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Reduced order model for simultaneous growth of multiple closely-spaced radial hydraulic fractures

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ABSTRACT

A new reduced order model (ROM) provides rapid and reasonably accurate prediction of the complex behavior of multiple, simultaneously growing radial hydraulic fractures. The method entails vastly reducing the degrees of freedom typically associated with fully-coupled simulations of this multiple moving boundary problem by coupling together an approximation of the influence of the stress interaction among the fractures ("stress shadow") with an approximation of fluid flow and elasticity, ensuring preservation of global volume balance, global energy balance, elasticity, and compatibility of the crack opening with the inlet fluid flux. Validating with large scale ("high-fidelity") simulations shows the ROM solution captures not only the basic suppression of interior hydraulic fractures in a uniformly-spaced array due to the well-known stress shadowing phenomenon, but also complex behaviors arising when the spacing among the hydraulic fractures is non-uniform. The simulator's usefulness is demonstrated through a proof-of-concept optimization whereby non-uniform spacing and stage length are chosen to maximize the fracture surface area and/or the uniformity of growth associated with each stimulation treatment.

1. Introduction

Reduced order models (ROMs) have a great potential for enabling optimization and uncertainty quantification for hydraulic fracturing. However, ascertaining the essential ingredients necessary for a reasonably accurate and suitable efficient ROM for simulating systems of multiple, simultaneously-growing hydraulic fractures remains a challenging and open problem.

Hydraulic fracturing (HF) is a well stimulation technique used in many industrial applications include mining, waste disposal, and enhanced geothermal systems [1–3] The most well-known application is its use for increasing the rate at which oil and gas can be extracted from wells. In this application, pressurized fluid drives growth of cracks through the reservoir rock, carrying granular proppant that is left behind in the created fractures. The resulting high conductivity pathways promote an increased flow of hydrocarbons from the reservoir formation towards the well (as described in further detail by e.g. [4]). Both vertical and horizontal wells are stimulated in this way, with vertical well simulation comprising most cases over the 70 year history of hydraulic fracturing and horizontal well fracturing comprising the essential advance for unlocking unconventional (low-permeability) resources in the past two to three decades [5]. Essentially all horizontal wells in uncon-

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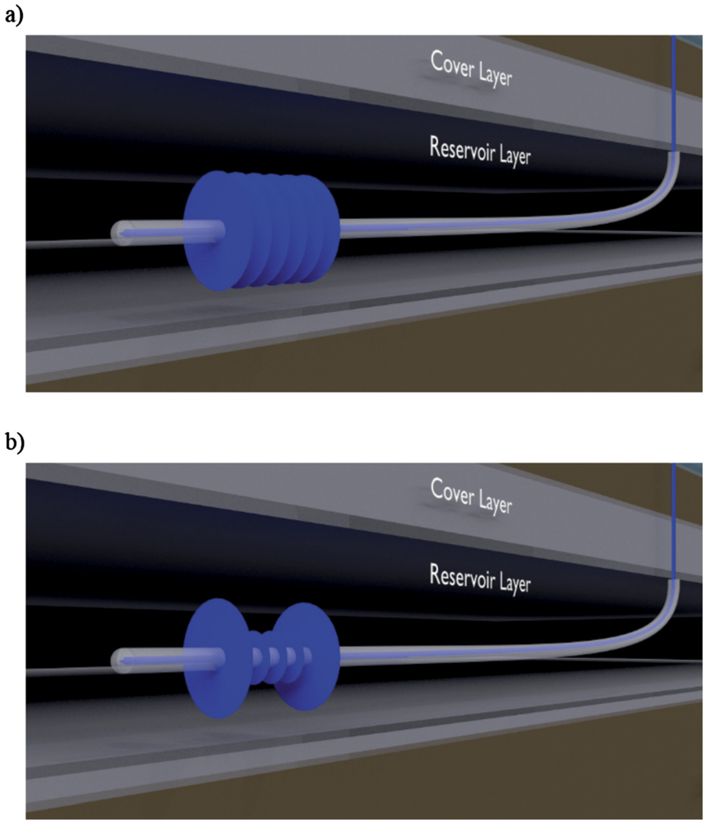

Fig. 1. Illustration of multiple, simultaneous HFs in one stage showing. (a) Ideal, uniform result, and (b) Result in which central fractures are suppressed.

ventional reservoirs (such as shale gas and oil) are treated by hydraulic fracturing, and the most common approach is to stimulate in a sequential manner from the "toe" to the "heel" of the well (see description in e.g. [6]). Within each of these sequential "stages", multiple clusters of perforations comprise the reservoir entry points, with the intention that injected fluid is reasonably uniformly distributed among these possible entry points, thereby uniformly stimulating the reservoir rock. Although such a multistage technique has enabled tremendous cost savings, analysis of production logs over several basins tends to show that between 20 to 40 percent of perforation clusters do not contribute to production [7], indicating current simulation strategies are highly non-optimal. One contributing factor is the non-uniformity of reservoir properties, including the in-situ stresses along the well e.g. [8,9]. Another factor is almost certainly the widely recognized phenomenon known of "stress shadowing" (see e.g. field evidence in [10]). Stress shadowing refers to suppression of some HFs as a result of the compressive stresses exerted on them by other, nearby HFs (e.g. [11–13]). One result is that the ideal case of uniform hydraulic fracture growth (Fig. 1(a)) is probably never achieved. Instead, some hydraulic fractures are suppressed due to the presence of locally elevated compressive stress (Fig. 1(b) as previously discussed by e.g. [14], see also. [11,12,15–18]).

While there are certainly demonstrations showing use of hydraulic fracture simulators to identify approaches that improve uniformity of stimulation (see e.g. [6,19]), optimization is challenging because of the simulations' computational intensity. Overcoming this challenge has opened a growing area of interest in generating reduced order models for hydraulic fractures, for example following formalisms that involve order reduction via an empirical search for eigenfunction bases that can be used to capture system behavior over some subdivision of the time domain [20–24]. Here we follow a different approach, but the goal is the same, namely, to obtain a reduced order model that provides a useful approximation to the full model, and with the key feature being capturing interaction of simultaneously growing hydraulic fractures.

While there are several possible threads in the literature that aim generally at simulating and optimizing multistage completions, here we will briefly introduce the background most relevant to the current contribution. The Implicit Level Set Algorithm, or "ILSA" [25] was extended by [19] for multiple parallel-planar HFs, including full 3D elastic coupling between the simultaneously propagating fractures ("ILSA II"). This simulator has been used to demonstrate that the stress shadow effect can be reduced with appropriate placement of interior HFs close to the outer HFs to inhibit their growth relative to the other fractures in the array.

Although ILSA II is a fully coupled benchmark simulator (to use terminology commonly contrasted with ROMs, we also can call this a "large scale" or "high-fidelity" model), implementing state of the art approaches to enable accurate calculations on very coarse meshes, the model can require several days, and sometimes over one week, to compute a multi-fracture result at typical reservoir length and time scales (note timing is for single node calculations, ∼2.5 GHz