Perforating Deep Wells ... Smartly!

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Abstract

Perforating is probably the most important of all completion functions in cased holes. The process involves many human/equipment constraints and its effectiveness is influenced by numerous system environment factors.

A methodology capable of resolving the difficulties associated with the less optimal historical methods in perforating is a hybrid intelligent system integrating a fuzzy expert-system and an artificial neural-network. Both Expert System and Neural Network technologies have developed to the point that the advantages of each can be combined into more powerful (Hybrid) systems. The goal of this paper is to demonstrate the practicality of making available such a system. The system is aimed at creating an improved perforation design/completion methodology, identifying and treating perforations’ damage, and forecasting and projecting actual deliverability from the perforations. As proposed, the system considers the effects of various environmental factors, existing/anticipated wellbore conditions, human/equipment constraints, and near-wellbore reservoir anisotropy, laminations, and natural fractures on the perforating design and analysis processes. Perforation is the last “hurdle” in the process of successfully producing a well. Optimizing its design/completion and solving its problems will, undoubtedly, result in a substantial economic impact in terms of production cost and efficiency.
1 Perforating: An Overview

The main objective of perforating is usually to establish communication between the wellbore and reservoir fluids. Adequate communication with the reservoir, as well as proper isolation between various zones, at pay depth is essential to evaluate and optimize the production of hydrocarbons. The process is widely used and adopted, and affects the majority of wells drilled worldwide.

Before selecting a perforating technique, one must fully understand current and long term completion objectives as well as well operating conditions. The perforation selection process is indeed affected, among others, by existing and anticipated pressure environment in the well [1], need for and type of well stimulation programs [2], need for and type of sand exclusion measures ([3] – [6]), purpose of the completion itself (production or injection), and whether this is an original completion or a workover [7]. In addition, numerous environmental factors (formation compressive strength ([8] – [10]), cement sheath thickness [10], casing grade strength [11], geothermal effects [12], etc.) should be considered while designing and completing any perforating job. Although one doesn’t have any control over these factors, one should be aware of their influence on the perforating operation.

On top of being almost irreversible, the process is (accordingly) delicate and is (probably) the most important function in cased hole completions. Perforations represent the last portion of reservoir inflow and directly affect well productivity ([13] – [15]). The determination of proper perforation type and technique will undoubtedly, result in both cost savings and improved dollar revenues. This paper aims at highlighting the need for a smart system for well perforating design, completion, and problem diagnosis and at describing the many different processes involved in developing such an intelligent tool.

2 Special Perforating Jobs

The selection of the perforating technique is also influenced by the need and type of the well stimulation process and/or sand exclusion method. Perforations play a crucial role in achieving a successful fracturing/acidizing and sand control well treatment.

Perforation design for a well which will be hydraulically fractured is usually controlled by the requirements to place the stimulation treatment [16]. Key parameters are the number of perforating shots per foot, perforations’ depth, and perforations’ phasing and orientation. Fracture initiation delineates the communication path between the wellbore and fracture plane [17]. The initiation process is dependent on the orientation of the perforations with the far field stress and the local pore pressure builds up relative to the injection pressure [18]. Nonplanar fracture geometries such as multiple
strands, reoriented, and T-shaped (Fig.1 [17]) have a negative impact on the potential to successfully stimulate the pay-zone. Typically, the objective is to ensure the existence of a single fracture, with optimum width, that propagates perpendicular to the minimum horizontal stress. In addition, no uniform criteria exist within the industry for defining optimum perforation density and phasing. Operators are using a variety of techniques based on their experience and on some adopted rules-of-thumb.

![Possible Fracture orientations from Horizontal Well. [17]](image)

**Figure 1:** Possible Fracture orientations from Horizontal Well. [17]

Perforating for sand control requires different guidelines and serves completely different purposes than perforating for hydraulic fracturing or acidizing. Where sand control is needed it can be assumed that there will not be a permanent, open-perforation tunnel beyond the cement sheath. The perforation channel behind the casing will most probably be filled with packing material. Designing perforations for pre-packed gravel packing demands short cylindrical perforation openings (Fig.2 [3]). Perforations are the basic problem in this case. Crushed formation particles and metallic particles from the jet charge act to restrict the placement of packing material into the perforation tunnel. Everything must be aimed at obtaining large-diameter clean perforations. For gravel packing, large-diameter perforations are more important than perforation length, provided that the perforations effectively communicate with the formation (reservoir).
According to the nature of the reservoir, the well may be either completed with formation stimulation, such as hydraulic fracturing and/or acidizing, or naturally with sand-exclusion and control. Each completion method requires different approach to perforating and sometimes even demands an unorthodox/unconventional (heuristics-based) perforating procedural guidelines.

3 Knowledge-Based Perforating Constraints

It is well known that many human and numerous equipment constraints play major roles in resulting a less than optimal perforating job.

Some of the prevalent human causes for failed/unsatisfactory perforating results probably are (1) a lack of understanding of what is required for successfully perforating a well, (2) a rather widespread practice of awarding perforating jobs on the basis of price rather than job quality [12], (3) poor perforating design, (4) poor selection or poor application of a good selection of perforating fluid [7], (5) a lack of awareness of the well environmental factors and of existing or anticipated wellbore conditions.

Because the perforation operation is equipment intensive, there are equipment constraints: (1) casing deformation or damage/fracture can result from inadequate use of perforating guns [19]; (2) plugging perfs with shaped-charge debris [13]; (3) inadequate gun clearance [20]; (4) damaged primacord; (5) poor quality booster; (6) poor quality or aging main explosive [21]; and (7)
poor quality and improper perforating charge.

In addition to problems associated with system geometry (shot density, perforation dimensions, perforation phasing), impairments sometimes result from the perforating process itself. In conventional jet perforating systems, holes are made through casing and cement and no material is removed. The perforation hole volume is obtained by compaction of material around the hole. The crushed zone around the perforations essentially increases the vertical resistance to flow and, accordingly, adds to the vertical skin. Because of this damage, common perforating practices provide only 80% of productivity of an ideal undamaged perforation [5]. In addition, whenever a workover operation is needed, kill fluid is pumped into the well to control it. The invasion of filtrate from the kill into the perforations causes a deposition of filter cake at the face of the perforation tunnel and reduces its permeability [22]. Accordingly, it is very essential to identify the type/degree of occurred damage and to use proper damage removal/treatment technique(s).

King and Buckley [21] conducted a study on cases of formation damage occurring upon initial perforating completion and continuing past standard perforating breakdown attempts or small matrix acidizing jobs. A common denominator in several of these cases appeared to be the performance of perforating charges and its support system.

Well completions should be designed to minimize workovers and recompletion jobs. For optimum design of a completion one should choose the most effective perforating system, charges, guns, and shot density that will result in a productivity ratio, PR, of near-one (production flow of the perforated interval equals open hole production of the same interval), even after 50% of perforations have plugged off [23]. One should then select the most effective perforating pressure that the formation and/or well mechanical system will permit in an effort to achieve damage-free, near-zero skin, completion. In short, perforating is a knowledge-intensive subject and a problem domain where expert heuristics needs to be considered in almost every step of the design and completion process.

### 4 Recognition/Prediction Problems

A large number of variables (wellbore pressure; formation strength; near-wellbore reservoir anisotropy, laminations, or natural fractures ([24], [25]); chemical incompatibilities between completion and formation fluids; perforations geometry; geothermal effects; perforations plugging; casing and cement damage; etc.) affect the perforation completion process. Therefore, perforated completions seldom perform as expected. It is imperative that each perforation job be evaluated to confirm its efficiency and to decide upon the remedial actions needed. “Accurate” estimates of the productivity are generally required to predict well performance and to evaluate completion
success. Several studies ([14], [26] - [30]) have investigated the relative effect of the parameters which define a perforated completion system on the productivity of the well using experimental, analytical or numerical models. However, current experimental setups do not (and cannot) simulate actual perforated-wellbore completion conditions; analytical treatments are extremely difficult (because of the spiral distribution of perforations in the wellbore axial direction and the presence of the wellbore itself) even with simplifying assumptions; and numerical techniques, while they provide useful insight into predicting the productivity, are complex, expensive and mostly proprietary. Probably, the best evaluation of any perforating completion is its performance during production. This performance is affected by many factors (human, operational, reservoir, etc.) that are not necessarily a part of the completion process. After a number of completions, however, trends in performance can be established. This kind of problems accordingly suggests the appropriateness of the artificial neural network technology.

The importance of good depth control can never be over-emphasised. Remedial measures to correct problems caused by perforating off-target are costly, time consuming, difficult to analyse, frustrating, and to the least misleading. The problem is misleading to the extent that many other reasons are often suggested to explain well’s poor performance caused by shooting off-depth. The accepted method of ensuring accurate perforation depth is to run a cased-hole log (Casing Collar Locator, CCL) and correlate it with open-hole measurements (Gamma Ray-Neutron, GR/N, logs). In addition to the correlation problem, corrections needs to be made on both (open-hole and cased-hole) measurements to adjust for vertical displacements of logs measure points. If either measurement-correction is made in the wrong direction, the resulting error will be twice the amount of the displacement being corrected.

Accordingly, while numerous heuristic-based constraints are involved in the perforating process and suggesting the appropriateness of this topic as an expert-system application; there are some other perforating problems that can best be solved using the Artificial Neural Network (ANN) technology. Namely the following two problems: (1) depth control to avoid any off-target perforating, and (2) perforating job evaluation and well performance prediction.

5 Summary and Conclusions

Knowledge-based systems perform reasoning using domain-specific rules, facts, heuristics and “tricks-of-the-trade” for a well defined and narrow problem domain. They are especially useful for interacting with the user to define a specific problem and bring in facts peculiar to the problem being solved. Neural networks, with their remarkable ability to derive meaning from com-
complicated or imprecise data, are used to extract patterns and detect trends that are too complex to be noticed by standard computing techniques. Neural computing can offer the advantage of execution speed once the network has been trained. Since Neural Networks are best at identifying trends and patterns in data (pattern recognition), they are also well suited for prediction or forecasting needs.

Selecting the proper perforating technique requires full understanding of the pressure environment in the well, a decision on whether or not the well will be stimulated and how, whether or not a sanding treatment is needed and of what type, whether this is a new completion or a workover, and whether the well is to be used for production or injection. While shape and geometrical distribution of perforations, degree of perforation damage and perforating efficiency strongly influence the final outcome; the selection of proper perforating hardware is essential for the optimization of well productivity (or injectivity). In short, the process relies heavily on heuristics and know-how and requires proper planning and execution.

It is generally recognized that the productivity analysis of perforated completions, because of the complex 3D flow into a spiral system of perforations, is not easily amenable to analytical treatments. "Friendly" numerical methods, on the other hand, are scarce, mostly proprietary, complex and to the least time consuming. Moreover, the importance of good perforating depth control can never be over-emphasized. Remedial measures to correct problems caused by perforating off target are always costly and often misleading. Accordingly, this domain involves also complex productivity-prediction and serious depth-recognition problems.

The proposed hybrid "intelligent" system is based on alternate and improved methodologies adopted from the AI (Artificial Intelligence) technology. These methodologies are: fuzzy expert systems and artificial neural networks. Expert systems and artificial neural networks are well established that in fact represent complimentary approaches. The logical, perceptive, heuristic, and mechanical nature of expert systems very well compliment the numeric, associative, self-organizing, biological nature of neural networks. Fuzzy logic and expert systems, on the other hand, are natural combinations because fuzzy concepts are naturally presented in the form of rules in fuzzy expert systems.

The itemized list of the proposed-system objectives includes: (1) decision on the completion type (cased-hole or open-hole) and accordingly, on the need for perforating; (2) decision on perforation completion objectives (natural, sand-control, or stimulation) (3) classification of applicable perforating techniques; (4) selection of appropriate perforating procedure(s); (5) design of the perforating job (number of shots per foot, perforations' depth, perforations' phasing and orientation, etc.); (6) selection of effective perforating system, charges, and guns; (7) selection/design of perforating completion fluid; (8) re-completion (of perforations) in workover wells; (9) identification
of type/degree of perforation damage and recommendation on proper damage removal/treatment technique(s); (10) sensitivity analysis and perforation economics; (11) recognition of correct perforating depth required to avoid off-target perforating; and (12) evaluation of the perforating job and prediction of well performance.

References


