Available online at www.sciencedirect.com
ScienceDirect
Journal of Hydrodynamics
2017,29(6):907-916
DOI: 10.1016/S1001-6058(16)60805-3
www.sciencedirect.com/
science/journal/10016058

Bubbly shock propagation as a mechanism of shedding in separated cavitating flows*

Harish Ganesh[1], Simo A. Mäkiharju[2], Steven L. Ceccio[1]
1. *University of Michigan, Ann Arbor, USA, E-mail: gharish@umich.edu*
2. *University of California, Berkeley, USA*

(Received 24 October, 2017, Revised 26 October, 2017)

Abstract: Stable attached partial cavitation in separated flows can transition to cloud shedding, and the mechanism of transition has been attributed to the presence of a re-entrant liquid jet. Our findings have revealed the presence of propagating bubbly shock waves as an alternative dominant mechanism of shedding when the compressibility of the bubbly mixture is appreciable. In the present paper, we discuss dynamics associated with these bubbly shock waves, interaction of shock waves with obstacles in their path, and means to manipulate their properties to control the shedding process by non-condensable gas injection.

Key words: Partial cavitation, bubbly shock waves, cloud cavitation, X-ray densitometry

Corresponding author

Steven L. Ceccio is the Vincent T. and Gloria M. Gorguze Professor of Engineering and the Associate Dean for Research of the University of Michigan College of Engineering. He has appointments in Naval Architecture and Marine Engineering, Mechanical Engineering, and Applied Mechanics. He received his B. S. degree in mechanical engineering from the University of Michigan in 1985. He received his M. S. degree in 1986, and his Ph. D. in 1990 both in mechanical engineering from the California Institute of Technology. Upon completion of post-doctoral studies, also at the California Institute of Technology, he was appointed as an Assistant Professor in Mechanical Engineering at the University of Michigan, Ann Arbor in 1990. He was promoted to Associate Professor with tenure in 1996, and Professor in 2003. He served as an Associate Vice President for Research at the University of Michigan from 2004 to 2009 and as the Director of the Naval Engineering Education Center from 2010 to 2015. He was the Chair of the Department of Naval Architecture and Marine Engineering at the University of Michigan from 2011 to 2016 and the inaugural ABS Professor of Marine and Offshore Design and Performance. Prof. Ceccio's research focuses on the fluid mechanics of multiphase flows and high Reynolds number flows, including flow in propulsors and turbomachinery, cavitating flows, vortical flows, friction drag reduction, the dynamics of liquid-gas, gas-solid, and three-phase disperse flows, and the development of flow diagnostics. He has served as an Associate Editor of the Journal of Fluids Engineering. He has also acted as a consultant to government and industry. Prof. Ceccio is a fellow of the American Society of Mechanical Engineers and of the American Physical Society, and he was named the 2014 Freeman Scholar by ASME.

---

* **Corresponding author:** Steven L. Ceccio,
E-mail: ceccio@umich.edu

Introduction

Hydrodynamic cavitation is characterized by the presence of vapor filled regions in a predominantly liquid flow, when the pressure in the region is close to vapor pressure. It can occur partially in regions where the static pressure is low, forming partial cavities, such as separated regions on lifting surfaces, cryogenic rocket motor inducers, high-pressure diesel injectors. Stability of these partial cavities isclosely related to the flow conditions, with the cavities being generally stable at shorter cavity lengths (smaller volume). However, with a change in flow conditions, such stable cavities can experience auto oscillations of cavity length resulting in shedding of vapor clouds, termed as cloud cavitation, carrying away the vapor filled mixture that originally formed the cavity. Cloud cavitation and its onset have negative effects, as it is one of the principal agents of cavitation erosion and a source of significant noise. Reference [1] discusses the dynamics of partial cavity shedding in detail.

Mechanisms of transition from stable to shedding cavities has been studied extensively. Presence of a stagnation point at cavity closure can result in a reversed liquid flow propagating upstream into the cavity term as the “re-entrant liquid flow”, driven by the kinematics at cavity closure. Numerous studies such as References [2-5] have found the presence of a re-entrant liquid flow to be the dominant mechanism responsible for this transition. References [6-8] among others, investigated the conditions needed for the development of a re-entrant flow that would result in shedding. Reference [9] provides a good background on different studies and their outcomes in relation to the role of re-entrant liquid flow in causing transition.

Recently, Reference [9] reported the presence of propagating bubbly shock waves as a dominant mechanism of partial cavity shedding on a cavitating flow at a wedge apex. Using time-resolved X-ray densitometrysystem reported in Ref.[10], they were able to measure two-dimensional span-wise averaged void fraction flow field within the cavity. Measurements revealed instantaneous void fraction values to increase significantly, and in addition to the “re-entrant flow” induced shedding, another mechanism of shedding was also identified. It was the presence of a propagating void-fraction discontinuityas tall as the cavity that resulted in cavity pinch-off from the leading edge.

At high-void fraction values, the speed of sound of a liquid-vapor mixture can drop significantly as discussed in Refs.[11] and [12]. This can make the cavity mixture susceptible to shocking. By measuring averaged pressure underneath the shedding cavity and dynamic pressure on the wedge surface, Ref.[9] were able to measure shock properties and found them to be close to that predicted by simple one-dimensional conservation theory with no bubble dynamics. Apart from Ref.[9], high-fidelity numerical simulations by Refs.[13] and [14] on the same geometry as Ref.[9], also observed these propagating bubbly shocks as a dominant mechanism. Other recent studies such as Ref.[15] also observed propagating bubbly as a dominant mechanism of shedding on a different geometry. Thus, under severely cavitation conditions in which the void fraction values can reach in excess of 60% the presence of propagating bubbly shocks can be the dominant mechanism of shedding.

Speed of sound of a bubbly mixture depends on the void fraction, pressure and temperature within the cavity for a given flow speed, as discussed in Ref.[16]. By injecting non-condensable gas into the cavity, the properties of the bubbly mixture can be altered. The effect of non-condensable gas injection on a partial cavity was recently studied by Refs.[17] and [18]. Reference [18] carried out a detailed study on the influence of non-condensable gas injection into the same configuration studied by Ref.[9], and found that injection of relatively small quantities of non-condensable gas could alter the shedding and shock properties significantly.

In the present paper, we summarize all the studies carried out at the University of Michigan in the context of propagating bubbly shock waves, and their role in causing periodic shedding on a wedge apex. We will provide an overview of the properties of these bubbly shocks reported in Ref.[9]. We will also summarize the findings of the influence of non-condensable gas injection reported in Ref.[18]. In addition to this we will present preliminary results of the interaction of these shock waves with obstacles. Our hope to give the reader a good flavor of this mechanism of shedding under different operating conditions.

1. Experimental set-up

Experiments were carried out at the University of Michigan 9-Inch Water Tunnel. The tunnel has a 6:1 round contraction leading into a test section with a diameter of 0.230 m (9 inches). The test section then transitions to a square cross-section that is 0.210 m by 0.210 m with chamfered corners. The flow velocity in the tunnel test section can be varied from $U_0 = 0$ m/s to 18 m/s and the static pressure, p_0, from near vacuum to 200 kPa.

$$\sigma_0 = \frac{p_0 - p_v}{\frac{1}{2}\rho U_0^2} \tag{1}$$

For the present experiments, the test section was further reduced in area to a conduit that had a 0.076 m by 0.076 m cross-section. This was done to reduce the baseline X-ray attenuation produced by the non-cavitating flow. The wedge geometry was chosen asit