Antenna assembly for down-the-hole measuring probe for locating and sizing hydraulic fracturing cracks in rock mass

AP Khmelinin1*, AI Konurin1, DP Khmelinin1 and MI Konurina2
1Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
2National University of Science and Technology—MISIS, Moscow, Russia
E-mail: *khmelininap@gmail.com

Abstract. The authors discuss the problem connected with the assessment of hydraulic fracturing quality in oil-filled formations by means of location and sizing of hydrofractures. The proposed engineering solution is to design a down-the-hole measuring probe based on the ground penetrating radar method in the range of microwaves. The authors select the model and mode of an antenna assembly for the down-the-hole probe. The width of the the major maximum of the antenna assembly pattern is determined.

1. Introduction
Enhanced oil recovery is actually challenging due to the long operation and, accordingly, depletion of the most oil reservoirs while new oil exploration and production projects require high investments. Physical treatment of pay zones for increasing oil flow rates in producing wells enjoys higher popularity. One of such techniques commonly applied in the oil and gas industry is fracking [1].

Crucially important evaluation of fracking quality is currently carried out as calculation of a surplus oil inflow in wells after fracking. When post-frac production grows slightly, it is impossible to define the failure and to evaluate the quality of hydraulic fracturing due to the lack of tools to identify locations and geometry of created fractures.

Microseismic monitoring, though extensively developed in many countries, fails to ensure sufficient accuracy and unambiguousness of results to solve the mentioned problem in full [2].

In this respect, high-frequency ground penetrating radar with high resolution capability seems more attractive [3, 5]. GPR can be implemented as the Impulse Radar or as Frequency-Modulated-Continuous-Wave GPR [4].

The Impulse GPR is a wider used approach which includes generation of very short high-amplitude EM pulses in a test object by a transmitter antenna, receiving of the reflected pulses from the interface and timing of travel of the reflected pulse from the reflecting interface to a pickup antenna. The frequency range of the GPR impulse is wide, from 15 MHz to 3000 MHz, and depends on the engineering problem conditions and on the GPR equipment specifications. For instance, for the tests at great distances to the reflecting surface (a few hundreds of meters), the optimal frequencies range from 30 MHz to 500 MHz [5].

The common approaches to extending the pick-up range are the transmitter power multiplication, or the spectrum change or synchronous accumulation of generated impulses. Each method has its
natural constraints. In terms of advancement, synchronous accumulation and transmitter power multiplication are the most promising techniques [4].

2. Antenna assembly mode selection and justification
Mapping of three-dimensional position of hydraulic fractures is only possible from wells, which imposes significant limitations on geometry of a detecting device. In this case, electromechanical or electrical scanning of borehole environment seems the best-suited technique. Electrical scanning assumes that the transceiving antenna remains unmoved (rests in space) and scanning direction is changed through phase or frequency variation of the probing microwave signal [6]. Electromechanical scanning involves rotation of some elements in the antenna assembly to change the transmit and receive directions of probing signals. These scanning techniques govern the choice of antennas suitable for the set problem solution, for example, notch antennas, dipole aerials, or micro-strip phased array antennas.

The mainstream super wide-open radar sets are composed of very large antenna assemblies unserviceable in wells, and also are incapable to implement electrical scanning which is the most promising technique as the present study authors think.

A proper GPR set should enable adjustment of the probing signal and ensure continuous service. The optional versions of the antenna assemblies suitable for operation with the GPR set under development are discussed below.

3. Selection of an antenna assembly
Selection of an antenna assembly should consider the application environment constraint and the power characteristic of the GPR set.

For another thing, diameter of the GPR-based probe should be no more than 90 mm since the maximum diameter of wells in the oil industry is 120 mm.

Some antenna designs satisfy the mentioned size constraint and can operate in the mode of electrical scanning. Such antennas are the waveguide–notch array antennas and or micro-strip phased array antennas (Figures 1 and 2).

![Waveguide–notch array antenna](image)

**Figure 1.** Waveguide–notch array antenna.
Theoretically [5], the location and geometry of hydraulic fractures created in an oil-filled formation can be determined by a transmitter with frequency of 1 MHz at a distance to 50 m and by a transmitter with frequency of 10 MHz at a distance of 35 m at a radiating unit capacity of 100 W. With a transmitter frequency of 1 GHz, parameters of created fractures are theoretically estimable at a distance to 10 m.

Thus, the antenna assembly for the GPR-based probe being designed should possess sufficient electric strength to operate at the radiating unit capacity of 100 W, which is a material restriction for the use of the micro-strip phase array antennas.

Accordingly, the antenna assembly of the down-the-hole measuring probe should use the waveguide–notch array antennas.

4. Width of the major maximum of the antenna assembly pattern
A GPR probe can locate a hydraulic fracture and determine its geometry if the antenna assembly satisfies the narrow beam requirement. In this connection, we carry out modeling of the antenna pattern for the waveguide–notch array antennas.

In compliance with [5, 7], the electric field intensity of a radio wave is given by:

\[ E = E_m \cdot e^{-\beta r} \cdot \cos \omega(t - \frac{r}{a}) \]

where \( E_m \) is the peak intensity, W/m; \( \beta \) is the coefficient of EM wave attenuation in the propagation medium; \( \omega \) is the angular rate, rad/s; \( a \) is the coefficient of EM wave velocity, m/s; \( r \) is the distance of the wave travel, m.

The important modeling parameters are the specific inductive capacitvity \( \varepsilon' \) and the conductivity \( \sigma \) of oil-field formation to be subjected to EM wave treatment. These parameters depend on the probing signal frequency and are assumed to range from 4 to 15 for \( \varepsilon' \) and from 0.01 to 0.3 Cm/m for \( \sigma \) [8]. The value of conductivity increases at frequencies higher than 3 GHz; for this reason, the modeling assumes \( \varepsilon' \) and \( \sigma \) to be equal to 5 and 0.05, respectively, and the probing signal frequency to be equal to 10 MHz and 1 GHz.

The width of the major maximum of the antenna assembly pattern was calculated in MathCAD.

From the calculations implemented for the probing signal frequency of 12 MHz and for the 12-notch waveguide array antenna, the width of the major maximum of the antenna assembly pattern in the plane E is 112 degrees, which is unacceptable within the problem being solved.

At the probing signal frequency of 1 GHz and the same number of radiating units, the major maximum of the antenna assembly patterns narrows down to 33 degrees, which is tolerable for the problem solution on location and sizing of hydraulic fractures in an oil-filled formation.
5. Conclusions
The research findings allow some conclusions to be drawn, namely:

(1) The electrical scanning technique is applicable to determining special position and geometry of hydraulic fractures in an oil-filled formation;

(2) The size constraint of the antenna assembly to operate in a well at the signal power sufficient to ensure the wanted effective distance can be removed with the help of the waveguide–notch array antenna;

(3) The width of the major maximum of the antenna assembly pattern is equal to 33 degrees, which ensures positioning and sizing of hydraulic fractures in an oil-filled formation at the probing signal frequency of 1 GHz at 12 generating units in the waveguide–notch array antennas.

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