Model-based flow control for improved wind turbine efficiency

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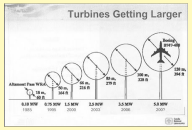
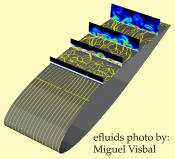
Motivation

- **Challenges:**
  - large size of modern turbines
  - complex flow dynamics (turbulence, wakes, . . .)

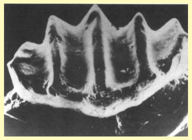




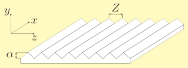
efluids photo by: Miguel Visbal

- **Objectives:**
  - turbulence suppression
  - skin-friction drag reduction
- **Ongoing research:**
  - control-oriented modeling of flow around turbines
  - model-based passive and active turbulent flow control

passive:

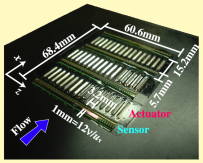


shark denticle



riblet-mounted blade

active:



hot-film sensors and wall-deformation actuators

(Yoshino *et al.* 2008)

Controlling turbulent flow

Navier-Stokes equations

$$\mathbf{u}_t \;=\; -(\mathbf{u}\cdot\nabla)\mathbf{u} \,-\, \nabla p \,+\, (1/R_\tau)\,\Delta\mathbf{u},$$

$$0 \;=\; \nabla\cdot\mathbf{u},$$

$\mathbf{u}$ - velocity, p - pressure, $R_\tau = \dfrac{\text{inertial forces}}{\text{viscous forces}}$

Turbulent flow model

1) Turbulent viscosity hypothesis

2) k-ϵ model $\quad \nu_T \;=\; c\,R_\tau^2\,\dfrac{k^2}{\epsilon}$

k - turbulent kinetic energy

ϵ - rate of dissipation of k

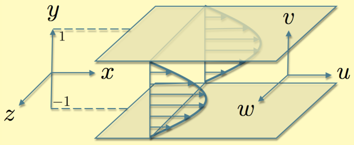
ν_T - turbulent viscosity

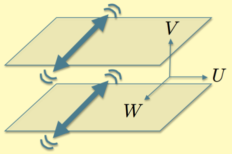
Challenge:

Determine the effect of control on ν_T

Drag reduction by transverse oscillations

- **Pressure driven channel flow**

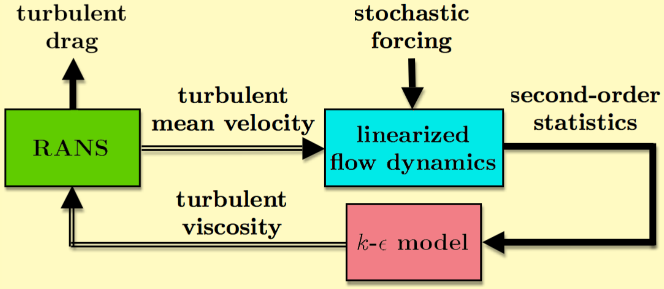




$$W(y = \pm 1, t) \;=\; 2\,\alpha \sin\,(\omega_t\, t)$$

α - oscillation amplitude, ω_t - oscillation frequency

Stochastically forced linearized equations



turbulent drag

stochastic forcing

RANS

turbulent mean velocity

linearized flow dynamics

second-order statistics

turbulent viscosity

k-ϵ model

Perturbation analysis

$$k \;=\; k_0 \,+\, \alpha^2\, k_2 \,+\, \mathcal{O}(\alpha^4)$$

$$\epsilon \;=\; \epsilon_0 \,+\, \alpha^2\, \epsilon_2 \,+\, \mathcal{O}(\alpha^4)$$

$$\Big\downarrow \; k\text{-}\epsilon \text{ model}$$

$$\nu_T \;=\; \nu_{T0} \,+\, \alpha^2\, \nu_{T2} \,+\, \mathcal{O}(\alpha^4)$$

Effect of control on drag and balance of power

Saved power: $\quad C_f \;=\; \Pi_{\text{save}} \;=\; \alpha^2\, \Pi_{\text{save},2} \,+\, \mathcal{O}(\alpha^4)$

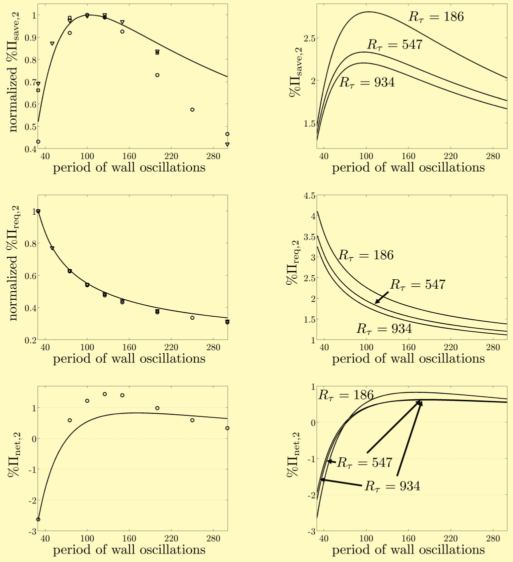
Required power: $\quad \Pi_{\text{req}} \;=\; \alpha^2\, \Pi_{\text{req},2} \,+\, \mathcal{O}(\alpha^4)$

Net power: $\quad \Pi_{\text{net}} \;=\; \alpha^2\, (\Pi_{\text{save},2} - \Pi_{\text{req},2}) \,+\, \mathcal{O}(\alpha^4)$

Turbulent drag reduction

perturbation analysis (solid curves)
numerical simulations (Quadrio & Ricco ’04) (symbols)

$R_\tau \;=\; 186$ larger R_τ



Remarks

- **Control-oriented model:** stochastically forced linearized Navier-Stokes equations with turbulent viscosity
  - simulation-free approach to predicting full-scale results
  - computationally efficient determination of the effect of control on turbulent viscosity
- **Sensor-free control:** facts revealed by perturbation analysis
  - period of oscillations that yield largest drag reduction
  - small oscillation amplitudes ⇝ positive net power balance
  - higher R_τ ⇝ smaller period of oscillations

Publication

[1] R. Moarref and M. R. Jovanović, "Turbulent drag reduction by transverse wall oscillation", *in Proceedings of the 2012 American Control Conference*, Montreal, Canada, 2012, submitted.

[2] R. Moarref and M. R. Jovanović, "Turbulent drag reduction by transverse wall oscillation", *64th Annual Meeting of the APS Division of Fluid Dynamics*, Volume 56, Number 18, Baltimore, MD, November 2011.