A Review of Works on Shaped Charges

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Abstract—**Shaped charges are used to pierce hard targets in all three versions of warfare land, air and naval. High explosives compositions fillings produce a thin high velocity metal jet which is used for target damage. Shaped charges can efficiently damage tanks possessing thick armour protection, bunkers and aircraft and are also useful for attacking ships and submarines. Shaped charges have a very long history since the Second World War Theoretical modeling started with the steady state theory of Birkhoff in 1948, which was modified by the non-steady state theory known as PER theory of shaped charges. To review the development in the shaped charges three stages are defined. In the first stage development until 1990 is presented when shaped charge theory was fully developed and penetration predictions with fairly good accuracy were possible. In the second stage, review of the work carried out in the last decade of the 20th century is discussed. During this period experimental verification of different parameters was established. The third stage deals with all the work carried out in the 21st century (2000-2010), including tools for advanced diagnostics, new fabrication and inspection, as well as new liner materials were included. The anomalies occurred were resolved by further refinements in the theoretical models.**

Keywords-high explosives; liners; jet formation; shaped charges; target penetration

I. INTRODUCTION

The weapon industry has concentrated on the growth of the lined cavity shaped explosive charges, often known as cone bombs, shaped charges or Munroe bombs during the last few decades [1]. During the World War II, various explosives developers and mining companies have focused their attentions on the use of lined cavity shaped charges in military and mining applications. In view of remarkable military achievements, the general lack of success in the civil uses suggests that perhaps the commercial investigator overlooked some factors in the design of shaped utilization. From what can be determined concerning most of the projects that failed, this was indeed the case. Two main factors are generally considered as the cause of disappointment. The first of these was the field of application. Most of the work was carried out with the aim of the lined cavity charge by secondary blasting tool but the lined cavity charge is most suitable for punching a hole in the target, not for breaking it. The second and most serious problem was the type of explosive used. Generally low velocity, low brisance explosive will not yield a workable lined cavity shaped charge. On the other side high velocity, high brisance explosive are difficult to manufacture. The lack of high explosive coupled with the fact that relatively little was known about the lined cavity shaped charge outside the ordnance circles meant that many of the early efforts failed to achieve workable shaped charges. The purpose of this paper is to provide a basic review of the history the shaped charge, main theories involved and to provide a detailed history.

II. HISTORY OF THE LINED CAVITY CHARGE PHENOMENA

The unlined cavity effect is primarily known as the Munroe effect in United States and U. K. and as the Neumann effect in most European countries, in honor of groundbreaking contributors. Both of them only reported the experimental results on the unlined cavity effect. The origin of the lined cavity explosive charges is dubious. It is proclaimed that Germany used the lined cavity shaped charges during World War I. Also some shaped researcher attributed the discovery of lined cavity charges to Neumann during World War II. Presently most of the investigators accredit the discovery of lined cavity shaped charge to R. W. Wood of the Johns Hopkins University, as he found that the dimpled blasting cap produced a high velocity jet of metallic particles from copper sheath comprising the dimple. Korolev and Pokrovskii in 1944 published an article in Russia about the jets emitted by No. 8 blasting cap covered with copper. Many nations started research on the basis of Dr. Wood's discovery to utilize the lined cavity weapons. Most of these projects were successful. The most well known lined cavity weapon of that time was the bazooka, which consists of a lined cavity shaped mounted on a small rocket. Many other lined cavity weapons have been used for demolition purposes but most of the research publications have been classified due to military interests. The research on fundamentals of lined cavity shaped charges was not available since 1940. The mining and allied industries were highly disappointed from results regarding the lined cavity phenomena. Failures were occurring due to lack of data available at that time. This started to change after 1946 with published research mainly focusing on non-military applications (mining, drilling, tunnel construction etc). Shaped charges started to become commercially available in late 40s and related brief articles surfaced. To summarize the historical aspects, a considerable fundamental literature is now available concerning the hydrodynamic mechanism of jet formation. Only limited data is available for other mechanism and a very little data is available on penetration on targets, especially non ductile targets such as rock and other earth materials.

Shaped charges are cylindrical explosive filled charges with hollow cavity at one end and a detonator on the opposite side of the cavity. They are known as hollow charges or sometimes as explosively formed penetrators (EFP). The hollow cavity is usually lined with a metallic material made of copper, steel or aluminum. On detonation of the explosive charge, huge pressure up to around 300 kbr is generated and the metallic liner collapses to form a high velocity jet, whose tip may attain a velocity in excess of 10 km/sec and rearward tail called "slug" can attain a velocity up to 2 km/sec. The velocity gradients along the length of the jet leads to jet stretching. The jet continues to stretch and after a certain limit it fractures under the effect of severe elongation, if uninterrupted. The most common terms used in shaped charge phenomena are explosive, liner, casing, booster and target. Generally copper liner is preferred due to ease of fabrication and easy analysis. The most common shape of liner used is conical. The main parameters of the shaped charges including performance and dimensional parameters are expressed in terms of charge diameter (D). The charge length, stand-off distance, target penetration have been described in terms of multiples of the shaped charge diameter (D). The explosives used are described by velocity of detonation and Chapman-Jouguet (C-J) pressure. The liner material in theoretical modeling is described its density, dynamic strength and thickness.. The geometry of the lined cavity is described by the apex angle, which is an important factor for the performance assessment of the shaped charge.. The shaped charges can be fabricated as unconfined charges or confined charges with aluminum and steel casing.

The hydrodynamic theory basically known as PER theory [2] was verified by experiments and the effect of target strength in penetration depth assessment was highlighted in [3]. Aluminum, steel and lead were used as the target materials and it was observed that the static strength was not sufficient for depth of penetration measurements. Dynamic strength was determined and it was established that the ratio of the dynamic strength to the static strength varies for various materials. The Hydrodynamic theory started gaining in importance with little modification based on experimental results and the sequence of events occurring during the shaped charge detonation. Several research articles have been cited in [4]. In the US Army Military Command Pamphlet (AMCP), the steps related to the design of the shaped charge were enumerated in detail in [5]. The copper cone diameter (D) is empirically related to the thickness of the armour (T) plate by the relation D=(T+2)/5. For short stand-off distances, copper, aluminum, steel, zinc, lead or glass liners are preferred depending upon their penetration capability. The materials having high ductility always give better penetration. The copper liner gives a better penetration at a stand-off distance 1-3 charge diameter (CD) in case of fixed steel target, while aluminum gives maximum penetration at a stand-off distance of 5-7CD. Hence for maximum penetration at a short stand-off distance, copper liner should be preferred. For longer stand-off distances like aircraft as a target, the low density liner should like aluminum should be preferred, because low density target receives highest penetration with a low density liner. It is also mentioned in the literature that cone apex angle for a shaped charge should be between 40° and 60°. Since a liner with a smaller cone apex angle gives penetration at smaller stand-off distances. However machining the liner with a small cone apex angle is a challenge. The maximum wall thickness is also in the range of 2-4% of the CD.

The generalized analytical approach to shaped charge design is presented in [6]. This report describes the practical aspects of the shaped-charge warhead design and discussion on the utilization of the non-steady state theory for jet formation and 1-dimensional finite difference continuum mechanics formulation to calculate the whole process of jet formation for any generalized asymmetric shaped charge has been made. This report also includes experimental findings. The liner velocity is not constant and acceleration is discontinuous. The velocity gradients at the time of collapse decreases with increase of liner radius. In [7], experimental observations were presented and an attempt was made to describe shaped charge effects using a computer code, known as HOCC. It was concluded that the complete shaped charge effect has many intermediate phenomena, like charge diameter, lengthening if metallic liner, velocity of detonation of the explosive used, booster location etc. it was very cumbersome to isolate these effects. The PIESES code handled these aspects, but with more complexities. In [8], the PER theory was modified slightly to match the experimental results, making it more versatile for different formulations. The advantages of these developments are: the input of geometrical parameters and coefficients to the program in a functional form makes it easy to use. The computer runtime is short and the parametric study can be facilitated in the software. In [9], the jet formation is studied using radiographic technique and some preliminary calculations are made regarding jet stability. In [10], the jet breakup and penetration of the broken jet is studied. The jet breakup is studied using stability approach based on 1-dimensional stability theory for stretching of plastic jets. It is observed that if the stretching rate is decreased, the rate of disturbance growth increases. However if the ratio of flow stress to the density is increased, the rate of disturbance growth also increases.

The theory and design of shaped charges were so refined during the 80s that a manual was published [11]. This manual included both the principals of Birkhoff and PER. This report highlights the parameters governing the shaped charge design by real experiments. In another report from US Army Ballistic Research Laboratory [12], an assumption based on the fact, that jet curvature is the major factor for non-ideal jet penetration is established. The concept of tandem shaped charge which consists of two shaped charges, a precursor and the main charge emerged in the 70s. Both are placed in tandem and ignited one after another for longer penetration. The increase in penetration from a shaped charge was described by providing a follow-through charge in the jet-hole created by the initial shaped charge. The tandem warhead used two shaped charges, one behind the other, with the rear charge also called the initial charge initiated first. The front charge had a central opening called aperture, through which the jet from rear charge is passed. The slug from the rear charge is restricted by the aperture diameter, and this ignites the front shaped charge. The front has the explosive of higher velocity of detonation than the rear charge [13]. A tandem shaped charge warhead is described in [14], with the main aim of the improvement in performance, reduction in weight of the warhead and neutralization of the active armour on the tanks. Overall the theory about the shaped charges, their designs, their modeling, experimental testing, development of 1-D software, validation through 2-D software and several other empirical equation related were perfected in the 90s. The shaped charge modeling entered a new phase in this decade, with concepts based on development and simulation.

III. DEVELOPMENTS DURING 1990-2000

During this period the interest on shaped charges studies was renewed. Many important conclusions were made from experimental results and utilization of these results into the theory of the shaped charge became prime concern. Various articles of the diagnostic tools for shaped charge studies were explored. 450 kV Flash X-ray radiographic technique was used to investigate the shaped charges of different calibers (30, 60 and 90 mm) in [15]. The Compendium of work done until 1993 is available in a very precise form in [16], which includes separate chapters on shaped charge mechanism, the jet formation, the experimental evidence and penetration of targets. In [17], 3-D computer codes were proposed for penetration performance of the shaped charge jets. The use of copper-tungsten alloys for shaped charge liners lead to an improvement in jet penetration against homogeneous steel targets [18]. In [19], a density deficit of at least 6.5% was proposed as one of the unexplained effects of the shaped charge jet. Density deficit is present in stretching, unarticulated shaped charge jet, after all known sources of errors are evaluated and all contributing factors are considered. It is proposed that a "vacancy avalanche" mechanism, which is operating only during the highest strain-rate interval, preceding particulation, can generate high transient vacancy concentrations required to explain the observed density deficit. In [20], the largest shaped charge ever built was presented. Shaped charge was successfully tested in penetrating 3.4 meters in high-strength armour steel. The largest shaped charge ever built produced a jet of molybdenum, which travelled several meters in air before interaction with several block of steel. The simulations were performed using CALE (C-language-based Arbitrary Lagrangian-Eulerian), a 2-dimensional hydrodynamic code. Authors used X-radiography, the rotating mirror, a kind of motion picture camera, which can shoot millions of frames in a second. The newest tool was the image-converter (IC) camera was developed in the mid-1980s, which provided the higher solution images of jet formation and early flight of the shaped charge jet.

In [21], the shape of the liner was changed to enhance the penetration of a well-perforator. The main objective was to increase jet energy and performance as much as possible. The strategy was to replace the conical liner with a bell-shaped with variable thickness. The outcome was an improved design which produced a jet with 10% more kinetic energy than before. The penetration into concrete targets was increased by 28% from that of a reference range. In [22], the shaped charge jet effect on glass armor was examined. The shaped charges with a caliber of 115 mm were fired at a constant stand-off distance of 3CD (charge diameter) from 0-60 degree NATO angles. The jet tip velocities and the length of the disturbed jets were analyzed using double flash-ray pictures. Under small angles the tip regions and under large angles the residual jet velocity regions, have been more disturbed. This results because under small angles the closure effect of the glass is more efficient. Research on modeling of shaped charge jets carried out in Japan is presented in [23]. The shaped charge jet formation and its penetration against targets was simulated using AUTODYN-2D Hydrocode with a conical liner of aluminum. In this paper the mass decrease of the jet during the flight towards the target is investigated. The density and jet shape effects on the crater formation in the target were simulated. These findings are useful for the calibration of jet mass and the jet velocity. In the area of tandem shaped charge warheads, efforts were made to improve the performance against the advancements in tank protection domain. The development of active armour necessitated on board adjustments of initiation delay and angle of attack on active targets [24]. The calculation based on different combinations of measured mean distances from different sensors were presented in the patent. The method for stand-off distance approximation used for warhead activation is also discussed. In [25], the precursor of kinetic energy and chemical energy warheads were made attachable without affecting the overall length of the warhead. During the last decades of the 20th century, many new ideas were proposed based on modeling. X-ray has been used in experimental observations for understanding the particle velocity and jet breakup time. Different hydrocodes have been used to carry out the simulation regarding shaped charge phenomena. Investigations were made in which copper liner was replaced with copper-tungsten, molybdenum, aluminum, magnesium, graphite and other composite materials. Steel, glass and lead were investigated as target materials.

IV. DEVELOPMENTS DURING 2000-2010

During this period, the theory became more refined and most of the research work was focused on matching the simulated results with the experimental results. The diagnostic tools and the experiments planned were matured with great precision and variable parameters. The cut-off velocity for a shaped charge was investigated and a model was developed for limiting velocity in [26]. In [27] limiting velocity below a certain target's strength was investigated. The limiting velocity depends upon target hardness and density. The aluminum and titanium alloys having high hardness have been used in this paper having limiting velocity of about 3.0km/sec. A preliminary experimental study was carried out to understand the penetration effectiveness of titanium against shaped charge jets [28]. Shaped charge jets emerged from 100-mm charge diameters with 42°, apex cone angles fabricated from tantalum were directed towards titanium targets. This work indicates the first study of hypervelocity, high density jet penetration into titanium alloys. In [29], various penetration degradation mechanisms were investigated. The mechanisms included 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. In each case the effects of one or more copper particles impacting upon a semi-infinite Rolled Homogeneous Armour target were modeled. It was concluded that the particle shape and impact speed are the significant factors that contribute to the penetration degradation. In [30], authors investigated shaped charge jet particulation, which was modeled as asymmetrical, dynamic necking instability of a viscoplastic metallic material. Liner perturbation analysis was used to model the jet breakup time, velocities and their aspect ratio. Comparisons were made with the experimental results obtained from flash radiographs for copper jets. A good agreement was obtained between theoretical and experimental data using typical values of the strength and strain rate sensitivity of copper at high strain rates. In [31], authors described a novel investigation of the impact of hollow shaped charge impact on steel target. The impact speeds considered were between 2 to 8 km/sec. It was observed that a reverse jet, travelling back through the hollow section, was formed, which was similar to that observed by earlier workers. It was concluded that the presence of hollowness is likely to cause significant disruption to the penetration process in real jets. The selection criteria for liner material was discussed in [32]. The high ductility of the liner materials during their jet elongation was strongly correlated with the microscopic structure, which depended on the original material properties and the mechanism used to produce the liners. It was amazing that the jet was influenced by the original crystal structure during the particulation process, even after undergoing sever deformation, collapse and flow. In [33], a closed form analytical solution derived 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. The associated governing equation was solved by the Laplace transformation and elementary eigen-function expansion methods. The shape of the jet was computed using analytical model and the results were compared with CTH (hydrocode) simulations and the limited experimental data. The results showed reasonable agreement. The issue of rotational symmetry, the effect of boundary loading disturbance to the jet and the effect of finite arrival time of detonation wave conditions were also simulated.

In [34], authors analyzed a copper liner and compared the numerical and experimental results for shaped charge jets. Shaped charge jet breakup was analyzed by a combination of numerical /analytical analysis. The dependence of fragmentation characteristics on the grain size in the liner was also well predicted. Shaped charge effects were investigated in [35]. Shaped charges with higher jet tip velocities resulted in more residual penetration behind special targets. Shaped charges having larger diameters gave more residual penetration behind special targets compared with smaller base diameters. In [36], authors investigated the penetration reduction at larger stand-off and presented an explanation which differed from already existing conventional explanations. The common reason for penetration retardation is lateral dispersion of the jets, but this cannot be accomplished using flash radiographic investigations. The elasto-plastic model for shaped charge jet penetration was investigated in [37]. This paper included the detailed mathematical modeling of high-rate penetration of a metal target by high velocity shaped charge jet. The main idea was to investigate the penetration velocity, be it subsonic, transonic or supersonic. This was achieved by considering the residual stresses produced by the moving plasticized region of the target. In [38], experimental evidence was proposed to correlate the parameters responsible for the estimation of shaped charge jet breakup time. It was proposed that The Vpl parameter depends on the ratio of the liner thickness (TL) to the explosive charge diameter (CD) via relation 1/Vpl=13.9-101×(TL/CD). An attempt to explain this formula was made. In [39], authors presented warhead simulation studies. The effects of performance parameters like confinement, length of warhead, length to charge diameter ratio, etc in rolled Homogeneous Armour (RHA) were discussed. The shift of the initiation system towards the shaped charge liner resulted in no improved performance. In [40], the advantages of field filled shaped charges with liquid explosives were listed as minimized toxic and explosive hazards, consistent performance, rapid filling, safe transportation, easy decommissioning and a cheap alternative. The superiority of diethylenetriamine (DETA) and ethylenediamine (EDA) over other amines was stated. However the disadvantages of increased toxicity and transient time dependant variation in sensitivity had to be accepted by the user. In an extension of the above work, a thick plastic tube having 4 mm thickness was filled with gelled nitromethane (NM) and was fitted with 1.25 mm thick copper cone having apex angle of 60°. The shaped charge was tested against mild steel (MS) target at a stand-off distance of 5 CD [41]. In the explosive filling, gelling, the addition of micro-balloons and ployox reduced the velocity of detonation and penetration of the charge. It was also reported that with 10% concentration of both additives, the copper liner spattered onto the plate and a penetration of the order of only 15 mm was achieved, because of the VOD reduction to 4292 m/s.

The design constraint for smaller shaped charge warheads was elaborated in [42]. The experimental results for small caliber tandem warhead concluded that the stand-off distance would be smaller than 6.5 times the diameter of the charge. The shielding should be in the middle of two charges. The detonation device for the first shaped charge should be smaller than the second with a short delay. The performance of KE penetrator including a precursor shaped charge was increased. In [43], the penetration of the shaped charge against sand targets using hydro-codes was investigated. The tandem shaped charge was examined experimentally using the design of detonation interrupter and detonation propagation parameters in [44]. A proper design of detonation interrupter and detonation propagation parameters could lead to the best coupling of the two-stage shaped charge during formation and relay penetration. The penetration depth was increased about 10-15% and radial crater by a shaped charge jet penetration was enlarged. The influence of asymmetry in trumpeted shaped charge liners on their performance was also investigated in [45]. Four defects of the shaped charge had been analyzed within the scope of the work, as off-centre ignition of the explosive charge, detachment of the high explosive filling from the casing, air bubbles inside the high explosive filling and shaped charge liners dimensional inaccuracies. The effect of each defect on the jet performance was determined in terms of radial drift velocities. In [46], a patent was presented in the area of tandem shaped charge for a long ignition delay between the front and rare charges. The patent suggested the explosive reduction and heavy confinement for the front charge to offset the ill-effects of poor penetration by the rear charge. A 50-60% explosive reduction, 20-40% reduction in overall warhead length and 10-20% weight reduction is claimed in the embodiment. Additionally, movement of confinement from the central axis resulted in a clear passage for the jet of the secondary rear charge. In [47], a shaped charge assembly consisting of a first shaped charge, a wave shaping relay charge and a second charge was placed in housing. The assembly was 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 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.

To summarize, during the 00s, consolidation of theory and simulation of experimental observations were the main emphasis in the area of shaped charges. In addition, several new concepts were proposed and experimentally tested. Tantalum liner was used in shaped charges against titanium targets. Among the new areas of research, the jet cut-off velocity, the study in penetration degradation, the effect of liner thickness, the reduction in penetration at increased standoff distance, the use of NM as an explosive filling in shaped charges, and the parameters for performance of tandem shaped charges etc. were investigated during this period.

V. CONCLUSION

Shaped charge modeling is a dynamic field, which is continuously growing. The present review is focused on works related to the theoretical modeling of the shaped charges. Three distinct periods are considered in this paper: the period before 1990 as the era of theory development, the 1990s as the decade that brought the experimentation and validation of several 1D codes and the 2000s as the decade where various new aspects such as the use and theoretical investigation of the filled shaped charges having liquid explosives along with perturbation parametric studies surfaced.

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