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Experimental investigations of rate effects on drilling forces under bottomhole pressure

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ABSTRACT

The purpose of this study is to examine cutting speed and bottomhole pressure effects on cutting forces acting on PDC cutters during the oil and gas drilling process. A set of single cutter tests was performed in three sedimentary rocks of different permeabilities. Dry tests were carried out at atmospheric pressure and at different cutting speeds. As previously observed in the literature, these tests show that cutting forces increase with the cutting speed, especially the normal component. The same tests were performed at 20 MPa bottomhole pressure. It appears that the cutting speed effect on cutting forces in the medium and low permeability rocks is moderate and weak, respectively. By contrast, rate effects in the highly permeable rock are significant and overcome rate effects observed in dry experiments by an order of magnitude. Interestingly, these observations are similar to those observed in submarine soil ploughing at high hydrostatic pressure. These results are believed to represent an important step into a deeper understanding of the oil and gas drilling process.

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1. Introduction

Most of the existing PDC cutter rock interaction models are rate-independent (Sellami et al., 1989; Detournay and Drescher, 1992; Detournay and Defourny, 1992; Gerbaud, 1999; Menand, 2001; Dagrain et al., 2001; Gerbaud et al., 2006). However, several experimental results tend to show that cutting forces can be rate dependent both at the drillbit scale (Dufeyte and Henneuse, 1991; Brett, 1992; Pavone and Desplans, 1994; Reckmann et al., 2007; Pelfrene, 2010; Jain et al., 2011) and at the cutter scale (Pelfrene, 2010; Kolle, 1996).

At the drillbit scale, such rate effects have been observed in the field in the shape of a decreasing relationship between the torque on bit (TOB) and the rotary speed (RPM) under constant weight on bit (WOB), generally associated with stick-slip vibrations (Dufeyte and Henneuse, 1991; Pavone and Desplans, 1994; Reckmann et al., 2007; Jain et al., 2011). These have been observed during laboratory drilling bench tests too, both under flexible (Brett, 1992) and rigid shaft conditions (Pelfrene, 2010; Wiercigroch el al., 2015).

The causal relationship between these rate effects and the stick-slip phenomenon has been demonstrated by many authors through drillstring dynamic modelling (Brett, 1992; Reckmann et al., 2007; Pelfrene, 2010; Jain et al., 2011; Jansen, 1993; Leine et al., 2002; Patil and Teodoriu, 2013). Furthermore, Pelfrene (2010) has shown both experimentally and theoretically that the falling torque characteristics observed at the drillbit scale can be explained by a hardening effect observed at the PDC cutter scale on both components of the cutting forces, especially the normal one. This hardening effect has been attributed to the dynamic shearing of a dense layer of crushed rock trapped at the tip of the PDC cutter. The author has deduced from these results that the drillbit design, via its cutter setup, could be used to control the intensity of rate effects at the drillbit scale and hence to mitigate stick-slip based on the optimization of the drillbit design (Pelfrene et al., 2011). This conclusion has been confirmed in the field by Jain et al. (2011).

In order to accurately predict forces acting on PDC drillbits and hence to optimize the drillbit design process, the most realistic PDC cutter rock interaction model is needed. However, most of the existing laboratory experiments on top of which PDC cutter rock interaction models are built, have been conducted in absence of either a bottomhole pressure representative of real drilling conditions or a varying cutting speed again representative of real drilling conditions.

In the oil and gas drilling literature, the effect of the bottomhole pressure has only been studied by a few authors. Sellami (1990) shows that cutting forces do not depend on differential pressure in low permeability formations. For example, in the case of a hard coarse grains Buxy limestone and a hard fine grains Saint-Anne limestone, the author shows that cutting forces are a

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function of the mud pressure p_m, rather than a function of the differential pressure, defined as $(p_m - p)$, where p is the formation initial pore pressure. The same conclusion is drawn by Detournay and Tan (2002) in tested impermeable shales. The authors explain these observations by an undrained regime flow which takes place during the cutting process of shear dilatant rocks like shales. The theoretical basis of this interpretation has been shown earlier by Detournay and Atkinson (2000).

The combined effect of the bottomhole pressure and the cutting speed in the oil and gas drilling literature has only been investigated by Kolle (1996) during single cutter experiments performed in five rocks of different poromechanical characteristics using Thermally Stabilized Diamond cutters at 0.3 mm Depth Of Cut (DOC). The author observes a significant hardening effect in the permeable Berea Sandstone ($k = 5\ 10^{-15}\ \mathrm{m}^2$) when the cutting speed increases from 0.5 to 8 m/s, under all tested bottomhole pressures between 10 and 70 MPa. This effect is much lower under atmospheric pressure. In most of the other tested rocks of lower permeabilities ($k < 3\ 10^{-17}\ \mathrm{m}^2$), this effect is also much lower, under all tested bottomhole pressures between atmospheric pressure and 70 MPa. Except for results obtained in permeable Colton Sandstone ($k = 3\ 10^{-16}\ \mathrm{m}^2$) which are somehow inconsistent, the author concludes that these experimental results are consistent with a model of dynamic confinement pressures based on pore volume dilatancy in the rock ahead of the cutter, developed earlier (Kolle, 1993).

Contrary to the oil and gas drilling literature, rate effects were the subject of many research works in submarine soil ploughing. A rich literature review of velocity effects in this field can be found in Lauder (2010). One of the first lab tests was achieved by Grinsted in 1983 (cited by Palmer (1999)). The author shows that rate effects are absent in dry ploughing. However, experiments in saturated soils under hydrostatic pressure show that rate effects can be very significant and mainly depend on the permeability and the density of the soil (Palmer, 1999). This effect is generally attributed to the fact that an increase in the cutting velocity leads to a shrink in the pore pressure, causing an increase in the effective stress. This interpretation strongly echoes the one provided by Kolle (1996), Detournay and Atkinson (2000) in the field of oil and gas drilling.

This paper aims at extending the scope of previous experimental studies dealing with the coupling between rate effects and bottomhole pressure to conditions representative of the oil and gas PDC drilling process. An extensive experimental campaign was driven on a drillability cell at Mines ParisTech. In the first part, the experimental facility and procedure are presented. Then experimental results are provided. Finally, these results are discussed in the last part of this paper.

2. Experimental facility

2.1. Drillability Cell

The High-Pressure Drillability Cell is located in the drilling lab of Mines ParisTech at Pau in France. It allows the simulation of single-cutter/rock interaction under controlled rotational speed (RPM), depth of cut (DOC) and bottomhole pressure. The advantage of this device is its ability to reach high cutting velocity under high down-hole pressure. Drilling fluid pressure, confining and pore pressures can be controlled separately providing down-hole conditions close to realistic deep oil drilling. The confining pressure is applied on the lateral side of the jackted rock sample. The mechanical capacities of the device are improved in order to be able to test hard formations under high DOC and down-hole pressure.

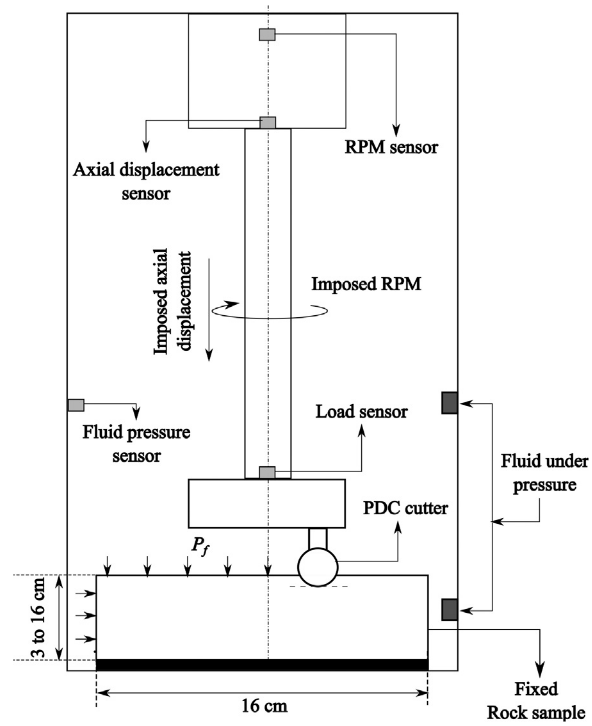

Fig. 1. Drillability Cell configuration.

Table 1
Characteristics of the Drillability Cell.

Rotary speed	6–300 RPM
Fluid pressure	1–100 MPa
Normal force F_n	0–50 kN
Tangential force F_c	0–20 kN

Fig. 1 gives a schematic view of the High-Pressure Drillabilty Cell of Mines ParisTech. A 16 cm diameter rock sample is initially fixed inside the cell. A special system guarantees the flatness of the rock sample. Thus, a constant DOC is ensured during the drilling test. The motor shaft, in which the PDC cutter is already fixed, is animated with a helical motion with constant RPM and constant DOC..

Electric pumps are used to control down-hole pressures of up to 100 MPa. The rotation speed can be changed from 6 to 300 RPM in order to cover an important range of cutting velocities encountered in drilling fields. The cutting radius is 4.5 cm. Table 1 details the Drillability Cell capacities in terms of cutting speed, fluid pressure and admissible loads.

2.2. Experimental procedure

We first perform dry single-cutter tests in order to study the rotary speed effects in the absence of mud and compare them with previous works. Then we reproduce the same experiments at 20 MPa bottomhole pressure using a low-chemical-activity oil. We first need to saturate the rock samples within the mud fluid before performing the cutting tests. Fig. 2 shows the evolution of the fluid content in the highly permeable Vosges Sandstone at ambient pressure and 20 MPa. It can be seen that fluid content at atmospheric pressure saturation increases rapidly during the first hours which corresponds likely to the filling of the macro-porosity of the rock. The fluid content continues to increase slightly after 14 days without filling all the pores (20% of the Vosges Sandstone volume). By contrast, saturation at 20 MPa is more efficient. Less than five

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