



Robust controller design for automated kick handling in managed pressure drilling

Ulf Jakob F. Aarsnes^{a,b,*}, Behçet Açıkmüşe^c, Adrian Ambrus^d, Ole Morten Aamo^a

^a Department of Engineering Cybernetics, NTNU, Trondheim, Norway

^b DrillWell, International Research Institute of Stavanger, Oslo, Norway

^c William E. Boeing Department of Aeronautics and Astronautics, University of Washington, Seattle, United States

^d Department of Mechanical Engineering, University of Texas at Austin, United States

ARTICLE INFO

Article history:

Received 10 December 2015

Received in revised form 27 May 2016

Accepted 2 September 2016

Keywords:

Drilling
Kick handling
Two-phase flow
Automatic control
Robust control
LMIs

ABSTRACT

The problem considered in this paper is that of controlling downhole pressure during oil and gas well drilling, with a particular focus on handling gas kicks leading to two-phase gas–liquid flow conditions. We identify a first-order approximation to the infinite-dimensional system which captures the dominating mode of the pressure dynamics in the frequency range of interest, while the high-frequency pressure dynamics are represented by a multiplicative uncertainty. This approximation is then modified to accommodate the changes to the dynamics introduced by the two-phase flow. The linearized plant has an open-loop time constant which varies between 2 and 600 s depending on operating point and gas distribution in the well. Robust controller design is then performed using linear matrix inequalities (LMIs) via a polytopic norm-bounded description of both the high-frequency multiplicative, and the low-frequency parametric uncertainty. It is shown that, in order to achieve acceptable performance over such a large range of open loop time constants, a time-varying controller gain is required. The main contribution of the paper is to achieve this control objective systematically by formulating the control design problem as an LMI optimization problem. Then optimal solutions of the LMI problem can be obtained in polynomial time by using modern interior point method (IPM) numerical solution algorithms.

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1. Introduction

With the depletion of easily accessible hydrocarbon resources, the focus of the upstream oil and gas industry has shifted toward harsher environments such as complex geo-pressured deepwater prospects [1]. When drilling wells in such environments, it is highly important to maintain the downhole drilling mud pressure at a value above the reservoir pore pressure and also the pressure required for geomechanical wellbore stability, while keeping it below the formation fracture pressure [1].

This means, effectively, that the control goal is to keep the pressure at the bottom of the well within set constraints [2]. The constant bottom-hole pressure managed pressure drilling (MPD) technique addresses this problem by applying additional back-pressure via an automatically controlled choke valve at the well outlet [3]. A key challenge associated with introducing automated

choke control in drilling is dealing with influx of gas, referred to as a gas kick, which occurs when pressure in the open-hole section (i.e. the section of the well where casing and cement have not yet been set, exposing the well to formation fluids) is below the pressure in the surrounding reservoir. In such a scenario, the system response to actuation changes greatly due to the increased flow and compressibility introduced by the gas influx. At the same time, rapid and precise control becomes essential as the pressure in the well must be controlled to a higher set-point to stop the gas influx [4]. Failure to react appropriately to a kick incident can lead to a blow-out which has potentially catastrophic consequences, affecting not only rig personnel safety, but also the surrounding environment, project economics, and, ultimately, the company and industry reputation [1].

1.1. Control of gas kicks

Automatic choke control of gas kicks has previously been considered in the literature [4–8]. These investigations typically consider single-phase flow and do not explicitly try to quantify and handle the significant effect the gas influx has on the system

* Corresponding author at: DrillWell, International Research Institute of Stavanger, Oslo, Norway.

E-mail address: ulf.jakob.aarsnes@itk.ntnu.no (U.J.F. Aarsnes).

dynamics. Failure to do so may lead to degraded performance of the control algorithms and, in some cases, instability [9].

This paper presents an approach to explicitly capture the effect of the gas influx and incorporate this in the controller design.

1.2. Key challenges and control approach

The control problem poses the following key challenges for effective controller design:

- The distributed pressure dynamics are described by an infinite-dimensional model.
- The choke valve actuation is non-linear.
- Large variation in plant parameters in the presence of gas.

To address these challenges, the infinite-dimensional plant is approximated with a first-order model and the resulting high-frequency error is represented as a multiplicative uncertainty. The effect of the actuation non-linearity and changes in plant parameters due to gas influx is captured through explicit relations resulting in a linear time-varying first order plant with multiplicative uncertainty.

This plant is represented by a norm-bounded polytopic linear differential inclusion (LDI) which allows for robust controller design using LMIs [10]. First, an approach is taken where a static feedback controller is designed, but due to the wide range of plant parameters encountered, the resulting performance of the controller is poor. To address this, a second approach is proposed where a robust, time-varying controller is designed using an estimate of the plant time constant and a bound on estimate uncertainty.

The controller is tested in simulations with an explicit numerical implementation of the drift-flux model (DFM) representing the two-phase flow dynamics [11,12].

1.3. Robust control using LMIs

Often when controller design is performed, there can be a disconnect between the control objective and the parameters that are adjusted to achieve it. For example, one could be trading off robustness versus performance by adjusting the relative weighting between control effort and error penalty in an LQR controller. Although this typically yields satisfactory results, in the present control problem, it is desirable to specify the control problem to be solved directly: i.e. maximize the performance subject to the robustness constraint. For the present problem this can be achieved systematically by using LMIs, which motivates the approach taken in this paper.

LMIs present a rigorous framework to handle model uncertainties [14,15]. They are used to bound the uncertainties in the model via convex constraints [16], which result in convex optimization problems for control synthesis. The resulting optimization problems have linear inequality constraints on matrix solution variables, which are called LMIs and have been utilized to tackle many control problems [17–19] as a systematic approach to ensure control design objectives within the uncertainties inherent in the system.

2. Model description

Our goal in this section is to obtain a low-order approximation of the pressure dynamics in the wellbore annulus, and be able to quantify the resulting error in the frequency domain. This will enable us to design robust low-order controllers.

To this end, we will take the following steps:

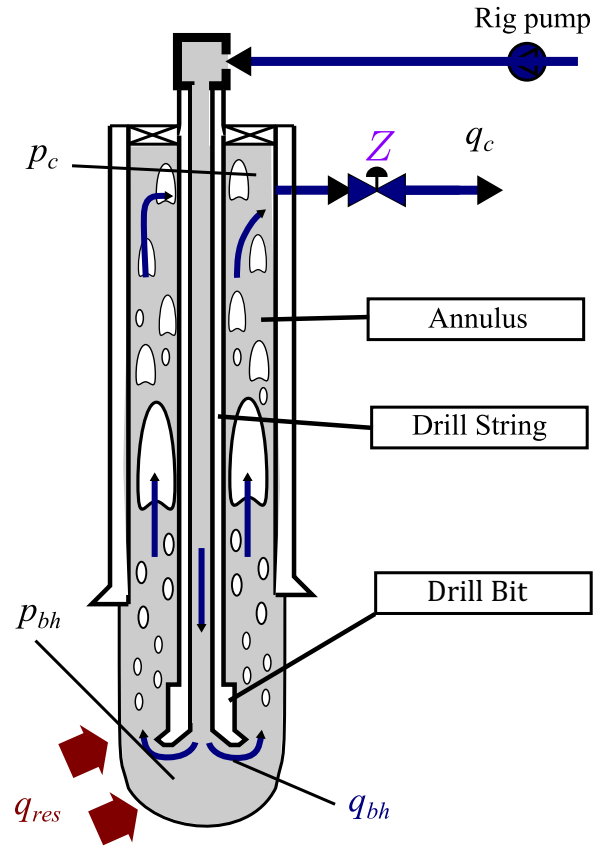


Fig. 1. Schematic of a vertical well with gas influx (from [13]).

1. Obtain a high-order LTI representation of the two-phase pressure dynamics, in Section 2.3.
2. Approximate the high order LTI model with a first-order plant and quantify the resulting uncertainty, in Section 2.2.
3. Modify the first-order approximation from Step 2 to accommodate the effect of the two-phase dynamics and quantify the resulting uncertainty, in Section 2.4.

2.1. Single-phase infinite-dimensional model

As a starting point for understanding the implications of representing the distributed pressure dynamics with a low-order approximation, we consider a hydraulic transmission line model [20]. The states of interest are the flow rate through the back-pressure choke $q_c(t)$, the flow rate into the bottom of the well $q_{bh}(t)$, and the pressure at the wellhead $p_c(t)$ and bottom $p_{bh}(t)$, see also Fig. 1.

We are concerned with the transient pressure behavior, which is captured by variables describing perturbations from an initial steady state. Assuming the system to initially be at rest at an equilibrium with states denoted by $\bar{q}_c = \bar{q}_{bh} = \bar{q}$ and $\bar{p}_c, \bar{p}_{bh}$, we will use the perturbed variables:

$$\tilde{q}_c(t) = q_c(t) - \bar{q}, \quad \tilde{q}_{bh}(t) = q_{bh}(t) - \bar{q}, \quad (1)$$

$$\tilde{p}_c(t) = p_c(t) - \bar{p}_c, \quad \tilde{p}_{bh}(t) = p_{bh}(t) - \bar{p}_{bh}. \quad (2)$$

Perturbed downhole pressure, which we desire to control, and perturbed choke back-pressure are related to the changes in flow through the choke by a wave equation describing distributed hydraulics in the well. For single-phase flow these dynamics can be expressed by the irrational transfer matrix derived in Appendix

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