Spectral/hp element methods: Recent developments, applications, and perspectives

The spectral/hp element method combines the geometric flexibility of the classical h-type finite element technique with the desirable numerical properties of spectral methods, employing high-degree piecewise polynomial basis functions on coarse finite element-type meshes. The spatial approximation is based upon orthogonal polynomials, such as Legendre or Chebychev polynomials, modified to accommodate a $C^0$-continuous expansion. Computationally and theoretically, by increasing the polynomial order $p$, high-precision solutions and fast convergence can be obtained and, in particular, under certain regularity assumptions an exponential reduction in approximation error between numerical and exact solutions can be achieved. This method has now been applied in many simulation studies of both fundamental and practical engineering flows. This paper briefly describes the formulation of the spectral/hp element method and provides an overview of its application to computational fluid dynamics. In particular, it focuses on the use of the spectral/hp element method in transitional flows and ocean engineering. Finally, some of the major challenges to be overcome in order to use the spectral/hp element method in more complex science and engineering applications are discussed.
Finite volume method room acoustic simulations integrated into the architectural design process

In many cases, room acoustics are neglected during the early stage of building design. This can result in serious acoustical problems that could have been easily avoided and can be difficult or expensive to remedy at later stages. Ideally, the room acoustic design should interact with the architectural design from the earliest design stage, as a part of a holistic design process. A new procedure to integrate room acoustics into architectural design is being developed in a Ph.D. project, with the aim of promoting this early stage holistic design process. This project aims to develop a new hybrid simulation tool combining wave-based and geometrical acoustics methods. One of the important aspects is the flexibility to represent realistic geometric shapes, for which the finite volume method (FVM) is chosen for the wave-based part of the tool. As a starting point, the computational efficiency of high-order two-dimensional FVM for defining an efficient wave-based simulation tool is investigated. Preliminary two-dimensional FVM simulation results are presented, which illuminate the suitability for handling complex geometries compared to other wave based simulation methods.
Multilevel techniques for Reservoir Simulation

The subject of this thesis is the development, application and study of novel multilevel methods for the acceleration and improvement of reservoir simulation techniques. The motivation for addressing this topic is a need for more accurate predictions of porous media flow and the ability to carry out these computations in a timely manner. This will lead to better decision making in the production of oil and gas. The goal is attained in various ways throughout the thesis work. Specifically, three fields of multilevel methods have been addressed in this work, namely

- Nonlinear multigrid (the Full Approximation Scheme)
- Variational (Galerkin) upscaling
- Linear solvers and preconditioners

First, a nonlinear multigrid scheme in the form of the Full Approximation Scheme (FAS) is implemented and studied for a 3D three-phase compressible rock/fluids immiscible reservoir simulator with a coupled well model. In a fair way, it is compared to the state-of-the-art solution scheme used in industry and research simulators. It is found that FAS improves time-to-solution by having a larger basin of attraction, faster initial convergence, data locality and a lower memory footprint. The study is extended to include a hybrid strategy, where FAS is combined with Newton’s method to construct a multilevel nonlinear preconditioner. This method demonstrates high efficiency and robustness.

Second, an improved IMPES formulated reservoir simulator is implemented using a novel variational upscaling approach based on element-based Algebraic Multigrid (AMGe). In particular, an advanced AMGe technique with guaranteed approximation properties is used to construct a coarse multilevel hierarchy of Raviart-Thomas and L2 spaces for the Galerkin coarsening of a mixed formulation of the reservoir simulation equations. By experimentation it is found that the AMGe based upscaling technique provided very accurate results while reducing the computational time proportionally to the reduction in degrees of freedom. Furthermore, it is demonstrated that the AMGe coarse spaces (interpolation operators) can be used for both variational upscaling and the construction of linear solvers. In particular, it is found to be beneficial (or even necessary) to apply an AMGe based multigrid solver to solve the upscaled problems. It is found that the AMGe upscaling changes the spectral properties of the matrix, which renders well-known state-of-the-art solvers for this type of system useless.

Third, FAS is combined with AMGe with guaranteed approximation properties to obtain a nonlinear multigrid solver for unstructured meshes. The FAS-AMGe solver is applied to a simplistic but numerically challenging mixed (velocity-pressure) model for porous media flow. In a fair way, FAS-AMGe is compared to Newton’s method and Picard iterations. It is found that FAS-AMGe is faster for the cases considered.

Finally, a number of multigrid linear solvers and preconditioners are implemented for various linear systems. In particular AMGe are used in the construction of multigrid preconditioners. These are compared to two state-of-the-art block diagonal preconditioners based on 1) a Schur complement with an Algebraic Multigrid (AMG) solver and 2) an augmented Lagrangian formulation using the Auxiliary Space AMG solver.

In addition to the research mentioned above, a sequential in-house COmpositional reservoir Simulator (COSI) with many features is parallelized in a distributed setting (MPI) using the PETSc framework. A parallel preconditioner based on the Constrained Pressure Residual method, Algebraic Multigrid and Restricted Additive Overlapping Schwarz with Incomplete LU solves on each subdomain is implemented. It is found that switching the traditionally used method, namely parallel ILU, with Restricted Additive Overlapping Schwarz results in a significant increase in parallel scalability while still maintaining similar robustness and efficiency.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Center for Energy Resources Engineering
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Numerical Multilevel Upscaling for Incompressible Flow in Reservoir Simulation: An Element-based Algebraic Multigrid (AMGe) Approach

We study the application of a finite element numerical upscaling technique to the incompressible two-phase porous media total velocity formulation. Specifically, an element agglomeration based Algebraic Multigrid (AMGe) technique with improved approximation proper ties [37] is used, for the first time, to generate upscaled and accurate coarse systems for the reservoir simulation equations. The upscaling technique is applied to both the mixed system for velocity and pressure and to the hyperbolic transport equations providing fully upscaled systems. By introducing additional degrees of freedom associated with non-planar interfaces between agglomerates, the coarse velocity space has guaranteed approximation properties. The employed AMGe technique provides coarse spaces with desirable local mass conservation and stability properties analogous to the original pair of Raviart-Thomas and piecewise discontinuous polynomial spaces, resulting in strong mass conservation for the upscaled systems. Due to the guaranteed approximation properties and the generic nature of the AMGe method, recursive multilevel upscaling is automatically obtained. Furthermore, this technique works for both structured and unstructured meshes. Multiscale Mixed Finite Elements exhibit accuracy for general unstructured meshes but do not in general lead to nested hierarchy of spaces. Multiscale multilevel mimetic finite differences generate nested spaces but lack the adaptivity of the flux representation on coarser levels that the proposed AMGe approach offers. Thus, the proposed approach can be seen as a rigorous bridge that merges the best properties of these two existing methods. The accuracy and stability of the studied multilevel AMGe upscaling technique is demonstrated on two challenging test cases.

General information
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A robust WENO scheme for nonlinear waves in a moving reference frame

For robust nonlinear wave simulation in a moving reference frame, we recast the free surface problem in Hamilton-Jacobi form and propose a Weighted Essentially Non-Oscillatory (WENO) scheme to automatically handle the upwinding of the convective term. A new automatic procedure for deriving the linear WENO weights based on a Taylor series expansion is introduced. A simplified smoothness indicator is proposed and is shown to perform well. The scheme is combined with high-order explicit Runge-Kutta time integration and a dissipative Lax-Friedrichs-type flux to solve for nonlinear wave propagation in a moving frame of reference. The WENO scheme is robust and less dissipative than the equivalent order upwind-biased finite difference scheme for all ratios of frame of reference to wave propagation speed tested. This provides the basis for solving general nonlinear wave-structure interaction problems at forward speed.

General information
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Organisations: Department of Mechanical Engineering, Fluid Mechanics, Coastal and Maritime Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing
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A stabilised nodal spectral element method for fully nonlinear water waves

We present an arbitrary-order spectral element method for general-purpose simulation of non-overturning water waves, described by fully nonlinear potential theory. The method can be viewed as a high-order extension of the classical finite element method proposed by Cai et al. (1998) [5], although the numerical implementation differs greatly. Features of the proposed spectral element method include: nodal Lagrange basis functions, a general quadrature-free approach and gradient recovery using global L2 projections. The quartic nonlinear terms present in the Zakharov form of the free surface conditions can cause severe aliasing problems and consequently numerical instability for marginally resolved or very steep waves. We show how the scheme can be stabilised through a combination of over-integration of the Galerkin projections and a mild spectral filtering on a per element basis. This effectively removes any aliasing driven instabilities while retaining the high-order accuracy of the numerical scheme. The additional computational cost of the over-integration is found insignificant compared to the cost of solving the Laplace problem. The model is applied to several benchmark cases in two dimensions. The results confirm the high order accuracy of the model (exponential convergence), and demonstrate the potential for accuracy and speedup. The results of numerical experiments are in excellent agreement with both analytical and experimental results for strongly nonlinear and irregular dispersive wave propagation. The benefit of using a high-order – possibly adapted – spatial discretisation for accurate water wave propagation over long times and distances is particularly attractive for marine hydrodynamics applications.
DeRisk - Accurate prediction of ULS wave loads. Outlook and first results

Loads from extreme waves can be dimensioning for the substructures of offshore wind turbines. The DeRisk project (2015-2019) aims at an improved load evaluation procedure for extreme waves through application of advanced wave models, laboratory tests of load effects, development of hydrodynamic load models, aero-elastic response calculations and statistical analysis. This first paper from the project outlines the content and philosophy behind DeRisk. Next, the first results from laboratory tests with irregular waves are presented, including results for 2D and 3D focused wave groups. The results of focused wave group tests and a 6-hour (full scale duration) test are reproduced numerically by re-application of the wave paddle signal in a fully nonlinear potential flow wave model. A good match for the free surface elevation and associated exceedance probability curve is obtained. Finally, the utilization of DeRisk’s results in practical design is discussed. (C) 2016 Published by Elsevier Ltd.

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Development of a numerical modelling tool for combined near field and far field wave transformations using a coupling of potential flow solvers

Wave energy converters (WECs) need to be deployed in large numbers in an array layout in order to have a significant power production. Each WEC has an impact on the incoming wave field, diffracting, reflecting and radiating waves. Simulating the wave transformations within and around a WEC farm is complex; it is difficult to simulate both near field and far field effects with a single numerical model, with relatively fast computing times. Within this research a numerical tool is developed to model near-field and far-field wave transformations caused by WECs. The tool is based on the coupling of a wave-structure interaction solver and a wave propagation model, both based on the potential flow theory. This paper discusses the coupling method and illustrates the functionality with a proof-of-concept. Additionally, a projection of the evolution of the numerical tool is given. It can be concluded that the coupling of the two solvers is an efficient and promising numerical tool to perform simulations on near – and far field wave elevations and kinematics nearby WEC farms.

Efficient uncertainty quantification of a fully nonlinear and dispersive water wave model with random inputs

A major challenge in next-generation industrial applications is to improve numerical analysis by quantifying uncertainties in predictions. In this work we present a formulation of a fully nonlinear and dispersive potential flow water wave model with random inputs for the probabilistic description of the evolution of waves. The model is analyzed using random sampling techniques and nonintrusive methods based on generalized polynomial chaos (PC). These methods allow us to accurately and efficiently estimate the probability distribution of the solution and require only the computation of the solution at different points in the parameter space, allowing for the reuse of existing simulation software. The choice of the applied methods is driven by the number of uncertain input parameters and by the fact that finding the solution of the considered model is computationally intensive. We revisit experimental benchmarks often used for validation of deterministic water
wave models. Based on numerical experiments and assumed uncertainties in boundary data, our analysis reveals that some of the known discrepancies from deterministic simulation in comparison with experimental measurements could be partially explained by the variability in the model input. Finally, we present a synthetic experiment studying the variance-based sensitivity of the wave load on an offshore structure to a number of input uncertainties. In the numerical examples presented the PC methods exhibit fast convergence, suggesting that the problem is amenable to analysis using such methods.

General information
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Scopus rating (2013): SJR 0.678 SNIP 1.387 CiteScore 1.19
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Scopus rating (2012): SJR 0.589 SNIP 1.077 CiteScore 1.06
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BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.457 SNIP 1.004 CiteScore 0.86
ISI indexed (2011): ISI indexed yes
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Scopus rating (2010): SJR 0.535 SNIP 0.934
Web of Science (2010): Indexed yes
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Scopus rating (2009): SJR 0.538 SNIP 0.998
BFI (2008): BFI-level 1
Scopus rating (2008): SJR 0.494 SNIP 0.757
Scopus rating (2007): SJR 0.607 SNIP 0.751
Web of Science (2007): Indexed yes
Scopus rating (2006): SJR 0.783 SNIP 1.099
Web of Science (2006): Indexed yes
Scopus rating (2005): SJR 0.557 SNIP 0.939
Scopus rating (2004): SJR 0.642 SNIP 0.869
Scopus rating (2003): SJR 0.837 SNIP 0.994
Scopus rating (2002): SJR 0.468 SNIP 0.556
Nonlinear Multigrid for Reservoir Simulation

A feasibility study is presented on the effectiveness of applying nonlinear multigrid methods for efficient reservoir simulation of subsurface flow in porous media. A conventional strategy modeled after global linearization by means of Newton's method is compared with an alternative strategy modeled after local linearization, leading to a nonlinear multigrid method in the form of the full-approximation scheme (FAS). It is demonstrated through numerical experiments that, without loss of robustness, the FAS method can outperform the conventional techniques in terms of algorithmic and numerical efficiency for a black-oil model. Furthermore, the use of the FAS method enables a significant reduction in memory usage compared with conventional techniques, which suggests new possibilities for improved large-scale reservoir simulation and numerical efficiency. Last, nonlinear multilevel preconditioning in the form of a hybrid-FAS/Newton strategy is demonstrated to increase robustness and efficiency.

General information

State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Abingdon Technology Center, Technical University of Denmark
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Scopus rating (2015): SJR 0.976 SNIP 1.838 CiteScore 2.37
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BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.993 SNIP 1.773 CiteScore 2.25
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Web of Science (2013): Indexed yes
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Scopus rating (2012): SJR 1.047 SNIP 1.757 CiteScore 2.13
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Nonlinear Multigrid solver exploiting AMGe Coarse Spaces with Approximation Properties

The paper introduces a nonlinear multigrid solver for mixed finite element discretizations based on the Full Approximation Scheme (FAS) and element-based Algebraic Multigrid (AMGe). The main motivation to use FAS for unstructured problems is the guaranteed approximation property of the AMGe coarse spaces that were developed recently at Lawrence Livermore National Laboratory. These give the ability to derive stable and accurate coarse nonlinear discretization problems. The previous attempts (including ones with the original AMGe method), were less successful due to lack of such good approximation properties of the coarse spaces. With coarse spaces with approximation properties, our FAS approach on unstructured meshes has the ability to be as powerful/successful as FAS on geometrically refined meshes. For comparison, Newton’s method and Picard iterations with an inner state-of-the-art linear solver are compared to FAS on a nonlinear saddle point problem with applications to porous media flow. It is demonstrated that FAS is faster than Newton’s method and Picard iterations for the experiments considered here. Due to the guaranteed approximation properties of our AMGe, the coarse spaces are very accurate, providing a solver with the potential for mesh-independent convergence on general unstructured meshes.

General information

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Organisations: Department of Applied Mathematics and Computer Science , Scientific Computing
Authors: Christensen, M. L. C. (Ekstem), Villa, U. (Ekstem), Engsig-Karup, A. P. (Intern), Vassilevski, P. (Ekstem)
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On nonlinear wave-structure interaction using an immersed boundary method in 2D

Introduction
We present our progress on the development and preliminary benchmarking results of a new efficient methodology for solving fully non-linear potential flow wave-structure interaction problems. The new model utilises the efficiency of finite difference methods on structured grids. The structure geometry is introduced using an Immersed Boundary Method (IBM) and the body boundary condition (BC) is satisfied with a Weighted Least Squares (WLS) approximation [7]. This allows complex geometries to be represented with high accuracy. The stability of the scheme is ensured by adopting the Weighted Essentially Non-Oscillatory (WENO) scheme [8] together with a Lax-Friedrichs type flux applied to the free surface conditions in Hamilton-Jacobi form. This work can be viewed as a novel extension of the flexible order finite difference potential flow solver OceanWave3D [2] to include the presence of a structure. The method obtains an optimum scaling of the solution effort [2] and has been implemented on massively parallel GPU architectures using the CUDA API [3] making it suitable for high resolution flow simulations. This combination of novel and robust numerical methods aims at creating new efficient tools for non-linear wave-structure interaction problems. The scheme is validated using the forced heaving motion of a two-dimensional (2D) horizontal circular cylinder with promising results, although there are still challenges to be overcome in terms of properly capturing the behavior of the intersection between the body and the free-surface.

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Organisations: Department of Mechanical Engineering, Fluid Mechanics, Coastal and Maritime Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing
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Robust Numerical Methods for Nonlinear Wave-Structure Interaction in a Moving Frame of Reference
This project is focused on improving the state of the art for predicting the interaction between nonlinear ocean waves and marine structures. To achieve this goal, a flexible order finite difference potential flow solver has been extended to calculate for fully nonlinear wave-structure interaction problems at forward speed.

The model utilises the efficiency of finite difference methods on structured grids and exploits the flexibility of a novel Immersed Boundary Method (IBM) based on Weighted Least Squares (WLS) for the approximation of the no-flux boundary condition on the body surface. As a result, the grid generation is very simple and the need for regridding when considering moving body problems is avoided. The temporal oscillations related to the IBM method and moving boundaries are minimized by sufficient spatial resolution and an increased time-step size.

For a smooth and continuous transformation a continuous free surface is required over the entire domain. Thus, an artificial free surface that respects this property is created in the interior of the body using a seventh order polynomial. The forward speed problem is formulated in a moving coordinate system attached to the mean position of the body. Robust approximations for all combinations of forward speed and wave velocity are obtained by expressing the free surface boundary conditions in Hamilton-Jacobi form and using a Weighted Essentially Non-Oscillatory (WENO) scheme for the convective derivatives. The linear WENO weights are derived with a new procedure that is suitable for numerical implementation and avoids the limitations of existing tabulated WENO coefficients. Furthermore, a simplified smoothness indicator that performs as well as the tabulated versions is proposed. Explicit high-order Runge-Kutta time integration and a Lax-Friedrichs-type numerical flux complete the scheme. The solver was tested on the two-dimensional zero speed wave radiation problem and the steady forward speed problem with satisfactory results and thus, the proof of concept for extending the methodology to three dimensions is established.

General information
Spectral Tensor-Train Decomposition

The accurate approximation of high-dimensional functions is an essential task in uncertainty quantification and many other fields. We propose a new function approximation scheme based on a spectral extension of the tensor-train (TT) decomposition. We first define a functional version of the TT decomposition and analyze its properties. We obtain results on the convergence of the decomposition, revealing links between the regularity of the function, the dimension of the input space, and the TT ranks. We also show that the regularity of the target function is preserved by the univariate functions (i.e., the "cores") comprising the functional TT decomposition. This result motivates an approximation scheme employing polynomial approximations of the cores. For functions with appropriate regularity, the resulting spectral tensor-train decomposition combines the favorable dimension-scaling of the TT decomposition with the spectral convergence rate of polynomial approximations, yielding efficient and accurate surrogates for high-dimensional functions. To construct these decompositions, we use the sampling algorithm TT-DMRG-cross to obtain the TT decomposition of tensors resulting from suitable discretizations of the target function. We assess the performance of the method on a range of numerical examples: a modified set of Genz functions with dimension up to 100, and functions with mixed Fourier modes or with local features. We observe significant improvements in performance over an anisotropic adaptive Smolyak approach. The method is also used to approximate the solution of an elliptic PDE with random input data. The open source software and examples presented in this work are available online (http://pypi.python.org/pypi/TensorToolbox/).
We introduce a new stabilized high-order and unstructured numerical model for modeling fully nonlinear and dispersive water waves. The model is based on a nodal spectral element method of arbitrary order in space and a -transformed formulation due to Cai, Langtangen, Nielsen and Tveito (1998). In the present paper we use a single layer of quadratic (in 2D) and prismatic (in 3D) elements. The model has been stabilized through a combination of over-integration of the Galerkin projections and a mild modal filter. We present numerical tests of nonlinear waves serving as a proof-of-concept validation for this new high-order model. The model is shown to exhibit exponential convergence even for very steep waves and there is a good agreement to analytic and experimental data.
Adaptive spectral tensor-strain decomposition for the construction of surrogate models

The construction of surrogate models is important as a mean of acceleration in computational methods for uncertainty quantification (UQ). When the forward model is particularly expensive, surrogate models can be used for the forward propagation of uncertainty [4] and the solution of inference problems [5]. An adaptive construction is necessary to meet the prescribed accuracy tolerances with the lowest computational effort.

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A Spectral Element Method for Nonlinear and Dispersive Water Waves

The use of flexible mesh discretisation methods are important for simulation of nonlinear wave-structure interactions in offshore and marine settings such as harbour and coastal areas. For real applications, development of efficient models for wave propagation based on unstructured discretisation methods is of key interest. We present a high-order general-purpose three-dimensional numerical model solving fully nonlinear and dispersive potential flow equations with a free surface.

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Computational Hydrodynamics: How Portable and Scalable Are Heterogeneous Programming Paradigms?

New many-core era applications at the interface of mathematics and computer science adopt modern parallel programming paradigms and expose parallelism through proper algorithms. We present new performance results for a novel massively parallel free surface wave model suitable for advanced simulations in arbitrary size Numerical Wave Tanks.
The application has already been studied in a series of works (see References) and is demonstrated to exhibit excellent performance portability and scalability using hybrid MPI-OpenCL/CUDA. Furthermore, it can be executed on arbitrary heterogeneous multi-device system sizes from desktops to large HPC systems such as superclusters and in the cloud utilizing heterogeneous devices like multi-core CPUs, GPUs, and Xeon Phi coprocessors. The numerical efficiency is evaluated on heterogeneous devices like multi-core CPUs, GPUs and Xeon Phi coprocessors to test the performance with respect to both portability and scalability. This study contributes to investigating the potential of code acceleration for reducing turn-around times of industrial CFD applications on heterogeneous hardware.

On Devising Boussinesq-type Equations with Bounded Eigenspectra: Two Horizontal Dimensions

Boussinesq-type equations are used to describe the propagation and transformation of free-surface waves in the nearshore region. The nonlinear and dispersive performance of the equations are determined by tunable parameters. Recently the authors presented conditions on the free parameters under which a Nwogu-type equations would yield bounded eigenspectra [5]. This leads to a global conditional CFL time-step restriction which is shown to not be affected by the discretisation method and in this sense the CFL condition is tamed to impose a minimal constraint. In this paper we extend the previous study and provide numerical experimentswich confirms the theoretical results also is valid in two horizontal dimensions.

Spectral element modelling of floating bodies in a Boussinesq framework

The wave energy sector relies heavily on the use of linear hydrodynamic models for the assessment of motions, loads and power production. The linear codes are computationally efficient and produce good results if applied within their application window. However, recent studies using two-phase VOF-RANS simulations of point-absorbers close to resonance have indicated that there might be significant differences between the power production using linear hydrodynamics and VOF-RANS. At present VOF-RANS simulations are too computational expensive to be used in the design cycle. In shallow and intermediate waters a possible middle way between the highly simplified and fast linear hydrodynamics and the very complete but slow VOF-RANS simulations is to use nonlinear, dispersive wave equations of Boussinesq-type. Jiang (2001) presented a unified approach for including bodies into the Boussinesq framework and solved the system with finite differences. In the unified approach the pressure working on the body are solved for using the instantaneous draft. In this study we will outline how to implement the approach of Jiang in a spectral/hp element setting, and simulate the heave motion of a body using different asymptotic wave equations. We will especially focus on the
stabilization of the coupled system.

**General Information**

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**Uncertainty Quantification with Applications to Engineering Problems**

The systematic quantification of the uncertainties affecting dynamical systems and the characterization of the uncertainty of their outcomes is critical for engineering design and analysis, where risks must be reduced as much as possible. Uncertainties stem naturally from our limitations in measurements, predictions and manufacturing, and we can say that any dynamical system used in engineering is subject to some of these uncertainties.

The first part of this work presents an overview of the mathematical framework used in Uncertainty Quantification (UQ) analysis and introduces the spectral tensor-train (STT) decomposition, a novel high-order method for the effective propagation of uncertainties which aims at providing an exponential convergence rate while tackling the curse of dimensionality. The curse of dimensionality is a problem that afflicts many methods based on meta-models, for which the computational cost increases exponentially with the number of inputs of the approximated function – which we will call dimension in the following.

The STT-decomposition is based on the Polynomial Chaos (PC) approximation and the low-rank decomposition of the function describing the Quantity of Interest of the considered problem. The low-rank decomposition is obtained through the discrete tensor-train decomposition, which is constructed using an optimization algorithm for the selection of the relevant points on which the function needs to be evaluated. The selection of these points is informed by the approximated function and thus it is able to adapt to its features. The number of function evaluations needed for the construction grows only linearly with the dimension and quadratically with the rank.

In this work we will present and use the functional counterpart of this low-rank decomposition and, after proving some auxiliary properties, we will apply PC on it, obtaining the STT-decomposition. This will allow the decoupling of each dimension, leading to a much cheaper construction of the PC surrogate. In the associated paper, the capabilities of the STT-decomposition are checked on commonly used test functions and on an elliptic problem with random inputs.

This work will also present three active research directions aimed at improving the efficiency of the STT-decomposition. In this context, we propose three new strategies for solving the ordering problem suffered by the tensor-train decomposition, for computing better estimates with respect to the norms usually employed in UQ and for the anisotropic adaptivity of the method.

The second part of this work presents engineering applications of the UQ framework. Both the applications are characterized by functions whose evaluation is computationally expensive and thus the UQ analysis of the associated systems will benefit greatly from the application of methods which require few function evaluations.

We first consider the propagation of the uncertainty and the sensitivity analysis of the non-linear dynamics of railway vehicles with suspension components whose characteristics are uncertain. These analysis are carried out using mostly PC methods, and resorting to random sampling methods for comparison and when strictly necessary.

The second application of the UQ framework is on the propagation of the uncertainties entering a fully non-linear and dispersive model of water waves. This computationally challenging task is tackled with the adoption of state-of-the-art software for its numerical solution and of efficient PC methods. The aim of this study is the construction of stochastic benchmarks where to test UQ methodologies before being applied to full-scale problems, where efficient methods are necessary with today's computational resources.

The outcome of this work was also the creation of several freely available Python modules for Uncertainty Quantification, which are listed and described in the appendix.
Analysis of efficient preconditioned defect correction methods for nonlinear water waves

Robust computational procedures for the solution of non-hydrostatic, free surface, irrotational and inviscid free-surface water waves in three space dimensions can be based on iterative preconditioned defect correction (PDC) methods. Such methods can be made efficient and scalable to enable prediction of free-surface wave transformation and accurate wave kinematics in both deep and shallow waters in large marine areas or for predicting the outcome of experiments in large numerical wave tanks. We revisit the classical governing equations are fully nonlinear and dispersive potential flow equations. We present new detailed fundamental analysis using finite-amplitude wave solutions for iterative solvers. We demonstrate that the PDC method in combination with a high-order discretization method enables efficient and scalable solution of the linear system of equations arising in potential flow models. Our study is particularly relevant for fast and efficient simulation of non-breaking fully nonlinear water waves over varying bottom topography that may be limited by computational resources or requirements. To gain insight into algorithmic properties and proper choices of discretization parameters for different PDC strategies, we study systematically limits of accuracy, convergence rate, algorithmic and numerical efficiency and scalability of the most efficient known PDC methods. These strategies are of interest, because they enable generalization of geometric multigrid methods to high-order accurate discretizations and enable significant improvement in numerical efficiency while incurring minimal storage requirements. We demonstrate robustness using such PDC methods for practical ranges of interest for coastal and maritime engineering, that is, from shallow to deep water, and report details of numerical experiments that can be used for benchmarking purposes.
A non-linear wave decomposition model for efficient wave–structure interaction. Part A: Formulation, validations and analysis

This paper deals with the development of an enhanced model for solving wave–wave and wave–structure interaction problems. We describe the application of a non-linear splitting method originally suggested by Di Mascio et al. [1], to the high-order finite difference model developed by Bingham et al. [2] and extended by Engsig-Karup et al. [3] and [4]. The enhanced strategy is based on splitting all solution variables into incident and scattered fields, where the incident field is assumed to be known and only the scattered field needs to be computed by the numerical model. Although this splitting technique has been applied to both potential flow and Navier–Stokes solvers in the past, it has not been thoroughly described and analyzed, nor has it been presented in widely read journals. Here we describe the method in detail and carefully analyze its performance using several 2D linear and non-linear test cases. In particular, we consider the extreme case of non-linear waves up to the point of breaking reflecting from a vertical wall; and conclude that no limitations are imposed by adopting this splitting. The advantages of this strategy in terms of robustness, accuracy and efficiency are also demonstrated by comparison with the more common strategy of solving the incident and scattered fields together.
On devising Boussinesq-type models with bounded eigenspectra: One horizontal dimension

The propagation of water waves in the nearshore region can be described by depth-integrated Boussinesq-type equations. The dispersive and nonlinear characteristics of the equations are governed by tunable parameters. We examine the associated linear eigenproblem both analytically and numerically using a spectral element method of arbitrary spatial order $p$. It is shown that existing sets of parameters, found by optimising the linear dispersion relation, give rise to unbounded eigenspectra which govern stability. For explicit time-stepping schemes the global CFL time-step restriction typically requires $\Delta t \propto p^{-2}$. We derive and present conditions on the parameters under which implicitly-implicit Boussinesq-type equations will exhibit bounded eigenspectra. Two new bounded versions having comparable nonlinear and dispersive properties as the equations of Nwogu (1993) and Schäffer and Madsen (1995) are introduced. Using spectral element simulations of stream function waves it is illustrated that (i) the bounded equations capture the physics of the wave motion as well as the standard unbounded equations, and (ii) the bounded equations are computationally more efficient when explicit time-stepping schemes are used. Thus the bounded equations were found to lead to more robust and efficient numerical schemes without compromising the accuracy.
On the numerical and computational aspects of non-smoothnesses that occur in railway vehicle dynamics

The paper contains a report of the experiences with numerical analyses of railway vehicle dynamical systems, which all are nonlinear, non-smooth and stiff high-dimensional systems. Some results are shown, but the emphasis is on the numerical methods of solution and lessons learned. But for two examples the dynamical problems are formulated as systems of ordinary differential-algebraic equations due to the geometric constraints. The non-smoothnesses have been neglected, smoothened or entered into the dynamical systems as switching boundaries with relations, which govern the continuation of the solutions across these boundaries. We compare the resulting solutions that are found with the three different strategies of handling the non-smoothnesses. Several integrators – both explicit and implicit ones – have been tested and their performances are evaluated and compared with respect to accuracy, and computation time.

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Authors: True, H. (Intern), Engsig-Karup, A. P. (Intern), Bigoni, D. (Intern)
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Sensitivity Analysis of the Critical Speed in Railway Vehicle Dynamics

We present an approach to global sensitivity analysis aiming at the reduction of its computational cost without compromising the results. The method is based on sampling methods, cubature rules, High-Dimensional Model Representation and Total Sensitivity Indices. The approach has a general applicability in many engineering fields and does not require the knowledge of the particular solver of the dynamical system. This analysis can be used as part of the virtual homologation procedure and to help engineers during the design phase of complex systems. The method is applied to a half car with a two-axle Cooperrider bogie, in order to study the sensitivity of the critical speed with respect to suspension parameters. The importance of a certain suspension component is expressed by the variance in critical speed that is ascribable to it. This proves to be useful in the identification of parameters for which the exactness of their values is critically important.

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Scopus rating (2008): SJR 0.744 SNIP 2.057
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Spectral Tensor-Train Decomposition for low-rank surrogate models

The construction of surrogate models is very important as a mean of acceleration in computational methods for uncertainty quantification (UQ). When the forward model is particularly expensive compared to the accuracy loss due to the use of a surrogate – as for example in computational fluid dynamics (CFD) – the latter can be used for the forward propagation of uncertainty [7] and the solution of inference problems.

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Stable finite difference discretizations of the forward speed seakeeping problem

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Anwendung der "Uncertainty Quantification" bei eisenbahndynamischen Problemen

The paper describes the results of the application of "Uncertainty Quantification" methods in railway vehicle dynamics. The system parameters are given by probability distributions. The results of the application of the Monte-Carlo and generalized Polynomial Chaos methods to a simple bogie model will be discussed.
Designing Scientific Software for Heterogeneous Computing: With application to large-scale water wave simulations

The main objective with the present study has been to investigate parallel numerical algorithms with the purpose of running efficiently and scalably on modern many-core heterogeneous hardware. In order to obtain good efficiency and scalability on modern multi- and many-core architectures, algorithms and data structures must be designed to utilize the underlying parallel architecture. The architectural changes in hardware design within the last decade, from single to multi and many-core architectures, require software developers to identify and properly implement methods that both exploit concurrency and maintain numerical efficiency.

Graphical Processing Units (GPUs) have proven to be very effective units for computing the solution of scientific problems described by partial differential equations (PDEs). GPUs have today become standard devices in portable, desktop, and supercomputers, which makes parallel software design applicable, but also a challenge for scientific software developers at all levels. We have developed a generic C++ library for fast prototyping of large-scale PDE solvers based on flexible-order finite difference approximations on structured regular grids. The library is designed with a high abstraction interface to improve developer productivity. The library is based on modern template-based design concepts as described in Glimberg, Engsig-Karup, Nielsen & Dammann (2013). The library utilizes heterogeneous CPU/GPU environments in order to maximize computational throughput by favoring data locality and low-storage algorithms, which are becoming more and more important as the number of concurrent cores per processor increases.

We demonstrate in a proof-of-concept the advantages of the library by assembling a generic nonlinear free surface water wave solver based on unified potential flow theory, for fast simulation of large-scale phenomena, such as long distance wave propagation over varying depths or within large coastal regions. Simulations that are valuable within maritime engineering because of the adjustable properties that follow from the flexible-order implementation. We extend the novel work on an efficient and robust iterative parallel solution strategy proposed by Engsig-Karup, Madsen & Glimberg (2011), for the bottleneck problem of solving a _-transformed Laplace problem in three dimensions at every time integration step. A geometric multigrid preconditioned defect correction scheme is used to attain high-order accurate solutions with fast convergence and scalable work effort. To minimize data storage and enhance performance, the numerical method is based on matrix-free finite difference approximations, implemented to run efficiently on many-core GPUs. Also, single-precision calculations are found to be attractive for reducing transfers and enhancing performance for both pure single and mixed-precision calculations without compromising robustness. A structured multi-block approach is presented that decomposes the problem into several subdomains, supporting flexible block structures to match the physical domain. For data communication across processor nodes, messages are sent using MPI to repeatedly update boundary information between adjacent coupled subdomains. The impact on convergence and performance scalability using the proposed hybrid CUDA-MPI strategy will be presented. A survey of the convergence and performance properties of the preconditioned defect correction method is carried out with special focus on large-scale multi-GPU simulations. Results indicate that a limited number of multigrid restrictions are required, and that it is strongly coupled to the wave resolutions. These results are encouraging for the heterogeneous multi-GPU systems as they reduce the communication overhead significantly and prevent both global coarse grid corrections and inefficient processor utilization at the coarsest levels.

We find that spatial domain decomposition scales well for large problems sizes, but for problems of limited sizes, the maximum attainable speedup is reached for a low number of processors, as it leads to an unfavorable communication to compute ratio. To circumvent this, we have considered a recently proposed parallel-in-time algorithm referred to as Parareal, in an attempt to introduce algorithmic concurrency in the time discretization. Parareal may be perceived as a two level multigrid method in time, where the numerical solution is first sequentially advanced via course integration and then updated simultaneously on multiple GPUs in a predictor-corrector fashion. A parameter study is performed to establish proper choices for maximizing speedup and parallel efficiency. The Parareal algorithm is found to be sensitive to a number of numerical and physical parameters, making practical speedup a matter of parameter tuning. Results are presented to confirm that it is possible to attain reasonable speedups, independently of the spatial problem size.

To improve application range, curvilinear grid transformations are introduced to allow representation of complex boundary geometries. The curvilinear transformations increase the complexity of the implementation of the model equations. A number of free surface water wave cases have been demonstrated with boundary-fitted geometries, where the combination of a flexible geometry representation and a fast numerical solver can be a valuable engineering tool for large-scale simulation of real maritime scenarios.

The present study touches some of the many possibilities that modern heterogeneous computing can bring if careful and parallel-aware design decisions are made. Though several free surface examples are outlined, we are yet to demonstrate results from a real large-scale engineering case.

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Authors: Glimberg, S. L. (Intern), Engsig-Karup, A. P. (Intern), Dammann, B. (Intern)
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Development of a GPU-accelerated MIKE 21 Solver for Water Wave Dynamics
With encouragement by the company DHI are the aim of this B.Sc. thesis1 to investigate, whether if it is possible to accelerate the simulation speed of DHIs commercial product MIKE 21 HD, by formulating a parallel solution scheme and implementing it to be executed on a CUDA-enabled GPU (massive parallel hardware).

Development of software components for heterogeneous many-core architectures

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Development of software components for heterogeneous many-core architectures

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Efficient Hybrid-Spectral Model for Fully Nonlinear Numerical Wave Tank

A new hybrid-spectral solution strategy is proposed for the simulation of the fully nonlinear free surface equations based on potential flow theory. A Fourier collocation method is adopted horizontally for the discretization of the free surface equations. This is combined with a modal Chebyshev Tau method in the vertical for the discretization of the Laplace equation in the fluid domain, which yields a sparse and spectrally accurate Dirichlet-to-Neumann operator. The Laplace problem is solved with an efficient Defect Correction method preconditioned with a spectral discretization of the linearized wave problem, ensuring fast convergence and optimal scaling with the problem size. Preliminary results for very nonlinear waves show expected convergence rates and a clear advantage of using spectral schemes.

Fast hydrodynamics on heterogenous many-core hardware

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Multiscale Simulation of Breaking Wave Impacts

The purpose of this project is to make an accurate, robust, geometric flexible and efficient model for calculation of forces on structures from nonlinear ocean waves and breaking wave impacts. Accurate prediction of the extreme forces on wind turbine foundations, breakwaters and tidal or wave power devises are important for enhancement structural designs. The proposed model is based on an incompressible and inviscid flow approximation and the governing equations are applied in an arbitrary Lagrangian-Eulerian moving frame of reference (ALE). The Runge-Kutta method (RK) is used for time integration and mass conservation is satisfied through a pressure-corrector type calculation of the pressure. The weighted least squares method (WLS) is combined with approximate Riemann solvers to introduce numerical smoothing of the solution around steep gradients in the velocity and pressure fields. The Poisson equation is solved and the pressure boundary conditions are satisfied by a generalized finite pointset method (GFPM); This provides a geometrically flexible and stable solution for the fluid pressure. The numerical approximations of these equations are performed on unstructured point distributions and the solutions for velocity and pressure are represented by WLS approximation of multivariate polynomials. The stencils for the ALE-WLS and GFPM methods are found through a breadth first search (BFS) in a modified Delaunay graph. This graph is the discrete representation of the fluid domain and the connectivity between the calculation points. The graph is updated according to the evolving topology of the fluid domain caused by the fluid reaching or leaving a solid boundary or the free surface colliding with itself or another free-surface. After each time step the fluid domain is checked for any of these intersections and the topology is updated accordingly in its graph representation. The calculation points move in a Lagrangian way and this can cause ill-conditioning of the generalized Vandermonde matrix in the WLS and GFPM methods. To prevent this the point set is refined and coarsened by a fill-distance based adaptivity method and redistributed via a point position filtering method. The incompressible and inviscid ALE-WLS model is applied to the following standard validation test cases: deforming elliptical drop, small amplitude standing waves and the dam break problem. The deforming elliptical drop test show that the model can calculate the kinematics and dynamics of this free surface flow accurately and robustly. Long time integration of this small amplitude periodic motion is possible due to accurate free surface evolution and small errors in the fluid volume. The dam break test case shows that the incompressible and inviscid ALE-WLS model can calculate nonlinear fluid motion, fluid structure impacts and overturning waves. The propagation speed of the wetting front and impact pressures are compared to experiments and the results compare reasonably well. The incompressible and inviscid ALE-WLS model is coupled with the potential flow model of Engsig-Karup et al. [2009], to perform multiscale calculation of breaking wave impacts on a vertical breakwater. The potential flow model provides accurate calculation of the wave transformation from offshore to the vicinity of the breakwater. The wave breaking close to the breakwater and the wave impact are calculated by the incompressible ALE-WLS model. The forces calculated with the incompressible and inviscid ALE-WLS model are ~ 1 - 2 times the corresponding compressible calculations in Bredmose et al. [2009] for the calculations without trapped air. Among the contributions of this project are the ALE-WLS method combined with approximate Riemann solvers and the generalization of the FPM method to arbitrary order of accuracy. The WLS and GFPM stencils found using the BFS data structure, which is updated due to topology changes of the evolving fluid domain. This extension combined with ALE-WLS and approximate Riemann solvers gives a numerical model capable of calculation of forces due to breaking wave impacts. The incompressible and inviscid ALE-WLS model has been coupled with a potential flow model to provide multiscale calculation of forces from breaking wave impacts on structures.
Real-Time Simulation of Ship-Structure and Ship-Ship Interaction

This paper gives the status of the development of a ship-hydrodynamic model for real-time ship-wave calculation and ship-structure and ship-ship interaction in a full mission marine simulator. The hydrodynamic model is based on potential flow theory, linear or non-linear free surface boundary condition and higher-order accurate numerical approximations. The equations presented facilitate both Neumann-Kelvin and double-body linearizations. The body boundary condition on the ship hull is approximated by a static and dynamic moving pressure distribution. The pressure distribution method is used, because it is simple, easy to implement and computationally efficient. Multiple many-core graphical processing units (GPUs) are used for parallel execution and the model is implemented using a combination of C/C++, CUDA and MPI. Two ship hydrodynamic cases are presented: Kriso Container Carrier at steady forward speed and lock entrance of a TEU 12.000 Container Carrier. These calculations reveal that the pressure distribution model is a too simple approximation of the body boundary condition and that it has the limitations of a flat-ship approximation. It is necessary to investigate more accurate approximations of the body boundary condition, which does not compromise the overall computational efficiency.

Sensitivity Analysis of the Critical Speed in Railway Vehicle Dynamics

We present an approach to global sensitivity analysis aiming at the reduction of its computational cost without compromising the results. The method is based on sampling methods, cubature rules, High-Dimensional Model Representation and Total Sensitivity Indices. The approach has a general applicability in many engineering fields and does not require the knowledge of the particular solver of the dynamical system. This analysis can be used as part of the virtual homologation procedure and to help engineers during the design phase of complex systems. The method is applied to a half car with a two-axle Cooperrider bogie, in order to study the sensitivity of the critical speed with respect to suspension parameters. The importance of a certain suspension component is expressed by the variance in critical speed that is ascribable to it. This proves to be useful in the identification of parameters for which the exactness of their values is critically important.
Stochastic Wave Dynamics and Uncertainty Quantification

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Towards real time simulation of ship-ship interaction - Part II: double body flow linearization and GPU implementation

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A comparative study of two fast nonlinear free-surface water wave models
This paper presents a comparison in terms of accuracy and efficiency between two fully nonlinear potential flow solvers for the solution of gravity wave propagation. One model is based on the high-order spectral (HOS) method, whereas the second model is the high-order finite difference model OceanWave3D. Although both models solve the nonlinear potential flow problem, they make use of two different approaches. The HOS model uses a modal expansion in the vertical direction to collapse the numerical solution to the two-dimensional horizontal plane. On the other hand, the finite difference model simply directly solves the three-dimensional problem. Both models have been well validated on standard test cases and shown to exhibit attractive convergence properties and an optimal scaling of the computational effort with increasing problem size. These two models are compared for solution of a typical problem: propagation of highly nonlinear periodic waves on a finite constant-depth domain. The HOS model is found to be more efficient than OceanWave3D with a difference dependent on the level of accuracy needed as well as the wave steepness. Also, the higher the order of the finite difference schemes used in OceanWave3D, the closer the results come to the HOS model.

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A Generic High-performance GPU-based Library for PDE solvers

Recent development of massively parallel processors such as graphical processing units (GPUs), has already proven to be very effective for a vast amount of scientific applications. One major benefit of the GPU, is that it is already a standard device in most affordable desktop computers. Thus, the privilege of high-performance parallel computing is now in principle accessible for many scientific users, no matter their economic resources. Though being highly effective units, GPUs and parallel architectures in general, pose challenges for software developers to utilize their efficiency. Sequential legacy codes are not always easily parallelized and the time spent on conversion might not pay o in the end. We present a highly generic C++ library for fast assembling of partial differential equation (PDE) solvers, aiming at utilizing the computational resources of GPUs. The library requires a minimum of GPU computing knowledge, while still oering the possibility to customize user-specic solvers at kernel level if desired.

Spatial dierential operators are based on matrix free exible order nite dierence approximations. These matrix free operators minimize both memory consumption and main memory access, two important features for ecient GPU utilization and for enabling solution of large problems. In order to solve the large linear systems of equations, arising from the discretization of PDEs, the library includes a set of common iterative solvers. All iterative solvers are based on template arguments, such that vector and matrix classes, along with their underlying implementations, can be freely interchanged or new schemes developed without much coding eort. The generic nature of the library, along with a predened set of interface rules, allow us to set up the components for PDE solver through type binder denitions. We encourage this use of parameterized binding objects, as it allows the user to control the assembling of PDE solvers at a high abstraction level, without necessarily having to change internal code.

We will illustrate the assembling of a tool using our library for fast and scalable simulation of fully nonlinear free surface water waves over uneven depths[1, 2, 3]. The wave model is based on the potential ow formulation, with the computational bottleneck of solving a fully three dimensional Laplace problem eciently. A robust h- or p-multigrid preconditioned defect correction method is applied to keep storage low and algorithmic eciency high. Performance analysis of the implemented wave model shows that performance is comparable to a dedicated (non-library version) reference GPU-based solver. Work in progress also address the problem of simulating water waves at very large scales. Therefore we added an MPI layer to support domain decomposition preconditioning using multiple GPUs. The wave tool is to be used for ecient analysis of both coastal engineering problems and interactive real-time computing of ship-wave problems. Such applications will benet well from high-performance software. We will report our recent progress on the development of the new tool for coastal engineering.
A Generic High-performance GPU-based Library for PDE solvers

Adapting to new programming models for modern multi- and many-core architectures requires code-rewriting and changing algorithms and data structures, in order to achieve good efficiency and scalability. We present a generic library for solving large scale partial differential equations (PDEs), capable of utilizing heterogeneous CPU/GPU environments. The library can be used for fast proto-typing of PDE solvers, based on finite difference approximations of spatial derivatives in one, two, or three dimensions. In order to efficiently solve large scale problems, we keep memory consumption and memory access low, using a low-storage implementation of flexible-order finite difference operators. We will illustrate the use of library components by assembling such matrix-free operators to be used with one of the supported iterative solvers, such as GMRES, CG, Multigrid or Defect Correction. As a proto-type for large scale PDE solvers, we present the assembling of a tool for simulation of three dimensional fully nonlinear water waves. Measurements show scalable performance results - in the same order as a dedicated non-library version of the wave tool. Introducing a domain decomposition preconditioner based on a multigrid method, further extends support for multiple GPUs and allows for improvements in performance as well as increased problem sizes.

A GPU-based High-Performance Library with Application to Nonlinear Water Waves
**A High-Order WENO Finite Difference Water Wave Model for Interactive Ship-Wave Simulation**

**General Information**
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Department of Mechanical Engineering, Fluid Mechanics, Coastal and Maritime Engineering
Authors: Engsig-Karup, A. P. (Intern), Lindberg, O. (Intern), Glimberg, S. L. (Intern), Dammann, B. (Intern), Bingham, H. B. (Intern), Madsen, P. A. (Intern)
Number of pages: 2
Publication date: 2012
Main Research Area: Technical/natural sciences
Source: dtu
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Publication: Research - peer-review › Paper – Annual report year: 2012

**An ALE Weighted Least Squares Method for Simulation of Violent Water Wave Impact**

**General Information**
State: Published
Organisations: Fluid Mechanics, Coastal and Maritime Engineering, Department of Mechanical Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Lindberg, O. (Intern), Engsig-Karup, A. P. (Intern), Bingham, H. B. (Intern)
Number of pages: 2
Publication date: 2012
Main Research Area: Technical/natural sciences
Source: dtu
Source-ID: u::6060
Publication: Research - peer-review › Paper – Annual report year: 2012

**Comparison of Classical and Modern Uncertainty Qualification Methods for the Calculation of Critical Speeds in Railway Vehicle Dynamics**

This paper describes the results of the application of Uncertainty Quantification methods to a railway vehicle dynamical example. Uncertainty Quantification methods take the probability distribution of the system parameters that stems from the parameter tolerances into account in the result. In this paper the methods are applied to a lowdimensional vehicle dynamical model composed by a two-axle bogie, which is connected to a car body by a lateral linear spring, a lateral damper and a torsional spring.

Their characteristics are not deterministically defined, but they are defined by probability distributions. The model - but with deterministically defined parameters - was studied in [1], and this article will focus on the calculation of the critical speed of the model, when the distribution of the parameters is taken into account.

Results of the application of the traditional Monte Carlo sampling method will be compared with the results of the application of advanced Uncertainty Quantification methods such as generalized Polynomial Chaos (gPC) [2]. We highlight the computational performance and fast convergence that result from the application of advanced Uncertainty Quantification methods. Generalized Polynomial Chaos will be presented in both the Galerkin and Collocation form with emphasis on the pros and cons of each of those approaches.

**General Information**
State: Published
High-order Finite Difference Solution of Euler Equations for Nonlinear Water Waves

The incompressible Euler equations are solved with a free surface, the position of which is captured by applying an Eulerian kinematic boundary condition. The solution strategy follows that of [1, 2], applying a coordinate-transformation to obtain a time-constant spatial computational domain which is discretized using arbitrary-order finite difference schemes on a staggered grid with one optional stretching in each coordinate direction. The momentum equations and kinematic free surface condition are integrated in time using the classic fourth-order Runge-Kutta scheme. Mass conservation is satisfied implicitly, at the end of each time stage, by constructing the pressure from a discrete Poisson equation, derived from the discrete continuity and momentum equations and taking the time-dependent physical domain into account. An efficient preconditioned Defect Correction (DC) solution of the discrete Poisson equation for the pressure is presented, in which the
The preconditioning step is based on an order-multigrid formulation with a direct solution on the lowest order-level. This ensures fast convergence of the DC method with a computational effort which scales linearly with the problem size. Results obtained with a two-dimensional implementation of the model are compared with highly accurate stream function solutions to the nonlinear wave problem, which show the approximately expected convergence rates and a clear advantage of using high-order finite difference schemes in combination with the Euler equations.

Nonlinear Multigrid for Reservoir Simulation

General information
State: Published
Organisations: Department of Chemical and Biochemical Engineering, Department of Informatics and Mathematical Modeling, Computing, Technical University of Denmark
Authors: Christensen, M. L. C. (Intern), Eskildsen, K. L. (Ekstern), Engsig-Karup, A. P. (Intern), Wakefield, M. (Ekstern)
Number of pages: 1
Publication date: 2012
Event: Poster session presented at SIAM SPE Conference on Mathematical Methods in Fluid Dynamics and Simulation of Giant Oil and Gas Reservoirs, Istanbul, Turkey.
Main Research Area: Technical/natural sciences
Electronic versions:
PosterSPE.pdf
Source: dtu
Source-ID: u::6057
Publication: Research - peer-review › Poster – Annual report year: 2012

Parallel Programming using OpenCL on Modern Architectures

This report is intended as a quick introduction to the OpenCL framework and the aim is to facilitate a smooth transfer into the use OpenCL C for developers with previous GPGPU experience. The purpose of OpenCL is to allow for developers to use all compute resources available on a heterogeneous hardware platform. As well as being an introduction to OpenCL, the report also presents an overview of AMD GPU hardware, covering both the VLIW5/4 architectures and the upcoming Graphics-Core-Next architecture which is to form the basis of AMD's future generation GPUs that are to be as capable at compute as they are at graphics. To conclude the presentation of OpenCL as a language for compute, a matrix-matrix multiplication example is devised and optimized for the VLIW4, Tesla and Fermi architectures. The performance is measured as a function of both matrix and work-group size and results are discussed. Where applicable, the equivalent CUDA implementation is tested for comparison.

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Nielsen, A. S. (Ekstern), Engsig-Karup, A. P. (Intern), Dammann, B. (Intern)
Number of pages: 49
Publication date: 2012
Towards Real Time Simulation of Ship-Ship Interaction

We present recent and preliminary work directed towards the development of a simplified, physics-based model for improved simulation of ship-ship interaction that can be used for both analysis and real-time computing (i.e. with real-time constraints due to visualization). The goal is to implement the model into a large maritime simulator for training of naval officers, in particular tug boat helmsmen. Tug boat simulators are used for training of communication and situation awareness during manoeuvre involved with towing of large vessels. A main objective of the work is to improve and enable more accurate (realistic) and much faster ship-wave and ship-ship simulations than are currently possible. The coupling of simulation with visualization should improve the visual experience such that it can be perceived as more realistic in training. Today the state-of-art in real-time ship-ship interaction is for efficiency reasons and time-constraints in visualization based on model experiments in towing tanks and precomputed force tables. We anticipate that the fast, and highly parallel, algorithm described by Engsig-Karup et al. [2011] for execution on affordable modern high-throughput Graphics Processing Units (GPUs) can provide the basis for efficient simulations in combination with an accurate free-surface model for Ship-Ship simulation. Another area of application is the determination of wave disturbances from a ship in a coastal environment, channels and harbours. The model proposed in the following can in a simple and efficient way calculate the wave field from a ship sailing in a finite depth sea, even with variations in the height of sea bed. The generated wave field can be applied as an input to other models that simulate the marine environment on a larger scale.

Uncertainty Quantification on High-speed Railway Dynamics

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Bigoni, D. (Intern), Engsig-Karup, A. P. (Intern), True, H. (Intern)
Publication date: 2012
Event: Poster session presented at Uncertainty Quantification for High-Performance Computing Workshop, Oak Ridge, TN, United States.
Main Research Area: Technical/natural sciences
Electronic versions: poster.pdf
A Fast GPU-accelerated Mixed-precision Strategy for Fully Nonlinear Water Wave Computations

We present performance results of a mixed-precision strategy developed to improve a recently developed massively parallel GPU-accelerated tool for fast and scalable simulation of unsteady fully nonlinear free surface water waves over uneven depths (Engsig-Karup et al. 2011). The underlying wave model is based on a potential flow formulation, which requires efficient solution of a Laplace problem at large-scales. We report recent results on a new mixed-precision strategy for efficient iterative high-order accurate and scalable solution of the Laplace problem using a multigrid-preconditioned defect correction method. The improved strategy improves the performance by exploiting architectural features of modern GPUs for mixed precision computations and is tested in a recently developed generic library for fast prototyping of PDE solvers. The new wave tool is applicable to solve and analyze large-scale wave problems in coastal and offshore engineering.

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Technical University of Denmark
Authors: Glimberg, S. L. (Intern), Engsig-Karup, A. P. (Intern), Madsen, M. G. (Ekstern)
Number of pages: 8
Publication date: 2011

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Main Research Area: Technical/natural sciences
Conference: ENUMATH 2012, Leicester, United Kingdom, 05/09/2012 - 05/09/2012
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Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

A Fast Mixed-Precision Strategy for Iterative GPU-Based Solution of the Laplace Equation

Our work is concerned with the development of a generic high-performance library for scientific computing. The library is targeted for assembling flexible-order finite-difference solvers for PDEs. Our goal is to enable fast solution of large PDE systems, fully exploiting the massively parallel architecture of Graphics Processing Units. We will detail a strategy for an iterative mixed-precision p-multigrid solver of the Laplace equation, which appears as a computational bottleneck in applications in coastal and offshore engineering.

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Glimberg, S. L. (Intern), Engsig-Karup, A. P. (Intern)
Publication date: 2011

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sllides_glimberg.pdf
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Publication: Research › Sound/Visual production (digital) – Annual report year: 2011

A massively parallel GPU-accelerated model for analysis of fully nonlinear free surface waves

We implement and evaluate a massively parallel and scalable algorithm based on a multigrid preconditioned Defect Correction method for the simulation of fully nonlinear free surface flows. The simulations are based on a potential model that describes wave propagation over uneven bottoms in three space dimensions and is useful for fast analysis and prediction purposes in coastal and offshore engineering. A dedicated numerical model based on the proposed algorithm is executed in parallel by utilizing affordable modern special purpose graphics processing unit (GPU). The model is based on a low-storage flexible-order accurate finite difference method that is known to be efficient and scalable on a CPU core (single thread). To achieve parallel performance of the relatively complex numerical model, we investigate a new trend in high-performance computing where many-core GPUs are utilized as high-throughput co-processors to the CPU. We describe and demonstrate how this approach makes it possible to do fast desktop computations for large nonlinear wave problems in numerical wave tanks (NWTs) with close to 50/100 million total grid points in double/ single precision with 4 GB global device memory available. A new code base has been developed in C++ and compute unified device architecture C and is found to improve the runtime more than an order in magnitude in double precision arithmetic for the
same accuracy over an existing CPU (single thread) Fortran 90 code when executed on a single modern GPU. These significant improvements are achieved by carefully implementing the algorithm to minimize data-transfer and take advantage of the massive multi-threading capability of the GPU device.

**General information**

State: Published

Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Technical University of Denmark

Authors: Engsig-Karup, A. P. (Intern), Madsen, M. G. (Ekstern), Glimberg, S. L. (Intern)

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- Web of Science (2003): Indexed yes
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Development of a new massively parallel tool for nonlinear free surface wave simulation

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Technical University of Denmark
Authors: Engsig-Karup, A. P. (Intern), Madsen, M. G. (Ekstern)
Publication date: 2011
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General-Purpose Graphics Processing Units (GPGPU), Parallel programming, High-Performance Computing, Scientific GPU Computing
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Publication: Research › Poster – Annual report year: 2011

Fast high-performance modeling tools for many-core architectures

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Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing, Discrete mathematics, Department of Mathematics, Technical University of Denmark
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GPU, Scientific computing, model based control
Links: http://gpulab.imm.dtu.dk/
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Improved Software Implementation of DES Using CUDA and OpenCL

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State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Discrete mathematics, Department of Mathematics, Technical University of Denmark
Authors: Noer, D. (Ekstern), Engsig-Karup, A. P. (Intern), Zenner, E. (Intern)
Publication date: 2011

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http://www.uni-weimar.de/cms/medien/mediensicherheit/weworc-2011/home.html
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Introduction to GPU Programming

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Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Engsig-Karup, A. P. (Intern)
Publication date: 2011

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Main Research Area: Technical/natural sciences
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http://gpulab.imm.dtu.dk/courses.html
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Publication: Research › Sound/Visual production (digital) – Annual report year: 2011

On a fast GPU-accelerated massively parallel method for fully nonlinear water wave computations

General information
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Technical University of Denmark
Authors: Engsig-Karup, A. P. (Intern), Madsen, M. G. (Ekstern), Glimberg, S. L. (Intern)
Publication date: 2011

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Electronic versions: EngsigKarupEtAl.pdf
Links:
http://www2.le.ac.uk/departments/mathematics/research/enumath2011

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Publication: Research - peer-review › Article in proceedings – Annual report year: 2011

Towards fast real-time analysis of large wave problems on desktop architectures

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Engsig-Karup, A. P. (Intern)
Publication date: 2011

Publication information
Original language: English
Main Research Area: Technical/natural sciences
Very fast simulation of nonlinear water waves in very large numerical wave tanks on affordable graphics cards

An Efficient GPU-Accelerated Model for Fully Nonlinear Water Waves

Development of an efficient GPU-accelerated model for fully nonlinear water waves
This contribution presents our recent progress on developing an efficient fully-nonlinear potential flow model for simulating 3D wave-wave and wave-structure interaction over arbitrary depths (i.e. in coastal and offshore environment). The model is based on a high-order finite difference scheme OceanWave3D presented in [1, 2]. A nonlinear decomposition of the solution into incident and scattered fields is used to increase the efficiency of the wave-structure interaction problem resolution. Application of the method to the diffraction of nonlinear waves around a fixed, bottom mounted circular cylinder are presented and compared to the fully nonlinear potential code XWAVE as well as to experiments.
Meshfree simulation of free surface flow and fluid-structure interaction

General information
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Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Lindberg, O. (Intern), Bingham, H. B. (Intern), Engsig-Karup, A. P. (Intern)
Publication date: 2010

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Publication: Research - peer-review › Article in proceedings – Annual report year: 2010

Multi-block, boundary-fitted solutions for 3D nonlinear wave-structure interaction

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Bingham, H. B. (Intern), Ducrozet, G. (Intern), Engsig-Karup, A. P. (Intern)
Pages: 04
Publication date: 2010

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Title of host publication: International Workshop on Water Waves and Floating Bodies
Main Research Area: Technical/natural sciences
Conference: 25th International Workshop on Water Waves and Floating Bodies, Harbin, China, 09/05/2010 - 09/05/2010
Electronic versions: iwwfb25_04.pdf
An efficient flexible-order model for 3D nonlinear water waves

The flexible-order, finite difference based fully nonlinear potential flow model described in [H.B. Bingham, H. Zhang, On the accuracy of finite difference solutions for nonlinear water waves, J. Eng. Math. 58 (2007) 211-228] is extended to three dimensions (3D). In order to obtain an optimal scaling of the solution effort multigrid is employed to precondition a GMRES iterative solution of the discretized Laplace problem. A robust multigrid method based on Gauss-Seidel smoothing is found to require special treatment of the boundary conditions along solid boundaries, and in particular on the sea bottom. A new discretization scheme using one layer of grid points outside the fluid domain is presented and shown to provide convergent solutions over the full physical and discrete parameter space of interest. Linear analysis of the fundamental properties of the scheme with respect to accuracy, robustness and energy conservation are presented together with demonstrations of grid independent iteration count and optimal scaling of the solution effort. Calculations are made for 3D nonlinear wave problems for steep nonlinear waves and a shoaling problem which show good agreement with experimental measurements and other calculations from the literature.

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State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Authors: Engsig-Karup, A. P. (Intern), Bingham, H. B. (Intern), Lindberg, O. (Intern)
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Publication date: 2009
Main Research Area: Technical/natural sciences

Publication information
Journal: Journal of Computational Physics
Volume: 228
Boundary-fitted solutions for 3D nonlinear water wave-structure interaction

The Spectral/hp-Finite Element Method for Partial Differential Equations

This set of lecture notes provides an elementary introduction to both the classical Finite Element Method (FEM) and the extended Spectral/hp-$\$-$\$-Finite Element Method for solving Partial Differential Equations (PDEs). Many problems in science and engineering can be formulated mathematically and involves one or more PDEs. The FEM is nowadays an important numerical discretization technique for approximately solving such mathematical equations on a computer. The set of lecture notes has been written for engineering students for use in the short three-week course \cite{BarkerReffstrup1998} The Finite Element Method for Partial Differential Equations given at the Technical University of Denmark. The basic aim of the current lecture notes follows that of the earlier successful lecture notes for the course \cite{BarkerReffstrup1998}, which is to describe the FEM in a way that supports the reader in implementing the method independently. The original set of course notes has been modified and updated and additional chapters describing the high-order extensions to form the Spectral/hp-$\$-$\$-Finite Element Method have been included. Thus the significant contributions of Chapters 1, 2 and 5 covering the classical Finite Element Method are in large parts due to V. A. Barker and J. Reffstrup. With this set of lecture notes it should be possible for the reader to make a Spectral/hp-$\$-$\$-FEM toolbox in successive steps with the support given in the text. Emphasis is on the practical details supported with basic and sufficient theory to build the foundation in a three weeks period where the tools are developed and applied immediately. Furthermore, the aim of Spectral/hp-$\$-$\$-FEM toolbox is to provide a simple and generic framework for developing small prototype applications rather than directly approaching large-scale models. With this in mind, the goal is to let the reader encounter the typical problems involved in the practical implementation of these models and thereby gain a fundamental understanding of the algorithms and their practical implementation. For the practical work, a number of templates described using pseudo programming code, should be understood and converted by the reader to a programming language in a concrete implementation. A number of exercises is given which in a step-by-step manner guides the reader toward developing the necessary subroutines which can be used to solve typical and fairly general PDEs in one or two spatial dimensions. In the course the chosen programming environment is Matlab, however, this is by no means a necessary requirement. The mathematical level needed to grasp the details of this set of notes requires an elementary background in mathematical analysis and linear algebra. Each chapter is supplemented with hands-on exercises and the amount of material covered is intended to be balanced in such a way that each subject amounts to approximately one weeks work including producing a small report to document and communicate the work effort. This set of lecture notes is currently a working draft and may contain some (hopefully) minor errors. Any suggestions for improving the notes or feedback on errors and the content and its structure will be highly appreciated. Please report to the email apek@imm.dtu.dk. \ \ \ Allan P. Engsig-Karup, \today.
Toward a scalable flexible-order model for 3D nonlinear water waves

For marine and coastal applications, current work are directed toward the development of a scalable numerical 3D model for fully nonlinear potential water waves over arbitrary depths. The model is high-order accurate, robust and efficient for large-scale problems, and support will be included for flexibility in the description of structures by the use of curvilinear boundary-fitted meshes. The mathematical equations for potential waves in the physical domain is transformed through $\sigma$-mapping(s) to a time-invariant boundary-fitted domain which then becomes a basis for an efficient solution strategy on a time-invariant mesh. The 3D numerical model is based on a finite difference method as in the original works \cite{LiFleming1997,BinghamZhang2007}. Full details and other aspects of an improved 3D solution can be found in \cite{EBL08}. The new and improved approach for three-dimensional problems employs a GMRES solver with multigrid preconditioning to achieve optimal scaling of the overall solution effort, i.e., directly with $\text{Sn}$ the total number of grid points. Grid independent iteration count and optimal scaling has been demonstrated to be independent of the mesh and the physics. A robust method is achieved through a special treatment of the boundary conditions along solid boundaries using a fictitious a ghost point technique, and is necessary for a robust multigrid preconditioning strategy. The solution strategy is found to be both robust for general nonlinear wave problems, with no need for additional smoothing or filtering over that imposed naturally by the finite difference scheme. By the adjusting the numerical discretization parameters, the accuracy in dispersion and flow kinematics (accuracy) together with the solution effort (efficiency) can be optimized for the model to be nearly competitive with dedicated models based on simplified equations, e.g. Boussinesq-type equations. At the symposium, we will present examples demonstrating the fundamental properties of the numerical model (OceanWave3D) together with the latest achievements.

DG-FEM solution for nonlinear wave-structure interaction using Boussinesq-type equations

We present a high-order nodal Discontinuous Galerkin Finite Element Method (DG-FEM) solution based on a set of highly accurate Boussinesq-type equations for solving general water-wave problems in complex geometries. A nodal DG-FEM is used for the spatial discretization to solve the Boussinesq equations in complex and curvilinear geometries which amends the application range of previous numerical models that have been based on structured Cartesian grids. The Boussinesq method provides the basis for the accurate description of fully nonlinear and dispersive water waves in both shallow and deep waters within the breaking limit. To demonstrate the current applicability of the model both linear and mildly nonlinear test cases are considered in two horizontal dimensions where the water waves interact with bottom-mounted fully reflecting structures. It is established that, by simple symmetry considerations combined with a mirror principle, it is possible to impose weak slip boundary conditions for both structured and general curvilinear wall boundaries while maintaining the accuracy of the scheme. As is standard for current high-order Boussinesq-type models, arbitrary waves can be generated and absorbed in the interior of the computational domain using a flexible relaxation technique applied on the free surface variables.
An efficient flexible-order model for coastal and ocean water waves

Current work are directed toward the development of an improved numerical 3D model for fully nonlinear potential water waves over arbitrary depths. The model is high-order accurate, robust and efficient for large-scale problems, and support will be included for flexibility in the description of structures. The mathematical equations for potential waves in the physical domain is transformed through \$\sigma\$-mapping(s) to a time-invariant boundary-fitted domain which then becomes a basis for an efficient solution strategy. The improved 3D numerical model is based on a finite difference method as in the original works \cite{LiFleming1997,BinghamZhang2007}. The new and improved approach employs a GMRES solver with multigrid preconditioning to achieve optimal scaling of the overall solution effort, i.e., directly with \$Sn\$ the total number of grid points. A robust method is achieved through a special treatment of the boundary conditions along solid boundaries, and is necessary for a robust multigrid preconditioning strategy. Full details and other aspects of the 3D solution will appear in \cite{EngsigKarupBinghamLindberg2008}. At the symposium, we will present examples demonstrating the fundamental properties of the numerical model together with the latests achievements.

Briefly on grid generation

Efficient Solution of the 3D Laplace Problem for Nonlinear Wave-Structure Interaction
Improved velocity potential formulations of highly accurate Boussinesq-type models

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Bingham, H. B. (Intern), Engsig-Karup, A. P. (Intern), Fuhrman, D. R. (Intern), Madsen, P. A. (Intern)
Pages: 191-203
Publication date: 2008

Host publication information
Title of host publication: 31. International Conference on Coastal Engineering
Publisher: American Society of Civil Engineers
Volume: 1-5
Main Research Area: Technical/natural sciences
Electronic versions:
BinghamEtAlICCE2008Paper.pdf
Source: orbit
Source-ID: 233427
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Multigrid preconditioning for efficient solution of the 3D Laplace problem for wave-body interaction

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Authors: Bingham, H. B. (Intern), Engsig-Karup, A. P. (Intern), Lindberg, O. (Intern)
Publication date: 2008

Host publication information
Title of host publication: International Workshop on Water Waves and Floating Bodies
Main Research Area: Technical/natural sciences
Workshop: 23rd International Workshop on Water Waves and Floating Bodies, Jeju Island, Korea, Republic of, 13/04/2008 - 13/04/2008
Electronic versions:
BinghamEtAlWWWFB23_submit.pdf
Source: orbit
Source-ID: 223365
Publication: Research - peer-review › Article in proceedings – Annual report year: 2008

Unstructured nodal DG-FEM solution of high-order Boussinesq-type equations
The main objective of the present study has been to develop a numerical model and investigate solution techniques for solving the recently derived high-order Boussinesq equations of \cite{MBL02} in irregular domains in one and two horizontal dimensions. The Boussinesq-type methods are the simplest alternative to solving full three-dimensional wave problems by e.g. Navier-Stokes equations, which can capture all the important wave phenomena such as diffraction,
refraction, nonlinear wave-wave interactions and interaction with structures.

The main goal can be reached by using multi-domain methods with support for a spatial discretization based on unstructured grids. In the current work, a standard method of lines approach has been adapted, and the method of choice for the spatial discretization is the nodal Discontinuous Galerkin Finite element method (DG-FEM), which provides a highly flexible basis for the model. This method is combined with an explicit Runge-Kutta method for the temporal discretization. The resulting discrete set of equations enables us to simulate water waves accurately in complex geometric settings and possibly employ local adaption techniques to optimize the computational effort.

As of today, the high-order Boussinesq equations represent the most advanced set of Boussinesq-type equations capable of modelling nonlinear and dispersive waves from shallow to deep water without the practical limitations of classical Boussinesq-type equations.

The high-order Boussinesq equations constitute a highly complex system of coupled equations which put any numerical method to the test. The main problems that need to be overcome to solve the equations are the treatment of strongly nonlinear convection-type terms and spatially varying coefficient terms; efficient and robust solution of the resultant time-dependent linear system; and the numerical treatment of high-order and cross-differential derivatives. The suggested solution strategy of the current work is based on a collocation approach where the DG-FEM is used to approximate spatial derivatives and the boundary conditions are imposed weakly using a symmetry technique. Since collocation methods are prone to aliasing errors, various anti-aliasing strategies are applied for the stabilization of the models. A practical and relatively straightforward discretization is applied, which is based on a simple treatment of slip boundary conditions at wall surfaces.

A linear Fourier analysis has been applied to obtain generic analytical results which can be used for validating the discrete implementation and provide the basis for choosing stable discretization parameters as well as giving new insight into the properties of the high-order Boussinesq equations. Remarkably, it is demonstrated that the linear eigenspectra of the linearized semi-discrete equation system is bounded and hence the stable time increment is not dictated by the spatial discretization. This is a favorable property for explicit time-integration schemes as the stable time increment is not subject to severe restrictions which can affect the performance of the scheme. It is demonstrated that the discrete properties of both DG-FEM and finite difference methods can be discretized to mimic the analytical properties.

It is investigated mathematically and demonstrated numerically how the relaxation method of [cite(LD83)] can be applied in spectral/$hp$ multi-domain methods for both accurate internal wave generation of arbitrary wave fields and efficient absorption near domain boundaries. The method is considered to be particular attractive for wave generation purposes for use with high-order Boussinesq models as it alleviates the need for specifying consistent boundary conditions, and importantly, it is a very straightforward and flexible method.

The DG-FEM models have been applied to a number of tests in both one and two horizontal dimensions with the objective of both validating the setup against known analytical and experimental test results, and at the same time demonstrating the attractive properties of the method. It has been demonstrated that difficult nonlinear and dispersive wave problems can be solved accurately in one horizontal dimension. In two horizontal dimensions it has been demonstrated that the model can solve problems in both regular and irregular geometries and by comparison with analytical results it is shown that the results are in general in excellent agreement.

Thus, it has been established that the DG-FEM can be used to solve this relatively complicated system of equations. The computational efficiency of the method has yet to be demonstrated.
A high-order finite difference method for nonlinear wave-structure interaction

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering
Authors: Bingham, H. B. (Intern), Engsig-Karup, A. P. (Intern), Lindberg, O. (Intern)
Publication date: 2007

Host publication information
Title of host publication: International Workshop on Water Waves and Floating Bodies
Volume: 22
Main Research Area: Technical/natural sciences
Links:
http://www.iwwwfb.org
Source: orbit
Source-ID: 208758
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

DG-FEM solution for nonlinear wave-structure interaction using Boussinesq-type equations

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling, Rice University
Authors: Engsig-Karup, A. P. (Intern), Hesthaven, J. (Intern), Bingham, H. B. (Intern), Warburton, T. (Ekstern)
Publication date: 2007

Host publication information
Title of host publication: International Conference On Spectral and High Order Methods
Main Research Area: Technical/natural sciences
Electronic versions:
abstract.pdf
Source: orbit
Source-ID: 223366
Publication: Research - peer-review › Article in proceedings – Annual report year: 2007

An unstructured DG-FEM method for nonlinear wave-structure interaction

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Engsig-Karup, A. P. (Intern), Bingham, H. B. (Intern), Hesthaven, J. (Intern), Madsen, P. A. (Intern)
Publication date: 2006

Host publication information
Title of host publication: International Workshop on Water Waves and Floating Bodies
Volume: 21
Main Research Area: Technical/natural sciences
Workshop: 21st International Workshop on Water Waves and Floating Bodies, Loughborough, United Kingdom, 02/04/2006 - 02/04/2006
Electronic versions:
paper.pdf
Source: orbit
Source-ID: 223367
Publication: Research - peer-review › Article in proceedings – Annual report year: 2006

DG-FEM in computational hydrodynamics

General information
State: Published
We present a discontinuous Galerkin finite element method (DG-FEM) solution to a set of high-order Boussinesq-type equations for modelling highly nonlinear and dispersive water waves in one and two horizontal dimensions. The continuous equations are discretized using nodal polynomial basis functions of arbitrary order in space on each element of an unstructured computational domain. A fourth order explicit Runge-Kutta scheme is used to advance the solution in time. Methods for introducing artificial damping to control mild nonlinear instabilities are also discussed. The accuracy and convergence of the model with both h (grid size) and p (order) refinement are verified for the linearized equations, and calculations are provided for two nonlinear test cases in one horizontal dimension: harmonic generation over a submerged bar; and reflection of a steep solitary wave from a vertical wall. Test cases for two horizontal dimensions will be considered in a future paper.
A nodal discontinuous Galerkin spectral/hp method for high order Boussinesq-type equations

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Scientific Computing, Department of Informatics and Mathematical Modeling
Authors: Engsig-Karup, A. P. (Intern), Bingham, H. B. (Intern), Hesthaven, J. (Intern), Madsen, P. A. (Intern)
Publication date: 2005

Host publication information
Title of host publication: Third M.I.T. Conference on Computational Fluid and Solid Mechanics
Main Research Area: Technical/natural sciences
Conference: Third M.I.T. Conference on Computational Fluid and Solid Mechanics, 01/01/2005
Electronic versions:
abstract.pdf
Source: orbit
Source-ID: 223368
Publication: Research - peer-review › Article in proceedings – Annual report year: 2005

Coastal and ocean wave modelling

General information
State: Published
Organisations: Coastal, Maritime and Structural Engineering, Department of Mechanical Engineering, Ecole Generaliste d'Ingenieurs de Marseille
Authors: Bingham, H. (Intern), Madsen, P. A. (Intern), Fuhrman, D. R. (Intern), Engsig-Karup, A. P. (Intern), Jamois, E. (Ekstern)
Publication date: 2005
Event: Poster session presented at DCSC seminardag, Aarhus, Denmark, .
Main Research Area: Technical/natural sciences
Source: orbit
Source-ID: 183314
Publication: Research › Poster – Annual report year: 2005

The next step in coastal numerical models: spectral/hp element methods?
In this paper we outline the application of spectral/hp element methods for modelling nonlinear and dispersive waves. We present one- and two-dimensional test cases for the shallow water equations and Boussinesq-type equations – including highly dispersive Boussinesq-type equations.

General information
State: Published
Projects:

**Extension of a Fast Potential Flow Solver to Fully-Nonlinear Wave Loading on Offshore Structures**

Department of Mechanical Engineering  
Period: 15/09/2017 → 14/09/2020  
Number of participants: 5  
PhD Student:  
Hicks, Jacob Bjarke Hansen (Intern)  
Supervisor:  
Engsig-Karup, Allan Peter (Intern)  
Lindberg, Ole (Intern)  
Read, Robert (Intern)  
Main Supervisor:  
Bingham, Harry B. (Intern)  

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Grundforskningsfonden  
Project: PhD

**Architecture acoustics: an improved design process using integrated hybrid room acoustic simulations**

Department of Electrical Engineering  
Period: 01/11/2016 → 31/10/2019  
Number of participants: 4  
PhD Student:  
Pind Jörgensson, Finnur Kári (Intern)  
Supervisor:  
Engsig-Karup, Allan Peter (Intern)  
Strømann-Andersen, Jakob Bjørn (Intern)  
Main Supervisor:  
Jeong, Cheol-Ho (Intern)  

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Industrial PhD  
Project: PhD

**High Performance Computational Methods for Low-Noise Supercontinuum Lasers for Optical Coherence Tomography Systems**

Technical University of Denmark
**Optimal Control of PDE-Constrained Systems**

Technical University of Denmark

Period: 15/09/2015 → 25/01/2019

Number of participants: 4

Phd Student: Christiansen, Lasse Hjuler (Intern)

Supervisor: Engsig-Karup, Allan Peter (Intern)

Main Supervisor: Jørgensen, John Bagterp (Intern)

**Financing sources**

Source: Internal funding (public)

Name of research programme: Institut stipendie (DTU)

Project: PhD

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**Low noise femtosecond supercontinuum sources**

Department of Photonics Engineering

Period: 01/09/2015 → 31/08/2018

Number of participants: 4

Phd Student: Bravo Gonzalo, Ivan (Intern)

Supervisor: Engsig-Karup, Allan Peter (Intern)

Main Supervisor: Bang, Ole (Intern)

**Financing sources**

Source: Internal funding (public)

Name of research programme: Grundforskningsfonden

Project: PhD

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**Stochastic Simulations for Uncertainty Quantification of wave loads**

Technical University of Denmark

Period: 01/08/2015 → 31/10/2015

Number of participants: 4

Phd Student: Jensen, Claus Lenander (Intern)

Supervisor: Bigoni, Daniele (Intern)

Bredmose, Henrik (Intern)
Main Supervisor:
Engsig-Karup, Allan Peter (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansieret - Andet
Project: PhD

Multiscale modelling for reservoir-well simulation at DTU compute
Technical University of Denmark
Period: 01/11/2014 → 31/07/2017
Number of participants: 4
Phd Student:
Quadrio, Nathan (Intern)
Supervisor:
Byrne, Michael (Ekstern)
Glømberg, Stefan Lemvig (Intern)
Main Supervisor:
Engsig-Karup, Allan Peter (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Samfinansierede - Virksomhed
Project: PhD

Fast Methods for Predicting the Added Resistance on Ships
Department of Mechanical Engineering
Period: 01/09/2013 → 09/12/2016
Number of participants: 7
Phd Student:
Kontos, Stavros (Intern)
Supervisor:
Engsig-Karup, Allan Peter (Intern)
Lindberg, Ole (Intern)
Main Supervisor:
Bingham, Harry B. (Intern)
Examiner:
Jensen, Jørgen Juncher (Intern)
Dumbser, Michael (Ekstern)
Ferrant, Pierre (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut, samfinansiering

Relations
Publications:
Robust Numerical Methods for Nonlinear Wave-Structure Interaction in a Moving Frame of Reference
Project: PhD

Efficient Large-Scale Reservoir Simulation on Modern Many-Core Hardware
Technical University of Denmark
Period: 01/04/2013 → 30/09/2016
Number of participants: 7
Phd Student:
Christensen, Max la Cour (Intern)
Supervisor:
Glømberg, Stefan Lemvig (Intern)
Main Supervisor:
Engsig-Karup, Allan Peter (Intern)
Examiner:
Hesthaven, Jan (Intern)
Hesthaven, Jan (Intern)
Lukyanov, Alexander (Ekstern)
Lukyanov, Alexander (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU

Relations
Publications:
Multilevel techniques for Reservoir Simulation
Project: PhD

Optimization Algorithms for Experimental Design, Parameter Estimation, and Control of Dynamic Systems
Technical University of Denmark
Period: 01/10/2012 → 20/04/2016
Number of participants: 6
Phd Student:
Frison, Gianluca (Intern)
Supervisor:
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Engsig-Karup, Allan Peter (Intern)
Axehill, Daniel (Ekstern)
Ferreau, Hans Joachim (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Large-Scale Computational Electromagnetics for Reflector Antenna Analysis
Technical University of Denmark
Period: 15/12/2011 → 19/03/2015
Number of participants: 7
Phd Student:
Borries, Oscar Peter (Intern)
Supervisor:
Jørgensen, Erik (Intern)
Meincke, Peter (Intern)
Main Supervisor:
Hansen, Per Christian (Intern)
Examiner:
Engsig-Karup, Allan Peter (Intern)
Gustafsson, Mats (Ekstern)
Lee, Jin-Fa (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: ErhvervsPhD-ordningen VTU
Project: PhD
Uncertainty Quantification for advanced engineering applications

Technical University of Denmark
Period: 15/12/2011 → 19/03/2015
Number of participants: 7
Phd Student:
Bigoni, Daniele (Intern)
Supervisor:
Hesthaven, Jan (Intern)
True, Hans (Intern)
Main Supervisor:
Engsig-Karup, Allan Peter (Intern)
Examiner:
Sørensen, Mads Peter (Intern)
Funfschilling, Christine (Ekstern)
Le Maitre, Olivier P. (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU)
Project: PhD

Modelling Nonlinear Wave Interaction with Floating Ocean Energy Devices

Department of Mechanical Engineering
Period: 01/10/2010 → 01/09/2015
Number of participants: 6
Phd Student:
Christiansen, Torben Robert Bilgrav (Intern)
Supervisor:
Engsig-Karup, Allan Peter (Intern)
Main Supervisor:
Bingham, Harry B. (Intern)
Examiner:
Fuhrman, David R. (Intern)
Dumbser, Michael (Ekstern)
Molin, Bernard (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 DTU-stip, 2/3 FUR/andet
Project: PhD

Adaptive Simulations of Nonlinear Structures in Magnetized Plasma

Department of Physics
Period: 15/09/2010 → 24/10/2014
Number of participants: 4
Phd Student:
Treue, Frederik (Intern)
Supervisor:
Engsig-Karup, Allan Peter (Intern)
Evgrafov, Anton (Intern)
Main Supervisor:
Naulin, Volker (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD
Scientific GPU Computing for PDE Solvers
Department of Informatics and Mathematical Modeling
Period: 01/05/2010 → 12/12/2013
Number of participants: 6
Phd Student:
Glimberg, Stefan Lemvig (Intern)
Supervisor:
Dammann, Bernd (Intern)
Main Supervisor:
Engsig-Karup, Allan Peter (Intern)
Examiner:
Walther, Jens Honore (Intern)
Cai, Xing (Ekstern)
Olson, Luke (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

Computation of Superconducting Wind Turbine Generators
Department of Mathematics
Period: 15/12/2008 → 24/05/2012
Number of participants: 8
Phd Student:
Rodriguez Zermeno, Victor Manuel (Intern)
Supervisor:
Anbarasu, Ramasamy (Ekstern)
Kjær, Philip Carne (Ekstern)
Pedersen, Niels Falsig (Intern)
Main Supervisor:
Sørensen, Mads Peter (Intern)
Examiner:
Engsig-Karup, Allan Peter (Intern)
Campbell, Archibald M. (Ekstern)
Grilli, Francesco (Ekstern)

Financing sources
Source: Internal funding (public)
Name of research programme: 1/3 FUU, 1/3 inst 1/3 Andet
Project: PhD

Multiscale Simulation of Wave Forces on Ocean Energy Devices
Department of Mechanical Engineering
Period: 15/08/2008 → 28/08/2012
Number of participants: 7
Phd Student:
Lindberg, Ole (Intern)
Supervisor:
Engsig-Karup, Allan Peter (Intern)
Walther, Jens Honore (Intern)
Main Supervisor:
Bingham, Harry B. (Intern)
Examiner:
Bredmose, Henrik (Intern)
Dumbser, Michael (Ekstern)
Grue, John (Ekstern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: Institut stipendie (DTU) Samf.
Project: PhD

**Numerical Methods for Simulation and Optimization of Enhanced Oil Recovery Methods**

Department of Informatics and Mathematical Modeling
Period: 01/01/2008 → 24/08/2012
Number of participants: 6
Phd Student: Völcker, Carsten (Intern)
Supervisor: Thomsen, Per Grove (Intern)
Main Supervisor: Jørgensen, John Bagterp (Intern)
Examiner: Engsig-Karup, Allan Peter (Intern)
Foss, Bjarne Anton (Ekstern)
Kristensen, Morten Rode (Intern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: Forskningsrådsfinansiering
Project: PhD

**Efficient solutions to the exact Laplace problem for nonlinear water waves**

Coastal, Maritime and Structural Engineering

Department of Mechanical Engineering
Period: 01/08/2006 → 15/08/2008
Number of participants: 2
Contact person: Bingham, Harry B. (Intern)
Project Manager, organisational: Engsig-Karup, Allan Peter (Intern)

**Financing sources**
Source: Forskningsrådene - SNF
Name of research programme: Forskningsrådene - STVF
Project

**A Multidomain Spectral Method for Nonlinear Water Waves**

Department of Mechanical Engineering
Period: 01/08/2003 → 02/01/2007
Number of participants: 5
Phd Student: Engsig-Karup, Allan Peter (Intern)
Supervisor: Bingham, Harry B. (Intern)
Main Supervisor: Madsen, Per A. (Intern)
Examiner: Thomsen, Per Grove (Intern)
Grue, John (Ekstern)

**Financing sources**
Source: Internal funding (public)
Name of research programme: DTU-lønnet stipendie
Project: PhD