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Programme Area: Marine

Project: PerAWAT

Title: Influence of Free Surface Waves on the Performance and Wake Structure of a Ducted Horizontal Axis Tidal Turbine

Abstract:

This deliverable presents the simulation and analysis of the influence of surface waves on the performance, loading and wake of a ducted marine turbine. A full scale rotor is simulated using three-dimensional Computational Fluid Dynamics (Ansys Fluent) in which the rotor is embedded within a rotating sliding mesh within an outer stationary duct. The turbine is subjected to a sheared flow profile with surface waves aligned with the current flow direction. Performance is assessed over a range of tip-speed-ratios.

Context:

The Performance Assessment of Wave and Tidal Array Systems (PerAWaT) project, launched in October 2009 with £8m of ETI investment. The project delivered validated, commercial software tools capable of significantly reducing the levels of uncertainty associated with predicting the energy yield of major wave and tidal stream energy arrays. It also produced information that will help reduce commercial risk of future large scale wave and tidal array developments.

Energy Technologies Institute

PerAWaT

WG3 WP1 D7: Influence of free surface waves on the performance and wake structure of a ducted horizontal axis tidal turbine

Authors C. F. Fleming, R. H. J. Willden

Version 1.0

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Revision History		
Issue / Version	**Issue Date**	**Summary**
0.1	9/12/13	First draft for review by GH
1.0	9/01/14	Final version following review by GH

Executive Summary

This deliverable presents the simulation and analysis of the influence of surface waves on the performance, loading and wake of a ducted marine turbine. A full scale rotor is simulated using three-dimensional Computational Fluid Dynamics (Ansys Fluent) in which the rotor is embedded within a rotating sliding mesh within an outer stationary duct. The turbine is subjected to a sheared flow profile with surface waves aligned with the current flow direction. Performance is assessed over a range of tip-speed-ratios. It is found that surface waves have a detrimental effect on the mean power of the turbine, which is reduced by c. 20% for the waves considered, which is very similar to the power reduction for the bare turbine. Mean thrust is also reduced but to a lesser extent. Blade thrust and power are observed to fluctuate with significant amplitude as the blade rotates (far more so than for the case of shear flow with no waves reported in D4). Blade thrust fluctuates by c. ± 10% about its mean value, whilst blade power fluctuates by c. ± 100% about its mean value. These fluctuations are smaller than those for the bare axial flow turbine (by a factor of around two). Further, the maximum blade torque fluctuation is around the same as the mean blade torque such that the instantaneous torque is rarely negative; compared to the bare axial flow turbine the blades of which experience long periods of negative power contribution. Thus the ducted turbine in sheared flow with waves delivers lower power yield but its blades experience substantially reduced fluctuating loads.

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1 Introduction

The objective of this work is to investigate the effect of free surface waves on the performance of a ducted tidal turbine in sheared flow. The results of this model are compared with corresponding data from deliverable WG3 WP1 D4. In that deliverable, a full scale ducted tidal turbine is simulated in a variety of sheared flow conditions and a non-deforming free surface. One of the cases from the D4 parametric study is reproduced here, so that the effect of wave action on performance and wake recovery may be examined.

Relevant details of the D4 model, such as blockage and boundary conditions, are given in section 3. Alterations to this model, some of which have been described already in deliverables D5 and D6, are also discussed.

In deliverable D6 it has been seen that the impact of perturbations to wave parameters; height, wavelength and flow alignment, is only slight on the performance and wake recovery of a bare axial flow turbine. In the present work, due to time constraints at the end of the project, and following guidance from the Steering Committee (meeting held 11th September 2013) the simulation stencil was curtailed to examine the performance and wake recovery of the ducted turbine in the presence of a single wave state (the base wave state used in the D6 deliverable). Multiple tip-speed-ratios are considered to develop a useful power curve.

Finally, a standardized presentation of the results for the full set of simulated cases is given in the Appendix.

2 Deliverable objectives

The aim of this deliverable is to examine the influence of free surface waves on the performance, loading and wake structure of a ducted axial flow tidal turbine. The computational model developed in deliverables D1 - D4 has been extended in deliverables D5 and D6 to allow free surface waves in combination with a sheared velocity profile.

The case of waves aligned with the current direction is then investigated and compared to the case with no waves (Rigid lid base case from D4). Perturbations on wavelength, wave height and wave alignment are not considered (see Introduction).

The near wake model developed in D4 is also compared with wake data from the present simulations.

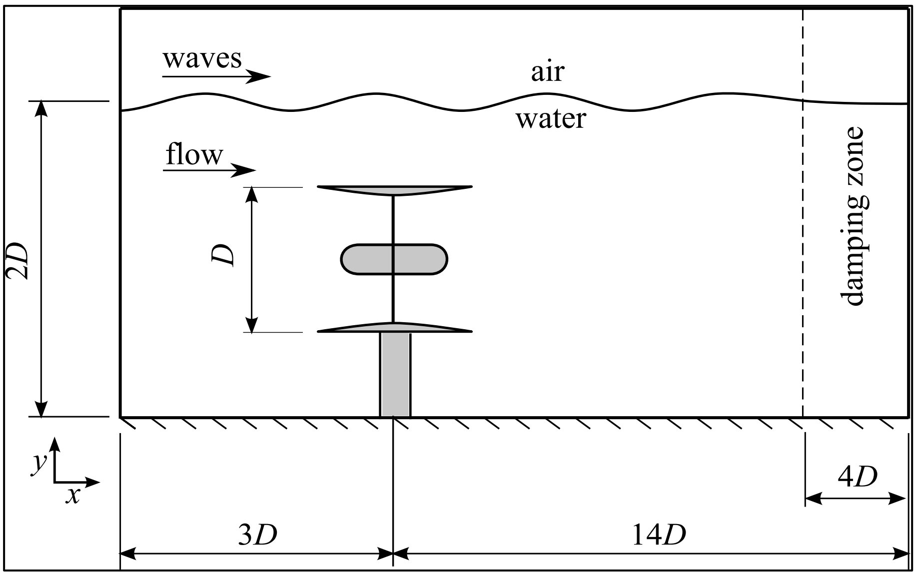
3 Computational model

The Reynolds averaged Navier-Stokes (RANS) equation model presented in D5 had the capacity to model linear free surface waves using an open channel wave boundary condition, which is a built-in feature of ANSYS Fluent v14.5 and is based on the volume of fluid (VOF) method. However, this wave model was found to be incompatible with a sheared velocity profile.

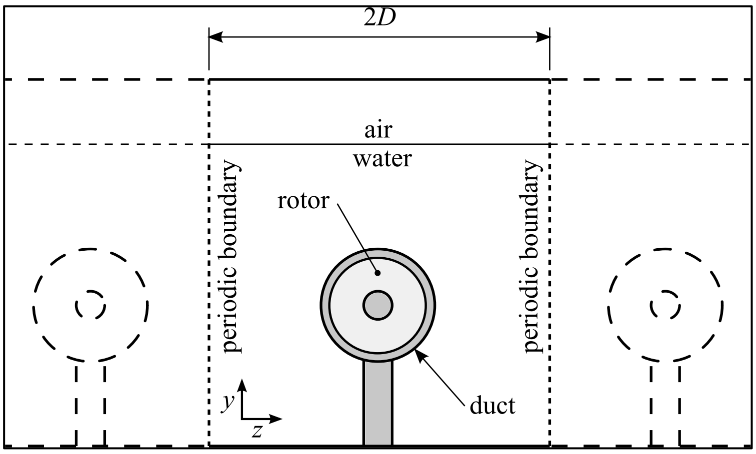
3.1 D4 Model - reference case without waves

The current model is based on case ‘Q’ from deliverable WG3 WP1 D4. This case is a simulation of the PerAWaT ducted turbine, which has outer diameter equal to that of the bare axial flow turbine considered in D4 and D6, in a numerical channel measuring $4D$ in width and $2D$ in height. The resulting area blockage is B = 9.8%. Symmetry conditions at the lateral boundaries represent an infinite fence of such turbines with a centre-to-centre spacing of $4D$. A symmetry condition is applied at the upper boundary, approximating the free surface as a rigid lid. A bed roughness coefficient of $c_f = 0.0035$ (corresponding to the lower shear case ‘S1’ in deliverable D4) is prescribed at the lower boundary of the domain. The effect of this condition is to maintain the sheared velocity profile that is applied at the inlet to the domain.

3.2 Alterations to D4 rigid lid model



(a)



(b)

Figure 1: (a) Elevation and (b) end views of the ducted turbine with a deforming free surface model.

As was the case for the axial flow turbine in waves presented in D6, the domain is lengthened in the streamwise direction relative to that used in the rigid lid cases of D4, to extend 14D downstream of the rotor plane, with the final 4D used as a wave damping zone. An additional mesh region is added above the mean water line to enable simulation of the air phase and the air-water interface.

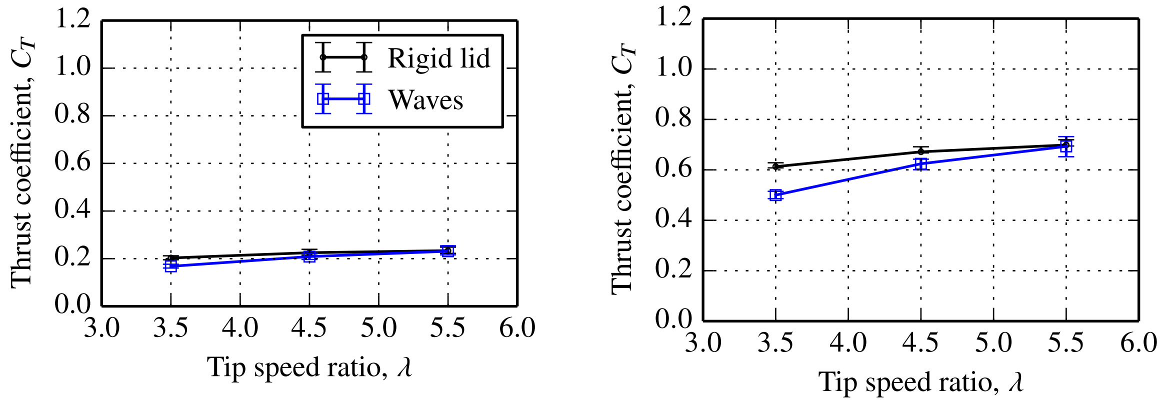
4 Parametric Study

The flow past the ducted turbine in the presence of a representative wave is simulated at each of three tip speed ratios so as to capture the peak power operating point of the turbine. Details of the simulation cases for this deliverable are tabulated below, and the simulation results included in the Appendix.

Table 1: Simulation matrix for deliverable D7.

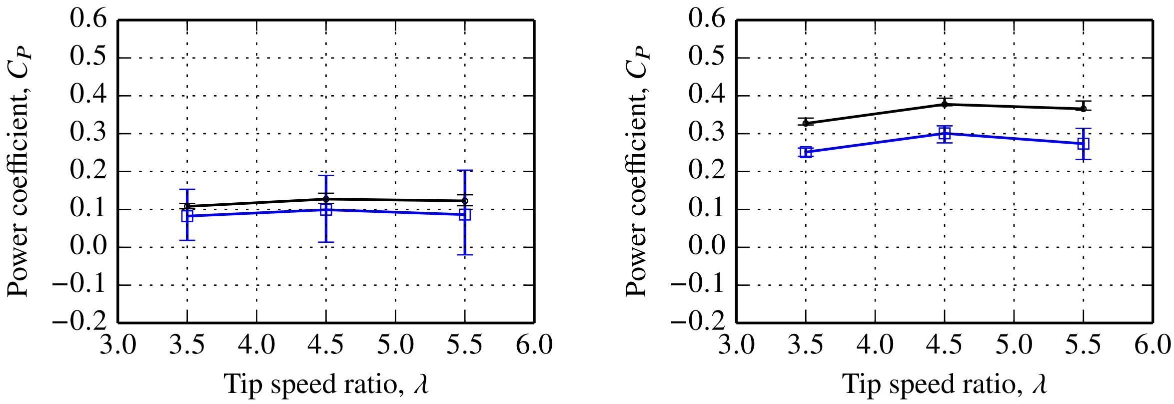
Case	Wavelength, λ_w [m]	Height, H_w [m]	Heading, ϕ_w [°]	Tip speed ratio, λ
1	55	1	0	3.5
2	55	1	0	4.5
3	55	1	0	5.5

5 Influence of waves



(a) Blade thrust coefficient

(b) Rotor thrust coefficient



(c) Blade power coefficient

(d) Rotor power coefficient

Figure 2: Comparison of thrust and power for rigid lid and waves cases.

We start by noting the form of the ducted power and thrust curves in the case of a rigid lid (now waves) upper boundary condition. These are the simulations reported in D4 and reproduced in part in Section 6 for ease of reference. The power reaches a peak value of $C_{P\,max} = 0.377$ which is substantially less than that for the bare axial flow turbine of the same total outer diameter $C_{P\,max} = 0.466$ (see D4 and D6). Further we note that this power is achieved at lower rotor thrust as there is also substantial thrust on the duct itself (see D4 for further details).

Also of note for the rigid lid case is that the magnitude of the fluctuations (due to vertical shear) in both thrust and power coefficients, for both rotor and blade, are reduced for the ducted turbine relative to the bare turbine (see both the vertical bars in the summary Figures 2 or 3, and the time traces of Section 6). This can be attributed to the effect of the duct aligning (unshearing) the approaching velocity profile around the mouth of the duct. The resulting rotor thrust and torque ripple are barely discernable.

Turning to the case with waves we observe (see Table 2 below) a modest reduction in the peak turbine power of 20% relative to the rigid lid case. This is almost precisely the same reduction observed for the axial flow turbine in the presence of the same waves. However, in the ducted turbine case the magnitude of the fluctuating components of blade and rotor thrust and power are reduced relative to those of the bare turbine. For the bare turbine case the largest fluctuations were seen in blade power, of c. 200% blade mean power. For the ducted case the blade power again exhibits the largest fluctuations but these are now of magnitude c. 100% blade mean power with only limited negative power / torque observed. This pattern is repeated across all quantities, with the duct acting to substantially reduce the magnitude of the load fluctuations experienced by the turbine.

As in the axial flow turbine case rotor power and thrust spectra are dominated by the wave frequency, whilst blade spectra are dominated by the rotational frequency (although this is not clear for the 5.5 tip-speed-ratio case due to the close proximity of the rotational and wave frequencies).

The wake of the ducted turbine is seen to recover faster, pressure equalization at around 2D downstream of rotor plane, than occurred in the absence of waves. This behaviour is noted to be similar to that for the bare axial flow turbine.

Table 2: The effect of waves on peak thrust and power of a ducted turbine.

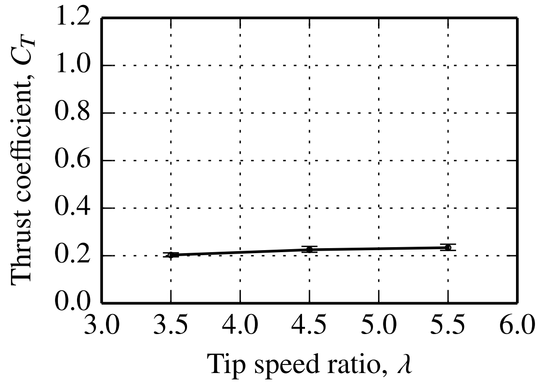
Case	$C_{P\,max}$	$C_T\ at\ C_{P\,max}$
Rigid lid	0.377	0.672
Waves, $H_W = 1$m	0.300	0.624

6 Reference case - Rigid Lid

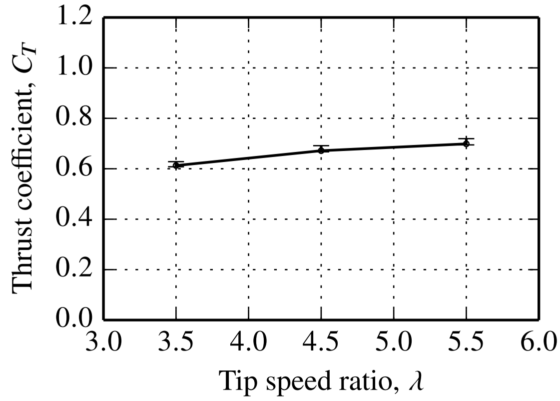
6.1.1 Details

This “no wave” case corresponds to case ‘Q’ from deliverable WG3 WP1 D4. The bed roughness coefficient, which governs the level of velocity shear, is $c_f = 0.0035$.

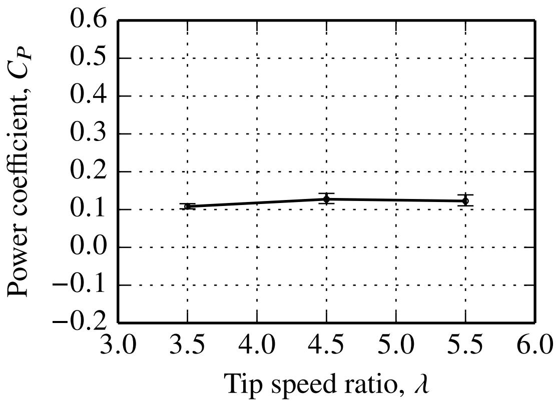
6.1.2 Performance



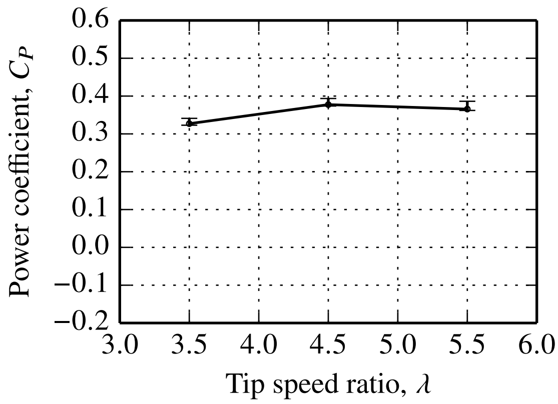
(a) Blade thrust coefficient



(b) Rotor thrust coefficient



(c) Blade power coefficient



(d) Rotor power coefficient

Figure 3: Blade and rotor thrust and power coefficients for the “no wave” reference case. Time mean values are displayed as points and vertical bars represent the range of the computed quantity.

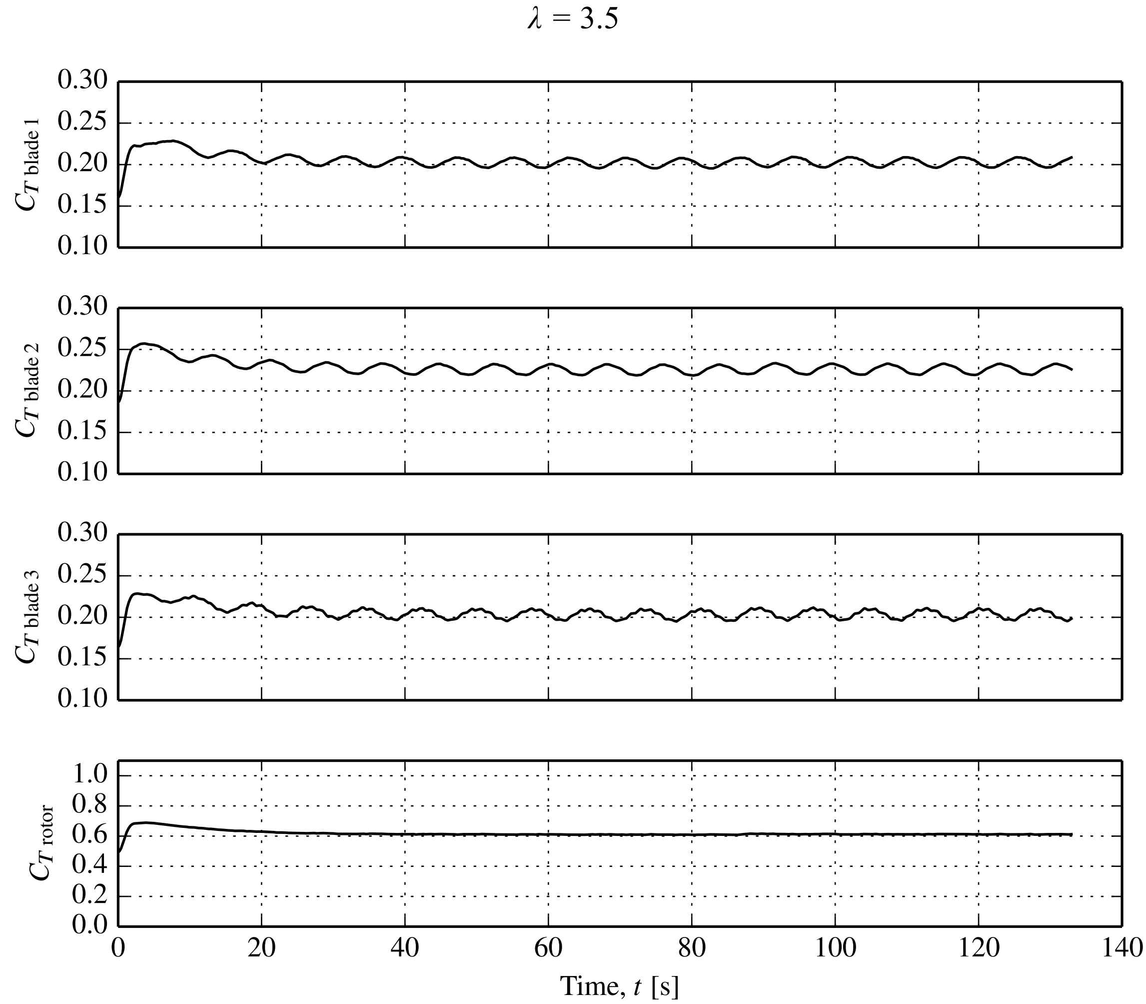


Figure 4: Blade and rotor load histories. Rigid lid case, λ = 3.5.

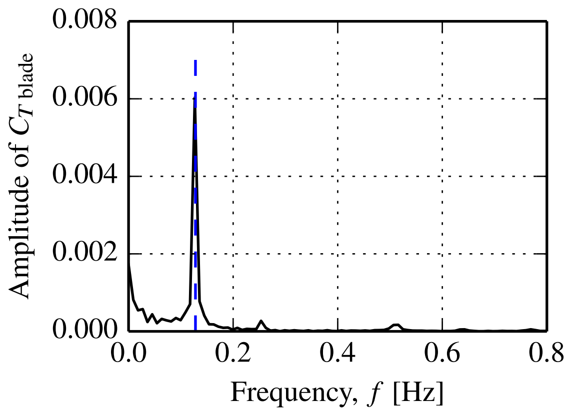


Figure 5: Blade thrust spectrum. Blue - rotor frequency. Rigid lid case, λ = 3.5.

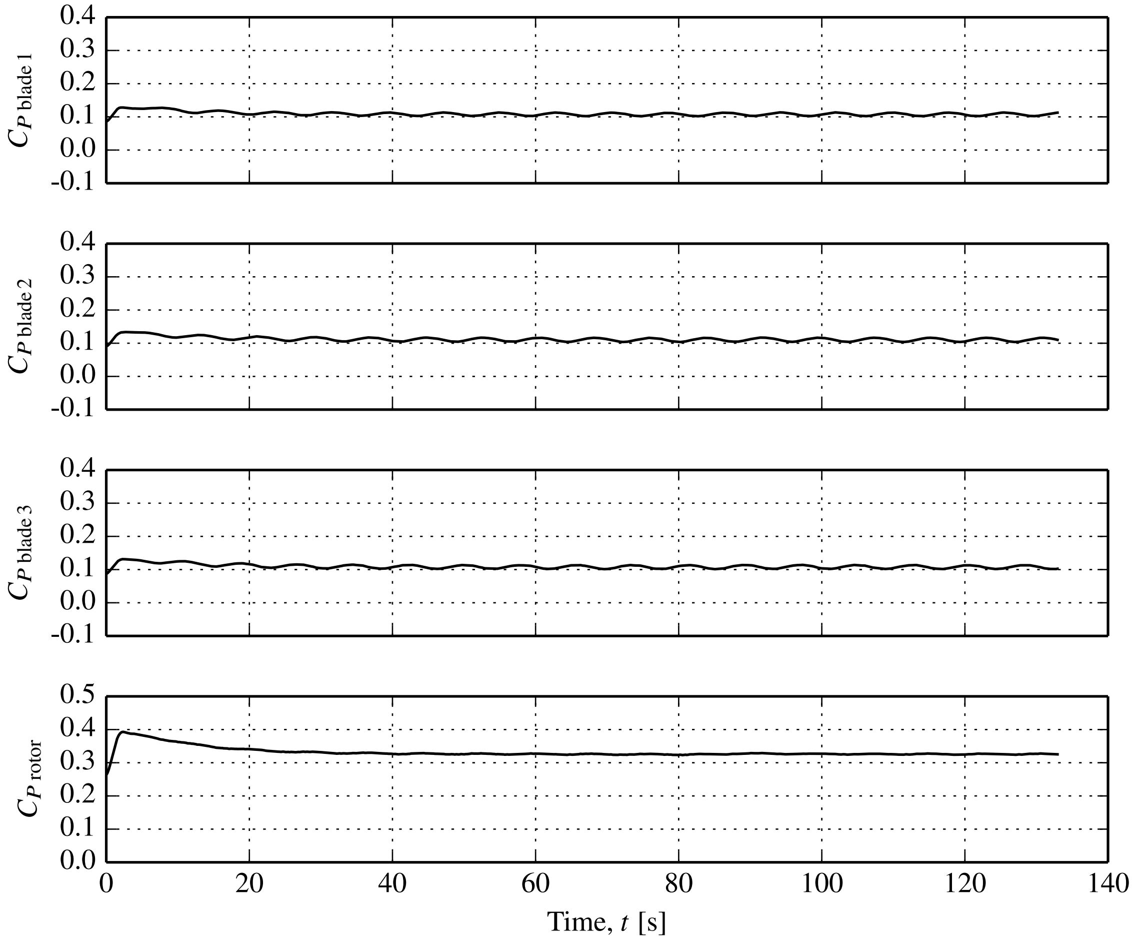


Figure 6: Blade and rotor power histories. Rigid lid case, λ = 3.5.

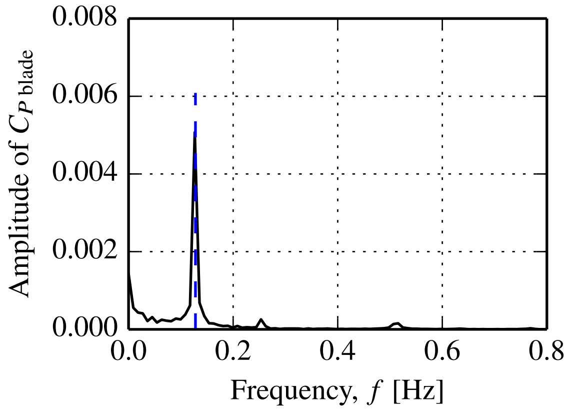


Figure 7:Blade power spectrum. Blue - rotor frequency. Rigid lid case, λ = 3.5.

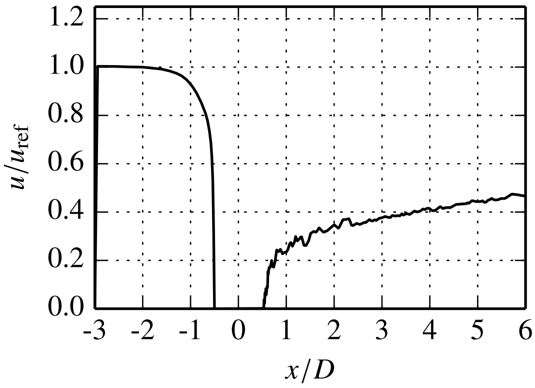


Figure 8: Centre-line streamwise velocity component. Rigid lid case, λ = 3.5.

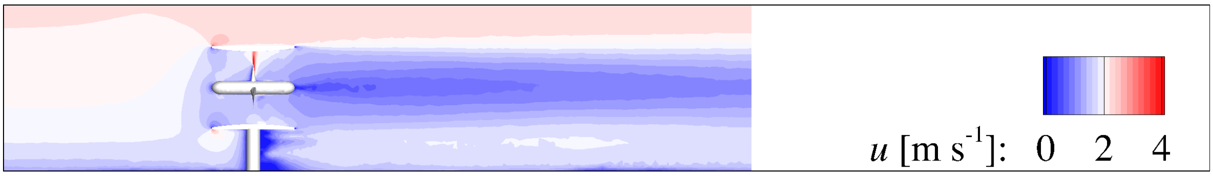


Figure 9: Centre plane velocity field. Rigid lid case, λ = 3.5.

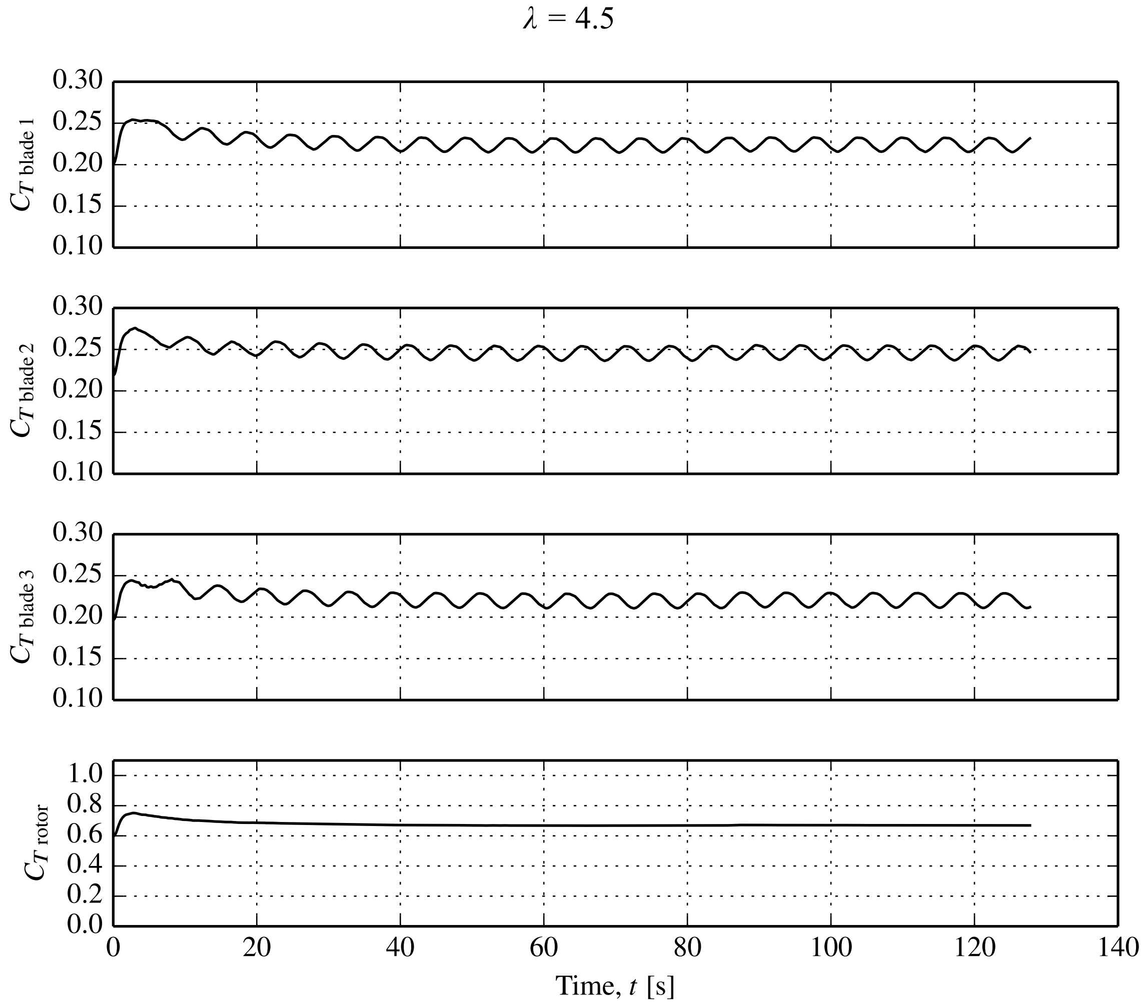


Figure 10: Blade and rotor load histories. Rigid lid case, λ = 4.5.

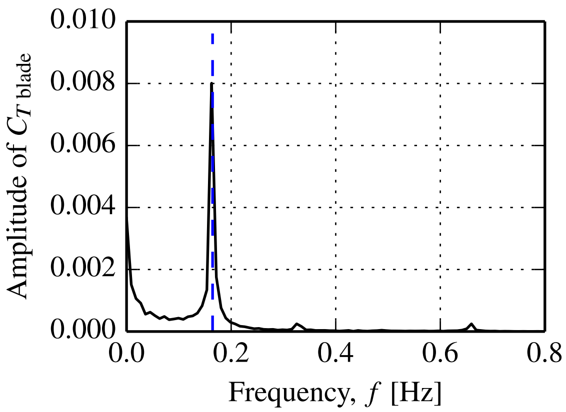


Figure 11: Blade thrust spectrum. Blue - rotor frequency. Rigid lid case, λ = 4.5.

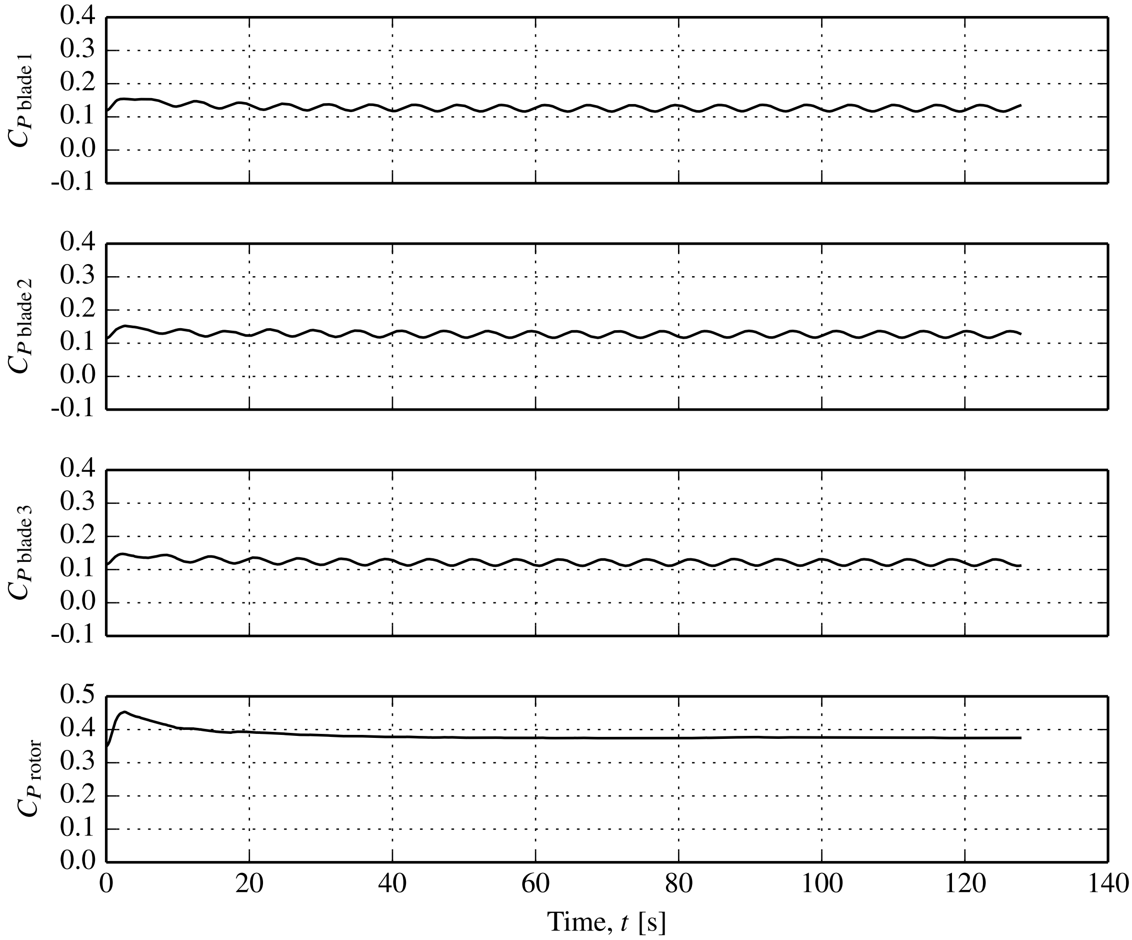


Figure 12: Blade and rotor power histories. Rigid lid case, λ = 4.5.

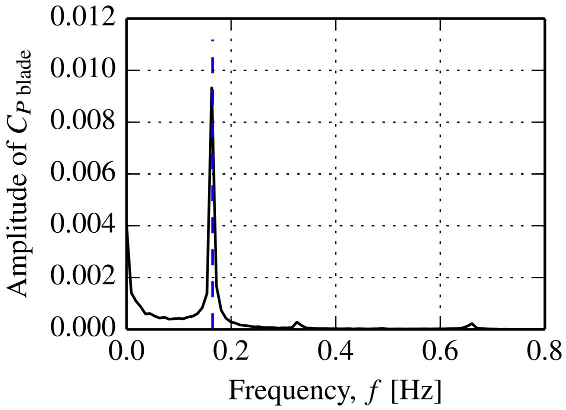


Figure 13: Blade power spectrum. Blue - rotor frequency. Rigid lid case, λ = 4.5.

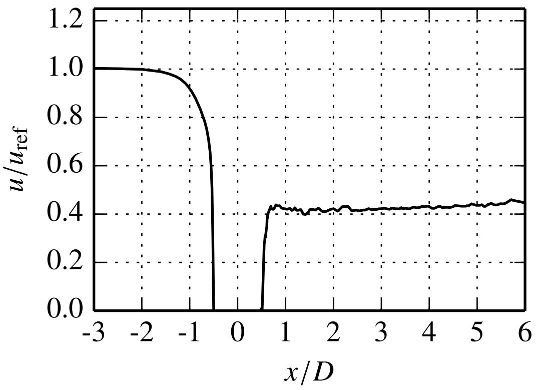


Figure 14: Centre-line streamwise velocity component. Rigid lid case, λ = 4.5.

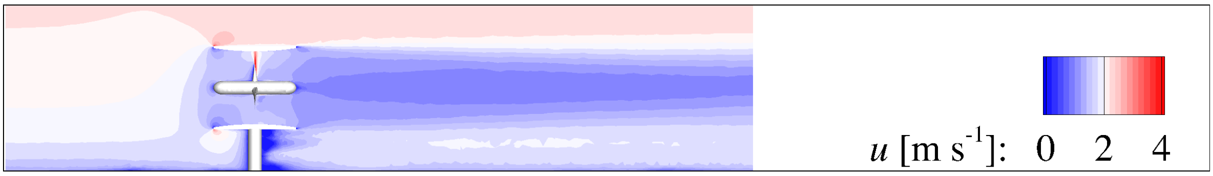


Figure 15: Centre plane velocity field. Rigid lid case, λ = 4.5.

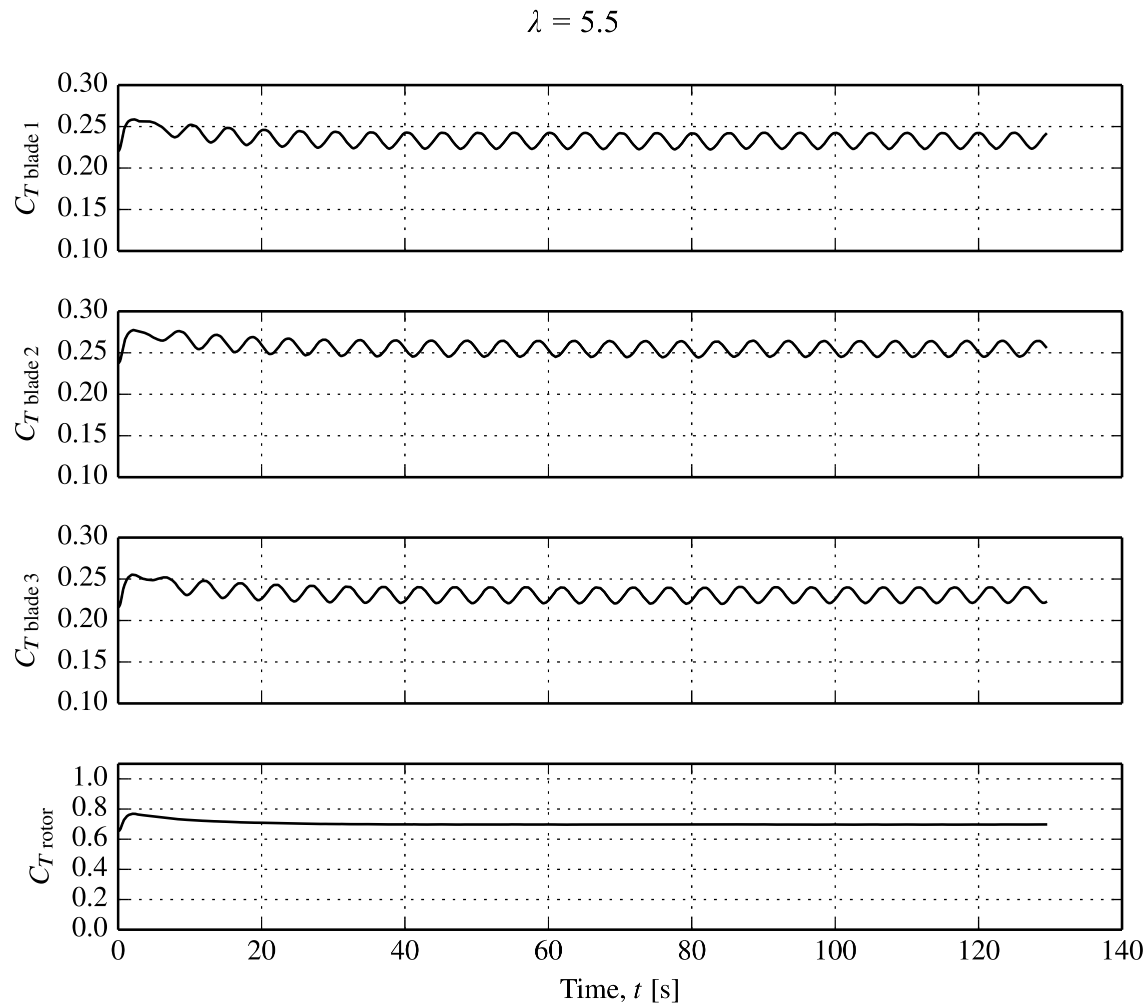


Figure 16: Blade and rotor load histories. Rigid lid case, λ = 5.5.

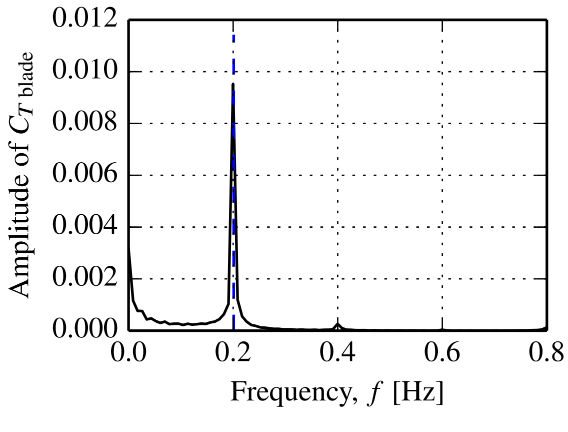


Figure 17: Blade thrust spectrum. Blue - rotor frequency. Rigid lid case, λ = 5.5.

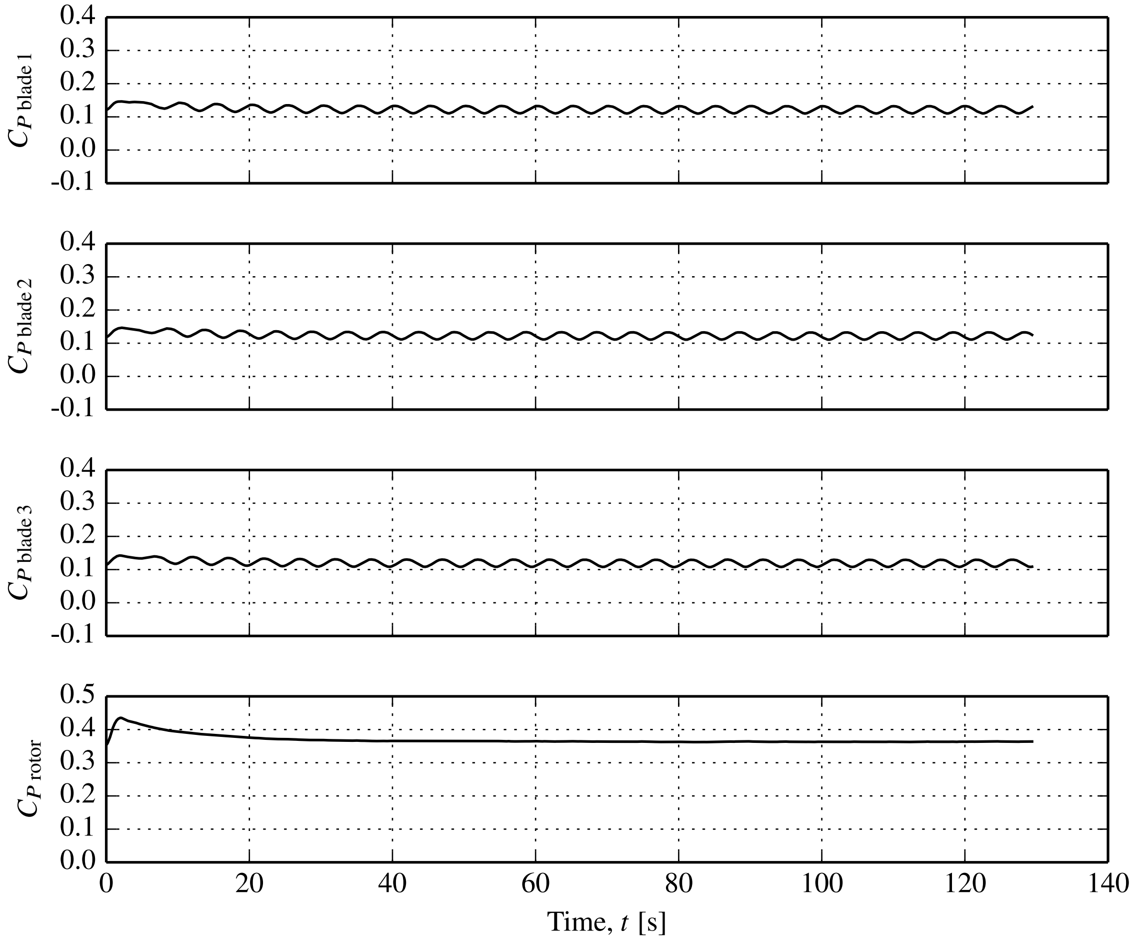


Figure 18: Blade and rotor power histories. Rigid lid case, λ = 5.5.

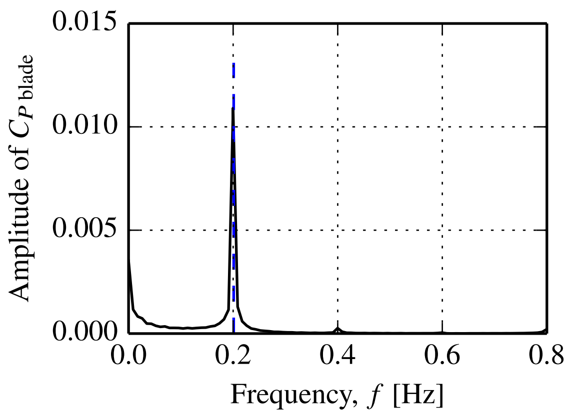


Figure 19: Blade power spectrum. Blue - rotor frequency. Rigid lid case, λ = 5.5.

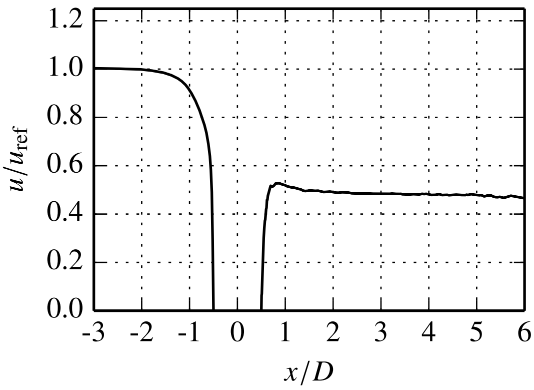


Figure 20: Centre-line streamwise velocity component. Rigid lid case, λ = 5.5.

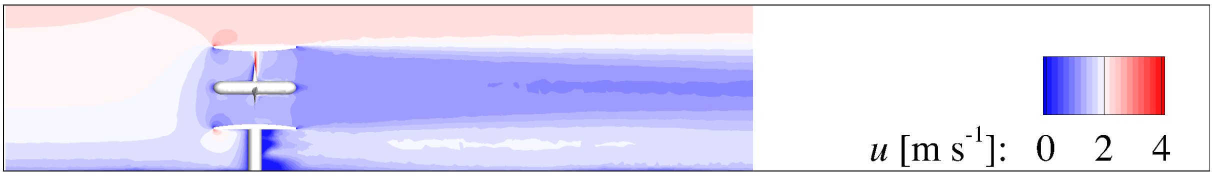


Figure 21: Centre plane velocity field. Rigid lid case, λ = 5.5.

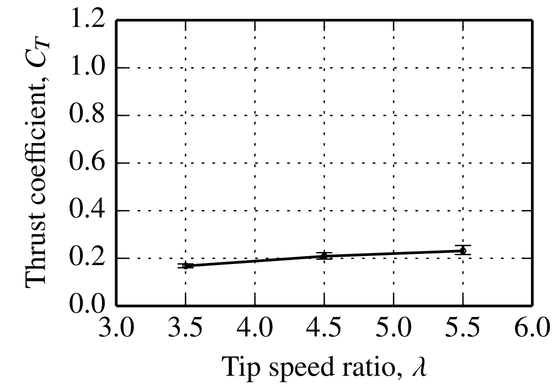
Appendix

6.2 Case 1 - Base case

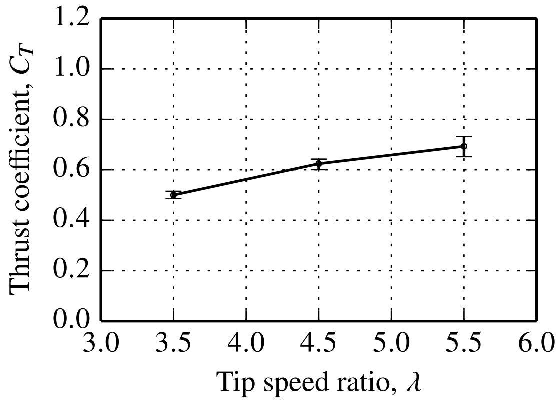
6.2.1 Details

λ_{w}	55 m
H_{w}	1 m
ϕ_{w}	0°

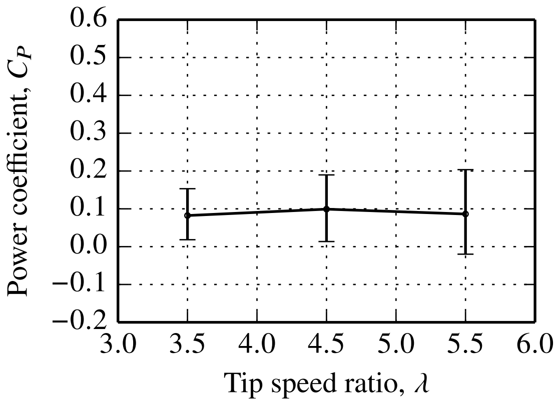
6.2.2 Performance



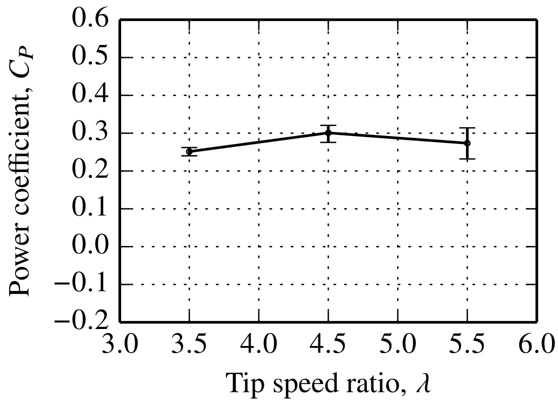
(a) Blade thrust coefficient



(b) Rotor thrust coefficient



(c) Blade power coefficient



(d) Rotor power coefficient

Figure 22: Blade and rotor thrust and power coefficients for the wave base case. Time mean values are displayed as points and vertical bars represent the range of the computed quantity.

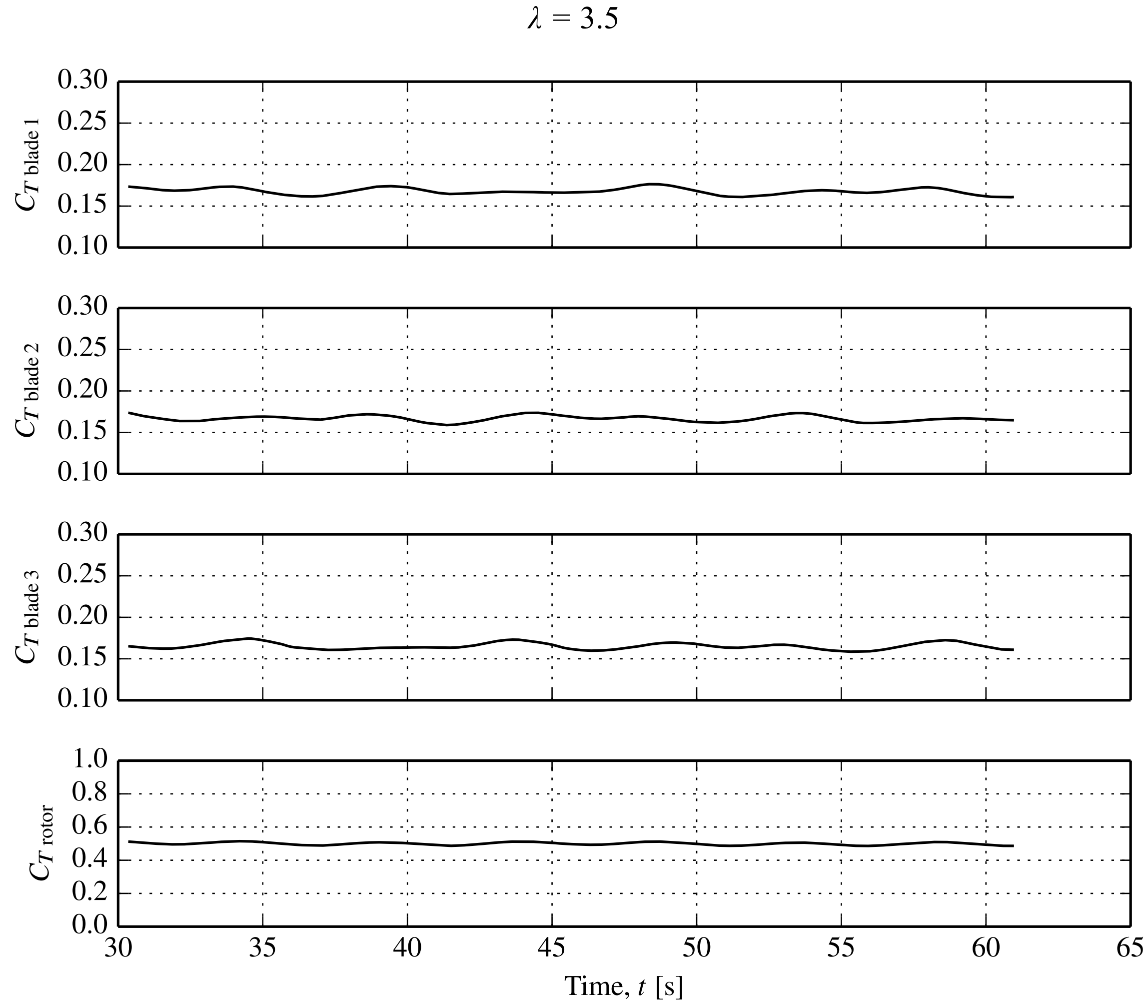


Figure 23: Blade and rotor load histories. Wave height = 1 m, wave length = 55 m, λ = 3.5.

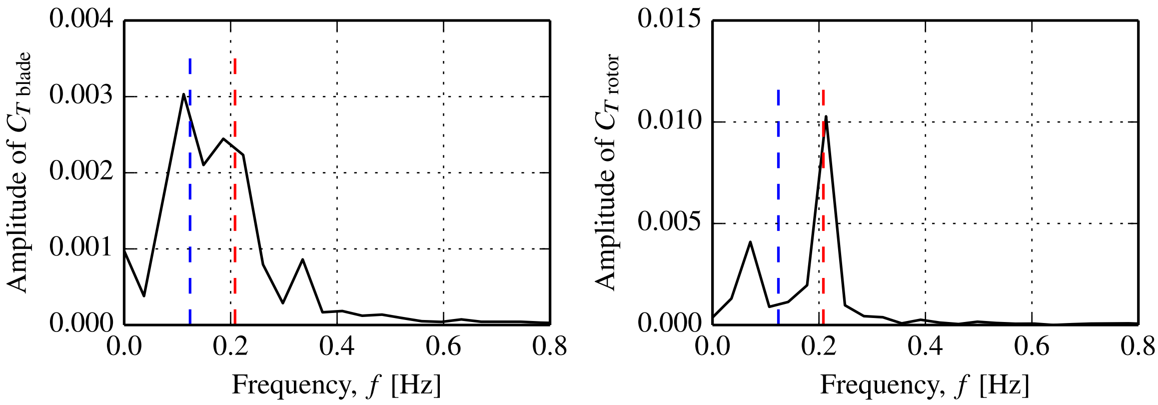


Figure 24: Thrust spectra; (a) blade, (b) rotor. Blue - rotor frequency, red - wave frequency. Rigid lid case, λ = 3.5.

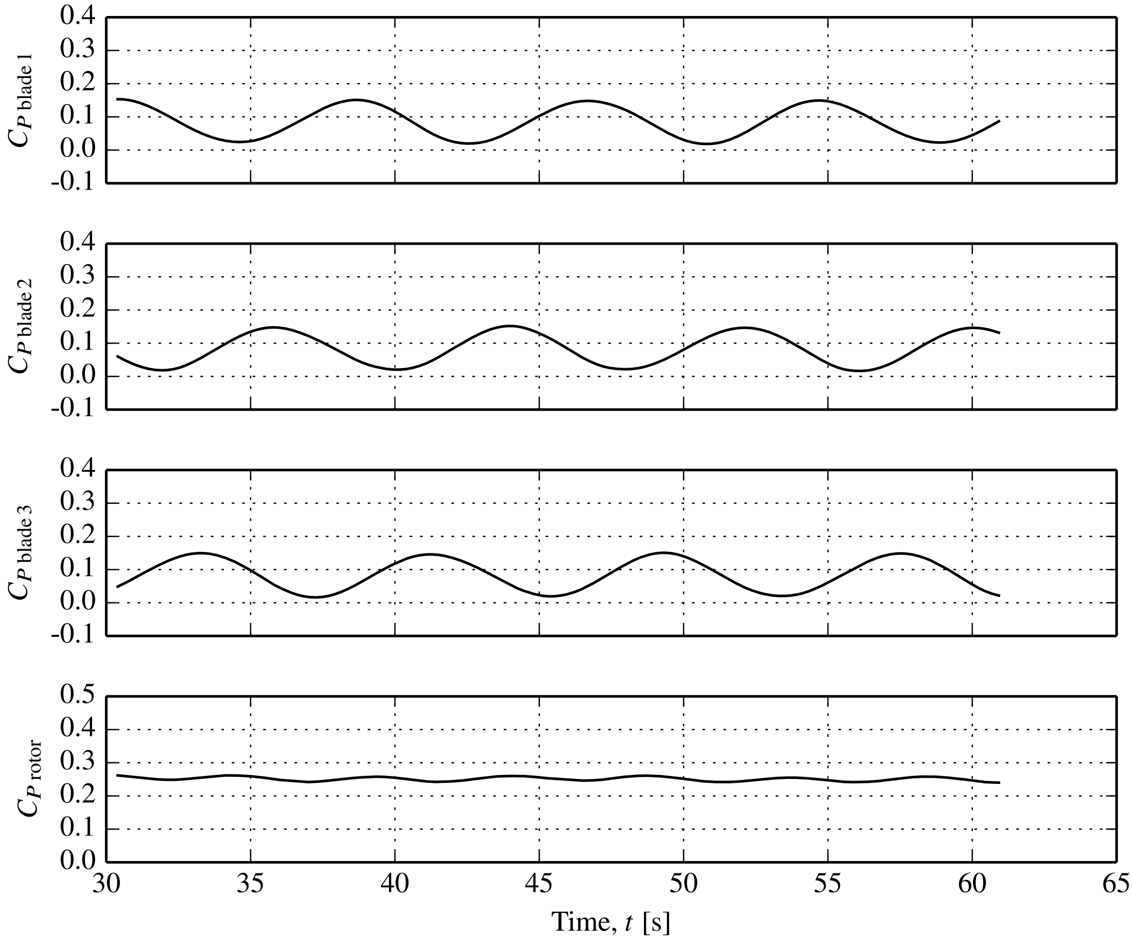


Figure 25: Blade and rotor power histories. Wave height = 1 m, wave length = 55 m, λ = 3.5.

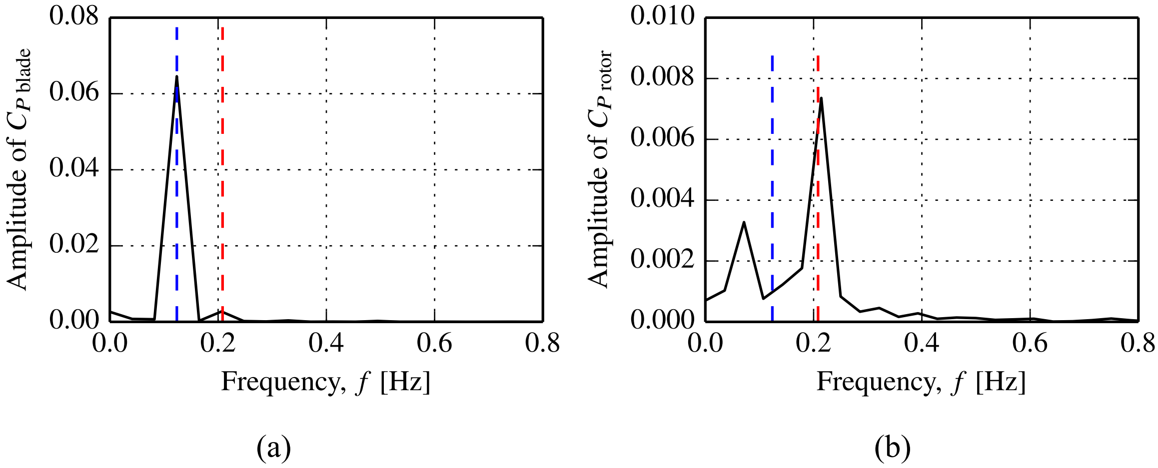


Figure 26: Power spectra; (a) blade, (b) rotor. Blue - rotor frequency, red - wave frequency. Wave height = 1 m, wave length = 55 m, λ = 3.5.

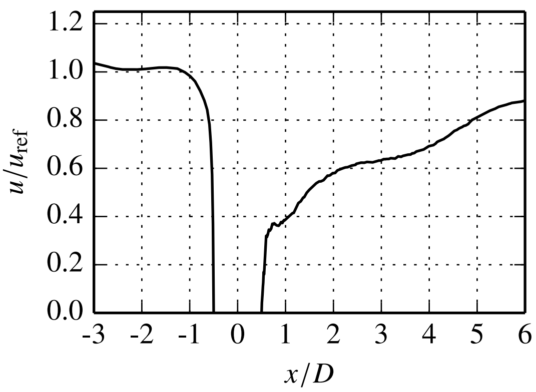


Figure 27: Centre plane velocity field. Wave height = 1 m, wave length = 55 m, λ = 3.5.

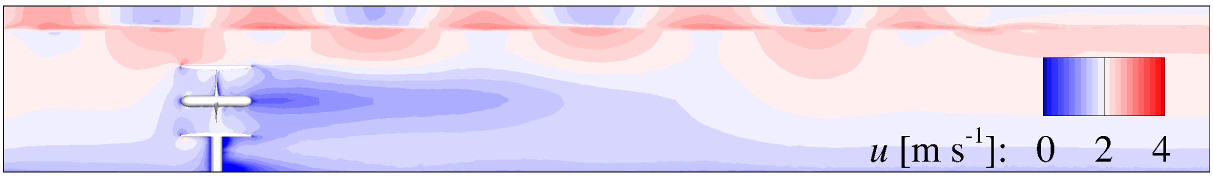


Figure 28: Centre-line streamwise velocity component. Wave height = 1 m, wave length = 55m, λ = 3.5.

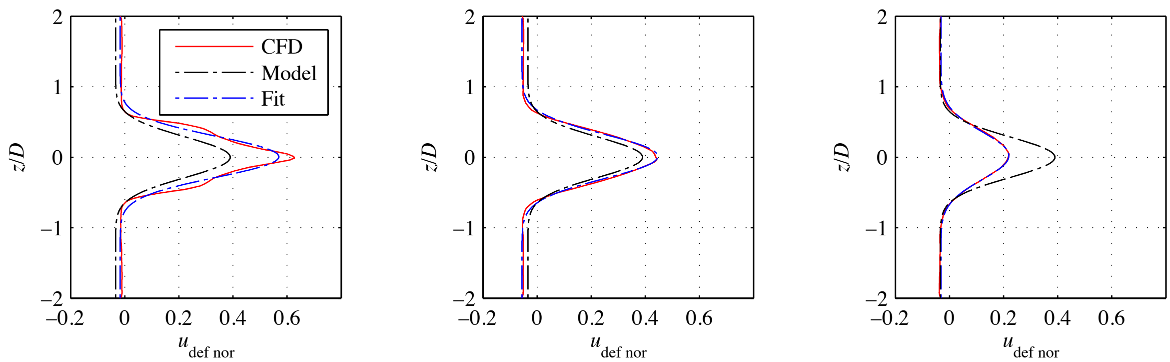


Figure 29: Parametric model of wake velocity deficit (Left to right, x =1D, 2D, 5D). Wave height = 1 m, wave length = 55 m, λ = 3.5.

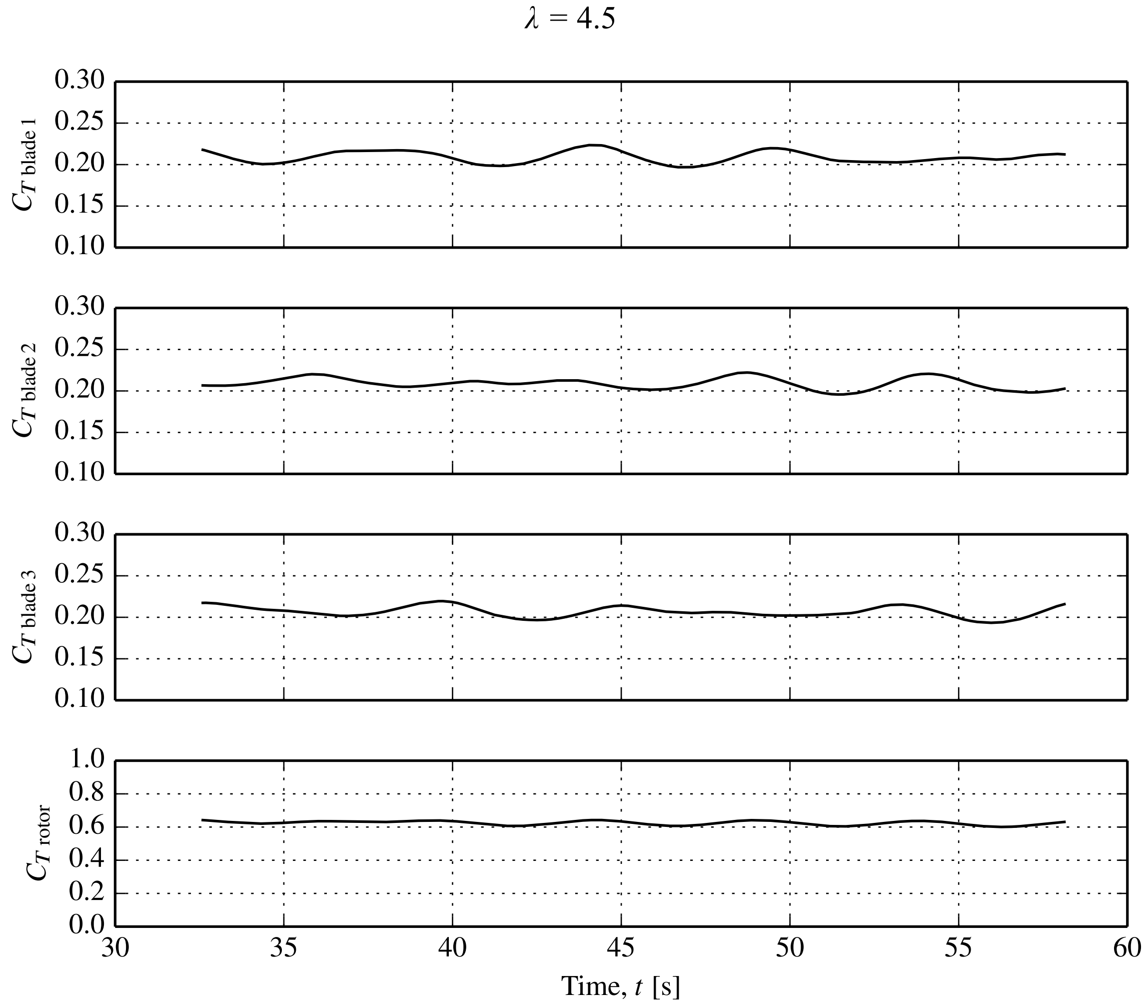


Figure 30: Blade and rotor load histories. Wave height = 1 m, wave length = 55 m, λ = 4.5.

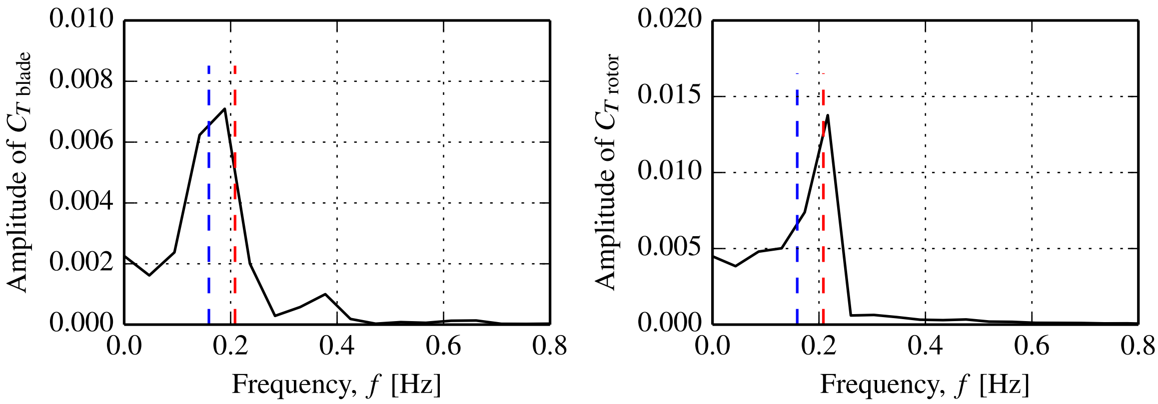


Figure 31: Thrust spectra; (a) blade, (b) rotor. Blue - rotor frequency, red - wave frequency. Wave height = 1 m, wave length = 55 m, λ = 4.5.

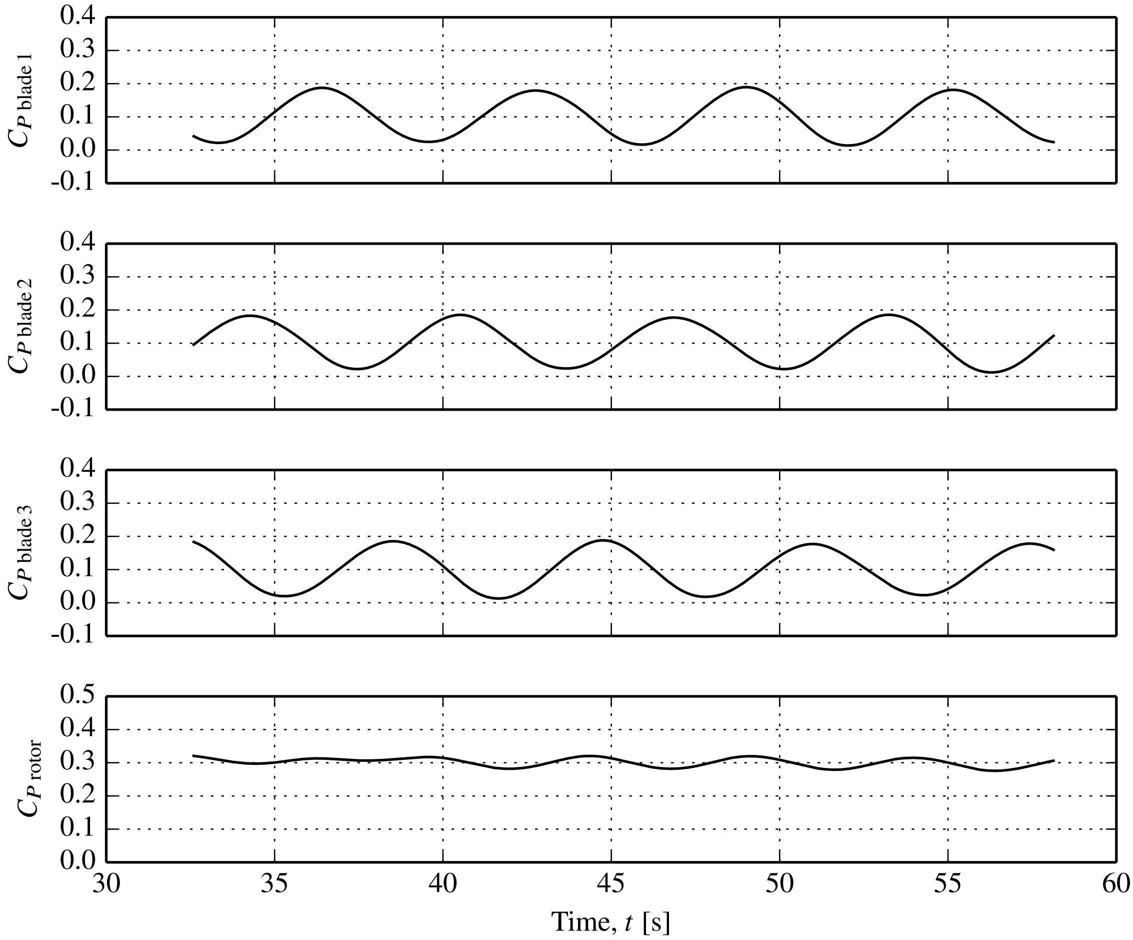


Figure 32: Blade and rotor power histories. Wave height = 1 m, wave length = 55 m, λ = 4.5.

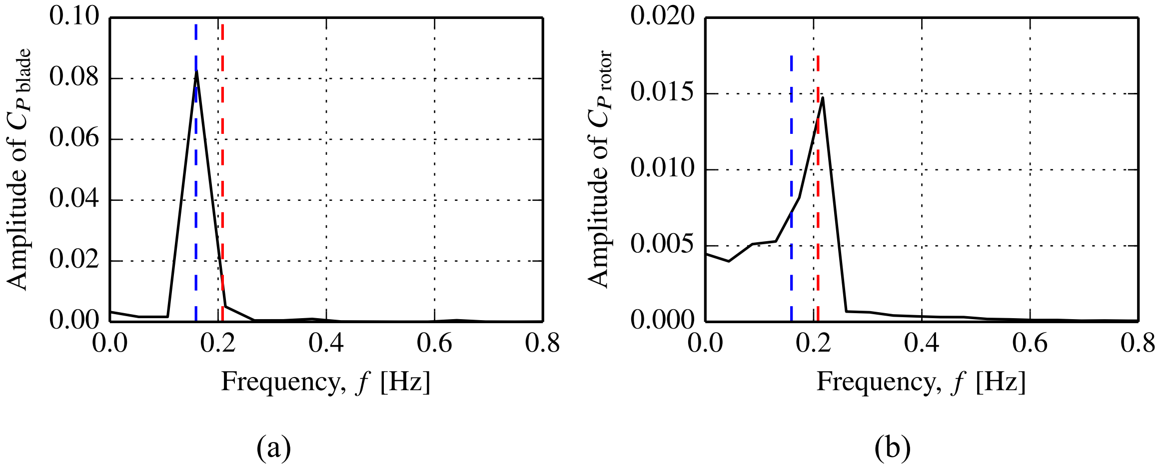


Figure 33: Power spectra; (a) blade, (b) rotor. Blue - rotor frequency, red - wave frequency. Wave height = 1 m, wave length = 55 m, λ = 4.5.

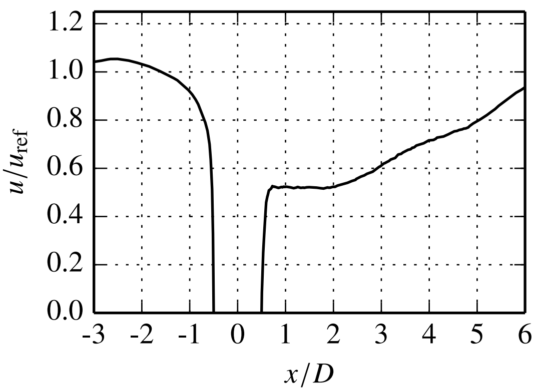


Figure 34: Centre plane velocity field. Wave height = 1 m, wave length = 55 m, λ = 4.5.

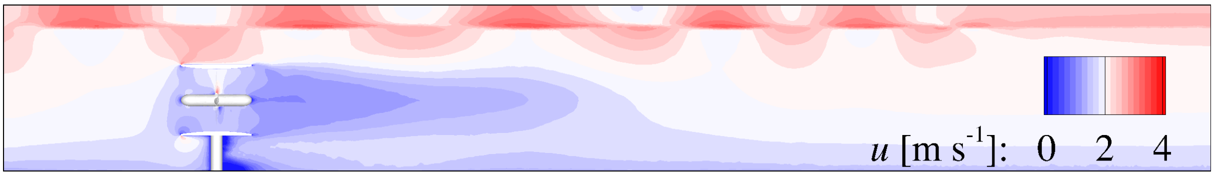


Figure 35: Centre-line streamwise velocity component. Wave height = 1 m, wave length = 55m, λ = 4.5.

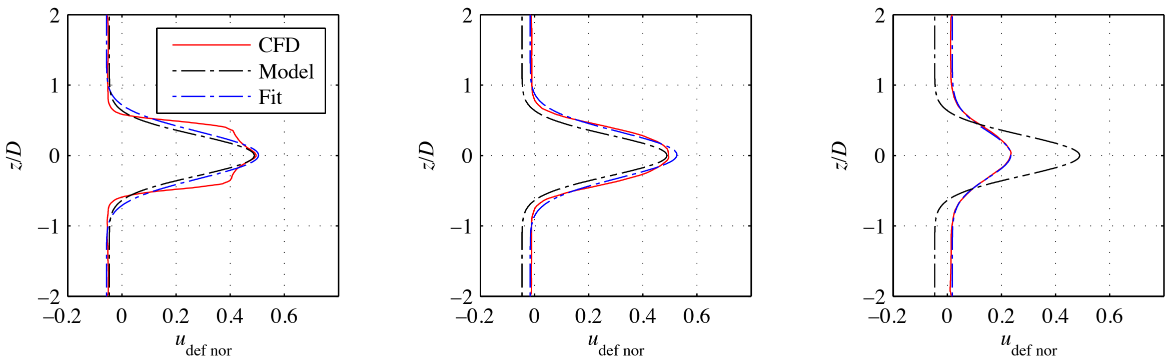


Figure 36: Parametric model of wake velocity deficit (Left to right, x =1D, 2D, 5D). Wave height = 1 m, wave length = 55 m, λ = 4.5.

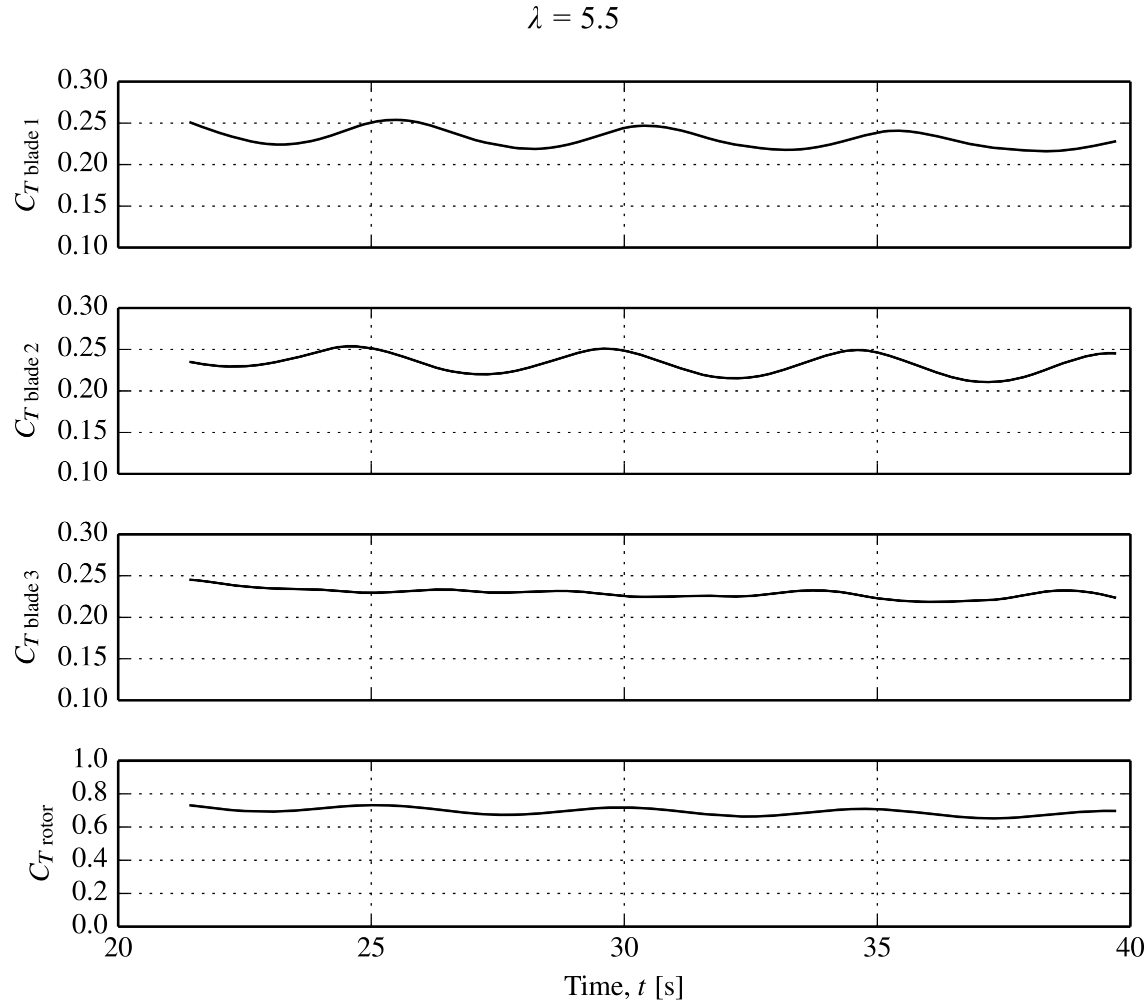


Figure 37: Blade and rotor load histories. Wave height = 1 m, wave length = 55 m, λ = 5.5.

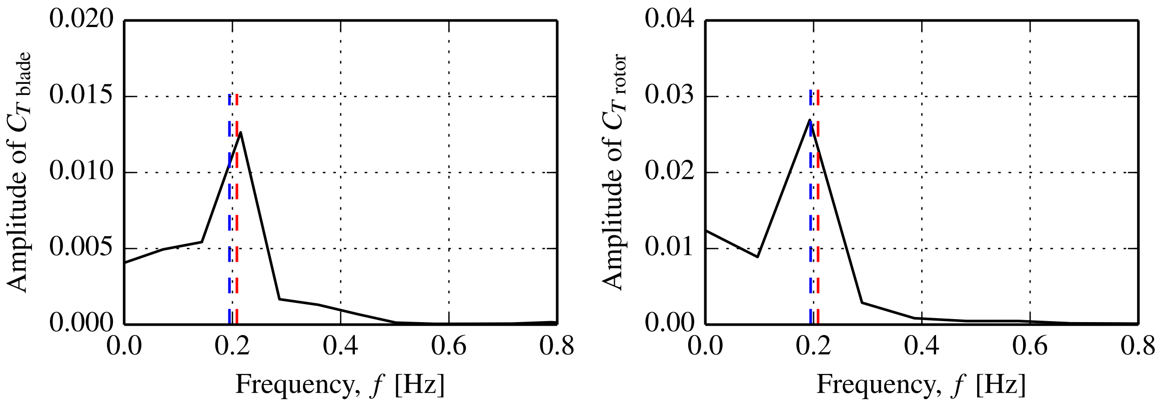


Figure 38: Thrust spectra; (a) blade, (b) rotor. Blue - rotor frequency, red - wave frequency. Wave height = 1 m, wave length = 55 m, λ = 5.5.

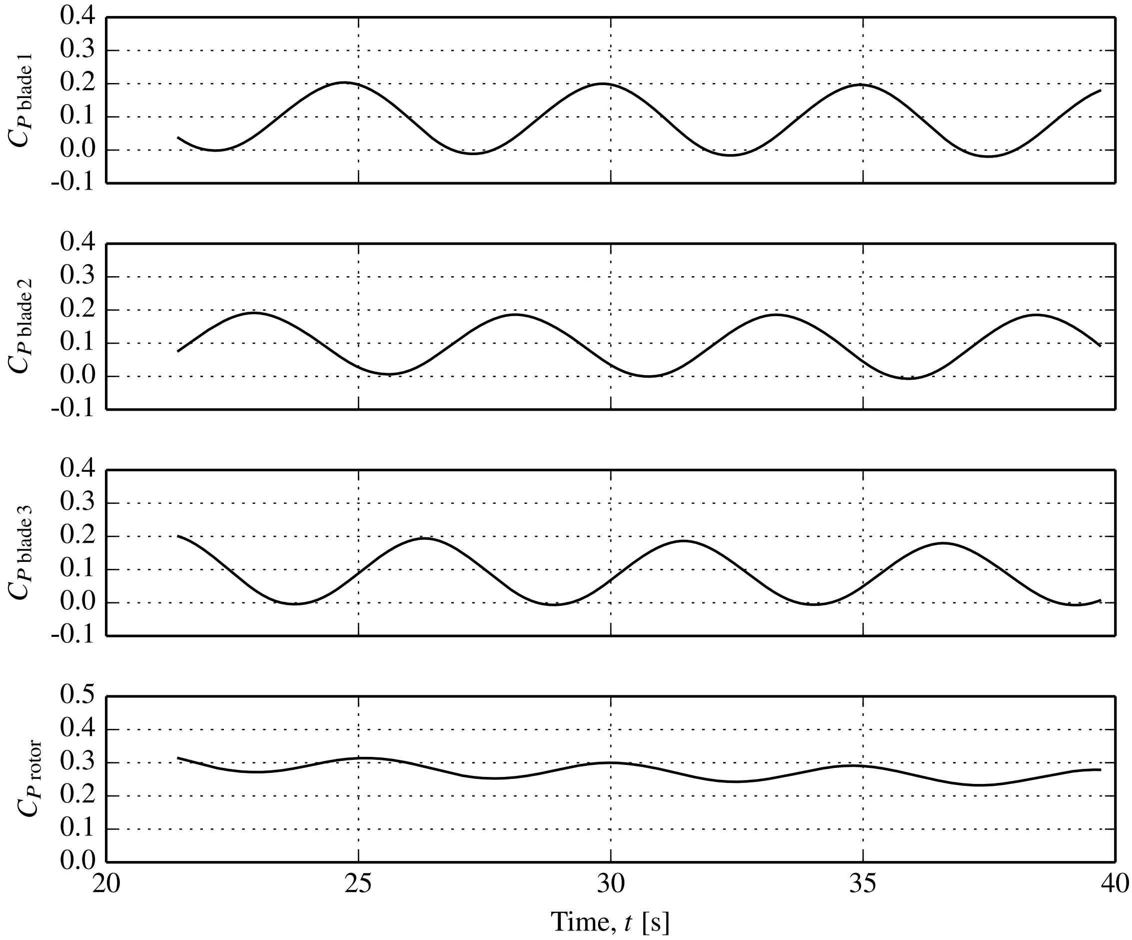
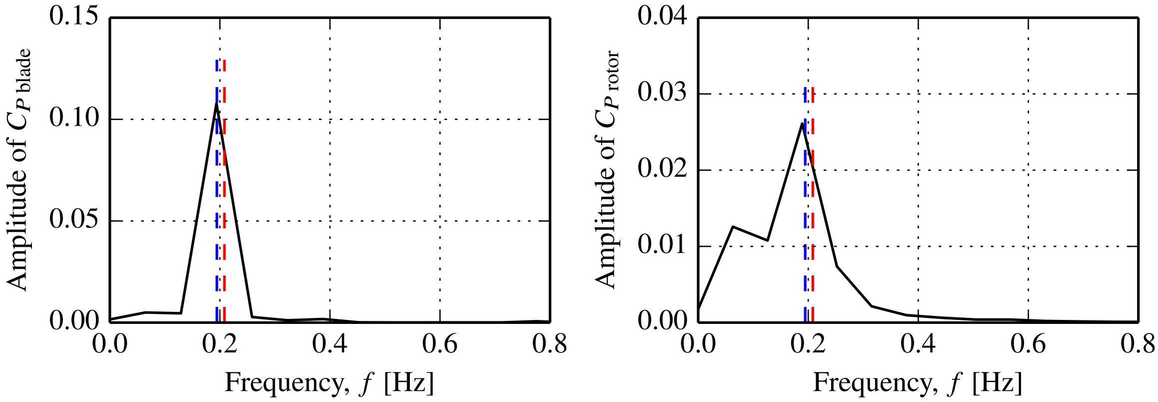


Figure 39: Blade and rotor power histories. Wave height = 1 m, wave length = 55 m, λ = 5.5.



(a) (b)

Figure 40: Power spectra; (a) blade, (b) rotor. Blue - rotor frequency, red - wave frequency. Wave height = 1 m, wave length = 55 m, λ = 5.5.

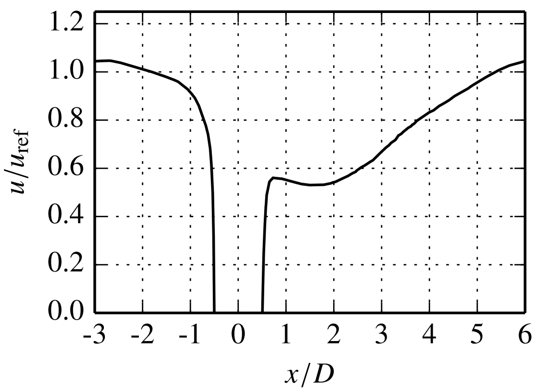


Figure 41: Centre plane velocity field. Wave height = 1 m, wave length = 55 m, λ = 5.5.

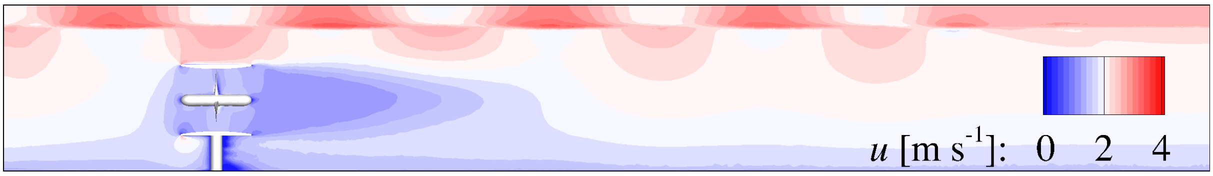


Figure 42: Centre-line streamwise velocity component. Wave height = 1 m, wave length = 55m, λ = 5.5.

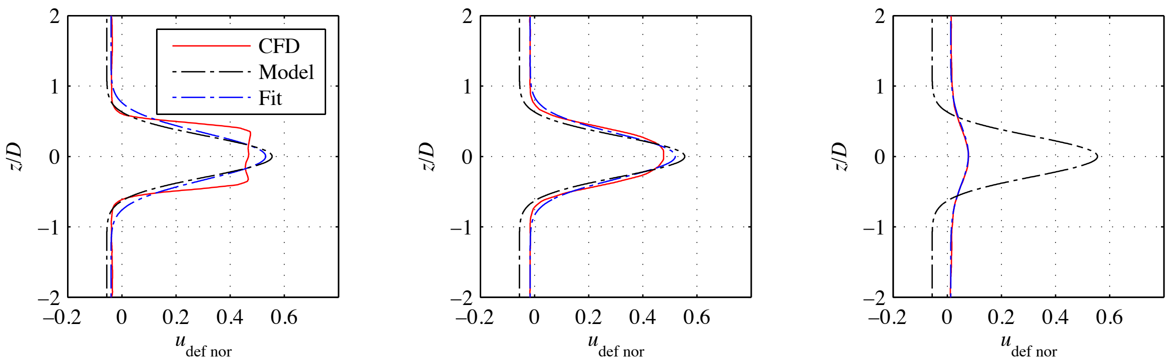


Figure 43: Parametric model of wake velocity deficit (Left to right, x =1D, 2D, 5D). Wave height = 1 m, wave length = 55 m, λ = 5.5.