J. Wind Eng. Ind. Aerodyn. 135 (2014) 46–56

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Effects of free-stream turbulence and Reynolds number on the separated shear layer from a circular cylinder

Imed Khabbouchi [a,b], Hachimi Fellouah [c,*], Mohsen Ferchichi [a], Mohamed Sadok Guellouz [b]

[a] Department of Mechanical and Aerospace Engineering, Royal Military College of Canada, Kingston, Ont., Canada
[b] LESTE, Ecole Nationale d'Ingénieurs de Monastir, University of Monastir, Monastir 5000, Tunisia
[c] Department of Mechanical Engineering, Université de Sherbrooke, Sherbrooke, Que., Canada

ARTICLE INFO

Article history:
Received 24 February 2014
Received in revised form
8 September 2014
Accepted 6 October 2014

Keywords:
Cylinder flow
Shear layer frequency
von Kármán vortex frequency
Free stream turbulence

ABSTRACT

In this experimental investigation, hotwire measurements were used to study the development of a separating shear layer in the near wake of a circular cylinder. The main purpose was to investigate the effects of the free stream turbulence intensity, *Ti*, on the separating shear layer. The measurements were performed over a range of *Re*, based on the cylinder diameter and mean free-stream velocity, between 4.5×10^3 and 4.7×10^4, and free stream turbulence intensities of 0.25%, 2.2%, 3.4% and 6.2%.

Mean and turbulent velocities in the separating shear layer plotted in self-similar coordinates showed that the shear layer evolved downstream approximately as a plane mixing layer when $Ti \le 2.2\%$, while for high *Ti* ($Ti \ge 3.4\%$) a departure from similarity was observed for downstream locations $x/D \ge 1.1$. The shear layer transition point moved closer to the cylinder and the longitudinal distance at which the separating shear layer can no longer be approximated by a mixing layer decreased as *Ti* increased. Power spectra measurements showed peaks related to the shear layer frequency, f_{sl}, and its harmonics. In agreement with the self-similarity study, these peaks became broader and indiscernible as *Ti* was increased, and at the highest *Ti* of 6.2%, peaks related to f_{sl} and its harmonics could no longer be seen in the power spectra at all *Re* investigated in this work.

The present measurements suggested that the appearance of peaks at f_{sl} and its harmonics in the power spectra is well tied to the extent by which the separating shear layer behaves as a mixing layer. The free stream turbulence seemed to amplify the turbulence content of the separating shear layer thus promoting and accelerating the breakdown of the shear layer vortices. It also decreased the large vortex formation length which limited the downstream development region of the separating shear layer hence preventing the latter from developing in a manner similar to that of a mixing layer. The overall quantitative effect of the free stream turbulence on the development of the separating shear layer was measured by the change in the exponent of the functional relationship relating f_{sl} and *Re* (i.e. $f_{sh}/f_v \sim Re^n$ where f_v is the von Kármán vortex shedding frequency) with *Ti*. The present measurements have shown that the exponent *n* increased with increasing *Ti* namely, *n* was found to increase from 0.56 to 0.65 as *Ti* increased from 0.25% to 3.4%. Finally, a model has been developed showing that an increase in the free-stream turbulence intensity has, qualitatively, similar effects on the separated shear layer as an increase in *Re*.

1. Introduction

The flow around a circular cylinder in cross-flow arrangement has been greatly investigated in the literature because of its simple geometry and the rich flow phenomena associated with it (Williamson, 1996; Tsutsui and Igarashi, 2002). It is well known that in such a flow, the boundary layers forming on both sides of the cylinder surface separate to form alternately separating shear layers which evolve downstream and roll up to form the well-known von Kármán vortices that are shed in the cylinder wake. The regime of the separated shear layer, whether laminar, transitional or turbulent, dictates the nature of vortex shedding and the nature of the flow dynamics of the cylinder wake (Bimbato et al., 2013).

The evolution of the separated shear layer from laminar to turbulent extends over a Reynolds number based on cylinder diameter, ranging from $Re = 350$ to $Re = 2 \times 10^5$ which was labeled as “the transitional shear layer flow” (Zdravkovich, 1997). Within this range, the latter author further identified three sub ranges; lower ($350 < Re < 1-2 \times 10^3$), intermediate ($1-2 \times 10^3 < Re < 2-4 \times 10^4$)

* Corresponding author.
E-mail address: Hachimi.Fellouah@USherbrooke.ca (H. Fellouah).

http://dx.doi.org/10.1016/j.jweia.2014.10.005
0167-6105/

and upper ($2-4\times10^4<Re<2\times10^5$) ranges. Instabilities in the separating shear layer (also known as Kelvin–Helmholtz instabilities) have been identified in a number of experimental studies as high frequency patches in the velocity signals at *Re* as low as 350 (Gerrard, 1978). Much of the focus of the studies on the separating shear layer from a cylinder was on the instability frequency, f_{sl}, and its relationship to *Re*. Among the earliest investigations on the subject is that of Bloor (1964). She observed the instability at *Re* of 1.3×10^3 and suggested that $(f_{sl}/f_v)\propto Re^n$ where f_v is the von Kármán vortex shedding frequency and f_{sl} the shear layer frequency for *Re* up to 1.9×10^4. Above Re of 1.9×10^4, transition waves could no more be identified due to full breakdown of the shear layer vortices to turbulence. Using dimensional argument, in which the boundary layer thickness at the separation point and the free stream velocity are used, Bloor (1964) arrived at a value of 0.5 for the exponent *n*.

Since the work done by Bloor (1964), many experimental investigations were conducted to confirm the dependence of the ratio f_{sl}/f_v on *Re*. There has been an unequivocal support to the power law functional form except in Mi et al. (2011) who proposed a third order polynomial dependence of f_{sl}/f_v on *Re* in their experimental study of the thermal wake from a passively heated circular cylinder. However, the exponent $n=0.5$ (Bloor, 1964) has not found the same unanimous support and, only a few experimental studies confirmed this value namely, Kourta et al. (1987), and Mihailovic and Corke (1997). Kourta et al. (1987) and Rajagopalan and Antonia (2005) estimated the *n* value based on Gerrard (1978) data and found a value of 0.5 as well. Values of the exponent *n* ranging from 0.5 to about 0.87 were reported in a number of experimental studies. Wei and Smith (1986) obtained a value of $n=0.87$ from flow visualization and $n=0.77$ from hot-wire measurements. The latter authors plotted Bloor's data and showed that the exponent was 0.73. They argued that the shear layer momentum thickness in the linear growth region should be the length scale for transition of the shear layer rather than the boundary layer thickness at the separation point proposed by Bloor (1964). Prasad and Williamson (1997) performed least square analysis on their data along with those published in other experimental studies and arrived at a value of 0.67 for the exponent *n*. They devised a scaling model for the shear layer frequency based on the momentum thickness of the shear layer at the transition point and the mean streamwise velocity at the separation point. This model led to $n=0.69$. This value is close to the estimates of Rajagopalan and Antonia (2005) ($n=0.62$ when they fitted their data only, and $n=0.65$ when they included data of other studies) for *Re* in the range 10^3–10^5. Thompson and Hourigan (2005) fitted the data of Norberg (1987) and Prasad and Williamson (1997) over two discrete ranges of *Re*, namely $1.5\times10^3\le Re\le5\times10^3$ and $10^4\le Re\le5\times10^4$ and obtained $n=0.57$ in the lower interval and $n=0.52$ for the upper interval. These authors presented a model based on the boundary layer thickness at separation that supported their *n* values. Khor et al. (2011) fitted existing data from various references on shear layer frequency and showed that the exponent, *n*, was always larger than 0.5 and it can vary between 0.53 and 0.87. The authors argued that previous experiments may have been subjected to external effects, and they used an alternative technique based on power spectral density estimates that would eliminate the influence of any perturbation of the free stream, to determine the exponents *n* and found an exponent that matched the data of Prasad and Williamson (1997) and Norberg (1987) suggesting the data of the latter two experiments should be a benchmark for n estimates.

The separating shear layer evolution has been generally compared to that of a mixing layer due to the formation of small scale vortices similar to those found in a mixing layer (Prasad and Williamson, 1997; Roshko, 1993; Williamson, 1996 and others). Obviously, the evolution of the shear layer downstream is fundamentally different from a mixing layer due to the formation of Karman vortices in the wake of the cylinder. This comparison also extends to vortex pairing that takes place in a shear layer as seen in a mixing layer. In earlier studies, a form of forcing on the wake was required to observe vortex pairing for example, Unal and Rockwell (1988) observed shear layer vortex pairing when they used a splitter plate to prevent the formation of von Kármán vortices. Chyu and Rockwell (1996) and Mihailovic and Corke (1997) observed shear layer vortex paring when they forced the shear layer at f_{sl} and its sub-harmonics. Rajagopalan and Antonia (2005) observed peaks in the power spectra of the streamwise velocity component, *u*, at the sub-harmonic $f_{sl}/2$ that was considered as a strong evidence of the pairing between the shear layer vortices; Ahmed and Wagner (2003) observed sub-harmonic peaks at $f_{sl}/2$ for *Re* up to 4.5×10^4; Perret (2009) experimentally investigated the near wake development of the shear layer of a circular cylinder using PIV at Re of 12.5×10^3 and reported that the spatial vortex separation distance varied downstream from the origin of the shear layer suggesting the shear layer, qualitatively, resembled a turbulent mixing layer; Mi et al. (2011) observed a decrease in the separated shear layer frequency, f_{sl}, in the spectra of the temperature fluctuations in the near wake of a slightly heated cylinder as the shear layer developed downstream. This shift in f_{sl} was interpreted as consequence of pairing between the vortices of the wake shear layer.

The effect of *Re* on the development of the separating shear layer at low free stream turbulence intensity, *Ti*, has been undertaken in a number of papers since the work of Bloor (1964). Previous studies related to the influence of free stream turbulence for example Norberg (1986), Gerrard (1965, 1966), Arie et al. (1981) and Khabbouchi et al. (2010) focused essentially on the wake flow in particular on the vortex formation length, L_f. But, the effect of *Ti* on the separating shear layer and on the shear layer frequency has not been addressed in the literature except in Norberg (1987). Zdravkovich (1997) suggested that the separating shear layer may be very sensitive to the perturbations in the incoming flow, for instance the increase of the free stream turbulence intensity leads to “faster” transition to turbulence of the separated shear layer. On the other hand, Norberg (1987) reported that increasing *Ti* from 0.1% to 1.4% had no discernible effect on the development of the shear layer or on the value of the power law exponent *n*. Unfortunately, as the free stream turbulence values used in Norberg (1987) were low to draw broad conclusions, the effect of *Ti* on the separated shear layer is yet to be fully understood. The general consensus is that the free-stream turbulence would undoubtedly affect the development of the shear layer, it is therefore the objective of the present work to quantify this effect. In the present work, a single hot-wire anemometry was employed to investigate the effect of *Ti* intensities ranging between 0.25% and 6.2%, on the separated shear layer in the near wake of circular cylinder for $4.5\times10^3\le Re\le4.5\times10^4$ first, to quantitatively suggest corrections to the exponent value n to account for *Ti* effects and secondly, to determine the limiting *Ti* for which the shear layer vortices no longer exist and for which the functional relationship ceases to apply. In relation to the latter point, the assumption that the shear layer could evolve in the same way as a mixing layer before it rolls-up into von Kármán vortices, and the occurrence and the development of the shear layer instability, then the pairing between the shear layer vortices, will be examined for varying free stream turbulence and *Re*. While this work may seem fundamental in nature, it actually can be of important practical significance, for example in the past few decades a new line of research related to active flow control emerged (see Gad-el-Hak, 2000 for a comprehensive review on the subject). Active flow control of boundary layers requires accurate knowledge of instability frequencies including Kelvin-Helmholtz instability frequencies, therefore studying these instabilities in the context of their interactions with free stream turbulence would be of great value for successful active flow control strategies.