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A numerical study on high-speed water jet impact

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ABSTRACT

The usage of water jets has spread into numerous fields and for multifaceted purposes such as cleaning, cutting, and punching various materials. Because the impact occurs over an extremely short period, the target may deform elastically or plastically at high rates of strain. The dynamics of this process are complex and not fully understood. This paper applies a numerical method to simulate the phenomenon. A water jet with a spherical head was used at a speed of 570 m/s to impact on a structure, which was a flat plate made of Polymethyl-Methacrylate (PMMA). The Couple Eulerian Lagragian (CEL) method was used to simulate the entire process and eliminated abruption caused by large distortion of elements. Water-hammer pressure and the subsequent stagnation pressure on the surface of the plate were performed to evaluate the distribution of the pressure on the impact surface and the resulting deformation of the structure. The simulation results were reflected in the calculation using empirical formulas and were further validated using Obara's experiment. Whereas facets of this phenomenon could not be fully modeled, the numerical simulation supplied accurate quantitative details of stress, strain, and deformation fields that would be costly and difficult to reproduce experimentally.

1. Introduction

The impact of a high-speed liquid jet has long been of interest to researchers because of its potential practical uses in daily life. Water jet technology has rapidly expanded and is now applied in numerous fields, including automotive, mining, construction, or engineering to clean parts, welding, punch, or even for the rapid forming of metal sheets and tubes (Chizari et al., 2008, 2009; Mabrouki et al., 2000; Turgutlu et al., 1995). The popular method to produce a high-speed is forcing a packet of liquid through a converging nozzle. By using this method, the water packet is accelerated and the water jet can attain the speed up to 4000 m/s. The mechanics of such a high speed liquid jet were investigated both experimentally and theoretically (Field and Lesser, 1977). However, a high-velocity liquid striking against a solid surface has the potential to create serious problems, such as damage to the surface of an aircraft during a high-speed flight in the rain or the impact of a high-velocity jet developed during the collapse phase of a spherical bubble in an underwater explosion. Therefore, having a clear understanding of this phenomenon might help control the damage and make this technology of practical use in many aspects of daily life.

The potential problems of a high-speed water jet's impact have received considerable attention in both experimental and numerical studies. Recent papers have addressed the capabilities of the water jet technique in several areas such as using Finite Element Analysis (FEA) to simulating welding (Chizari et al., 2008), tube forming (Chizari et al., 2009), or applying the Ls-Dyna3D code to investigate the decoating process (Mabrouki et al., 2000). However, this process is complex and not fully understood because the impact occurs over a short period and difficulties in simulating the properties of fluid and other technical problems, such as solving fluid-structure interaction, the abortion of analysis due to extremely distort elements or many such studies.

When a high-speed water jet hits a flat solid, the initial pressure is comparable to the water-hammer pressure, where peak pressure depends on liquid density, the sonic velocity of the liquid and impact velocity. The high pressure lasts for such a short period that a release wave generated at the contact edge of the jet is required to reach the central point. At the next stage, high pressure decreases and remains in a stagnated state which lasts for a relatively longer period (Cook, 1928). After the pressure peaks in value, it immediately begins to fall. Decay time is normally greater than the peak time of the water-hammer pressure (Brunton, 1966; Smith and Kinslow, 1975). In other recent experiments (Shi et al., 1995; Obara et al., 1995), normal-impact pressure on the impact surface was

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determined, and peak pressure and stagnation pressure fit well with Cook's theory.

In a study conducted by Smith and Kinslow (1975), the distribution of peak pressure on the impact area was determined, and the highest pressure was assumed to generate at the center of the impact area rather than near the contact edge of the liquid jet. To further study the distribution of pressure, another study calculated the Lagrangian histories for 100 stations placed along the surface of the target (Bourne, 2005). However, there was no clear conclusion for this problem, and to date the pressure distribution remains controversial because there is no consensus to fully explain the occurrence of all failures on the impact area (e.g., ring crater, cracks, and lip lines). Another area that has received researchers' attention is radial flow because it is considered to be the cause of shear action. Under certain conditions, the flow velocity of the liquid along the surface and away from the center of impact is greater than the impact velocity itself. Measured values showed the difference to be as much as two to three times the impact velocity. This high-speed lateral flow results in erosion failure and usually involves removal of material from the surface (Brunton, 1966).

To examine the mechanism that results in damage, differing materials have been used in a range of studies (Bowden et al., 1958; Bowden and Brunton, 1961; Bowden and Field, 1964; Brunton, 1966; Smith and Kinslow, 1975). The deformation of the structures is considered to relate to two types of impact stresses, namely the stress caused by the water hammer effect leading to short-term compression of the surface and the stress associated with erosive scouring action of high-velocity tangential flow. The impingement of the jet caused different damage in ductile and brittle solids. In the former, a simple surface depression in the form of surface pits with outer lops were produced, where the size of the surface depression was measured equally in the diameter to the jet head. In the latter, circumferential fractures were created with ring cracks and occasionally, in materials showing tendency to deform plastically, subsurface shear cracks (Brunton, 1966). The appearance of ring and star cracks was also seen in an experiment by Bowden et al. (1958) using non-metals, where the failure in hard and soft metals was presented.

Because the erosion or material damages occur during a period of the order of a few microseconds after the initial contact, major emphasis is on this period. At the initial stage of impact, when the contact region is expanding faster than the wave in the liquid, this causes compressible behavior in the liquid, the compression wave (shock wave) spreading into the liquid causes other phenomena such as edge pressure, jetting and cavitation in the liquid. Especially at the time the wave motion in the liquid overtakes the expanding contact edge and moves up to the free surface of liquid, the edge pressure can attain values up to about three times the normal impact pressure. The detail information of those events and factors in determining material loss and erosion can be found in related studies Field et al. (1985), Lesser (1981), Lesser and Field (1983).

For further understanding about the high-speed liquid jet impact phenomena, experiments of liquid jet impact on the water surface were conducted Bourne et al. (1996), Obara et al. (1995). High speed camera was used to monitor the impact process. A system of shocks and release waves as well as the creation of cavitation cloud in the liquid were observed. Besides, the results also indicated the importance of taking in to account the compressible effects of liquid into studying the liquid impact process.

Although these studies provided substantial information on the relationship between various factors and program comprehension, many factors remain unexplored. This paper describes a numerical study applying the CEL technique to simulate the process of water jet impact, with results verified by Cook's theory (1928), Bowden's experiment (1961) and Obara's experiment (1995).

2. Theoretical background

Empirical formulations are simple tools for calculating the pressure exerted on the impacted surface structures, but they do not help predict the damage of targets because of impingement. The numerical method has recently become one of the most widely used simulations available for mechanical, aerospace, and civil engineers because it saves both money and time compared to experimental methods. The CEL technique, which is embedded in ABAQUS software, can eliminate the difficulties in simulation such as high rate of strain, large distortion of elements, and other potential matters.

2.1. Empirical formulation

When a water jet impacts a flat solid, the initial pressure is comparable to the water-hammer pressure (Cook, 1928).

$$P = \rho v c \quad (1)$$

where P is the pressure, ρ is the liquid density, v is the impact velocity, and c is the sonic velocity of the liquid. The initial high pressure given by Eq. (1) decreases rapidly because of release waves propagating into the jet from the circumference. If impingement continues until a steady state is reached, the pressure approaches hydro-dynamical pressure.

$$P = \frac{1}{2}\rho v^2 \quad (2)$$

The water-hammer pressure lasts for only the time it takes the release wave, which is generated at the contact edge of the jet, to reach the central point. The duration, $\Delta\tau$, of this peak pressure with respect to the diameter, d, of the water jet is shown in the following equation:

$$\Delta\tau = \frac{d}{2c} \quad (3)$$

When taking the elastic deformation of the solid into account, Eq. (1) would be modified and is given by:

$$P = \frac{\rho_1 c_1 \rho_2 c_2 v}{\rho_1 c_1 + \rho_2 c_2} \quad (4)$$

where ρ_1, ρ_2 and c_1, c_2 are the respective densities and sound speeds in the liquid and solid.

For the impingement of a spherical liquid drop, the maximum pressure is the water-hammer pressure. Engel proposed (Brunton, 1966):

$$P = \frac{\alpha}{2}\rho v c \quad (5)$$

where factor α depends on impact velocity and approaches unity for high velocities. The maximum pressure proposed by Engel would thus be $1/2\rho v c$ (the factor of 1/2 is a consequence of the spherical shape of the drop).

2.2. Finite element background

ABAQUS/Explicit code version 6.9-1 was developed to simulate and analyze nonlinear physical phenomena found in real-life situations (where such phenomena manifest with large deformations in short durations). The explicit finite element program is based on a mathematical technique for integrating the equation of motion through time. Used in combination with a lumped mass matrix, this technique allows the program to calculate the nodal accelerations at any time. Based on the accelerations, velocities and displacements of the nodal can be determined using an integral calculation. The accelerations at the beginning of increment are