Shaped Charge Technology: A Review

[1]Madan Kumar Sharma, [2]Neeraj Kumar
[1]M. Tech. Student, Dept. of Mechanical Engg., USET, Rayat-Bahra University, Mohali
[2]Assistant Professor, Dept. of Mechanical Engg., USET, Rayat-Bahra University, Mohali

Abstract: This paper presents a detailed review on the shaped charge technology. The concept of shaped charge is explained by elaborating the Munroe effect and liner collapse phenomena. The military as well as civil applications of this technique is highlighted. The development of shaped charge technology is reviewed from historical perspective to present day guided missiles. Thereafter, a theoretical insight of hydrodynamic penetration phenomena is presented. The stress wave propagation concept is explained which governs the target damage. The various study approaches which are used in the analysis of such type of short duration events are enumerated. A brief description of the explosive and shaped charge liner characteristics is highlighted. At the end, the flash X-ray diagnostic facility which is used for the evaluation of a shaped charge jet characteristics is described. Finally, this review paper has been concluded by focusing on the current design and development scenario in the field of shaped charge.

Index Terms- Shaped charge jet, liner, impact phenomena, Munroe effect, Flash X-ray.

Introduction

A shaped charge is an explosive device which is designed to concentrate the effect of the explosive's energy. It consists of a concave shaped metallic hemispherical or conical liner backed by a high explosive in a nylon, aluminium or steel casing. The schematic arrangement of various components of a shaped charge is shown in Fig. 1.

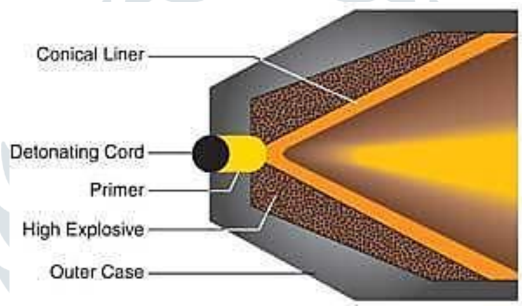

Figure 1: Schematic diagram of a shaped charge

When the explosive is detonated, pressure produced by the detonation of the explosive drives the liner material in the cavity inward to collapse upon its axis. The metallic liner is compressed and squeezed forward to form a high velocity jet. The jet stretches due to the velocity gradient between the tip and tail. Conventional shaped charges are constructed with a charge case, a hollow conical liner within the case, and a high explosive material positioned between the liner and case. A detonator is activated to initiate the explosive material to generate a detonation wave. This wave collapses the liner and a high velocity metallic jet is formed which penetrates the target and inflicts the desired damage from a certain standoff distance. It is the distance from the base of the shaped charge to the target surface.

Applications of Shaped Charge

Shaped charges are extremely useful when an intense and localized force is required to pierce a structure /target. The application of shaped charge is primarily in the field of warfare. It was introduced to battlefield as an anti-tank device in World War II. The common term in military terminology for shaped charge warheads is high explosive anti-tank (HEAT). HEAT warheads are frequently used in anti-tank guided missiles, unguided rockets, gun-fire projectiles (both spun and unspun), rifle grenades, land mines, bomblets, torpedoes and various other weapons. The targets are armours, bunkers, concrete, soil and other field fortifications.

In non-military applications, shaped charges are used in explosive demolition of buildings and structures, in particular for cutting through metal piles, columns and beams and for boring holes. In steelmaking, small shaped charges are often used to pierce taps that have become plugged with slag. They are also used in mining, tunneling quarrying, breaking up ice and drilling post holes. Shaped charges are used extensively in the petroleum and natural gas industries, in particular in the completion of oil and gas wells, in which they are detonated to perforate the metal casing of the well at intervals to admit the influx of oil and gas.

Historical Perspective

Charles Edward Munroe was the inventor of "The Monroe Effect" in explosives in 1885. He noted that a high explosive with a cavity facing a target left an indentation. The earliest known reference to the effect appears to be 1792 and there is some indication that mining engineers may have exploited the phenomenon over 150 years ago. The Monroe Effect was rediscovered by Von Neumann in 1911 but no practical applications were developed. Shaped charges were first developed after World War I to penetrate tanks and other armoured equipment. A cylindrical charge that lies flat against the armour and is being initiated in one end gives a directed detonation effect so that a hole is created at the point of contact is Generation I. If that charge is equipped with a conical hole the force of the explosion will be channelled further and increases the chances for a penetration it is Generation II. The most common type of hollow charge munitions is the jet creating hollow charge, also called Hollow Charge Generation III. The other type of hollow charge munition is the projectile creating munition. It is referred to as Generation IV. Gen I and Gen II (developed during the WW II) are predecessors to Gen III and IV but they are no longer in use in any munitions. During WW II, Henry Mohaupt, a chemical engineer, was a machine gunner in the Swiss Army found in his research that strange things happened when he tried to propel metal discs with conically hollowed out explosive charges. This led him to place a steel cone in the hollowed out explosive; when this device was moved away from the target, no fragmentation of the metal cone occurred, and a narrow hole in the target was created, a hole much deeper than the diameter of the cone. The present day guided missiles, such as Shillelagh, TOW, Dragon, and Hellfire, have high penetration capability by using shaped charge warheads with accurate fire at long range.

Theoretical Overview

Shaped charge is indeed an extraordinary phenomenon that is beyond the scale of normal physics, which explains why its fundamental theoretical mechanism is by no means fully understood. When the high explosive in a shaped charge detonates, a spherical detonation wave propagates outwards from the detonator location. The detonation wave propagates with a velocity of the order of few km/s and generates pressure of few GPa. Under such condition, liner material is accelerated and collapses to form stretching jet. The shaped charge jet tip reaches velocity of the order of few km/s in few microseconds after detonation depending upon the shaped charge geometry and liner material. Due to velocity gradient, the jet stretches out and finally fractures into a column of particles and hence particulation (breakup) occurs. The stretching of the jet occurs at a very high strain rates of 104 to 107 per second. Jonas A Zukas have reported in “High Velocity Impact Dynamics” that liner collapse and target penetration both can be assumed as inviscid and incompressible fluids and can be analyzed based upon the hydrodynamic flow concept. However, it is well reported in literature that the jet is solid metal and not in molten state. Accordingly, the following mystery is the first confusion: The jet appears to behave like a fluid, and yet it is known to be a solid. The hypervelocity hydrodynamic impact (unlike lower speed KE penetration) results in a mushroom head penetration, such that the hole diameter is larger than the penetrator diameter. The dynamic compressive yield stress of the target is exceeded by a factor of at least one thousand times, so that only the densities of the target and jet materials are important. In such type of hypervelocity impact phenomena, it is necessary to observe the rate at which phenomena is changing. Another important aspect is the disturbance which is propagated in the form of stress waves at sonic speed. In quasi-static deformation, we have a situation of static equilibrium. When the deformation is imparted at a very high rate, a part of the body is stressed while the other part has not experienced this stress yet. Stress has to propagate through the body. Such intense, short-duration loading especially where the energy is carried by stress waves can result in material failure when they interact with material interfaces, free surfaces or each other. A Wave propagation event occurs over a very short time frame, usually on the order of microseconds to milliseconds and involves peak strain rates in the range of 104 – 107 per second. In such types of impact problems were the phenomenon is governed by the stress wave propagation, generally, there are three categories of study approaches-experimental, analytical and numerical simulations. Numerical simulations by using an explicit nonlinear dynamic finite element analysis computer code are far more general in scope. The computer programs are called Hydrocodes which are designed initially for problems where the loading was so intense that a solid behaves like a fluid i.e. hydrodynamically. Modern Hydrocodes have evolved from their origin and can now handle problems involving elastic, plastic and hydrodynamic behavior. These codes are based on the fundamental mass, momentum and energy conservation laws. Along with these conservation laws, a suitable constitutive model together with a failure criterion is used to describe the dynamic deformation of solid material. As the practical impact problems, quite often, involves complex geometries and nonlinearities in material behavior, it is practically impossible to exactly solve an impact problem analytically. The most general approach is a numerical one.

Characteristics of Explosive

For maximum penetration of target, an explosive with a high velocity of detonation and pressure is needed. The most common explosive used is HMX, but it is very sensitive. It is normally used as polymer-bonded explosive (PBX) having reduced sensitivity. HMX with TNT is easy to cast and less sensitive. HMX and TNT composition is called Octol. Other explosives are RDX-based compositions, as PBXs or mixtures with TNT. Some explosives consists powdered aluminum to increase their blast, but this results in decreased performance of the shaped charge as the main intension is to achieve high detonation velocity for optimum penetration. High-detonation velocity explosive CL-20 in shaped-charge warheads is at research level As discussed above, the performance of explosive for shaped charge application depends upon the detonation velocity (VOD) of explosive. Higher the detonation velocity better will be the performance. Machined explosives charge has higher density than cast charge, thus higher detonation velocity. In this way machined explosives charge is preferred over cast charge. Moreover, it has more uniform composition.

Characteristics of Liner

The liner is a critical component of shaped charge. The penetration capability highly depends on the characteristics of jet formation from the collapse of liner material under very high pressure of high explosive. The design of liner involves finalization of shape, liner diameter, thickness, material and manufacturing method. The penetration depth is directly proportional to the square root of the density of liner material and maximum length of jet. The jet length is calculated as the product of tip velocity and particulation (breakup) time which are governed by bulk sound speed and ductility of material respectively. Accordingly, the following formula for the penetration depth has been published by Manfred Held in his paper "Hydrodynamic theory of shaped charge jet" in the year 1991.

$$P = (V_{j0} - V_{jmin})\, t_p \sqrt{\frac{\rho_j}{\rho_{min}}}$$

Where,

P	=	Maximum depth of penetration.
V_{jo}	=	Jet tip velocity
V_{jmin}	=	Cut-off velocity
t_p	=	Particulation time
ρ_j	=	Liner material density
ρ_t	=	Target material density

The maximum jet tip velocities for different liner materials cannot be infinite. It is limited by the bulk-sound velocity of the liner material. Copper is selected as shaped charge liner, because it has excellent ductility, high density and good bulk sound speed.

Detonation of high explosive generates very high pressure of the order of few hundred kilobars. Such an enormous pressure, squeezes and collapses the liner material to form high velocity stretching jet. During motion, the individual liner elements in preferred sliding plane deviate from axis, which causes the spin. The spin effect of shaped charge particles is compensated by rotation of grains during shear forming or flow forming process. This is known as self-spin effect. To achieve this, the liners are generally fabricated by flow forming process. Performance of flow formed process is better than machined liners. Moreover, machined liners involve wastage of scrap. Thus flow formed liners involves saving of materials subject to fabrication cost of die.

Flash X-Ray Facility

The Flash X-Ray technique is widely used to evaluate the characteristics of shaped charge jet. The comprehensive description on this type of facility is well reported by Jamet, Thomer, Webster and Finfera in 1976. When the performance of a shaped charge is to be evaluated, it is the high velocity stretching jet and the target which are of prime concern. The detonation of high explosive produces an intense flash of light and detonation products which obscure the visibility of stretching jet which moves with high velocity. Due to aforesaid reasons, even high speed videography is not capable to portray the characteristics and clear image of jet. Accordingly, the flash radiographic technique is used for the analysis. A Flash X-Ray is similar to the conventional X-ray facility except that here the shot is taken in less than one-millionth of a second. Even at such a very short duration exposure, the image of jet is not much clear and sharp. This technique uses a high frequency and short wavelength electromagnetic wave. The X-ray is produced when an accelerated beam of electrons at 150 to 2000 kV strikes tungsten target. In conventional X-ray facilities which are used in medical and industrial fields, the pulse of electron beam is of longer duration. In flash X-ray technique, the pulse duration is less than a microsecond. The selection of voltage depends upon the type of explosive / metal under investigation. The film used in this technique has a thin layer of emulsion on both sides to absorb radiation. The intensifying screens are the integral part of the facility placed on both sides of film which enhances the exposure of radiation by flash. About the selection of a suitable intensifying screen and a film, Bryant and Lucero have published paper in 1984 in the proceedings of Flash Radiographic Symposia.

Conclusion

A glimpse of shaped charge technology is presented in this review paper along with its military as well as civil applications. A detailed explanation on the jet formation process has been described and various study approaches like analytical, experimental and numerical is enumerated. A brief review on the characteristics of explosive and liner as well as flash X-Ray diagnostic facility was also reported. Early work on shaped charges and maximization of penetration capabilities were based largely on trial and error experiments. Now a days, the modelling codes can predict with high accuracy how a shaped charge will behave. While the concept of a metal surface being squeezed forward may seem relatively straightforward, the physics of shaped charges is very complex. The design and development of shaped charge and Explosively Formed Penetrator (EFP) based warheads is going on globally. The research aims at the development of more lighter and smaller shaped charges and its variants like EFP warheads with higher damage capabilities. To keep pace with the advancements in the field of shaped charge warheads against MBT's, modern ships, submarine, etc., advanced state-of-the-art shaped charge technique is evolving.

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