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Automatic tuning of paper machines cross-direction controllers via linear matrix inequalities

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Abstract

The paper machine cross-direction (CD) process is a large-scale spatially distributed system. It is known to be severely ill-conditioned as the gain rolls down to zero for some of the process directions. This article presents an automatic tuning technique for loop-shaping low order spatially localized CD controllers. Following closed-loop identification of the process model, the CD controller is synthesized through a Linear Matrix Inequalities (LMI) feasibility problem to guarantee nominal stability, performance and robustness to model uncertainties. Robust stability and performance of the controller in the presence of parametric uncertainties are investigated through the ν-gap metric. The performance of the LMI loop-shaped controller is illustrated through comparing it to an industrial CD controller that has been implemented in paper mills.

Keywords: Cross-direction control; Multi-variable loop-shaping; Linear matrix inequalities

1. Introduction

Paper properties are controlled by a set of actuator arrays acting in the cross-direction (CD) as the paper sheet moves along the machine direction (MD). The actuator arrays include slice lip, dilution actuator, steam box, rewet shower and induction heating. The paper profile is monitored through a set of scanning sensors traversing back and forth across the sheet. The CD multi-variable process can have from 30 to 300 actuators and 200 to 1000 measurement points. The CD controller is designed to attenuate the effects of disturbances while providing robustness against modeling uncertainties. In Duncan (1989), fourier transform analysis of the actuator spatial response showed that it could be separated into controllable and uncontrollable components. One approach to simplify the design problem is to reduce

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the dimensionality through basis function representations Rigopoulos (1999), gram polynomials in Kristinnson and Dumont (1996),Heath (1996) and modal decomposition in Featherstone et al. (2000). Control design for circulant symmetric plants have been presented in Hovd and Skogestad (1994) and Laughlin et al. (1993). Algorithms to design low order robust tunable CD controller were presented in VanAntwerp et al. (2001). A two dimensional loop-shaping technique for industrial CD controllers has been implemented in many paper mills as part of a commercial product Stewart et al. (2003a) and Stewart et al. (2003b). A technique for modifying the CD controllers designed through two-dimensional loop-shaping to handle edge effects is presented in Mijanovic (2004) and Mijanovic et al. (2003). In Gorinevsky et al. (2008), designing a controller for steady-state performance and robustness in spatially distributed feedback systems was proposed. In Featherstone and Braatz (1997), Featherstone and Braatz (1998a) and Featherstone and Braatz (1998b) it has been shown that explicit constraint handling is not always needed when robust control design methods are used as directions corresponding to low gains are not manipulated by the SVD controller. The same argument is adopted in the CD controller in Taylor and Duncan (2010). Under this assumption, IMC-based CD controllers were discussed in Kristinnson and Dumont (1996),Laughlin et al. (1993), Rojas et al. (2002) and VanAntwerp et al. (2001). In Farahmand et al. (2010), an iterative adaptive robust control based on the windsurfing approach for unconstrained IMC is proposed. A CD controller similar to that of an IMC is combined with an observer designed to minimize the process and model mismatch is presented in Hur et al. (2011). A constrained IMC CD controller that acts on a subset of the controllable process modes was developed in Heath and Wills (2004). In Morales and Heath (2011), a robust stability test was developed for constrained CD control via the theory of Integral constraints.

Model predictive control (MPC) has been considered for the control of paper machines Duncan and Corscadden (1998),Rigopoulos et al. (1472) and Zheng (1999). A linear or quadratic optimization problem is solved online at every sampling instance subject to specific constraints. Due to the large scale nature of the problem, it is not always feasible to solve the optimization problem within the sampling time. The MPC problem was solved for a reduced order model in Rigopoulos and Arkun (2003). The work in VanAntwerp and Braatz (2000a) and VanAntwerp and Braatz (2000b) replaced the actuator constraints with an optimal 2-norm approximation to speed up the computations. In Fan (2003) and Fan et al. (2004), an industrial CD model predictive controller (MPC) was developed through a rectangular circulant matrix decomposition of the process. Although CD MPC is gaining popularity in the industry, traditional CD control using Dahlin controllers is still common Chu et al. (2011).

The synthesis of a CD controller using techniques like H_∞,H_2 can be intractable with the existing computing power. The number of inputs and outputs in the multi-variable process are an order of magnitude higher than other process control applications. Conventional control design techniques will result in a fully centralized controller linking each actuator with every measurement data-box. This will add needless real-time computational complexity for systems with hundreds of actuators and sensors. The industrial CD controller structure from Stewart et al. (2003a) is adopted in this work. The two-dimensional loop-shaping technique presented in Stewart et al. (2003a) and Stewart et al. (2003b) results in a non-localized controller. A few iterations are performed manually until a trade-off between performance and localization is achieved. The main contribution of this article is to develop a tuning technique for loop-shaping a robust low order spatially localized CD controller. An online automatic tuning tool requires a fast autonomous controller synthesis algorithm that does not need manual intervention. Upon identifying CD models in closed-loop using the approaches developed in Ammar and Dumont (2013) and Ammar (2014), a Linear Matrix Inequality (LMI) feasibility problem is solved to synthesize a CD controller that guarantees closed-loop nominal stability, performance and robustness to modeling uncertainties. The tuning technique is accompanied by a robust stability and performance test to guarantee robustness to the expected variations in the process spatial and dynamic responses.

The CD process model, the industrial CD controller and closed-loop requirements are presented in Section 2. A technique for loop-shaping CD multi-variable controllers using LMI's is presented in Section 3. A ν-gap approach to ensure the feedback loop's robust stability and robust performance in the presence of parameter uncertainties is developed in Section 4. In Section 5, the proposed control synthesis technique is validated by comparing the automatically tuned controller's performance to the industrial CD controller from Stewart et al. (2003a).

2. Problem statement

The CD process describes the relation between an actuator array and a controlled property. It is modeled as a constant spatial interaction matrix cascaded by a first order transfer function with dead-time. The dead-time represents