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Brief paper

Plasma vertical stabilization with actuation constraints in the DIII-D tokamak☆

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Abstract

In the advanced tokamak (AT) operating mode of the DIII-D tokamak, an integrated multivariable controller takes into account highly coupled influences of plasma equilibrium shape, profile, and stability control. Time-scale separation in the system allows a multi-loop design: the inner loop closed by the nominal vertical controller designed to control a linear exponentially unstable plant and the outer loop closed by the nominal shape controller designed to control a linear stabilized plant. Due to actuator constraints, the nominal vertical controller fails to stabilize the vertical position of the plasma inside the tokamak when large or fast disturbances are present or when the references coming from the shape controller change suddenly. Anti-windup synthesis is proposed in this paper to find a nonlinear modification of the nominal vertical controller that prevents vertical instability and undesirable oscillations but leaves the inner loop unmodified when there is no input saturation.
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1. Introduction

Demands for more varied shapes of the plasma and requirements for high performance regulation of the plasma boundary and internal profiles are the common denominator of the advanced tokamak (AT) operating mode in DIII-D (Luxon, 2002). This operating mode requires multivariable control techniques (Walker et al., 2003) to take into account the highly coupled influences of equilibrium shape, profile, and stability control. The initial step toward integrating multiple individual controls is implementation of a multivariable shape and vertical controller for routine operational use which can be integrated in the long term with control of plasma profiles such as pressure, radial E-field, and current profiles.

The problem of vertical and shape control in tokamaks was and is still extensively studied in the fusion community. A recent summary of the existing work in the field can be found in Albanese and Ambrosino (2000). Several solutions for the design of the nominal controller were proposed for different tokamaks using varied control techniques based on linearized models. Although the saturation of coil currents and voltages (actuators) is a common problem in tokamaks and there were efforts to minimize the control demand for shape and vertical control and to avoid saturation (Ambrosino, Ariola, Pironti, Portone, & Walker, 2001), the saturation of the actuators was rarely taken into account in the design of the controllers until recently

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(Scibile & Kouvaritakis, 2001; Favez, Mullhaupt, Srinivasan, Lister, & Bonvin, 2003). Although similar in concept, our work uses a different approach to the problem: anti-windup compensator. The input constraints are not taken into account at the moment of designing the nominal controller. The goal is not the design of the nominal controller but the design of an anti-windup compensator that blends any given nominal controller, which is designed to fulfill some local (saturation is not considered) performance criterion, with a nonlinear feedback designed to guarantee stability in the presence of input saturation but not necessarily tuned for local performance.

The paper is organized as follows. Section 2 introduces the strategy proposed for plasma shape and vertical position control in the DIII-D tokamak. Section 3 introduces the basics of the anti-windup method. The characteristics of our plant and its controllable region are presented in Section 4. The design of the anti-windup compensator is presented in Section 5. Some implementation issues are discussed in the same section. Finally, the conclusions are presented in Section 6.

2. Control Strategy

Time-scale separation of vertical and shape control appears to be critical for DIII-D, since multivariable shape controllers can require significant computation. Fig. 1 shows the closed-loop system comprised of the DIII-D plant and stabilizing vertical controller. This system is stable and the 6 coil currents F2A, F2B, F6A, F6B, F7A, and F7B are approximately controlled to a set of input reference values. As a result, this system can act as an inner control loop for shape control.

The problem of highly nonlinear outer power supplies (choppers) was addressed previously by constructing closed-loop controllers using a nonlinear output inversion. However, this solution, for the outer loop, is not fast enough to be implemented in the inner loop. A possible approach to deal with the inner choppers is shown in Fig. 1. To take into account the nonlinear nature of the choppers, we now incorporate them into an augmented saturation block. The nominal linear vertical controller is synthesized without using a model of the choppers and its output y_c is equal to the coil voltages in the absence of saturation. A chopper inverse function, which is part of the vertical controller, computes the necessary command voltages V_c within the saturation levels to make u equal to y_c. When $|y_c|$ is large, the saturation block will obviously result in $|u|$ being smaller than $|y_c|$. Although the saturation levels of the command voltages V_c are still fixed values (± 10 V), the saturation levels of the augmented saturation block are functions of time, i.e., of the coil load currents I_L and DC charging supply voltage V_{ps}.

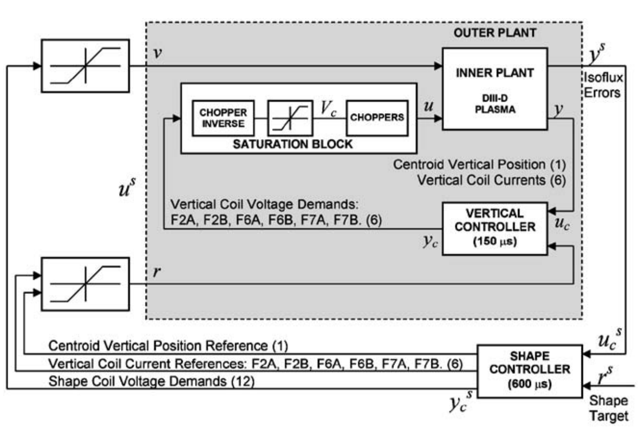

Fig. 1. Plant Architecture.

To make this approach successful, the inner controller (vertical controller, Fig. 1) must guarantee stability of the plant for all commands coming from the outer controller (shape controller, Fig. 1). However, the constraints on the input of the inner plant due to the saturation of the actuators may prevent this goal from being achieved. The saturation of the coil voltages cannot only degrade the performance of the inner closed-loop system but also impede the vertical stabilization when the synthesis of the nominal inner controller does not account for plant input saturation. The inner loop design must take care then of the windup of that loop and ensure vertical stability for any command coming from the outer controller. We understand as windup the phenomenon characterized by degradation of nominal performance and even loss of stability due to magnitude and/or rate limits in the control actuaction devices. The anti-windup synthesis problem is to find a nonlinear modification of the predesigned nominal linear controller that prevents vertical instability and undesirable oscillations (keeping the nominal controller well-behaved) but leaves the nominal closed loop unmodified when there is no input saturation. This problem is different from the problem of synthesizing a controller that accounts for input saturation without requiring it to match a given predesigned arbitrary controller locally. Several survey papers (Hanus, 1988; Åström & Rundqwist, 1989; Morari, 1993) describe early ad-hoc anti-windup methods. Recently several other approaches have been proposed (Gilbert & Kolmanovsky, 1999; Bemporad & Morari, 1999; Zheng, Kothare, & Morari, 1994; Scibile & Kouvaritakis, 2000; Shamma, 2000; Mulder, Kothare, & Morari, 2001; Miyamoto & Vinnicombe, 1996). Due to the characteristics of our problem we follow the ideas discussed in Teel (1999) for exponentially unstable linear systems.

3. Anti-windup compensator fundamentals

We consider exponentially unstable linear plants with control input $u \in \Re^m$ and measurements $y \in \Re^p$. We write the model of our system in state-space form, $\dot{x} = Ax + Bu$, separating the stable modes ($x_s \in \Re^{n_s}$) from the exponentially

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