Surface wave effect on marine current turbine, modelling and analysis

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The effect of surface waves on the hydrodynamic performance of a marine current turbine (MCT) is studied using the unsteady BEM method. The calculation are found to be in a very good agreement with experimental results of a small scale MCT. It is shown that a large amplitude wave, but still a long wave can affect the time-averaged coefficient of power and also introduce non-linearity in the time response of the turbine particularly at low tip speed ratio. This can have consequence for an effective control of the turbine. Instantaneous blade loading and power spectra are given and analyzed.

Keywords-tidal energy, turbine, surface wave, BEM, blade loading

I. Introduction

Marine energy is an important form of renewable energy, particularly to countries with long coastal lines as the UK and India. Tidal energy is a promising technology following recent successful implementations of underwater hydro-kinetic turbines, powered by the tidal current stream and not requiring the build up of large barrages [1]. Much of the technology and modeling used for the marine current turbine (MCT) has been imported from the wind power industry which in turn has relied on aerospace technology developed for propellers and fans. However, the free-stream MCT faces challenges different from its wind turbine counterpart. While the flow direction is well known in advance, it turns to the opposite direction during the day and flow unsteadiness can be enhanced by gravity waves as well as cavitation. The latter can occur for high flow velocities and when the blade passes near the free (water) surface reducing the static pressure below the threshold level. This is not common for MCTs [2]. However, the effect of gravity waves and particularly surface waves (i.e. maximum water displacement at the free surface) is more common and can degrade the turbine performance.

Surface waves can be driven by wind and are particularly enhanced by the wind if their phase speed is comparable with the wind speed. Objects such as vessels can also cause waves and swells can also occur. Although the theory beyond gravity waves is well known [3], not much attention has been given for their effects on MCT until recently. Barltrop et al. [4] used linear wave theory, the Blade Element Momentum (BEM) approach and towing tank to investigate the effect of free surface waves on a model turbine of a three-blades horizontal axis MCT (HAMCT). A similar approach was used by Galloway et al. [5]. Both concluded that the time-averaged power coefficient is not much affected by the free surface waves, but high unsteadiness can occur in the blade loading that may affect its long-term structural integrity. More dependence was found on the wave's frequency than the wave's amplitude and form.

Lunzik et al. [6] also used towing tank experiments to investigate the effect of small amplitude free surface waves on a small scale three-blades HAMCT. They concentrated on an “intermediate” wave length of about $h/\lambda=0.34$, where h is the undisturbed water's depth and λ is the wave length. They also found a small effect on the time-averaged power coefficient Cp of the turbine, but time fluctuations were found, matching the passing of the wave's crest and trough over the turbine.

Lust et al. [7] pursued towing tank experiments for a small scale two-blades HAMCT and used computations based on the BEM model. They concentrated on linear surface waves over deep water with waves of amplitude of up to 0.2 m. They actually found a mild improvement in the time-averaged Cp of a high tip-speed-ratio (TSR) due to increase in the coefficient of thrust (drag) C_T. Increase in Cp as the wave's crest passed over the MCT and decrease as the trough passed was also confirmed. Reasonable agreement was found with the BEM calculations.

Bai et al. [8] used the Large Eddy Simulation (LES) approach, where the fluid flow was coupled with a three-blades rotor using the immersed boundary method. Good agreement was found with experimental results, showing complex turbulent wake behind the rotor. Small effect was found for the free surface as no surface waves were imposed although the free surface was allowed to move.

The purpose of this study is to present an investigation of the effect of the free surface wave's amplitude and frequency on the MCT operation and performance. This investigation is part of a project aimed at investigating the viability of MCTs to provide energy to Indian remote islands. These turbines should show robustness, steady performance and minimum maintenance requirements. Flow unsteadiness caused by surface waves can adversely affect such turbines.

For the study presented in this paper, we use the unsteady BEM approach as it is a rapid numerical solver enabling us to examine a wide range of wave variables at a low computational cost. It has already been demonstrated that such approach can reasonably predict well the turbine's time response to free surface waves [4, 5 ,7]. More comprehensive methods of Computational Fluid Dynamics (CFD) as LES [8] that can predict the interaction between the free surface wave and the turbulent wake [9] will be employed in a separate study for conditions of interest identified through the current study. A brief summary of our unsteady BEM approach is presented next, followed by results and analysis.

II. MATHEMATICAL AND NUMERICAL FORMULATION

We assume a submerged horizontal axis marine turbine (HAMCT) subject to a steady free stream speed U and the influnce of gravity waves acting on the water surface, which we call free surface, see Fig. 1a. The free surface waves are modelled as Stokes waves and their flow induced velocities are superimposed over the free stream speed U. This leads to the flow instantaneous velocity vector;

$$\bar{u}=[U+u_r(z,t)]\hat{x}+w_r(z,t)\hat{z} \quad , \tag{1}$$

u_r and w_r are the Stokes wave velocities at the location of the MCT [3] which we take as x=0 as was done previously for linear waves [5]. Basically Stokes wave is a high order non-linear wave and we take the terms up to second order of kA, where k is the wave number and A is the wave amplitude. A full mathematical description of Stokes waves is given in [3]. It is assumed that the wave length is long enough to neglect its axial variation along the control volume of the momentum calculation of the MCT at that instant of time, which corresponds to the requirement of kA < 1. The wave frequency ω is related to its wave number k through the following dispersion relation [3];

$$(\omega-kU)^2=gk\tanh(kh) \quad , \tag{2}$$

where h is the water's depth and g is the gravity acceleration. One should note that Eq. (2) accounts for the Doppler effect and thus there can be two positive roots of k for a given positive ω , which corresponds to a downstream propagating wave. Our interest lays in the longer wave (low k) as we expect the wave's velocities to decay as exp(-|k|z) and thus the lower k is, the greater the effect of the wave is at deeper depths.

The loadings and power produced by the turbine is calculated using the unsteady BEM approach. In this paper we only give a brief summary of our approach. The interested reader can find more details on the various aspects of the steady and unsteady BEM methods in [5, 10]. The axial and tangential velocities 'seen' by a radial element of the blade can be written as

$$\bar{v}_{rel}=[U(1-a)+u_r(z,t)]\hat{x}+[\Omega r a'+w_r(z,t)\cos(\psi)]\hat{\psi} \quad ,(3)$$

where

$$d\psi/dt=\Omega \quad , \tag{4}$$

and ψ is the azimuthal angle, see Fig. 1b. a(r,ψ) and a'(r,ψ) are the axial and tangential velocity induction factors to be calculated by the BEM method. This is done by calculating the axial force and torque acting on each radial element of the blade using the momentum theory and the known aero/hydrodynamics of the blade's profile. Both approaches must yield the same result and thus the two expressions for the axial force are required to yield the same value and the same holds for the torque expressions. This yields two non-linear equations for a and a' that typically are solved by a linear iterative solver. Please note that while for the steady BEM approach where uniform axial velocity is assumed, a and a' are taken as dependent only r and assumed to be identical for all the blades, in our case they can differ from blade to blade and they also depend on time as the azimuthal angle ψ varies with time.

At a high axial induction factor of a>0.4 the wake behind the rotor becomes highly turbulent and thus the momentum expression for the axial force is no longer appropriate. It is replaced in our calculation by Glauert's correction [10]. Tip and hub losses are calculated using Prandtl's or Goldstein's loss factors. The variation of the blade's profile lift and drag coefficients with the angle of attack can be obtained from experimental data, freeware as Xfoil and JavaFoil and CFD computations. Post-stall variation of the blade's profile lift and drag coefficients with the angle of attack are calculated using Viterna & Janetzke's empirical expressions [11].

The unsteadiness in the flow caused by u_r and w_r will cause unsteadiness in the blade's hydrodynamics and in the wake. The TUDK dynamic wake model is used to account for the wake's unsteadinesses [10]. It is a relative simple engineering model that accounts for the time-delay of the turbine in reacting to the unsteadiness in the flow and is added as a correction after the steady BEM calculation. The unsteadiness in the blade profile's hydrodynamics is accounted using Theodorsen's theory for attached flow over an aerofoil and 0ye's dynamic stall model for when the flow becomes detached [12].

III. RESULTS AND ANALYSIS

For this study we chose to use the the three-blades model of [6] as the HAMCT. This is simply because our group already has good experience in studying its blade profile E387 [13], and the BEM method requires good knowledge of the profile's lift and drag coefficients variation with the angle of attack. The turbine's diameter is 0.46 m and it was placed 0.782 m beneath the undistributed water surface in a towing tank of 1.6 m depth.

The variation of the power coefficient Cp with the tip speed ratio TSR is shown in Fig 2a for the case with no surface waves. A very good agreement is revealed between the BEM results and the reported experimental results [6], expect for TSR>8 which is of low importance as the Cp already declines to levels of no practical use. Small scale turbine blade's hydrodynamics like this one are sensitive to the Reynolds number more than their full scale counterparts. In this study we took the hydrodynamics of the blade of as of $Re_C=10^5$ for r<0.7R and its tip as of 2 10^5 with linear variation between them. As the TSR increases and the incoming velocity stays constant as in [6] the profile Reynold number changes and thus re-distributing the hydro/aerodynamic data along the blade should improve the BEM accuracy for high TSR, but as noted above that level of TSR is not of strong operational interest.

The time variation of Cp when TSR=5.5 and with a small surface wave of an amplitude of 0.04 m and a time period of 1.78 s is shown in Fig 2b. Again an excellent agreement with the experimental results is revealed. The peaks and troughs of Cp are in phase with the peaks and troughs of the surface wave. This can be explained by looking at the Stokes velocity potential:

$$\phi=\upsilon_1 A\cosh[k(z+h)]\sin(\theta)+\upsilon_2 A^2\cosh[k(z+h)]\sin(2\theta)+.. \quad ,(5)$$

where the surface wave is

$$\eta=A\cos(\theta)+\mu_2 A^2\cos(2\theta)+.. \quad , \quad (6)$$

and

$$\theta=kx-\omega t \; , \; (u_r, w_r)=\nabla\phi \quad . \quad (7)$$

υ_1, υ_2 and μ_2 are positive expressions containing k, g, ω and U. Thus u_r is in phase with η and it increases the axial velocity seen by the turbine peaks, while one should note that Cp is defined as $P/(0.5\rho U^3\pi R^2)$ and thus it can go above the Betz limit as u_r is added to U by Eq. (1). A similar process was noted by [6, 7] but they more emphasized on w_r becoming zero at the peaks and troughs of Cp while we found this process to be more affect by u_r.

The time oscillations of Cp in Fig 2b are very periodic (except at t=0 that is affected by the numerical initial condition) and correspond to the surface wave frequency. Increasing the wave amplitude from 4 cm to 15 cm causes a significant increase in the amplitude of the fluctuations and a shift upwards in the time-averaged Cp as seen in Fig 3b. Reducing the TSR from 5.5 to 4 while keeping the surface wave frequency the same causes a steepening of the time oscillations of Cp which is a hallmark of a non-linear interaction as seen in Fig 3a. This is better seen in the time variation of the coefficient of thrust (drag) C_T presented in Figs 4. A clear steepening is seen at TSR=4 and A=0.15 cm. C_T time averaged value is also reduced, while is less affected in TSR=5.5

The instantaneous radial distribution of d(Cp)/d(r/R) and $d(C_T)/d(r/R)$ are shown in Figs 5 and 6. As expected the maximum occurs near the blade tip, before the tip loss factors reduce the load towards the tip. The difference between the crest (t=T/4) and trough (t=T/2) is higher for A=0.15 cm than A=0.04 cm in both cases of TSR and as expected. However, the distribution of TSR=4 at A=0.15 m less declines towards the hub than in TSR=5.5. The radial distribution of the thrust coefficient shows a similar behavior where TSR=4 shows a higher difference between the crest (t=T/4) and trough (t=T/2) as compared to TSR=5.5.

Finally, the power spectra of the coefficient of thrust are shown in Figs 7 for TSR=4 and 5.5. Power spectra are notoriously noisy due to any mild non-periodicity, nevertheless the surface wave frequency is clearly evident in both cases of TSRs and is noted on the figures. The first harmonic is also evident for A=0.15 cm and much clearer for TSR=4 than for TSR=5.5, pointing again towards non-linear interaction for low TSR.

IV. Summary and CoNCLUSIONs

Hydrodynamic calculations based on the unsteady BEM method have been pursued to assess the effect of free surface waves on marine current turbines (MCTs). Very good agreement between the BEM calculations and experimental results of a small scale MCT were found both for the time-averaged and time varying coefficient of power with a small amplitude surface wave.

It was shown that large waves, but still long in sense of kA<1 can affect in a different way the turbine performance by changing its time averaged coefficients of thrust and power while introducing non-linear behavior in the time variations of those coefficients, particularly for low TSR. This was also exhibited in a noticeable first harmonic of the surface wave affecting the turbine time-response. Future plans include detailed CFD study of the water surface and sea bed topography coupled with the turbine operation and the development of a control law to mitigate those unsteadiness effects.

Acknowledgment

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(a) (b)

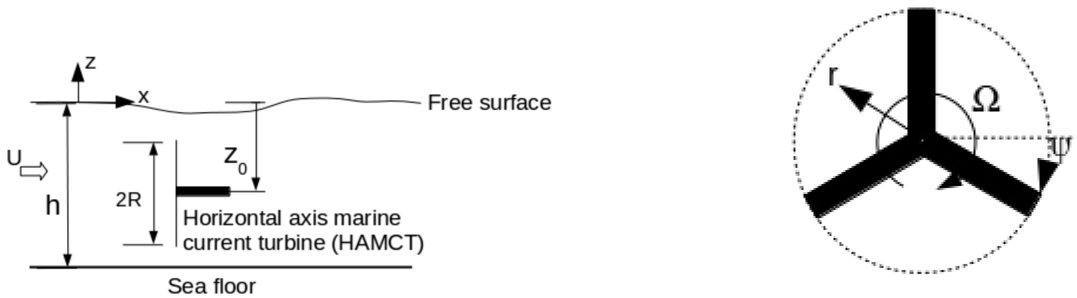


Figure 1 Schematic description of (a) the horizontal axis marine turbine configuration and (b) its rotor

(a) (b)

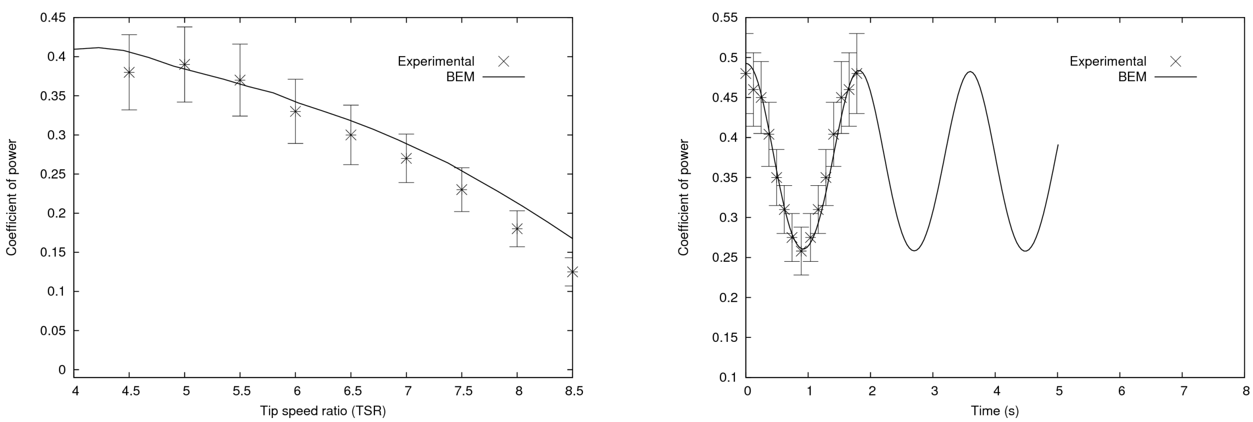
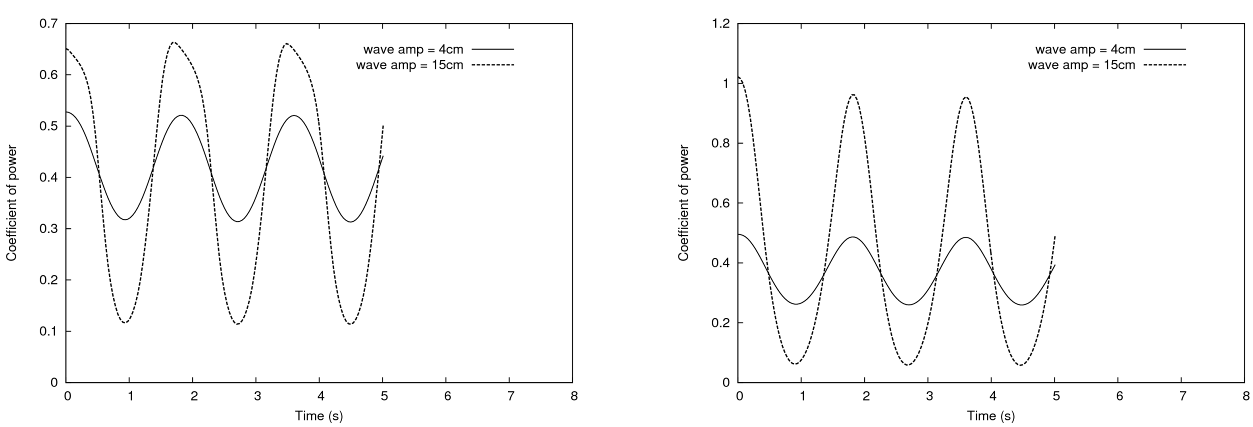


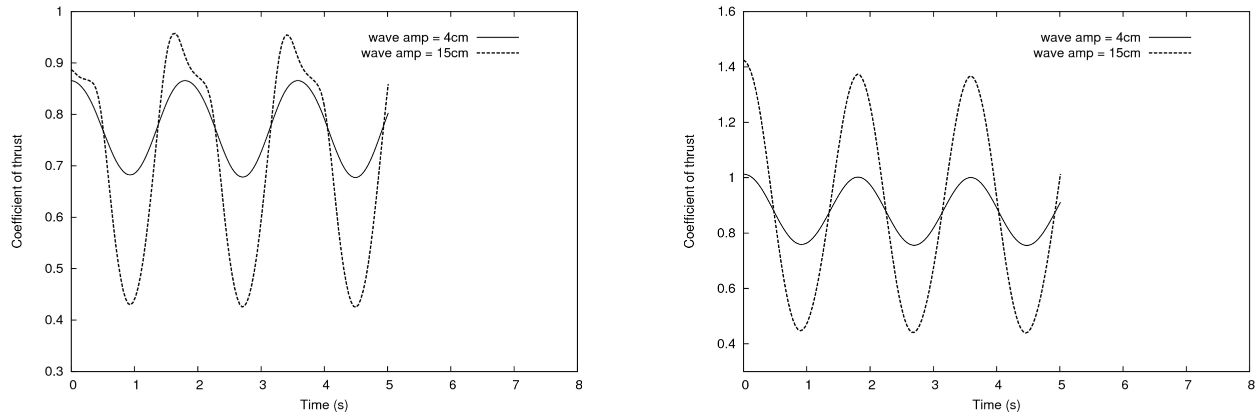
Figure 2: (a) The tip speed ratio variation of the time-averaged coefficient of power with no surface waves and (b) the time variation of the instantaneous coefficient of power for TSR=5.5, surface wave of 4 cm amplitude and a time period of1.78 s that are plotted for the model HAMCT of [6]

(a) (b)



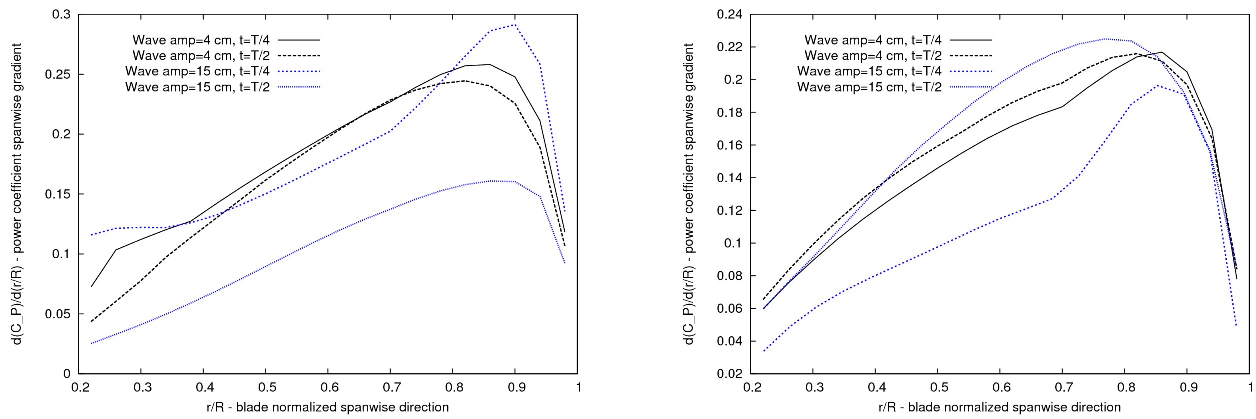
Figures 3: Time variation of the power coefficient for the HAMCT model of Figs 2 that is calculated using the unsteady BEM approach for (a) TSR=4 and (b) TSR=5.5. The surface wave time period is held as T=1.78 s and the wave amplitude (water displacement) is noted in the legend.

(a) (b)



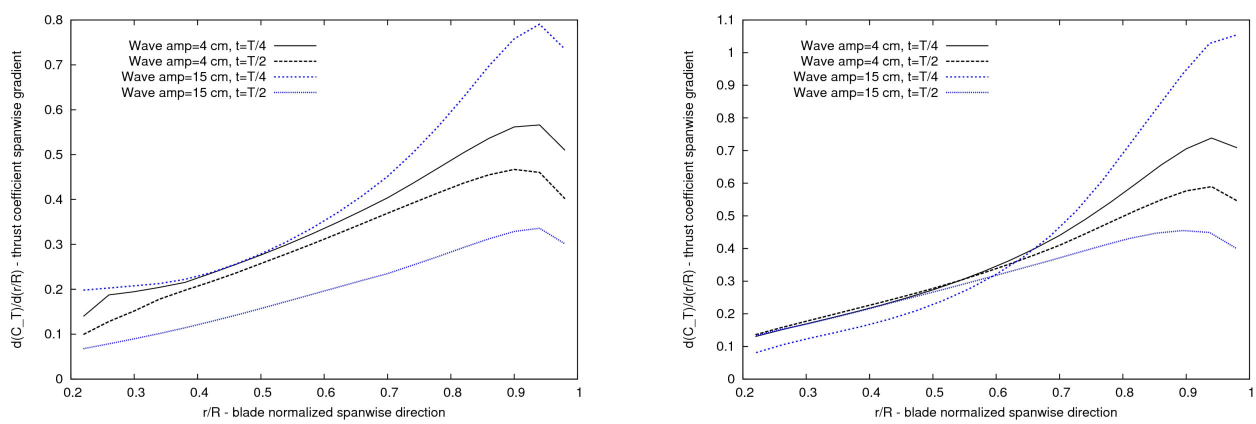
Figures 4: Time variation of the thrust coefficient for the HAMCT model of Figs 2 that is calculated for (a) TSR=4 and (b) TSR=5.5. The surface wave time period is held as T=1.78 s.

(a) (b)



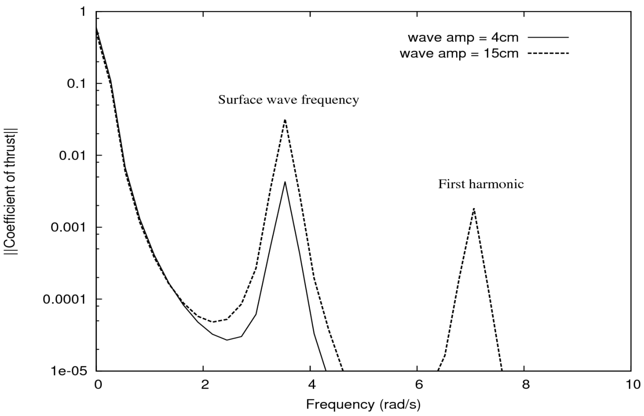
Figures 5: Instantaneous power loading on Blade 1 of the HAMCT model of Figs 2 that is calculated for (a) TSR=4 and (b) TSR=5.5. The surface wave time period is held as T=1.78 s.

(a) (b)

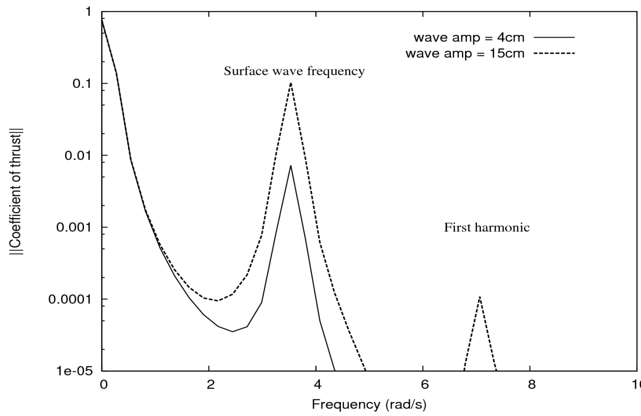


Figures 6: Instantaneous thrust (drag) loading on Blade 1 of the HAMCT model of Figs 2 that is calculated for (a) TSR=4 and (b) TSR=5.5. The surface wave time period is held as T=1.78 s.

(a)



(b)



Figures 7: Power spectra of the coefficient of thrust for (a) TSR=4 and (b) TSR=5.5 that correspond to the time plots of Figs 4.

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