple empirical cutoff model that agrees with RHA penetration data at short and long standoff is described.

Heider et al. [39] modelled simultaneous action of a shaped charge with a kinetic energy projectile and numerical simulation studies were also presented for tandem warheads consisting of a precursor shaped charge and a following kinetic energy (KE) projectile containing a high explosive filling. This paper presents numerical simulations to analyze the penetration process of tandem systems. Experimental data were used to verify the simulation results.

Murphy et al. [40] described the effect of a delayed jet impact on concrete using experimental evidence. The effects of multiple and delayed jet impact and penetration on the borehole diameter in concrete targets are discussed in this paper. The paper demonstrates that the "jet energy per unit hole volume constant" for concrete can be substantially altered by the use of multiple and delayed jet impacts. It has been shown that enhanced entrance crater formation results from the simultaneous impact and penetration of three shaped-charge jets. It is also shown that borehole diameter is enhanced by the simultaneous impact and penetration of multiple shaped-charge jets, followed by the delayed impact and penetration of a single shaped-charge jet.

Mostert et al. [41] described the effect of the variation in liner wall thickness. Penetration trials were conducted with shaped charges of a specific design. The copper liners used in the high precision charges were within specification in terms of roundness, but had known wall thickness variations in planes perpendicular to the symmetry axis. The radial velocity of the jet, which is used as an input in the model, was deduced from orthogonal streak measurements, as well as from numerical/analytical simulations.

Rodriguez et al. [42] described particulation of a shaped-charge jet, which is modelled as the axis symmetrical, dynamic necking instability of a viscoplastic metallic material. Analytical/numerical predictions were obtained from a linear perturbation analysis for the jet breakup time, the fragment velocities and their aspect ratio. Comparisons were attempted with experimental data obtained from flash radiographs of copper jets. Rugosity measurements carried out on intact recovered fragments provide realistic estimates for the geometrical imperfections of the jets. Despite the simplicity of the model, a good agreement between theoretical and experimental data is obtained when using typical values of the strength and strain rate sensitivity of copper at high strain rates.

Mills et al. [43] described a novel investigation of the impact of hollow shaped charge jet particles on a steel target. The range of impact speeds considered was 2 to 8 km/s, the upper limit of which was greatly above the ranges considered in previous studies of such impacts. An Eulerian hydro code, developed in-house, was used. It was shown that the penetration achieved by a single individual hollow particle was the same as that for a solid one of the same mass. However, it was demonstrated that a reverse jet, travelling back through the hollow section, was formed, which was similar to that seen by earlier workers, but it was travelling much faster. This jet can cause significant disruption to the following particles. It was concluded that the presence of hollowness is likely to cause significant disruption to the penetration process in real jets.

The material selection criteria were further debated in a paper by Held [44]. The enormous ductility of the liner materials during their jet elongation, with their varied appearances during particulation, was strongly correlated with the microscopic crystal structure, which depended on the original material properties and the processes used to produce the liners. It is surprising that the jet was influenced by the original crystal structure during the particulation processes, even after undergoing severe deformation, collapse and flow. If, instead of ductile necking, the particles break under shear failure, then the penetration performance can be drastically reduced with increasing stand-off, because the jet particles were tumbling and moving transversely.

The metallurgical aspects of penetrated targets were investigated and micrograph and phase changes were analyzed in one of the papers [45]. The “white” etching layer on the perforation surface and adiabatic shear bands (ASBs) in the matrix of ultra-high strength, steel plates penetrated by shaped charge jets, were investigated. It was shown that the phase transformation took place in the "white" etching layer on the perforation surface during penetration. The microstructure of the "white" etching layer was a mixture of martensite and austenite, both of nanometer scale. The ASBs in the matrix are composed of local shear deformation zones (LSDZs) and heat affect zones (HAZs). No evidence of phase transformation was found in the HAZs of ASBs. The temperature rise on the perforation surface and within ASBs was estimated.

Chant [46] derived a closed form analytical solution for an unsteady, inviscid jet caused by the asymmetric collapse of a 2-D ring using linearized, small disturbance, velocity potential theory and classical analytical methods. Both the Laplace transformation and elementary Eigen-function expansions were used to solve the associated governing equations. The jet shape that was computed using the analytical model was compared with CTH (hydrocode) simulations and limited experimental data and shown to provide reasonable agreement. Jet spreading was shown to be consistent with classical turbulent jet scaling, in accordance with known shaped charge jet hydrodynamic assumptions. Numerical issues associated with rotational symmetry, the effect of boundary loading disturbance to the jet and the effect of finite arrival time detonation wave conditions were also simulated.

Petit et al. [47] analyzed a copper liner and compared numerical and experimental results for shaped charge jets. Experimental data on the fragmentation of copper shaped charge jets were presented and the techniques used for data processing were described. A combined numerical/analytical analysis was designed to describe shaped charge jet breakup. The method overcame drawbacks from exclusively numerical or analytical analyses, such as mesh sensitivity or an oversimplified description. It yielded predictions for break-up time, total number, and cumulative length of fragments in fairly good agreement with the experimental data. The dependence of fragmentation characteristics on the grain size in the liner was also well predicted.

Shaped charge effects were investigated by M. Held [48]. Shaped charges with higher jet tip velocities resulted in more residual penetration behind special targets, as demonstrated by bulging and ERA sandwiches, compared to charges with lower jet tip velocities. Shaped charges with larger base diameters gave more residual penetration behind special targets compared to shaped charges with smaller base diameters. They still had the same penetration potential in semi-infinite, rolled homogeneous armours (RHA). Precision shaped charges with the same base diameter as normal shaped charges gave more residual penetration behind special targets; even the differences in depth were remarkably reduced.

Gunnar Wijk et al. [49] investigated the reduction in penetration at increased standoff and presented an explanation which differed from conventional explanations. The common reason cited for such phenomena is lateral dispersion of jets or tumbling of jet particles, but this cannot be supplemented by flash radiographic investigation. For precision shaped charges such events were not taking place. Instead it was suggested that the main reason for this was that previously eroded jet material in the hole eroded the remaining shaped charge jet fragments on their way to the bottom of the hole. Computer simulations, in which eroded jet and target material were not immediately eliminated, once they were eroded, showed that the explanation was qualitatively reasonable. Unfortunately, it is very difficult to design a qualitatively realistic physical model that accounted for this secondary erosion effect, due to the complicated nature of the interaction in question. The study was further extended in another report [50]. A new model of rigid and eroding projectile penetration and perforation, including production of target fragments, had been suggested. The model of eroding projectile penetration had been used for shaped charge jet penetration. The intended application of the developed model was in the computer program for the assessment of the effects on, and the vulnerability of, complex targets like tanks, aircraft and naval ships.

In a paper by the International Society of Explosive Engineers [50], the mechanism of run up in the context of shaped charges was explained and investigated. The term 'run up' described the finite time or distance from the point of initiation to full and steady state reaction. In the application of linear shaped charges (LSCs), this was denoted as the distance from an initiation start to the point of steady state penetration (starting point of the maximum penetration). Most explosives exhibited this characteristic. This was because an explosive charge is generally initiated by a smaller device (initiator), therefore it had to build up to its full strength, taking a finite time and distance to do so. This run up was not constant under all conditions but varied with the input/initial shock pressure. When an explosive that had a long aspect ratio (width vs. length) or a stick shape was initiated at one end, the actual run up can be measured as a distance between the initial priming point to the point of maximum explosion power. This was called the 'Run up distance'. Usually, pinpointing the position or location of the maximum explosion power state (steady state) was difficult without sophisticated laboratory equipment. However, in the case of LSCs, it can be easily identified through investigating the penetration profile in a suitable target material. It was simply measured as the distance between the initiation point and the maximum penetration point by dissecting the penetrated target along with the penetration.

The elasto-plastic model for the penetration by a shaped charge jet was investigated in one of the papers [51]. This paper presents details of the mathematical modelling of high-rate penetration of a metal target by a shaped charge device that produced a high-velocity jet. The key objective was to predict the penetration velocity, be it subsonic, transonic or supersonic. This was done by considering, on the local scale near to the tip of the penetrated cavity, an elastic-plastic, free boundary problem that took into account the residual stresses produced by the moving plasticized region of the target. It was the self-consistency of this elastic-plastic model that dictated predictions for the penetration velocity. It was noted during the investigation that the energy balance argument was not needed as would have been necessary, had there been significant fracture or melting of the target. Indeed, a theoretical scenario could, in principle, be used to predict thermal dissipation via an uncoupled calculation. This occurred because the violent penetration assumption was based purely on momentum considerations; for less violent penetration, the energy balance became increasingly important.

E. Hirsch [52] proposed experimental evidence to correlate the parameters responsible for the estimation of shaped charge jet break-up time. It was thus shown that the V_{pl} parameter depends on the ratio of the liner thickness (TL) to the explosive charge diameter (CD) via the formula: $1/V_{pl} = 13.9 - 101 \times (TL/CD)$. To determine how the numbers used in this formula change with the liner material and its metallurgical state, and with the type of explosive used, measurements should be made as prescribed in the paper. An attempt to begin explaining this formula is made in the discussion. The paper also included work on an analytical computer code [53]. The results revealed that V_{pl} – a measure relating a local variation in the jet kinetic energy to the local material strength during jet elongation – had an inverse dependence on liner thickness. This dependence appeared to be affected by the initial coupling of the explosive's detonation into the liner, wherein the coupled energy changes the liner material structure and properties.

The design process of a 0.7 m shaped charge for rock drilling was explained in paper [54]. This paper described the design, analysis and field test of a 0.7 m (28 in) conical shaped charge (CSC). The goal was to design a shaped charge that could produce a ~25 cm (9.8 in) diameter, ~6 m (19.7 ft) deep hole in rock and concrete. The preliminary results, obtained with the analytical code, were verified independently with a hydrocode. After the shaped charge was designed and analyzed, it was fabricated and field tested by firing it into Tuff rock. The shaped charge fulfilled the program requirements and the test results closely agreed with the analyses.

Some of the theoretical issues encountered for the penetration behavior of an oil-well perforating charge were investigated using a jet formed from an unsintered, powdered metal (PM) liner [55]. Appropriate treatment of the jet's porous compressible nature filled the gap between the classical "continuous" and "fully particulated" jet penetration models. Highly distended, low-velocity PM jets should effectively penetrate moderate-strength geologic targets. It was demonstrated that the initial transient shock pressures might be much higher than steady-state penetration pressures because the initial penetration rates might be higher than the steady-state penetration rates. This, in conjunction with the well-known "residual penetration" phenomenon, indicated that a non-continuous jet's penetration might be strongly influenced by transient effects.

In a finite element simulation study of shaped charge jets, the effect of angular velocity on the penetration of a shaped charge jet was simulated [56]. Jet material was analyzed as an elastic as well as an elastic-plastic material, and the critical stress strains appeared earlier in the case of pure elastic behaviour of jet material, and it was smaller by 6% in the case of elastic-plastic behaviour of the same material. The critical stress zone appeared in the rear part of the jet, where its diameter became largest. The rotation caused very intense contraction of cross-sections in the frontal zone of the jet and radial spreading in the rear part. At same time, the total length of the jet shortened significantly and caused an evident decrease in the jet's penetrability.

Arnold et al. [57] described warhead simulation studies. The effects of significant performance parameters like confinement, length of warhead, etc on the penetration performance in RHA targets was discussed. Additional numerical simulations were carried out in the first part of this paper. The evaluation of exclusive thin/thick and ductile/brittle casings revealed trends for improved performance when using a thick and/or brittle casing material. The numerical simulations also suggested an increased performance with thicker casings, but no answer could be given concerning the question of ductile/brittle material. The shift of the initiation system towards the SC liner resulted in no improved performance. Finally, the closing of the penetrator hull showed satisfactory results.

At the same symposium [58], another paper described the feasibility and engineering design of a conceptual "non-explosive" explosive shaped charge tool that can be adapted for the purpose of mitigating and neutralizing explosive ordnance during military and homeland security operations. Nitromethane (NM), a low-cost commercial solvent, was used as the energetic material. The conceptual device was packaged in a shaped plastic container with a hollow-cavity that was sufficiently flexible to permit a wide range of liners of equal included volume, which could be added just prior to deployment, along with automated injection of a sensitizer. The range of performance of a 25mm charge diameter device against Composition B and TNT was compared. The effects of key design parameters such as sensitizer concentration, charge diameter, initiation front geometry, run-up distance, charge confinement, liner configuration, and charge performance were also presented. The observed variations in detonation velocity during the initial stages of run-up and the use of the Lee-Tarver model in correlating jet impact initiation were also reported.

The main advantage of using NM is proven homogeneity of the filling. Since NM is liquid at room temperature, it can be filled without any density variation in the prepared charges. Conventional melt-cast, solid explosives are filled at high temperature in liquid form in the charges and allowed to solidify. Instead of this, simple pouring NM at room temperature can effect the filling of NM. This makes the device suitable for filling under field-conditions. An empty charge container can become a shaped charge if filled with NM. The lower density of NM (1.12 g/cm^3) as compared to conventional solid explosives (1.75 g/cm^3) can be offset by incorporating a suitable gelling agent. The NM filling is relatively safe to handle and in fact addition of sensitizing agents is done to initiate the charges. The performance parameters of sensitized NM as the explosive were investigated in paper [59]. In this case, sensitization was achieved by polymer foam and glass micro-balloons suspended in polymer-thickened NM.

In another paper, the advantages of field filled shaped charges having liquid explosives were listed as minimized toxic and explosive hazards, consistent performance, rapid filling, safe transportation, easy decommissioning and a cheap alternative [60]. Sensitization of the NM by adding amines in small percentages was implemented for shaped charge applications. The superiority of diethylenetriamine (DETA) and ethylenediamine (EDA) over other amines was stated. However the disadvantages of increased toxicity and a transient, time dependent variation in sensitivity had to be accepted by the users. Another scheme for sensitization was by using expanded polymer foams and hollow glass micro-balloons. These referred to the physical sensitization of NM and this mechanism was dependent upon entrapment of gas bubbles, which could not be displaced by NM in the sensitizer. Since glass micro-balloons were light in weight, dispersion in NM was realized either by increasing the viscosity of NM through the addition of polymeric polyetheneoxide or by trapping the micro-balloons in polymer foams. NM gelled with a gelling agent and micro-balloons was used and the VOD was found to increase with gel density. The density of NM with 5% polyox (gelling agent) and 5% micro-balloons was found to be 1.04 g/cm^3 with a VOD of 5300 m/s. NM based shaped charges were successfully used for the disposal of bombs, and the TNT based explosive fillings of the bomb deflagrated without any obvious sign of detonation.

As an extension to the above work, a 4 mm thick plastic tube was filled with gelled NM and was fitted with a 1.25 mm thick copper cone with a cone angle of 60°. This was tested against an MS target positioned at an optimum standoff distance of 5 cone diameters [61]. NM sensitized with DETA resulted in the formation of a copper jet of adequate strength and a penetration of 52 mm was realized. In the explosive filling, gelling by the addition of micro-balloons and polyox resulted in the reduction of VOD and penetration of the charge. For 5% each of micro-balloons and polyox, the VOD realized was 4880 m/s and a penetration of only 30 mm was achieved. It was also reported that with a 10% concentration of both the additives, the copper liner spatterred onto the plate and a penetration of the order of only 15mm was achieved because the VOD was reduced to 4292 m/s.

The criterion of a certain minimum critical energy needed for penetration was proposed and confirmed by the experiments in article [62]. The critical energy, defined as proportional to the square of the velocity and the jet diameter (V^2d), was explained. On a conceptual front, it was proposed that to dispose of a munition by deflagration of its filling, it was desired to produce just sufficient energy from an NM charge to penetrate the casing and induce a burning reaction in the charge under disposal. It was also indicated that explosives can withstand very high pressures, if it is applied very slowly and the rate of pressure rise is more important than the actual pressure levels. So, an alternative critical power density criteria was proposed, where the rate of energy deposition per unit mass (in W/kg) has been postulated as an important criteria. This critical power input per unit mass was equivalent to V^3/d. For non-initiation of deflagration DDT, an energy density of 108 W/kg was sufficient, whilst with 1011 W/kg energy, initiation to deflagration was likely to lead to DDT. Contrary to this, if a high energy density of 1014 W/kg was applied, detonation was very likely to occur. Compared to conventional explosive formulations like PE4, NM filled shaped charges had a lower jet tip velocity and a bigger jet diameter. Thus the chances of the occurrence of DDT were reduced. This was also practically demonstrated. The heat dose from 1000-lb bombs was observed to cause second degree burns for personnel less than 30 m upwind from the event. The blast overpressure could cause injury to personnel standing within a 23-m circle. The decommissioning of unused NM filled warheads by simply washing with warm water was reported.

The design constraint for small shaped charge warheads was enumerated in one of the papers [63]. According to the experimental results from a small-caliber tandem warhead, the conclusions included – (i) the length of standoff would be smaller than 6.5 times the diameter of the charge, (ii) the shielding of the explosive should be put reasonably in the middle of two charges, (iii) it is necessary to design an unloading pressure device, (iv) the detonating device for igniting the first shaped charge should be smaller and simpler, (v) a short delay time is satisfactory. At the same symposium, penetration of concrete by numerical simulation of tandem shaped charges was reported [39]. Attention has been focused on the material modeling of the concrete target, especially for a description of the material damage, due to the penetration of the precursor shaped charge, to reproduce crater profiles. The penetration depths produced by shaped charge jets and KE penetrators were verified with experimental results and analytical, empirical calculations. The performance of a KE penetrator including a precursor shaped charge was significantly increased. A further paper [65], reported penetration of shaped charges in sand using hydro-codes.

The two stage shaped charge (also called tandem shaped charge) was investigated experimentally through the design of the detonation interrupter and detonation propagation parameters [64]. A reasonable design of the detonation interrupter and detonation propagation parameters could attain the best coupling of the two-stage shaped charge during formation and relay penetration. The results of experiments showed that the two stage shaped charge can effectively increase the penetration ability, the depth of penetration increases by about 10-15%, and the radial crater by a shaped charge jet penetration is enlarged.

In a technical note [65], the penetration performance of a shaped charge into concrete was experimentally determined. The cone angle and liner materials were varied and a comparison of a shaped charge with a kinetic energy projectile was also reported. The shaped charges exhibited more penetration depth and larger spalling area compared to the kinetic energy projectiles. The hole diameter became larger and the penetration depth was reduced with an increase in cone angle. A copper liner gave longer penetration and a smaller hole diameter than an aluminum liner. The penetration of a steel liner was measured and had a value between that for copper and aluminum liners.

The effect of asymmetry in trumpet shaped liners on their performance was also investigated by O. Ayisit [66]. Four types of shaped charge defects had been analyzed within the scope of the work, as off-centre initiation of the explosive charge, detachment of the high explosive filling from the casing, air bubbles inside the high explosive filling and shaped charge liner dimensional inaccuracies. The response of the jet against each of the above defects was determined in terms of off-axis velocities, named as radial drift velocities, induced throughout the jet.

The liners of shaped charges were manufactured and evaluated using powder metallurgy technology [67]. A homogeneous one made of copper powder and a heavy one made of a copper and tungsten powder blend was used in the study. Laminar liners, consisting of two layers made from powders of different densities, were also examined. The X-ray pulse technique was applied in order to investigate the process of jet stream formation. The radiograms revealed the discontinuous (discrete) structure of the jets formed from powder liners. The corresponding computer simulations of jet formation were also presented.

In paper [68], a method of shaped charge simulation based on the FEM techniques was presented. The function of a shaped charge has several phases, which were modelled separately − the initiation of detonation, the propagation of the detonation wave through the explosive charge, the formation of the shaped charge jet and slag, jet stretching and jet penetration. The coupled FEM based on Eulerian-Lagrangian meshing was used to describe the phases of detonation wave propagation as well as the jet formation and jet stretching. But Lagrangian meshing was used to describe the jet penetration, as the last phase of shaped charge functioning. During penetration, very intense erosion of the jet material appeared so that the eroded Lagrangian cells must be removed from the calculation. To correctly calculate the jet penetration, the coefficient of erosion was introduced in the FEM solver. The results of the experimental determination of jet erosion during penetration through a steel obstacle were presented. The numerical results were validated using a 64 mm shaped charge for jet formation and penetration.

In one of the reports published by the Naval Postgraduate School, California [69], multi-material shaped charge liners for the purposes of, for example, diagnosing jet formation, overcoming coherent flow limitations, and enhancing behind the target effects, were numerically simulated using software − ANSYS AUTODYN. This research showed the possibilities for generating stable, multi-material, coaxial, shaped charge jets. The general design criteria and guidelines for the multi-material, coaxial jetting and penetration were developed and investigated, based on experimental data and simulation of a 100 mm charge. Furthermore, the influence on jet coherency and the effect of density variation on penetration were studied. The findings were in agreement with Harisson's and Walker's coherency theory, showing that the flow velocity was the key factor for jet coherency.

In the latest paper [70], the capability of the generalized interpolation material point (GIMP) method in the simulation of penetration events was investigated. A series of experiments was performed wherein a shaped charge jet penetrated into a stack of aluminum plates. Electronic switches were used to measure the penetration time history, and flash x-ray techniques were used to measure the density, length, radius and velocity of the shaped charge jet. The simulations of the penetration event were performed using the Uintah MPM/GIMP code, with several different models of the shaped charge jet being used. The predicted penetration time history for each jet model was compared with the experimentally observed penetration history. It was found that the characteristics of the predicted penetration were dependent upon the way that the jet data are translated to a discrete description. The discrete jet descriptions were modified such that the predicted penetration histories fell very close to the range of the experimental data. In comparing the various discrete jet descriptions, it was found that the cumulative, kinetic energy flux curve represents an important way of characterizing the penetration characteristics of the jet. The GIMP method was found to be well suited for the simulation of high rate penetration events.

In the area of tandem shaped charges, a patent [71] was filed for a long ignition delay (2000 microseconds) between the front and rear charges. For such charges, earlier state-of-the art demanded a heavy shield between both charges. The patent proposed a reduction of the explosive quantity and heavy confinement for the front charge to offset the ill-effects of poor penetration by rear charge. A 50-60% reduction in explosive quantity, 20-40% reduction in overall length of the warhead and 10-20% weight reduction is claimed in the embodiment. A jet tip velocity of 5.5 km/s for a heavily confined charge is claimed against 4.5 km/s for a standard unconfined charge. Additionally, movement of confinement away from the central axis resulted in a clear passage for the jet of the secondary rear charge.

As per another patent [72], a shaped charge assembly comprising of a first shaped charge, a wave shaping relay charge and a second charge were located in one housing (Figure 2E). The assembly is configured in such a way that a first active element formed by initiation of the first shaped charge detonated the wave shaping relay charge, which in turn initiated the second shaped charge to form a second active element. The first active element moved out of the housing to cause damage of the first kind to an external target, and the second element caused damage to the second kind of the target.

During the last decade (2000-2010), consolidation of theory and simulation of experimental observations were the main emphasis in the area of shaped charges. In addition, several new concepts were also proposed and experimentally tested. A tantalum liner material was used in shaped charges against a titanium target. Laminated bi-metallic liners and unsintered, powdered metal liners were also investigated during this period. For oil-well exploration and rock-drilling, the effectiveness of shaped charges were investigated on concrete and soil. Amongst new areas of research, the jet cut-off velocity, the degradation study of penetration, the effect of liner thickness, the reduction in penetration on increased stand-off, the mechanism of run-up distance, the use of NM as an explosive filling in shaped charges, and parameters for the performance of tandem shaped charges etc were investigated during this period.

Unexplored areas

No doubt, with the advent of modern measurement methods and machineries, experiments with shaped charges will be further refined. Although the theory of shaped charge generation and target interaction are completely developed and predictions from several 1D and 2D hydrodynamic codes are also possible for shaped charges, certain areas still need further exploration. Since most of the research findings have been concentrated on material selection, shaping, metallurgy and manufacturing aspects of shaped charge liners, the unexplored areas, where more effort is needed in the future, include liner development.

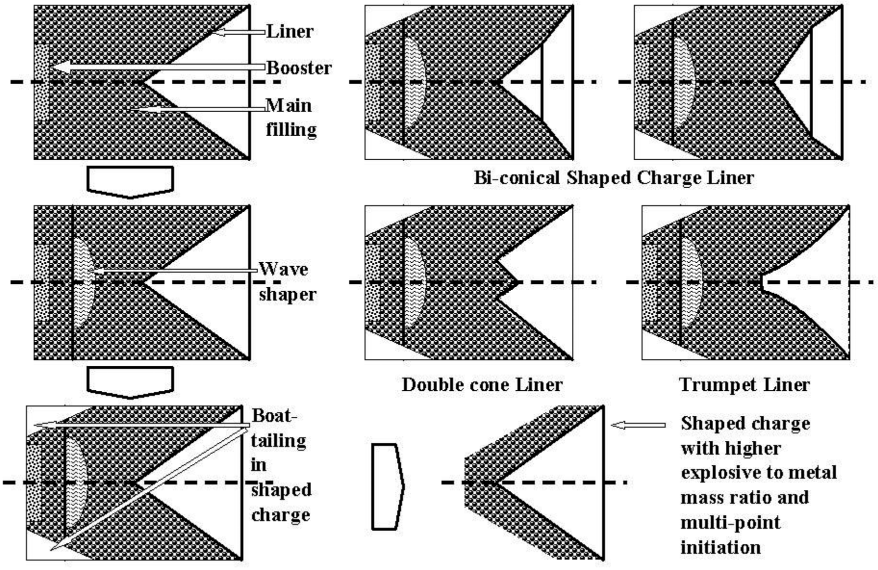

Figure 3. Evolution of various shaped charge geometries.

A brief summary of the evolution of the geometrical concepts used for shaped charges is depicted in Figure 3. Initially shaped charges were simple with the main filling initiated by a booster and the effect was created by a shaped copper liner. Since the tip section is responsible for highest jet-velocity, the thickness of the liner is varied from the tip to the base of the liner. However the introduction of non-explosive wave-shapers was a major breakthrough in the evolution of shaped charge liners. The shaped charge may be made of any low density material like silicone rubber, polyurethane foam, aluminum or even an air-gap. The purpose of the wave shaper is to restrict the shock wave to reach the tip of the liner cone first. The shock travels through a narrow annular area and a larger mass is diverted to the jet to get more jet-break-up time and a longer jet. Furthermore, it was observed that the rear corner section of the charge is not of any use, and even after removing those parts of the charge, it is possible to get the same, and in some cases improved, performance. The same is implemented by boat-tailing of the main-filling. For simultaneous collapse of the entire cone, an explosive charge to liner mass ratio is reduced and the explosive is placed parallel to the liner cone. This requires multi-point initiation for better liner collapse and has a reduced explosive loading with the same cutting efficiency.

A close matching of analytical solutions from various hydro-codes to experimental results is a challenging task and this is clearly brought out in a thesis on modelling of shaped charge [73]. Numerical simulation is a time consuming task, requiring a considerable amount of computational resources, experienced users for accurate modelling of the problem and access to advanced software. As an alternative, analytical calculation methods can be used for the quick prediction of shaped charge performance for limited geometries. However, the use of pure analytical tools, without a considerable amount of experimental work and diagnostic techniques, may result in inaccurate performance predictions. So, both numerical and analytical tools are essential in shaped charge design.

Although several materials have been tried as liner materials e.g. aluminum, steel, tantalum, ceramics, bi-metals etc, for practical purposes copper is the only versatile, universally accepted and tested material for shaped charge liners. The shapes of liners investigated by various researchers have also been changed. Bi-conical, with a base of a higher cone-angle as well as a lower cone angle, as compared to the liner tip, has been tried. A double cone or ‘W’-shaped liner cavity and a trumpet shaped liner have also been investigated, but conical liners have been investigated, experimentally tested and modelled to a larger extent.

The dynamic strength of the material for a liner of a shaped charge is still an unknown area. Several researchers have tried to correlate it with the static strength of the materials, but a constant relation does not exist and dynamic strength becomes an elusive quantity for shaped charge designers. Another area is selection of the material for the liner, which is a compromise between ease of manufacture, ductility of the selected materials and target penetration capability. The basic anomaly in the selection of the liner material is density, which should be low for a high jet velocity for a given quantity of explosive, and at the same time high for better penetration. These contradictory requirements need further exploration. In addition to this, liners made of ceramics and powdered materials are also being explored and they are found to give penetration in different targets. These liner materials offset the ductility requirements of the liner and some new theory has to be developed for penetration of such brittle liner materials.

The manufacturing aspects of liners are another area, where a compromise between forming and machining is needed. That precision improves penetration is a well established finding, but the practical achievement of precision and the level of precision at which the performance enhancement of shaped charge ceases, is not known. The thickness variation of liners, the concentric assembly of liner and explosive charge, the arrival of a symmetrical detonation wave at the liner apex, are some of the prime requirements, where more attention is needed in future.

From a practical point of view, a warhead or projectile never strikes the target in a perpendicular direction. It is observed that the target is always hit at sub-optimal standoffs and, sometimes, at other than normal directions. This aspect needs further enhancement of the mathematical complexity of the penetration mechanism. The target thickness varies, as does the jet length. Striking a moving target adds another dimension to the already complex problem of shaped charge action.

The modelling aspect of shaped charges cannot be completed without discussing tandem shaped charges, where two shaped charges are placed one behind the other. Such charges are found to be very effective in defeating main battle tanks (MBT) protected by explosive reactive armour (ERA). The precursor charge (preceding smaller charge) initiates the ERA, while the main charge penetrates the tank. The modelling of such charges introduces several other variables. The separation of the charges, the time delay between their initiations, and the protection of the main charge from the blast of the precursor charge etc result in inconsistent performance of such tandem shaped charge warheads. A numerical simulation using Autodyn-3D has been presented to study these effects [74].

Improvement in explosive performance is another area, where efforts are now diverted. The current explosive requirements are concentrated around the development and use of more energetic explosive compounds. RDX is replaced by HMX, and now work is on for further enhancing the energy by using CL-20. A limited comparative study for replacing HMX by CL-20 in shaped charges has been investigated and a marked improved in penetration is reported [75]. Explosive-formulations with thermally-stable molecules are also being tried, where the performance is not compromised, but safety is enhanced. The use of insensitive and eco-friendly explosives for shaped charge fillings is also being explored, expecting a similar performance, but the mathematical equations used for conventional explosive charges may result in some surprises.

The casing of shaped charges was not given sufficient attention in these studies. It is clear that except for indicating that an explosive charge is confined or unconfined, due to the presence or absence of a casing, neither experimental nor parametric work have been reported on the casing of shaped charges. Although this may be an insignificant parameter as compared to liner or explosive, accurate predictions need thorough modelling of shaped charge casing materials, casing strength and casing thickness.

Conclusion

Shaped charge modelling is a dynamic field, which is continuously growing. As the number of research articles on shaped charges is continuously overflowing in the domain of military engineering, a review of papers relevant for the modelling of shaped charges has been undertaken. The penetration of concrete, the metallurgical aspects of the jet and other peripheral references have been avoided, and this review paper concentrates on those papers related to the theoretical modelling of shaped charges. The developments before 1990 are collected together, this being an era for the development of theory. The intermediate era of 1990 to 2000 depicts an era of exhaustive experimentation and validation of several 1D codes developed at various institutions all over the world. An exhaustive literature survey from 2000 to 2010, revealed that every aspect of shaped charges, along with perturbation parametric studies, were undertaken during this period. Experiments with advanced instruments were carried out and the refinement of existing models was performed. The use and theoretical investigation of field filled, shaped charges having liquid explosives like gelled nitromethane and micro-balloon filled nitromethane for the demolition of unexploded ordnance, were also investigated during the last decade. Unexplored areas of shaped charge modelling were also enumerated for the future researchers.

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