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Rotor Generated Vortices: Structure and Stability

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ABSTRACT

The structure of the vortical wake generated by a rotor is analyzed in the framework of a Joukowski model using a vortex filament approach. The different operational regimes of an helicopter in vertical flight are considered. The stability of the vortical wake is also analysed by looking at the spatio-temporal evolution of linear perturbations introduced in the rotor plane and compared to available theoretical results. A global instability is discovered in rapid descent flight when the wake is in the Vortex Ring State (VRS).

We study the structure and stability of the vortical wake generated by a two-blade Joukowski rotor of radius R_b , rotating at angular velocity Ω , in an axial wind of velocity V_∞ . In this rotor model, each blade is assumed to emit a free tip vortex of circulation Γ and a hub vortex of opposite circulation centered on the rotor axis. Considering a fixed vortex core size a and neglecting viscosity, the vortex dynamics is computed by a free vortex method [1] using the Biot-Savart law. The problem is defined by three non-dimensionalized parameters: the tip speed ratio $\lambda = R_b\Omega/V_\infty$, the vortex strength $\eta = \Gamma/\Omega R_b^2$ and the vortex thickness $\varepsilon = a/R_b$. For a small and fixed vortex thickness $\varepsilon = 0.01$, we first show that stationary solutions (in the rotating frame) can be obtained for almost all values of λ and η except in a small parameter region indicated in gray in figure 1.

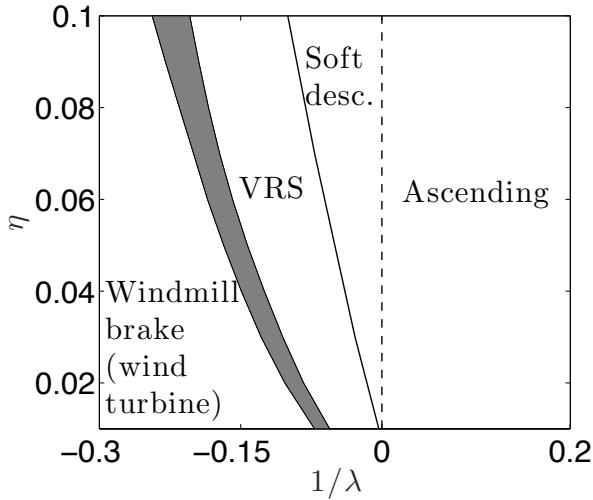


Fig. 1 Helicopter flight regimes in the $(1/\lambda, \eta)$ plane for a two-blade rotor for $\varepsilon = 0.01$.

In this figure are indicated the different flight regimes of a helicopter associated with each solution. Of particular interest is the so-called Vortex Ring State (VRS) occurring during rapid descent that cannot be described by the general momentum theory [2]. In this regime, vortices are present on both sides of the rotor plane as illustrated in figure 2.

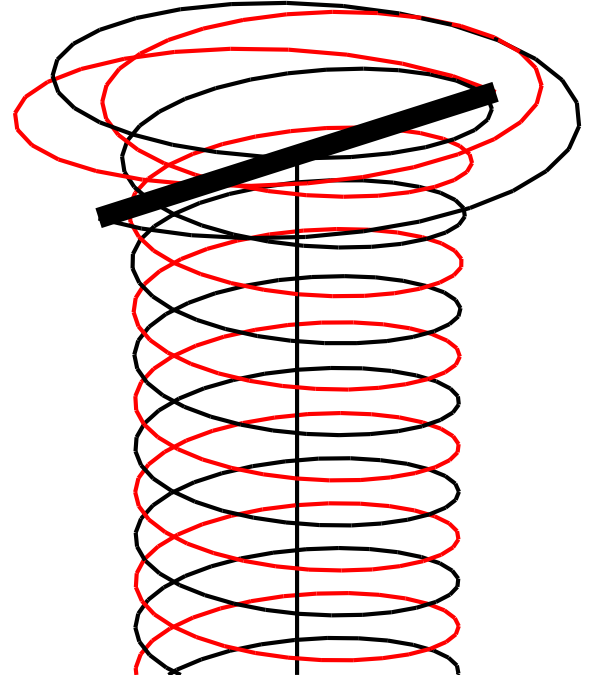


Fig. 2 Vortex-Ring-State structure for $\lambda = -15$, $\eta = 0.04$ and $\varepsilon = 0.01$.

The stability of the various solutions is also addressed by analyzing the linear response to a Dirac perturbation applied at the rotor tip. For most flight regimes, the flow is found to be convectively unstable: the perturbation grows but is advected away from the rotor plane. The property of the wave packet far away has been compared to the theoretical predictions for uniform helices [3] and a very good agreement has been observed [see figure 3].

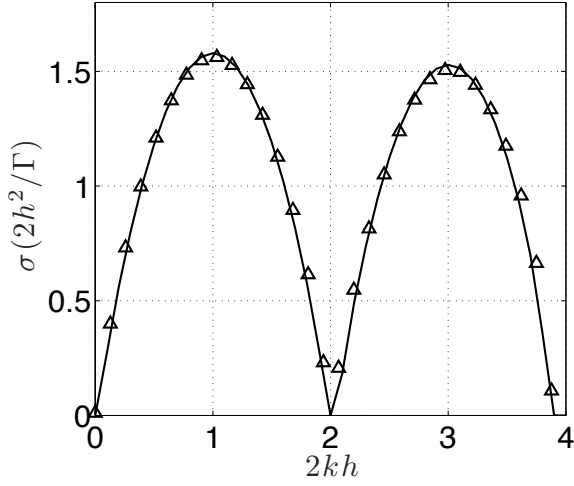


Fig. 3 Growth rate versus wavenumber normalized by the far-wake helix pitch h for $\lambda = \infty$, $\eta = 0.02$ and $\varepsilon = 0.01$. Symbols: numerics. Line: Gupta & Loewy theory [3].

In the VRS regime, a different behavior is observed: the perturbation continues to grow in the neighborhood of the rotor and a well-defined global mode emerges everywhere. The rotor wake has become globally unstable.

References

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- [3] B. P. Gupta, R. G. Loewy, *AIAA J.* 12 (1974), 1381-1387.