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Fault Diagnosis in Managed Pressure Drilling Using Nonlinear Adaptive Observers

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Abstract— **A bank of nonlinear adaptive observers is used for fault diagnosis in oil and gas drilling where managed pressure drilling (MPD) is applied. The particular fault considered is formation of a pack-off, causing increased friction in one part of the annulus. The process model is a simplified hydraulics model with a Newtonian fluid. All states in the model are assumed measurable, an assumption based on planned implementation of the wired drill pipe measurement technology. A fault detection observer is used to detect that a pack-off is being formed somewhere in the annulus. Then a set of fault isolation and approximation observers, one for each possible fault, is used to isolate the location of the pack-off and estimating its magnitude. Isolation is done by using residuals of annular friction estimation. The method for fault diagnosis is illustrated in a simulation study.**

Index Terms— **fault diagnosis, nonlinear adaptive observer, managed pressure drilling**

I. INTRODUCTION

Drilling of onshore and offshore oil and gas wells has traditionally been done manually by a driller. As technology has advanced, more sophisticated online measurements have been available, e.g., depth, penetration rate, topside pump rates and pressures, and drilling fluid (“mud”) flow return rate from the borehole. These measurements have mainly been used as information to the driller, and have to a little extent been used for automated closed-loop control or automated diagnosis of the operation. One of the exceptions where automated control has been applied is managed pressure drilling (MPD), where closed loop control of topside chokes keeps annular wellbore pressure within margins of pore pressure and fracture pressure.

A new measurement technology called wired drill pipe has recently been introduced (e.g., [1]), which increases the bandwidth and sampling rate drastically compared to traditional mud pulse telemetry. It will then be possible to have a more continuous measurement of downhole conditions during drilling such as downhole pressure and rate of penetration, as well as added measurements such as flow through the bit and distributed pressure and temperature sensors along the drill string [2]. This technology may become instrumental in future drilling operations, as an increasing number of wells are less accessible, at high depths with small pressure margins. Operating within smaller margins, increased supervision of the drilling operation will be even more important. Incidents such as kicks (uncontrolled influx into the wellbore), pack-off (wellbore plugged around the drill string), loss of drilling fluid to the formation, and blocking of the drill bit need to be detected and handled.

In this paper the work done in, e.g., [3], [4] will be used as background for including early fault warning of when and where a pack-off is being formed in the annulus, using a bank of adaptive nonlinear observers. By utilizing the wired drill pipe technology, the pack-off can be located with much higher accuracy. A similar study has also recently been done on a well in the Gulf of Mexico, but with manual detection of the pack-off formation [2]. Detection was done by observing an increase in equivalent circulating pressure for all pressure sensors below the pack-off. Another example of using the technology for diagnosis has recently been studied in [5], where an uncented Kalman filter (UKF) has been used to detect and isolate a kick.

This rest of the paper is organized in seven short sections. In the following section the concept of fault diagnosis is explained with emphasis on application in an MPD system. In Sec. III the model of the drilling process is presented, with some unknown parameters representing process friction and faults. In Sec. IV a nonlinear adaptive observer for the process is presented, and in Sec. V the concept of using a bank of these observers for fault diagnosis is described. How this can be implemented for the drilling process is explained in Sec. VI. We then carry out a simulation case in Sec. VII and give some concluding remarks in Sec. VIII.

II. FAULT DIAGNOSIS

System faults, disturbances and modeling error will all alter a system’s behavior. The difference is that disturbances and modeling error are factors which typically are suppressed by filtering and robust control, whereas faults in a system must be detected and handled. There have been published several books on the subject lately [7]–[9]. The problem of *fault diagnosis* consist of first

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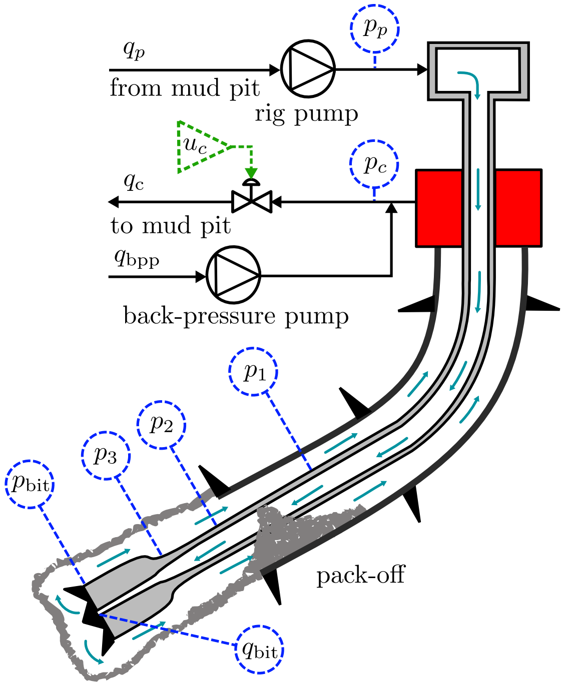

Fig. 1. Detection of pack-off in MPD (Adapted from [6]). The measurements are labelled with blue circles.

detecting the error through *fault detection*, finding the source of the problem through *fault isolation* and then identify its magnitude through *fault identification*. Fault diagnosis is not only important in itself, but also key if a good fault-tolerant control system is to be implemented [10]. Adaptive observers for fault diagnosis has been studied in, e.g., [11], [12]. The ideas have then been extended to have a bank of adaptive observers [13]–[15]. Extended Kalman filters can also be used to design adaptive observers, but will usually only guarantee local convergence [11], [13].

The method in this paper is to use a bank of Lyapunov based adaptive observers in order to detect and isolate a fault using measurements from the wired drill pipe. The formation of a pack-off is typically an incipient (slowly varying) fault represented by increased friction, favoring the use of adaptive observers with parameter estimation [16]. In addition there is an overall annular wall friction which can vary for other reasons. The idea behind the fault diagnosis setup is that a fault between two pressure sensors will give an increased pressure differential between these sensors. The bank of observers consists of one observer detecting that a fault has occurred, and one observer for each possible fault each assuming that only the corresponding fault has occurred. Then only the observer estimating the actual fault will get a correct estimate, isolating the fault.

III. HYDRAULIC DRILLING MODEL

The model used is based on the simple hydraulics model in [6], where a schematic overview is shown in Fig. 1. The model has simple one-phase incompressible flow relationships for a Newtonian fluid, and can be represented as

$$\frac{dp_p}{dt} = \frac{\beta_d}{V_d}(q_p - q_{\mathrm{bit}}) \tag{1a}$$

$$\frac{dp_c}{dt} = \frac{\beta_a}{V_a}(q_{\mathrm{bit}} + q_{\mathrm{bpp}} - q_c) \tag{1b}$$

$$\frac{dq_{\mathrm{bit}}}{dt} = \frac{1}{M}\left(p_p - p_c - F(q_{\mathrm{bit}}, \theta) - (\rho_a - \rho_d) g h_{\mathrm{TVD}}\right) \tag{1c}$$

where p_p [bar] is the drilling pump pressure, p_c [bar] is the choke pressure, q_{bit} [L/s] is the flow through the drill bit, and q_{bpp} [L/s] is the back-pressure pump. In the drill string and annulus, respectively, the bulk modulus is $\beta_{\{d,a\}}$ [bar] and the volume is $V_{\{d,a\}}$ [L]. The vector θ is the unknown parameters. The choke flow can be represented by the choke equation [17]

$$q_c = C_v u_c \sqrt{p_c - p_0}$$

where C_v is the choke constant, u_c is the choke opening, and p_0 is atmospheric pressure. The densities $\rho_{\{d,a\}}$ [kg/m^3] and cross sections $A_{\{d,a\}}$ [m^2] of the drill pipe and annulus are assumed known. Thus

$$M_i = \int_{L_{i-1}}^{L_i} \frac{\rho_i(x)}{A_i(x)} dx, \quad i \in \{d, a\}$$

is assumed know, where M_i [bar $\cdot$ s^2/L] is the integrated density per cross section over the segment $\Delta L_i = L_i$ [m]$-$ L_{i-1} [m]. We will use $M = M_d + M_a$ as the total integrated value of the hydraulic system from the the pump to the choke. Furthermore, the true vertical depth h_{TVD} [m] is assumed known.

A. Friction model

The total friction $F(q, \theta)$ in the system (1) can be divided into friction through drill string $F_d(q)$, including pipe friction and bit friction, and annular friction $F_a(q, \theta)$. As argued in [6] the flow dynamics will be faster than the pressure dynamics, and we can thus assume that the flow through the system can be approximated by the measured flow q_{bit} through the bit. Furthermore, since we measure the pressure drop $p_{\mathrm{bit}} - p_p$ over the drill string and assume known density ρ_d and viscosity μ_d, the friction $F_d(q)$ in the drill string can be assumed known and given as

$$F_d(q) = F_{\mathrm{pipe}}(\rho_d, \mu_d, L_d, q) + k_{\mathrm{bit}}(\rho_d) q^2$$

where pipe friction is modeled based on Newtonian fluid assumption including laminar flow, turbulent flow, and a transition zone.

The flow in the annulus is modeled in a similar way, but for the observer design we will assume that this flow is laminar, without loss of generality. For laminar flow of a Newtonian fluid, the pressure drop $F_{a,i}(q, \theta) = \psi c_i q$ in an annular segment i will be dependent on the length and diameter of the segment by a factor c_i, as well as some unknown parameter $\theta = \psi$. The constant c_i can be calculated as

$$c_i = \int_{L_i}^{L_{i+1}} \frac{1}{(d_h(l) - d_o(l))^2 \, (d_h^2(l) - d_o^2(l))} dl$$

where $d_h(l)$ [m] is the annular diameter and $d_o(l)$ [m] is the outer drill string diameter. $\Delta L_i = L_{i+1} - L_i$ [m] is the length of the segment.

B. Pack-off in the annulus

The fault studied in this paper is the formation of a pack-off, which is a (partially) plugged annulus around the drill string caused by accumulation of cuttings. One of the reasons for this to happen can be a too low circulation flow [18]. Pack-off is modeled using the orifice equation for incompressible fluids [17]. The friction $F_a(q,\theta)$ in the annulus can thus be represented as

$$F_a(q,\theta) = \sum_{i=1}^{N} F_{a,i}(q,\theta) = \sum_{i=1}^{N} \left(\psi c_i q + \phi_i q^2\right) \quad (2)$$

where $\theta = \begin{bmatrix}\psi, & \phi^\top\end{bmatrix}^\top$ are the unknown parameters we wish to estimate, and N is the number of annular segments between pressure measurements, and thus also number of faults. We will distinguish between the unknown annular friction parameter ψ and the parameters representing the set of possible faults

$$\mathcal{F} := \{\phi_1, \ldots, \phi_N\} \quad (3)$$

where each element is the friction parameter ϕ_i in (2) corresponding to increased pressure due to, e.g., pack-off.

C. Measurements with wired drill pipe

In addition to the topside pressures p_p and p_c, wired drill pipe is used to measure downhole pressure p_{bit} and flow q_{bit}, as well as three pressure measurements p_1, p_2, p_3 along the annulus, see Fig. 1. By defining $F_{a,i}(q,\theta)$ in (2) as the friction between the pressure sensors in the annulus, the following equations represent the relation between pressure and friction

$$\begin{aligned}
p_1 &= p_c + F_{a,1}(q,\theta) + G_1(\rho_a)\\
p_2 &= p_1 + F_{a,2}(q,\theta) + G_2(\rho_a)\\
p_3 &= p_2 + F_{a,3}(q,\theta) + G_3(\rho_a)\\
p_{\text{bit}} &= p_3 + F_{a,4}(q,\theta) + G_4(\rho_a)
\end{aligned}$$

where $G_i(\rho_a)$ is the hydrostatic pressure difference between the two measurement points.

IV. NONLINEAR ADAPTIVE OBSERVER FRAMEWORK

In this section we will present the nonlinear adaptive observer used as a basis for parameter and fault estimation. It is assumed that all states are measured, giving the system on the form

$$\dot{x} = \alpha(x,z,u) + \beta(x,z,u)\theta \quad (4a)$$

$$z = \eta(x,z,u) + \lambda(x,z,u)\theta \quad (4b)$$

where $x(t) \in \mathbb{R}^n$ are the states, $z(t) \in \mathbb{R}^m$ are additional measurements, $u(t) \in \mathbb{R}^p$ are the inputs, $\theta \in \mathbb{R}^q$ are unknown parameters, and $\alpha(\cdot)$, $\beta(\cdot)$, $\eta(\cdot)$ and $\lambda(\cdot)$ are locally Lipschitz. The observer with theorem and proof is based on an observer in [19], adapted to the system representation (4).

Theorem 1: Given an observer on the form

$$\dot{\hat{x}} = \alpha(x,z,u) + \beta(x,z,u)\hat{\theta} - K_x(\hat{x} - x) \quad (5a)$$

$$\dot{\hat{\theta}} = -\Gamma\beta^\top(x,z,u)(\hat{x} - x) - \Lambda\lambda^\top(x,z,u)(\hat{z} - z) \quad (5b)$$

$$\hat{z} = \eta(x,z,u) + \lambda(x,z,u)\hat{\theta} \quad (5c)$$

where $K_x, \Lambda, \Gamma > 0$ are tuning matrices, and with $\dot{\theta} = 0$. Let $e_x = \hat{x} - x$ and $e_\theta = \hat{\theta} - \theta$ be variables for the error dynamics, where $e = \begin{bmatrix}e_x^\top, & e_\theta^\top\end{bmatrix}^\top = 0$ is an equilibrium point. Then $e = 0$ is globally exponentially stable if

$$\Gamma^{-1}\Lambda\lambda^\top(\cdot)\lambda(\cdot) - \beta^\top(\cdot)K^\top K\beta(\cdot) > kI_q \quad (6)$$

for some constant $k > 0$, where $I_q \in \mathbb{R}^{q\times q}$ is the identity matrix.

Proof: Let a continuously differentiable positive definite Lyapunov function be given by $V = \frac{1}{2}e_x^\top K_x^{-1}e_x + \frac{1}{2}e_\theta^\top\Gamma^{-1}e_\theta$. Then the time-derivative of V is given by

$$\begin{aligned}
\dot{V} &= e_x^\top K_x^{-1}\dot{e}_x + e_\theta^\top\Gamma^{-1}\dot{e}_\theta\\
&= e_x^\top K_x^{-1}\beta(\cdot)e_\theta - e_x^\top e_x\\
&\quad - e_\theta^\top\beta^\top(\cdot)e_x - e_\theta^\top\Gamma^{-1}\Lambda\lambda^\top(\cdot)e_z\\
&= e_x^\top K_x^{-1}\beta(\cdot)e_\theta - e_x^\top e_x\\
&\quad - e_\theta^\top\beta^\top(\cdot)e_x - e_\theta^\top\Gamma^{-1}\Lambda\lambda^\top(\cdot)\lambda(\cdot)e_\theta
\end{aligned}$$

where it has been used that $\dot{e}_x = \beta(\cdot)e_\theta - K_x e_x$, $\dot{e}_\theta = \dot{\hat{\theta}} - \dot{\theta} = \dot{\hat{\theta}} = \Gamma\beta^\top(\cdot)e_x - \Lambda\lambda^\top(\cdot)e_z$, $e_z = \lambda(\cdot)e_\theta$. Using that $e_x^\top K_x^{-1}\beta(\cdot)e_\theta - e_\theta^\top\beta^\top(\cdot)e_x = -\frac{1}{2}e_x^\top\left(I_n - K_x^{-1}\right)\beta(\cdot)e_\theta - \frac{1}{2}e_\theta^\top\beta^\top(\cdot)\left(I_n - K_x^{-1}\right)^\top e_x$, we can write

$$\begin{aligned}
\dot{V} &= -\begin{bmatrix}e_x^\top, & e_\theta^\top\end{bmatrix}\begin{bmatrix} I_n & K\beta(\cdot)\\ \beta^\top(\cdot)K^\top & \Gamma^{-1}\Lambda\lambda^\top(\cdot)\lambda(\cdot)\end{bmatrix}\begin{bmatrix}e_x\\ e_\theta\end{bmatrix}\\
&= -e^\top\Phi(\cdot)e
\end{aligned}$$

where $K = \frac{1}{2}(I_n - K_x^{-1})$. From Proposition 16.2 in [20] on the Schur complement, we have that $\Phi(\cdot) > kI_{n+q}$, if and only if $\Gamma^{-1}\Lambda\lambda^\top(\cdot)\lambda(\cdot) - \beta^\top(\cdot)K^\top K\beta(\cdot) > kI_q$, using that I_q is invertible and positive definite. Provided that (6) holds, $\dot{V} < -k\|e\|^2$ and thus according to Theorem 4.10 in [21] the equilibrium point $e = 0$ is globally exponentially stable. ■

Note that if $\beta(\cdot)$ is bounded and $\lambda^\top(\cdot)\lambda(\cdot) > 0$ there exist some tuning parameters K_x, Γ and Λ such that (6) is fulfilled. The matrix function $\beta(\cdot)$ is bounded as the physical flow $x_3 = q_{\text{bit}}$ through the system always will be bounded, while $\lambda^\top(\cdot)\lambda(\cdot) > 0$ can be interpreted as a requirement for persistence of excitation.

V. A BANK OF OBSERVERS FOR FAULT DIAGNOSIS

The procedure of making a bank of $N+1$ observers, where N is the number of faults in some fault class $\mathcal{F}$, is based on the methods presented in [13], [22]. The idea is to have one *fault detection observer* (FDO) to detect faults. After a fault is detected, the N remaining *fault isolation and approximation observers* (FIAOs) are used to isolate the fault and estimate its magnitude. There are two ways of using a bank of observers for fault diagnosis [22]. In the *dedicated observer scheme* (DOS) proposed by Clark [23] each observer is sensitive to one fault, while in the *generalized observer scheme* (GOS) proposed by Frank [16] each observer is sensitive to all faults but one.

In this paper we will use the DOS scheme. The FDO only estimates the unknown process parameters ψ, while the jth FIAO in addition estimates one possible fault parameter ϕ_j in $\mathcal{F}$, while assuming the rest of ϕ zero.

A. Fault detection observer (FDO)

The FDO will be used to detect that a fault has occurred by detecting changes in the estimate of the plant parameters ψ without estimating the fault parameters ϕ. The observer (5) with $\phi_j = 0$ will be

$$\dot{\hat{x}}_0 = \alpha(x,u) + \beta_0(x)\hat{\psi}_0 - K_x(\hat{x}_0 - x) \tag{7a}$$

$$\dot{\hat{\psi}}_0 = -\Gamma_0\beta_0^\top(x,z)(\hat{x}_0 - x) - \Lambda_0\lambda_0^\top(x)(\hat{z}_0 - z) \tag{7b}$$

$$\hat{z}_0 = \eta(x,z) + \lambda_0(x)\hat{\psi}_0 \tag{7c}$$

where $\beta_0(x)$ and $\lambda_0(x)$ are reduced matrices with columns corresponding to ψ in $\beta(x)$ and $\lambda(x)$, respectively. The gain matrices are K_x, Γ_0 and Λ_0.

B. Fault isolation and approximation observers (FIAOs)

The FIAOs are designed such that each observer only estimates one of the faults ϕ_j in $\mathcal{F}$, in addition to the plant parameter ψ. The fault isolation observer for fault ϕ_j can then be written as

$$\dot{\hat{x}}_j = \alpha(x,u) + \beta_0(x)\hat{\psi}_j + \beta_j(x)\hat{\phi}_j - K_x(\hat{x} - x) \tag{8a}$$

$$\dot{\hat{\psi}}_j = -\Gamma_0\beta_0^\top(x,z)(\hat{x}_j - x) - \Lambda_0\lambda_0^\top(x)(\hat{z}_j - z) \tag{8b}$$

$$\dot{\hat{\phi}}_j = -\Gamma_j\beta_j^\top(x,z)(\hat{x}_j - x) - \Lambda_j\lambda_j^\top(x)(\hat{z}_j - z) \tag{8c}$$

$$\hat{z}_j = \eta(x,z) + \lambda_0(x)\hat{\psi}_j + \lambda_j(x)\hat{\phi}_j \tag{8d}$$

where $\beta_0(x)$ and $\lambda_0(x)$ are the same as in the FDO (7), and $\beta_j(x)$, $\lambda_j(x)$ are the corresponding regressors for $\hat{\phi}_j$. The tuning parameters will be the same as for the FDO in addition to Γ_j and Λ_j. Not that this observer is on the same form as (5), but with θ split into ψ and ϕ_j.

VI. FAULT DIAGNOSIS OF THE DRILLING PROCESS

In this section the methods for fault diagnosis presented in Sec. V will be applied to the drilling case. The simplified hydraulics drilling model (1) can be written on the form (4) where $z = \begin{bmatrix} p_1, & p_2, & p_3, & p_{\text{bit}} \end{bmatrix}^\top$, $x = \begin{bmatrix} p_p, & p_c, & q_{\text{bit}} \end{bmatrix}^\top$, $u = \begin{bmatrix} q_p, & q_{\text{bpp}}, & u_c \end{bmatrix}^\top$, and with system matrices

$$\alpha(x,u) = \begin{bmatrix} -\frac{\beta_d}{V_d}\left(x_3 - u_1\right) \\ \frac{\beta_a}{V_a}\left(x_3 + u_2 - C_v u_3\sqrt{x_2 - p_0}\right) \\ \frac{1}{M}\left(x_1 - x_2 - F_d(x_3) - \Delta\rho g h_{\text{TVD}}\right) \end{bmatrix} \tag{9a}$$

$$\eta(x,z) = \begin{bmatrix} x_2 - G_1 \\ z_1 - G_2 \\ z_2 - G_3 \\ z_3 - G_4 \end{bmatrix} \tag{9b}$$

where we have used $\Delta\rho = \rho_a - \rho_d$. Further will θ, $\beta(x)$ and $\lambda(x)$ be dependent on the specific FDO or FIAO.

A. Fault detection observer

In the fault detection observer a fault-free system is assumed, and thus only the annular friction $\theta = \psi$ of the parameters is estimated using the observer (7). In addition to (9) the corresponding system vectors will be

$$\beta_0(x) = \frac{1}{M}\begin{bmatrix} 0, & 0, & -x_3 \end{bmatrix}^\top \tag{10a}$$

$$\lambda_0(x) = \begin{bmatrix} c_1x_3, & c_2x_3, & c_3x_3, & c_4x_3 \end{bmatrix}^\top \tag{10b}$$

The requirement for convergence (6) will be $\frac{\Lambda_0}{\Gamma_0}(\sum_{i=1}^N c_i^2)x_3^2 + K_{3,3}^2x_3^2 > k$, where $K_{3,3}^2$ is the third row and third column of $\frac{1}{2}(I_3 - K_x^{-1})$. This will be fulfilled for non-zero flow $x_3 = q_{\text{bit}}$, and appropriate Γ_0, Λ_0, K.

B. Fault isolation and approximation observers

For each of the jth fault isolation and approximation observers the unknown friction ψ and the possible fault ϕ_j will be estimated, giving an unknown parameter vector $\theta = \begin{bmatrix} \psi, & \phi_j \end{bmatrix}^\top$. The system vectors $\beta_0(x)$ and $\lambda_0(x)$ are the same as (10), while the FIAO specific vectors will be

$$\beta_j(x) = \frac{1}{M}\begin{bmatrix} 0, & 0, & -x_3^2 \end{bmatrix}^\top, \quad \lambda_j(x) = x_3e_j \tag{11}$$

where e_j is the jth column of the identity matrix I_4. Here the requirement for convergence (6) will be

$$\begin{bmatrix} \frac{\Lambda_0}{\Gamma_0} & 0 \\ 0 & \frac{\Lambda_j}{\Gamma_j} \end{bmatrix} \begin{bmatrix} \left(\sum_{i=1}^N c_i^2\right)x_3^2 & c_j^2x_3^3 \\ c_j^2x_3^3 & x_3^4 \end{bmatrix} + \frac{K_{3,3}^2}{M^2}\begin{bmatrix} x_3^2 & x_3^3 \\ x_3^3 & x_3^4 \end{bmatrix} > kI_2$$

which also is fulfilled if x_3 is non-zero with some positive tuning parameters. Note that the last term is only positive semi-definite, meaning that convergence is enforced by the first term, representing the additional measurements z.

C. Residual generation and evaluation

Residuals are generated from the fault diagnosis method and define some measure on the fault in the system. In this paper the total annular friction $F_a(q,\theta)$ in (2) will be the basis for the residual generation and evaluation. Using the approach in [13], we can define the residual as

$$\xi_j := \hat{F}_a(q,\hat{\psi}_0,0) - \hat{F}_a(q,\hat{\psi}_j,\hat{\phi}_j) \tag{12}$$

where $\hat{F}_a(q,\hat{\psi}_0,0)$ is the estimated annular friction in the FDO and $\hat{F}_a(q,\hat{\psi}_j,\hat{\phi}_j)$ is the estimated friction in the jth FIAO. The idea is that if there is a fault ϕ_j in the fault set $\mathcal{F}$ defined in (3), the jth FIAO will successfully estimate the friction, making ξ_j (close to) zero. Note that as in [13], this method is limited to the case of a single fault happening.

The FDO for the drilling process is designed to detect increases in the total annular pressure which is similar to finding the equivalent circulating density. Of the available additional measurements z, only the pressure in the top and bottom of the annulus will be used for the FDO, making $z = p_{\text{bit}}$.

A threshold μ_{det} on $\hat{\psi}_0$ will be used for fault detection, giving a fault time t_{fault} if the threshold is exceeded, i.e., $\hat{\psi}_0 > \mu_{\text{det}}$. Then a threshold μ_{isol} on ξ_j is used for fault isolation, where a fault is isolated if $\xi_j < \mu_{\text{isol}}$. The magnitude of the fault will then be $\hat{F}_{\text{fault}} := \hat{\phi}_j q^2$. In order to make the detection and isolation more robust, a simple exponential moving average filter [24]

$$s_k = (1-\alpha)s_{k-1} + \alpha s_k \tag{13}$$

with forgetting factor α is used to filter $\hat{\psi}_0$ and ξ_j.

VII. Simulation of the drilling model

The drilling model (1) is simulated using a fifth order fixed step solver with added Gaussian measurement noise with standard deviations $\sigma_x = \begin{bmatrix}0.5, & 0.1, & 0.1\end{bmatrix}^\top$ and $\sigma_z = \begin{bmatrix}0.5, & 0.5, & 0.5, & 0.5\end{bmatrix}^\top$. The parameter values are given in Tab. I based on an example in [25], and where the the back-pressure pump is not used ($q_{\text{bpp}} = 0\,\text{L/s}$). The model contains a marine riser, drill collars, drill pipe and drill bit, giving different diameters for different sections of the drill string and annulus. The model's initial values $x(0)$ are $p_p(0) = 230\,\text{bar}$, $p_c(0) = 2.2\,\text{bar}$ and $q_{\text{bit}}(0) = 22\,\text{L/s}$ The observers are initialized with $\hat{x}(0) = 0.7x(0)$, $\hat{\psi}_j(0) = 0.7$, and $\hat{\phi}_j(0) = 0$. The observer gains found through tuning are $K_x = \text{diag}\{0.5, 0.5, 3\}$, $\Gamma_0 = \Lambda_0 = 1 \times 10^{-3}$ and $\Gamma_j = \Lambda_j = 1 \times 10^{-6}$. The pump is initially running with flow $q_p = 22\,\text{L/s}$. At 10 minutes the pump is turned off resulting in zero flow through the bit until it is turned on again at 30 minutes. This mimics the common situation of a pipe connection. Note that the initial pump flow gives turbulent flow in the annulus, even though the observer was designed for laminar flow, see Sec. III-A.

TABLE I

Drilling model parameters.

β_a	5 000 bar	Effective bulk modulus annulus
β_d	14 000 bar	Effective bulk modulus drill string
M_a	$5.2\,\text{bar} \cdot \text{s}^2/\text{L}$	Integrated density per cross section
M_d	$10.8\,\text{bar} \cdot \text{s}^2/\text{L}$	Integrated density per cross section
V_a	287×10^3 L	Volume of fluid in annulus
V_d	61×10^3 L	Volume of fluid in drill string
ρ_a	1.30 kg/L	Density of fluid in annulus
ρ_d	1.10 kg/L	Density of fluid in drill string
μ_d, μ_a	0.038 Pa · s	Viscosity of drilling fluid
h_{TVD}	3760 m	True vertical depth of bit
L_d, L_a	6609 m	Length of drill string/annulus
u_c	30 %	Choke opening
μ_{det}	1.0 bar s/L	Fault detection threshold
μ_{isol}	0.20 bar	Fault isolation threshold

The simulated state estimation is shown in Fig. 2. The good state estimation is as expected, since all states are directly measured. When the flow is zero, the pump pressure p_p is reduced to the difference in hydrostatic pressure between the drill string and the annulus, caused by different densities. The choke pressure p_c is now atmospheric. The parameter estimation is shown in Fig. 3 where $\hat{\psi}_0$ is the annular friction coefficient estimated by the FDO and $\hat{\psi}_j$, $j \in \{1, \dots, 4\}$ are the parameters estimated by the FIAOs. A fault is detected when a filtered $\hat{\psi}_0$ exceeds the threshold μ_{det}. This happens at $t_{\text{fault}} = 26.23\,\text{min}$. The actual pack-off ϕ_2 between pressure sensors p_1 and p_2 starts to form at $t = 16.7\,\text{min}$, shown in the lower plot in Fig. 3. The estimates $\hat{\phi}_j$ shown in the same plot are the estimates of fault ϕ_j by the jth FIAO. It can clearly be seen that the fault ϕ_2 is correctly estimated by the FIAO number 2, while the other FIAOs erroneously tries to estimate the fault to be in ϕ_1, ϕ_3 and ϕ_4, respectively. The reason that the fault is detected first after circulation resumes, is the requirement of a non-zero $q_{\text{bit}} = x_3$, as discussed in Sec. VI. Intuitively, this can be explained by the fact that the effect of increased friction is not seen when there is no flow, which also can be seen from the friction estimate in the upper plot in Fig. 4.

The residuals shown in the lower plot in Fig. 4 are the filtered signal of (12) using filter (13). A fault is isolated if after $t > t_{\text{fault}}$, the filtered ξ_j is below the threshold μ_{isol}. This happens for residual ξ_2, thus isolating the fault to a pack-off being formed between measurements p_1 and p_2, see Fig. 1. The magnitude of the fault in terms of pressure loss due to friction will then be given as $\hat{F}_{\text{fault}} = \hat{\phi}_2 x_3^2 = 9.7\,\text{bar}$ at full circulation.

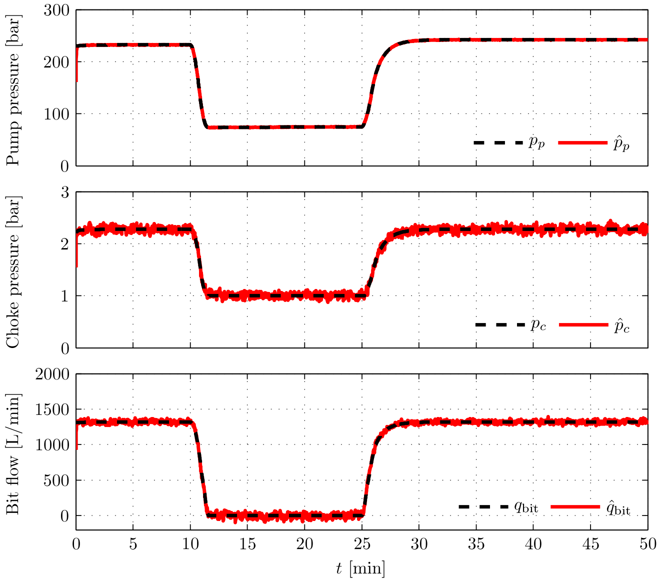

Fig. 2. State estimation of pump pressure, choke pressure and bit flow.

VIII. Conclusion

In this paper a simplified nonlinear hydraulics model for drilling of oil and gas is combined with a bank of nonlinear adaptive observers in order to detect, isolate and identify that a pack-off is being formed. Utilizing the additional measurements available in the novel wired drill pipe technology, all states in the model are assumed directly measured in addition to a set of pressure transmitters distributed along the drill string. A fault detection observer is used in order to detect that a fault

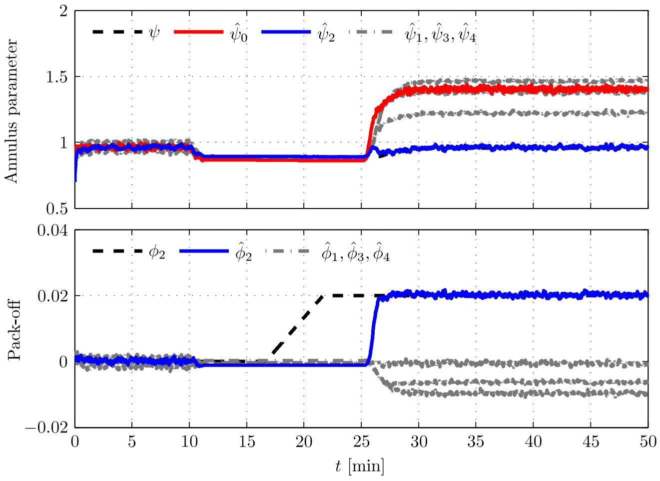

Fig. 3. Estimation of friction parameter ψ_0 in the annulus by the FDO (red), and fault parameter ϕ_j by the jth FIAO. The fault is correctly estimated by $\hat{\phi}_2$ (blue), and incorrectly by the other $\hat{\phi}_j$ (grey).

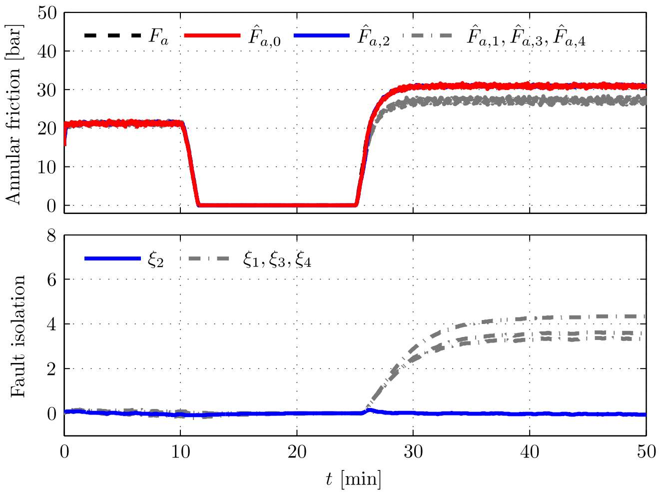

Fig. 4. Friction estimates $\hat{F}_a$ and filtered fault isolation ξ_j. In the lower plot, the fault (blue) is isolated by FIAO-2 to be ϕ_2, while the other ξ_j are plotted in grey.

occurs. Then a set of fault isolation and approximation observers are used to isolate the position of the fault as well as its magnitude. Simulation of the simplified model shows that a fault is successfully detected and isolated between two pressure sensors as long as there is circulation of drilling fluid. As future work we hope to apply this method in a high-fidelity drilling simulation environment as well as on a real data set.

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