Research for a better future

Development of an unsteady lifting line model for wind turbine applications

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Aerodynamic Model of Wind Turbines

CFD (actuator line, actuator disc)

High computational cost

Free-vortex method

Increasing computational cost

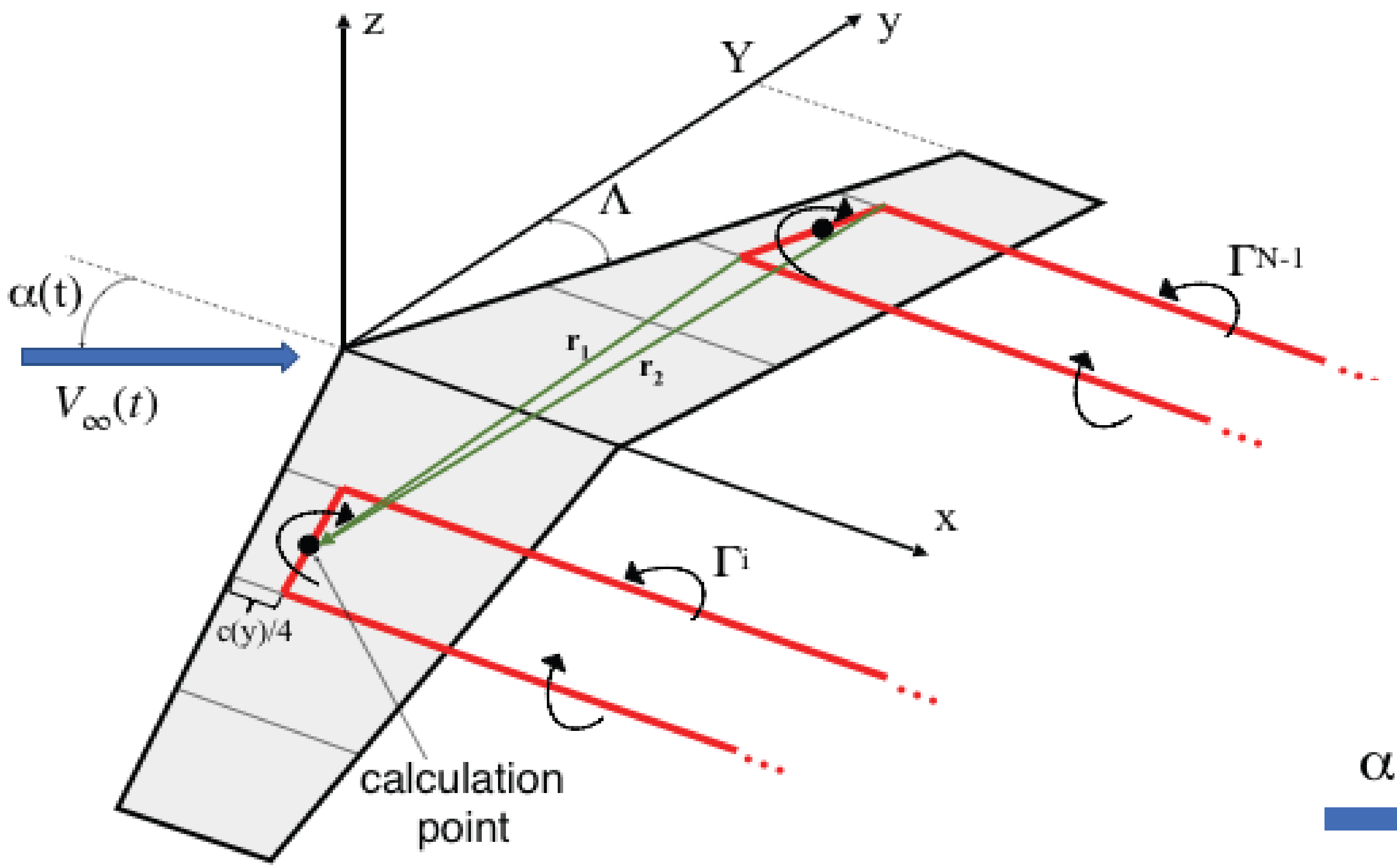
BEM (Blade Element Momentum)

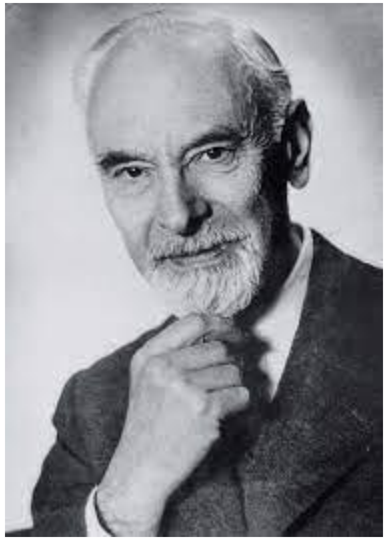
Low computational cost

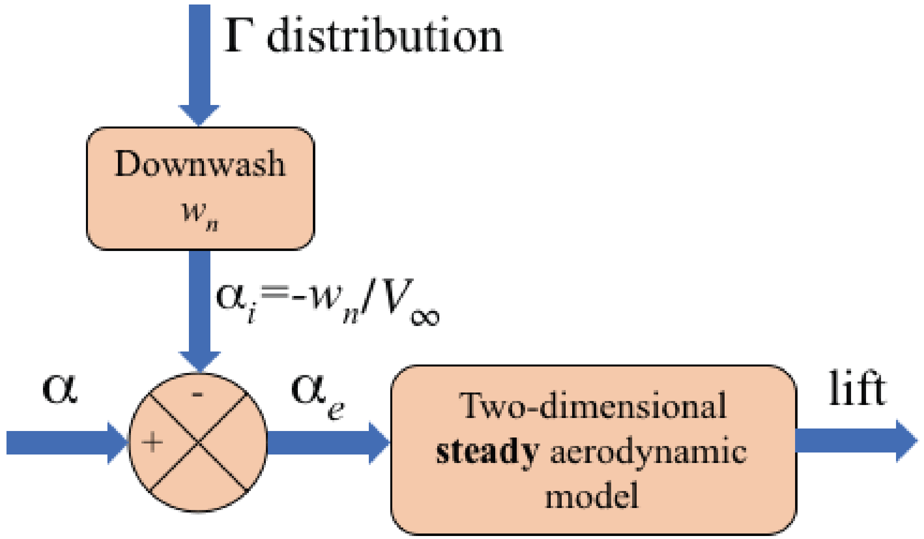
van der Laan, M.P., et al. "Power curve and wake analyses of the Vestas multi-rotor demonstrator." *Wind Energy Science* 4.2 (2019): 251-271.

UNSTEADY LIFTING LINE

The classical Lifting Line Theory







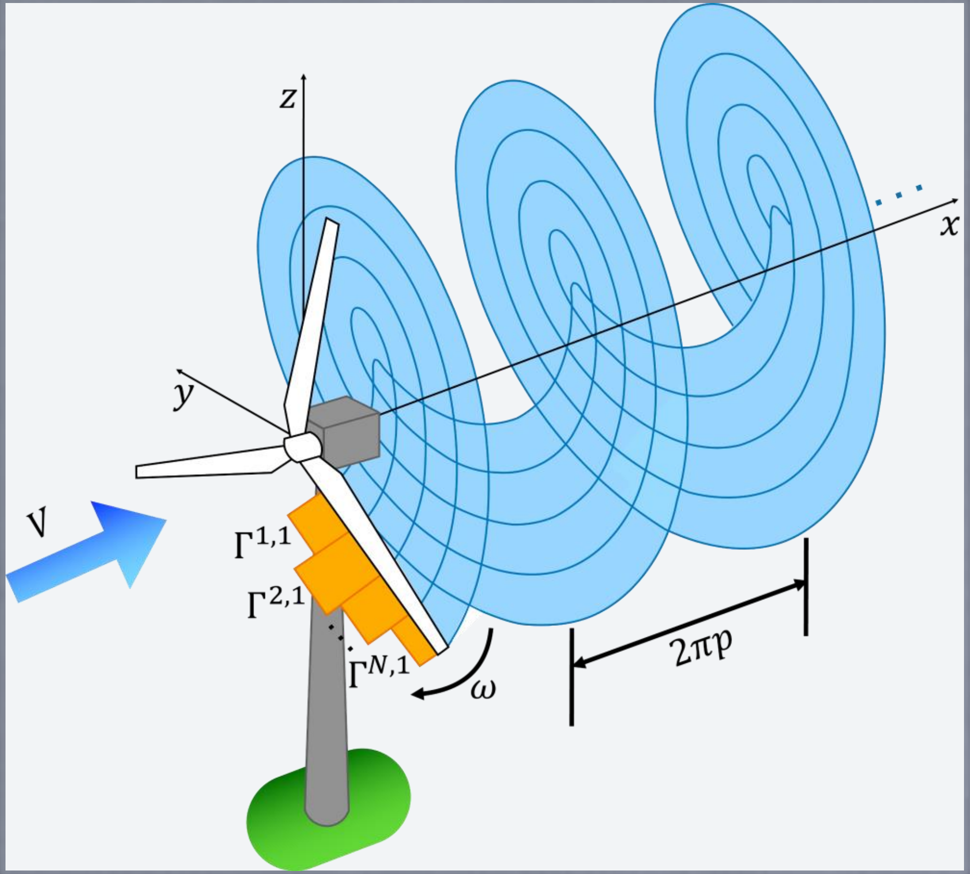
$$\begin{cases} v_a^{i,j} = \sum_{l=1}^{N} \sum_{m=1}^{N_B} \hat{v}_a^{i,j,l,m}\, \Gamma^{l,m} \\ v_t^{i,j} = \sum_{l=1}^{N} \sum_{m=1}^{N_B} \hat{v}_t^{i,j,l,m}\, \Gamma^{l,m} \end{cases}$$

$$U^{i,j} = \sqrt{\left(V - v_a^{i,j}\right)^2 + \left(\omega r^{i,j} + v_t^{i,j}\right)^2}$$

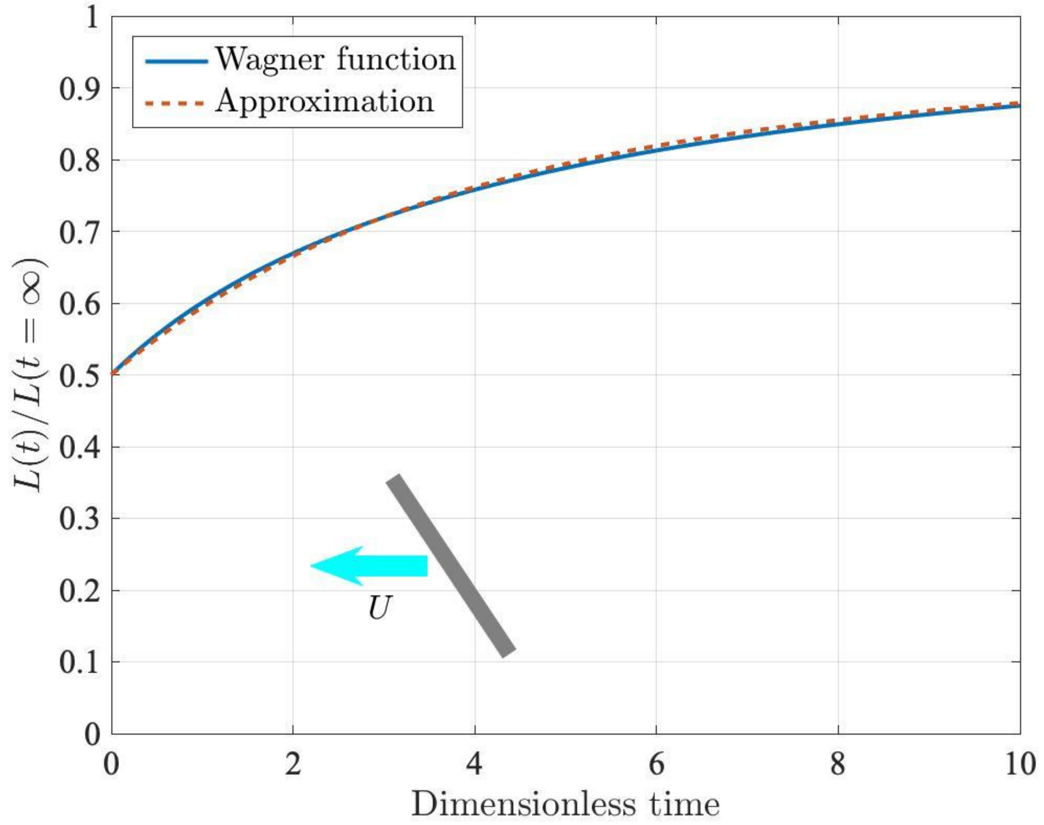
$$\tan \beta^{i,j} = \frac{V - v_a^{i,j}}{\omega r^{i,j} + v_t^{i,j}}$$

$$\alpha^{i,j} = \beta^{i,j} - \theta^{i,j}$$

$$\Gamma^{\mathrm{i,j}} = 0.5 c^{i,j} U^{i,j} c_l\left(\alpha^{i,j}\right)$$

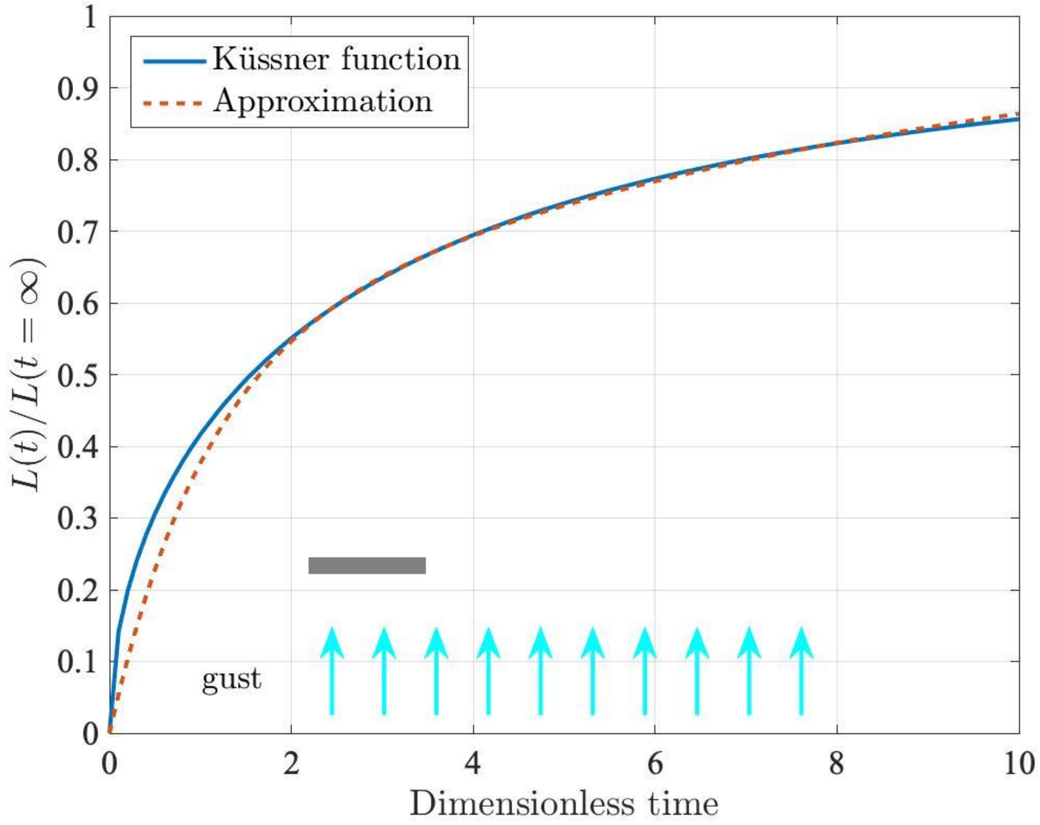


Indicial response (Wagner problem)



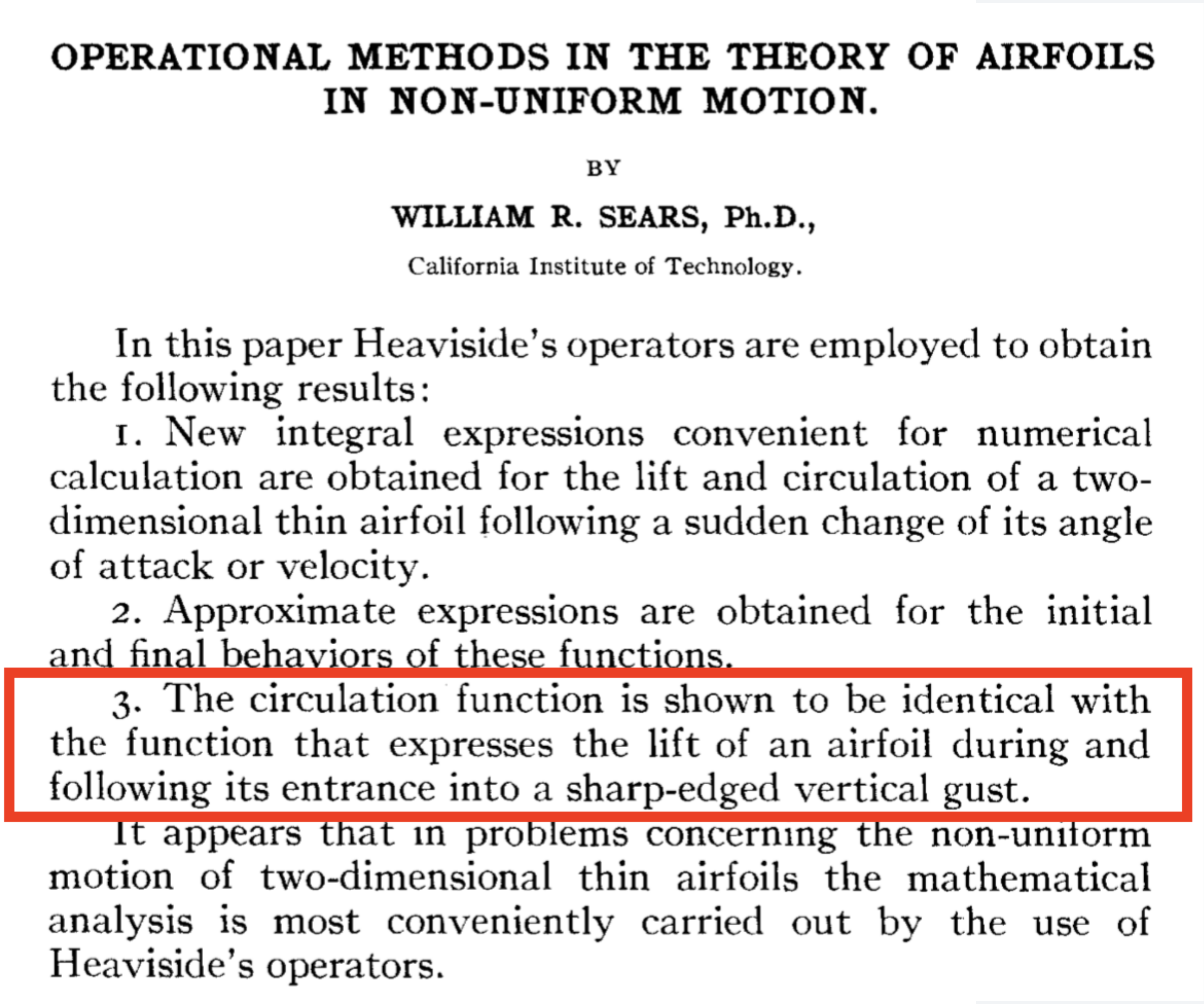
$$\phi(s) = 1 - \int_0^\infty \frac{e^{-sx}dx}{x^2\{[K_0(x)-K_1(x)]^2+\pi^2[I_0(x)+I_1(x)]^2\}}$$

$$\phi(s) \approx 1 - 0.165e^{-0.0455s} - 0.335e^{-0.3s}$$



$$\psi(s) = 1 - \int_0^\infty \frac{[I_0(x)+I_1(x)]e^{-x(s-1)}dx}{x^2\{[K_0(x)-K_1(x)]^2+\pi^2[I_0(x)+I_1(x)]^2\}}$$

$$\psi(s) \approx 1 - 0.5e^{-0.13s} - 0.5e^{-s}$$



OPERATIONAL METHODS IN THE THEORY OF AIRFOILS IN NON-UNIFORM MOTION.

BY

WILLIAM R. SEARS, Ph.D.,

California Institute of Technology.

In this paper Heaviside's operators are employed to obtain the following results:

1. New integral expressions convenient for numerical calculation are obtained for the lift and circulation of a two-dimensional thin airfoil following a sudden change of its angle of attack or velocity.

2. Approximate expressions are obtained for the initial and final behaviors of these functions.

3. The circulation function is shown to be identical with the function that expresses the lift of an airfoil during and following its entrance into a sharp-edged vertical gust.

It appears that in problems concerning the non-uniform motion of two-dimensional thin airfoils the mathematical analysis is most conveniently carried out by the use of Heaviside's operators.

$$\frac{\Gamma(s)}{\Gamma_{QS}} = \psi(s)$$

Küssner function

DUHAMEL'S PRINCIPLE

$$\Gamma(s) = \Gamma_{QS}(0)\psi(s) + \int_0^s \frac{d\Gamma_{QS}(\vartheta)}{d\vartheta}\psi(s-\vartheta)d\vartheta$$

approximation

$$\Gamma(t) = \Gamma_{QS}(t)\psi(0) - \int_0^t \Gamma_{QS}(\tau)\frac{d\psi(t-\tau)}{d\tau}d\tau$$

$$\Gamma(t) = \int_0^t \frac{\Gamma_{QS}(\tau)2U}{c}\left[A_{\psi 1}b_{\psi 1}e^{-\frac{b_{\psi 1}2U}{c}(t-\tau)} + A_{\psi 2}b_{\psi 2}e^{-\frac{b_{\psi 2}2U}{c}(t-\tau)}\right]d\tau$$

$$\Gamma(t) = x_{\psi 1}(t) + x_{\psi 2}(t)$$

$$\dot{x}_{\psi 1} = \frac{2Ub_{\psi 1}}{c}\left[-x_{\psi 1}(t) + A_{\psi 1}\Gamma_{QS}(t)\right]$$

$$\dot{x}_{\psi 2} = \frac{2Ub_{\psi 2}}{c}\left[-x_{\psi 2}(t) + A_{\psi 2}\Gamma_{QS}(t)\right]$$

$$L(t) = \rho U[0.5\Gamma_{QS}(t) + x_{\phi 1}(t) + x_{\phi 2}(t)]$$

$$\dot{x}_{\phi 1} = \frac{2Ub_{\phi 1}}{c}\left[-x_{\phi 1}(t) + A_{\phi 1}\Gamma_{QS}(t)\right]$$

$$\dot{x}_{\phi 2} = \frac{2Ub_{\phi 2}}{c}\left[-x_{\phi 2}(t) + A_{\phi 2}\Gamma_{QS}(t)\right]$$

$$\Gamma_{QS}(t) = \frac{1}{2}c\left[U(t)c_{l,s}(\alpha) + \pi c\left(\frac{1}{2} - a\right)\dot{\alpha}(t)\right]$$

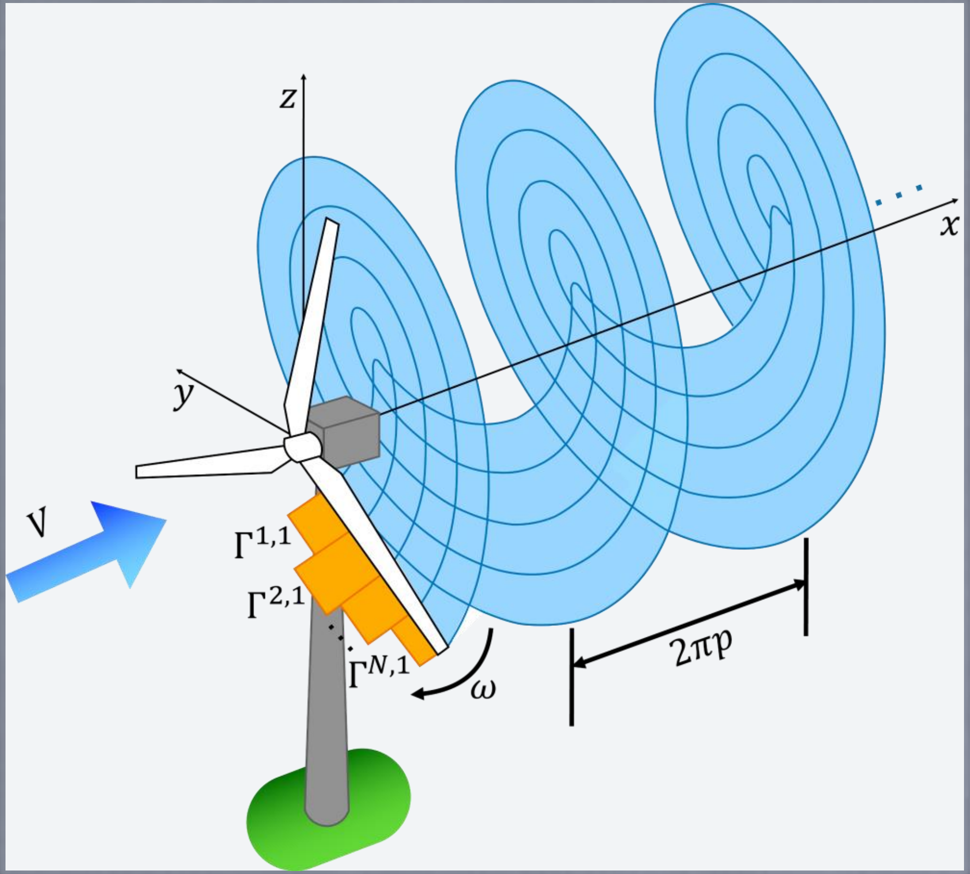
$$\begin{cases} v_a^{i,j} = \sum_{l=1}^{N} \sum_{m=1}^{N_B} \hat{v}_a^{i,j,l,m}\, \Gamma^{l,m} \\ v_t^{i,j} = \sum_{l=1}^{N} \sum_{m=1}^{N_B} \hat{v}_t^{i,j,l,m}\, \Gamma^{l,m} \end{cases}$$

$$U^{i,j}, \beta^{i,j} \text{ AND } \alpha^{i,j} = \beta^{i,j} - \theta^{i,j}$$

$$\Gamma_{QS}^{i,j} = \frac{1}{2} c^{i,j} [U^{i,j} c_{l,s}(\alpha^{i,j}) + \pi c^{i,j} \left(\frac{1}{2} - a\right) \dot{\theta}^{i,j}]$$

$$\Gamma^{i,j}(t) = x_{\psi 1}^{i,j}(t) + x_{\psi 2}^{i,j}(t)$$

$$L^{i,j}(t) = \rho U^{i,j} [0.5 \Gamma_{QS}^{i,j}(t) + x_{\phi 1}^{i,j}(t) + x_{\phi 2}^{i,j}(t)]$$



ROTORVEX

Validation

The Science of Making Torque from Wind (TORQUE 2016) IOP Publishing
Journal of Physics: Conference Series **753** (2016) 092001 doi:10.1088/1742-6596/753/9/092001

Wind tunnel validation of AeroDyn within LIFES50+ project: imposed Surge and Pitch tests

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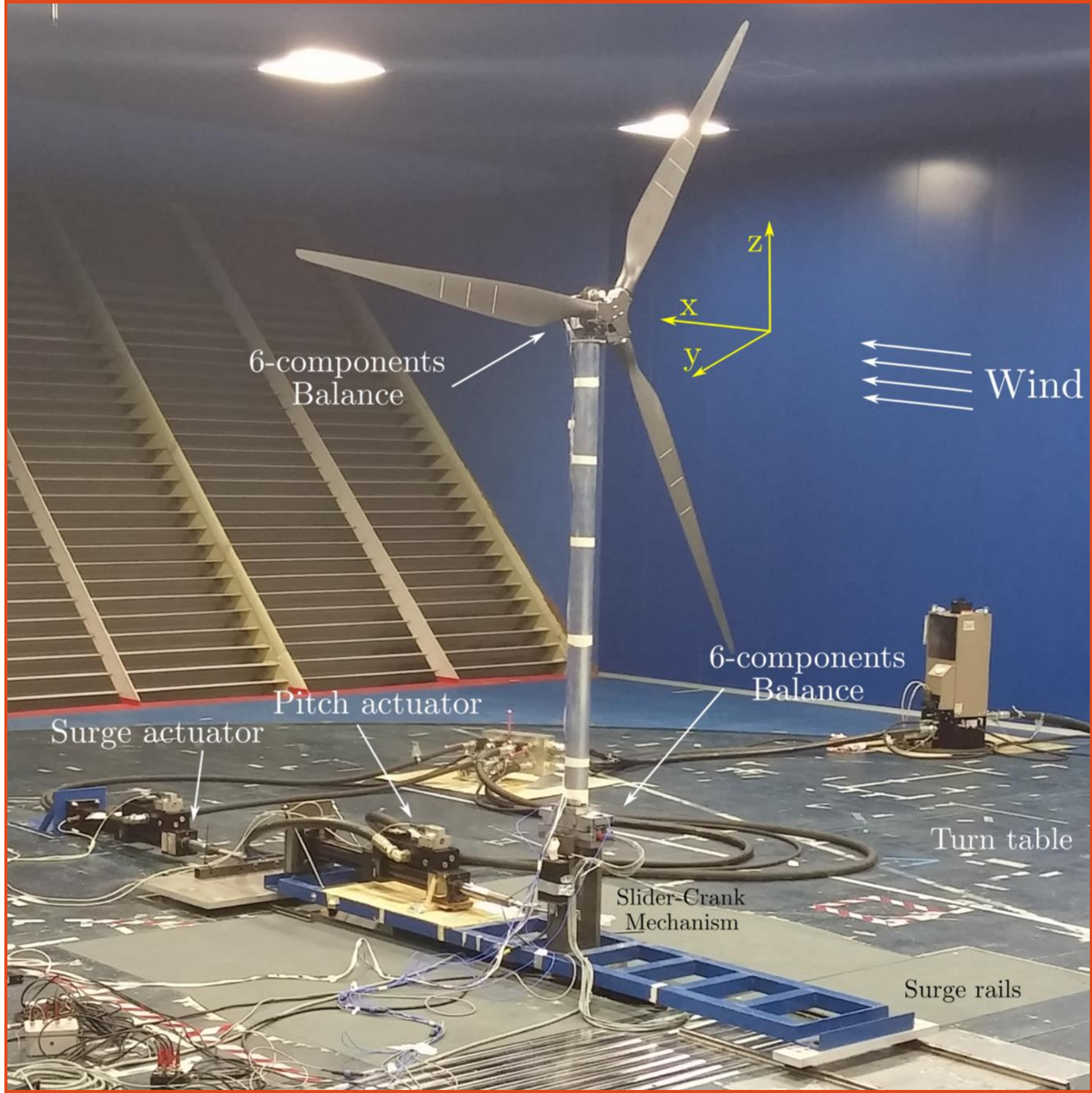
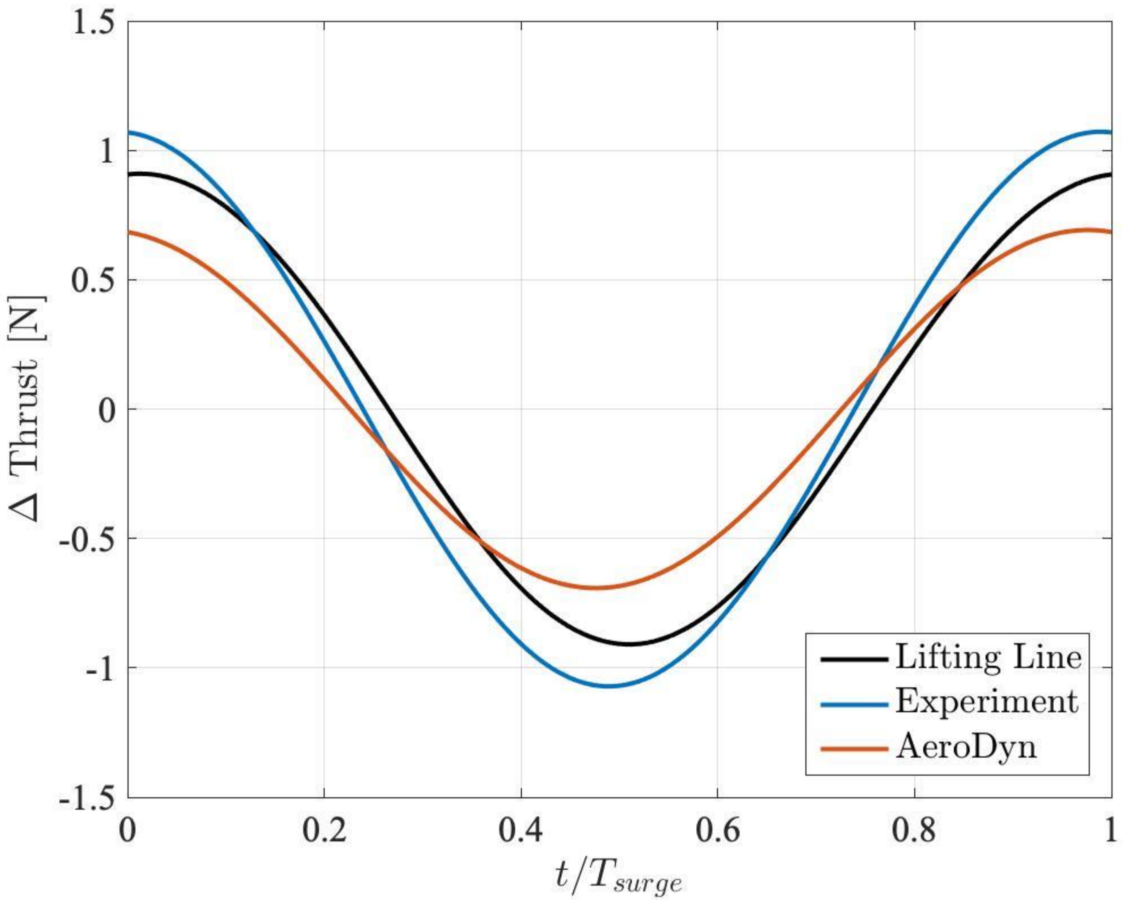
Abstract. This paper presents the first set of results of the steady and unsteady wind tunnel tests, performed at Politecnico di Milano wind tunnel, on a 1/75 rigid scale model of the DTU 10 MW wind turbine, within the LIFES50+ project. The aim of these tests is the validation of the open source code AeroDyn developed at NREL. Numerical and experimental steady results are compared in terms of thrust and torque coefficients, showing good agreement, as well as for unsteady measurements gathered with a 2 degree-of-freedom test rig, capable of imposing the displacements at the base of the model, and providing the surge and pitch motion of the floating offshore wind turbine (FOWT) scale model. The measurements of the unsteady test configuration are compared with AeroDyn/Dynin module results, implementing the generalized dynamic wake (GDW) model. Numerical and experimental comparison showed similar behaviours in terms of non linear hysteresis, however some discrepancies are herein reported and need further data analysis and interpretations about the aerodynamic integral quantities, with a special attention to the physics of the unsteady phenomenon.

1. Introduction

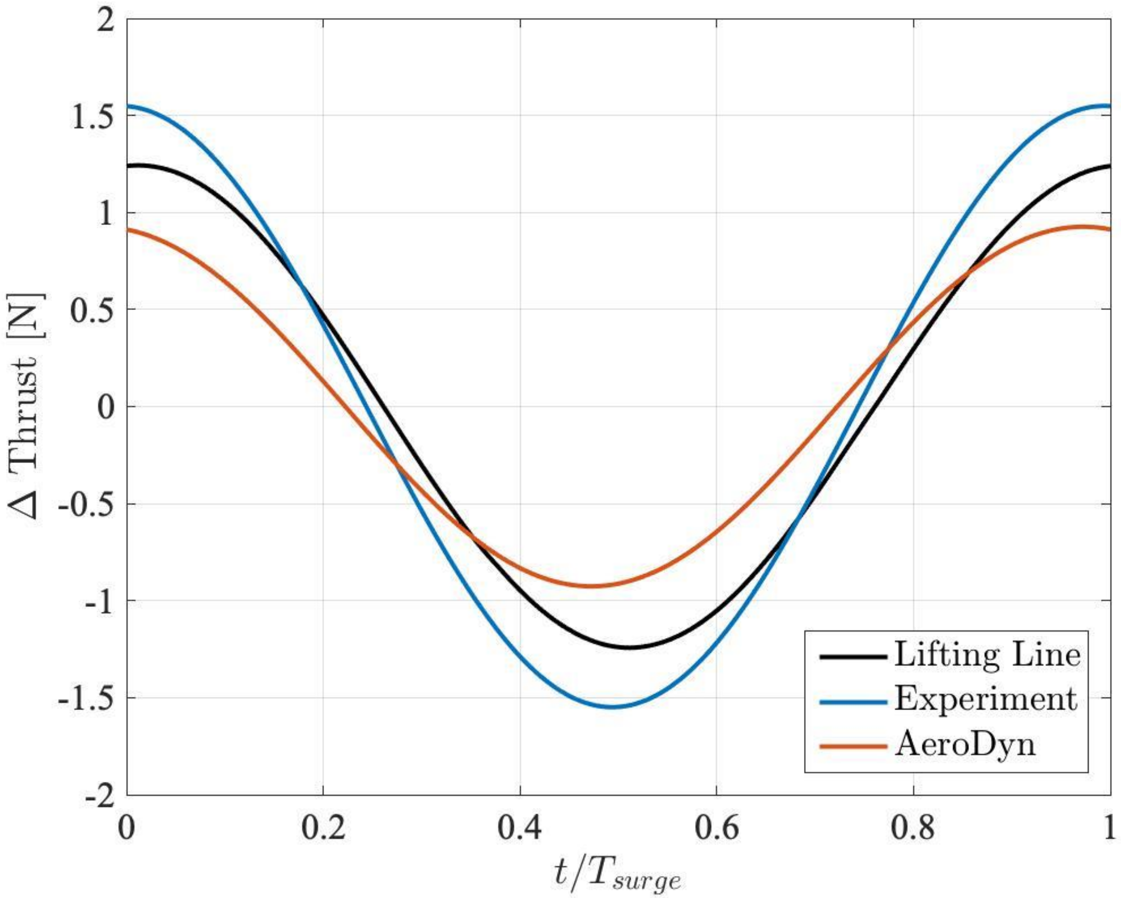
Lifes50+ is an EU H2020 project which aims at proving cost effective technology for floating substructures for 10MW wind turbines, at water depths greater than 50 m. The objective is optimizing and qualifying to a Technology Readiness Level (TRL) of 5, i.e. technology validated in relevant environment, two innovative substructure designs for 10MW wind turbines, as well as, developing a methodology for the evaluation process of floating substructures. For this project, the reference 10 MW wind turbine developed by DTU [1] is taken as reference for numerical and experimental studies.



Surging oscillations

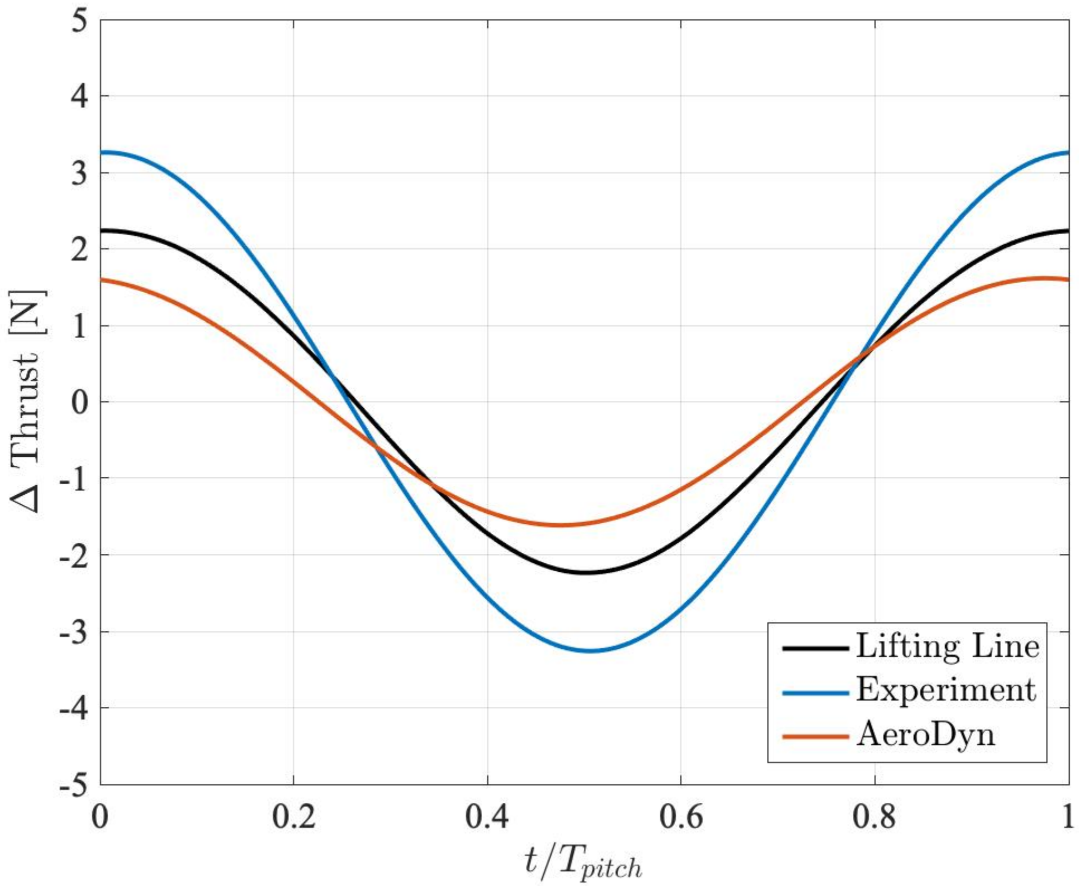


$$A_{sur} = 0.01m, \omega_{sur} = 2.1Hz$$
$$V = 2.33m/s$$

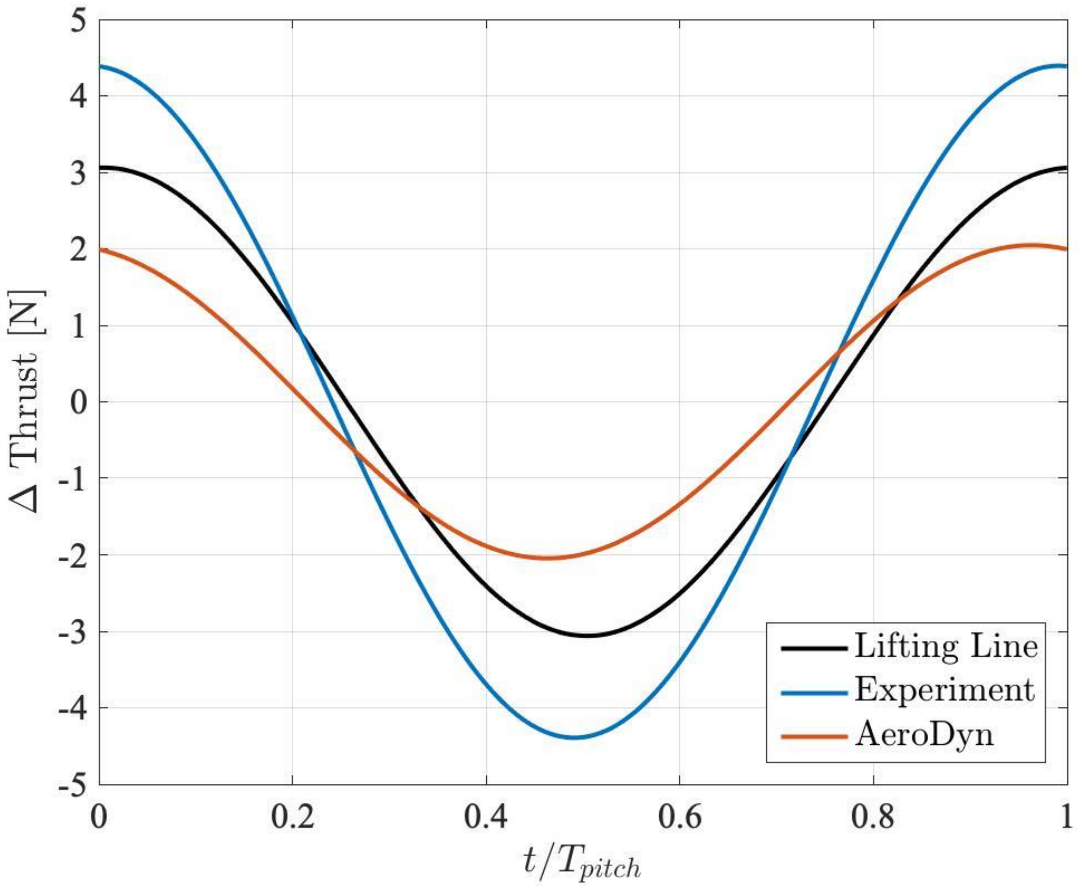


$$A_{sur} = 0.01m, \omega_{sur} = 2.1Hz$$
$$V = 3.67m/s$$

Pitching oscillations



$$A_{pit} = 3°, \omega_{pit} = 0.65Hz$$
$$V = 2.33m/s$$



$$A_{pit} = 3°, \omega_{pit} = 0.65Hz$$
$$V = 3.67m/s$$

Concluding remarks

Development of a state-space model for circulation dynamics

Formulation, implementation and validation of an efficient unsteady lifting line model

Easy inclusion of several rotors into the model

Alternative for analyses when BEM shows its limitations

Thank you for your attention!

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