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A torque estimator-based control strategy for oil-well drill-string torsional vibrations active damping including an auto-tuning algorithm

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ABSTRACT

Considerable compliance of the lengthy oil-well drill string combined with low tool inertia and stick–slip friction between the tool and the rock bed causes notable undesired torsional vibrations of the drill-string electrical drive. In order to attenuate the torsional vibrations and, thus, improve both the quality and the productivity of the drilling process, an automatically tuned active damping control strategy based on drill-string torque estimation is proposed in the paper. The core of the strategy includes a proportional-integral (PI) controller extended with estimator-based drill-string torque feedback loop. Furthermore, an appropriate algorithm that prevents drill-string back-spinning caused by the limited braking power of the power converter is presented. Finally, an auto-tuning algorithm is proposed, which is built around an adaptive Kalman filter-based estimator of drill-string drive natural frequencies. The drill-string control strategy is verified experimentally using a drill string hardware-in-the-loop setup under the laboratory conditions, as well as on an actual oil-drilling rig.

1. Introduction

The boreholes of oil exploration and exploitation wells are typically drilled by means of a rock cutting tool (drill bit), which is attached at the end of a rather long drill string consisting of many smaller interconnected drill-pipe sections, and driven by a speed-controlled electrical drive (Beck et al., 1996). Due to large lengths and small cross-sections of the drilling pipes, low tool inertia, and emphasized tool vs. rock bed friction, the overall drill-string electrical drive is prone to poorly damped torsional vibrations including the stick–slip behavior (Jansen & van den Steen, 1995; Mihajlovic, Van Veggel, Van de Wouw, & Nijmeijer, 2004). These vibrations can be provoked either by the variable cutting/friction forces or the time-varying operator's commands, such as a sudden change of drill-string servomotor speed reference or variations of the weight-on-bit (WoB) command (especially in the case of manual WoB control). Apart from the torsional drill-string vibrations, the drill string system is also subject to lateral and axial vibrations caused by drill string vs. borehole and tool vs. rock bed interactions (Christoforou & Yigit, 2003; Jansen, 1993).

Since the torsional vibrations contribute to aging and wear of drill-string drive components and reduce the efficiency/productivity of the drilling process, they need to be suppressed by means of appropriate vibration-damping measures. This can be achieved by designing a passive vibration absorber mounted at the bottom side of the drill string (Navarro-López & Suarez-Cortez, 2004; Viguié et al., 2009). Another hardware-based measure, proposed in Richardson and Küttel (2000), includes an additional hydraulic torque drive system placed within the bottom-hole-assembly (BHA). The main disadvantages of such hardware-based solutions are that they increase the drilling system complexity and cost, and they may need to be specifically tailored for the particular drilling system. In order to avoid these disadvantages, many research and development efforts have been targeted towards active damping solutions. They can be divided into two main groups: (i) direct active damping strategies realized either by emulating a passive absorber behavior (Jansen & van den Steen, 1995), or by using a more advanced (typically state-variable) drill-string speed controller structures (Tucker & Wang, 1999; Abdulgalil & Siguerdidjane, 2005; Al-Hiddabi, Samanta & Seibi, 2003; Puebla & Alvarez-Ramirez, 2008; Navarro-López & Licéaga-Castro, 2009; Serrarens, van de Molengraft, Kok, & van den Steen, 1998; Karkoub, Zribi, Elchaar, & Lamont, 2010), and (ii) indirect approaches typically based on a WoB control system coupled with the main drill-string speed controller (Canudas-de-Wit, Rubio & Corchero, 2008; Navarro-López & Suarez-Cortez, 2004).

The engineering practice has shown that the active damping control strategy should meet the following requirements:

1. *Effective attenuation of drill-string torsional vibrations.* The higher the level of vibration damping is, the drilling process

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Nomenclature

c	drill-string stiffness coefficient (N m/rad)
d	drill-string damping coefficient (N m s/rad)
$d_{i,dp}$, $d_{i,hw}$, $d_{i,c}$	inner diameters of regular drill-pipes, HWDP and collars (m)
$d_{o,dp}$, $d_{o,hw}$, $d_{o,c}$	outer diameters of regular drill-pipes, HWDP and collars (m)
D_2, D_3, D_4	damping optimum characteristic ratios of closed-loop system
D_{2o}, D_{3o}	characteristic ratios of Luenberger estimator
J_1, J_2	motor-side and tool-side inertia (kg m^2)
J_{tool}, J_{dp}, J_{hw}, J_c	tool, drill-pipe, HWDP and collar inertia (kg m^2)
l_{dp}, l_{hw}, l_c	lengths of drill-pipes, HWDP and collars (m)
G	shear modulus of steel (N/m^2)
i	gearbox (transmission) ratio
K_{1e}	Luenberger estimator speed gain (s^{-1})
K_{2e}	Luenberger estimator torque gain (N m/rad)
K_{3e}	Luenberger estimator torque derivative gain (N m s^{-1} rad^{-1})
K_R	PIm and PI controller proportional gain (N m s/rad)
K_m	PIm controller torque gain
T_I	PIm and PI controller integral time constant (s)
m_{1R}	motor torque command (N m)
m, m_{f2}	drill-string torque and tool friction torque (N m)
$M_{max,op}$, M_{max}	operator's and actual (modified) torque limit (N m)
M_{res}	safe torque reserve (N m)
M_S, M_C	breakaway torque and Coulomb friction torque (N m)
r_M, r_{EM}	inertia ratio and frequency ratio
T	sampling time (s)
T_m, T_Σ	equivalent time constant of motor open-loop system (s)
T_e	closed-loop system equivalent time constant (s)
T_{eo}	Luenberger estimator equivalent time constant (s)
$\Delta\alpha$	torsional angle (rad)
$\Delta\omega$	speed difference (rad/s)
ω_1, ω_2	motor and tool speed (rad/s)
ω_{1s}	motor speed at the torque saturation point (rad/s)
$\omega_{R,op}$, ω_R	operator's and actual (modified) speed reference (rad/s)
Ω_0, Ω_{01}, Ω_{02}	drill-string drive, motor-side and tool-side natural frequencies (rad/s)
ζ	damping coefficient of closed-loop control system
$\hat{}$	estimated value
BHA	bottom-hole assembly
HWDP	heavy-weight drill-pipes
IAE	integral of absolute error
WoB	weight-on-bit (t)

becomes more productive and easier to handle by the operator.

2. *Prevention of the so-called drill-string drive back-spinning*, caused by a limited braking power of the motor power converter, drill string compliance, and the tool stick–slip friction effects, in order to avoid the potential damage to the drive (e.g. unfastening of drill string sections and gearbox damage).
3. *Control strategy adaptation* with respect to varying drill string length and variable (borehole-dependent) tool-side configuration, which can be realized by means of either auto-tuning or self-tuning approach (cf. Åström & Wittenmark, 1989). In order to facilitate reliable on-line tuning of the controller, a simple and straightforward analytical tuning procedure is desired.
4. *Control strategy robustness* with respect to variations of other drill-string drive parameters such as motor torque constant and drive moments of inertia.
5. *Simplicity of implementation* is also desired, so that the control strategy can be realized on a typical low-cost industrial programmable logic controller (PLC).

In terms of the requirement on simplicity of the overall drill-string control system, the direct active damping approaches are mostly used in applications and they are considered in this paper. While various active-damping control strategies have been proposed in the literature, they do not appear to consider or meet all of the above requirements. Tucker and Wang (1999) consider a proportional-integral (PI) speed controller, whose design is based on a spatially distributed drill string model. However, this low-order controller may have difficulty in achieving a full potential of torsional vibration damping, and its tuning procedure may not be convenient for auto-tuning purposes. A full-order state controller based on the two-mass elastic process model is proposed by Al-Hiddabi et al. (2003), but the "critical" aspect of robustness of full-order nonlinear state estimation in the presence of unknown stick–slip friction is not considered. The controller sensitivity with respect to process parameter variations has been addressed in the literature by extending the controller with a nonlinear drill-string parameter estimator (Puebla & Alvarez-Ramirez, 2008), or by using an inherently robust controller such as a sliding-mode controller (Abdulgalil & Siguerdidjane, 2005; Navarro-López & Licéaga-Castro, 2009) or an H_∞ design-based controller (Serrarens et al., 1998). However, the control/estimation approaches proposed by Puebla and Alvarez-Ramirez (2008), Abdulgalil and Siguerdidjane (2005), and Navarro-López and Licéaga-Castro (2009) again require a full-order state feedback or the full-order estimator, which may not be feasible/robust in practical applications. The input–output type H_∞ controller (Serrarens et al., 1998) appears to be well-suited for practical applications, but it is not quite clear from the presented results if such a constant-parameter high-order controller can provide consistent quality of performance for a wide range of drill string lengths and configurations. None of the available papers discusses the drill-string back-spinning phenomenon caused by the limited servomotor braking power. It should be noted, though, that a method of handling a stuck tool situation by means of a state controller with a WoB feedforward action is presented in Navarro-López (2009), but it does not take into account the braking power/torque saturation effect.

The main aim of this work has been to develop and implement a drill-string drive control strategy that meets all of above design requirements. The overall structure of the proposed control strategy is shown in Fig. 1, with definitions of symbols (variables) given in the Nomenclature section. Among several possible state controller structures (Deur, Koledić, & Perić, 1998; Leonhard, 1985; Schäfer, 1992), the PI motor speed controller extended with a drill-string torque feedback is used (Section 3), because of the following advantages: (i) good performance (fast response) for the particular case of low load/tool inertia (Deur et al., 1998) and (ii) no requirement for a tool speed estimator which is typically sensitive to time-varying nonlinear load friction effects (Schäfer, 1992). A Luenberger observer, which is also described in Section 3, is used to estimate the drill-string torque as a disturbance variable (Pavković, Perić, & Deur, 2000; Schäfer, 1992; Weihrich, 1978). The special case of pure PI controller (no