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Real-time monitoring of mechanical specific energy and bit wear using control engineering systems

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ABSTRACT

Drilling of oil and gas wells utilize drilling mechanical energy to crush formation rocks through drill bits. Due to the friction with the formation rocks, the bit cutters suffer a continuous wear with the progress of the drilling causing reduction in rate of penetration. Real-time bit wear is a challenge in drilling as there is no absolute physical model.

This paper presents new philosophy based on control engineering systems to simulate bit behavior and estimate the transferred and wasted mechanical energy to predict drilling performance efficiency.

Analytical model has been developed to predict drilling performance by analyzing the real-time transferred drilling mechanical energy consumed by the drill bits, the model will assist in optimizing the hydraulic energy and take the proper time decision to pull the dulled bits.

The model consists of a first order differential equation solved to predict the effect of drilling parameters on drill bit wear; while, the bit wear equation enters in a second order differential equation solved by Laplace transformation, and expressed as a transfer function representation which allows in analyzing the drilling performance, and also expressed as real-time of bit displacement achieved by the input drilling energy.

The poles of denominator of the transfer function have been analyzed as a complex conjugate pairs; the location of the real part of the complex roots indicates the amount of real-time consumed mechanical energy by the drilling bits to destroy formation rocks. While, the location of imaginary roots indicates the amount of wasted mechanical energy due to bit wear.

The effect of hydraulic energy on drilling performance has been simulated using closed loop transfer function, which allows for monitoring the wasted mechanical energy, and the wasted hours of bit life consumed in extra cutting due to insufficient hydraulic energy.

The results show that the visual representation for poles location allows real-time monitoring for the performance of the transferred mechanical energy due to both bit dullness and to insufficient hydraulic energy explicitly. The results also show high decline rate in transferred mechanical energy always occurs within small values of bit dullness compared with that occurred in large values of bit dullness, which confirm the real field observations. The comparison with field examples proves the model reliability in predicting the drilling performance.

1. Introduction

Drilling for oil and gas wells is an expensive operation; saving costs can be achieved by reducing the operating time. Utilizing maximum drilling efficiency with a highest attainable penetration rate is the most active way to reduce the drilling time.

Formation rocks can be drilled by applying a certain mechanical energy exerted on formation rocks. This energy consists mainly from weight on bit (WOB), rotary speed (N) and torque (T), which can be transferred by the bit cutters to drill formation rocks. Thus, the bit condition has a direct effect on the energy transmission to crush formation rocks. In addition, the bit diameter has also a direct effect on penetration rate; this assumes penetration rate is directly proportional to weight per bit diameter.

Increasing weight on bit (WOB) and bit revolution per minute (N) have a significant effect on drilling speed (ROP), increasing WOB lead to increase the cutters pushed depth into the formation; while, increasing N lead to increase the cutting rotation (Hankins et al., 2015).

These two major parameters, in addition to the torque and bit diameter have been utilized by several researchers to develop mechanical specific energy models to show energy efficiency being converted to rate of penetration at the drilling bits (Chen el al. 2014).

The most practical current concept to evaluate the drilling efficiency is the mechanical specific energy which was first introduced by Teale (1965). Teale defined the mechanical specific energy as the amount of energy required to destroy a unit volume of rock. This model ignored the effects of bit dullness, hydraulic energy on drilling efficiency as well

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Nomenclature

A_b	Drill bit area, in^2
B	The rate of resisted force term consumed by drill bit dullness, $\frac{Ib_f \cdot h}{ft}$
B_s	Bit cutters compressive strength, $\frac{Ib_f}{in^2}$
D_b	Bit diameter, in.
$d_{(t)}$	Bit dullness as function of drilling time, Dimensionless
E_h	Hydraulic energy efficiency, Dimensionless
E_m	Mechanical energy efficiency, Dimensionless
$E_{(t)}$	Mechanical energy affects on bit dullness, Dimensionless
$f_{d(t)}$	Drill bit damping force term, Ib_f
$f_{i(t)}$	Input mechanical force term, Ib_f
$f_{s(t)}$	The resisted force term by rock compressive strength, Ib_f
$G_{(s)}$	Second order open loop transfer function, $\frac{ft}{Ib_f \cdot h}$
$G_{(s)cl}$	Second order closed loop transfer function, $\frac{ft}{Ib_f \cdot h}$
g_c	Mass conversion unit=32.174 $\frac{Ib_m \cdot ft}{Ib_f \cdot S^2}$
HMSE	Hydro-mechanical specific energy, Psi
K_1	Drill bit drilling capacity, Dimensionless
K_2	Inverse of (K_s), $\frac{ft}{Ib_f}$
K_d	Disturbance function, Dimensionless
KIb	Kilo pounds
K_s	Input force term resisted by rock confined compressive strength per foot, $\frac{Ib_f}{ft}$
l_t	Cutters' length, in.
MSE	Mechanical specific energy, Psi
MSE_{new}	New analytical MSE model, Psi
N	Revolution per minute, rad/min
PDC	Poly Diamond Crystalline bits
ROP	Rate of penetration, ft/h
R_s	Formation rocks compressive strength, $\frac{Ib_f}{in^2}$
S	Seconds
s	Laplace transforms
T	Torque, Ib_f.ft
t	Drilling time, hours
$U_{(t)}$	Input drilling force term, Ib_f
WOB	Weight on bit, Ib_f
$y_{(t)}$	Drill bit vertical displacement per unit time=ROP, ft/h

Greek symbols

ε	Bit damping factor, Dimensionless
ε_o	Original bit damping factor, Dimensionless
ε_t	Real time bit damping factor, Dimensionless
j	Imaginary part of complex conjugate pairs, Dimensionless
τ	First order time constant, h
μ_b	Bit-specific coefficient of sliding friction, Dimensionless
ω_d	Damped frequency, rad/S
ω_n	Natural frequency, rad/S

as the effect of rock confined compressive strength being drilled.

After Teale, other authors also developed models for the mechanical specific energy, for example; Pessier and Fear (1992) stated that the conventional way to determine drilling performance is to compare actual performance to statistical standards derived from offset records, these standards are subjective and variable, and they cannot provide more than short-range performance and trends in well known, older fields. They lack the power of physical models to establish absolute, technical performance standards. Pessier et al. introduced a term of bit-specific coefficient of sliding friction as key index of drilling performance and makes bit selection and the diagnosis of failures and drilling practices more accurate and less ambiguous. Dupriest and Koederitz (2005), prevailed that maximum drilling efficiency was usually seen about 35% at peak performance; while, Cherif and Bits (2012), thought the mechanical efficiency (E_m) were about 0.26–0.64. These models have been listed in Table 1.

Some authors also reported for the shortage of these mechanical specific energy models to predict the real-time drilling efficiency; (Jardine, 1990), stated that ROP decreases with bit wear and when this falls to some pre-determined value the bit should be replaced; such changes, may be confused by changes in rock strength or type and fall short of an ideal quantitative indication of bit wear. (Rashidi et al., 2008), stated that the mechanical energy and drillability change when the bits are worn; that is due to mechanical energy equations does not involve the bit wear.

In order to obtain more realistic results, some authors tried to develop techniques or adding terms to the original model of mechanical specific energy introduced by Teale, (Waughman et al., 2003) provided a method for estimating mechanical specific energy for each specific drilled lithology section using Gamma ray readings, they prevailed that this method can give a good indication of bit performance.

Parallel to mechanical energy, there must also be a specific hydraulic energy to lift the drilled cuttings, to ensure cuttings do not impede the bit to formation contact. Thus, the hydraulic energy must be adjusted with the consumed mechanical energy transferred by the bit cutters to drill formation rocks to achieve cost effective drilling.

(Armenta, 2008) stated that the rock is broken by mechanical energy component and the drilled cutting is removed by the hydraulic energy component. He added the effect of hydraulic horse power to the original mechanical specific energy developed by Teale, to match its effect on drilling efficiency. (Mohan et al., 2015) presented new correlation identifying inefficient drilling conditions throughout introducing Hydro-mechanical specific energy (HMSE), which encompasses hydraulic as well as mechanical energy. HMSE quantifies the amount of energy required to drill a unit volume of rock and remove it from underneath the bit. They consider the new hydraulic term is the key to correctly match the amount of energy required to drill and overcome the strength and stresses of formation being drilled. Also, this new term illustrates how much hydraulic energy is needed to drill faster when the mechanical energy is increased.

As well as the rate of penetration is function of rock compressive strength bit wear is also affected by the efficiency of hydraulic energy used to lift the drilled cuttings. Thus, the models of mechanical specific energy cannot provide more than a rough indication or qualitative analysis for the drilling efficiency, unless exact bit wear and rock compressive strength can be in-situ determined while drilling; and then any comparison, just on the basis of drilling time per unit depth, is useless if the models don't consider the variation in drilling parameters.

Therefore, an equation for real-time consumed mechanical energy and bit wear as a function of drilling time is required.

Table 1
Current mechanical specific energy models.

No	Model	Model formula
1	Teale (1965)	$MSE=\frac{WOB}{A_b} + \frac{120\pi N . T}{A_b . ROP}$
2	Pessier and Fear (1992)	$MSE = WOB(\frac{1}{D_b} + \frac{13.33\mu_b N}{A_b . ROP})$ $\mu_b=36(\frac{T}{D_b . WOB})$
3	Dupriest and Koederitz (2005)	$MSE = 0.35(\frac{WOB}{A_b} + \frac{120\pi N . T}{A_b . ROP})$
4	Cherif and Bits (2012)	$MSE=E_m(\frac{4WOB}{\pi D_b^2} + \frac{480N . T}{\pi D_b^2 . ROP})$