Journal of Fluids and Structures 65 (2016) 138–154

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Vortex shedding and structural loading characteristics of finned cylinders

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ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
26 April 2016
Accepted 29 April 2016
Available online 6 June 2016

Keywords:
Vortex shedding
Finned cylinders
Bluff body aerodynamics
Structural loading
Effective diameter

ABSTRACT

The flow development and structural loading characteristics of cylinders with equispaced circular fins were studied experimentally for a range of fin pitches with constant fin thickness and diameter. The experiments were performed for a range of Reynolds numbers, corresponding to the shear layer transition turbulent shedding regime. Time-resolved planar Particle Image Velocimetry and direct mean drag and fluctuating lift measurements are employed to relate spatio-temporal flow development to structural loading. The results show that wake development is dominated by vortex shedding for all the cases examined. However, the fin pitch ratio has a significant effect on vortex shedding characteristics. The addition of fins increases the characteristic spatial and temporal scales of the main spanwise vortices forming in the near wake. As the fin pitch is decreased to a critical value, the coalescence of boundary layers between the adjacent fins leads to a significant enlargement of the vortex formation region. A modified vortex shedding frequency scaling is proposed, based on the effective diameter, that incorporates a Reynolds number dependence associated with the lateral boundary layers developing on the fin surfaces. A detailed analysis is conducted to characterize the strength of the vortical structures forming in the near wake. The addition of the fins is shown to produce a stabilizing effect on the roll-up process, associated with a reduction in the generation of smaller scale, three-dimensional structures. The results demonstrate that the addition of fins leads to an increase in the mean drag, which is driven primarily by the associated increase in skin friction. The significant effect of the fin pitch ratio on the characteristics of the shed vortices as well as the size of the vortex formation region is shown to lead to substantial variations in the fluctuating loads.

1. Introduction

Both structural vibrations and acoustic resonance have been linked to vortex shedding for isolated cylinders or cylinder arrays (Eid and Ziada, 2011; Nemoto et al., 1997; Weaver and Fitzpatrick, 1988; Chen, 1968). Since heat exchangers often utilize finned cylindrical geometries in these configurations (Mair et al., 1975; Ziada et al., 2005; Eid and Ziada, 2011; Ryu et al., 2003; Hamakawa et al., 2008, 2010; Khashehchi et al., 2014; Nakamura and Igarashi, 2008; Nemoto et al., 1997; Wang and Chi, 2000a, 2000b; Rich, 1973), an understanding of the salient characteristics of vortex shedding and the related structural dynamics is vital to engineering design. In practice, there is a wide variety of geometries of finned tube heat

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http://dx.doi.org/10.1016/j.jfluidstructs.2016.04.008
0889-9746/

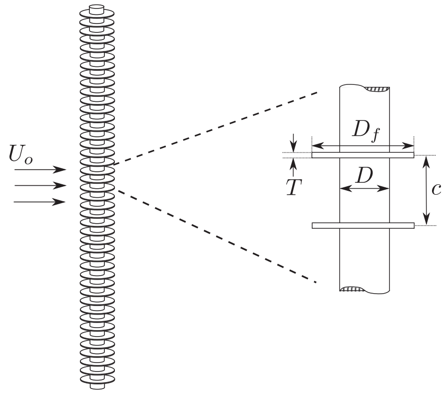

Fig. 1. Isolated finned cylinder geometry consisting of a base cylinder of diameter D with circular fins having thickness T and diameter D_f, separated by pitch c.

exchangers (e.g., number of cylinders, fin shape, and orientation). The current study focuses on the flow development and structural loading of a single, isolated cylinder with circular, parallel fins in cross-flow. Fig. 1 defines the geometry of interest, which is characterized by the pitch ratio c/D, diameter ratio D_f/D, and thickness ratio T/D.

The effect of a singular fin on the flow development of an otherwise uniform cylinder may be deduced from the investigations of low aspect ratio, dual step cylinders, where a single fin is affixed at the mid-span of a uniform cylinder. Experimental and numerical studies of this flow, in both laminar (Williamson, 1992; McClure et al., 2015) and turbulent shedding regimes (Morton and Yarusevych, 2012, 2014), show that the fin introduces a perturbation to the wake vortices which induces vortex dislocations downstream. The resulting disruption of the spanwise correlation and local elongation of the vortex formation region lead to the overall decrease in fluctuating lift (McClure et al., 2015). The elongation of the vortex formation region in the wake of the fin is linked to secondary flows induced by the development of lateral and streamwise vorticity at the fin surface and the resulting increase in base pressure leads to simultaneous reductions in the mean drag (McClure et al., 2015).

Previous studies on isolated cylinders with parallel or helically serrated fins have detected periodic vortex shedding in the wake (Mair et al., 1975; Ziada et al., 2005; Eid and Ziada, 2011; Ryu et al., 2003; Hamakawa et al., 2008, 2010; Khashehchi et al., 2014; Nakamura and Igarashi, 2008). Moreover, the addition of the fins can increase the spanwise coherence of the wake vortices (Ziada et al., 2005; Eid and Ziada, 2011; Hamakawa et al., 2008, 2010). The analysis of wake velocity spectra presented by Ziada et al. (2005) indicates strengthening of velocity fluctuations associated with the shedding frequency and its harmonics. However, despite increased shedding coherence and velocity fluctuations at the shedding frequency, Hamakawa et al. (2008, 2010) suggest that increased acoustic noise generation and fluctuating lift force are not always observed concomitantly. Specifically, for $c/D = 0.8$, the RMS of the fluctuating lift and far-field sound pressures are approximately the same as a bare cylinder of base diameter (Hamakawa et al., 2010), and these parameters increase with decreasing pitch ratio to $c/D = 0.27$. However for low pitch-ratio finned cylinder models, the results of Hamakawa et al. (2008, 2010) and Khashehchi et al. (2014) show a significant elongation of the vortex formation region for $c/D = 0.11–0.16$ and $c/D = 0.14$, respectively, which is linked to a reduction of fluctuating lift and far-field sound pressures for low c/D in Hamakawa et al. (2010). The flow visualization images of Nakamura and Igarashi (2008), which show the spanwise development of the vortices shed from finned cylinders with high fin spacing and thickness, $2.0 \le c/D \le 9.0$ and $0.33 \le T/D \le 4.0$, indicate that vortex shedding occurs in discrete cells, implying that fins disrupt the coherence of vortex shedding across the span.

The results of previous studies suggest that the vortex shedding frequency (f_S) varies with c/D, T/D, and D_f/D (Mair et al., 1975; Hamakawa et al., 2010; Eid and Ziada, 2011), and a number of different length scales (W) have been proposed for the Strouhal number ($St_W = f_S W/U_o$, where U_o is the free-stream velocity). Mair et al. (1975) investigated finned cylinders for $0.06 \le c/D \le 0.8$, $0.0224 \le T/D \le 0.064$, $1.2 \le D_f/D \le 1.4$, and $1.6 \times 10^4 \le Re_D \le 4.6 \times 10^4$. They introduce the definition of the effective diameter D_{eff},

$$D_{eff} = D + \frac{T}{c}(D_f - D) \tag{1}$$

as the characteristic length scale, which nearly collapsed their Strouhal number data to $St_{D_{eff}} \approx 0.19$. The proposed effective diameter definition (Eq. (1)) is based on equating the projected area of the finned cylinder to that of an equivalent uniform cylinder of diameter D_{eff}. To adapt the proposed length scale to cylinders with helically wound fins, Hamakawa et al. (2008, 2010) account for the angular projection of the fins on the equivalent diameter. For helically wound, serrated fins with low c/D ($0.08 \le c/D \le 0.17$), Ryu et al. (2003) suggest the use of the hydraulic diameter D_h,