Significance of unsteady aerodynamics in floating wind turbine design

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Introduction

In the future, as floating offshore wind turbines evolve, engineers will probably need to redesign turbines completely to be better integrated with their floating support. For such a design process, it is not enough to be able to analyse an existing design; they will need to know what can be simplified and/or ignored in the initial design. In particular, as a step towards determining which types of motion are the most damaging, it becomes necessary to find out how important unsteady aerodynamics are.

Methodology

Theodorsen's model [1] and an analytical model of Van der Wall and Leishman [2], discretised in the time domain and coded in MATLAB, were used to analyse the fully-attached unsteady aerodynamics. Quasi-steady and fully-attached unsteady models were matched by comparing loads on the NREL 5MW base turbine blade [3].

A parallel study was performed in FAST [4] using the OC3-Hywind model [5]. This study included the whole spectrum of unsteady aerodynamics (dynamic inflow, attached flow, separated flow and dynamic stall).

Results

A simple calculation using reduced frequency, a non-dimensional parameter that helps to identify the unsteadiness of the flow, shows that for an excitation frequency of 0.2 Hz different blade sections of an NREL 5 MW turbine's blade would see varying flow states over its span, including unsteady and highly-unsteady (Fig. 1).

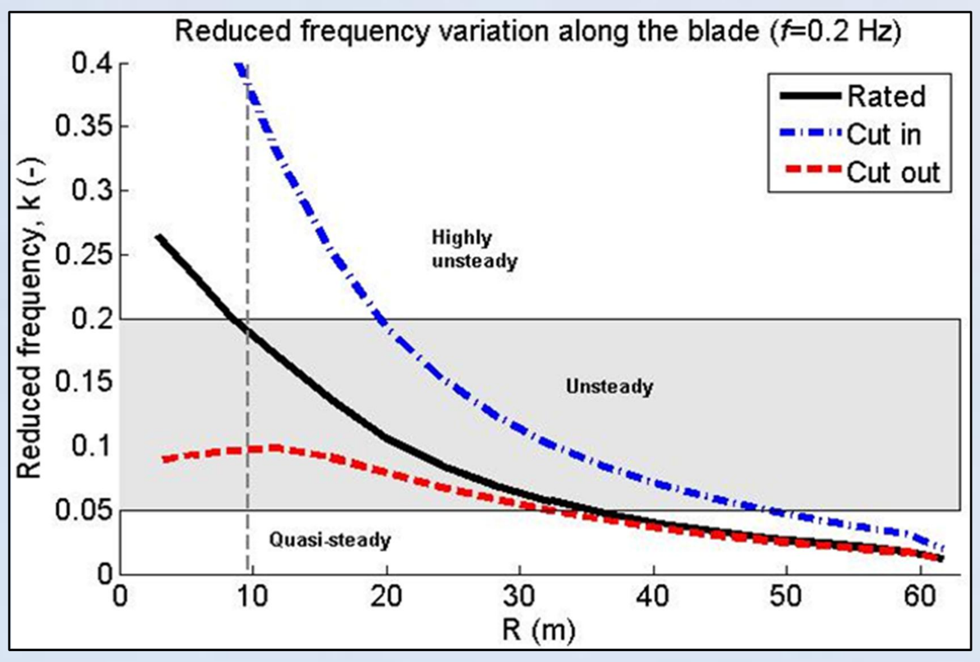

Fig. 1 – Reduced frequency variation along the blade span

Theodorsen showed that fully-attached lift on a rigid blade in harmonic plunging (heaving) and pitching motion can be expressed using Theodorsen's function.

Fig. 2 shows thrust force on the NREL 5 MW turbine's blade in plunging (a) and pitching (b) motion calculated using Theodorsen's function.

Reduction in the thrust force amplitude and phase shift are clearly seen in both motions.

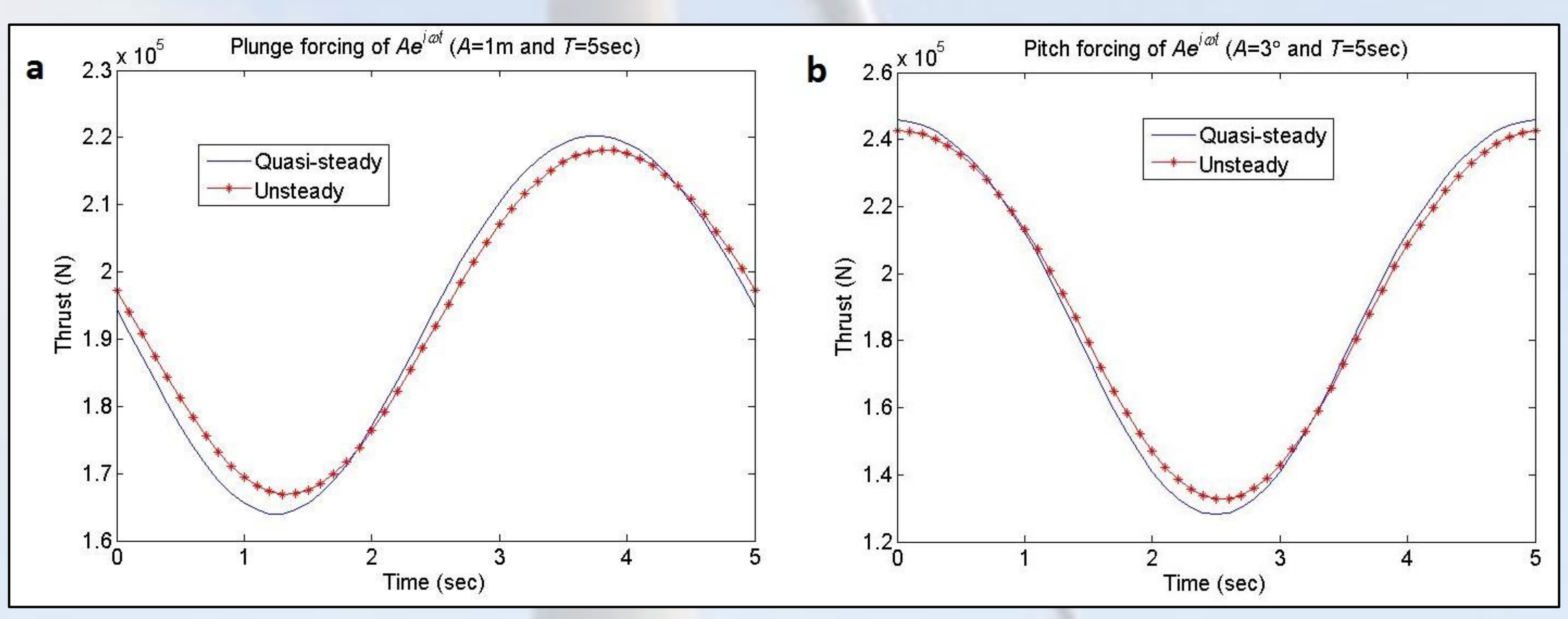

Fig. 2 (a) Thrust force on an NREL 5 MW blade in harmonic plunging; (b) pitching

Theodorsen theory applies only to constant free-stream velocity, which is rarely the case for wind turbines.

Van der Wall and Leishman improved the work of Theodorsen to account for the varying free-stream velocity by inserting it in the Duhamel's integral form.

Also, comapred to Theodorsen's theory, Van der Wall's and Leishman's theory is not constrained to any specific motion.

Fig. 3 (a) shows thrust force on an NREL 5 MW turbine blade calculated using Van der Wall and Leishman model for thin aerofoil theory (thin) and C_L look-up tables (look-up) using quasi-steady and fully-attached unsteady aerodynamics assumption.

Both sets of results show a phase shift and reduction in loading amplitude in the fully-attached unsteady case compared to quasi-steady. This is consistent with findings from Theodorsen theory (Fig. 2 (a) and (b)).

Fig. 3 (b) shows the difference in the amplitude of thrust force as the percentage of quasi-steady. These results show no dependence on amplitude of motion as thin aerofoil theory is purely linear. As the period of motion increases, the fully-attached results tend to quasi-steady.

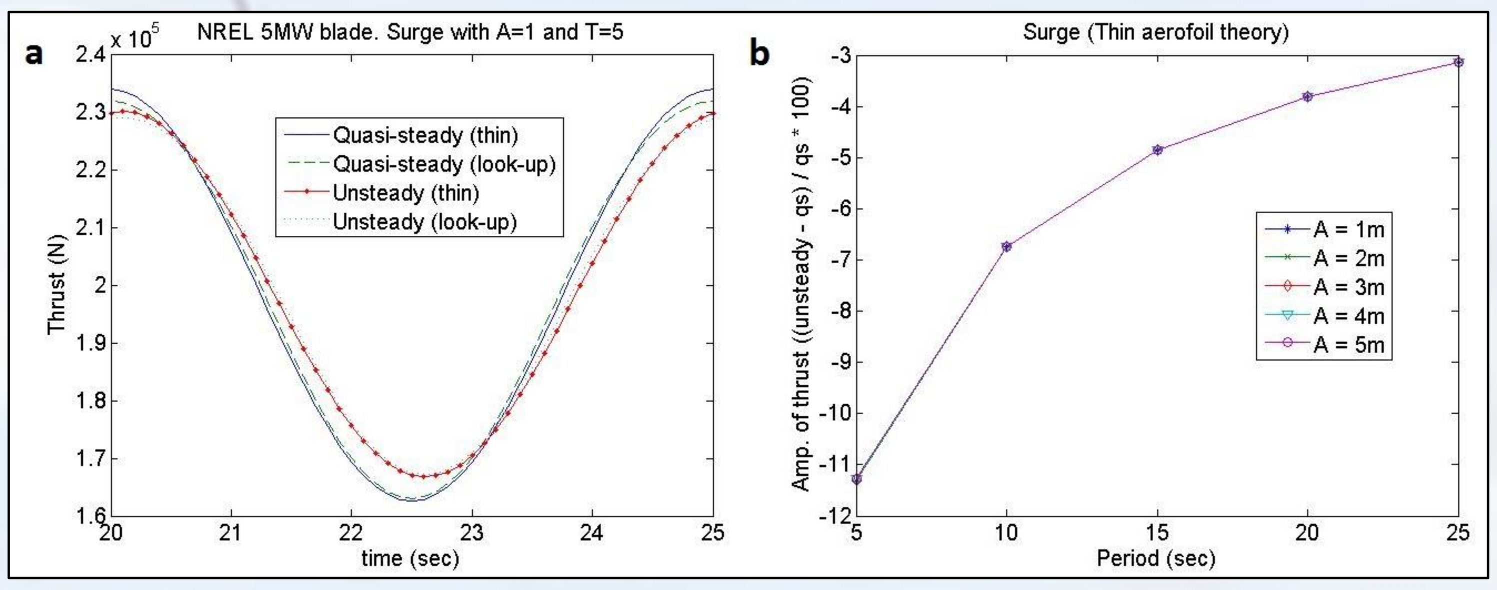

Fig. 3 (a) Thrust force on an NREL 5 MW blade; (b) Percentage difference in thrust amplitude

OC3-Hywind was analysed using FAST. Each degree-of-freedom was simulated separately, and loads on the turbine compared between the quasi-steady and unsteady aerodynamic models.

In Fig. 4 amplitudes of displacement (a) are almost identical, while the amplitude of thrust force on the rotor (b) is significantly larger in the unsteady aerodynamics simulations, which, partially, is the result of the aerodynamic damping, which for 1.57 m displacement in surge, was shown to be 2.3 and 3.7 % for the quasi-steady and unsteady simulations.

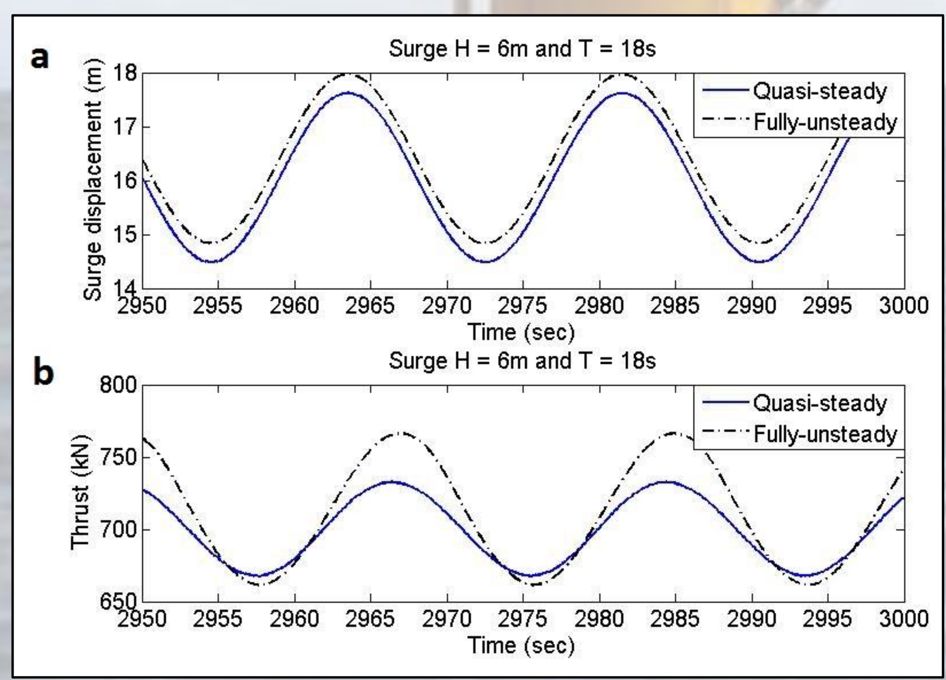

Fig. 4 (a) Surge displacement; (b) Thrust force on the rotor

Tower base side-side moment and the corresponding amplitude spectrum are shown in Fig. 5. Fully-unsteady results show a much large loading on the tower base with many more frequency components present in the amplitude spectrum.

A combination of the 7th wave harmonic and tower side-side mode results in a significant increase of the amplitude of that frequency component.

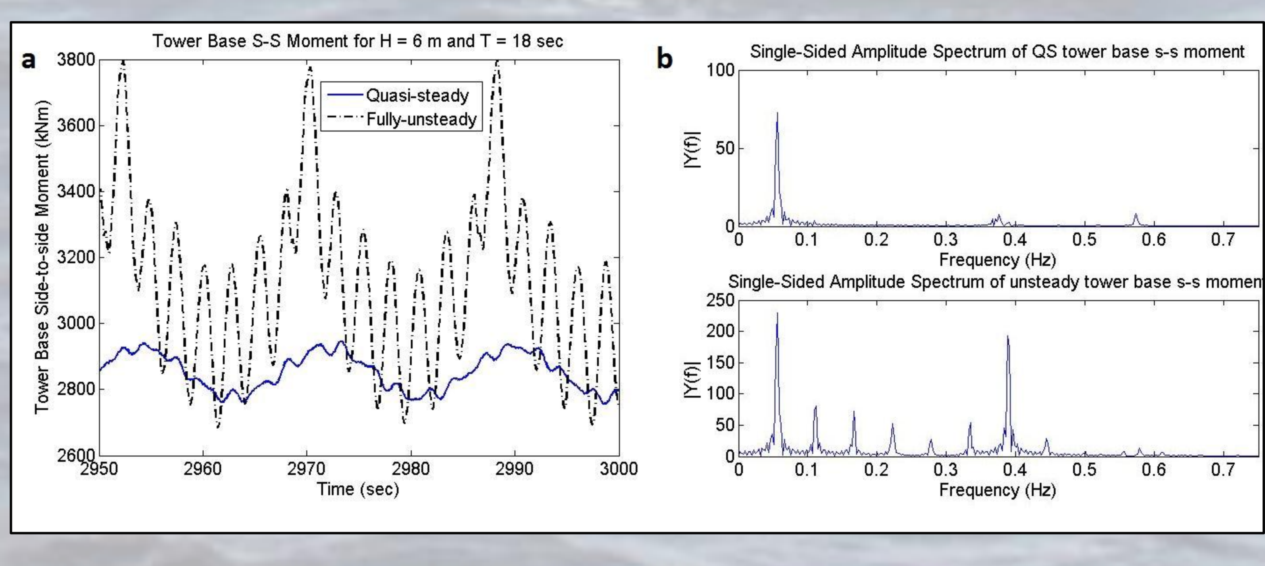

Fig. 5 (a) Tower base side-side moment; (b) Amplitude spectrum of the side-side moment

Conclusions

Two different theories were used to compare quasi-steady and fully-attached unsteady loads on a turbine. Both theories showed a very good agreement of results with fully-attached unsteady loads having a slightly larger mean thrust load, smaller thrust amplitude and a phase lag compared to the quasi-steady results.

Fully-unsteady results, obtained using FAST, showed some similarities to the fully-attached codes. Mainly, in the higher mean loads compared to the quasi-steady results. However, the amplitude of the loading was always larger in the fully-unsteady aerodynamics when compared to quasi-steady loads.

A much higher aerodynamic damping was obtained using fully-unsteady aerodynamics assumption (3.7 % vs. 2.3 % in quasi-steady).

High non-linearity of dynamic inflow leads to more pronounced wave harmonics, which, when coinciding with other natural frequencies of the system, can be very damaging to system.

References

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