Nonlinear Model Predictive Control of Managed Pressure Drilling based on Hammerstein-Wiener piecewise linear models

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Automation systems are increasingly important in many industries, especially those in competitive scenarios that encourage improved economic margins and reduced risk. Automation systems not only improve safety and convenience but also, perhaps most beneficially, enable optimization strategies that are less consistent with manual operation. The oil well drilling industry is transitioning to automation systems like the refining and petrochemical industry. The rapidly changing crude oil market combined with developing alternative energy sources creates renewed interest in drilling automation. Recent outstanding breakthroughs in the drilling industry give many opportunities to apply a variety of automation and optimization strategies. Most of all, managed pressure drilling (MPD) opens the way to control the drilling process in a closed loop fashion. However, the inherent nonlinearity and semi-batch nature of the drilling process gives many challenges to apply an automation strategy.

Typically, two approaches are used to develop a nonlinear model predictive control (NMPC) schemes. The first approach is based on first principles models that describe the fundamental physics of the process. The second approach employs a derivative form of empirical models, termed "black box models", identified from the existing process data. While first principles models describe the process dynamics in more detail, they normally require more computational time to solve the complicated fundamental equations [1]. Computation time of solving first principles models might not be adequate for control purposes in real time applications. Many previous research studies in drilling automation have established low order first principles models by capturing the main dynamics of the drilling process [2-5]. Although using low order models reduces the computational time significantly, those models use several variables that are not measured and must be estimated. In contrast with first principles models, black box models retain the all advantages of linear MPC that is widely used in many industries [6]. Hammerstein-Wiener models are the most widely implemented method of black box nonlinear models in industry [7].

This work discusses the development of Hammerstein-Wiener based NMPC for the drilling process. The Hammerstein-Wiener models employ a piecewise linear function to process the input value. These Hammerstein-Wiener models apply a nonlinear static element and linear dynamic element, allowing a gain-scheduling concept for nonlinear control [7]. The control performance and computation time of the Hammerstein-Wiener based NMPC is compared to the typical lower order first principles NMPC in various scenarios that frequently occur in drilling operations, such as unexpected gas influx from the formation due to a drill pipe connection procedure. The case study is verified with a high fidelity drilling simulator under certain well conditions [8] shown in Table 1.

Table1. Well conditions of the WeMod (high-fidelity hydraulic simulator)

Parameter	Value
Well depth	11,800 ft
Riser inner diameter	19''

Water depth	590 ft
Casing inner diameter	9''
Casing depth	7,100 ft
Drill string average outer diameter	4.5''
BHA length	150 ft
BHA average outer diameter	6.7''
Open hole/bit size	8.5''
Reservoir depth	9840 ft
Reservoir Pore Pressure	401.0 bar/1.364 s.g.
Initial mud density	1.24 s.g.

This investigation also details strategies to estimate downhole pressure. Previous research studies consider the automation strategy assuming that reliable downhole measurements from wired drill pipe (WDP) technology are available [9]. However, the majority of drill rigs are still operating without WDP. In order to apply the control system to a majority of drilling rigs in current operation, it is necessary to establish the framework to estimate the downhole properties instead of directly measuring the value. In order to estimate the downhole pressure, a moving horizon estimator (MHE) and a lower order model are employed.

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