Experimental Thermal and Fluid Science 90 (2018) 212–219

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Modification of the modal characteristics of a square cylinder wake obstructed by a multi-scale array of obstacles

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ARTICLE INFO

Keywords:
Proper Orthogonal Decomposition
Wake
Confined square cylinder
Multi cylinder array

ABSTRACT

An experimental study was undertaken to investigate the changes on the turbulent wake of a confined square cylinder, caused by the introduction of three multi-scale arrays of obstacles. The arrays were introduced upstream, downstream and around the square cylinder, using the same obstacles in all cases. The results show that changes on the confinement caused by the introduced elements produce an increase of the shedding frequencies and on the energy contribution of the leading modes obtained by a Proper Orthogonal Decomposition, POD. The results also show that different modifications of the wake properties are observed if the obstacles are located either upstream or downstream of the square cylinder. When the obstacles are mainly located upstream it is possible to observe an increase in the peak magnitude of Turbulent Kinetic Energy in the wake. These changes are associated to a redistribution of the energy contribution of the POD modes. For larger regions obstructed upstream, the leading modes reduce their energy contribution, while the higher order modes increase it. It is also observed that an increased reattachment length can be obtained by locating most of the array downstream of the square cylinder. All these observations are discussed in terms of the expected interactions of flow structures. From the results it is possible to conclude that the general spatial patterns of the POD modes are not changed importantly by the introduction of the arrangements compared with the unconfined case and previously reported confined cases with lower Reynolds number. The most relevant changes for the confined obstructed case analysed here can be found in the shedding frequency and the modal energy distribution.

1. Introduction

The turbulent wake produced by a single square cylinder is a well known fluid mechanics problem, but it is still of much interest today, especially in the built environment due to the direct applicability to high-rise buildings [15,16]. For a square cylinder, unlike a circular one, the separation points of the flow are fixed, meaning the properties of the wake in a turbulent flow are relatively insensitive to changes of the Reynolds number [31,10], $Re_D = U_\infty D/\mu$, where U_∞ is the incoming flow velocity, D is the side length of the square cylinder, and ν is the kinematic viscosity of the fluid. However there are a number other parameters which modify the wake properties. Significant effects can be caused by changes of the incoming turbulent intensities, u'/U. A higher u'/U induces a rise in the base pressure, leading to a reduction in the mean drag [23]. In addition, an increase of the base pressure can cause a protracted position of the reattachment point of the separated shear layers [5]. Another effect of an increased u'/U is an expansion of the thickness of the separated shear layers [23] and a decrease of the vortex shedding frequency [2,12,4]. This evidence suggest that for a constant Re_D, the lower the drag, the furthest downstream the position of the reattachment point, thus the larger the recirculation bubble.

Another important parameter controlling the properties of the wake is the confinement or blockage ratio, $BR = D/B$, where B is the width of the channel. Richter and Naudascher [34], Mukhopadhyay et al. [28], Davis et al. [8] concluded that the confinement of a cylinder can increase the drag and the vortex shedding frequency. Based on the reduction of drag, this could imply a decreased size of the recirculation bubble.

In the context of the flow around two twin square cylinders separated in the spanwise flow direction, Kolar et al. [20], More et al. [27] found that positioning two square cylinders close to each other could have an important effect on the properties of the individuals and combined wake. They found the cylinders are separated by spacing $S_D \lesssim 1.1D$, they acted as a single bluff body, but with a reduced drag. At a greater spacing $1.1D \lesssim S_D \lesssim 2.2D$ the individual wakes were bi-modal, and directed towards one of the cylinders. Finally when the spacing was $S_D \gtrsim 2.2D$, in the near field, the wake of both cylinders acted independently. Analogously, but in the context of the flow around square

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http://dx.doi.org/10.1016/j.expthermflusci.2017.09.019
Received 29 March 2017; Received in revised form 10 August 2017; Accepted 22 September 2017
Available online 22 September 2017

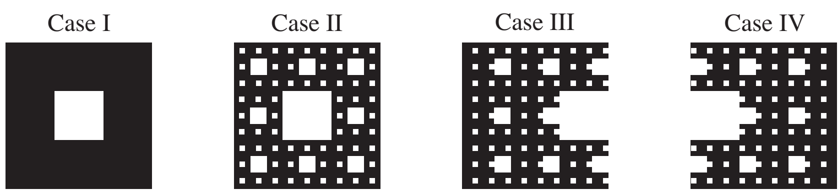

Fig. 1. Plan view of experimental cases.

Table 1
PIV experimental parameters.

Seeding	Type	Polyamide powder
	Specific gravity	1.016 gcm^{-1}
	Diameter	100 µm
Light sheet	Laser type	Double pulsed Nd:YAG
	Maximum energy	200 mJ
	Wave length	532 nm
	Thickness	2 mm
Camera	Type	Imager MX 4 M
	Resolution	2048 × 2048 px
	Pixel size	0.21 mm
	Lens focal length	24 mm
Imaging	Viewing area	440 mm × 440 mm
PIV Analysis	Interrogation area	Final integration window size 16 px × 16 px
	Overlap	75%
	Approximate resolution	3.5 mm × 3.5 mm × 3.5 mm

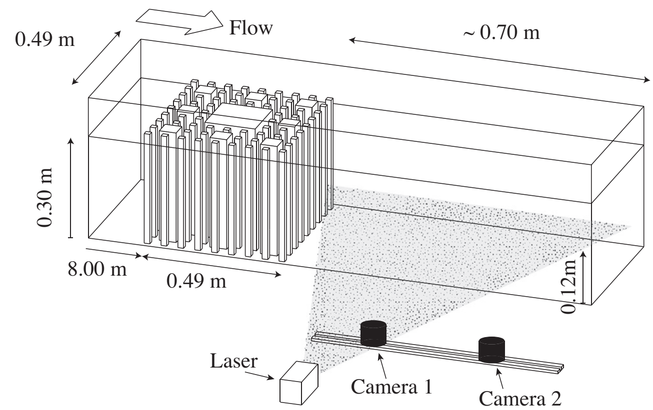

Fig. 2. View of the measurement section and experimental setup (not to scale).

cylinders in a longitudinal tandem arrangement, Liu and Chen [25], Zhou and Yiu [41] observed that if two cylinders were placed in a streamwise tandem, the separation affects the properties of the furthest downstream wake. At $S_D \lesssim 2.0D$ the cylinders acted as a single body and the frequency of vortex shedding spectrum was broadband around the peak frequency. Increasing the spacing, $2.0D \lesssim S_D \lesssim 3.0D$, a recirculation region was created between the two cylinders. This region intermittently injects vorticity, also changing the properties of the wake [24]. Finally $S_D \gtrsim 8.0D$ the two cylinder acted independently, however the vorticity of the structures shed downstream was reduced by the influence of the wake developed upstream. This means that, in an array, the distribution of elements should produce different resulting flow structures which should be a function of the gaps between the obstacles, and also the length scale of the cylinders involved. As a matter of fact previous work on the interaction between cylinders arranged in a stream- or spanwise orientation has shown that the wake generated by the largest cylinder dominates the flow, and that the characteristics of the resulting flow field are a function of the ratio between the cylinder sizes and the spacing between them [7,40,22,11,18]. Furthermore, even though it is possible to find in the literature studies characterising the arrays of square cylinders and circular cylinders of uniform scales [1,42,29,37], to the best of these authors knowledge there has been no reported research on the flow interactions produced by multi-scale arrays.

In the present work an experimental study is undertaken to quantify the modifications of the wake generated by a confined square cylinder, when it is surrounded by smaller multi-scale square elements. The aim of this work is two fold: First to investigate how surrounding a confined square cylinder with smaller elements can modify the wake, and second to investigate how different arrangements of these elements can change its properties. As previous research has shown that real world distributions of obstacles can be well represented by fractal geometry [3], this work reproduces a self-similar situation deriving the arrangement of the smaller elements from a Sierpinski Carpet [36]. To elucidate the flow regions of high spatial coherence, in the near wake of the obstacles, a Proper Orthogonal Decomposition (POD) is used. As there is no modal decomposition available in the literature for the flow around a confined square cylinder for a high Re_D, this research also expands the observations obtained for a confined flow at low Re_D [33].

1.1. Proper orthogonal decomposition

A POD extracts spatially orthogonal modes ordering them by their contribution to the total variance. Due to the fact that in a wake the large-scale turbulent structures contribute importantly to the turbulent kinetic energy, it is assumed here that POD can be reliably used to analyse these structures. POD was independently derived by a number of individuals and consequently takes a variety of names in different fields such as Karhunen-Loève Decomposition, Singular Value Decomposition (SVD) and Principal Components Analysis (PCA) [21,26,19,32,30]. In this work POD is performed on the measured velocity fields. A set of $t = 1,2,...,T$ temporally ordered velocity fields, $\mathbf{V}(x,y;t)$ are considered, each of size $X \times Y$. The method requires the construction of an $N \times T$ matrix $\mathbf{W}$ from T columns $\mathbf{w}(t)$ of length $N = XY$, each one corresponding to a column-vector version of a transformed snapshot $\mathbf{V}(x,y;t)$. A POD can be obtained by:

$$\mathbf{W} \equiv \Phi \mathbf{S} \mathbf{C}^* \tag{1}$$

where $\mathbf{S}$ is a matrix of size $R \times R$, (R are the number of modes of the decomposition, and $(\cdot)^*$ represents a conjugate transpose matrix operation). The $\lambda = \text{diag}(\mathbf{S})^2/(N-1)$ is the vector containing the contribution to the total variance of each R. The elements in λ are ordered in descending rank order, i.e. ($\lambda_1 \geqslant \lambda_2 \geqslant ...\lambda_R \geqslant 0$). In practical terms the matrix Φ of size $N \times R$ contains the spatial structure of each of the modes and the matrix $\mathbf{C}$ of size $R \times R$ contains the coefficients representing the time evolution of the modal structures as shown by [6,14].

2. Experimental setup

Four experimental cases are examined in this work. The first one corresponds to the benchmark and will be termed case I. This case is a single confined square cylinder, with a length scale of a third of the channel width. Case II, corresponds to a deterministic Sierpinski carpet [36], with three iterations, where iteration I is of the same dimension and position as the cylinder used in case I. In this work iteration I represents the cylinder of interest while iteration II & III correspond to the length scales of the elements surrounding iteration I. Following the