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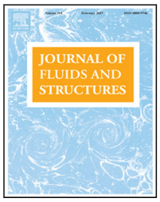

Effect of the angle of attack on the transient lift during the interaction of a vortex with a flat plate. Potential theory and experimental results

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ABSTRACT

The dynamics of a two-dimensional vortex interacting with a flat plate at different angles of attack α is analysed using potential flow theory based on conformal mapping varying the nondimensional separation distance h/c of the upstream incoming vortex to the plate (c is the chord length of the plate) and the vortex intensity Γ_l. Transient lift forces measured in a wind tunnel are also compared with the potential theory results for a given Γ_l and several values of h/c and α. For the Reynolds number considered in the experiments (about 25 000) it is found that the potential theory predicts reasonably well the transient fluctuation in the lift force provided that the separation distance is not too close to the critical one h^*/c at which the vortex trajectory given by the potential theory bifurcates. We find that the separation distance generating the highest induced lift is around this critical value h^*/c, which, according to the potential theory, is displaced about $-2.3(1-0.07|\Gamma_l|^{1/2})\alpha$ in relation to the zero angle of attack for the same Γ_l. Potential theory also predicts that the maximum peak of the lift fluctuation depends on α only through the relative separation $|h-h^*|/c$, and that the maximum lift is substantially larger when a clockwise vortex passes below the plate than when it passes above the plate, for the same vortex intensity Γ_l and relative separation distance. The opposite happens for a counter-clockwise vortex. This asymmetry in the maximum lift fluctuation increases slightly with $|\Gamma_l|$, approaching a ratio of almost two for large $|\Gamma_l|$.

1. Introduction

The aerodynamic interaction between a vortex and a foil has been widely modelled from two-dimensional potential flow theory based on conformal transformation to gain physical insight of some technological problems related to the blade–vortex interaction such as the enhancing of lift and propulsion (Saffman and Sheffield, 1977; Poling et al., 1989; Streitlien et al., 1996; Pitt and Babinsky, 2013) or the generation of sound (Howe, 2003). Parallel blade–vortex interaction is a complex phenomena relevant for the understanding of the aerodynamic performance in general, and the unsteady loading, noise generation and vibration in particular, of a great variety of machines and engineering configurations such as helicopters, turbines, propellers, tandem wings, energy conversion systems, among others (see, e.g., Wilder and Telionis, 1998; Rockwell, 1998; Rival et al., 2010; Peng and Gregory, 2015).

Here we focus on the problem of lift enhancement on a foil (a flat plate for simplicity) generated by a passing travelling vortex drifted by the stream. Particularly, we analyse the peak intensity of the lift fluctuation in terms of the nondimensional

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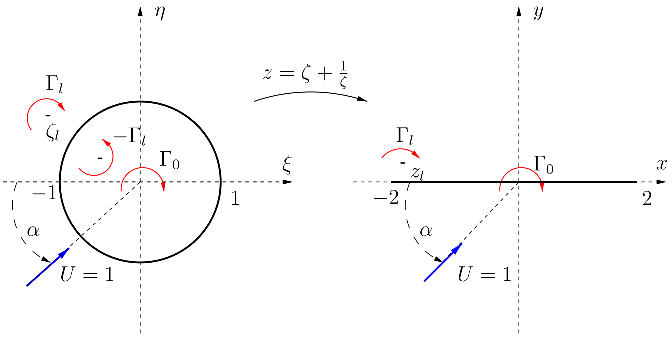

Fig. 1. Joukowski transformation between the ζ-plane (left) and the z-plane (right). $U = 1$ in the nondimensional variables used in the text.

vortex intensity Γ_l and the nondimensional upstream separation distance h/c of its centre when the angle of attack α between the plate and the incoming current is varied (c is the chord length of the plate; see Section 2.1 for the exact definitions of these quantities). As demonstrated in several experimental studies, and most particularly in the recent work by Peng and Gregory (2017), significant differences in pressure and loading fluctuations may be caused by small changes in vortex trajectory, which we show here to depend strongly on the angle of attack of the target foil. Although we do not consider viscous effects nor the possible cutting of the vortex by the plate, which are both very relevant for small separation distances (e.g., Ziada and Rockwell, 1982; Rival et al., 2010; Peng and Gregory, 2017), by comparing with experimental measurements in a wind tunnel we show that the most relevant features of the lift fluctuation may be captured by a two-dimensional potential theory, provided that the separation distance is not very close to the critical distance h^*/c for which the vortex trajectory bifurcates from the upper to the lower side of the foil, or vice versa. We shall see that potential theory predicts a maximum of the lift peak at this bifurcation value of h/c, for which we report its dependence on α and Γ_l. Once $|h-h^*|/c$ is not too small, the lift pulse predicted by the potential theory agrees reasonably well with the experimental results, allowing for a practical characterization of the peak of the lift fluctuation as a function of the nondimensional parameters. These results may be useful for explaining some features of the vortex–blade interaction found in experimental measurements and in numerical simulations, specially for a better understanding of the unsteady lift enhancement in a couple of flapping wings in a tandem configuration (e.g., Thomas et al., 2004; Ortega-Casanova and Fernandez-Feria, 2016), a problem which has motivated the present work.

2. Potential theory formulation

2.1. Vortex trajectory

As a simple model for the interaction of the travelling vortex with the flat plate we use the two-dimensional (2D) potential flow theory through the complex potential $f(z)$, where $z = x+iy$ is the complex plane of the 2D flow. We use nondimensional variables, with lengths scaled with a quarter of the chord of the plate, $c/4$, velocities with the free stream speed U, so that time is scaled with $c/(4U)$. The plate is located in the x-axis and the free stream current forms an angle α with that axis. We use conformal mapping from the flow on a cylinder of radius unity (that is why we use $c/4$ as the scaling length) and centre at the origin of the complex plane $\zeta = \xi + i\eta$ into the complex plane $z = x + iy$ of the plate through Joukowski's transformation (see Fig. 1)

$$z = \zeta + \frac{1}{\zeta}. \tag{1}$$

We shall consider the effect of a potential vortex of nondimensional circulation Γ_l (scaled with $Uc/4$) centred at $z_l = x_l+iy_l$ (Fig. 1) at a given instant of time t. Thus, on using the circle theorem (Milne-Thomson, 1996), the nondimensional complex potential on the ζ-plane at an arbitrary instant t can be written as

$$w(\zeta) = \zeta e^{-i\alpha} + \frac{e^{i\alpha}}{\zeta} + \frac{i\Gamma_l}{2\pi}\ln\frac{(\zeta-\zeta_l)\zeta}{1-\zeta\zeta_l^*}, \tag{2}$$

where the ζ_l is the centre of the vortex in the ζ-plane, with $|\zeta_l| \geq 1$, and the asterisk superscript denotes a complex conjugate (note that, contrary to the usual notation, we choose $\Gamma_l > 0$ for a vortex rotating clockwise). There are two image vortices, one of strength Γ_l at the origin and another one of strength $-\Gamma_l$ at the point $\zeta = 1/\zeta_l^*$. To this potential (2) we shall add a bound circulation centred at the origin to account for the circulation around the plate generated by the trailing-edge vortices through Kelvin circulation theorem and Kutta–Joukowski condition at the trailing-edge (see below). This bound circulation,