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Flow-induced loading on and unsteady flow structure in the wake of bluff perforated plates at zero incidence

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HIGHLIGHTS

- Effects of transverse perforations are studied via PIV and direct force measurment.
- Trailing-edge vortex shedding and flow-induced loading frequencies show agreement.
- The vortex shedding frequency decreases as the diameter of perforations increases.
- The largest perforations suppress the velocity fluctuations in the near-wake.
- For smaller perforations, the velocity fluctuations in the near-wake are enhanced.

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ABSTRACT

Flow over rectangular plates positioned at zero incidence can result in high-amplitude forces on the plates. In this study, we apply particle image velocimetry (PIV) and direct force measurements to investigate the effect of transverse perforations on the flow-induced loading on and the flow structure in the near-wake of the plates. We compare plates with different characteristic diameter of the perforations, as well as a reference configuration without perforations, in terms of the spectra of the flow-induced forces, frequencies of the trailing edge vortex shedding and boundary layer profiles at the trailing edge at different planes across the perforation patterns for a range of inflow velocities. The three-dimensionality of the near-wake of the perforated plate is related to the proximity of the individual perforations to the trailing edge of the plate. In the vicinity of the perforations, transverse oscillations of the flow velocity in the wake become suppressed as the diameter of the perforations increases.

1. Introduction

Rectangular plates aligned with the incoming fluid flow are common in various engineering systems. Despite the substantial amount of literature that exists on this topic, some important fluid-dynamic aspects remain unresolved. The reason for this situation is the fact that in many applications the effects of fluid-dynamic loading, vibrations and noise are often considered separately.

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On one hand, the fundamental studies on the fluid–structure interactions (FSI) of stationary, solid plates at zero incidence provided framework for understanding of the sources of the flow-induced excitations. These studies, including those by Parker (1966), Nakamura and Nakashima (1986), Naudascher and Rockwell (1994) and Nakamura et al. (1996) characterized the FSI by the predominant frequencies of the flow and/or structure oscillations f , which is often presented as the Strouhal number $St = fL/U$, where L is the characteristic length and U is the characteristic flow velocity. Many studies to date examined the effects of the Reynolds number (Okajima, 1982), chord-to-thickness ratio of the plate (Nakamura et al., 1991), array configurations (Guillaume and LaRue, 2001; Parker, 1966) and wall confinement (Guillaume and LaRue, 2005; Malavasi and Guadagnini, 2007; Malavasi and Zappa, 2009; Negri et al., 2011; Arslan et al., 2013) on the force coefficients and the Strouhal number. It has been established that the flow structure around bluff rectangular plates can be broadly classified based on the flow separation from the leading edge of the plate and subsequent reattachment, or lack thereof, to the surface of the plate or to the trailing edge. These flow regimes depend on the chord-to-thickness ratio of the plate (Nakamura et al., 1991). In the present case, the long plate configurations were considered, which resulted in the flow reattachment well upstream of the trailing edge.

On the other hand, effects of elasticity and porosity of a semi-infinite plate interacting with a turbulent eddy on radiated acoustic noise were investigated theoretically, using the Weiner–Hopf technique, by Jaworski and Peake (2013), and the related experimental measurements of the fluctuating pressure due to flow over a porous surface with flexible bristles were performed by Clark et al. (2014). Moreover, flow-acoustic resonance received significant attention over the years (Parker, 1966; Parker and Welsh, 1983; Welsh et al., 1984; Howe, 1986, 1997a, b; Oshkai and Velikorodny, 2013; Bossi and Malavasi, 2014) as the dominant mechanism for generating unsteady pressure and velocity pulsations in engineering applications, such as splitter plates in pipelines.

In the present work, we have considered dynamic and kinematics measurements to provide answers to some of the open questions about the effects of transverse perforations on the fluid–structure and the fluid loading on a long rectangular plate at zero incident. The work builds upon the results presented in recent papers (Bossi et al., 2017a, b) where, through force measurements, we describe the dynamic effects of perforation in terms of loading and its frequencies. Here, we complement the previous experiments by coupling the force measurements with flow velocity measurements using PIV to better understand the effects of the perforations on the boundary layer and to relate the local effect of the individual perforations on the frequency and the magnitude of the velocity fluctuations in the near-wake. To do this, we consider an experimental system, in which the vortex shedding frequencies were clearly separated from those of the available acoustic modes. Thus, the unsteady loading on the plate was due to purely hydrodynamic effects. The dynamic and kinematic observations allow us to provide insight into the physical origin of the flow-induced loading on perforated plates. Moreover, we describe the relationship between the staggered perforation patterns and the structure of the resulting wake.

2. Experimental system and techniques

2.1. Flow facility

The experiments were conducted in a flow visualization water channel at the University of Victoria. The flow was conditioned using five fine mesh screens and a polycarbonate honeycomb section with round cells with the diameter of 4 mm. A converging section with a contraction area ratio of 6:1 was located upstream of the test section. This configuration resulted in the inflow velocity U ranging from 0.20 m/s to 0.55 m/s, with the turbulence intensities less than 1%. The test section had a square cross-section of 45 cm $\times$ 45 cm and a length of 250 cm.

The flat plate was positioned parallel to the flow, in the middle of the test section to avoid interference between the wake of the plate and the walls. The plate was cantilevered at the top edge and attached to the frame of the water channel by a support structure that incorporated a load cell for direct force measurements, as shown in Fig. 1. The free end of the plate was located 2.5 mm away from the bottom of the test section to minimize the effects of flow separation from the free edge. In the present study, the end effects were neglected, since the plate did not undergo significant motion, with the exception of a single case, in which the amplitude of the oscillations of the free end did not exceed 1 mm. For all the cases considered herein, the water depth W was equal to 41.5 cm, so that the free-surface level coincided with the edge of the clamp, as shown in Fig. 2.

2.2. Perforated plates

Three plates with transverse perforations were considered, in addition to a reference plate with no perforations, which is referred to as pattern P0. The three perforation patterns had the same staggered arrangement, as shown in Fig. 3, but had different perforation diameters $\delta_h = 9.4$ mm, 12.7 mm, 19.5 mm, referred to as patterns P1, P2 and P3, respectively. The spacing between the perforations was also equal to δ_h, so that all three plates had the same equivalent area ratio, $\beta = (nA_p/At)^{0.5} = 0.4$, where n is the number of perforations, A_p is the area of a single perforation, A_t is the total wetted area of the plate. The thickness of the plates P0, P1 and P2 was $t = 12.5$ mm and P3 had a thickness of $t = 12.3$ mm. All plates had a chord length $C = 292.1$ mm. The plates were made of clear polycarbonate plastic sheet, with the density and the moduli of elasticity and rigidity of $\rho = 1245.6$ kg/m^3, $E = 2.6$ GPa and $G = 2.3$ GPa, respectively. The natural vibrational frequency (f_0) of the plates was measured by conducting damping tests in still water, which yielded natural frequencies of $f_0 = 5.1$ Hz and $f_0 = 7.8$ Hz for the solid and the perforated plates, respectively.