Computers & Fluids 86 (2013) 77–85

Contents lists available at ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Smoothed particle hydrodynamics modeling of linear shaped charge with jet formation and penetration effects

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ARTICLE INFO

Article history:
Received 23 October 2012
Received in revised form 11 April 2013
Accepted 28 June 2013
Available online 5 July 2013

Keywords:
Shaped-charge jet
Smoothed particle hydrodynamics (SPH)
Penetration
Kernel gradient correction

ABSTRACT

Shaped charge, as a frequently used form of explosive charge for military and industrial applications, can produce powerful metal jet and lead to stronger penetration effects onto targets than normal charges. After the explosion of high explosive (HE) charge, the detonation produced explosive gas can exert tremendous pressure on surrounding metal case and liner with very large deformation and even quick phase-transition. In this paper, the entire process of HE detonation and explosion, explosion-driven metal deformation and jet formation as well as the penetrating effects is modeled using a smoothed particle hydrodynamics (SPH) method. SPH is a Lagrangian, meshfree particle method, and has been widely applied to different areas in engineering and science. A modified scheme for approximating kernel gradient (kernel gradient correction, or KGC) has been used in the SPH simulation to achieve better accuracy and stability. The modified SPH method is first validated with the simulation of a benchmark problem of a TNT slab detonation, which shows accurate pressure profiles. It is then applied to simulating two different computational models of shaped-charge jet with or without charge cases. It is found that for these two models there is no significant discrepancy for the length and velocity of the jet, while the shapes of the jet tip are different. The modified SPH method is also used to investigate the penetrating effects on a steel target plate induced by a linear shaped charge jet. The effectiveness of the SPH model is demonstrated by the good agreement of the computational results with experimental observations and the good energy conservation during the entire process.

1. Introduction

A shaped charge is generally a high explosive charge with a hollow cavity (usually cone shape) at one end with a thin layer of liner, and a detonator at the opposite end (illustrated in Fig. 1) [1–3]. The gaseous products produced in the detonation process can exert extremely high pressure and high temperature on surrounding case and liner (usually a metal, such as copper or aluminum), causing very large deformation and even liquefaction. When detonation shock engulfs the lined cavity, the softened or liquefied liner moves towards the centerline or charge axis of symmetry, and forms a metal jet with large kinetic energy. With the evolution of the HE detonation process, the metal jet is gradually accelerated and elongated with increasing velocity until the HE detonation process completes. The focusing of the metal jet can create an intense localized force, which is capable of creating a deeper crater on a plate than that created by explosive charges without a hollow cavity, even though more explosive is available in the latter cases. Therefore shaped charges are commonly used in military for penetrating hardened tanks and targets, and in industry for cutting metals, rocks and mineral layers through using a specially designed charge devices. The shaped charge devices can usually be categorized into two classes, linear shaped charges and cylinder shaped charges. Fig. 2 shows an illustration of a typical linear shaped charge.

Investigations of shaped charges and the corresponding damaging effects date back to several decades ago. Though many researchers have conducted a large amount of work using theoretical analysis, numerical modeling, and laboratory or even field experiment, publically available literature is limited due to the restrictions from military establishments. Theoretical analyses on shaped charges usually start from simplified assumptions, and then are tested and corrected with experimental observations. For example, by assuming that the pressure of the explosive gas drops to zero as soon as the liner start to collapse and the liner material behaves like an incompressible inviscid fluid, Birkhoff et al. [2] provided a theoretical analysis of the shaped charge jet based on Bernoulli's equation. The validity of similar theoretical

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http://dx.doi.org/10.1016/j.compfluid.2013.06.033

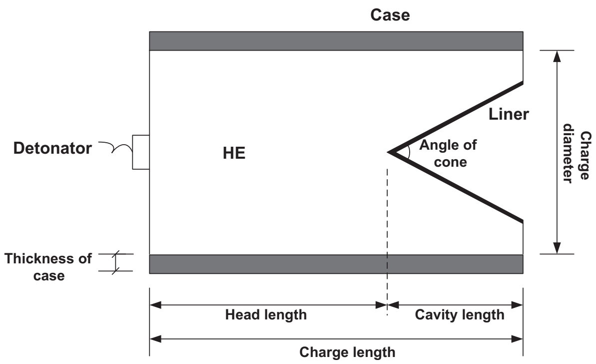

Fig. 1. An illustration of a typical shaped charge in two dimensional spaces.

analyses is experimentally verified later by Eichelberger [4]. In experiment, Green obtained the first X-ray photograph of a shaped charge jet in 1974 [5]. Raftenberg presented an experimental investigation of RHA (Rolled Homogeneous Armor) plate perforation by a shaped-charge jet [6]. Yu et al. also provided an experimental investigation of a shaped charge on the jet formation and its penetration effects onto rocks [7]. However, experimental works are generally expensive and sometimes certain physical phenomena related to shaped charges cannot be scaled in a practical experimental setup. Therefore, experimental works are usually combined with numerical simulations for detailed analyses. For example, through comparing numerical results and experimental observations, Wang et al. investigated the metal jet formation of a shaped charge with a copper liner [8]. Katayama et al. studied the penetration process of a shaped with an aluminum liner by an inhibited shaped charge launcher experimentally and numerically with commercial software, AUTODYN-2D [9].

With the advancement of the computer hardware and computational techniques, more and more researches on shaped charges are focused on numerical simulations. Computer simulation enables parametric studies to be carried out without having to resort to expensive firing trials, and is very useful in designing shaped charges or protection systems against shaped charges. Some wave propagation hydro-codes [10–16], which were originally developed to solve problems characterized by the presence of shock waves, localized materials response and impulsive loadings, have been tried to simulate shaped charges. Most of these applications are generally grid-based numerical methods such as the finite element methods (FEM) or finite difference methods (FDM). Some of them are associated with combined features such as Arbitrary Lagrange–Eulerian (ALE) coupling and Coupling Eulerian–Lagrangian (CEL) [17,18]. For example, Molinari simulated the shaped charge jet formation using finite element method [19]. Ayisit investigated the influences of geometric symmetry of the shaped charge device

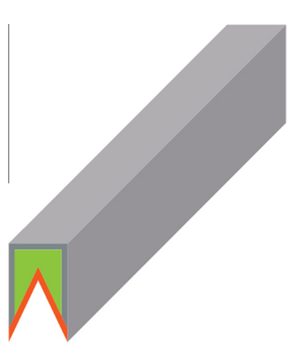

Fig. 2. An illustration of a typical linear shaped charge.

[20], while Karlsson also simulated the shaped charge jet formation [21]. In both work, a commercial software, AUTODYN, is used, while jet and target plate are computed within Euler and Lagrange frame separately. Though many successful achievements have been made for these methods in modeling shaped charges, some numerical difficulties still exist. These numerical difficulties generally arise from large deformations, large inhomogeneities, and moving interfaces, free or movable boundaries when simulating shaped charges including HE detonation and explosion, explosion-driven metal deformation and jet formation, target damaging and penetration.

Recently growing interests have been focused on the meshfree methods, which are expected to be superior to the traditional FDM and FEM, especially for applications with moving features such as free surfaces, evolutionary interfaces and large deformations. Among the meshfree methods, smoothed particle hydrodynamics (SPH) method [22–24] is unique in computational fluid and solid dynamics. As a comparatively new computational method, SPH combines the advantages of meshfree, Lagrangian and particle methods. First, in SPH, particles are used to represent the state of a system and these particles can freely move according to internal particle interactions and external forces. Therefore it can naturally obtain history of fluid/solid motion, and can easily track material interfaces, free surfaces and moving boundaries. The meshfree nature of SPH method remove the difficulties due to large deformations since SPH uses particles rather than mesh as a computational frame to approximate related governing equations. These features of SPH make it fairly attractive in modeling high explosive detonation and explosion, underwater explosion, and hydrodynamics with material strength such as impact and penetrations [25–31].

There are also some preliminary works of using SPH to model shaped charges. For example, Liu et al. first simulated the detonation and explosion process of two-dimensional shaped charges with different shapes of cavity [32] using SPH method. It is found that SPH can effectively model the explosive gas jet formation and dispersion. The work did not consider surrounding metal case and liner which present additional challenges in numerical simulation due to the existence of multi-material (explosive-metal) and multi-phase (solid–gas–liquid). Yang et al. also provided an SPH simulation of shaped charge jet formation in which both the explosive and metal liner are considered [33]. Existing works on SPH modeling of shaped charge is usually based on conventional SPH method, which is believed to have poor performances especially in modeling problems with highly disordered particles [25]. They lack quantitative and even qualitative comparisons with experimental results, and also lack validation and verification in energy conservation.

In this paper, we shall present a modified SPH model for simulating linear shaped charges with HE detonation and explosion, and hydrodynamics with material strength including explosion-driven metal deformation and jet formation as well the penetrating effects onto a target plate. As the size of a linear-shaped in longitudinal direction is much larger than those in other two directions, the linear shaped charge can be modeled as a plane strain problem in a two-dimensional space. Three numerical examples shall be provided to validate the effectiveness of the SPH model in simulating linear shaped charges.

2. Smoothed particle hydrodynamics (SPH)

2.1. Basic concept of SPH

SPH was originally invented to solve astrophysical problems in three dimensional open spaces as the collective movement of those