Morphing blades: this is how they work

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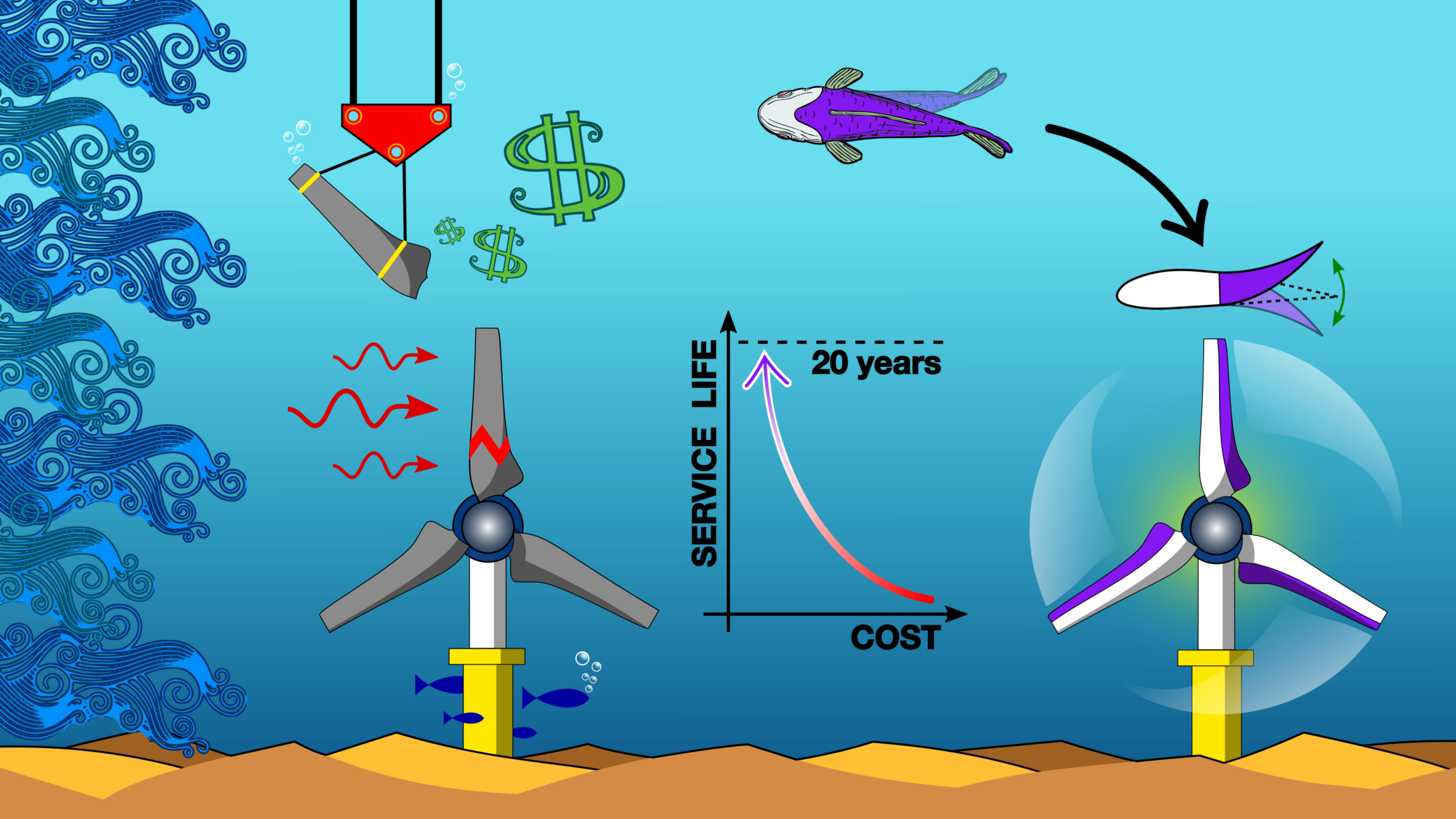
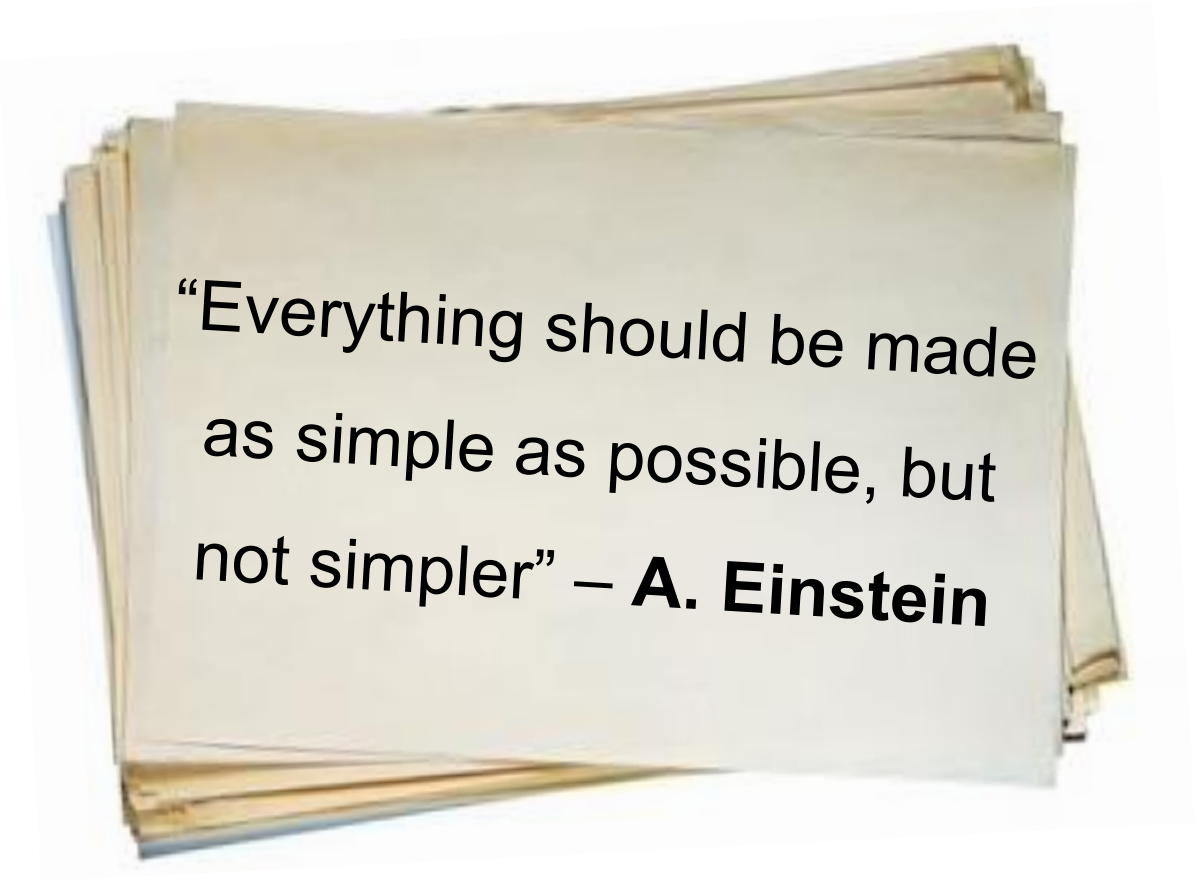
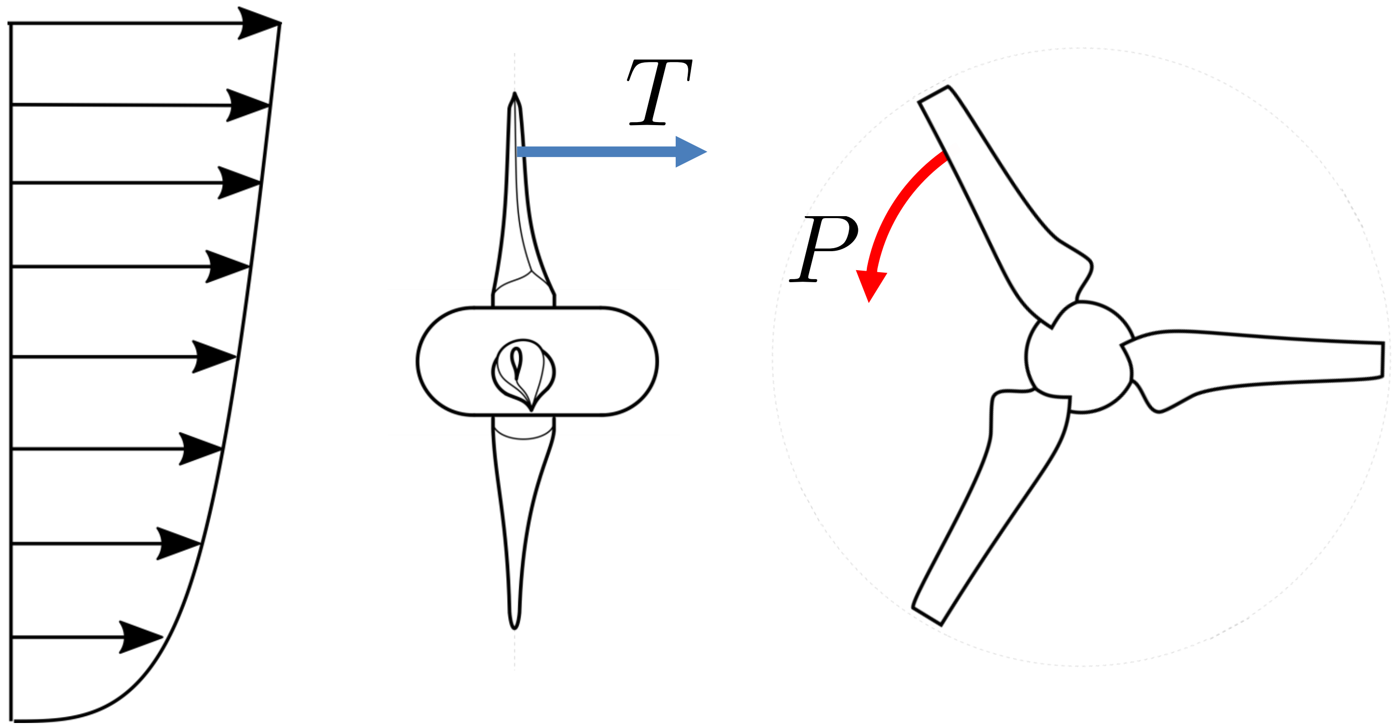
Dr. Ignazio Maria Viola

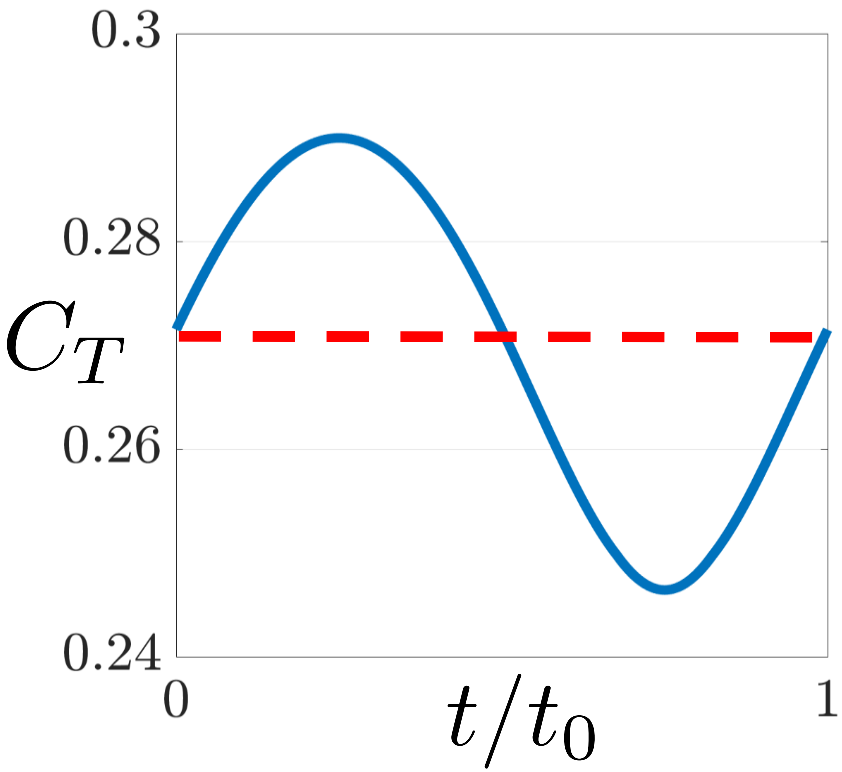

SERVICE LIFE
20 years
COST

Can I make “morphing blade”simple?



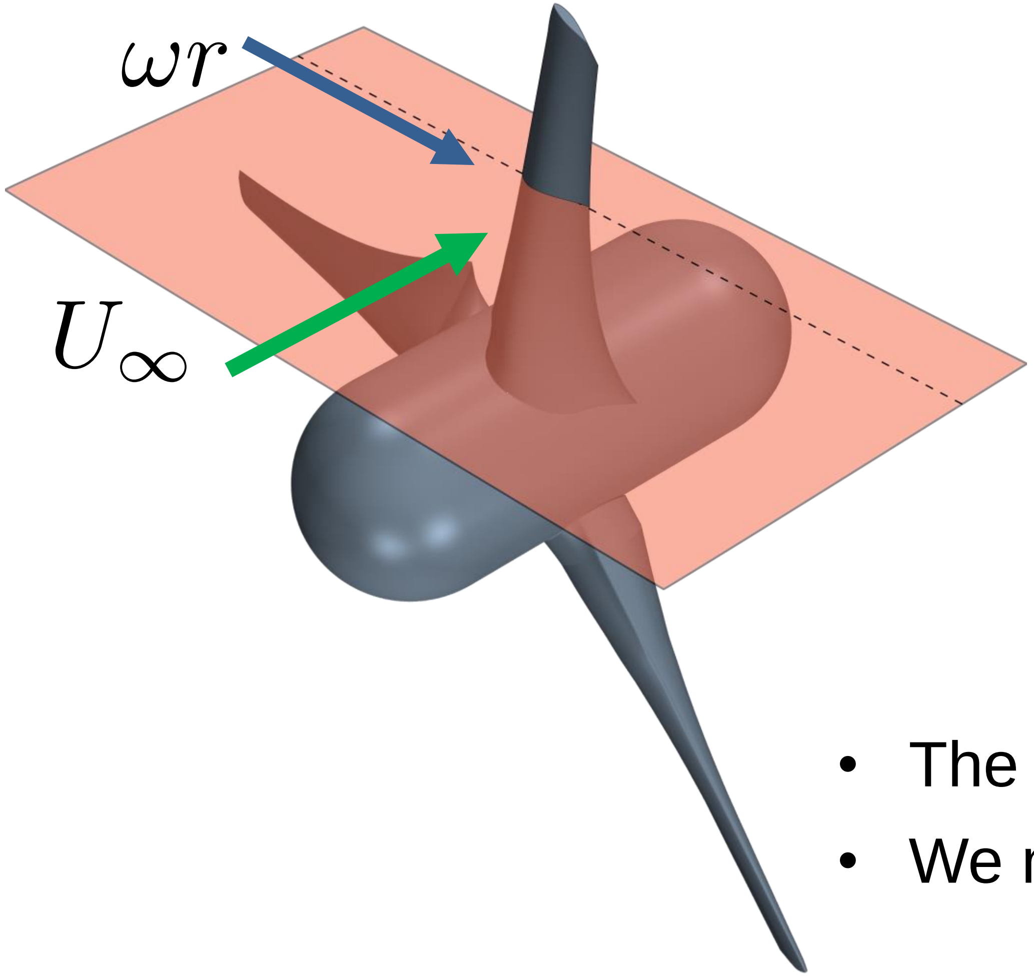
A simple method – test case

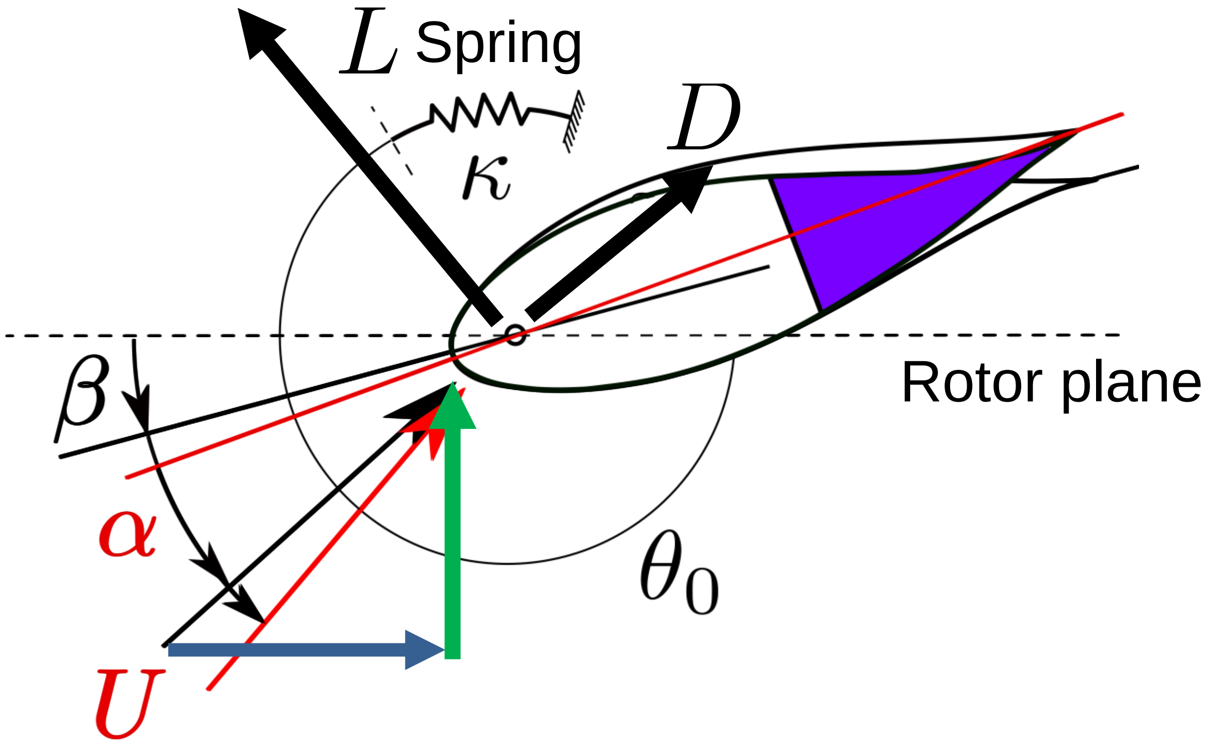




- **Objectives**:
  - Minimize the thrust fluctuations
  - Keep constant the average power generated

A simple method – model setup



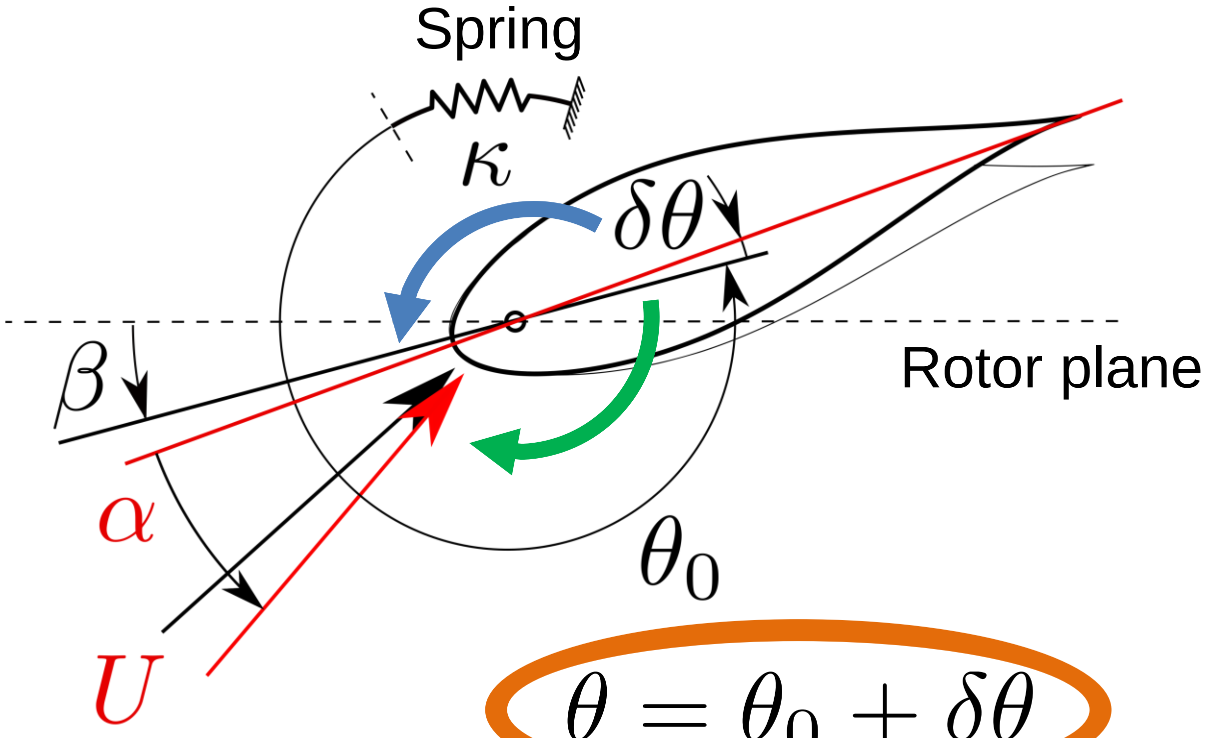


- The blade morphing reduces the effective angle of attack
- We model the blade flexibility using a torsional spring

A simple method – model equations

A. Quasisteady model:

$$\underbrace{\boxed{M_{\mathrm{hs}}(U,\alpha)}}_{\text{Hydrostatic moment}} - \underbrace{\boxed{\kappa\theta}}_{\text{Spring reaction}} = 0$$



$$\theta = \theta_0 + \delta\theta$$

B. Unsteady model:

$$\boxed{M_{\mathrm{hd}}(U,\alpha,f)} - \boxed{\kappa\theta} - \overbrace{\boxed{\mu\dot{\theta}}}^{\text{Damping}} + \overbrace{\boxed{M_{\mathrm{c}}}}^{\text{Centrifugal moment}} = \boxed{J\ddot{\theta}} \rightarrow \text{Blade inertia}$$

A simple method – linear equations

Average flow

A. Quasisteady model:

Angle of attack fluctuations

$$M_{\mathrm{hs}}(U,\alpha) = \frac{1}{2}\rho U^2 c^2 \left[C_{M,\alpha}\left(\alpha_0+\delta\alpha\right)+C_{M,0}\right]$$

Pitch acceleration

B. Unsteady model: Theodorsen's theory

$$\begin{aligned} M_{\mathrm{hd}}(U,\alpha,k) = & \rho b^3 \pi \left[\left(\frac{1}{2}-\frac{d}{b}\right) U\delta\dot{\alpha} + b\left(\frac{1}{8}+\left(\frac{d}{b}\right)^2\right)\delta\ddot{\theta}\right] \\ & - 2\rho U b^3 \pi \left(\frac{1}{2}+\frac{d}{b}\right) C(k) \left(\frac{1}{2}-\frac{d}{b}\right)\delta\dot{\theta} \\ & + \frac{1}{2}\rho U^2 c^2 C_{M,\alpha} C(k)\delta\alpha + \underbrace{\frac{1}{2}\rho U^2 c^2 \left[C_{M,\alpha}\alpha_0 + C_{M,0}\right]}_{\text{Average flow}} \end{aligned}$$

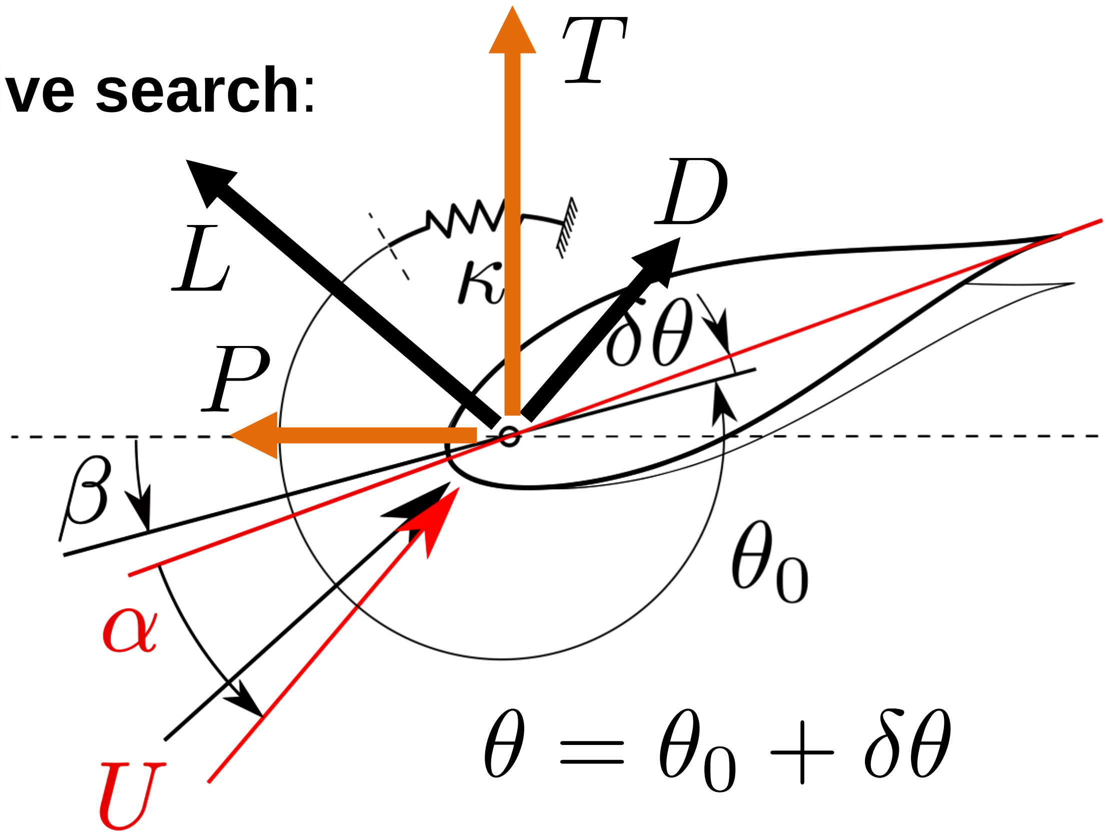
Pitch rate

Reduced frequency:

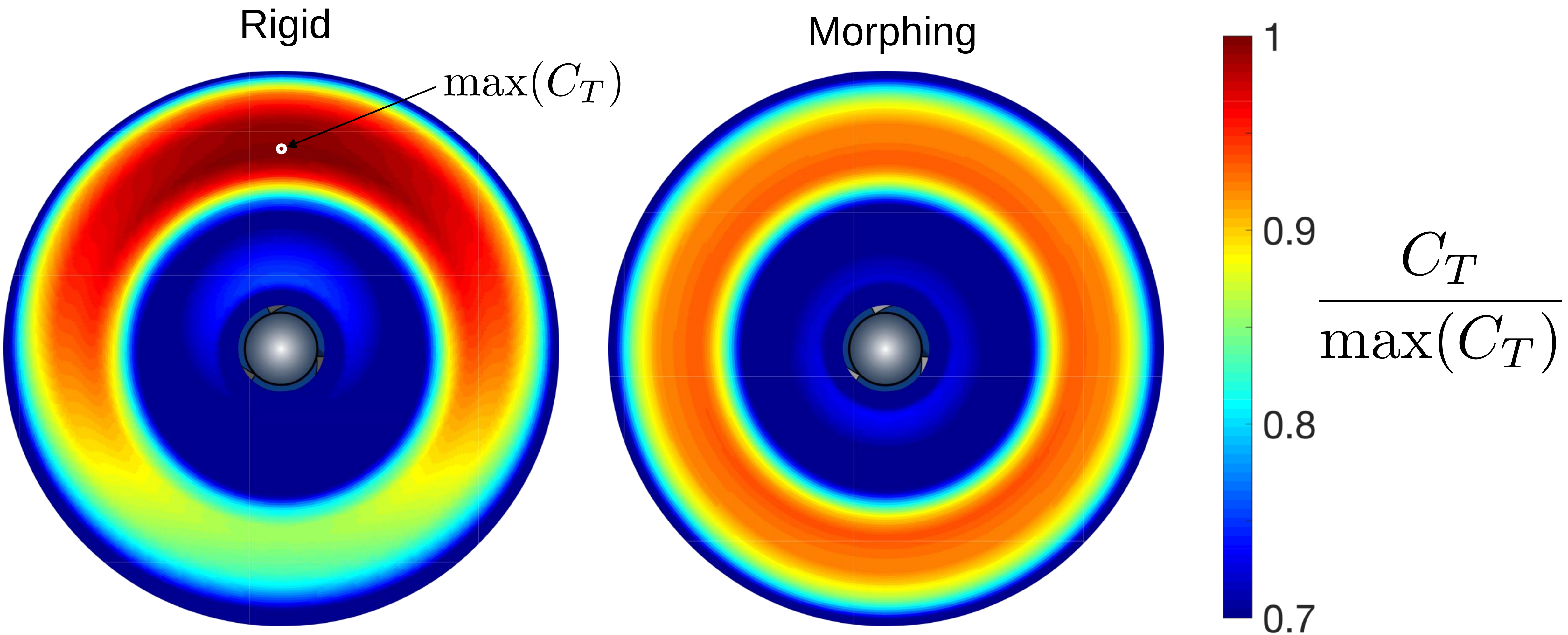
$$k = \frac{\pi f c}{U}$$

A simple method – optimal solution

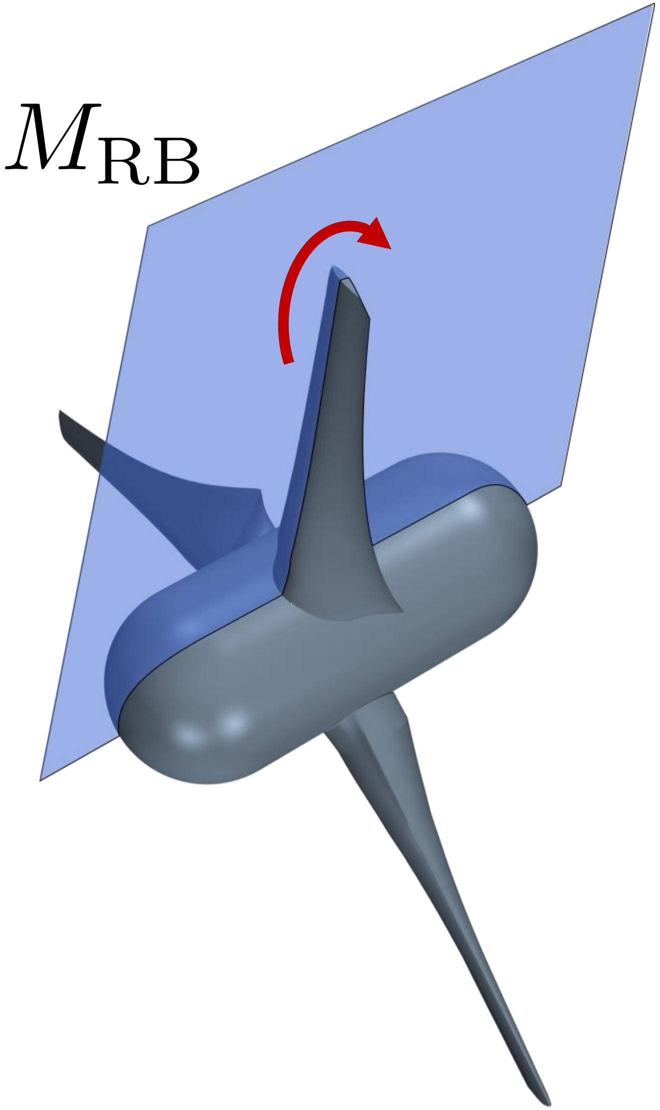
1. Blade deflection and loads are computed for every timestep
2. Thrust and power are evaluated
3. The optimal spring is found by **exhaustive search**:
   - Test different spring stiffnesses
   - Select the spring that minimises the fluctuations of the thrust



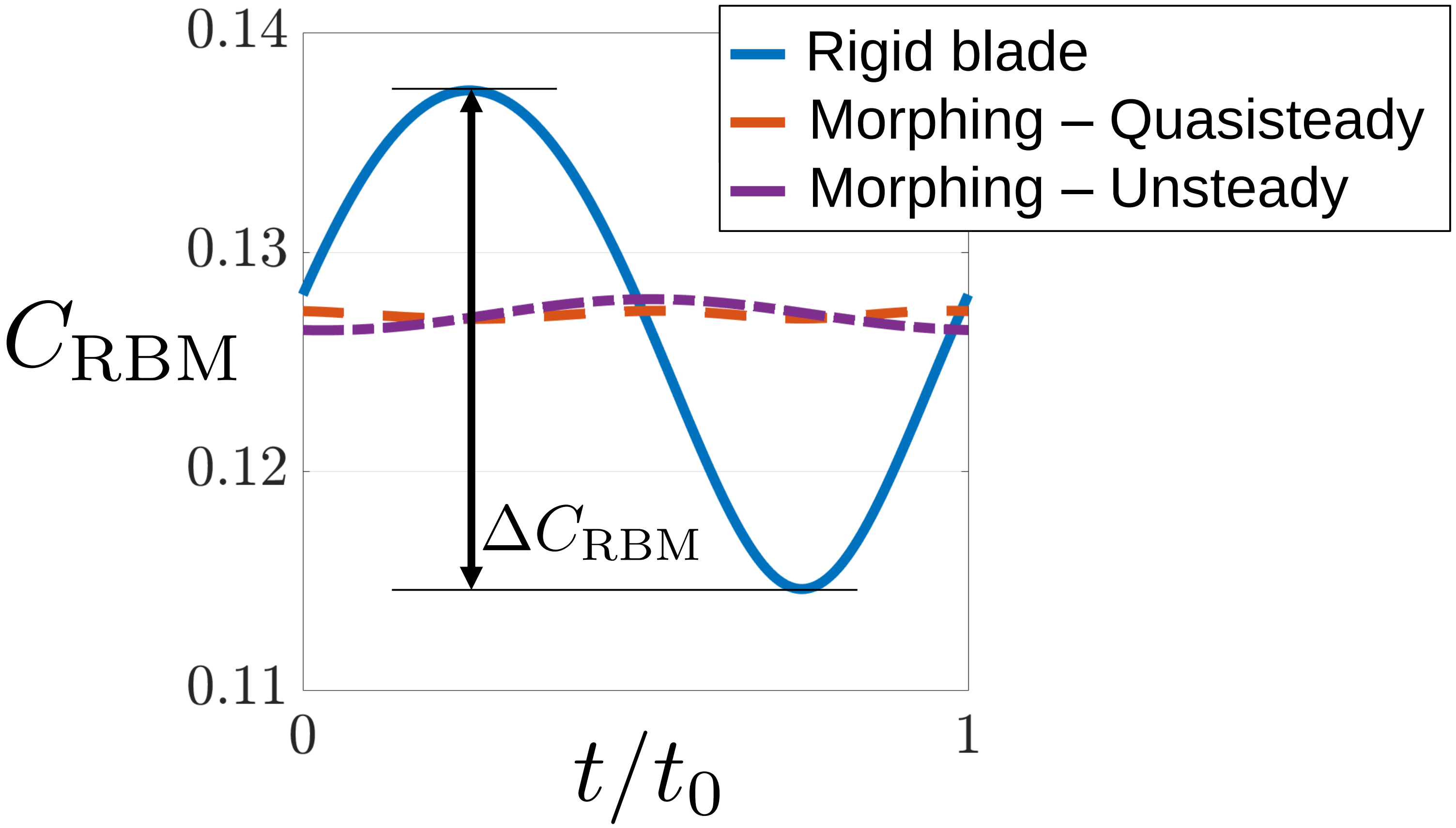
Results



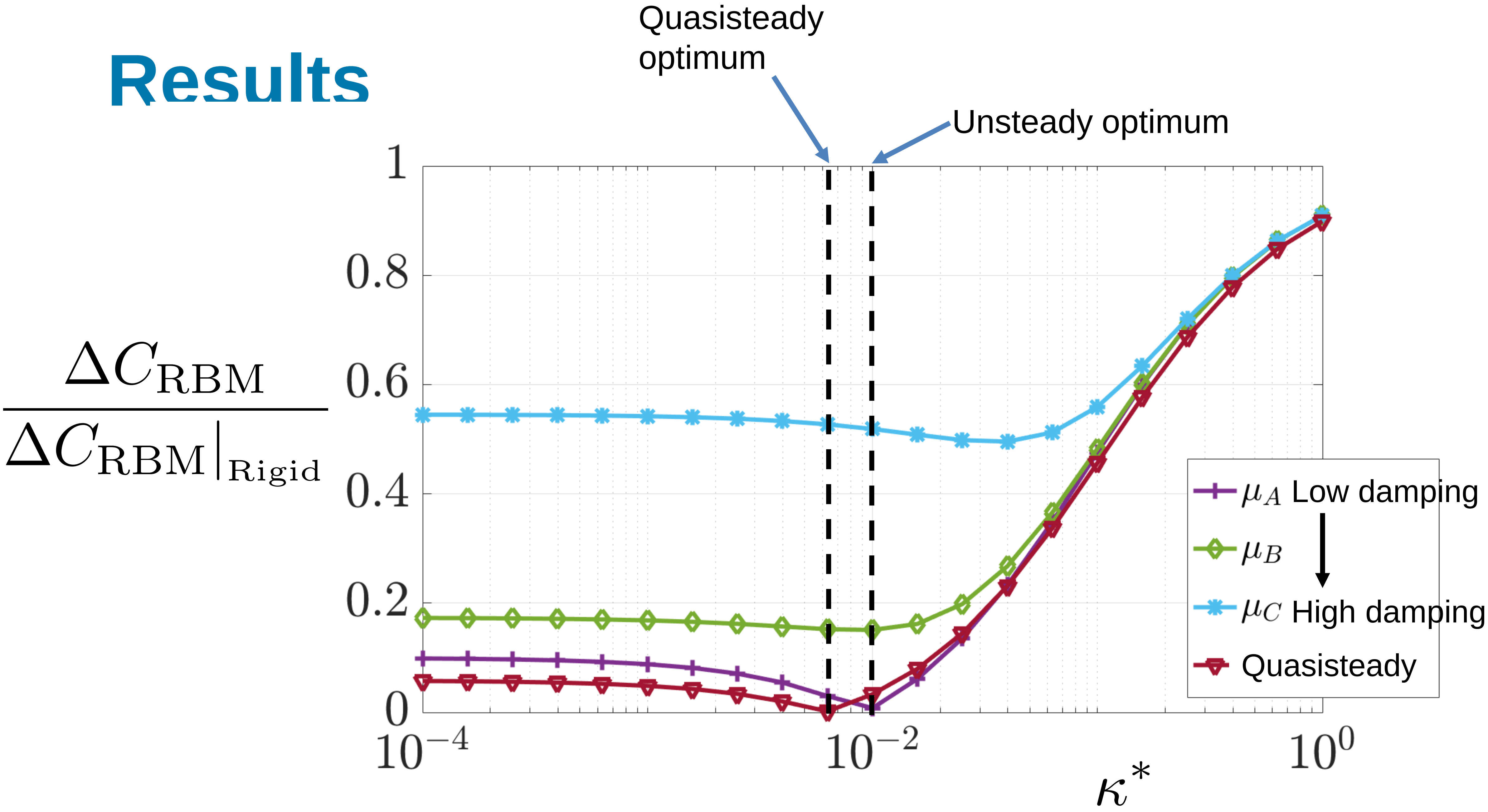
Results



	Fluctuations ΔC_{RBM}	
	% mean C_{RBM}	% reduction
Rigid blade	18	-
Morphing - QS	< 0.5	98
Morphing - UN	< 3	93



Results



Quasisteady optimum
Unsteady optimum
$\frac{\Delta C_{\mathrm{RBM}}}{\Delta C_{\mathrm{RBM}}\big|_{\mathrm{Rigid}}}$
1
0.8
0.6
0.4
0.2
0
10^{-4}
10^{-2}
10^{0}
κ^*
μ_A Low damping
μ_B
μ_C High damping
Quasisteady

Conclusion

- Morphing blades allow considerable load alleviation, no loss of power output
- Simple, clear model:
  - Underpins the basic principles of load alleviation by morphing blades
- Small amplitude fluctuations for morphing blades: linear theory provides accurate performance predictions

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Thanks!

VOILAb Vortex Interaction Collaboratory

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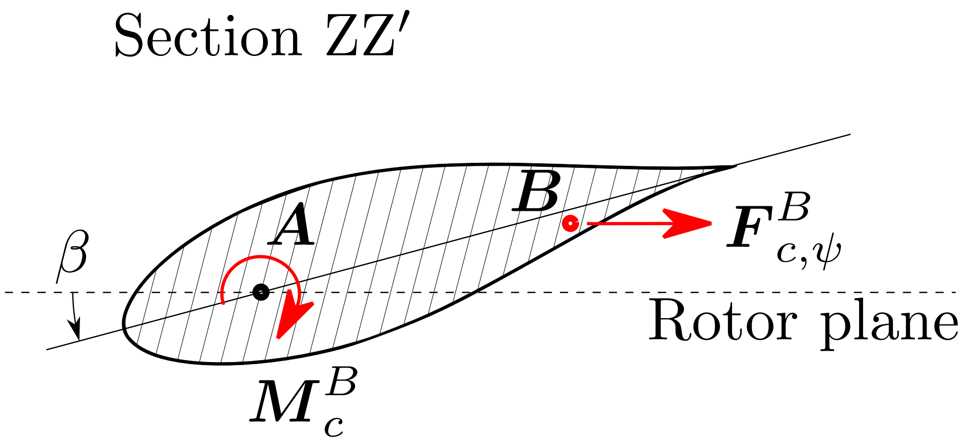
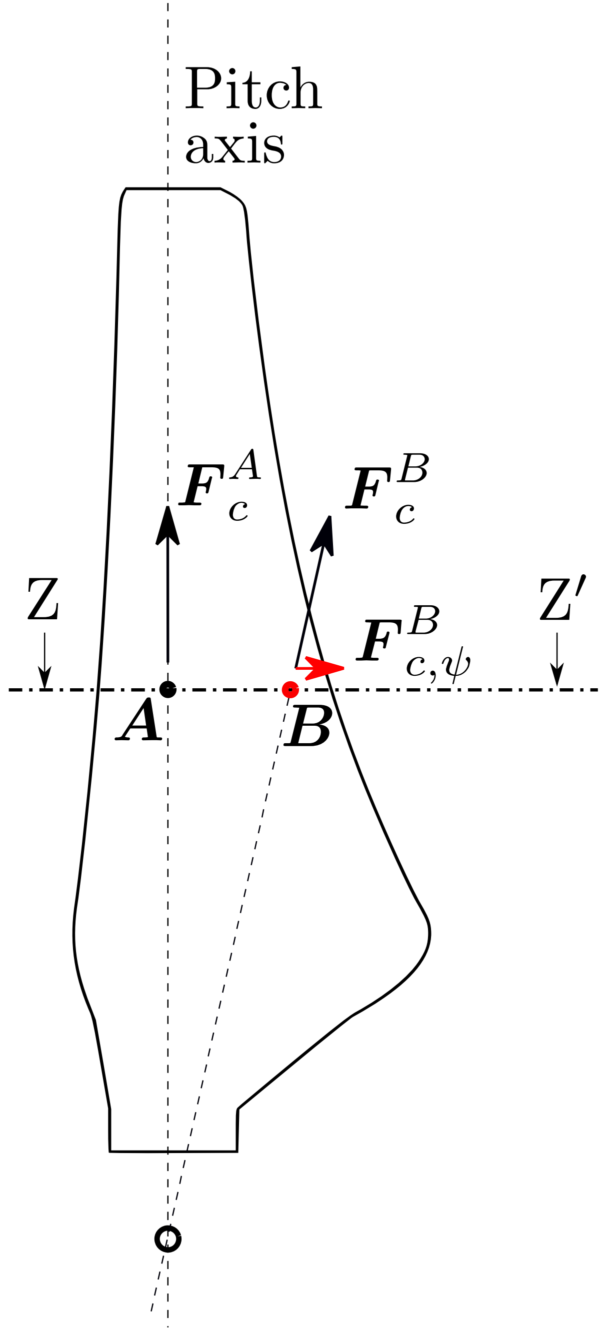
futureWind 2020
& Marine

Centrifugal moment



$$\boldsymbol{M}_{\mathbf{c}}^{B} = \overline{\boldsymbol{AB}} \wedge \boldsymbol{F}_{\mathbf{c},\psi}^{B}$$



A simple method – model equations

A. Quasisteady model:

$$M_{\mathrm{hs}}(U,\alpha) - \kappa\theta = 0$$

$$M_{\mathrm{hs}}(U_0,\alpha_0) - \kappa\theta = 0$$

Average inflow:

$$U = U_0$$
$$\alpha = \alpha_0$$

$$\theta_0 = \frac{M_{\mathrm{hs}}(U_0,\alpha_0)}{\kappa}$$ **Preload**

$$\boxed{\theta = \theta_0 + \delta\theta}$$

Generic inflow:

$$U = U_0 + \delta U$$
$$\alpha = \alpha_0 + \delta\alpha$$

$$\underbrace{M_{\mathrm{hs}}(U,\alpha_0) + \delta M_{\mathrm{hs}}(U,\delta\alpha)}_{\text{Linearised form}} - \kappa\theta = 0$$

A simple method – solution procedure

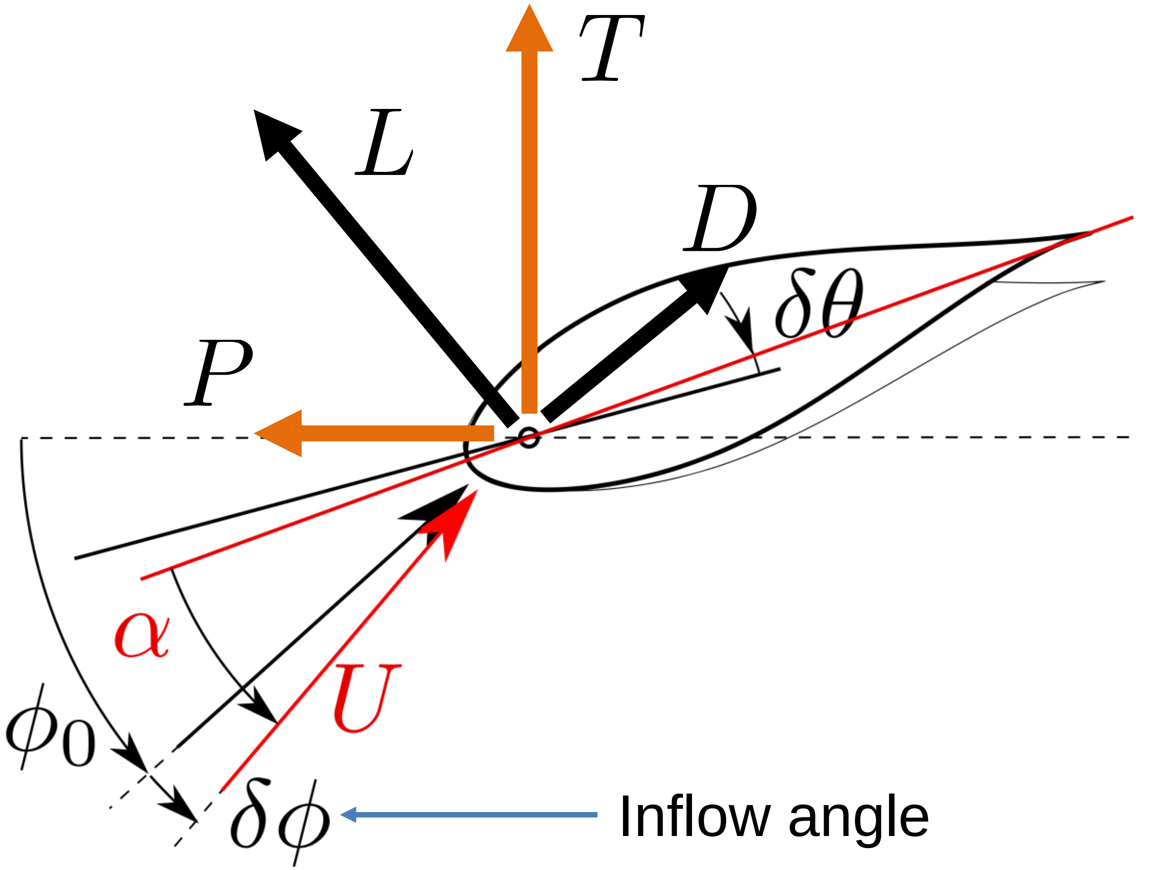
A. Quasisteady model:

1. $\delta M_{\mathrm{hs}}(U, \delta\alpha) - \kappa\delta\theta = 0$

2. $\delta\alpha = \delta\phi - \delta\theta$

3. $$\begin{cases} L = \frac{1}{2}\rho U^2 c C_L\left(\alpha_0 + \delta\alpha\right) \\ D = \frac{1}{2}\rho U^2 c C_D\left(\alpha_0 + \delta\alpha\right) \end{cases}$$

4. $$\begin{cases} T = L\cos\phi + D\sin\phi \\ P = \omega r\left(L\sin\phi - D\cos\phi\right) \end{cases}$$



A simple method – solution procedure

B. Unsteady model:

1. $$\delta M_{\mathrm{hd}}(U, \delta\alpha, f) - \kappa\delta\theta - \mu\delta\dot{\theta} + \delta M_{\mathrm{c}} = J\delta\ddot{\theta}$$

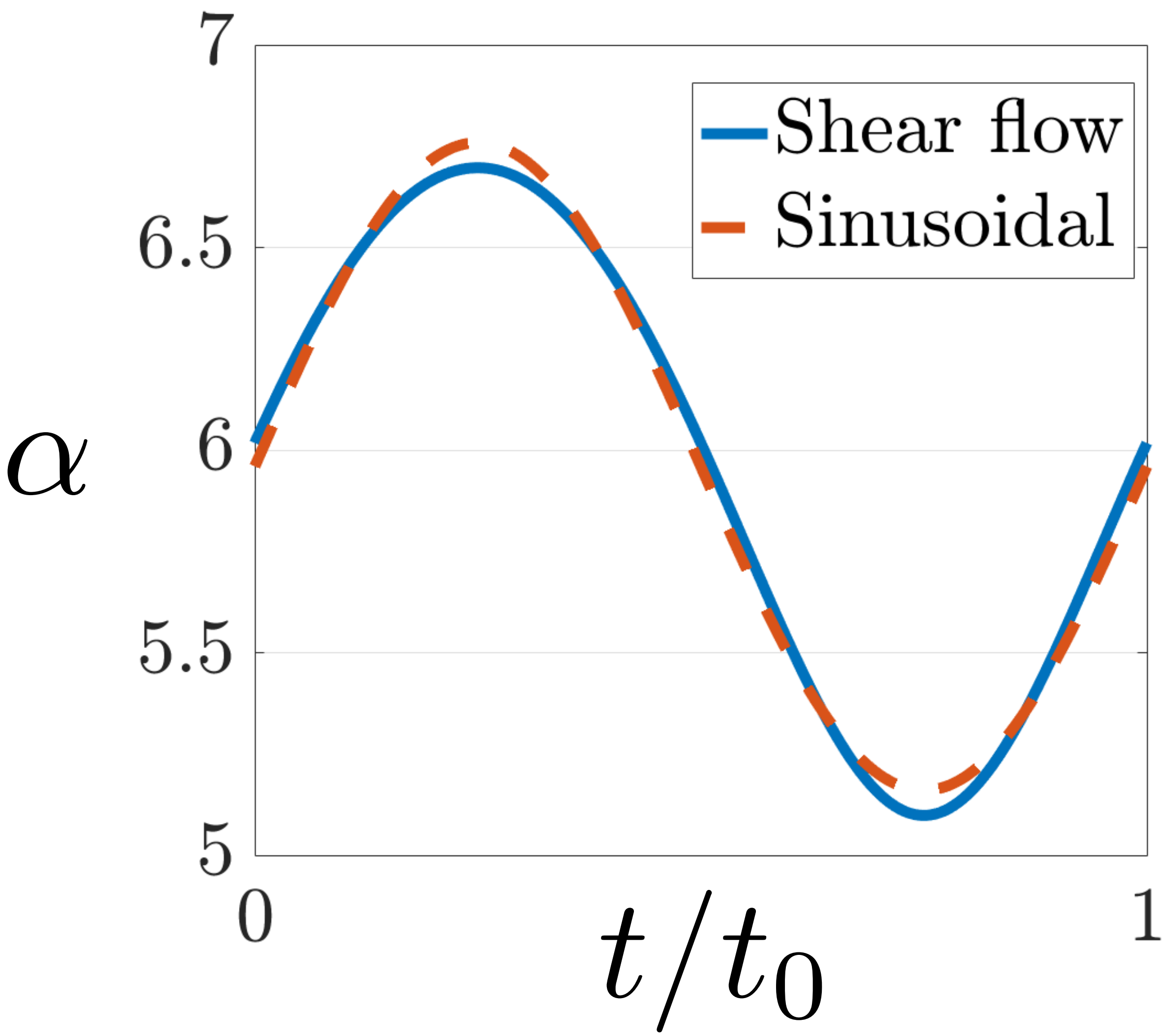
- $\delta\phi = \Delta\phi \exp(i\omega t) \longrightarrow \delta\theta = \Delta\theta \exp(i\omega t + \chi)$

$$\delta\dot{\theta} = i\omega\delta\theta, \quad \delta\ddot{\theta} = -\omega^2\delta\theta$$

3. $$L = \pi\rho b^2 \left[U\delta\dot{\alpha} - b\left(\frac{d}{b}\right)\delta\ddot{\theta}\right] + 2\pi\rho U b^2 C(k)\left(\frac{1}{2} - \frac{d}{b}\right)\delta\dot{\theta} + \frac{1}{2}\rho U^2 c\left[C(k)C_L(\delta\alpha) + C_L(\alpha_0)\right]$$

Inflow fluctuations

- Sinusoidal approximation
  - Same average value
  - Same amplitude



Inflow fluctuations

- Combined effect of inflow velocity and angle of attack