International Journal of Multiphase Flow 89 (2017) 207–217

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

journal homepage: www.elsevier.com/locate/ijmulflow

Experimental investigation of cavitating structures in the near wake of a cylinder

Pankaj Kumar, Dhiman Chatterjee*, Shamit Bakshi

Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India

ARTICLE INFO

Article history:
Received 19 February 2016
Revised 12 August 2016
Accepted 24 September 2016
Available online 11 November 2016

Keywords:
Cavitation
High speed images
Shear layer
Formation length

ABSTRACT

An experimental investigation of cavitating structures in the near-wake region of a cylinder is presented. From high-speed imaging of this subcritical flow (Reynolds number of 64,000), it is found that inception of cavities occurs in the shear layer. At the developed cavitation condition, the cavities in the separated zone and the free shear layer merge. A distinct spanwise variation in cavitation activity is observed. The non-dimensionalized correlation length at inception varies from close to a non-cavitating value of about 3.5 to about 1 at developed cavitation. The non-dimensionalized length of formation, characterized by crossover of the free shear layer and the wake axis, increases from 1 to 1.8 as the cavitation number is reduced from 85% to 50% of the inception value. A frequency analysis of the cavity dynamics indicates that although the vortex shedding frequency is dominant in the shear layer, there are peaks corresponding to other frequencies in other flow regions. The presence of a sharp peak at 125 Hz, corresponding to a Strouhal number of 0.2, along with a range of frequencies, is also verified independently through measurement of fluctuating pressure at the cylinder surface.

1. Introduction

Non-cavitating flow past a circular cylinder has been the subject of extensive research, since this simple geometry exhibits interesting fluid phenomena and also has wide engineering applications. This flow is classified as subcritical, critical or supercritical, depending on the value of the Reynolds number *Re* (Roshko, 1961; Schewe, 1983; Zdravkovich, 1997), with each flow regime exhibiting distinctive features, such as the location of the transition to turbulence (in the wake, shear layer or boundary layer) and different characteristic frequencies of pressure and velocity fluctuations. A review of the literature reveals that most investigations have been carried out at low *Re* and have been directed at understanding two-dimensional vortex shedding as well as the origin and growth of three-dimensional disturbances, which can be important even for nominally two-dimensional cylinders (Roshko, 1993; Williamson, 1996). The transition in the wake takes place at much lower *Re*. Distinct irregularities in velocity fluctuations becomes visible as *Re* exceeds 300 (Roshko, 1954), which Roshko (1954) characterized as the irregular regime. Bloor (1964) observed the first transition eddies at $Re = 1300$ and found the frequency of the transition eddies to scale as $Re^{0.5}$. Wei and Smith (1986) noted that the formation of 'secondary vortices' was linked with these high-frequency fluctuations and their results showed an $Re^{0.77}$ dependence. As transition proceeds to the shear layer, the coefficient of base suction pressure ($-C_{p_b}$) increases, the Reynolds stress level increases and the Strouhal number gradually decreases (Norberg, 1994). With further increase in *Re* in the upper subcritical regime ($2 \times 10^4 < Re < 2 \times 10^5$), the flow features change. There have been fewer studies of this regime, which is briefly described in the next paragraph.

One important characteristic of the wake is the eddy-formation region. This region has been defined differently by different researchers: as the region behind the cylinder up to the minimum of the measured C_p distribution along the wake axis (Linke, 1931), as the region where low-frequency oscillations disappear (Bloor, 1964), as the location at which the free shear layer crosses the wake axis (Bloor and Gerrard, 1966) and as the location of maximum fluctuations u'_{max} in the wake (Griffin and Votaw, 1972). The formation length (L_f) is the distance, along the flow direction, of the eddy-formation region from the cylinder centre. This formation length (L_f), when non-dimensionalized with the cylinder diameter (d), decreases with increasing *Re* in the range $Re = 10^3 - 2 \times 10^5$ and is typically less than 2 above $Re = 10\,000$. The aspect ratio L/D of the cylinder, besides the *Re* of the flow, also influences this value. This shortening of L_f, coupled with a widening of the shear layer at higher *Re*, was first observed by Gerrard (1966). Unal and Rockwell (1988) used a flow visualization technique to reveal the

* Corresponding author. Fax: +9144 22574652.
E-mail address: dhiman@iitm.ac.in (D. Chatterjee).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.09.025

decrease in L_f. Further increase in *Re* does not lead to any significant shortening of L_f. The overall organization of the flow regimes behind a cylinder in the subcritical regime was nicely shown in an experiment by Maekawa and Mizuno (1967), who used hot-wire signals to detect the free shear layer and the near-wake characteristics at $Re = 65 \times 10^3$. It was found that the signals detected in the near wake are random low-frequency velocity fluctuations, while those from the free shear layer exhibit the vortex-shedding frequency. In the region downstream of the formation region along the axis, there are two components to the signal, which signifies alternating crossing of flows from the two sides of the wake. This feature is probed further in the present work in the context of cavitating flow.

The flow is inherently and highly three-dimensional, but, as indicated by Szepessy and Bearman (1992), for very small L/D values, nominally 'two-dimensional' conditions can be assumed. The correlation length, i.e. the length within which the pressure signals are highly correlated (with correlation coefficient ≥ 0.5) along the spanwise direction, was found to be 2.5 times the cylinder diameter for $Re \simeq 71 \times 10^3$ (Szepessy and Bearman, 1992) and 3.5 times the cylinder diameter for $Re \simeq 43 \times 10^3$ (Szepessy, 1994). In the present work, the L/D of the cylinder is similar to that in Szepessy and Bearman (1992), which helps to reveal the influence of the extent of cavitation activity on the correlation length.

In comparison with non-cavitating flow, there has been relatively less research on cavitating flow past a circular cylinder. Furthermore, most investigations to date have examined the critical and supercritical flow regimes. A survey of the literature on cavitating flow past a circular cylinder shows that the major thrust of research has been on determining variations in overall cavity geometry (length and width) and drag coefficient as functions of cavitation number. For example, in one of the earliest pieces of work in this area, Shalnev (1965) obtained the cavity length and width and the drag coefficient as functions of the blockage factor in a constrained test section. The significance of the blockage factor was also discussed by Ramamurthy and Bhaskaran (1977) and Rao and Chandrasekhara (1976). The effects of cavitation number on cavity length and width as well as on vortex-shedding frequency were studied by Varga and Sebestyen (1966) for supercritical flow. Rao and Chandrasekhara (1976), on the basis of high-speed movies, noted that there were considerable longitudinal oscillations downstream of the cavity. This finding highlights the importance of characterizing local cavity oscillations in order to understand the interaction of vortices with the cavity. In a related study of local dynamics, Fry (1984) determined the cavitation noise spectrum at different downstream locations in the wake for different cavitation numbers. His results indicate that the peak noise was observed when the cavity length was twice the cylinder diameter. Matsudaira et al. (1992) measured the dynamic pressure due to bubble collapse at several locations in the wake of a cylinder for an *Re* range of 4.5×10^5–6×10^5. In the supercritical flow regime, they found that the frequency of peaks due to impulsive pressure was high at $x/d \simeq 1.3$ in the separation region, while in the vortex-formation region ($2.1 < x/d < 2.9$), peaks were fewer and were mixed with background turbulent fluctuations. They further found that, with a decrease in cavitation number, the cavity length determined from pressure contour maps increased and extended downstream. Investigation of the local cavity dynamics using high-speed imaging forms an important part of the present work.

It is clear from the literature cited above that there has been a few investigations of cavitating flow past a cylinder in the upper subcritical flow region ($20,000 < Re < 200,000$). Studies of non-cavitating flow in this regime have led to interesting observations such as the organization of flow regimes (Maekawa and Mizuno, 1967), the phase drift and the associated three-dimensionality beyond a certain spanwise distance (Szepessy, 1994; Szepessy and Bearman, 1992). Hence the pertinent question that needs to be addressed is the way in which these observations may be modified as we move gradually from non-cavitating through weakly cavitating to a highly cavitating regime at the same value of *Re*. Furthermore, most work, even in the critical or supercritical regime, has been related to measurements of cylinder surface pressure and drag, overall cavity structure, and cavitation-induced noise, and has not dealt with cavity dynamics. Following Fry (1984), we suggest that although cavity length and cavity-shedding frequency have already been measured behind cavitating circular cylinders, these cannot explain the location of the peak noise value. Hence, in this work, we attempt to gain further insight by presenting results that relate the dynamics of cavitating structures and the frequency of fluctuation of cavities to the cavitation number. In Section 2, the experimental facility is described. This is followed by a description of the image processing in Section 3 and the results are then discussed in Section 4. Our conclusions are given in Section 5.

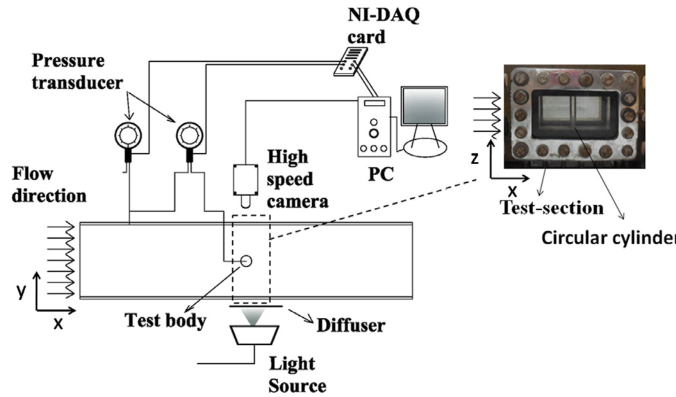

Fig. 1. Schematic plan view of the test section with instrument. The inset shows the front view of the cylinder inside the test section. Also shown is the (x, y, z) axis system used in this paper. The origin is at the centre of the cylinder and is aligned with the lower edge of the test-section window.

2. Experimental facility and methodology

The cavitation test rig used in the present study is described in detail by Kumar et al. (2014) and in this section we describe only the major aspects. The test section is 65 mm × 65 mm in cross-section and 300 mm in length. A honeycomb and settling chamber, together with a contraction nozzle, are used to reduce the turbulence level and make the flow uniform. Velocity measurements show that, except near the endwalls, the velocity is uniform and within 1.8% of the centreline velocity (Kumar, 2012). This ensures a nominally two-dimensional flow field. Independent pressure and velocity control are achieved through the use of a vacuum pump and a circulating water pump, respectively. The test-section pressure can be varied between 0.1 and 1 bar, while the test-section velocity ranges between 4 and 15 m/s. However, since *Re* affects the wake characteristics, in the work reported here, we used a constant test-section velocity of 6.4 m/s. The test body was a circular cylinder made of brass with a diameter of 10 mm and a surface roughness $R_a = 0.6\ \mu m$. Thus *Re* based on cylinder diameter was fixed at 6.4×10^4. The cylinder spanned from end to end in the test section, giving an aspect ratio of 6.5. The test-section static pressure and the cylinder wall pressure were measured using Honeywell smart pressure sensors (Fig. 1). The cylinder surface pressure data for non-cavitating case were compared with that available in literature and was found to be in good agreement (Kumar et al., 2016). The dynamic pressure on the cylinder wall was measured using a PCB miniature pressure transducer (model 112A22)