Wake Effects of Tidal Current Turbines

Mathew B.R. Topper

Supervised by
Professor Ian Bryden

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Decomposing a Power Curve

What are the pertinent physics that could effect a typical power curve for a tidal current turbine?

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Experimental Data

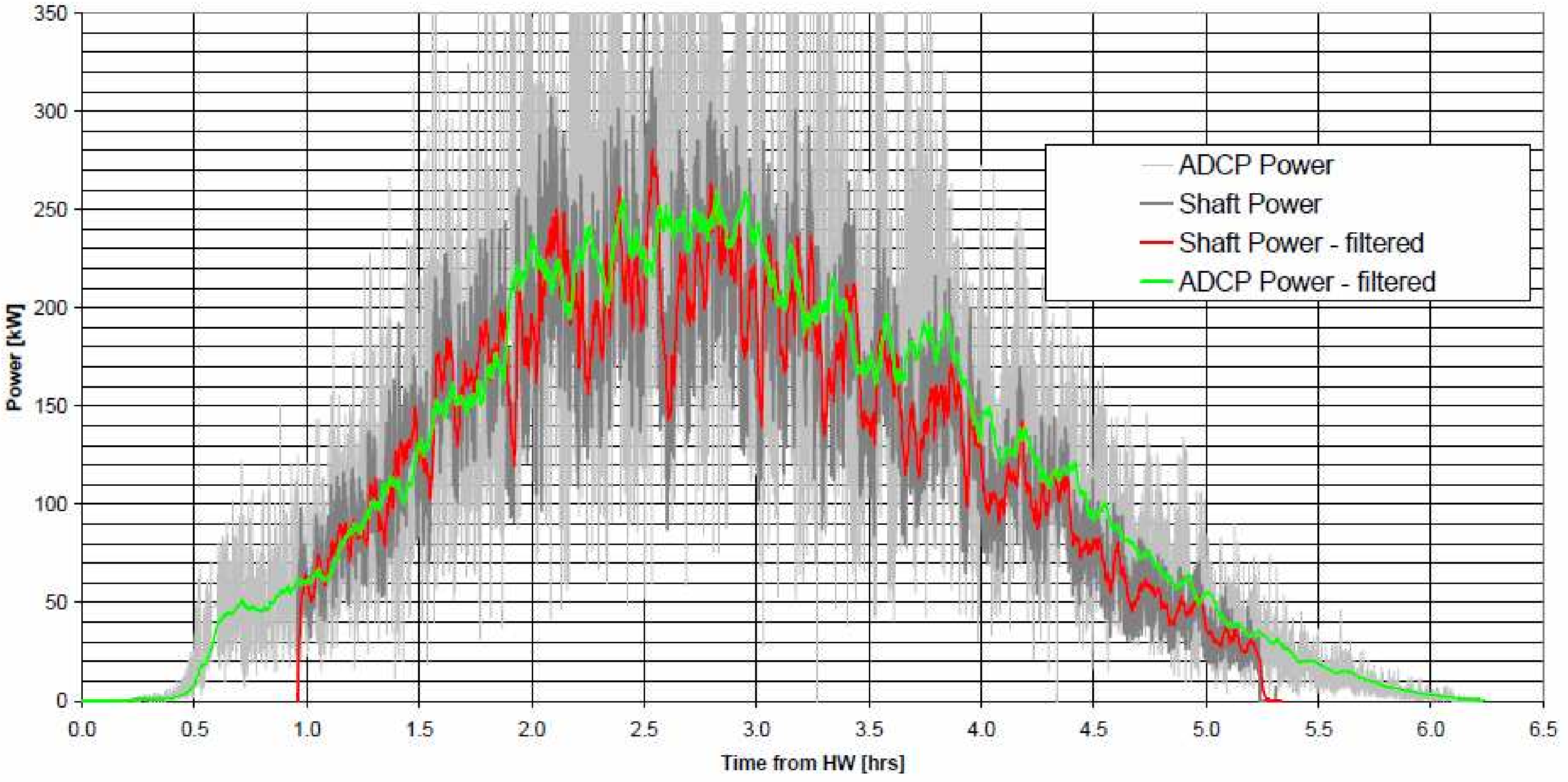

Figure 16: Typical test run results through two ebb tides, showing rotor shaft power versus time after high water.

Source: Development, Installation and Testing of a Large Scale Tidal Current Turbine, dti contract number: T/06/0021/00/REP, 2005

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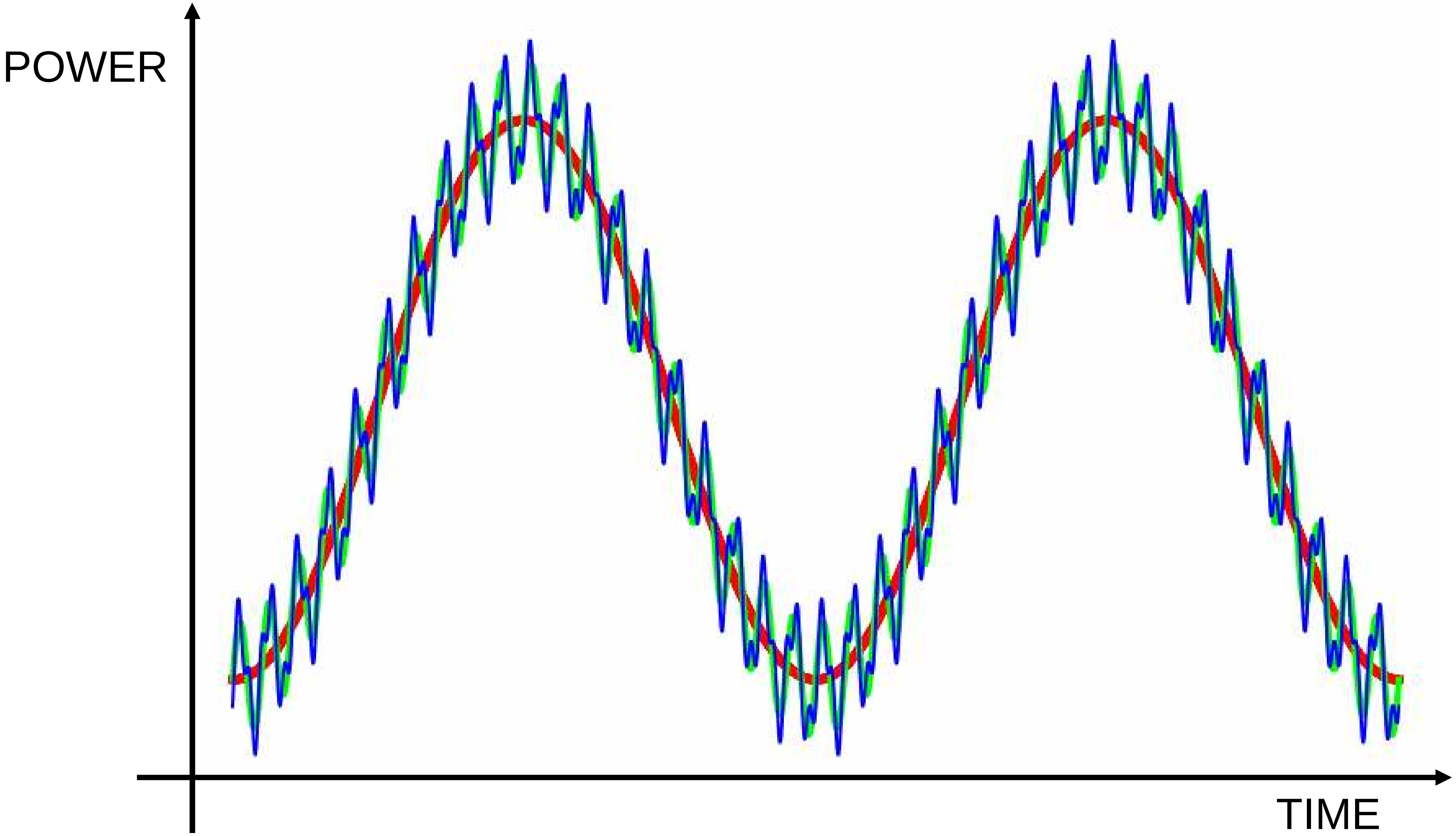
Illustrative Power Curve



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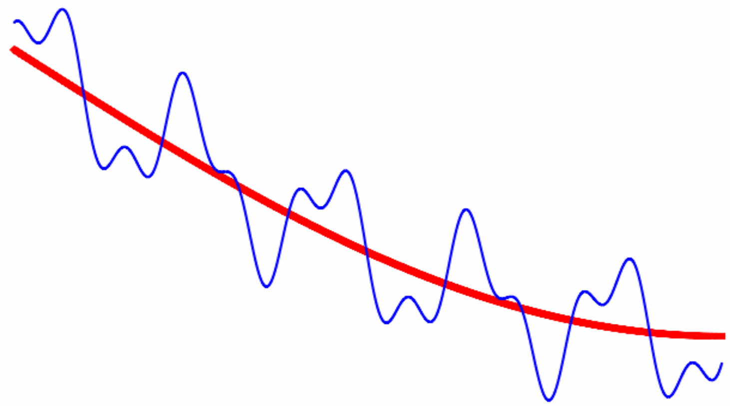
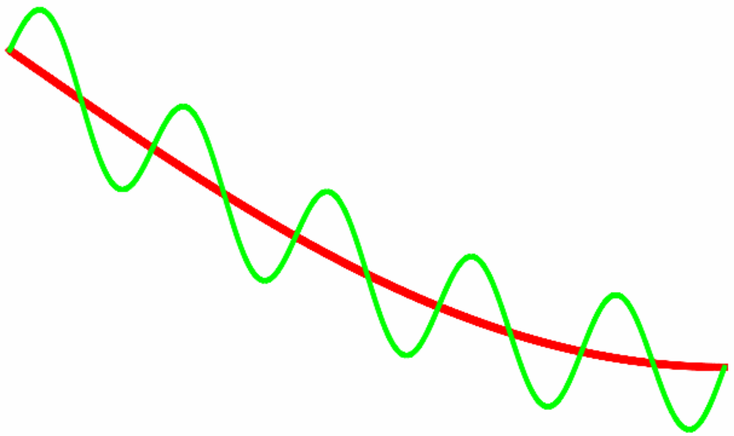
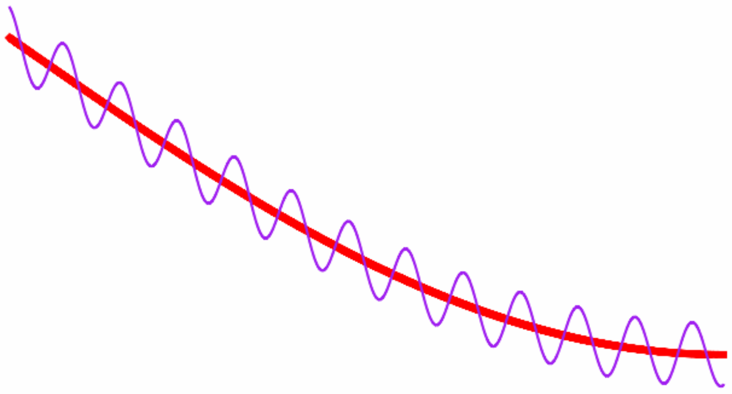
Decomposing the Curve



ORIGINAL POWER CURVE



FREE SURFACE INTERACTION



TURBULENCE

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Examining Free Surface Effects

How does the free surface interact with the wake of a tidal current turbine?

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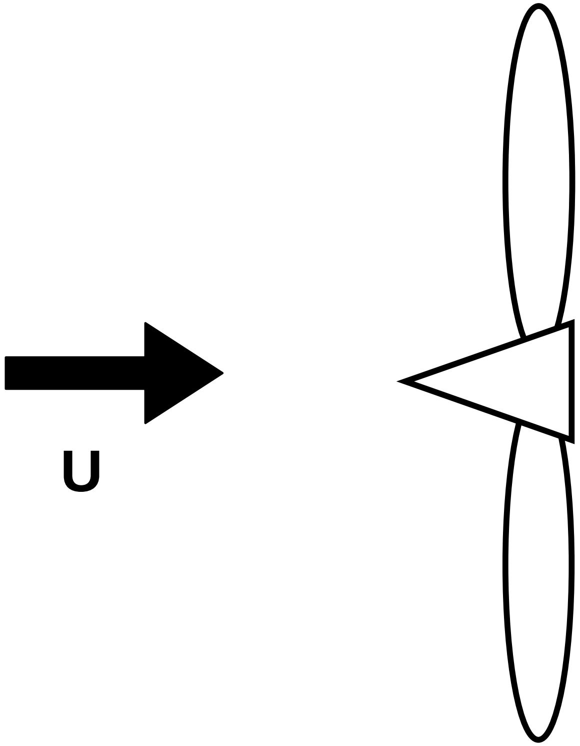
Wind Turbine



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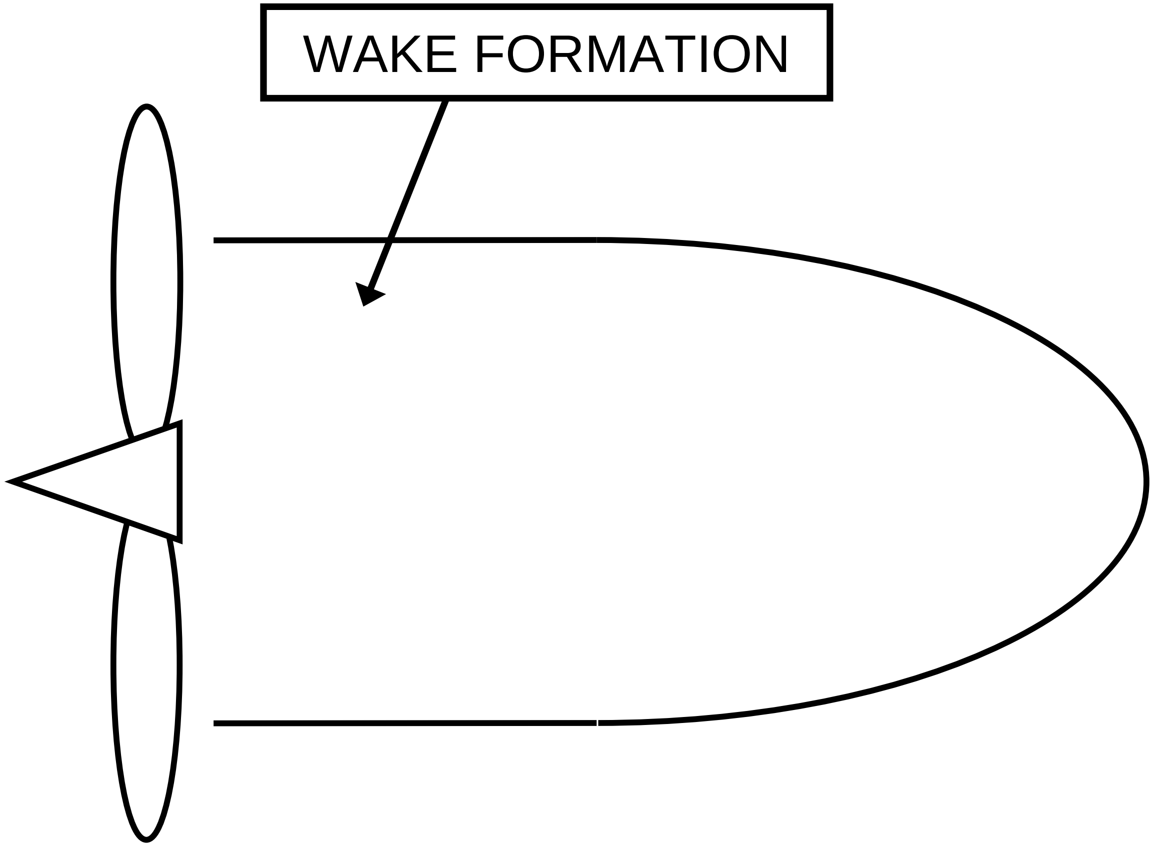
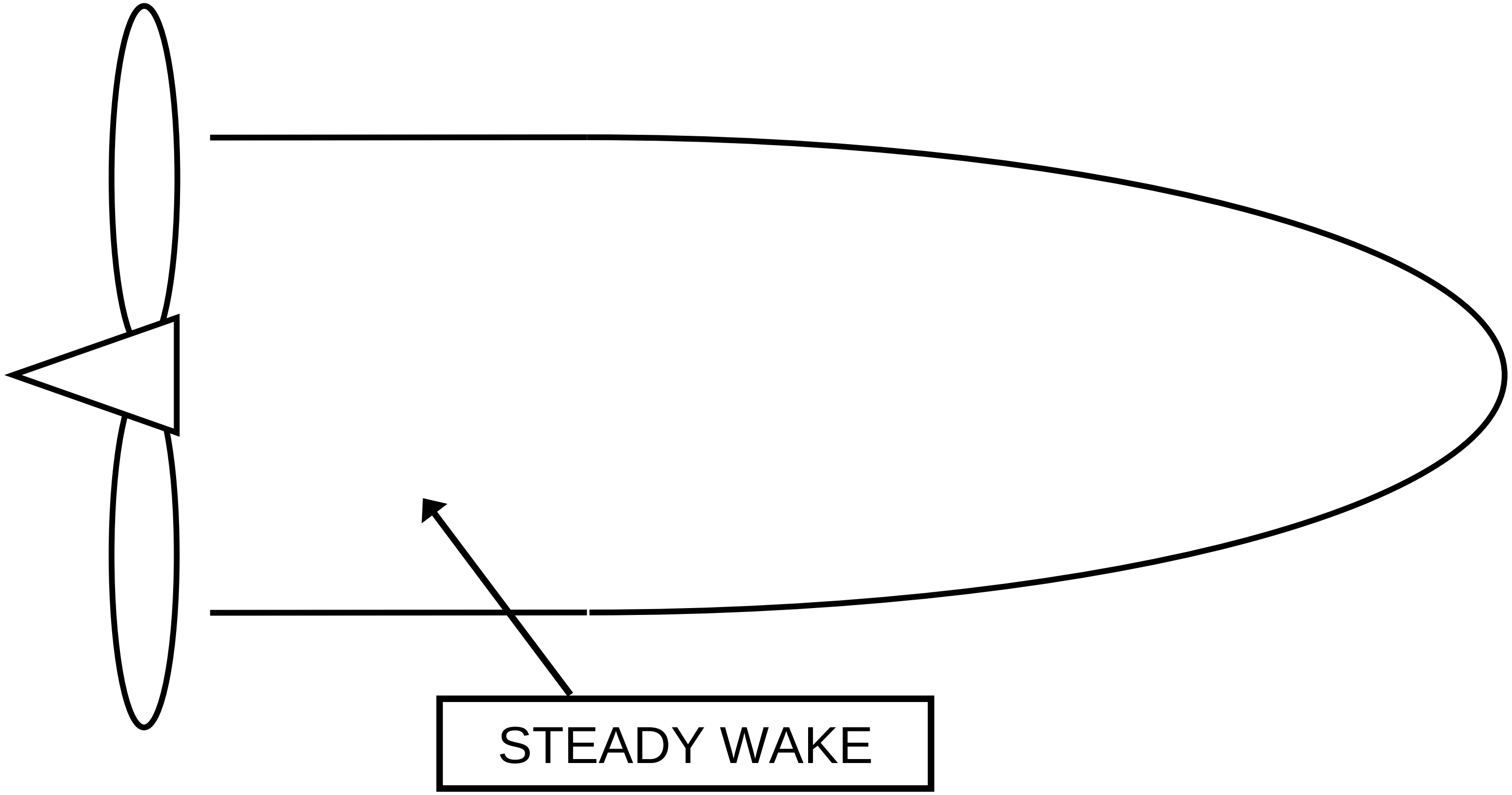
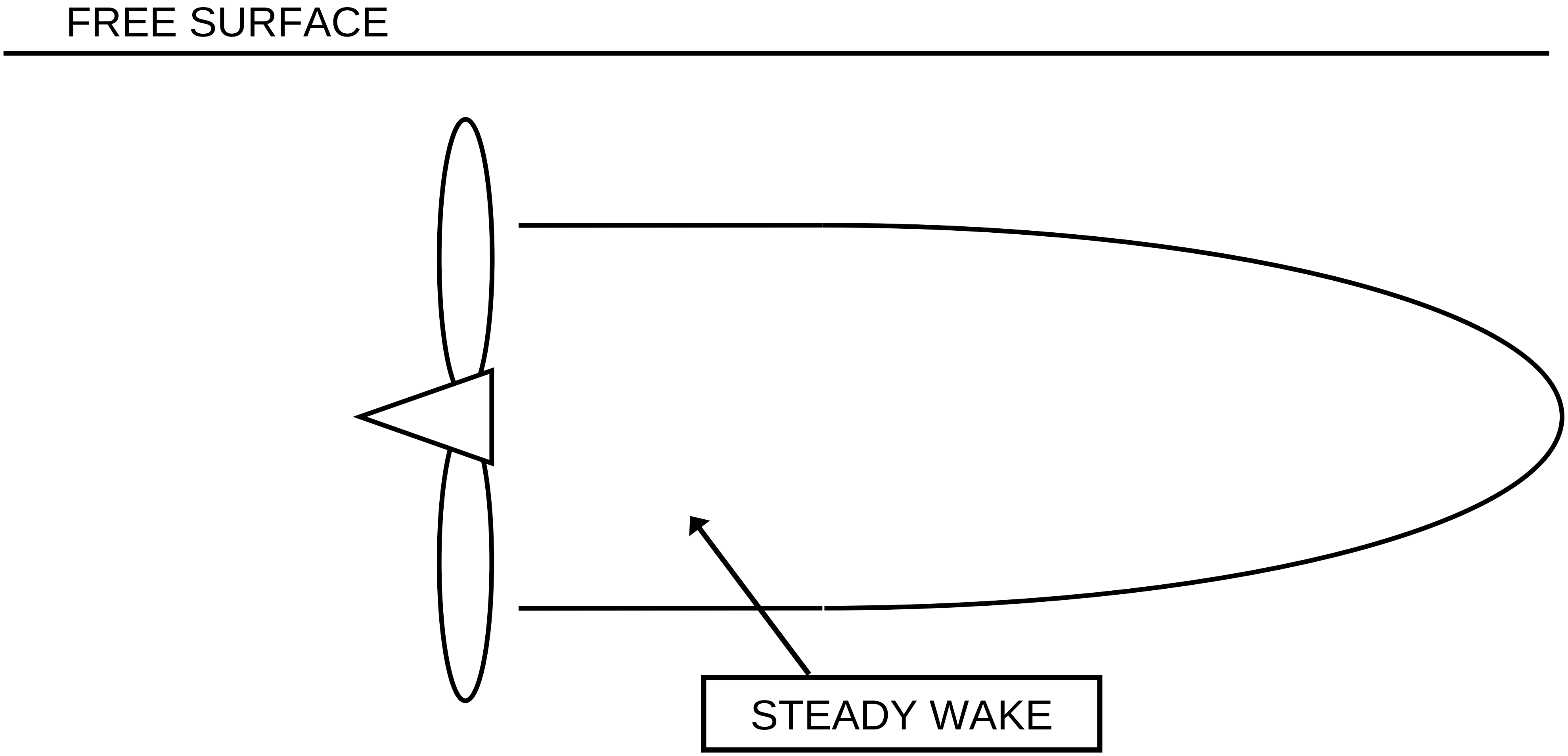

WAKE FORMATION

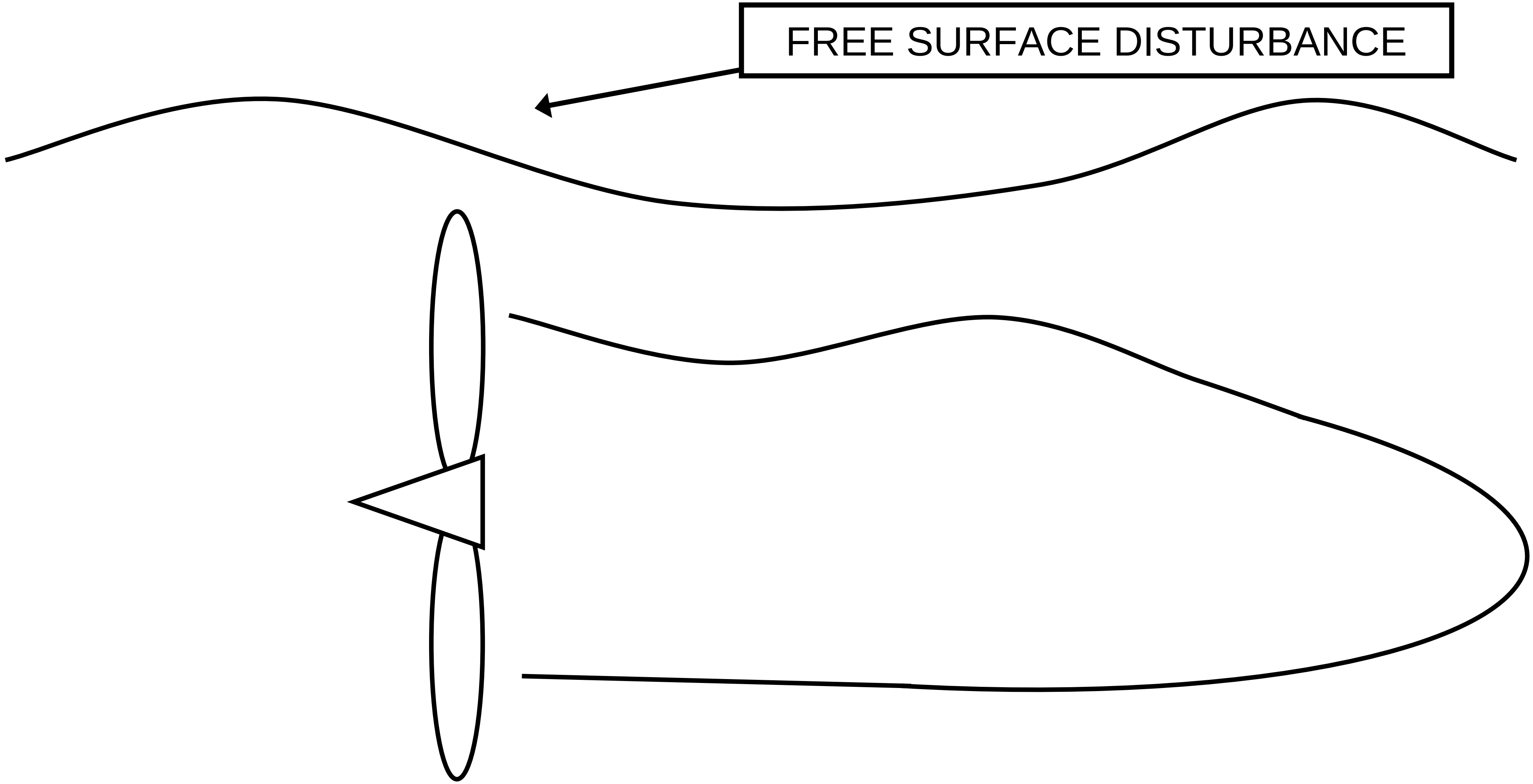

STEADY WAKE

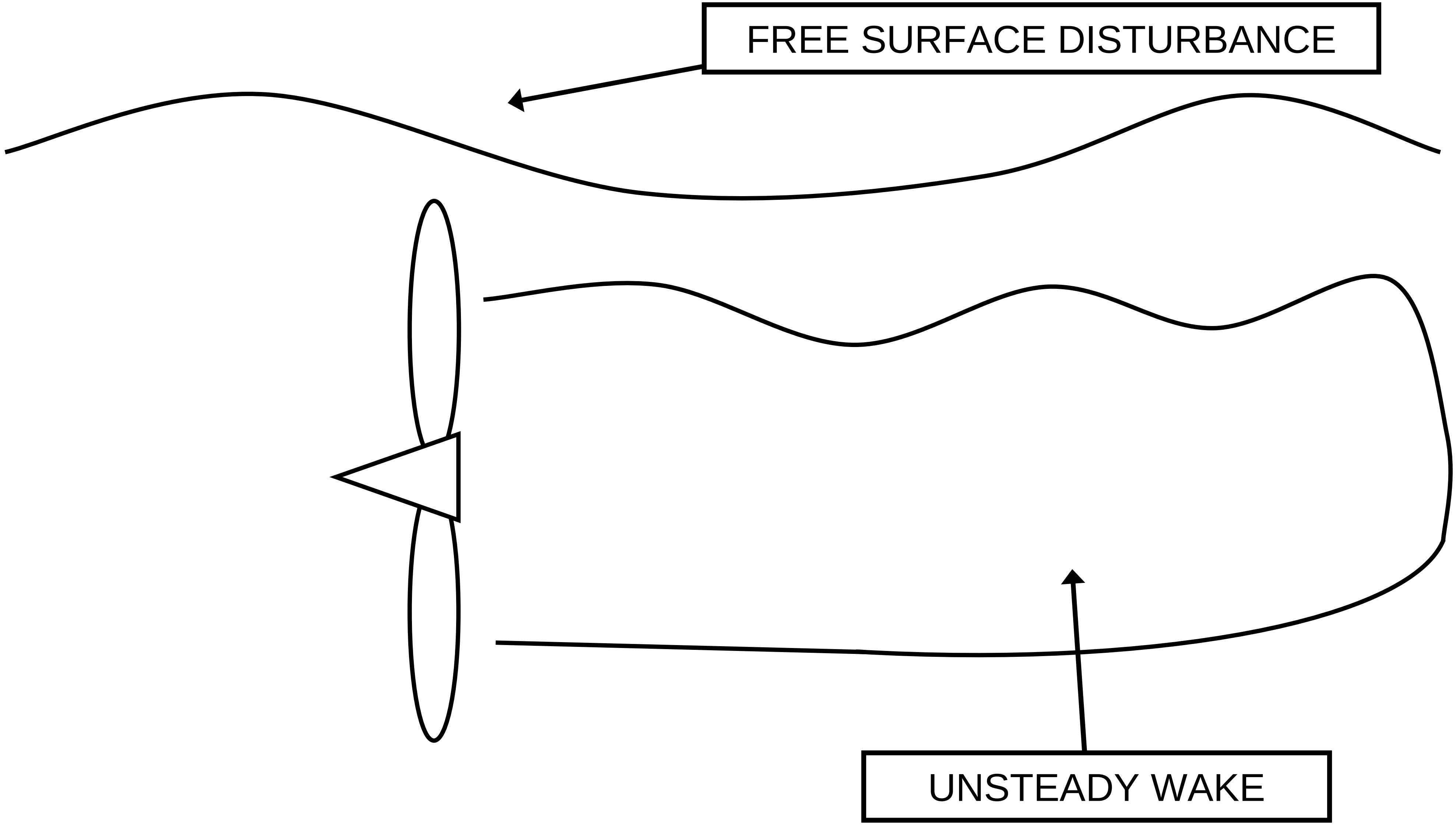
Tidal Turbine



FREE SURFACE

STEADY WAKE


FREE SURFACE DISTURBANCE


FREE SURFACE DISTURBANCE
UNSTEADY WAKE

Modelling Free Surface Problems

How can the effect of a free surface on a tidal turbine be modelled?

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Boundary Element Method

Computational Mechanics 32 (2003) 336–346 © Springer-Verlag 2003
DOI 10.1007/s00466-003-0491-7

Fully nonlinear wave-current interactions and kinematics by a BEM-based numerical wave tank

S. Ryu, M. H. Kim, P. J. Lynett

Abstract A numerical wave tank (NWT) with fully nonlinear free-surface boundary conditions is developed to investigate nonlinear wave–wave and wave–current interactions and the resulting kinematics. In the present paper, the variation of wave amplitude and wave length of a monochromatic wave under several different speeds of steady uniform currents is studied through direct numerical simulations in the time domain. The nonlinear wave–current interactions are solved using a boundary integral equation method (BIEM) and a Mixed Eulerian–Lagrangian (MEL) time marching scheme. Both a semi-Lagrangian approach and Lagrangian (material-node) approach are employed and their performance is compared. A regridding algorithm based on cubic spline fitting is devised for updating the free-surface moving boundary in a stable and accurate manner. The incident waves are generated by feeding prescribed analytical waves on the input boundary. An efficient artificial numerical beach is devised and applied to dissipate wave energy and minimize wave reflections from the downstream wall. Nonlinear wave kinematics as a result of nonlinear wave–current interactions is calculated and the results are compared with a multi-layer Boussinesq model. The spatial variation of nonlinear wave profiles and kinematics affected by currents are also addressed and discussed.

Keywords Wave-current interaction, Boundary Element Method, Numerical Wave Tank, Multi-layer Boussinesq model, Wave mechanics

1
Introduction

Wave-current interactions have been one of the most interesting, applicable topics in ocean engineering and physical oceanography. For instance, when ocean waves enter an inlet against an ebb current, changes of wave heights and wavelengths occur, which is important to the design or modification of inlet channels for navigation or dredging operations [18]. To solve wave–current interactions, Isaacson and Cheung [10], and Kim and Kim [12] used BEM and perturbation methods for sufficiently small Froude numbers. On the other hand, Celebi [3] and Celebi et al. [4] investigated transient and steady-state nonlinear wave–current-body interactions by a fully nonlinear 3-D numerical wave tank with a mixed Eulerian–Lagrangian (MEL) time stepping technique. A material node approach was used in their numerical scheme for updating the nonlinear free surface.

Though there are many papers dealing with wave–current interactions based on linear or perturbation theories, for instance the paper of Baddour and Song [1], publications on fully nonlinear wave–current interactions are rare. Furthermore, nonlinear wave–current interactions are very difficult subjects to be studied in the laboratory because it is not easy to generate a uniform steady current field with waves. In this paper, fully nonlinear wave–current interactions, BEM modeling, and the use of a Lagrangian and regridding scheme is addressed. A number of difficulties associated with numerical implementations are discussed. The change of wave amplitudes, shapes, and wave lengths due to coplanar and opposing uniform currents is also discussed. The wave induced particle velocities, particularly the wave kinematics above MWL, are also obtained. The nonlinear solutions are compared with those of linear theory.

Both Lagrangian (material-node) and semi-Lagrangian approaches are independently developed and the results are cross-checked. Several case studies are carried out to check the overall performance of the developed BEM and time-marching scheme. Various interesting features of the fully nonlinear wave–current interactions can be seen through those examples. The simulated results are compared with the results of a multi-layer Boussinesq model, which represents a very different type of model. The two independent numerical models are in excellent agreement both in free-surface profiles and kinematics.

2
Mathematical formulation

It is assumed that the fluid is irrotational and inviscid so that a velocity potential exists in the fluid domain. The domain and coordinate system are shown in Fig. 1. A Cartesian coordinate system is employed such that the $z = 0$ line corresponds to the still water level, z is positive upwards. Now the problem to solve is to determine the velocity potential that satisfies the Laplace equation:

$$\nabla^2 \phi = 0 \quad \text{in} \quad \Omega \tag{1}$$

where Ω denotes the fluid domain.

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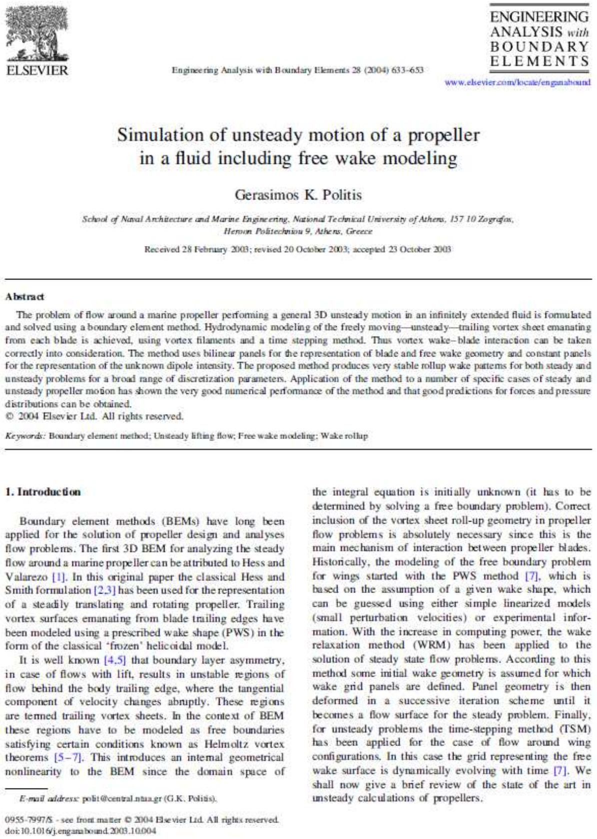
FREE SURFACE

(RYU, KIM, LYNETT; 2003)



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Engineering Analysis with Boundary Elements 28 (2004) 633–653

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Simulation of unsteady motion of a propeller in a fluid including free wake modeling

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Received 28 February 2003; revised 20 October 2003; accepted 23 October 2003

Abstract

The problem of flow around a marine propeller performing a general 3D unsteady motion in an infinitely extended fluid is formulated and solved using a boundary element method. Hydrodynamic modeling of the freely moving—unsteady—trailing vortex sheet emanating from each blade is achieved, using vortex filaments and a time stepping method. Thus vortex wake–blade interaction can be taken correctly into consideration. The method uses bilinear panels for the representation of blade and free wake geometry and constant panels for the representation of the unknown dipole intensity. The proposed method produces very stable rollup wake patterns for both steady and unsteady problems for a broad range of discretization parameters. Application of the method to a number of specific cases of steady and unsteady propeller motion has shown the very good numerical performance of the method and that good predictions for forces and pressure distributions can be obtained.

Keywords: Boundary element method; Unsteady lifting flow; Free wake modeling; Wake rollup

1. Introduction

Boundary element methods (BEMs) have long been applied for the solution of propeller design and analyses flow problems. The first 3D BEM for analyzing the steady flow around a marine propeller can be attributed to Hess and Valarezo [1]. In this original paper the classical Hess and Smith formulation [2,3] has been used for the representation of a steadily translating and rotating propeller. Trailing vortex surfaces emanating from blade trailing edges have been modeled using a prescribed wake shape (PWS) in the form of the classical 'frozen' helicoidal model.

It is well known [4,5] that boundary layer asymmetry, in case of flows with lift, results in unstable regions of flow behind the body trailing edge, where the tangential component of velocity changes abruptly. These regions are termed trailing vortex sheets. In the context of BEM these regions have to be modeled as free boundaries satisfying certain conditions known as Helmoltz vortex theorems [5–7]. This introduces an internal geometrical nonlinearity to the BEM since the domain space of the integral equation is initially unknown (it has to be determined by solving a free boundary problem). Correct inclusion of the vortex sheet roll-up geometry in propeller flow problems is absolutely necessary since this is the main mechanism of interaction between propeller blades. Historically, the modeling of the free boundary problem for wings started with the PWS method [7], which is based on the assumption of a given wake shape, which can be guessed using either simple linearized models (small perturbation velocities) or experimental information. With the increase in computing power, the wake relaxation method (WRM) has been applied to the solution of steady state flow problems. According to this method some initial wake geometry is assumed for which wake grid panels are defined. Panel geometry is then deformed in a successive iteration scheme until it becomes a flow surface for the steady problem. Finally, for unsteady problems the time-stepping method (TSM) has been applied for the case of flow around wing configurations. In this case the grid representing the free wake surface is dynamically evolving with time [7]. We shall now give a brief review of the state of the art in unsteady calculations of propellers.

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0955-7997/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enganabound.2003.10.004

LIFTING BODIES

(POLITIS; 2004)

INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS
Int. J. Numer. Meth. Fluids 2008; **56**:305–329
Published online 6 June 2007 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/fld.1527

Prediction of wave pattern and wave resistance of surface piercing bodies by a boundary element method

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SUMMARY

An iterative boundary element method, which was originally developed for both two- and three-dimensional cavitating hydrofoils moving steadily under a free surface, is modified and extended to predict the wave pattern and wave resistance of surface piercing bodies, such as ship hulls and vertical struts. The iterative nonlinear method, which is based on the Green theorem, allows the separation of the surface piercing body problem and the free-surface problem. The free-surface problem is also separated into two parts; namely, left and right (with respect to x axis) free-surface problems. Those all (three) problems are solved separately, with the effects of one on the other being accounted for in an iterative manner. The wetted surface of the body (ship hull or strut, including cavity surface if exists) and the left and right parts with respect to x axis of free surface are modelled with constant strength dipole and constant strength source panels. In order to prevent upstream waves, the source strengths from some distance in front of the body to the end of the truncated upstream boundary are enforced to be zero. No radiation condition is enforced for downstream and transverse boundaries. A transverse wave cut technique is used for the calculation of wave resistance. The method is first applied to a point source and a three-dimensional submerged cavitating hydrofoil to validate the method and a Wigley hull and a vertical strut to compare the results with those of experiments. Copyright © 2007 John Wiley & Sons, Ltd.

Received 14 November 2006; Revised 16 April 2007; Accepted 17 April 2007

KEY WORDS: wave resistance; ship waves; free surface; vertical strut; boundary element method; potential-based panel method; wave pattern; cavitating vertical hydrofoil; surface piercing strut

INTRODUCTION

Numerical prediction of wave pattern and wave resistance of surface piercing bodies, such as ships, vertical struts and hydrofoils is still of practical importance to engineers and designers. This paper addresses the steady-state characteristics of flow around surface piercing (even unsymmetrical or yawed) bodies. The iterative boundary element (Rankine panel) method (IBEM) developed

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COMBINED

(BAL; 2008)

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Research Challenges

- Higher Order Discretisation
  - Accurate calculation of wake velocity.
  - Correct treatment of trailing edge boundary condition.
- Galerkin Boundary Element Method
  - Provides accurate solution to wake velocities.
  - Novel application to lifting bodies.

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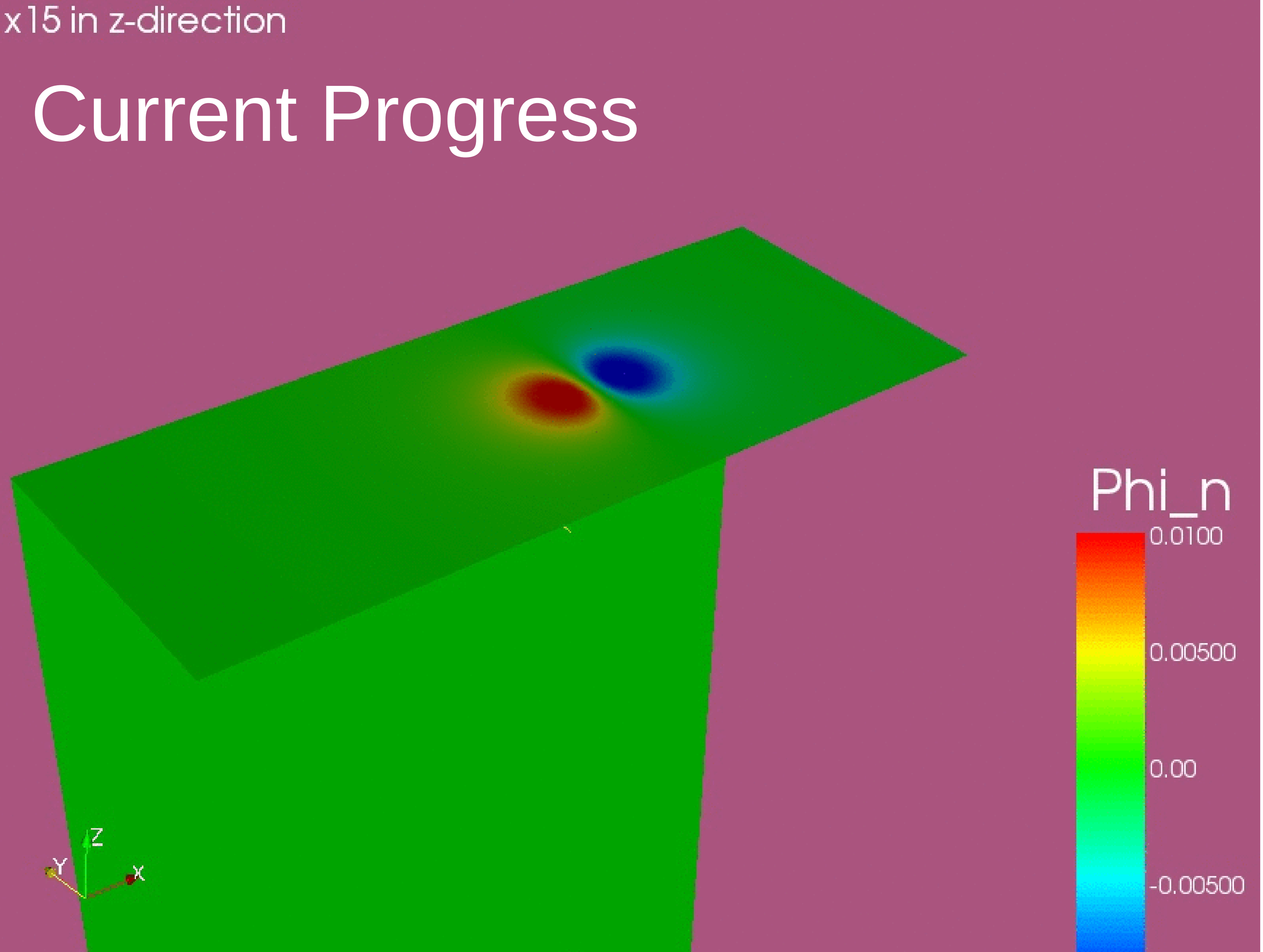
Current Progress



Dealing With Turbulence

What challenges must be overcome to produce models that include the effects of turbulence?

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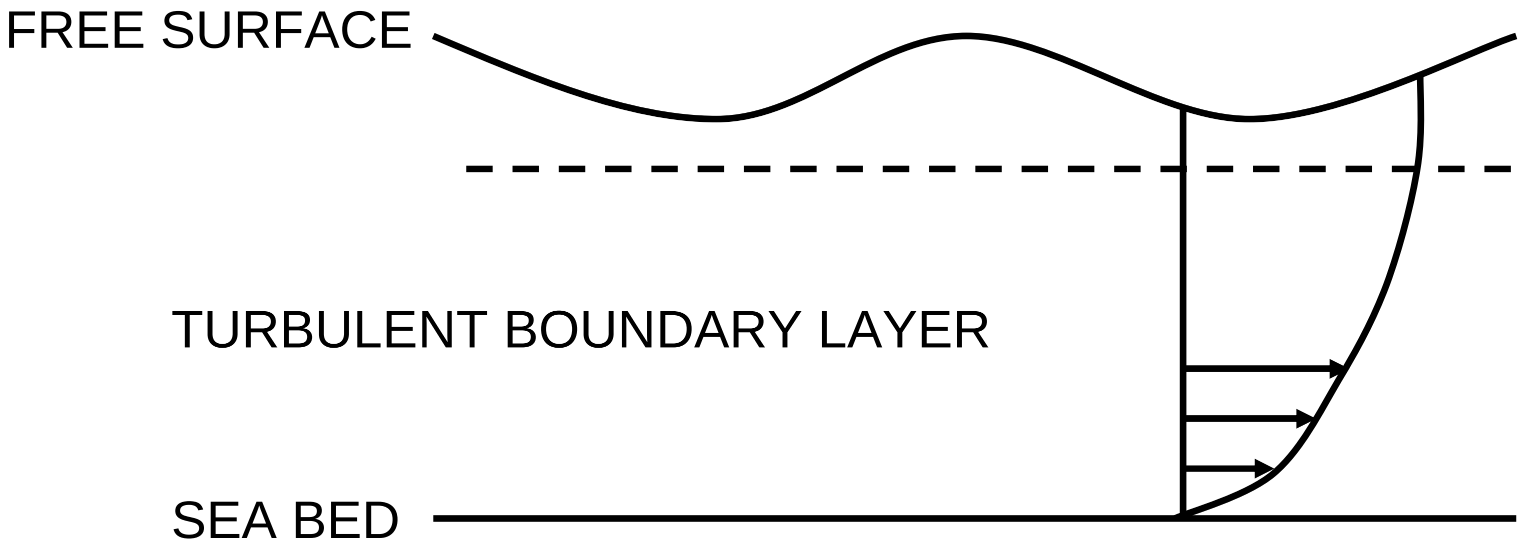
Turbulence

- Boundary Element Methods are inviscid and therefore can not deal with turbulence.
- Uncertainty about the turbulent boundary layer in a high energy (3+ m/s) tidal channel.



CLICK

Turbulence

- Boundary Element Methods are inviscid and therefore can not deal with turbulence.
- Uncertainty about the turbulent boundary layer in a high energy (3+ m/s) tidal channel.
- Turbulent time scales are likely to be in ranges that negate the use of unsteady RANS simulations (possible structural modelling?).
- Free surface simulation in RANS or LES models remains challenging.

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Conclusions

- Tidal Turbines are likely to be effected by free surface interaction and turbulence.
- The free surface and the wake of a tidal turbine will interact with each other.
- Boundary Element Methods can be used to quantify these effects.
- Numerical modelling of turbulence in high energy tidal channels requires better experimental data and more advanced models.

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THANK YOU