The Art, Craft and Science of Modelling Jet Impact in a Collapsing Cavitation Bubble

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Abstract. One of the key characteristics of the asymmetric collapse of a cavitation bubble near a rigid boundary is the development of a high speed liquid jet that penetrates the interior of the bubble, impacting on the other side to yield a toroidal bubble. After the formation of the toroidal bubble, a vigorous splash may occur that can lead to pressures on the boundary an order of magnitude greater than the impact pressures associated with the jet. Qualitative agreement with available experimental data is found although, as the bubble approaches minimum volume, shock waves are also observed which further complicate our full understanding of the mechanisms for damage.

Key words: cavitation bubble, jet impact, liquid jet, toroidal bubble, splash.

1. Introduction

The principal objectives of this study are to understand the flow and pressure fields surrounding the high speed liquid jet that threads a collapsing cavitation bubble and impacts on the far side, creating a toroidal bubble with an associated ring vortex-like flow field (i.e. with circulation). The experimental studies of Tomita and Shima [12], and further studies reported in this paper, indicate that the highest loadings on a nearby boundary can occur, not at jet impact, but sometime after the toroidal bubble has been formed, closer to minimum volume and before the bubble rebounds. One of the key parameters in this study is the dimensionless ‘stand-off’ distance, $y$, of the bubble from a boundary.

Cavitation bubbles are generated in a liquid when the local dynamic pressure falls beneath the saturated vapour pressure for a sufficient length of time. The generation of the bubble is facilitated by the occurrence of nuclei or small gas bubbles in the liquid. Other forms of cavitation bubble generation are associated with the concentrated deposition of energy as might occur due to a laser [4, 13] or
the high voltage discharge across electrodes [2, 9, 12]; these mechanisms are often being employed in laboratory situations to generate bubbles near boundaries. At a much larger scale, underwater explosions display similar characteristics of bubble behaviour with regard to high speed jet formation although here buoyancy forces play an important role that is not present in the smaller bubbles associated with cavitation phenomena.

Tomita and Shima [12] considered a range of values for the stand-off parameter $\gamma (\gamma = h/R_m, h = $ stand-off distance, $R_m = $ maximum bubble radius) from 0.4 to 1.41, recording considerable variations in the pressures on the boundary, both with changes in $\gamma$ and for each $\gamma$ as a function of time. For the range $0.8 < \gamma < 1.2$, pressures associated with jet impact and a splashing behaviour in the toroidal bubble appear to generate the highest pressures. Outside this range, shock wave behaviour may be important but is outside the remit of this paper. For $\gamma < 0.4$, with the occurrence of peak pressures after toroidal bubble formation, it was found that damage appeared to concentrate on a ring around the axis of symmetry. Tomita and Shima [12] make the remark concerning this range of $\gamma$, that the damage pattern resulting from a spark-induced bubble collapse may be caused by a local high pressure generated at the collision between the contracting bubble surface and the radial flow following liquid-jet impact on a solid boundary. Damage was not observed on the boundary by these authors for $\gamma > 1.0$, but recent work by Philipp and Lauterborn [6] has found evidence of a ring pattern of damage by using 100 collapses of identical bubbles.

In this paper we revisit these experimental studies with a more detailed analysis as well as considering a range of more recent experiments. The plan of the paper is to consider the experimental procedures in the next section, followed by a discussion of the fluid dynamic theory and numerical art and craft that is required to facilitate the calculations proceeding as far as they do. The penultimate section will bring out details of the latest calculations, comparing them with experiment and providing us with further insight into cavitation bubble damage.

2. Experimental Apparatus and Techniques

Cavitation bubbles were produced by either using an underwater spark discharge or by focusing a laser in water. A relatively large sized bubble was generated by underwater electric spark discharge which occurred at the gap of a pair of tungsten electrodes with diameters of 0.3 mm. Although the gap distance between the electrodes changed every discharge owing to electric erosion, reproducibility was guaranteed by taking more than twenty preparatory spark discharges when producing a bubble with the radius of 3.5 mm, which required a charge energy of 2.25 J [10, 12]. A ruby laser with pulse width of 20 ns and maximum power 60 MW was focused into tap water at room temperature to generate a small sized bubble. About 4 mJ of light energy was required to produce a bubble with radius 1 mm [13]. A schematic diagram of the experimental facility is illustrated in Figure 1.