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.
Nonlinear and dispersive free surface waves, Hydrodynamics, Spectral element method, Unstructured mesh, Finite element methods, High-order discretisation

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Publication: Research - peer-review › Journal article – Annual report year: 2016
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
State: Published
Organisations: Scientific Computing, Department of Applied Mathematics and Computer Science, Chalmers University of Technology
Authors: Bigoni, D. (Intern), Engsig-Karup, A. P. (Intern), Eskilsson, C. (Ekstern)
Pages: 87-113
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Main Research Area: Technical/natural sciences

Publication information
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BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): CiteScore 0.9 SJR 0.4 SNIP 1.005
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.37 SNIP 0.865 CiteScore 0.75
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.57 SNIP 1.043 CiteScore 0.97
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.678 SNIP 1.387 CiteScore 1.19
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.589 SNIP 1.077 CiteScore 1.06
ISI indexed (2012): ISI indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.457 SNIP 1.004 CiteScore 0.86
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 0.535 SNIP 0.934
Web of Science (2010): Indexed yes
BFI (2009): BFI-level 1
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
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-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/).
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.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Massachusetts Institute of Technology
Authors: Bigoni, D. (Intern), Engsig-Karup, A. P. (Intern), Marzouk, Y. M. (Ekstern)
Number of pages: 1
Publication date: 2015
Event: Poster session presented at SIAM Conference on Computational Science and Engineering (SIAM CSE 2015), Salt Lake City, Utah, United States.
Main Research Area: Technical/natural sciences
Electronic versions:
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.

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.
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.

**Sensitivity Analysis of the Critical Speed in Railway Vehicle Dynamics**

We 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.

**General information**

State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing
Authors: Bigoni, D. (Intern), True, H. (Intern), Engsig-Karup, A. P. (Intern)
Pages: 272-286
Publication date: 2014
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.

**General information**
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Massachusetts Institute of Technology
Authors: Bigoni, D. (Intern), Engsig-Karup, A. P. (Intern), Marzouk, Y. M. (Ekstern)
Number of pages: 1
Publication date: 2014
Event: Poster session presented at Spatial Statistics and Uncertainty Quantification on Supercomputers, Bath, United Kingdom.
Main Research Area: Technical/natural sciences
Electronic versions:
PosterBath2014.pdf
Source: PublicationPreSubmission
Source-ID: 127558223
Publication: Research – Poster – Annual report year: 2014

**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.

**General information**
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Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing
Authors: Bigoni, D. (Intern), Engsig-Karup, A. P. (Intern), True, H. (Intern)
Pages: 152-158
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Main Research Area: Technical/natural sciences
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Journal: ZE Vrail - Glaser’s Annalen
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Scopus rating (2013): SJR 0.159 SNIP 0
ISI indexed (2013): ISI indexed no
Scopus rating (2012): SJR 0.101 SNIP 0.041
ISI indexed (2012): ISI indexed no
Scopus rating (2011): SJR 0.173 SNIP 0.223
ISI indexed (2011): ISI indexed no
Scopus rating (2010): SJR 0.15 SNIP 0.108
Scopus rating (2009): SJR 0.172 SNIP 0.073
Scopus rating (2008): SJR 0.115 SNIP 0.101
Scopus rating (2007): SJR 0.147 SNIP 0.123
Scopus rating (2006): SJR 0.256 SNIP 0.153
Scopus rating (2005): SJR 0.338 SNIP 0.053
Scopus rating (2004): SJR 0.206 SNIP 0.04
Scopus rating (2003): SJR 0.384 SNIP 0.232
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Publication: Research - peer-review › Journal article – Annual report year: 2013
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 Cooperider 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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State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing
Authors: Bigoni, D. (Intern), True, H. (Intern), Engsig-Karup, A. P. (Intern)
Number of pages: 9
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Main Research Area: Technical/natural sciences
Conference: 23rd Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2013), Qingdao, China, 19/08/2013 - 19/08/2013
Electronic versions:
PaperFinal.pdf
Publication: Research - peer-review › Article in proceedings – Annual report year: 2013

Stochastic Wave Dynamics and Uncertainty Quantification

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing
Authors: Engsig-Karup, A. P. (Intern), Bigoni, D. (Intern), Glimberg, S. L. (Intern)
Number of pages: 1
Publication date: 2013
Event: Poster session presented at 38th Woudschoten Conference, Zeist, Netherlands.
Main Research Area: Technical/natural sciences
Electronic versions:
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Source-ID: u::10085
Publication: Research - peer-review › Poster – Annual report year: 2013

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 low-dimensional 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
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Uncertainty quantification of critical speed for railway vehicle dynamics

General information
State: Published
Organisations: Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Bigoni, D. (Intern)
Number of pages: 12
Publication date: 2012

Publication information
Media of output: PowerPoint
Original language: English
Main Research Area: Technical/natural sciences
Electronic versions: presentation.pdf

Relations
Activities:
BIT Circus 2012
Publication: Research › Sound/Visual production (digital) – Annual report year: 2012

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

Relations
Activities:
Uncertainty Quantification for High-Performance Computing Workshop
Publication: Research - peer-review › Poster – Annual report year: 2012
Projects:

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

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

Activities:

ASME 2013 Rail Transportation Division
Daniele Bigoni (Speaker)
Department of Applied Mathematics and Computer Science

Scientific Computing

Description
Participation and presentation of a paper by the title: "Modern uncertainty quantification methods in railroad vehicle dynamics".
Documents: 
Bigoni, Engsig-Karup, True - 2013 - Modern Uncertainty Quantification Methods in Railroad Vehicle Dynamics

Related event

ASME 2013 Rail Transportation Division Fall Technical Conference
15/10/2013 → 17/10/2013
Altoona, PA, United States
Activity: Talks and presentations › Conference presentations

23rd Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2013)
Period: 19 Aug 2013 → 23 Aug 2013
Daniele Bigoni (Speaker)
Department of Applied Mathematics and Computer Science
Scientific Computing

Description
Participation and presentation of a paper by with title "SENSITIVITY ANALYSIS OF THE CRITICAL SPEED IN RAILWAY VEHICLE DYNAMICS".
Documents:
Bigoni, True, Engsig-karup - 2013 - Sensitivity Analysis of the critical speed in railway vehicle dynamics

Related event
23rd Symposium on Dynamics of Vehicles on Roads and Tracks (IAVSD 2013)
19/08/2013 → 23/08/2013
Qingdao, China
Activity: Talks and presentations › Conference presentations

Uncertainty in Reservoir Characterization
Period: 18 Apr 2013 → 19 Apr 2013
Daniele Bigoni (Speaker)
Department of Applied Mathematics and Computer Science
Scientific Computing

Description
Presentation with title: "Spectral Methods for Uncertainty Quantification".

Related event
Uncertainty in Reservoir Characterization
18/04/2013 → 19/04/2013
Kgs. Lyngby, Denmark
Activity: Talks and presentations › Conference presentations

Comparison of Classical and Modern Uncertainty Qualification Methods for the Calculation of Critical Speeds in Railway Vehicle Dynamics
Period: 5 Nov 2012
Daniele Bigoni (Speaker)
Department of Informatics and Mathematical Modeling
Scientific Computing
Degree of recognition: International

Related event
Mini Conference on Vehicle system dynamics, identification and anomalies
05/11/2012 → 07/11/2012
Budapest, Hungary
Activity: Talks and presentations › Conference presentations

BIT Circus 2012
Daniele Bigoni (Participant)
Scientific Computing
Department of Informatics and Mathematical Modeling

Description
Participation to the BIT Circus 2012 held in DTU. Talk on "Uncertainty quantification of critical speed for railway vehicle dynamics" by D. Bigoni, A.P. Engsig-Karup, H.True, J.S. Hesthaven.

Documents:
Uncertainty quantification of critical speed for railway vehicle dynamics

Related event
BIT Circus 2012: Numerical Mathematics and Computational Science
23/08/2012 → 24/08/2012
Lyngby, Denmark
Activity: Attending an event › Participating in or organising a conference

Uncertainty Quantification for High-Performance Computing Workshop
Period: 2 May 2012 → 4 May 2012
Daniele Bigoni (Participant)

Scientific Computing
Department of Informatics and Mathematical Modeling

Description
Participation to the workshop and poster presentation with title: "Uncertainty Quantification on High Speed Railway Dynamics" by D. Bigoni, A.P. Engsig-Karup, H. True.

Documents:
Uncertainty Quantification on High Speed Railway Dynamics

Related event
Uncertainty Quantification for High-Performance Computing Workshop
02/05/2012 → 04/05/2012
Oak Ridge, TN, United States
Activity: Attending an event › Participating in or organising workshops, courses, seminars etc.