Cavitation Dynamics in Wakes Behind Bluff Bodies

[1,2]Lisa Deijlen; [1]Anubhav Bhatt; [1]Juliana Wu; [1]Harish Ganesh*; [1]Steven Ceccio

[1]University of Michigan, Ann Arbor, MI, USA; [2]University of Twente, Enschede, Netherlands

Abstract

Properties of wakes behind bluff bodies such as shedding frequency, vortex spacing, and drag change with the presence of cavitation. As extent of cavitation in the wake increases from inception to an attached super-cavity, wake shedding Strouhal number increases, reaching a peak value before decreasing as the wake forms a super cavity. The physical mechanism responsible for this observed change in shedding dynamics is yet to be fully understood. In the current study, we employed time resolved X-ray densitometry and high-speed videography to study the cavitation dynamics in the wake of a triangular, nominally two-dimensional wedge in a re-circulating water tunnel to understand the underlying mechanisms responsible for cavity formation and shedding. Mach numbers of the bubbly mixture, obtained based on base pressure and void fraction measurements, revealed that the flow transition from subsonic to supersonic coincides with the increase in Strouhal number suggesting the importance of compressibility effects on the wake dynamics.

Keywords: cavitation; bluff bodies; Strouhal number

Introduction

Wakes of bluff bodies placed in a steady inflow experience flow induced unsteadiness characterized by the shedding of alternate vortices, termed von Kármán vortex street. Characteristics of such flows has been studied extensively in the past, and it has been found that the wake properties such as vortex shedding frequency and form drag depend on the Reynolds number and blockage effects [1], [2], and [3]. In the case of a liquid flow capable of experiencing cavitation in the shed vortex cores, vortex shedding frequencies at given Reynolds number depend on the extent of cavitation, dictated by the mean pressure level.

Cavitating wakes produced by bluff bodies have been studied in the past by [4] and [5]. It was observed that the shedding frequency, characterized by the Strouhal number, with decreasing cavitation number, increases from the non-cavitating shedding frequency, attaining a peak value, and decrease again. More recently, [6] studied the effect of cavitation for sharp bluff bodies, and found that vortex spacing also changed with the extent of cavitation. However, despite thorough studies, no satisfactory mechanism responsible for the observed behavior has been proposed.

Cavitating flows with high vapor content can have low speed of sound values as discussed in [7] and [8]. Recently, [9], found that propagating bubbly shocks act as a primary mechanism of shedding in partial cavities. It was found that the compressibility of the bubbly mixture can play an important role in dictating the vapor-liquid flow dynamics. In the present study, the influence of the mixture compressibility on the observed wake cavitation dynamics is explored by measuring the void fraction flow fields, obtained using time-resolved X-ray densitometry. With the help of time synchronous unsteady base pressure measurements, and time-averaged base static pressure measurements, the role of mixture speed of sound is being tried to understand.

Experimental setup

Experiments were carried out at the University of Michigan 9-Inch re-circulating water tunnel. The tunnel has a 6:1 round contraction leading into a test section with a diameter of 23 cm. The test section then transitions to a square cross-section that is 21 cm by 21 cm. The flow velocity U_o in the tunnel test section can be varied from 0 to 18 m/s and the static inlet pressure p_o from near vacuum to 200 kPa absolute pressure. In the present experiments, the test section was further reduced in cross-sectional area to a conduit that had a 7.6 cm by 7.6 cm cross-section. This was done to reduce the baseline X-ray attenuation produced by the non-cavitating flow. A schematic of the test-section, wedge model, hydrophone, and measurement locations are shown in Figure 1. The set-up and the high-speed imaging is discussed in more detail in [9] and [10]. Details of the X-ray densitometry system can be found in [11].

*Corresponding Author, Harish Ganesh: gharish@umich.edu

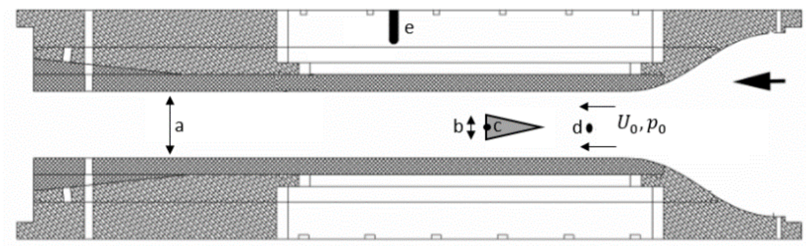

Figure 1: Schematic overview test section with (a) cross section of 7.6 cm by 7.6 cm, (b) wedge base height of 1.9 cm, (c, d) pressure transducers and (e) a hydrophone.

The static inlet pressure p_o was measured at (d) in Figure 1 using an absolute pressure transducer and was varied between 15 kPa to 100kPa. The flow velocity U_o was acquired by measuring the pressure drop across the contraction, upstream after a honey comb and point (d), and was set to 6 m/s. This gives an inlet cavitation number σ_o, Equation (1), in the range of 0.7 to 6.5.

$$\sigma_o = \frac{p_o - p_v}{(1/2)\rho_L U_o^2} \tag{1}$$

With the vapor pressure $p_v = 3.169$ kPa and the liquid density $\rho_L = 1000\ \mathrm{kg/m^3}$. The wedge has an apex angle of 15 degrees and a base height of 1.9 cm. The static pressure at the wedge base p_b and the dynamic pressure at the base of the wedge were measured using a static and a dynamic pressure transducer respectively at point (c) in Figure 1. To improve the visualization of the vortices, a mixture of milk and alcohol was injected through a single port at point (c) in Figure 1.

Results

Cavitation events in the wake were observed for $\sigma_o < 4.8$. The flow characteristics stay fairly constant for $2.5 < \sigma_o < 4.8$. However, for inlet cavitation numbers smaller than 2.5 changes in the flow are visible. Figure 2 shows the Strouhal number, Equation (2), with the frequency *f* obtained from the dynamic base pressure measurements and the wedge height *D* as function of inlet cavitation number σ_o. Similar to [4] and [5], a peak value in Strouhal number is observed. The inlet cavitation numbers were further examined using both high-speed cinematography and X-ray densitometry. Figure 3 (a)-(h), shows snapshots of the wake at four different cavitation numbers.

$$St = \frac{fD}{U_o} \tag{2}$$

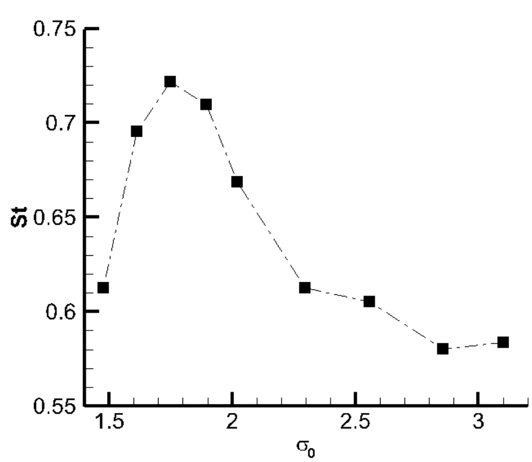

Figure 2: Strouhal number *St* as function of inlet cavitation number σ_o.

*Corresponding Author, Harish Ganesh: gharish@umich.edu

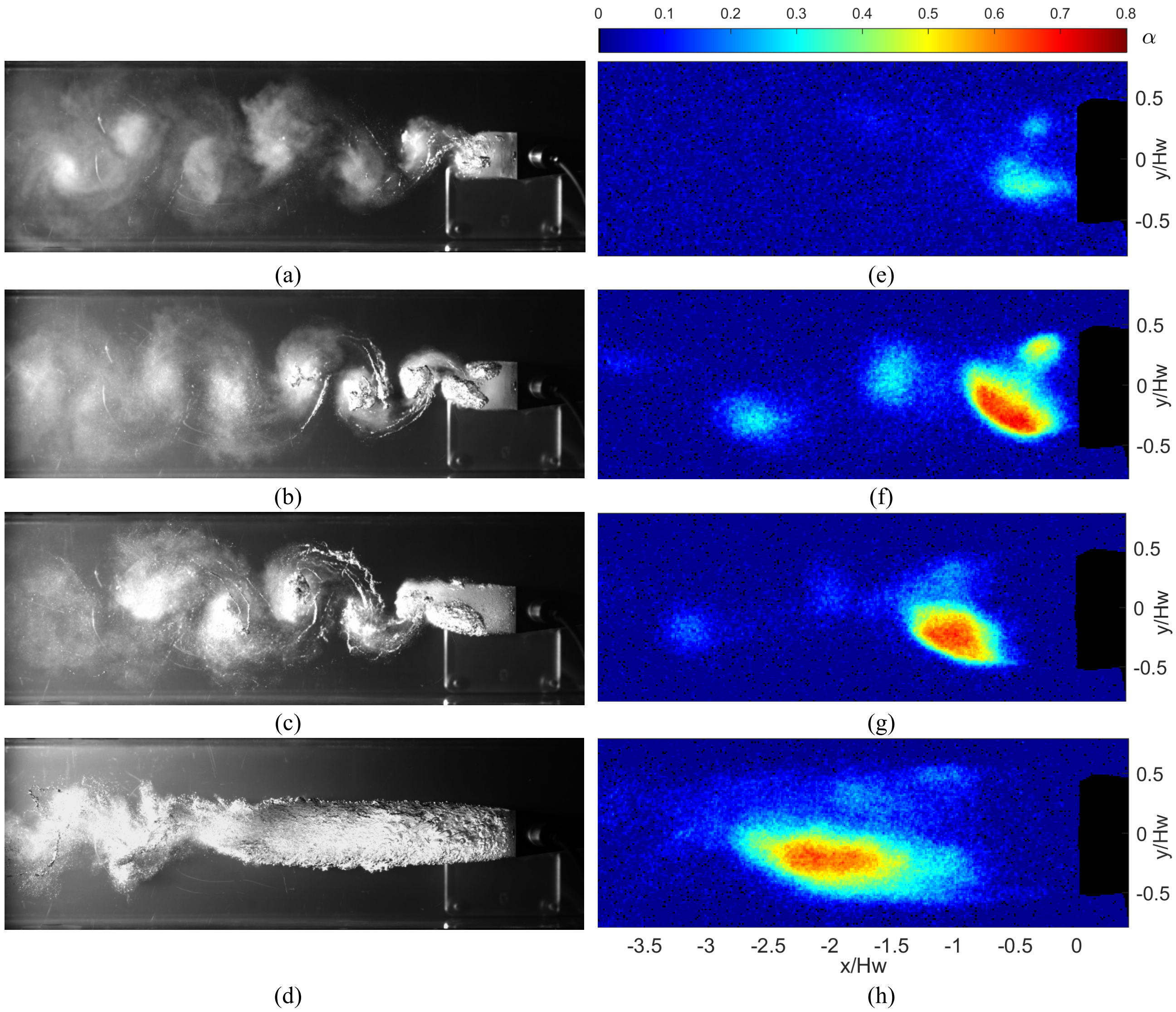

Figure 3: Instantaneous high-speed (a)-(d) and X-ray densitometry spanwise averaged void fraction field (e)-(h) snapshots of cavitation in the wake for different cavitation numbers, σ_o= 2.6 (a) and (e), σ_o= 1.9 (b) and (f), σ_o= 1.6 (c) and (g), and σ_o= 1.25 (d) and (h).

From Figure 3(a)-(d) it can be seen that the extent of cavitation increases with decreasing cavitation number, as expected. Examination of the void fraction flow fields in Figure 3(e)-(h) indicate that the instantaneous void fractions also increase in size, suggesting the presence of more vapor. In regions with such void fractions, the speed of sound of the mixture will drop significantly. The void fraction values α can be used to calculate the values for the speed of sound c and Mach number M using Equation (3), obtained from [7], and (4) respectively.

$$c = \sqrt{\frac{1}{\alpha(1-\alpha)}\frac{\left(k(p-p_v)\right)}{\rho_L}} \tag{3}$$

$$M = \frac{U_0}{c(1-\lambda)} \tag{4}$$

With the liquid density ρ_L, the polytrophic constant $k = 1.3$, the local static pressure p, the vapor pressure p_v and the blockage of the wedge in the test section $\lambda = 1/4$. In the wake region, the speed of sound c can be estimated with

*Corresponding Author, Harish Ganesh: gharish@umich.edu

Equation (3) in the wake region using the average static pressure at the base of the wedge p_b, at point (c) in Figure 1, as approximation for the local static pressure p. The Mach number M can then be estimated using Equation (4). Using this procedure, Figure 4(a)-(d) shows the instantaneous Mach number field, corresponding to the void fraction fields in Figure 3 (e)-(h). Hot spots, colors yellow to red in Figure 4, indicate $M > 1$ and thus the presence of supersonic flow.

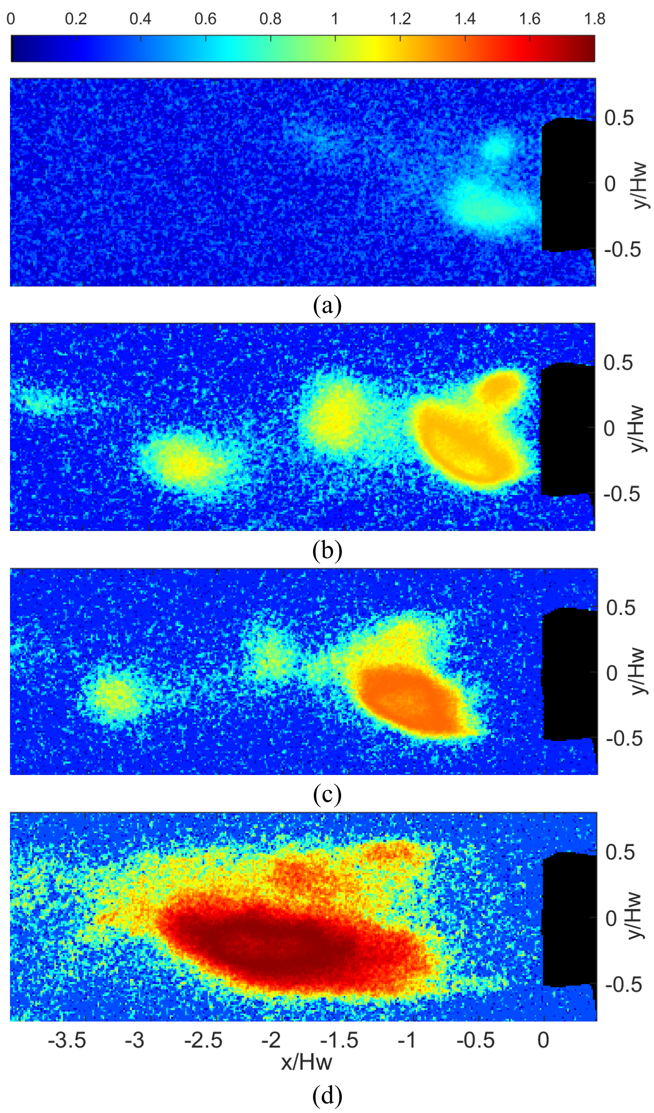

Figure 4: Instantaneous Mach number fields in the wake at cavitation numbers, σ_o= 2.6 (a), σ_o= 1.9 (b), σ_o= 1.6 (c) and σ_o= 1.25 (d).

The maximum Mach number that occurred within the time series was calculated. Figure 5 shows the Strouhal number based on base pressure measurements and the maximum Mach number in the flow field within time as function of inlet cavitation number σ_o. The Strouhal number increase occurs close to the point at which the average Mach number exceeds unity, suggesting the importance of compressibility effects in the observed change in the wake dynamics.

*Corresponding Author, Harish Ganesh: gharish@umich.edu

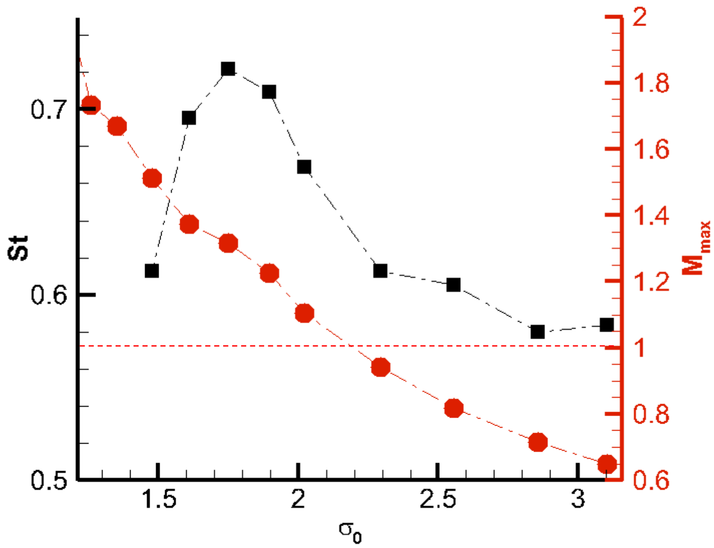

Figure 5: Strouhal number St (black) and Mach number M (red) as function of inlet cavitation number σ_o.

Acknowledgements

This work was funded by the Office of Naval Research under grant N00014-14- 1-0292, Dr. Ki-Han Kim program manager.

References

[1] Roshko, A. (1955). *On the wake and drag of bluff bodies*. Journal of the Aeronautical Sciences. 22(2), pp. 124-132.
[2] Saffman, P.G., Schatzman, J.C. (1982). *An inviscid model for the vortex-street wake*. Journal of Fluid Mechanics. 122, pp. 467-486.
[3] Gerrard, J.H. (1966). *The mechanics of the formation region of vortices behind bluff bodies*. Journal of Fluid Mechanics. 25(2), pp. 401-413.
[4] Young, J.O., Holl J.W. (1966). *Effects of cavitation on periodic wakes behind symmetric wedges*. Journal of Basic Engineering. 88(1), pp. 163-176.
[5] Ramamurthy, A.S., Bhaskaran, P. (1977). *Constrained Flow Past Cavitating Bluff Bodies*. Journal of Fluids Engineering. 99(4), pp. 717-726.
[6] Belahadji, B., Franc, J.P., Michel, J.M. (1995). *Cavitation in the rotational structures of a turbulent wake*. Journal of Fluid Mechanics. 287, pp. 383-403.
[7] Brennen, C.E. (2013). *Cavitation and bubble dynamics*. Cambridge University Press
[8] Crespo, A., (1969). *Sound and Shock Waves in Liquids Containing Bubbles*. Physics of Fluids. 12(11), pp. 2274-2282.
[9] Ganesh, H., Mäkiharju, S.A., Ceccio, S.L. (2016). *Bubbly shock propagation as a mechanism for sheet-to-cloud transition of partial cavities*. Journal of Fluid Mechanics. 802, pp. 37-78.
[10] Ganesh, H. (2015). *Bubbly Shock Propagation as a Cause of Sheet to Cloud Transition of Partial Cavitation and Stationary Cavitation Bubbles Forming on a Delta Wing Vortex.* Ph.D Thesis, University of Michigan.
[11] Mäkiharju, S.A., Gabillet, C., Paik, B.-G., Chang, N.A., Perlin, M., Ceccio, S.L (2013). *Time resolved two dimensional X-Ray densitometry of a two phase flow downstream of a ventilated cavity*. Experiments in Fluids. 54(7), pp. 1-21.

*Corresponding Author, Harish Ganesh: gharish@umich.edu