Modelling the Dynamics of Well Perforation

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Abstract

One of the crucial steps in the completion of many oil wells is their perforation, required to establish communication with the target reservoir. Perforation is a very short duration, high energy event in which a series of explosive shaped charges is fired to produce corresponding perforations into the hydrocarbon-bearing formation. This event gives rise to violent pressure and structural dynamics that die out within a second or two, depending on the specific completion design. During this time, the nature of the pressure dynamics and resulting fluid response determine the initial quality of the communication between the well and the formation, which has significant consequences for the overall productivity over the well's lifetime, as well as the integrity of the tool string components during the perforation event.

This paper describes the development and validation of an approach to simulating well perforation that was initially driven by the need to understand the causes of failures experienced in the field during some of these highly energetic events. The nature and scale of the problem presents some modelling challenges, but the value of the increased depth of insight provided by the LS-Dyna solution over legacy software is clear and makes a strong case for running enhanced predictive simulation as a matter of course. Applying a systems perspective to deliver a simulation capability focused on identification of risk to structural integrity as well as completion design optimization has delivered a tool that remains flexible and scalable in all of its components.

1 Introduction

A detailed understanding of the dynamic response of gun strings using explosive charges for oil well perforation is critical to the ongoing development of improved perforating systems, as well as the optimization of each perforation job and management of the associated risks. Numerical simulation is a key component of this understanding as it provides levels of insight that testing alone cannot. Simulation tools, however, have been focused on resolving the hydrodynamic behaviour of shaped charges in order to maximize their individual performance while system simulations, such as the one described in this paper, have been limited by oversimplification, resulting in insufficient fidelity and resolution to make truly informed design decisions [1][2][7]. The value of legacy models has been further reduced by the general lack of downhole data required for proper model calibration and validation. This paper describes the work and process applied in the development of a system solution able to deliver the required fidelity at a level of confidence established by calibration to measured data that ultimately advances the general understanding of the dynamic response of both wellbore fluids and tool strings during well perforation.

2 System approach

The need for a reliable simulation system was identified as a result of gun parting failures experienced in deep water wells around the world as wells became increasingly deep and operating pressures and temperatures rose. These are failures where the tubular tools that carry explosive charges separate across their section and result in part of the tool string dropping into the well, requiring extraction. Investigating these failures highlighted the shortcomings of legacy software solutions as well as the need to approach the architectural development of improved predictive tools in a way that would enable the selection of the best possible components for each system function, while maintaining the modularity and scalability necessary to keep evolving the system as new requirements would come to light.

The initial scope of simulation was limited to the fluid and structural dynamic response up to 100 ms after charge detonation as it focused explicitly on the parting failure mode. At this timescale, perforations and formation effects have a negligible effect on the response but encompass sufficient time to identify potential structural failures resulting from highly dynamic loading. This scope was gradually expanded to also include perforations and near wellbore flow effects that influence perforation cleanout (removal of debris generated by the perforation process) and initial well productivity, enabling valid longer duration simulations and opening up the opportunity to truly optimize the perforation string design to leverage the fluid response and pressure dynamics for maximization of perforation cleanout. The system and its components [7], in the current state, are depicted in Fig. 1.

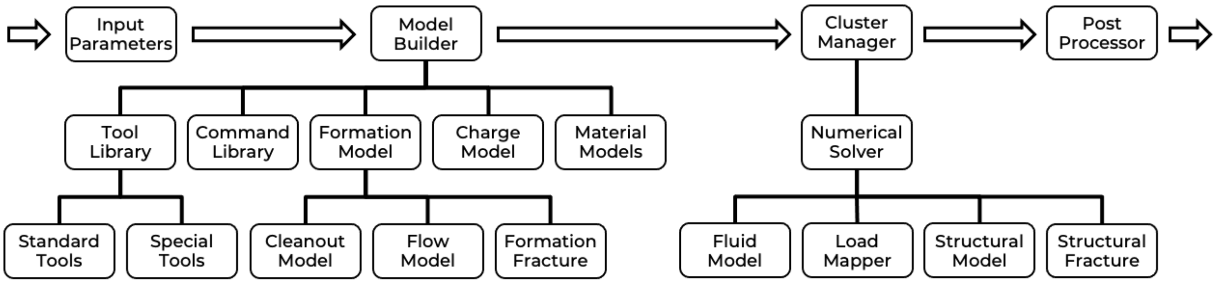

Fig. 1: Abstraction of analysis system components

In Fig. 1, the arrows indicate the principal workflow, which begins with collection of the job parameters that define the string and well conditions. These parameters are applied in a proprietary Model Builder, which defines the job, generates the mesh, and writes the model k files as well as other support files used for load mapping and fracture calculations, if required. The model files are managed by a proprietary cluster manager, which is responsible for calling the solver, in this case LS-Dyna, and other support programs in a predetermined sequence, queuing jobs, starting and stopping jobs and generating simplified results that enable analysis monitoring and flagging of potential buckling, burst, collapse and packer motion while the solution is running. Ultimately, the analysis output for reporting is generated through the post-processor, which in this case is LS-Prepost.

The modular nature of the depicted architecture has enabled continuous development of the solution capabilities, which over time have added an equation-based formation model and sub models. As new requirements and simulation scenarios continue to develop with the addition of new tools, advanced perforation strategies and more challenging conditions, new modules can be added to address them, including the ability to access multiple solvers or post processors, should this become a necessity.

3 Analysis approach

The solution comprises two models: A fluid model for resolving the fluid dynamics and the pressures imposed on the structure; and a solid model for determining the resulting forces, stresses and dynamic response. One of the biggest challenges faced in the simulation of downhole fluid dynamics is that of scale. Bottom hole assemblies can reach lengths of 1’000 to 1’500 m and the fluid model requires sufficient resolution in the gun sections that carry explosives to resolve pressure gradients well enough to impose realistic loads on the structural model. Clearly, a fully 3-dimensional fluid model with these characteristics would be impossible to run on all but the most powerful machines in a reasonable amount of time. Since the model is tubular and very slender, to circumvent this problem and reduce the model scale dramatically, an axisymmetric solution can be adopted for the fluid domain while maintaining a 3-dimensional structural model. This is effectively the trade-off that must inevitably be made between model complexity and efficiency in solution time. Adoption of an axisymmetric solution enabled a much-reduced model size and also enabled the fluid and solid models to be coupled through a simplified one-way fluid-structure interaction, allowing each to be optimized independently. Because this approach required a number of significant simplifying assumptions to be made about the nature of the pressure dynamics generated by the 3-dimensional charge pattern, a significant amount of effort went into its validation.

3.1 Validation of solution approach

Reducing the 3-dimensional charge pattern to an equivalent axisymmetric pattern requires the assumption to be made that pressure propagates sufficiently quickly across any model section to capture the key elements of fluid behaviour sufficiently accurately to properly represent the boundary pressures that impinge on the structure to generate the mechanical dynamic response. The validation was done in multiple steps:

- Validation of the solver with an axisymmetric shock tube model tested against an exact analytical solution for conditions similar to those that would be simulated in practice (Fig. 2 left). Variation of mesh size helped identify the required mesh resolution to balance solution speed with accuracy.
- Validation of the equivalence of the axisymmetric fluid solution with a 3-dimensional solution in a realistic model of charge detonation.
- Validation of the equivalence of the structural response of a 3-dimensional solid model when loaded with pressures extracted from a 3-dimensional fluid model and an equivalent axisymmetric fluid model, also shown in Fig. 2 (right).

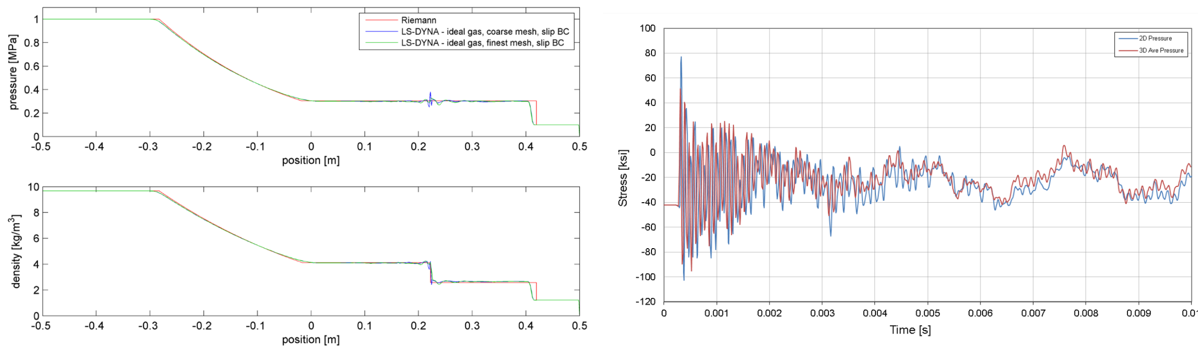

Fig. 2: Shock tube model validation (left) and structural response to pressure loads derived from axisymmetric and 3D fluid models (right)

Another assumption that must be made to decouple the fluid and structural models is that the fluid dynamics are dominant and drive the structural response while the structural dynamic response has a weak influence on the fluid dynamics and pressures. Decoupling the models is desirable because it enables models to be optimized independently. It also enables models to be run selectively, depending on the scope of the analysis. This assumption was validated directly through a campaign of instrumented surface testing by leveraging the calibration and validation of the different model elements.

3.2 Calibration of model elements

Calibration of the constitutive model parameters for key elements of the model is critically important in the overall performance and accuracy of the simulation. One of the most important is the calibration of explosive model parameters since all of the energy input into the simulation originates here. The explosives are modelled using a high explosive material model with a JWL equation of state. However, in order to reduce model complexity and size, the charge liner and the formation of the jet upon charge detonation are omitted. This requires the charge energy to be scaled through the JWL equation parameters and implies that each charge type should have its own calibration. This scaled value is known as a gun remnant [7].Fig. 2

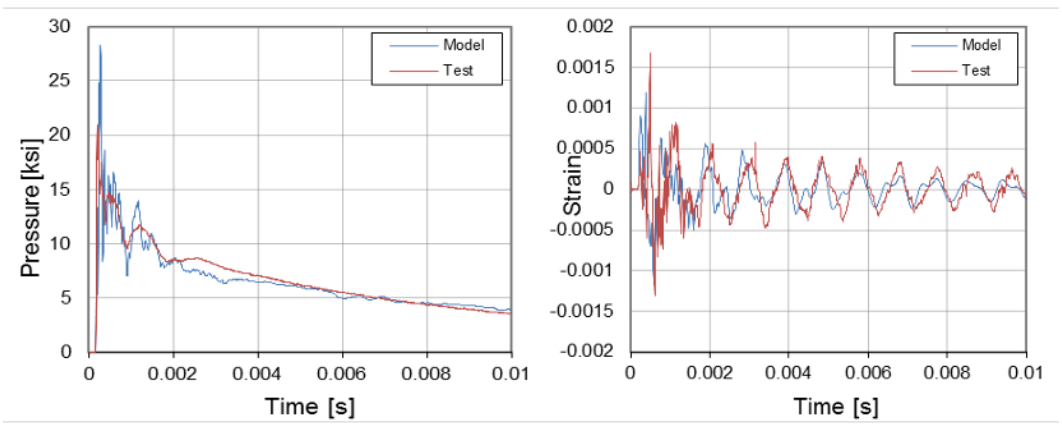

Fig. 3: Pressure and strain comparison for 13 x 23g HMX charge model and field test

Fig. 3 depicts the comparison between field test measurements for pressure and strain to simulated pressure (axisymmetric model) and strain (3-dimensional model) results for one of the numerous cases that were run. It must be highlighted that the loading for the structural model on the right is mapped from the output of the fluid model on the left, validating the uncoupled simulation and the axisymmetric fluid model configuration.

In order to enable accurate calibration of the models, a bespoke sensor tool was developed. This tool would enable pressure to be measured directly within the gun volume, something that had not been possible before this, and the strain to be measured directly adjacent to the gun. This tool was further developed to be able to be placed directly within the loaded sections of full-size strings in the field, aiding the further calibration of system level models.

3.3 Calibration of system model

Because the simulation capabilities are continuously being enhanced, calibration is an ongoing activity. Wherever possible, downhole data is collected from jobs around the world and simulated predictions are calibrated against it to improve system model accuracy. As simulations become increasingly complex, so too does the calibration task.

Fig. 4 depicts an early field test conducted on a real perforation job run in the Gulf of Mexico [7]. In this case, the string consisted of 3 guns, 2 of them fully loaded, and support equipment, terminated by an anchoring tool known as a packer. In this string, our custom-designed sensing tool was used to record the downhole data.

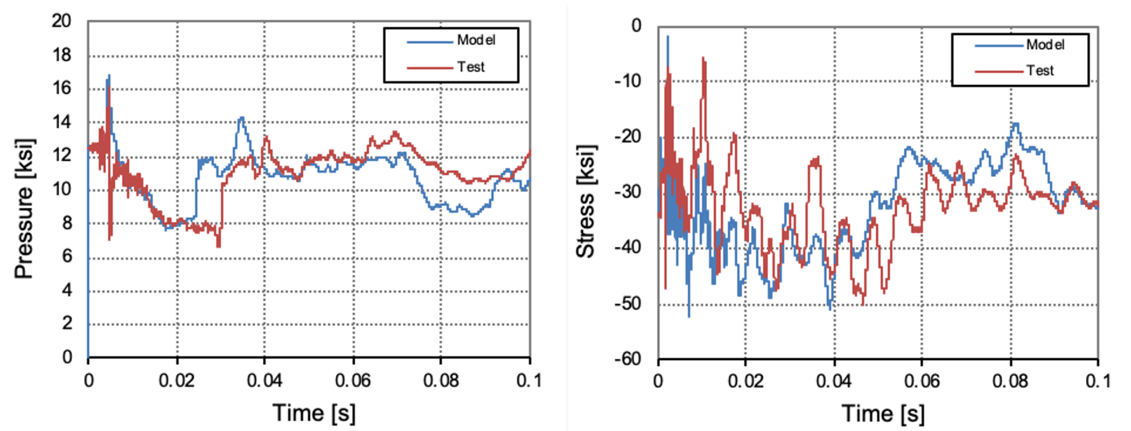

Fig. 4: Pressure and stress comparison for 3-gun system model and Gulf of Mexico field test

The fluid model, pictured on the left, returns a good match with the data, reproducing the main dynamic features and physical behaviour of the system well. In practice, pressure animations are studied in conjunction with the measured data to identify the sources and causes of these features. For example, the pressure drop occurring just after the initial pressure spike is attributed to the sudden ingress of fluid into the partially loaded top gun once this is perforated. This pressure underbalance, generally well predicted in amplitude and duration, is followed by a series of pressure peaks that originate from internal gun reflections that eventually work their way into the wellbore and are picked up by the pressure sensor. The drop in pressure seen at about 70 ms is associated with the pressure reflection coming off the packer, or upper boundary of the tool string. The small shift in the timing of the pressure rise seen at around 30 ms, although inconsequential in predicting cleanout or load magnitudes, indicates a potential mismatch with speed of sound characteristics of the wellbore fluids used in practice and a need for tuning of the Grüneisen equation of state parameters.

The predicted stress levels, derived from the measured strains, also compare well with data. Because of the complexity of this highly non-linear system and the uncertainty of the exact downhole conditions however, matching all strain/stress features is more difficult than matching pressures is. Considering that this was the first time a full-scale field test was conducted, the matching was regarded to be quite good, particularly in the first 10 to 15 ms. For a string such as the one modelled, this is sufficient time to evaluate the likelihood of a parting failure.

Such a system calibration is also used to validate assumptions and simplifications made in tool mesh design, port dimensions in transforming from 3 dimensions to 2 in the axisymmetric formulation, port opening timing that simulates gun perforation, charge dimensions, system level gun remnant, and so on. The addition of a formation model has further increased the complexity of model calibration but has also increased the model's utility in predicting perforation cleanout and initial productivity – two key perforation performance parameters – and has enabled the optimization of perforation strategies.

3.4 Equation based formation model [3][4][5][9]

Extending the simulation time beyond the 100 to 200 ms necessary to identify potentially damaging stress dynamics in even the longest models, requires the addition of a formation model that represents the perforations themselves and near wellbore formation flow. Once the perforations are generated, the high-pressure formation fluids near the now exposed reservoir surface are free to enter the wellbore in the case of a pressure underbalance, or to be forced into the formation by the wellbore fluid in the event of a pressure overbalance. This dynamic has to be considered when run times are extended to the 500 to 1000 ms range. One option is to simply extend the fluid mesh to include the formation, but this makes running the model much more expensive and was consequently rejected. Ultimately, the model was built using LS-Dyna's `*DEFINE_CURVE_FUNCTION` capability to model the formation. By setting up a system of equations that control the inflow boundary of each perforation based on local pressure and formation characteristics, the additional mesh can be avoided and an easily adaptable model can be set up. By selecting the set of equations to be applied in the Model Builder, it is possible to tailor the model to have no formation model at all, to consider perforation volume only, to calculate cleanout and formation flow, or to go as far as estimating perforation fracture growth. Naturally, each step adds some complexity and calculation effort, but the model generation with whichever set of equations is required is a matter of selecting the option for the desired set up and the equations are generated automatically by the Model Builder.

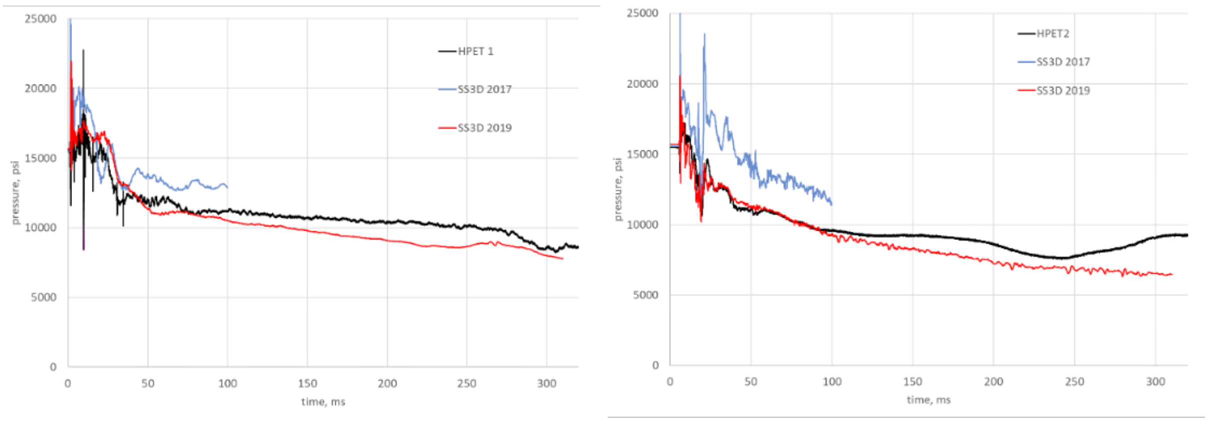

Fig. 5: Comparison of model performance before and after the addition of the formation model

Fig. 5 depicts model performance before (SS3D 2017) and after (SS3D 2019) the addition of the equation-based formation model. In this setup, data was collected at two locations in the string (HPET1 and HPET2)[1] and compared to the same locations in the simulation. The improvement in the longer timescale pressure response is evident at both measurement locations.

3.5 Fracture mechanics model

The gun parting failures that initiated the development of the simulation solution that is the object of this paper, all exhibited signs of high-speed crack propagation and brittle failure [6]. A study of the crack characteristics determined that linear elastic fracture mechanics principles apply, and that these cracks always propagate from the edges of the holes generated by the perforating jets because the act of perforation generates multiple small cracks around the circumference of every hole, providing thousands of potential initiation sites. Depending on the stress field dynamics around each hole, these initial cracks may propagate and potentially lead to failure. Although spent guns are not reused, their failure can result in enormous extraction costs for the operator to free the well from debris before production is possible.

It is clearly not possible to model each hole and crack explicitly in a string that may contain anything up to 20'000 such locations, and each location must be evaluated because regions where the local

[1] HPET is an in-line shock sensing tool offered by Halliburton Energy Services Wireline and Perforating.

constructive combination of stress is critical at any point in the simulation, are difficult to identify. Consequently, it was determined that the fracture calculation would be done as an automated post processing step utilizing the global stress histories at the hole locations, and that it would be an optional step in the analysis workflow. Such a model would require a characteristic initial crack length to be defined, which was done by studying the cracks found in multiple guns returned from the field. It would also require information about the material's fracture toughness as a function of strain rate since crack propagation in the failure cases clearly progressed at high speed, and it would require a geometric correction factor accounting for the local hole geometry. Finally, it would require a local stress history for each hole location, which would be extracted directly from the structural model results database at mesh locations defined in the Model Builder at the time of mesh generation.

Fig. 6 describes the process required to run the fracture dynamics calculation from the structural simulation results. The fracture analysis step is optional and can be run as required to determine the eventual onset of failure. The only input it requires (β, a and K_c are defined a priori for the system) is the stress history matrix for the hole locations, extracted from the results database after the completion of the structural simulation. Since the extraction of the stress history matrix can be time consuming, it is saved for subsequent use to enable iterations to be run on the fracture calculation without incurring the time penalty of results extraction every time. The fracture calculation module outputs a list of hole locations with a crack propagation and failure flag for each one.

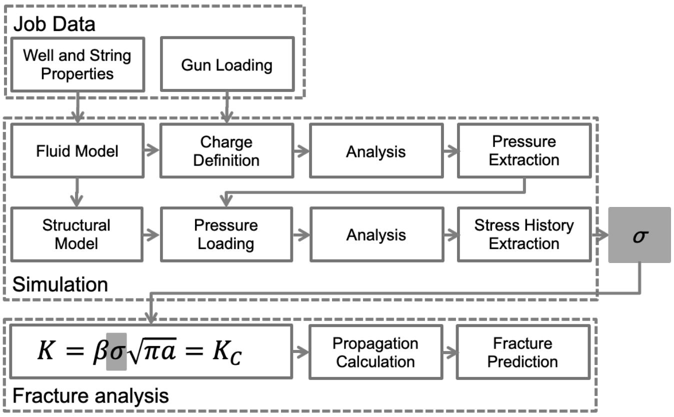

Fig. 6: Application of the fracture analysis module in the basic simulation workflow

4 Deployment

Owing to the modular nature of the simulation system, the workflow is flexible and can be tailored to the scope of each job depending on the purpose of the analysis. Known in the field as ShockSim3D (SS3D™)[2], it has been used to assist oil companies in risk assessment, perforation strategy optimization and failure analysis on well perforation jobs all over the world [8]. In this section, a brief summary of a recent perforation strategy optimization case is presented.

A dual reservoir, 3-zone completion was planned for a new offshore well. The challenging aspect of this perforation job was that the deeper reservoir was expected to be significantly lower in pressure than the upper. This is a challenge because in a single trip perforation the wellbore fluid is selected to ensure sufficient pressure is present after perforation of the primary reservoir that the formation fluids are prevented from entering the wellbore in an uncontrolled manner. Selecting the fluid weight to suit the upper, primary reservoir meant that the lower reservoir would be perforated with a significant initial overbalance that would make the generation of dynamic underbalance, necessary for debris removal during the dynamic response, difficult to achieve and potentially render the secondary reservoir unproductive.

Dynamic underbalance is generated once the gun tubes, initially filled with air at atmospheric pressure, are perforated and high-pressure fluid from the wellbore rushes in to fill them. This sudden removal of fluid from the wellbore results in a local drop in pressure that subsists until the guns are filled and fluid

[2] SS3D™ is a registered trademark of Halliburton Energy Services. SS3D™ was developed by Engenya GmbH and Starboard Innovations LLC with funding from Halliburton.

from above has refilled the wellbore. During this time, the pressure in the wellbore reaches a minimum and then returns to its original value exponentially over 1 to 2 seconds. This drop in pressure on the wellbore side, referred to as dynamic underbalance, causes fluid to rush out of the formation, and in so doing erodes the crushed debris present in the perforations created by the charge jet to leave behind a clean surface across which fluids can flow easily. Managing how these pressure dynamics happen provides the opportunity for optimization of the perforation strategy to maximize perforation cleanout, ultimately impacting well productivity positively.

In this case, the options for varying job parameters were limited to the charge density per unit length and the string position relative to the reservoir sections. In addition, while some uncertainty in the absolute reservoir pressures existed, the lower reservoir was expected to have significantly lower pressure than the upper. Consequently, a study was conducted with variation in charge loading density for varying pressure conditions. Fig. 7 shows the expected pressure as a function of depth 50 ms after the initiation of detonation for four cases:

- R2: Upper reservoir at high pressure and 12 shots per foot, lower reservoir at low pressure and 12 shots per foot
- R4: Upper reservoir at high pressure and 12 shots per foot, lower reservoir at low pressure and 9 shots per foot
- R5: Upper reservoir at nominal pressure and 12 shots per foot, lower reservoir at nominal pressure and 12 shots per foot
- R6: Upper reservoir at nominal pressure and 12 shots per foot, lower reservoir at nominal pressure and 9 shots per foot

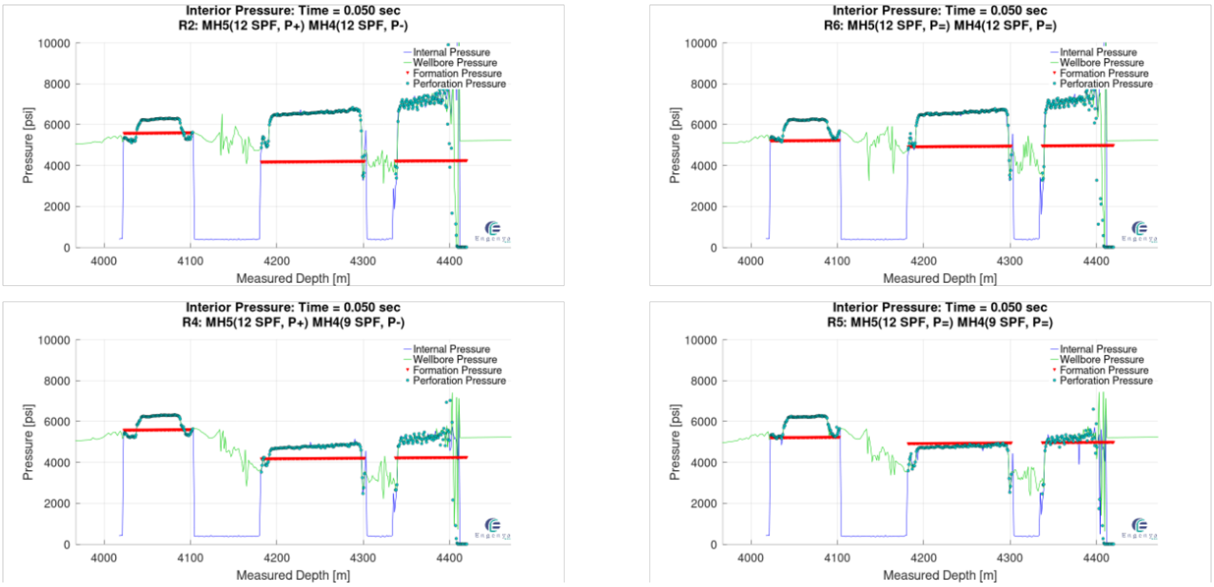

Fig. 7: Wellbore pressure as a function of depth just after completion of detonation

The reduction of charge loading in R4 and R6 results in an increase in gun free volume as well as a reduction in the initial overbalance pressure generated by the detonation. This is clearly seen in the lower two images of Fig. 7. The red lines in the images indicate the reservoir pressure level. Any pressure in the wellbore, indicated by the blue line, above this is overbalance and vice versa. The goal is to achieve dynamic pressure underbalance as soon as possible and hold it as long as possible to ensure perforation cleanout.

Reducing the gun loading has the advantage that dynamic underbalance is more easily achieved in cases where the initial pressure overbalance is high, as seen in the left images of Fig. 8. It is also seen that having a reduction in charge loading is not detrimental if the pressure is found to be nominal. Ultimately, optimizing the perforation strategy requires balancing the quality of cleanout, often achieved by reducing the density of perforations thereby losing flow area, with the number of perforations, more of which increase flow area but at an inferior quality of cleanout.

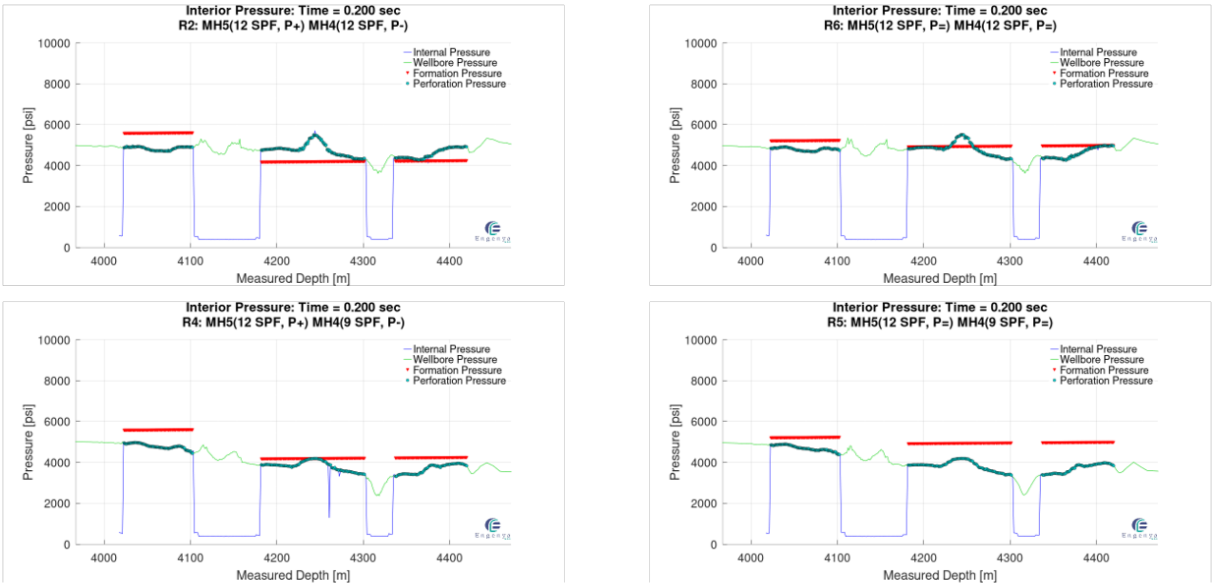

Fig. 8: Wellbore pressure as a function of depth 200 ms after start of detonation

Ultimately, the implications on productivity drive the selection of perforating strategy. This is clearly illustrated by Fig. 9, which shows total projected well cleanout efficiency on the left and the expected relative productivity on the right. The baseline case is represented by the R2 case, shown in blue. It is clear that this case is not expected to clean out very effectively due to the fact that the initial pressure overbalance is hard to overcome. It is also clear that there is a point where reducing the charge density, while cleaning out very efficiently, as in the R3 case (12 shots per foot and 6 shots per foot) shown in green, results in a penalty due to the reduction in number of perforations that cannot be overcome with even perfect cleanout.

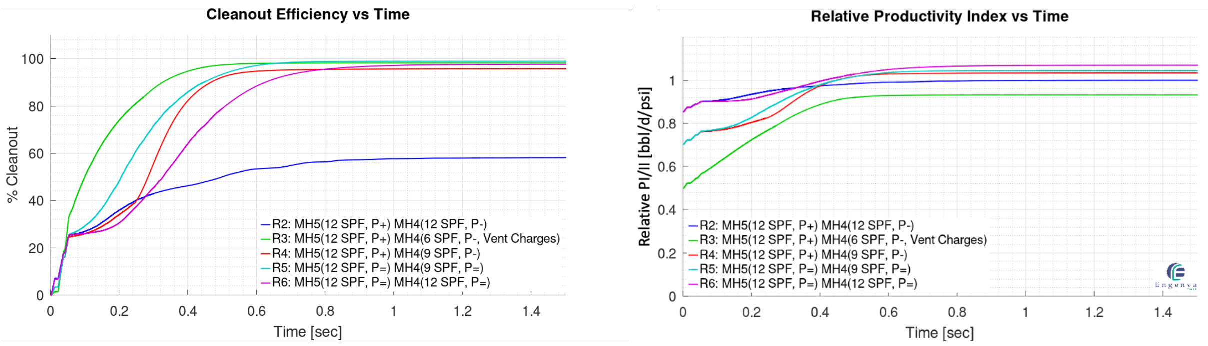

Fig. 9: Projected cleanout efficiency and relative productivity index for different cases

The conclusion that can be drawn from examining the curves on the right-hand side, is that selecting a strategy with 9 shots per foot on the lower reservoir would ensure that the pressure uncertainty is covered and a reasonable productivity can be expected in all but the worst conditions.

5 Summary

As well designs become increasingly challenging, the capabilities of this simulation solution over legacy solutions become increasingly sought after and appreciated. The modular approach applied to the assembly of a validated physical model enable not only tailored analysis studies to be run, but also the ongoing improvement of the model and the addition of capabilities as they may be required by the developing technology in the field of well perforations.

LS-Dyna has proven to be a capable and flexible solver, which offers broad functionality and tailorable solutions to the physical problems encountered in the field. In this application, the capabilities offered for the assessment of risk and optimization of perforation designs are unparalleled in the industry and contribute to lower the risk of failures and potential accidents, while helping to increase the productivity of new wells.

6 Acknowledgements

SS3D™ is a registered trademark of Halliburton Energy Services. SS3D™ was developed by Engenya GmbH and Starboard Innovations LLC with funding from Halliburton. SS3D™ is still being developed and has been deployed by Engenya and Starboard under license from Halliburton. The authors would like to thank the following people for their invaluable contributions in the development of SS3D™: Dr. T. Glenn, Dr. K. Ghandi, Mr. S. Pulitzer and Dr. G. Craddock. Finally, a word of thanks for their support and assistance in overcoming technical difficulties or providing solver adaptations goes to the team at Dynamore, who have supported this work for well over a decade.

7 Literature

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