Invitation to join a Research Consortium on:

CONTINUOUS INTERPRETATION

OF WELL TEST DATA

BY DECONVOLUTION

from

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EXECUTIVE SUMMARY

With current trends towards intelligent wells and fields, continuous bottomhole well pressure monitoring is becoming the norm in new field developments. Theoretically, this should allow operators to better control well performance and address problems before they become irreversible. In practice, the need to interpret the raw information provided by permanent gauges, and the lack of manpower or expertise for doing so prevents real time intervention. Therefore, some sort of automatic interpretation and alarm system is required to benefit from the full potential of downhole permanent gauges.

A new **deconvolution** algorithm developed at Imperial College by von Schroeter *et al*[1,2] makes the development of such tools possible. Contrary to deconvolution algorithms previously published in the literature, our algorithm provides stable results. Extensive usage at Imperial and, independently, at BP, has confirmed its huge potential for well test analysis of permanent pressure gauges: deconvolution provides information over a radius of investigation that corresponds to the total duration of the production period, which can be orders of magnitude greater than that available from individual flow periods used for conventional well test analysis. Alternatively, deconvolution can reduce considerably the required duration of an extended well test, by revealing boundaries not visible in individual flow periods.

Experience with our algorithm has identified a number of areas for improvement, most notably the need to handle interference effects in highly permeable formations. **The objective of this proposal is to address these issues in order to obtain a robust deconvolution algorithm that can be used by practicing engineers in a wide variety of field conditions to control and optimise well performance.**

The work will be performed by staff and MSc students from the Centre for Petroleum Studies at Imperial College, with input and guidance from industry partners.

BENEFITS

- Access to a stable deconvolution algorithm which allows to continuously interpret well test data from permanent downhole pressure gauges.
- Thorough interpretation of company’s own data, as part of the evaluation of the algorithm.
- Annual forum at Imperial College to review progress and provide input into research directions.

RESEARCH AREA

Permanent downhole pressure gauges are increasingly being installed in new developments around the world. Their reliability has greatly improved and they now can operate for several years. They provide a pressure record of everything that is happening to the well and, in the long term, they are likely to replace production tests for well and reservoir monitoring.

In theory, information from permanent gauges should permit operators to react to problems as soon as they appear. In practice, the need to interpret the raw information provided by permanent gauges and the lack of manpower and expertise for doing so prevents real time intervention. Instead, permanent gauge records are archived and only examined after the existence of a problem has been recognised, to identify its cause and evaluate possible solutions. Unfortunately, the corresponding delay often makes the damage irreversible.

Interpretation of permanent pressure gauge data is especially challenging because of the size of the data sets, which can consist of hundreds of un-planned flow periods at different rates and millions of pressure points stretched over thousands of hours of recording time. Such data sets contain information about the reservoir at distances from the well which can be several orders of magnitude larger than the radius of investigation of a single flow period, but the full potential information content cannot be obtained with conventional analysis methods. Conventional well test analysis is based on pressure derivatives, calculated over individual flow periods which are likely to be of short durations compared to the duration of the entire test and therefore may not show features, such as boundaries, that have actually been reached during the test. Furthermore, the individual flow periods must first be identified, which may be daunting considering the huge number of pressure points and rate changes. In addition, pressure derivatives are affected by all sorts of errors, notably in rates, and may be distorted by the differentiation algorithm, thus providing an incorrect picture of the well behaviour.

The full information potential can only be achieved with **deconvolution**. Deconvolution transforms variable rate pressure data into a single constant rate initial drawdown with duration equal to the total duration of the test and yields the corresponding pressure derivative normalised to a unit rate. The only assumption in deconvolution is that the data satisfy Duhamel's principle, i.e. that the pressure drop is the convolution product of the production rate and the reservoir impulse response:

$$\Delta p(t) = p_i - p(t) = \int_0^t q(\tau)\, g(t-\tau)\,\mathrm{d}\tau \qquad (1)$$

Here p, q, and g respectively denote the pressure, rate, and impulse response as functions of time, and p_i is the initial reservoir pressure. The desired normalised pressure derivative is simply the product of the impulse response with time:

$$\frac{\mathrm{d}\Delta p}{\mathrm{d}\ln t} = t\,g(t) \text{ for } q(\tau) = \begin{cases} 0 & \tau \le 0 \\ 1 & \tau > 0 \end{cases} \qquad (2)$$

Thus, at least in principle, estimating the pressure derivative involves nothing more than solving Equation (1) for the impulse response, and multiplying it by the time.

In practice, it is not that simple and most algorithms proposed in the literature give interpretable results only with data with moderate noise levels but fail with actual data if they are too noisy, which is the general case.

The only published algorithm that provides stable results is one which we have recently developed based on the Total Least Square method[1,2]. This algorithm estimates both rates and normalised derivative by minimising an error measure which is a weighted combination of pressure match, rate match, and a penalty term based on the overall curvature of the graphed derivative and whose purpose is to enforce smoothness of the result. The weight of the pressure match is normalized to one, thus the estimate depends on two weights, one for the rate match, the other for the roughness penalty. The user must choose a level of regularisation that imposes just enough smoothness to eliminate small-scale oscillations while preserving genuine reservoir features.

This algorithm has been used extensively in the last two years, both by ourselves[3] and by others with an independent implementation[4,5], and has become part of our interpretation tool kit, along with conventional analysis methods. **It is clear that deconvolution provides insight into well behaviour to a level never reached before, and represents as major a breakthrough in well test analysis as the derivative method when it was introduced twenty years ago.**

Experience, however, shows that a number of improvements are required for deconvolution to be routinely used as a well supervision tool applicable to all field situations.

Deconvolution can only be applied to systems governed by linear equations, which implies single-phase liquid flow in the reservoir. As with conventional analysis, it still works with gas or gas and liquid if pseudo-pressures are used. On the other hand, it does not work in its present form if there is interference from other active wells in the same reservoir, which is a common occurrence in high permeability reservoirs[6]. It also does not work if the initial pressure is non-uniform, or, in commingled reservoirs, if layers are at different initial average pressure.

Another problem still unresolved is the search for better, less subjective criteria for the selection of error weight and regularization parameter.

The proposed research aims at addressing these and other important issues to unleash the full potential of deconvolution for well test analysis, especially for the continuous real-time interpretation of permanent pressure gauge data.

OBJECTIVES

1) to extend the existing formulation for the deconvolution of well test data from a single well to perform simultaneous deconvolution of multiple, possibly overlapping segments of the pressure signal, yet allowing only a single, consistent update of the production rate signal ('Segmented deconvolution in time with consistency of rates and initial pressure');

2) to establish a sound mathematical framework for the analysis of well test data from multiple, possibly interfering wells by deconvolution ('Deconvolution in space');

3) to attempt a generalisation of the formulations obtained in parts 1) and 2) to the case with multiple, possibly interfering wells where the pressure signals recorded for each well are to be segmented and analyzed simultaneously, yet separately, allowing only a single, consistent update of each production signal ('Segmented deconvolution in time and space with consistency of rates and initial pressure');

4) to develop efficient algorithms for the numerical solution of these problems, and to improve the efficiency of the existing algorithm reported in [1,2];

5) to test these algorithms with simulated data sets; and

6) to apply the algorithms to field data sets provided by the sponsors.

SCOPE OF WORK

1) Segmented deconvolution in time with consistency of rates and initial pressure
This part of the project is intended to address concerns first formulated by Levitan[4] over the validity of deconvolution estimates obtained from entire long-term data sets from a single well, especially in situations in which significant changes in reservoir behaviour over time are to be expected. In such situations it would be desirable to subdivide the pressure signal into smaller segments and apply deconvolution separately to each of the segments paired with the corresponding segment of the rate signal. If this is done with our current deconvolution algorithm[3], there may not be sufficient information in each individual data segment in order to allow the joint estimation of pressure derivative, rate signal, and initial pressure[4]; moreover, in any case, the adapted initial pressures may differ, and likewise the adapted rate signals as far as they overlap in time.

Levitan's own strategy[4,5] involves accepting the given rate data without modification, which can be problematic since rates are usually much less accurately known than pressure data.

However, preliminary analysis suggests that consistency of initial pressures and adapted rates can be imposed through relatively minor modifications to our formulation, thereby reducing the degrees of freedom in a way that makes physical sense while retaining the option for a correction of rates and initial pressure which is consistent across data segments.

2) Deconvolution in space

Mutual interference of wells producing from the same reservoir represents a long-standing and difficult challenge for well test analysis in high permeability reservoirs. They are also a significant issue with multilateral wells. Current methodology for production optimisation in such cases is based on 'iterative refinement', yet appears neither systematic nor based on sound signal processing concepts, and as a result often unsuccessful.

What seems to be required instead is a formulation which models the influence of production from each well on the pressure signal in the same and also in all other wells. By the reciprocity theorem for Green's functions, the rate-normalized pressure derivative caused by either of a pair of communicating wells in the other is the same, and so for a total of n communicating wells, there are only $n(n+1)/2$ pressure derivative functions to be modelled and determined.

Our formulation of the deconvolution problem for a single well[1,2] can easily be generalised to the multi-well situation and thus provides a good starting point.

3) Segmented deconvolution in time and space with consistency of rates and initial pressure

This part of the project is simply the natural continuation of the preceding two, combining them in order to consider to what extent simultaneous, segmented deconvolution of data from multiple interfering wells is possible. The emphasis here will be on non-uniqueness issues; in particular on error bounds and their dependence on the geometry of the reservoir, the number of wells, the causal structure of the data set, etc.

4) Efficient Algorithms

The motivation for the development of efficient numerical algorithms to solve problems 1) - 3) is self-evident. As the use of permanent downhole gauges spreads throughout the industry, deconvolution tools must be able to handle data sets of ever-increasing size. Previous work with the existing algorithm[2,6] has highlighted the limits of our current solution procedure for the underlying separable nonlinear Least Squares problem which requires the storage of large matrices in memory at run-time. Recently, we noticed that a far less memory-intensive implementation is possible based on an algorithm due to Golub and Pereyra[7] in which the linear parameters are eliminated and the cost function is re-written as a function of the nonlinear parameters only. In our deconvolution problem, this means a reduction in the number of parameters by at least 1-2 orders of magnitude as the cost function is linear in rates and initial pressures and nonlinear only in the values of the pressure derivative at the chosen nodes; in our experience 40-50 nodes usually suffice. By contrast, the number of non-zero rate data points in a modern production data set can be hundreds or even thousands if the rates are reported as step-wise constant, and several orders of magnitude higher if they are continuously measured.

BRIEF RESUME OF PRINCIPAL RESEARCHERS

Prof. Alain C. Gringarten - Professor of Petroleum Engineering

Prof. Gringarten will be the principal investigator for this project. He holds the Chair of Petroleum Engineering at Imperial College in London and is also director of the Centre for Petroleum Studies, Department of Earth Science and Engineering, which covers all petroleum activities at Imperial. Before joining Imperial College in March 1997, Dr. Gringarten spent 25 years with service companies, first with Schlumberger where he was Director of Engineering and created their well test interpretation service; then with Scientific Software-Intercomp, where he held several senior technical, marketing and management positions including Executive Vice President for E&P Consulting and Products. Prof. Gringarten is a recognised expert in well test analysis and has published numerous articles on that subject. He received the Society of Petroleum Engineers (SPE) Formation Evaluation award for 2001, the 2003 SPE John Franklin Carll award, and was a SPE Distinguished Lecturer for 2003-2004. Prof. Gringarten holds an engineer degree from Ecole Centrale, Paris, France; and obtained an MSc and a Ph.D. in Petroleum Engineering from Stanford University.

Dr. Thomas von Schroeter – Research Associate

Dr von Schroeter has been a Research Associate in the Centre for Petroleum Studies, Department of Earth Science and Engineering, Imperial College London since 1998. He obtained a Diplom in Physics from the University of Göttingen, Germany, and a D. Phil. from the University of Oxford. His research interests include Fluid Mechanics, Numerical Analysis, and Signal Processing.

Centre for Petroleum Studies (CPS) at Imperial College

The Centre for Petroleum Studies is a focus for research, postgraduate teaching and professional development within the framework of petroleum sciences and engineering at Imperial College. Its main objectives are to facilitate multi-disciplinary research between geologists, geophysicists, petroleum engineers and members of other key disciplines in order to advance the state of the art in exploration, appraisal/development and reservoir management, and to plan and implement related postgraduate teaching programmes which reflect current best practice within the petroleum industry. The Centre has one of the largest concentrations of petroleum scientists and engineers in a UK academic institution, with almost 50 members of staff providing research expertise across the complete Exploration-Production spectrum.

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