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The effect of a splitter plate on the flow around a finite prism

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ABSTRACT

The effect of a wake-mounted splitter plate on the flow around a surface-mounted finite-height square prism was investigated experimentally in a low-speed wind tunnel. Measurements of the mean drag force and vortex shedding frequency were made at $\mathrm{Re}=7.4\times10^4$ for square prisms of aspect ratios AR=9, 7, 5 and 3. Measurements of the mean wake velocity field were made with a seven-hole pressure probe at $\mathrm{Re}=3.7\times10^4$ for square prisms of AR=9 and 5. The relative thickness of the boundary layer on the ground plane was $\delta/D=1.5$–1.6 (where D is the side length of the prism). The splitter plates were mounted vertically from the ground plane on the wake centreline, with a negligible gap between the leading edge of the plate and rear of the prism. The splitter plate heights were always the same as the heights of prisms, while the splitter plate lengths ranged from $L/D=1$ to 7. Compared to previously published results for an “infinite” square prism, a splitter plate is less effective at drag reduction, but more effective at vortex shedding suppression, when used with a finite-height square prism. Significant reduction in drag was realized only for short prisms (of $\mathrm{AR}\leq5$) when long splitter plates (of $L/D\geq5$) were used. In contrast, a splitter plate of length $L/D=3$ was sufficient to suppress vortex shedding for all aspect ratios tested. Compared to previous results for finite-height circular cylinders, finite-height square prisms typically need longer splitter plates for vortex shedding suppression. The effect of the splitter plate on the mean wake was to narrow the wake width close to the ground plane, stretch and weaken the streamwise vortex structures, and increase the lateral entrainment of ambient fluid towards the wake centreline. The splitter plate has little effect on the mean downwash. Long splitter plates resulted in the formation of additional streamwise vortex structures in the upper part of the wake.

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1. Introduction

Vortex shedding and high aerodynamic drag coefficients associated with flow around bluff bodies have motivated the development of active (requiring external energy input) and passive (no external energy input required) flow control devices to weaken or suppress vortex shedding, thereby alleviating the tendency for flow-induced vibration, and to modify the bluff body wake, thereby reducing the drag coefficient (e.g., Zdravkovich, 1981; Gad-el-Hak, 2000; Choi et al., 2008). The wake-mounted “splitter plate” is one of the simplest passive flow control devices used with bluff bodies, where a thin, rigid, flat, two-dimensional plate is mounted parallel to the flow on the wake centreline. The plate acts as “near-wake stabilizer” (Zdravkovich, 1981) through modifying the near wake vortex formation region (Choi et al., 2008).

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For a two-dimensional or "infinite" circular cylinder, a splitter plate may be effective at simultaneously suppressing vortex shedding and reducing drag (e.g., Apelt et al., 1973; Apelt and West, 1975; Kwon and Choi, 1996; Anderson and Szewczyk, 1997; Dehkordi and Jafari, 2010). Its effectiveness as a passive flow control device depends on the Reynolds number, Re ($=U_\infty D/\nu_\infty$, where U_∞ is the freestream velocity, D is the cylinder diameter, and ν_∞ is the kinematic viscosity), and various geometrical parameters, such as the plate's length, L, thickness, T, and the gap between the rear of the cylinder and the leading edge of the plate, G, relative to the size of the cylinder. In most studies, the plate is rigid, however the performance of flexible, hinged, and undulatory splitter plates have also been investigated (e.g., Wu and Shu, 2011; Wu et al., 2014). Splitter plates have also been used with other two-dimensional bluff bodies, including square and rectangular prisms (e.g., Bearman and Trueman, 1972; Mansingh and Oosthuizen, 1990; Hasan and Budairn, 1994; Park and Higuchi, 1998; Ozono, 1999; Rathakrishnan, 1999; Ali et al., 2011, 2012, 2013). By disrupting the interaction of the separated shear layers emanating from the cylinder or prism, the splitter plate acts to extend the vortex formation region, narrow the wake, and increase the base pressure close to the body (Anderson and Szewczyk, 1997). These effects result in a reduction of the vortex shedding frequency (represented in dimensionless form as the Strouhal number, $\mathrm{St}=fD/U_\infty$, where f is the vortex shedding frequency) and a decrease in drag force (represented by the dimensionless drag coefficient, $C_D=2F_D/(\rho_\infty U_\infty^2 DH)$, where F_D is the mean drag force, ρ_∞ is the fluid density, and H is the span or height of the cylinder or prism). The splitter plate may also influence a bluff body's tendency towards flow-induced vibration (e.g., Hu and Koterayama, 1994; Okajima et al., 2004; Stappenbelt, 2010; Assi and Bearman, 2015), the wake vortex dynamics of cylinders undergoing forced vibration (e.g., Hu et al., 2014), and flow-induced sound (e.g., Ali et al., 2010; Porteous et al., 2014). A more extensive review of the literature pertaining to bluff bodies with splitter plates can be found in Igbalajobi et al. (2013).

Many engineering applications involve the flow around surface-mounted finite-height bluff bodies (of width D and height H), where the flow field is strongly three-dimensional due to the flow over the free end and around the junction between the body and the ground plane. Complex vortex dynamics occur in the near wake as separated flow from the free end interacts with vortex shedding from the sides of the body (e.g., Sumner et al., 2004; Wang et al., 2006, 2012, 2014; Wang and Zhou, 2009; Bourgeois et al., 2011; Krajnović, 2011; Rostamy et al., 2012a,b; Sattari et al., 2012; Hosseini et al., 2013; Saha, 2013; Uffinger et al., 2013; Porteous et al., 2014; Saeedi et al., 2014; Vinuesa et al., 2015). The flow is strongly influenced by the body's aspect ratio, $\mathrm{AR}=H/D$, and the relative thickness of the boundary layer on the ground plane, δ/H or δ/D (e.g., El Hassan et al., 2015).

The effectiveness of a wake-mounted splitter plate has not been extensively studied for this class of three-dimensional flows. Okajima et al. (2004) showed how a splitter plate in the wake of a cantilevered circular cylinder influences its in-line oscillation behavior. For a cylinder of $\mathrm{AR}=10$, when adding a long splitter plate of length $L/D=15$, the amplitude response for in-line free vibration changed from two excitation regions to a single excitation region with increased amplitude. A recent study of the flow around a surface-mounted finite-height circular cylinder (Igbalajobi et al., 2013) showed that the performance of a splitter plate is dependent on the cylinder $\mathrm{AR}=H/D$ in addition to the standard geometrical parameters pertaining to the splitter plate, such as the relative length of the splitter plate, L/D, its relative thickness, T/D, and the relative gap between the trailing edge of the body and leading edge of the plate, G/D.

In the present study, the flow around a surface-mounted finite-height square prism (of width D and height H) is investigated experimentally using a low-speed wind tunnel, where the prism is partially immersed in a flat-plate boundary layer, and a splitter plate is mounted on the wake centreline (Fig. 1). Of interest in the present study are the combined effects of plate length (varying L/D) and aspect ratio (AR) on vortex shedding (St), the mean drag coefficient (C_D), and, unique to the present study, the wake mean velocity field (streamwise component u, cross-stream component v, wall-normal or vertical component w, oriented in the x, y, z directions, respectively) and mean streamwise vorticity (ω_x) field.

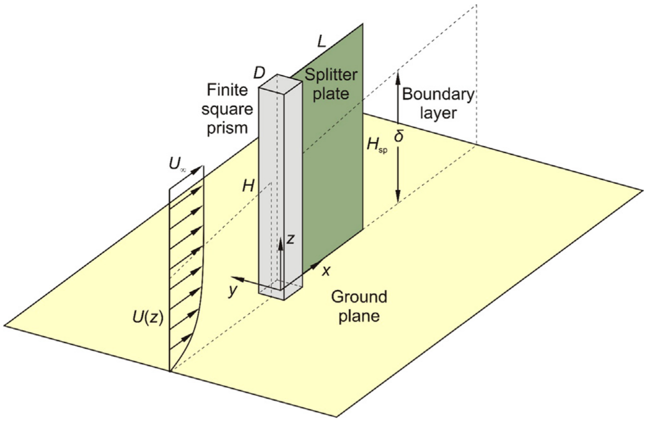

Fig. 1. Schematic of the flow around a surface-mounted finite-height square prism (of width D and height H) with a wake-mounted splitter plate (of length L and height H_{sp}), partially immersed in a flat-plate boundary layer (with thickness δ and mean streamwise velocity profile $U(z)$). Note the origin of the x (streamwise direction), y (cross-stream direction), z (wall-normal or vertical direction) coordinate system at the junction of the prism and the ground plane. The splitter plate is located on the wake centreline with no gap between the rear of the prism and the leading edge of the plate.

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