Computers and Geotechnics 102 (2018) 12–27

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

A mesh adaptive method for dynamic well stimulation

Reza Abedi[a], Omid Omidi[b,*], Saeid Enayatpour[c]

[a] Department of Mechanical, Aerospace and Biomedical Engineering, The University of Tennessee at Knoxville/Space Institute, TN, USA
[b] Department of Civil, Environmental and Architectural Engineering, The University of Kansas, Lawrence, KS, USA
[c] Center for Petroleum and Geosystems Engineering, The University of Texas at Austin, TX, USA

ARTICLE INFO

Keywords:
Dynamic fracture
Adaptive meshing
Interfacial damage
Discontinuous Galerkin
Rock fracturing
Arbitrary crack path

ABSTRACT

We utilize the adaptive meshing features of an asynchronous spacetime discontinuous Galerkin (aSDG) FE method to address rock fracturing in reservoir stimulations under high rate loadings. Our aSDG implementation adaptively aligns the element boundaries with crack-path trajectories obtained as a part of the solution and no discontinuous features are introduced within the elements. We propose a novel rate-dependent interfacial damage model to represent fracture processes on crack surfaces while the model incorporates various contact modes under transient settings. Several examples are discussed to demonstrate the effectiveness of our approach in resolving dynamic fracturing driven by the high internal fluid pressure.

1. Introduction

Increasing need for energy and rapid depletion of conventional hydrocarbon resources, has made recovery from tight formations including shales with permeabilities in nano to micro Darcy range, a challenging problem for oil and gas industry. Hydraulic fracturing (HF) is widely employed to stimulate oil and gas reservoirs to increase the productivity of these naturally fissured rock domains. This treatment, being developed rapidly, has changed the energy industry throughout the world. Understanding how fractures initiate and propagate from wellbore is necessary to efficiently perform such a costly treatment. Welbore perforation is commonly carried out prior to hydraulic fracturing. Perforations serve as fracture seeds or initiation points and facilitate the creation of hydraulic fractures. However, utilizing perforations as single fractures from the wellbore toward the reservoir can avoid multiple and reoriented fractures from a wellbore. A successful HF treatment to get a ramified fracture pattern highly depends on different parameters including the length and orientation of the perforations, the rate of loading, and the magnitude of in situ stress components known as stress anisotropy in the fracture plane.

Numerical simulations play a critical role in the analysis of hydraulic fracturing of unconventional hydrocarbon reservoirs. The ability to accurately predict hydraulically-induced crack patterns is of utmost importance. The more accurately microcrack formation and crack connectivity are modeled, the closer the computational predictions of the reservoir recoveries are to practice. Also by better modeling of the crack pattern interactions with natural faults, one can more reliably analyze the stability of the reservoir. Computational approaches for modeling rock fracturing are mainly categorized into discrete and continuum methods. Since rocks are granular materials, *discrete element methods* can be used for crack propagation studies [1,2]. Within the continuum approaches, cracks and defects are either directly modeled in the analysis or averaged into volumetric parameters that incorporate the overall degradation of rocks. Given that in HF, hydraulic loads need to be applied to existing crack surfaces, there are not many of the volumetric fracture models used for these applications. As examples from this group, we refer to *continuum-based damage models* used for HF simulations in [3,4].

We direct our attention to methods that attempt to incorporate cracks in the computational domain, rather than averaging them into volumetric parameters. In *finite element methods* (FEMs), sharp discontinuities can be either inserted between adjacent elements [5] or within elements, as in the *eXtended finite element methods* (XFEMs) [6–8], *generalized finite element methods* (GFEMs) [9], and other methods with embedded strong discontinuities. The XFEMs/GFEMs employ inter-element enrichment functions to enable modeling cracks within elements. Accordingly, these methods are very successful in modeling crack propagation because the finite element mesh can be created independently from the crack geometry. In particular, the domain geometry does not have to be re-meshed as the crack propagates.

Well stimulation technologies are generally classified into three approaches according to the rate at which energy is applied. At one extreme, conventional hydraulic fracturing, having a relatively low rate of loading, results in a single bi-winged fracture extending outward from a well, oriented perpendicular to the least principal rock stress while the potential penetration for the fracture can be large and in the

* Corresponding author.
E-mail address: o.omidi@gmail.com (O. Omidi).

https://doi.org/10.1016/j.compgeo.2018.05.006
Received 19 October 2017; Received in revised form 12 March 2018; Accepted 18 May 2018

order of hundreds of feet. However, having multiple perforations is not beneficial and in fact those would not be activated in this technique. On the other extreme, explosive fracturing [10,11], having a very rapid loading rate, results in a highly fractured zone radially around the wellbore, but usually not exceeding 10 feet. However, high induced compressive stresses in the vicinity of the wellbore can cause compaction decreasing the permeability of the near-wellbore region as a damaged zone. Pulse fracturing as the third approach is between these two extremes of the loading rates. Avoiding the damage associated with the explosive fracturing approach, this technique creates a radial fracture pattern, which is desirable. This technique results in multiple fractures extending radially from the wellbore with penetration on the order of 10–20 feet. For example, propellant fracturing [12] involving the pressure build-up due to propellant burning accompanied by a gas combustion is one kind of pulse fracturing methods. Pulse fracturing is also included in the early stage of conventional hydraulic fracturing when a high loading rate is applied as an instantaneous fracture creation and propagation after wellbore breakdown. The combination of pulse and hydraulic fracturing holds promise for tight formations as a hybrid method [13].

Even for hydraulic fracturing, dynamic effects are considered in some studies. For example, hydraulic loading causes microcracking and branches due to high internal fluid pressure and induces local dynamic fracture processes. These local dynamic fractures can occur even if conventional rates of hydraulic loading are applied. In fact ignoring the enhancement of effective permeability by microcracks has been leading to the underestimation of recovery rate of reservoirs. Quasi-static analyses cannot effectively model microcracking events, hence may result in such underestimation. For instance, [14] utilized a lattice bond cell model as a discrete element method to simulate dynamic HF. This study and other similar ones demonstrate the occurrence of various features of dynamic fracture such as microcracking, crack path oscillation, and crack branching. Also the early pump-in stage in the area close to the well [15] or cyclic application of loading [16,17] deal with load ramp times in the range of 0.1–10 s.

Most numerical studies of hydrocarbon reservoir stimulation, particularly for hydraulic fracturing, are limited to quasi-static analysis. In the present work we focus on dynamic ranges of loading, with load ramp times in the range of 1 ms to a few seconds, for several reasons. First, due to the occurrence of crack path oscillation, microcracking, and crack branching in dynamic setting, much more advanced computational fracture models are needed to capture such complex fracture patterns. As will be described later, modeling such dynamic features is particularly challenging with XFEMs and GFEMs. Thus the high loading rates better demonstrate the abilities of the proposed mesh adaptive approaches. Second, in addition to dynamic stimulations methods such as the hybrid approach by [13], incorporating inertia effects enables modeling the aforementioned transient dynamic effects pertained to hydraulic fracturing. Specifically, as will be discussed in Section 4.2.2 and 4.4, dynamic application of hydraulic loads can activate fracture in some perforations that otherwise remain inactive in a quasi-static model. This discussion demonstrates the need for advanced computational fracture models that can capture dynamic fracture response of a reservoir.

Employing the *asynchronous spacetime discontinuous Galerkin* (aSDG) finite element method formulated for elastodynamics [18], we propose an alternative approach for accurate modeling of the dynamic well stimulation. The key feature of the aSDG method is direct discretization of spacetime using unstructured grids that satisfy a special *causality* condition. This yields a local and asynchronous solution strategy with linear computational cost scaling versus number of elements. The method also enables arbitrarily high orders of accuracy both in space and time per element. Of particular importance to dynamic rock fracturing, it is the ability of the method to align inter-element boundaries with user-specified interfaces in spacetime. We use this feature and discuss adaptive operations by which we can directly align element boundaries with any specified crack direction in two spatial dimensions.

Beside the technical aspects of the underlying computational tool, the choice of fracture model on crack surfaces plays a crucial role in the fidelity of HF simulations. Most HF models are based on *linear elastic fracture mechanics* (LEFM). *Cohesive models* employ a *traction–separation relation* (TSR) to relate tractions to displacement jumps on a fracture surface. They remedy some of the shortcomings of LEFM theory such as their prediction of infinite stresses at a crack tip. Some examples of the use of cohesive models in hydraulic fracturing are [19–21]. In lieu of a cohesive model, we employ a rate–dependent interfacial damage model [5]. Beside fracture modes, our interfacial model also incorporates contact–stick and contact–slip modes which are very important in rock mechanics. The formulation and comparison of the interfacial damage model with cohesive models is presented in Section 3.2.

To compare our adaptive scheme for tracking crack patterns with popular XFEMs/GFEMs, we briefly discuss the main challenges in each model. XFEMs and GFEMs require enrichment functions that resemble analytical crack related fields within the elements. Any geometric or material complexities can make their derivation challenging. For example, due to the simplicity of LEFM theory, the majority of XFEMs/GFEMs represent crack tip fields using this theory. Also, crack branching, intersection, and microcracking inside an element are examples of geometric complexities. Finally, the accurate integration of enriched elements requires particular attention to quadrature rules employed. While our adaptive meshing scheme also permits modeling complex crack patterns, it is more flexible in handling nonlinear fracture models and complicated crack connection topologies. Examples from the work reported herein are the use of the nonlinear interfacial damage model on fracture surfaces, and flexibility of the method in modeling microcracks and crack branching events. We should, however, emphasize the main challenges of the proposed adaptive scheme. In general, aligning element boundaries with crack surfaces is quite challenging and requires an advanced tool such as the aSDG method. Also, we believe that extensions to three dimensional problems would be more difficult for mesh adaptive schemes than XFEMs and GFEMs.

The mesh adaptive aSDG method can be compared with the *universal mesh* method [22,23], in that both methods align element boundaries with crack segments. While in [22,23] the LEFM theory is used on crack surfaces, the enrichment of the fracture or hydraulic pressure models appears to be more straightforward than XFEMs and GFEMs as similar to the aSDG method no inter-element enrichment functions are required. There are, however, two main distinctions; first, universal meshing requires global operations on the finite element mesh. Second, universal meshes are mainly used for quasi-static analyses where microcracking and crack branching are uncommon. In contrast, adaptive operations are local in the aSDG method and a crack path is dynamically modified/adjusted. Moreover, the mesh adaptive operations can easily handle dynamic brittle fracture aspects such as microcracking and crack bifurcation.

The organization of the manuscript is as follows. In Section 2 we provide an overview of the aSDG method's meshing and adaptive operations from [5,24]. The main goal of Section 2 is to summarize these mesh adaptive approaches in the context of rock fracture and compare them with other existing approaches; *cf.* Section 2.3 for example. Section 3 summarizes general dynamic contact separation solutions from [25] and extends the interfacial damage formulation from [5], in that the contact and fracture solutions are integrated to form a macroscopic contact/fracture model for rocks; specifically, the application of hydraulic pressure for the separation mode, *cf.* (5), extends the fracture model in [5] to HF applications. Finally, several numerical examples in Section 4 demonstrate the ability of the proposed adaptive scheme in capturing complex fracture patterns encountered in HF applications under various loading rates.