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On stress wave interactions in liquid impact

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Abstract

There are many situations in which the impact of a liquid jet is of importance. Such an event induces stress fields that interact to apply localized compressive or tensile loading to the targets impacted. Initially, the surface sees compression, but, after a short time, tensile forces are also experienced. At later times, the flow of the rest of the following liquid onto the target applies a further loading of lesser magnitude. In this respect, jet impact differs from that induced by a drop having the same radius of curvature. Experimental and numerical studies of liquid jets hitting liquids are presented, with results showing the effects of a cavity collapse in a reactive material. It is shown that it is the jet impact that leads to ignition rather than other mechanisms in the observed behaviour.

Keywords: Bubble collapse; Shock wave; Jetting; Cavitation; Ignition; Hydrodynamic

1. Introduction

It was the work of Bowden that established the methodology for work in Cambridge studying the impact of a liquid jet with a target material [1]. The collision of a high-velocity mass of liquid generates short, high-pressure transients which can cause a range of effects to the surface and interior of the target material (see for example, [1,2]). The liquid jet work in the Cavendish in later years was designed to simulate the effect of liquid drops, such as may be encountered by aircraft travelling through rain. However, the problem is significant to a wide range of technologies as well as rain erosion, including cavitation, turbine blade erosion and jet cutting techniques. Here the pulse length is a variable fixed by the geometry of the impactor. In the case of bubble collapse, the target will be liquid and the same as that of the jet. However, in spite of a considerable number of engineering tests, there remain unexplained and poorly understood phenomena concerning the liquid impact and damage processes. The reason for this is that the diameter of the liquid drop or jet is generally too small to observe spatial details, and the damage takes place over an extremely short period of time (of the order of a few microseconds). At the present, the most modern approach to such problems is to fully describe the materials of interest with mathematical models, to incorporate these descriptions within a hydrocode, to validate these responses against well-instrumented tests, and then to use the resulting capability in a predictive way. Such a code can then be used to check, or even to suggest, analytical constructs describing the vital mechanisms for faster and more accurate design. This work will examine the validation of the liquid impact capability developed using a commercial hydrocode (see Section 3). It will address the symmetric impact problem, where a jet penetrates a liquid surface. The application of this will be to the asymmetric collapse of bubbles in liquids which leads to the formation of a jet which crosses the cavity. A later paper will show the asymmetric problem, where a jet impacts onto a solid which responds in a brittle or a ductile manner. It will be noted that this modelling is at a less-developed stage because mathematical material descriptions for these strain rates and modes of loading, and particularly failure, are only developed to first order.

There are useful analytical descriptions which apply to this problem derived through the development of the subject. Cook (1928) was amongst the first to point out that high

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pressures can be generated in liquid impact as a result of the so-called 'water-hammer' effect [3]. The water-hammer or shock pressure, P, for impact on a perfectly rigid target, is given by:

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

where ρ and c are the density and shock velocity for the undisturbed liquid, respectively, and v the jet impact velocity. Such pressures are a consequence of the conservation of linear momentum at the impact site. For a symmetric impact, where the target moves and is of the same impedance, the pressure is half this value. This loading at the impact site (in the case of a cylindrical jet), lasts only for the short period, τ, that it takes a release wave, generated at the contact edge of the jet, to reach the impact axis. This time can be expressed as:

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

where d is the diameter of the jet. For example, a water-hammer pressure of about 1.5 GPa lasting 1 μs is generated by an impact velocity of 1 km s^{-1} with a jet diameter of 3 mm. However, real jets have some curvature and then the time for which the high-pressure state lasts is shorter.

There have been studies of the interaction of a water jet with various target materials [1,2,4–6]. A direct impact causes damage that results from the interaction of the stress waves within the material [7,8]. Typically, there are also ancillary effects that result from the travel of a Rayleigh surface wave or from rear surface reflections if the target is of finite thickness [9]. For an impact velocity of hundreds of m s^{-1}, most ductile materials have compressive yield strengths below typical impact pressures, and surface pitting is commonly observed in metals. Their tensile strengths are of similar magnitude, tensile failures around the impact site are rarely observed (only with thin plates are spall failures at the rear surface seen). In brittle materials, however, the compressive strength is typically higher than that in tension, and so release interactions play a much more important role as has been discussed for the case of circumferential cracking [7]. In those materials, where the compressive strength is not exceeded, the material in the region beneath the impact itself remains undamaged but it has been noted that damage occurs near the edges of the contact where the stress can rise to several times that on the impact axis.

The surface areas of such regions were measured by Bowden and Brunton and seen to be related to the diameter of the jet head [1]. Heymann developed a theoretical treatment for the collision of a liquid sphere onto a solid surface in order to investigate the pressure distributions around the impact area, and found that the highest pressure was generated at the contact edge of the liquid-jet, and that this pressure progressively decreased from ca. three times the water-hammer pressure at the expected value on the impact axis [10]. More complete analyses by Lesser, taking into account the elasticity of the target material, also suggested that the edge pressures exceeded the central water-hammer pressure though they are of short duration [11]. Whilst used to explain the location of the circumferential crack on these materials, analytical models were unable to explain all the damage modes found in target materials, in particular the mechanism resulting in the central crack on the liquid-jet axis. Whilst compression wave interactions have been identified as important to failure mechanics, tensile wave interactions have received less attention. These efforts have generally been limited to analytically accounting for particular observations, however, hydrocode availability and sophistication allow such effects to be accurately accounted for. This has meant that modern material models, and the numerical maturity of the technique, coupled with increases in computation speed and accuracy have made integrating numerical modelling of all the phenomena a possibility. The difficulty in adequately describing failure is the principal weakness of present models, but in the future the full description of a structure will allow complete analysis of such loading.

Obara et al. conducted a series of experiments to investigate failure mechanisms in jet impact [12–14]. The waves and damage were visualised using an image converter high-speed camera and schlieren optics. Additionally, the damage patterns on and within the recovered targets were examined using optical microscopy. For the impacts on polymethylmethacrylate (PMMA), circumferential ring cracks were generated at the impact surface by the strong tensile stresses. At depth, the release waves overlap on the central axis and cause tensile failure. In the case of thin targets, spall fracture was generated by a further interaction of release waves. The middle portion of the target was also damaged by the interaction of the release and a shear wave generated by the closure of the sub-surface failure. Thus, four distinct failure mechanisms operated in the target in response to the stress wave loading which were dominated by the tensile weakness of the material.

A high-speed liquid jet is also produced within bubbles when they collapse asymmetrically. This was first suggested by Kornfeld and Sovorov [15] and experimentally confirmed by Benjamin and Ellis [16]. There has been a varied study of liquid microjets in the final stage of cavity collapse [6,17–24]. Tomita and Shima conducted an exhaustive investigation of bubble collapse and damage-pit formation [6]. In all of these works, it was difficult to observe details of the process since a microjet was produced in the interior of a bubble which cannot be observed. However, these difficulties were relaxed by using a two-dimensional analogue with some loss of quantitative rigour [18,23].

The collapse of a gas void within a reactive material has the potential to start local reaction leading to partial reaction or run to full detonation [25–28]. This acts as a means of sensitising an explosive for ignition on the one hand, but represents a potential safety problem for handling such materials on the other. The stimulus for ignition is always local high temperatures, and thus one must establish the means by which mechanical energy is converted into heat [25]. There are three main features of the collapse that provide a means