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Applications of Optimal Control Theory for Efficient Production Optimization of Realistic Reservoirs

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Abstract

In practical reservoir management, although the intent is generally the maximization of some key quantity (net present value or NPV, etc.), the operating parameters are seldom if ever determined using formal optimization techniques. The usual approach to do so is manually, which is quite time consuming and very likely to provide suboptimal results. With the advent of new numerical formulations and powerful computational resources, it now appears possible to apply systematic approaches for efficiently optimizing reservoir performance. In previous work, we incorporated adjoint-based optimal control procedures into a general-purpose simulator that allows the efficient long term maximization of NPV by optimally controlling well settings with time (similar developments have also been reported by others). Furthermore, our recent extensions, namely, a new "approximate feasible direction algorithm", enabled the treatment of nonlinear path inequality constraints efficiently and accurately, unlike any existing methods. Such constraints, which include total injection or production rate constraints for wells operating under bottomhole pressure (BHP) control, are typically present in practice and therefore must be included in the numerical optimization.

In this paper, we apply these state-of-the-art optimization procedures to realistic reservoir models, and validate the applicability and efficiency of the approximate feasible direction algorithm. We consider the 3D-2phase black oil models of a Gulf of Mexico (GOM) reservoir and the "Brugge" reservoir, which is a model developed by SPE for a comparative solution project on closed-loop reservoir management. The objective of the study is to maximize the NPV of the reservoirs over a period of 8 years for the GOM model and 20 years for the Brugge model by controlling the BHPs of the existing wells with time. The optimizations are subject to nonlinear operating constraints. Application of the optimization procedure is shown to lead to an increase in NPV of about 17% for the GOM model and 12% for Brugge over the base cases. The total number of simulations required was only about 30 and 10 respectively for the GOM and Brugge models, clearly demonstrating the efficiency of the approach and also confirming that such optimization techniques have considerable potential for practical reservoir management.

Introduction

With the recent explosion of global energy requirements attributed mainly to the booming third world economies, it is becoming increasingly difficult for oil companies to meet the growing demand for fossil fuels. Further, most of the existing major oilfields are already at a mature stage, and the number of new significant oilfields discovered per year is decreasing gradually (Brouwer, 2004). It has thus become increasingly important to produce existing fields as efficiently as possible, while decreasing development and maintenance cost simultaneously. Optimal control theory (Stengel, 1985, Bryson and Ho, 1975) is one of the possible approaches that might be deployed to tackle this imperative problem. The main benefit of the use of optimal control theory is its efficiency, which makes it possible to apply it to real reservoirs with very large simulation models, as opposed to many existing techniques.

This problem of maximization of a performance index (such as NPV) of a reservoir while minimizing costs and honoring operating and other constraints falls under the general category of optimal control problems with nonlinear control-state path inequality constraints (i.e., constraints that must be satisfied at every time step). A large variety of methods for solving such discrete-time optimal control problems now exist in control theory literature, including dynamic programming, neighboring extremal methods, gradient-based nonlinear programming methods (NLP), etc. These are discussed in detail in Stengel (1985) and Bryson and Ho (1975). Of these approaches, the NLP method combined with the *Maximum Principle* (Bryson and