Publications:

**A least squares approach for efficient and reliable short-term versus long-term optimization**

The uncertainties related to long-term forecasts of oil prices impose significant financial risk on ventures of oil production. To minimize risk, oil companies are inclined to maximize profit over short-term horizons ranging from months to a few years. In contrast, conventional production optimization maximizes long-term profits over horizons that span more than a decade. To address this challenge, the oil literature has introduced short-term versus long-term optimization. Ideally, this problem is solved by a posteriori multi-objective optimization methods that generate an approximation to the Pareto front of optimal short-term and long-term trade-offs. However, such methods rely on a large number of reservoir simulations and scale poorly with the number of objectives subject to optimization. Consequently, the large-scale nature of production optimization severely limits applications to real-life scenarios. More practical alternatives include ad hoc hierarchical switching schemes. As a drawback, such methods lack robustness due to unclear convergence properties and do not naturally generalize to cases of more than two objectives. Also, as this paper shows, the hierarchical formulation may skew the balance between the objectives, leaving an unfulfilled potential to increase profits. To promote efficient and reliable short-term versus long-term optimization, this paper introduces a natural way to characterize desirable Pareto points and proposes a novel least squares (LS) method. Unlike hierarchical approaches, the method is guaranteed to converge to a Pareto optimal point. Also, the LS method is designed to properly balance multiple objectives, independently of Pareto front’s shape. As such, the method poses a practical alternative to a posteriori methods in situations where the frontier is intractable to generate.

**General information**
- **State:** Published
- **Organisations:** Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing, Department of Informatics and Mathematical Modeling, Copenhagen Center for Health Technology
- **Authors:** Christiansen, L. H. (Intern), Capolei, A. (Intern), Jørgensen, J. B. (Intern)
- **Pages:** 411-26
- **Publication date:** 2017
- **Main Research Area:** Technical/natural sciences

**Publication information**
- **Journal:** Computational Geosciences
- **Volume:** 21
- **Issue number:** 3
An algorithm for gradient-based dynamic optimization of UV flash processes
This paper presents a novel single-shooting algorithm for gradient-based solution of optimal control problems with vapor-liquid equilibrium constraints. Such optimal control problems are important in several engineering applications, for instance in control of distillation columns, in certain two-phase flow problems, and in operation of oil reservoirs. The single-shooting algorithm uses an adjoint method for the computation of gradients. Furthermore, the algorithm uses either a simultaneous or a nested approach for the numerical solution of the dynamic vapor-liquid equilibrium model equations. Two numerical examples illustrate that the simultaneous approach is faster than the nested approach and that the efficiency of the underlying thermodynamic computations is important for the overall performance of the single-shooting algorithm. We
compare the performance of different optimization software as well as the performance of different compilers in a Linux operating system. These tests indicate that real-time nonlinear model predictive control of UV flash processes is computationally feasible.

**General information**

State: Accepted/In press
Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing
Authors: Ritschel, T. K. S. (Intern), Capolei, A. (Intern), Gaspar, J. (Intern), Jørgensen, J. B. (Intern)
Number of pages: 12
Publication date: 2017
Main Research Area: Technical/natural sciences

**Publication information**

Journal: Computers & Chemical Engineering
ISSN (Print): 0098-1354
Ratings:
- BFI (2018): BFI-level 2
- Web of Science (2018): Indexed yes
- BFI (2017): BFI-level 2
- Web of Science (2017): Indexed yes
- BFI (2016): BFI-level 2
- Scopus rating (2016): CiteScore 3.39 SJR 1.008 SNIP 1.607
- Web of Science (2016): Indexed yes
- BFI (2015): BFI-level 2
- Scopus rating (2015): SJR 1.122 SNIP 1.724 CiteScore 3.04
- Web of Science (2015): Indexed yes
- BFI (2014): BFI-level 2
- Scopus rating (2014): SJR 1.184 SNIP 1.738 CiteScore 3.22
- Web of Science (2014): Indexed yes
- BFI (2013): BFI-level 2
- Scopus rating (2013): SJR 1.223 SNIP 1.776 CiteScore 3.06
- ISI indexed (2013): ISI indexed yes
- Web of Science (2013): Indexed yes
- BFI (2012): BFI-level 2
- Scopus rating (2012): SJR 1.161 SNIP 1.92 CiteScore 3.05
- ISI indexed (2012): ISI indexed yes
- Web of Science (2012): Indexed yes
- BFI (2011): BFI-level 2
- Scopus rating (2011): SJR 1.185 SNIP 1.736 CiteScore 2.8
- ISI indexed (2011): ISI indexed yes
- Web of Science (2011): Indexed yes
- BFI (2010): BFI-level 2
- Scopus rating (2010): SJR 1.176 SNIP 1.796
- Web of Science (2010): Indexed yes
- BFI (2009): BFI-level 2
- Scopus rating (2009): SJR 1.154 SNIP 2.166
- Web of Science (2009): Indexed yes
- BFI (2008): BFI-level 2
- Scopus rating (2008): SJR 1.293 SNIP 2.127
- Web of Science (2008): Indexed yes
- Scopus rating (2007): SJR 1.625 SNIP 1.959
- Web of Science (2007): Indexed yes
- Scopus rating (2006): SJR 1.304 SNIP 1.936
- Scopus rating (2005): SJR 1.314 SNIP 1.953
- Web of Science (2005): Indexed yes
A Novel Approach for Risk Minimization in Life-Cycle Oil Production Optimization

The oil research community has invested much effort into computer aided optimization to enhance oil recovery. While simulation studies have demonstrated the potential of model-based technology to improve industrial standards, the largely unknown geology of subsurface reservoirs limits applications to commercial oil fields. In particular, uncertain model descriptions lead to risks of profit loss. To address the challenges of geological uncertainty, this paper proposes offset risk minimization. As opposed to existing methodologies of the oil literature, the offset approach minimizes risk of profit loss relative to industrial standards. A numerical case study compares the offset approach to a representative selection of current state-of-the-art methodologies. The results show that the offset approach offers the overall lowest risk of profit loss relative to industrial best practices. This suggests that it may be more relevant to consider offset risk minimization than conventional ensemble-based methods for the purpose of life-cycle production optimization.

Dynamic Optimization of UV Flash Processes

UV ash processes, also referred to as isoenergetic-isochoric ash processes, occur for dynamic simulation and optimization of vapor-liquid equilibrium processes. Dynamic optimization and nonlinear model predictive control of distillation columns, certain two-phase ow problems, as well as oil reservoirs with signi cant compositional and thermal e ects may be conducted as dynamic optimization of UV ash processes. The dynamic optimization problem involving a UV ash process is formulated as a bilevel optimization problem. This problem is solved using a gradient based single-shooting method. The gradients are computed using the adjoint method and di erent o-the-shelf optimization software (fmincon, IPOPT, KNITRO, NPSOL) are used for the numerical optimization. Computational results are reported for a ash process involving benzene, toluene and diphenyl. The computational experiments demonstrate that the optimization solver, the compiler, and high-performance linear algebra software are all important for e cient dynamic optimization of UV ash processes.
Multiple shooting applied to robust reservoir control optimization including output constraints on coherent risk measures

The production life of oil reservoirs starts under significant uncertainty regarding the actual economical return of the recovery process due to the lack of oil field data. Consequently, investors and operators make management decisions based on a limited and uncertain description of the reservoir. In this work, we propose a new formulation for robust optimization of reservoir well controls. It is inspired by the multiple shooting (MS) method which permits a broad range of parallelization opportunities and output constraint handling. This formulation exploits coherent risk measures, a concept traditionally used in finance, to bound the risk on constraint violation. We propose a reduced sequential quadratic programming (rSQP) algorithm to solve the underlying optimization problem. This algorithm exploits the structure of the coherent risk measures, thus a large set of constraints are solved within sub-problems. Moreover, a variable elimination procedure allows solving the optimization problem in a reduced space and an iterative active-set method helps to handle a large set of inequality constraints. Finally, we demonstrate the application of constraints to bound the risk of water production peaks rather than worst-case satisfaction.
Offset Risk Minimization for Open-loop Optimal Control of Oil Reservoirs

Simulation studies of oil field water flooding have demonstrated a significant potential of optimal control technology to improve industrial practices. However, real-life applications are challenged by unknown geological factors that make reservoir models highly uncertain. To minimize the associated financial risks, the oil literature has used ensemble-based methods to manipulate the net present value (NPV) distribution by optimizing sample estimated risk measures. In general, such methods successfully reduce overall risk. However, as this paper demonstrates, ensemble-based control strategies may result in individual profit outcomes that perform worse than real-life dominating strategies. This poses significant financial risks to oil companies whose main concern is to avoid unacceptable low profits. To remedy this, this paper proposes offset risk minimization. Unlike existing methodology, the offset method uses the NPV offset distribution to minimize risk relative to a competing reference strategy. Open-loop simulations of a 3D two-phase synthetic reservoir demonstrate the potential of offset risk minimization to significantly improve the worst case profit offset relative to real-life best practices. The results suggest that it may be more relevant to consider the NPV offset distribution than the NPV distribution when minimizing risk in production optimization.

General information
State: Published
Organisations: Center for Energy Resources Engineering, Department of Applied Mathematics and Computer Science, Scientific Computing
Authors: Capolei, A. (Intern), Christiansen, L. H. (Intern), Jørgensen, J. B. (Intern)
Pages: 10620-10625
Publication date: 2017
Conference: 20th IFAC World Congress 2017, Toulouse, France, 09/07/2017 - 09/07/2017
Main Research Area: Technical/natural sciences

Publication information
Journal: IFAC-PapersOnLine
Volume: 50
Issue number: 1
ISSN (Print): 2405-8963
Ratings:
Scopus rating (2016): CiteScore 0.45 SJR 0.263 SNIP 0.334
Scopus rating (2015): SJR 0.256 SNIP 0.324
The Adjoint Method for Gradient-based Dynamic Optimization of UV Flash Processes

This paper presents a novel single-shooting algorithm for gradient-based solution of optimal control problems with vapor-liquid equilibrium constraints. Dynamic optimization of UV flash processes is relevant in nonlinear model predictive control of distillation columns, certain two-phase flow problems, and oil reservoir production with significant compositional and thermal effects. Gradients are computed with the adjoint method and we use various optimization software (fmincon, IPOPT, KNITRO, and NPSOL) for the numerical optimization. We present computational results for a non-ideal five-component flash process which demonstrate the importance of the optimization solver, the compiler, and the linear algebra software for the efficiency of dynamic optimization of UV flash processes.

General information
State: Published
Organisations: Department of Applied Mathematics and Computer Science, Scientific Computing, Center for Energy Resources Engineering
Authors: Ritschel, T. K. S. (Intern), Capolei, A. (Intern), Jørgensen, J. B. (Intern)
Pages: 2071-2076
Publication date: 2017

Host publication information
Title of host publication: Proceedings of the 27th European Symposium on Computer Aided Process Engineering – ESCAPE 27
Volume: 40
Publisher: Elsevier

An open-source thermodynamic software library
This is a technical report which accompanies the article "An open-source thermodynamic software library" which describes an efficient Matlab and C implementation for evaluation of thermodynamic properties. In this technical report we present the model equations, that are also presented in the paper, together with a full set of first and second order derivatives with respect to temperature and pressure, and in cases where applicable, also with respect to mole numbers. The library is based on parameters and correlations from the DIPPR database and the Peng-Robinson and the Soave-Redlich-Kwong equations of state.
Time-explicit methods for joint economical and geological risk mitigation in production optimization

Real-life applications of production optimization face challenges of risks related to unpredictable fluctuations in oil prices and sparse geological data. Consequently, operating companies are reluctant to adopt model-based production optimization into their operations. Conventional production optimization methods focus on mitigation of geological risks related to the long-term net present value (NPV). A major drawback of such methods is that the time-dependent and exceedingly growing uncertainty of oil prices implies that long-term predictions become highly unreliable. Conventional methods therefore leave the oil production subject to substantial economical risk. To address this challenge, this paper introduces a novel set of time-explicit (TE) methods, which combine ideas of multi-objective optimization and ensemble-based risk mitigation into a computationally tractable joint effort of mitigating economical and geological risks. As opposed to conventional strategies that focus on a single long-term objective, TE methods seek to reduce risks and promote returns over the entire reservoir life by optimization of a given ensemble-based geological risk measure over time. By explicit involvement of time, economical risks are implicitly addressed by balancing short-term and long-term objectives throughout the reservoir life. Open-loop simulations of a two-phase synthetic reservoir demonstrate that TE methods may significantly improve short-term risk measures such as expected return, standard deviation and conditional value-at-risk compared to nominal, robust and mean-variance optimization. The gains in short-term objectives are obtained with none or only slight deterioration of long-term objectives.
In oil production optimization, we usually aim to maximize a deterministic scalar performance index such as the profit over the expected reservoir lifespan. However, when uncertainty in the parameters is considered, the profit results in a random variable that can assume a range of values depending on the value of the uncertain parameters. In this case, a problem reformulation is needed to properly define the optimization problem. In this paper we describe the concept of risk and we explore how to handle the risk by using appropriate risk measures. We provide a review on various risk measures reporting pro and cons for each of them. Finally, among the presented risk measures, we identify two of them as appropriate risk measures when minimizing the risk.

**Profit and Risk Measures in Oil Production Optimization**

In oil production optimization, we usually aim to maximize a deterministic scalar performance index such as the profit over the expected reservoir lifespan. However, when uncertainty in the parameters is considered, the profit results in a random variable that can assume a range of values depending on the value of the uncertain parameters. In this case, a problem reformulation is needed to properly define the optimization problem. In this paper we describe the concept of risk and we explore how to handle the risk by using appropriate risk measures. We provide a review on various risk measures reporting pro and cons for each of them. Finally, among the presented risk measures, we identify two of them as appropriate risk measures when minimizing the risk.

**General information**

State: Published
Organisations: Department of Applied Mathematics and Computer Science, Center for Energy Resources Engineering, Scientific Computing, Technical University of Denmark, Norwegian University of Science and Technology
Authors: Capolei, A. (Intern), Foss, B. (Ekstern), Jørgensen, J. B. (Ekstern)
A mean–variance objective for robust production optimization in uncertain geological scenarios

In this paper, we introduce a mean–variance criterion for production optimization of oil reservoirs and suggest the Sharpe ratio as a systematic procedure to optimally trade-off risk and return. We demonstrate by open-loop simulations of a two-phase synthetic oil field that the mean–variance criterion is able to mitigate the significant inherent geological uncertainties better than the alternative certainty equivalence and robust optimization strategies that have been suggested for production optimization. In production optimization, the optimal water injection profiles and the production borehole pressures are computed by solution of an optimal control problem that maximizes a financial measure such as the Net Present Value (NPV). The NPV is a stochastic variable as the reservoir parameters, such as the permeability field, are stochastic. In certainty equivalence optimization, the mean value of the permeability field is used in the maximization of the NPV of the reservoir over its lifetime. This approach neglects the significant uncertainty in the NPV. Robust optimization maximizes the expected NPV over an ensemble of permeability fields to overcome this shortcoming of certainty equivalence optimization. Robust optimization reduces the risk compared to certainty equivalence optimization because it considers an ensemble of permeability fields instead of just the mean permeability field. This is an indirect mechanism for risk mitigation as the risk does not enter the objective function directly. In the mean–variance bi-criterion objective function, risk appears directly, it also considers an ensemble of reservoir models, and has robust optimization as a special extreme case. The mean–variance objective is common for portfolio optimization problems in finance. The Markowitz portfolio optimization problem is the original and simplest example of a mean–variance criterion for mitigating risk. Risk is mitigated in oil production by including both the expected NPV (mean of NPV) and the risk (variance of NPV) for the ensemble of possible reservoir models. With the inclusion of the risk in the objective function, the Sharpe ratio can be used to compute the optimal water injection and production borehole pressure trajectories that give the optimal return–risk ratio. By simulation, we investigate and compare the performance of production optimization by mean–variance optimization, robust optimization, certainty equivalence optimization, and the reactive strategy. The optimization strategies are simulated in open-loop without feedback while the reactive strategy is based on feedback. The simulations demonstrate that certainty equivalence optimization and robust optimization are risky strategies. At the same computational effort as robust optimization, mean–variance optimization is able to reduce risk significantly at the cost of slightly smaller return. In this way, mean–variance optimization is a powerful tool for risk management and uncertainty mitigation in production optimization.
Nonlinear Model Predictive Control for Oil Reservoir Management

The current world average recovery factor from oil fields is widely agreed to be about 30-35%. An increase of 10% point of this recovery factor would bring about 500 billion of oil barrels, sufficient to meet 16 years of current global production. To realize this potential production increase, the research community is working on improving current feedback model-based optimal control technologies. The topic of this thesis is production optimization for water flooding in the secondary phase of...
oil recovery. We developed numerical methods for nonlinear model predictive control (NMPC) of an oil field. The controller consists of

-A model based optimizer for maximizing some predicted financial measure of the reservoir (e.g. the net present value).
-A parameter and state estimator.
-Use of the moving horizon principle for data assimilation and implementation of the computed control input.

The optimizer uses gradient-based optimization and the required gradients are computed by the adjoint method. We propose the use of efficient high order implicit time integration methods for the solution of the forward and the adjoint equations of the dynamical model. The Ensemble Kalman filter is used for data assimilation. Further, we studied the use of robust control strategies in both open-loop, i.e. without measurement feedback, and closed-loop, i.e. with measurement feedback, configurations.

This thesis has three main original contributions:

The first contribution in this thesis is to improve the computationally expensive gradient computation by using high-order ESDIRK (Explicit Singly Diagonally Implicit Runge-Kutta) temporal integration methods and continuous adjoints. The high order integration scheme allows larger time steps and therefore faster solution times. We compare gradient computation by the continuous adjoint method to the discrete adjoint method and the finite-difference method. We demonstrate that the optimization algorithm can be accelerated by using the continuous time adjoint equations. This is the first time in the literature that the higher order continuous adjoint and higher order discrete adjoint methods have been investigated for oil production optimization.

The second contribution of this thesis is the application of the Robust Optimization strategy in both open-loop (i.e. without measurement feedback) and closed-loop (i.e. with measurement feedback). In the oil industry, Robust Optimization has been suggested to compensate for inherent geological uncertainties in an oil field. In robust optimization of an oil reservoir, the water injection and production borehole pressures are computed such that the predicted net present value of an ensemble of permeability field realizations is maximized. In our study, the permeability field is the uncertain parameters. We compare the performance of the RO strategy to a certainty equivalent optimization strategy, based on the ensemble mean of the permeability field realizations as its permeability field, and to a reactive strategy. In open-loop, for the case studied, the reactive strategy performed better than the open-loop RO strategy. These observations are nontrivial, as previous literature suggests that the open-loop RO strategy performs better than the reactive strategy. Simulations indicate that the inferior performance of the open-loop RO strategy compared to the reactive strategy is due to the inability of the RO strategy to efficiently encompass ensembles with very different and conflicting optimal control trajectories. Hence, we propose a modified RO strategy that allow shut in of uneconomical wells. The modified RO strategy performs significantly better than the other open-loop strategies and the reactive strategy. Finally, this is the first time in literature that the RO optimization has been investigated in closed-loop. Surprisingly, for the case studied, the closed-loop certainty equivalent strategy yields a higher NPV than the closed-loop RO strategy. The uncertainty reduction of the permeability field estimate due to data assimilation explains the good performance of the closed-loop certainty equivalent optimization strategy. Consequently, in closed-loop, the increased computational effort of the RO strategy compared to the certainty equivalent strategy is not justified for the particular case studied in this paper.

The third contribution of this thesis is a mean-variance method for risk mitigation in production optimization of oil reservoirs. We introduce a return-risk bicriterion objective function for the profit-risk tradeoff. With this objective function we link the optimization problem in production optimization to the Markowitz portfolio optimization problem in finance or to the robust design problem in topology optimization. In this study we focus on open-loop configuration, i.e. without measurement feedback. We demonstrate that a return-risk bi-criterion objective function is a valuable tool for the profit-risk tradeoff. If combined with the previous contribution, this result trigger the necessity of comparing the closed-loop CE strategy with the closed-loop MV strategy.

The thesis consists of a summary report and a collection of five research papers written during the period May 2010 to August 2013. Three papers are published in conference proceedings, one paper is published in Computational Geosciences journal and another paper is submitted to Journal of Petroleum Science and Engineering.

**General information**

State: Published
Organisations: Department of Applied Mathematics and Computer Science, Center for Energy Resources Engineering, Scientific Computing
Authors: Capolei, A. (Intern), Jørgensen, J. B. (Intern)
Number of pages: 199
Publication date: 2013

**Publication information**

Place of publication: Kgs. Lyngby
Publisher: Technical University of Denmark (DTU)
Waterflooding optimization in uncertain geological scenarios

In conventional waterflooding of an oil field, feedback based optimal control technologies may enable higher oil recovery than with a conventional reactive strategy in which producers are closed based on water breakthrough. To compensate for the inherent geological uncertainties in an oil field, robust optimization has been suggested to improve and robustify optimal control strategies. In robust optimization of an oil reservoir, the water injection and production borehole pressures (bhp) are computed such that the predicted net present value (NPV) of an ensemble of permeability field realizations is maximized. In this paper, we both consider an open-loop optimization scenario, with no feedback, and a closed-loop optimization scenario. The closed-loop scenario is implemented in a moving horizon manner and feedback is obtained using an ensemble Kalman filter for estimation of the permeability field from the production data. For open-loop implementations, previous test case studies presented in the literature, show that a traditional robust optimization strategy (RO) gives a higher expected NPV with lower NPV standard deviation than a conventional reactive strategy. We present and study a test case where the opposite happen: The reactive strategy gives a higher expected NPV with a lower NPV standard deviation than the RO strategy. To improve the RO strategy, we propose a modified robust optimization strategy (modified RO) that can shut in uneconomical producer wells. This strategy inherits the features of both the reactive and the RO strategy. Simulations reveal that the modified RO strategy results in operations with larger returns and less risk than the reactive strategy, the RO strategy, and the certainty equivalent strategy. The returns are measured by the expected NPV and the risk is measured by the standard deviation of the NPV. In closed-loop optimization, we investigate and compare the performance of the RO strategy, the reactive strategy, and the certainty equivalent strategy. The certainty equivalent strategy is based on a single realization of the permeability field. It uses the mean of the ensemble as its permeability field. Simulations reveal that the RO strategy and the certainty equivalent strategy give a higher NPV compared to the reactive strategy. Surprisingly, the RO strategy and the certainty equivalent strategy give similar NPVs. Consequently, the certainty equivalent strategy is preferable in the closed-loop situation as it requires significantly less computational resources than the robust optimization strategy. The similarity of the certainty equivalent and the robust optimization based strategies for the closed-loop situation challenges the intuition of most reservoir engineers. Feedback reduces the uncertainty and this is the reason for the similar performance of the two strategies.
Computational Methods for Model Predictive Control: New Opportunities for Computational Scientists

Power Point presentation.

General information
State: Published
Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Automation and Control, Computer Science and Engineering, Mathematical Statistics, Technical University of Denmark
Number of pages: 64
Publication date: 2012

Publication information
Original language: English
Publisher: Technical University of Denmark (DTU)
Main Research Area: Technical/natural sciences
Electronic versions:
Computational Methods for Model Predictive Control.pdf
Source: dtu
Source-ID: u::4982
High Order Adjoint Derivatives using ESDIRK Methods for Oil Reservoir Production Optimization

In production optimization, computation of the gradients is the computationally expensive step. We improve the computational efficiency of such algorithms by improving the gradient computation using high-order ESDIRK (Explicit Singly Diagonally Implicit Runge-Kutta) temporal integration methods and continuous adjoints. The high order integration scheme allows larger time steps and therefore faster solution times. We compare gradient computation by the continuous adjoint method to the discrete adjoint method and the finite-difference method. The methods are implemented for a two-phase flow reservoir simulator. Computational experiments demonstrate that the accuracy of the sensitivities obtained by the adjoint methods are comparable to the accuracy obtained by the finite difference method. The continuous adjoint method is able to use a different time grid than the forward integration. Therefore, it can compute these sensitivities much faster than the discrete adjoint method and the finite-difference method. On the other hand, the discrete adjoint method produces the gradients of the numerical schemes, which is beneficial for the numerical optimization algorithm. Computational experiments show that when the time steps are controlled in a certain range, the continuous adjoint method produces gradients sufficiently accurate for the optimization algorithm and somewhat faster than the discrete adjoint method.

General information
State: Published
Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Department of Chemistry
Authors: Capolei, A. (Intern), Stenby, E. H. (Intern), Jørgensen, J. B. (Intern)
Number of pages: 21
Pages: A42
Publication date: 2012

Host publication information
Title of host publication: ECMOR XIII – 13th European Conference on the Mathematics of Oil Recovery
Main Research Area: Technical/natural sciences
Conference: 13th European Conference on the Mathematics of Oil Recovery (ECMOR XIII), Biarritz, France, 10/09/2012 - 10/09/2012
Source: dtu
Source-ID: u::4999
Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

Oil Reservoir Production Optimization using Single Shooting and ESDIRK Methods

Conventional recovery techniques enable recovery of 10-50% of the oil in an oil field. Advances in smart well technology and enhanced oil recovery techniques enable significant larger recovery. To realize this potential, feedback model-based optimal control technologies are needed to manipulate the injections and oil production such that flow is uniform in a given geological structure. Even in the case of conventional water flooding, feedback based optimal control technologies may enable higher oil recovery than with conventional operational strategies. The optimal control problems that must be solved are large-scale problems and require specialized numerical algorithms. In this paper, we combine a single shooting optimization algorithm based on sequential quadratic programming (SQP) with explicit singly diagonally implicit Runge-Kutta (ESDIRK) integration methods and the a continuous adjoint method for sensitivity computation. We demonstrate the procedure on a water flooding example with conventional injectors and producers.

General information
State: Published
Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Capolei, A. (Intern), Völcker, C. (Intern), Frydendall, J. (Intern), Jørgensen, J. B. (Intern)
Number of pages: 6
Pages: 286-291
Publication date: 2012

Host publication information
Title of host publication: Automatic Control in Offshore Oil and Gas Production
Volume: 1
Publisher: International Federation of Automatic Control
ISBN (Print): 978-3-902661-99-9
Series: IFAC Proceedings Volumes (IFAC-PapersOnline)
Main Research Area: Technical/natural sciences
Workshop: 2012 IFAC Workshop, Trondheim, Norway, 31/05/2012 - 31/05/2012
Optimisation of Oil Production in Two – Phase Flow Reservoir Using Simultaneous Method and Interior Point Optimiser

Natural petroleum reservoirs are characterised by 2-phase flow of oil and water in the porous media (e.g. rocks) which they are built of. Conventional methods of extracting oil from those fields, which utilise high initial pressure obtained from natural drive, leave more than 70 % of oil in the reservoir. A promising decrease of these remained resources can be provided by smart wells applying water injections to sustain satisfactory pressure level in the reservoir throughout the whole process of oil production. Basically to enhance secondary recovery of the remaining oil after drilling, water is injected at the injection wells of the down-hole pipes. This sustains the pressure in the reservoir and drives oil towards production wells. There are however, many factors contributing to the poor conventional secondary recovery methods e.g. strong surface tension, heterogeneity of the porous rock structure leading to change of permeability with position in the reservoir, or high oil viscosity. Therefore it is desired to take into account all these phenomena by implementing a realistic simulator of the 2-phase flow reservoir, which imposes the set of constraints on the state variables of optimisation problem. Then, thanks to optimal control, it is possible to adjust effectively injection valves to control 2 phase immiscible flow in every grid block of the reservoir and navigate oil to the production wells so it does not remain in the porous media. The use of such a smart technology known also as smart fields, or closed loop optimisation, can be used for optimising the reservoir performance in terms of net present value of oil recovery or another economic objective. In order to solve an optimal control problem we use a direct collocation method where we translate a continuous problem into a discrete one by applying explicit and implicit Euler methods. A substantial challenge of finding optimal solution in a robust way comes along with handling the scale of the optimal control problem due to discretisation in time and space. Consequently, an Ipopt(Interior Point Optimiser) open source software for large scale nonlinear optimisation was applied. Because of its versatile compatibility with programming technologies, a C++ programming language in Microsoft Visual Studio integrated development environment was used for modelling the optimal control problem. Thanks to object oriented features of the language, it was possible to approach the problem in a very modular way by automating the discretisation process and develop interfaces for retrieving information from a continuous problem. When tackling this problem, we reduce approximation error made by discretising of the original problem, by increasing the number of simulation steps and therefore it is necessary to solve large instances of the reformulation. As a result, it is very suitable to use Ipopt algorithm which implements an interior-point linesearch filter method making it very powerful for solving large problems with up to hundreds of millions of constraints and variables.

General information
State: Published
Organisations: Center for Energy Resources Engineering, Department of Chemical and Biochemical Engineering, CERE – Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing, Department of Chemistry
Pages: 191
Publication date: 2012

Host publication information
Title of host publication: Proceedings of the 17th Nordic Process Control Workshop
Place of publication: Kogens Lyngby
Publisher: Technical University of Denmark (DTU)
Editors: Jørgensen, J. B., Huusom, J. K., Sin, G.
ISBN (Print): 978-87-643-0946-1
Main Research Area: Technical/natural sciences
Conference: 17th Nordic Process Control Workshop, Kongens Lyngby, Denmark, 25/01/2012 - 25/01/2012
Electronic versions: IMM07.pdf
Links:
http://npcw17.imm.dtu.dk/

Source: orbit
Source-ID: 318551
Publication: Research - peer-review › Conference abstract in proceedings – Annual report year: 2012

Single Shooting and ESDIRK Methods for adjoint-based optimization of an oil reservoir
Conventional recovery techniques enable recovery of 10-50% of the oil in an oil field. Advances in smart well technology and enhanced oil recovery techniques enable significant larger recovery. To realize this potential, feedback model-based optimal control technologies are needed to manipulate the injections and oil production such that ow is uniform in a given geological structure. Even in the case of conventional water ooding, feedback based optimal control technologies may...
enable higher oil recovery than with conventional operational strategies. The optimal control problems that must be solved are large-scale problems and require specialized numerical algorithms. In this paper, we combine a single shooting optimization algorithm based on sequential quadratic programming (SQP) with explicit singly diagonally implicit Runge-Kutta (ESDIRK) integration methods and a continuous adjoint method for sensitivity computation. We demonstrate the procedure on a water flooding example with conventional injectors and producers.

**General information**
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering
Authors: Capolei, A. (Intern), Völcker, C. (Intern), Frydendall, J. (Intern), Jørgensen, J. B. (Intern)
Publication date: 2012

**Host publication information**
Title of host publication: Proceedings of the 17th Nordic Process Control Workshop
Place of publication: Kogens Lyngby
Publisher: Technical University of Denmark (DTU)
Editors: Jørgensen, J. B., Huusom, J. K., Sin, G.
ISBN (Print): 978-87-643-0946-1
Main Research Area: Technical/natural sciences
Conference: 17th Nordic Process Control Workshop, Kongens Lyngby, Denmark, 25/01/2012 - 25/01/2012
Oil Reservoir, Optimal Control, Numerical Methods, Optimization

**Single Shooting and ESDIRK Methods for adjoint-based optimization of an oil reservoir**

**General information**
State: Published
Organisations: Scientific Computing, Department of Informatics and Mathematical Modeling, Center for Energy Resources Engineering
Authors: Capolei, A. (Intern), Völcker, C. (Intern), Frydendall, J. (Intern), Jørgensen, J. B. (Intern)
Publication date: 2012

**Publication information**
Original language: English
Main Research Area: Technical/natural sciences
Electronic versions: IMM13.pdf
Links:
http://npcw17.imm.dtu.dk/
Source: orbit
Source-ID: 318560
Publication: Research - Sound/Visual production (digital) – Annual report year: 2012

**Solution of Constrained Optimal Control Problems Using Multiple Shooting and ESDIRK Methods**

In this paper, we describe a novel numerical algorithm for solution of constrained optimal control problems of the Bolza type for stiff and/or unstable systems. The numerical algorithm combines explicit singly diagonally implicit Runge-Kutta (ESDIRK) integration methods with a multiple shooting algorithm. As we consider stiff systems, implicit solvers with sensitivity computation capabilities for initial value problems must be used in the multiple shooting algorithm. Traditionally, multi-step methods based on the BDF algorithm have been used for such problems. The main novel contribution of this paper is the use of ESDIRK integration methods for solution of the initial value problems and the corresponding sensitivity equations arising in the multiple shooting algorithm. Compared to BDF-methods, ESDIRK-methods are advantageous in multiple shooting algorithms in which restarts and frequent discontinuities on each shooting interval are present. The ESDIRK methods are implemented using an inexact Newton method that reuses the factorization of the iteration matrix for the integration as well as the sensitivity computation. Numerical experiments are provided to demonstrate the algorithm.

**General information**
State: Published
Organisations: Center for Energy Resources Engineering, Department of Informatics and Mathematical Modeling, Scientific Computing
Authors: Capolei, A. (Intern), Jørgensen, J. B. (Intern)
Pages: 295-300
Publication date: 2012

**Host publication information**
Title of host publication: Proceedings of the 2012 American Control Conference
ISBN (Print): 978-1-4577-1094-0

Series: American Control Conference
ISSN: 0743-1619
Main Research Area: Technical/natural sciences
Conference: American Control Conference (ACC 2012), Montréal, Canada, 27/06/2012 - 27/06/2012

**Bibliographical note**
Paper number WeA08.6.
Publication: Research - peer-review › Article in proceedings – Annual report year: 2012

**Projects:**

**Simulation and Optimization of Oil Reservoirs in the Danish North Sea**
Technical University of Denmark
Period: 01/12/2015 → 30/11/2018
Number of participants: 4
Phd Student:
Hørsholt, Steen (Intern)
Supervisor:
Capolei, Andrea (Intern)
Nick, Hamid (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)

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

**Nonlinear Model Predictive Control for Oil Reservoirs**
Technical University of Denmark
Period: 15/08/2015 → 14/08/2018
Number of participants: 4
Phd Student:
Ritschel, Tobias Kasper Skovborg (Intern)
Supervisor:
Capolei, Andrea (Intern)
Poulsen, Niels Kjølstad (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)

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

**Numerical Methods for Reservoir Simulation and Optimization**
Department of Informatics and Mathematical Modeling
Period: 01/05/2010 → 25/04/2014
Number of participants: 5
Phd Student:
Capolei, Andrea (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)
Examiner:
Poulsen, Niels Kjølstad (Intern)
Jansen, Jan Dirk (Ekstern)
Knudsen, Jørgen K. H. (Ekstern)

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