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Numerical Analysis of Large-scale Offshore Vertical-axis Wind Turbine

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ABSTRACT

The new design of the Wind Energy Marine Unit (WEMU), a wind power plant with a large-scale, vertical-axis, water-supported rotor with rotary blades, is analyzed. The aerodynamic coefficients of the chosen blade airfoil are derived by a 3-D Navier-Stokes numerical simulation. The angles of the blades' rotation are calculated preliminarily and corrected after the simulation of flow through the turbine. Velocity maps and plots of blade torque are given. It is shown that the power coefficient comes close to the Betz limit. The WEMU's rated power capacity can be over 10 MW.

NOMENCLATURE

A: turbine cross-section area $= 2RH$
b: blade width (chord)
C_D: drag coefficient of blade
C_L: lift coefficient of blade
C_P: power coefficient of turbine
H: blade height (span)
k: turbulence kinetic energy
M_i: torque of blade i about turbine axis, $i = 1, \ldots, n$
M_W: total aerodynamic torque of turbine
n: number of blades
N_W: total aerodynamic power of turbine
p: pressure
R: radius of turbine
S: blade area $= bH$
u_∞: uniform wind velocity far from turbine
(u_1, u_2, u_3): mean absolute velocity
(u'_1, u'_2, u'_3): fluctuating component of absolute velocity
$\bar{u}_i$: ensemble-mean velocity of incident flow on blade i
(U_1, U_2, U_3): mean relative velocity
(U'_1, U'_2, U'_3): fluctuating component of relative velocity
v: linear speed of blades $= \omega R$
(x_1, x_2, x_3): position in stationary coordinate system
(X_1, X_2, X_3): position in coordinate system fixed to rotor
α_i: angle of attack of blade i
β_i: angle of blade i rotation
γ_i: angle between vectors $\bar{u}_i$ and u_∞
δ_{ij}: Kronecker delta
ε: dissipation rate of turbulence energy
θ: azimuth angle ($\theta = 0$ where blade moves upwind)
λ: nondimensional blade speed $= v/u_\infty$
μ: viscosity
μ_t: turbulent viscosity
ρ: air density
φ_i: angle between u_∞ and relative velocity in vicinity of blade i
ω: rotor angular velocity

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KEY WORDS: Wind, power, turbine, offshore, energy, blade, CFD.

INTRODUCTION

The following trends can be found in wind energy development:

• A growth of wind unit power capacity is accompanied by a gradual decrease of wind energy cost. However, now the cost decrease seems to have stopped. This can be considered a consequence of growing technological problems. Construction of wind turbines in the traditional Dutch design is already not rational for 10 MW of unit power (Klinger et al., 2002).

• There is a tendency to place wind farms offshore where the wind is strong and steady.

• Designers try to create turbines working within as wide a wind range as possible. However, if a light breeze blows or wind speed is above rated speed, the traditional propeller and Darrieus turbines do not work well.

• Environmental requirements are growing. Designers should make special arrangements to protect birds from fast rotating blades. Blade tip speed is limited by infrasonic emission.

• Because people already are not satisfied with the view of dozens of wind turbines monotonously rotating on their territory, designers are forced to attempt to partly hide the turbines or to build them into the landscape. Ernst et al. (2002) note that all these attempts are undoubtedly doomed to disappointment in principle.

Hence, the gradual transition to powerful offshore wind power plants has strong economical and ecological validity. At the same time, all present offshore turbines and those under construction have several essential shortcomings inherited from Dutch design, as, for instance, limited unit power capacity, infrasound emission and killing birds.

The Wind Energy Marine Unit (WEMU) has been suggested as an alternative design to the common cross-flow and propeller turbines (Cheboxarov and Cheboxarov, 2002; Cheboxarov et al., 2002a, b). The WEMU does not have the shortcomings mentioned above, but at the same time it closely follows modern trends of wind energy.

A large-scale, relatively narrow, ring pontoon with vertical axis (Fig. 1) is used as the rotor of the WEMU turbine. The pontoon rotates around a stationary base (tower) located on piles or a small island. There is a set of blades along the pontoon perimeter. For maximum turbine torque, the angular position of each blade is adjusted according to the local wind direction. The energy of the slow turbine's hub rotation is converted to the rapid rotation of a generator shaft by means of a hydraulic drive with impulse high head turbines.