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A coupled model for flexible rotors

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Rotors are present in various applications ranging from wind turbines to helicopters and propellers. The rotors are often made of flexible materials which implies that their geometry varies when the operational conditions change. The intrinsic difficulty of rotor modeling lies in the strong coupling between the flow generated by the rotor and the rotor itself that can deform under the action of the flow. In this talk, we propose a model where the strong coupling between the flexible rotor and its wake is taken into account. We are particularly interested in configurations where the general momentum theory [1] cannot be used (for example, for helicopters in descent flight).

The wake is described by a generalized Joukowski model. We assume that it is formed for each blade of a bound vortex on the blade and two free vortices of opposite circulation, same core size a , emitted at the radial locations R_i and R_e (see figure 1). These parameters are computed from the circulation profile $\Gamma(r)$ obtained on the blade by applying locally at each radial location r the 2D Kutta-Joukowski formula

$$\Gamma(r) = \frac{1}{2} C_L(\alpha(r)) U(r) c(r), \quad (1)$$

where $c(r)$ is the local chord, $C_L(\alpha(r))$ the lift coefficient of the chosen blade profile, $\alpha(r)$ the angle of attack of the flow, and $U(r)$ the norm of the velocity. The vortex circulation Γ_m is the maximum value of $\Gamma(r)$, and the emission locations R_i and R_e are the radial distances of the centroid of $\partial_r \Gamma$ on both sides of the maximum (see figure 1).

The wake is computed using a free-vortex method [2]. Each vortex is discretized in small vortex segments for which the induced velocity can be explicitly obtained from the Biot-Savart law [3]. We are considering helical wake structures that are stationary in the rotor frame. This frame is rotating at the rotor angular velocity Ω_R and translating at a velocity V_∞ corresponding to an external axial wind. For a prescribed rotor of N blades, the wake structure is characterized by five non-dimensional parameters

$$\lambda = \frac{\Omega_R R_b}{V_\infty}, \quad \eta = \frac{\Gamma_m}{\Omega_R R_b^2}, \quad R_e^* = \frac{R_e}{R_b}, \quad R_i^* = \frac{R_i}{R_b}, \quad \varepsilon = \frac{a}{R_b}, \quad (2)$$

where R_b is the blade length.

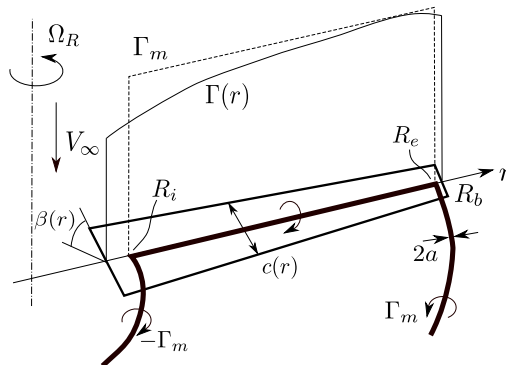


Figure 1: Generalized Joukowski model. The parameters (Γ_m , R_i and R_e) of the model are computed from the circulation profile $\Gamma(r)$ on the blade as explained in the text.

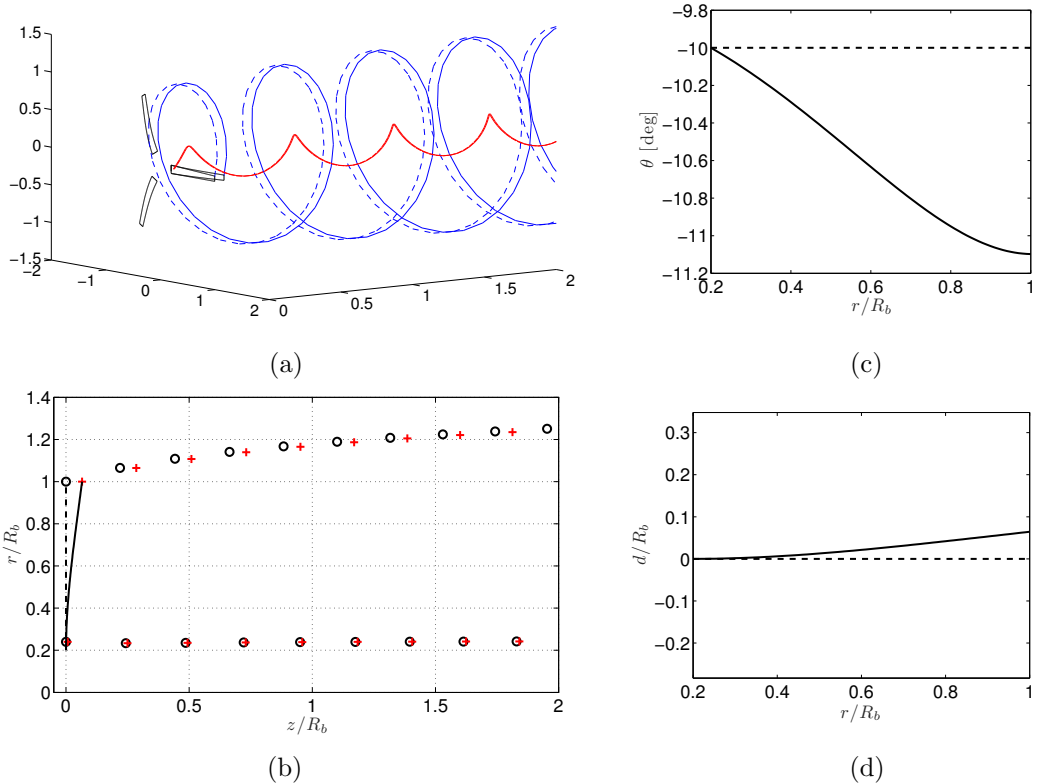


Figure 2: Illustration of the effect of blade flexibility on the wake structure and blade geometry. Dashed lines: wake and blades for the rigid case. solid lines: wake and blades for the flexible case. The undeformed blade is as illustrated in figure 1: it is a flat plate with a constant twist angle $\theta = -10^\circ$ and a linearly decreasing chord from $c(r = 0.2R_b) = 0.1R_b$ to $c(r = R_b) = 0.07R_b$. The wake parameters of the rigid rotor are $\lambda = 6.67$, $\eta = 0.0218$, $R_e^* = 0.99$, $R_i^* = 0.24$, $\varepsilon = 0.01$. The flexible blades have the characteristics: $E^* = 10^6$, $\nu = 0.5$. (a) 3D geometry of the rotor and of the wake. Only the deformation and the vortices emitted from a single blade are shown. (b) Locations of the vortices in the plane including a blade and the rotor axis. (c) Twist angle of the blade. (d) Bending of the blade.

The aerodynamic forces exerted on the blade are calculated using the blade element theory [2]. From the wake solution are deduced the angle of attack and the velocity amplitude at each radial location on the blade in the rotor plane. Then, the loads are deduced from the lift and drag coefficients C_L and C_D of the considered blade profile. The blade deformation is obtained using a ribbon model for the blade [4]. This 1D model is a beam model that allows to describe the nonlinear coupling between bending and torsion. In the simplest cases, we assume uniform elastic properties of the blades which are characterized by a Poisson ratio ν and a non-dimensional Young modulus $E^* = E/\rho_b\Omega^2 R_b^2$, where ρ_b is the density of the blade.

A typical example with a simple blade geometry is shown in figure 2. In these figures are shown both the case of a rigid rotor and of a flexible rotor for the same operational conditions (same V_∞ and same Ω_R). We do see the effect of blade flexibility. The blades do bend and twist in the presence of the flow. Moreover, this bending and twisting also affect the wake. When the blade bends, the vortices move streamwise and inward, which impacts the expansion of the wake. The vortex circulation is also slightly modified as η changes from 0.0218 to 0.0216 when the blades bend.

Other examples will be presented and compared to available data. The question of the stability will also be addressed. Both flow instabilities and instabilities associated with the blade flexibility will be discussed.

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