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Control and Verification of the Safety-Factor Profile in Tokamaks Using Sum-of-Squares Polynomials.

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Abstract: In this paper, we propose a method of using the sum-of-squares methodology to synthesize controllers for plasma stabilization in Tokamak reactors. We use a partial differential model of the poloidal magnetic flux gradient and attempt to stabilize a reference safety-factor profile. Our methods utilize full-state feedback control and are based on solving a dual version of the Lyapunov operator inequality. In addition, we implement the controller in-silico using experimental conditions inferred from the Tore Supra tokamak.

1. INTRODUCTION

Fossil fuel energy or cheap energy, as known in the common vernacular, until now has been responsible for quenching the ever increasing energy demands of the world. However, since fossil fuel reserves are limited, we would inevitably reach a maximum extraction rate of petroleum also known as *oil peak*. Once this *oil peak* is achieved there would be an energy shortfall. There is a general consensus that we will reach the *oil peak* sometime in the next five decades (Campbell and Laherrère [1998]). To fill the resultant energy shortfall various sources of energy are being investigated. One of the sources being currently researched is nuclear fusion wherein two light nuclei are fused together to produce a heavier nucleus and energy. Energy production using nuclear fusion has various advantages such as being clean and the ability to provide energy for several thousands of years (Pironti and Walker [2005]). Among the different possibilities to achieve sustained fusion reactions, the tokamak magnetic configuration, which motivated the ITER project (Green et al. [2003]), appears as the most promising.

The development of control protocols for tokamak plasmas is highly challenging due to the high order of the distributed dynamics associated with non-homogeneous transport phenomena, the multiple time-scales involved (Moreau et al. [2008]) and the instabilities associated with the magneto-hydro-dynamic (MHD) phenomena (Connor et al. [1998]). Additionally, several stabilization and regulation problems have to be solved using a limited number of actuators that have a relatively few degrees of freedom. Therefore, to make thermonuclear fusion an economically viable source of energy, several extremely demanding control problems have to be solved.

An important physical quantity related to the control of non-homogeneous transport is the magnetic field line pitch profile, also known as the *safety factor profile* or the q-profile (Wesson and Campbell [2004]). The q-profile is a common heuristic for setting operating conditions that avoid undesired MHD instabilities (Moreau et al. [2008]). Additionally, recent studies have shown the importance of the q-profile in triggering internal transport barriers (ITB) (Eriksson et al. [2002]), which significantly improve the energy confinement and assist in generating sawteeth that allow the removal of fusion ash (Helium, which is formed as Deuterium-Deuterium or Deuterium-Tritium fusion takes place) from the central plasma.

The safety factor profile is defined as the ratio of toroidal versus poloidal magnetic flux gradients. Neglecting the diamagnetic effect and thanks to the cylindrical approximation, the safety factor profile is defined in terms of the poloidal flux $\psi(x,t)$ as (Witrant et al. [2007])

$$q(x,t) \doteq \frac{\partial\phi/\partial x}{\partial\psi/\partial x} = \frac{-B_{\phi_0}a^2x}{\partial\psi/\partial x}, \tag{1}$$

where x is the normalized radius, t is time, B_{ϕ_0} is the toroidal magnetic field at the plasma center, a is the radius of the last closed magnetic surface (LCMS) and ϕ is the magnetic flux of the toroidal field. Thus to control the q-profile we control the gradient of the flux of the poloidal magnetic field ψ_x. In this paper we outline a method for designing controllers for regulating $\psi_x(x,t)$, about a desired reference profile.

Most of the previous results on tokamak poloidal flux control relied on linear finite-dimensional control theory applied to a discretized transport model (see Blum [1988]). We aim to design an infinite dimensional controller for the dynamics of $\psi_x(x,t)$ described by a partial differential equation (PDE), thus excluding the need to discretize the system model into a system of ordinary differential equations (ODE). Synthesis of infinite-dimensional controllers for PDEs has been studied

in the context of distributed parameter systems theory, with some interesting examples given in Curtain and Zwart [1995]. In this paper we use the sum-of-squares (SOS) framework and semidefinite programming (SDP) to find polynomial gains for a state feedback controller such that we can construct a Lyapunov function algorithmically for the controlled system. Note that the method for constructing Lyapunov functions algorithmically for PDEs using SOS polynomials is formulated in Papachristodoulou and Peet [2007].
We implement our approach using SOSTOOLS (Prajna et al. [2001]), a freely available MATLAB toolbox used for running algorithms for optimization, using SDP, over the set of SOS polynomials.
The paper is organized as follows. In section II background material is provided for the system model, SOS polynomials and Lyapunov stability theory. In Section III we formulate the problem to be solved. In Section IV we provide a discretization scheme to numerically solve the controlled PDE and finally in Section V results are provided for a controller synthesized using the method outlined in the paper.

2. PRELIMINARIES

2.1 Tore Supra poloidal magnetic flux model

Neglecting the diamagnetic effect and employing the cylindrical approximation of the plasma shape, the poloidal flux diffusion model presented in Blum [1988] was simplified and completed with peripheral physical variables definitions associated with Tore Supra automation in Witrant et al. [2007] to get

$$\frac{\partial \psi(x,t)}{\partial t} = \frac{\eta_{\|}(x,t)}{\mu_0 a^2}\frac{1}{x}\frac{\partial}{\partial x}\left(x\frac{\partial \psi(x,t)}{\partial x}\right) + \eta_{\|}(x,t)R_0 j_{ni}(x,t).$$

where R_0 is the magnetic centre location, μ_0 is the permeability of free space, $\eta_{\|}(x,t)$ the plasma resistivity and $j_{ni}(x,t)$ the non-inductive current density. $j_{ni}(x,t)$ can be written as the sum of external non-inductive current density and internally generated bootstrap current density, or

$$j_{ni}(x,t) = j_{eni}(x,t) + j_{bs}(x,t),$$

where, $j_{eni}(x,t)$ is the external non-inductive current density and $j_{bs}(x,t)$ is the bootstrap current density.
The dynamics of ψ_x, necessary to compute the q-profile as detailed in (1), is obtained by differentiating the above equation with respect to x as:

$$\frac{\partial \psi_x(x,t)}{\partial t} = \frac{1}{\mu_0 a^2}\frac{\partial}{\partial x}\left(\frac{\eta_{\|}(x,t)}{x}\frac{\partial}{\partial x}(x\psi_x(x,t))\right) + \ldots$$
$$+R_0\frac{\partial}{\partial x}\left(\eta_{\|}(x,t) j_{ni}(x,t)\right). \quad (2)$$

The boundary condition at the plasma center ($x = 0$) is

$$\psi_x(0,t) = 0. \quad (3)$$

On the LCMS ($x = 1$) the boundary condition is dictated by the external current carrying coils as

$$\psi_x(1,t) = -\frac{R_0\mu_0 I_p(t)}{2\pi},$$

where $I_p(t)$ is the plasma current and is regulated by poloidal current carrying coils. In the presented work we will assume I_p to be constant. Thus the LCMS boundary condition becomes

$$\psi_x(1,t) = -\frac{R_0\mu_0 I_p}{2\pi}. \quad (4)$$

2.2 Sum-of-Squares Polynomials

Sum-of-Squares is a powerful tool for optimization over the convex cone of positive polynomials. By definition, a polynomial $p(x)$ is SOS if it can be expressed as

$$p(x) = \sum_{i=1}^{N} p_i(x)^2,$$

where $p_i(x)$, $i = 1,\cdots,N$ are polynomials. Since any squared polynomial is non-negative, a SOS polynomial $p(x)$ will be non-negative. Although the question of polynomial positivity is NP-hard (Blum [1998]), the question of whether a polynomial is SOS is tractable thanks to the following result.

Theorem 1. (Parrilo [2000]). A polynomial $p(x)$, $x \in \mathbb{R}^n$ of degree $2d$ is sum-of-squares if and only if there exists a positive semidefinite matrix $Q \succeq 0$ such that

$$p(x) = Z(x)^T Q Z(x), \quad (5)$$

where $Z(x)$ is a vector of all possible monomials of degree d or less.

This theorem implies that we can test whether a polynomial is sum-of-squares using semidefinite programming. Since it is generally accepted that SDPs can be solved in polynomial time using interior point methods (Nesterov and Nemirovsky [1994]), the problem of checking whether a polynomial can be expressed as a sum of squared polynomials is tractable.
In this paper we will use SOS programming to ensure positivity/negativity of integrals with polynomial integrands. For example, suppose that we have the following integral with a polynomial integrand

$$V(t) = \int_{\Omega} p(x,t)dx,$$

where Ω is a closed subset of the complete metric space $\mathbb{R}^n$ and $t \in \mathbb{R}_+$. A sufficient condition for $V(t) \geq 0$ is that $p(x,t)$ be a SOS polynomial.

2.3 Lyapunov stability theory

In this section we will provide some background on stability. In addition, the well known *Lyapunov stability* theorem is also provided, which is integral to the main result provided in the paper.

Definition 1. Let S be a closed subset of a complete metric space with a metric d defined on it. A *dynamical system* on S is a family of maps $\Gamma(t) : S \to S$, $t \geq 0$ such that
(1) for each $t \geq 0$, $\Gamma(t)$ is continuous from S to S;
(2) for each $u \in S$, $t \to \Gamma(t)u$ is continuous;
(3) for any $u \in S$, $\Gamma(0)u = u$;
(4) $\Gamma(t_1)(\Gamma(t_2)u) = \Gamma(t_1 + t_2)u$, for all $t_1, t_2 \geq 0$ and $u \in S$.

Definition 2. For a given $u \in S$, the *trajectory* or the *orbit* of $\Gamma(t)$ for u is $\mathscr{B}(u) = \{\Gamma(t)u, t \geq 0\}$, where u is known as the initial condition.

Definition 3. $v \in S$ is a *steady state* of Γ if $\Gamma(t)v = v$ for all $t \geq 0$.

Definition 4. For a given dynamical system, Γ, the steady state, v, is *stable* if for every $\xi > 0$, there exists a $\delta(\xi) > 0$ such that $d(\Gamma(t)u, v) < \xi, \forall t \geq 0$ for any $u \in S$ which satisfies $d(u,v) < \delta(\xi)$.

Definition 5. For a given dynamical system, Γ, the steady state, v, is *asymptotically stable* if it is *stable* and there exists a ball of radius $\xi > 0$ centered at v, B_ξ, such that $u \in B_\xi$ implies $\lim_{t\to\infty} d(\Gamma(t)u, v) = 0$, where $B_\xi := \{u \in S \,|\, d(u,v) < \xi\}$.

Definition 6. For a given dynamical system, Γ, the steady state, v, is *globally asymptotically stable* if it is *stable* and $\lim_{t\to\infty} d(\Gamma(t)u, v) = 0$ for any $u \in S$.

Definition 7. Given a dynamical system $\Gamma(t)$, $t \geq 0$, a *Lyapunov function* $V : S \to \mathbb{R}$ is a continuous function on S such that

$$\dot{V}(u) = \lim_{t\to 0^+} \sup\{\frac{1}{t}\{V(\Gamma(t)u) - V(u)\} \leq 0$$

for all $u \in S$.

We now state the *Lyapunov stability* theorem.

Theorem 2. (Lyapunov [1992]). Let Γ be a dynamical system defined on S. Let 0 be a steady state in S. Suppose V is a Lyapunov function such that $V(0) = 0$, $\zeta(\|u\|) \geq V(u) \geq \mu(\|u\|)$ and $\dot{V}(u) \leq 0$, $u \in S$, $\|u\| = d(0,u)$ where $\mu(\cdot)$ and $\zeta(\cdot)$ are strictly increasing continuous functions with $\mu(0) = \zeta(0) = 0$ and $\mu(a) > 0$ and $\zeta(a) > 0$ for $a > 0$, then the origin is stable. Additionally suppose $\dot{V}(u) \leq -\gamma(\|u\|)$, where $\gamma(\cdot)$ is continuous strictly increasing with $\gamma(0) = 0$. Then the origin is globally asymptotically stable

3. MAIN RESULT

For a desired steady-state poloidal flux gradient profile $\psi_{x,ref}$, the dynamics of $\hat{\psi}_x = \psi_x - \psi_{x,ref}$ are

$$\frac{\partial \hat{\psi}_x(x,t)}{\partial t} = \frac{1}{\mu_0 a^2}\frac{\partial}{\partial x}\left(\frac{\eta_\parallel(x,t)}{x}\frac{\partial}{\partial x}\left(x\hat{\psi}_x(x,t)\right)\right) + R_0\frac{\partial}{\partial x}\left(\eta_\parallel(x,t)\, j_{eni}(x,t)\right), \quad (6)$$

with the boundary conditions

$$\hat{\psi}_x(0,t) = 0 \text{ and } \hat{\psi}_x(1,t) = 0. \quad (7)$$

In the following, we consider that the averaged value of bootstrap current is taken into account while choosing $\psi_{x,ref}$ and it's deviation from this average can be neglected. Hence, j_{bs} is no longer present in the above equation. Additionally, in order to simplify the controller synthesis we assume the plasma resitivity $\eta_\parallel$ to be at steady-state (constant temperature profiles). In future works we would be removing these assumptions. To simplify notation, when designing the controller, we use ψ instead of $\hat{\psi}$. We propose using a controller of the following form.

$$j_{eni}(x,t) = K_1(x)\psi_x + \frac{d}{dx}(K_2(x)\psi_x), \quad (8)$$

where $K_1(x)$ and $K_2(x)$ are polynomial gains. We are now ready to state the main theorem of the paper.

Theorem 3. Suppose that there exist polynomials $M(x)$, $Z_1(x)$ and $Z_2(x)$ and $\varepsilon > 0$ such that the following holds for $x \in [0,1]$

$$M(x) > \varepsilon I$$

$$\frac{1}{\mu_0 a^2} b_1\left(x, \frac{d}{dx}\right) M(x) + b_2\left(x, \frac{d}{dx}\right) Z_1(x) + b_3\left(x, \frac{d}{dx}\right) Z_2(x) < 0$$

$$\frac{1}{\mu_0 a^2} c_1(x) M(x) + c_2(x) Z_2(x) \leq 0.$$

Where

$$b_1\left(x, \frac{d}{dx}\right) = f(x)\left(\frac{\eta_{\parallel,x}}{x} - \frac{\eta_\parallel}{x^2}\right) + f'(x)\left(-\frac{\eta_\parallel}{x} + \eta_{\parallel,x}\right) + f''(x)\eta_\parallel + \frac{f(x)\eta_\parallel}{x}\frac{d}{dx} + \left(f(x)\eta_\parallel + f(x)\eta_{\parallel,x}\right)\frac{d^2}{dx^2},$$

$$b_2\left(x, \frac{d}{dx}\right) = -f'(x) + f(x)\frac{d}{dx},$$

$$b_3\left(x, \frac{d}{dx}\right) = \eta_{\parallel,x} f'(x) + \eta_\parallel f''(x) + \eta_{\parallel,x} f(x)\frac{d}{dx} + \eta_\parallel f(x)\frac{d^2}{dx^2},$$

$c_1(x) = -\eta_\parallel f(x), c_2(x) = -2\eta_\parallel f(x)$ and $f(x) = x^2(1-x)$.

Note that the spatial dependencies of $\eta_\parallel(x)$ has been dropped from the equations to conserve space. The notation $(\cdot)_x$ and $(\cdot)_{xx}$ represent first and second order spatial partial derivatives respectively.

Let

$K_1(x) = R_0^{-1}\eta_\parallel^{-1} Z_1(x) M(x)^{-1}$ and $K_2(x) = R_0^{-1} Z_2(x) M(x)^{-1}$.

Then the origin of equation (6) with controller (8) is globally asymptotically stable.

Proof 3. Let $\Gamma(t) : S \to S$ be the dynamical system defined by (6), where

$$S = \{y \in L_2[0,1] : y, y_x \text{ absolutely continuous },\; y_{xx} \in L_2[0,1], y(0) = y(1) = 0\}.$$

Here $L_2[0,1]$ is the space of square integrable functions mapping the interval $[0,1]$ to $\mathbb{R}$.

Suppose $y \in S$ is the initial condition i.e. $\psi_x(x,0) = y(x)$, then $\psi_x(x,t) = (\Gamma(t)y)(x)$. Let's define the following Lyapunov function

$$V(\Gamma(t)y) = \int_0^1 f(x)M(x)^{-1}\left((\Gamma(t)y)(x)\right)^2 dx. \quad (9)$$

Differentiating V along the trajectories of the PDE we get

$$\frac{d}{dt}V(\Gamma(t)z) = 2\int_0^1 x^2(1-x)M(x)^{-1}y(x)\left(\frac{d}{dt}\Gamma(t)y\right)(x)dx,$$

where, from (6) and (8), we get

$$\left(\frac{d}{dt}\Gamma(t)y\right)(x) = \frac{1}{\mu_0 a^2}\frac{\partial}{\partial x}\left(\frac{\eta_\parallel}{x}\frac{\partial}{\partial x}\left(x\left(\Gamma(t)y\right)(x)\right)\right) + R_0\frac{\partial}{\partial x}\left(\eta_\parallel K_1(x)\left(\Gamma(t)y\right)(x) + \eta_\parallel\frac{d}{dx}\left(K_2(x)\left(\Gamma(t)y\right)(x)\right)\right)$$

Thus

$$\dot{V}(\Gamma(t)y) = 2\int_0^1 f(x)M(x)^{-1}\frac{\left(\Gamma(t)y\right)(x)}{\mu_0 a^2}\frac{\partial}{\partial x}\left(\frac{\eta_\parallel}{x}\frac{d}{dx}\left(x\left(\Gamma(t)y\right)(x)\right)\right)dx + 2R_0\int_0^1 f(x)M(x)^{-1}\left(\Gamma(t)y\right)(x)\frac{d}{dx}\left(\eta_\parallel K_1(x)\left(\Gamma(t)y\right)(x)\right)dx + 2R_0\int_0^1\frac{f(x)}{M(x)}\left(\Gamma(t)y\right)(x)\frac{d}{dx}\left(\eta_\parallel\frac{d}{dx}\left(K_2(x)\left(\Gamma(t)y\right)(x)\right)\right)dx \quad (10)$$

We want to prove that if the hypotheses of the theorem hold true then $V(\Gamma(t)y) > 0, \forall t \geq 0$ and $\dot{V}(\Gamma(t)y) < 0, \forall t \geq 0$ for every $y \in S$.

Since by definition $\Gamma(t)y$ remains in the set S for all $t \geq 0$ for any $y \in S$, it would suffice to show that $V(z) > 0$ and $\dot{V}(z) < 0$ for all $z \in S$, where

$$V(z) = \int_0^1 f(x)M(x)^{-1}z(x)^2 dx$$

and

$$\begin{aligned}\dot V(z) =&2\int_0^1 f(x)M(x)^{-1}\frac{z(x)}{\mu_0 a^2}\frac{\partial}{\partial x}\left(\frac{\eta_\parallel}{x}\frac{d}{dx}(xz(x))\right)dx\\&+2R_0\int_0^1 f(x)M(x)^{-1}z(x)\frac{d}{dx}\left(\eta_\parallel K_1(x)z(x)\right)dx\\&+2R_0\int_0^1 f(x)M(x)^{-1}z(x)\frac{d}{dx}\left(\eta_\parallel\frac{d}{dx}(K_2(x)z(x))\right)dx.\end{aligned}$$

Suppose the hypotheses of the theorem hold. Then $M(x) > \varepsilon, \forall x \in [0,1]$. Then $M(x)^{-1}$ exists and is continuous. Furthermore there exists an $\varepsilon > 0$ such that $M(x)^{-1} > \varepsilon$. Now, for any $z \in S$,

$$f(x)M(x)^{-1}z(x)^2 \geq \varepsilon x^2(1-x)z(x)^2, \qquad \text{for all } x\in[0,1].$$

Then $V(z) > 0$ for all $z \neq 0$.
Recall $Z_1(x) = \eta_\parallel(x)R_0K_1(x)M(x)$ and $Z_2(x) = R_0K_2(x)M(x)$. Now, we define the function $y(x) = M(x)^{-1}z(x)$. Then $y \in S$ and $z(x) = M(x)y(x)$ and hence we have

$$\begin{aligned}\dot V(z) =&2\int_0^1 f(x)\frac{y(x)}{\mu_0 a^2}\frac{d}{dx}\left(\frac{\eta_\parallel}{x}\frac{d}{dx}(xM(x)y(x))\right)dx\\&+2\int_0^1 f(x)y(x)\frac{d}{dx}(Z_1(x)y(x))dx\\&+2\int_0^1 f(x)y(x)\frac{d}{dx}\left(\eta_\parallel\frac{d}{dx}(Z_2(x)y(x))\right)dx\\&=\frac{2}{\mu_0a^2}\dot V_1(z)+2\dot V_2(z)+2\dot V_3(z)\end{aligned}$$

where we have split the derivative into three terms. Note that we have left the terms in the form $V(z)$ to emphasize the dependency of y on z. Expanding the first term, we get

$$\begin{aligned}&\dot V_1(z) = \int_0^1 f(x)y(x)\frac{d}{dx}\left(\frac{\eta_\parallel}{x}\frac{d}{dx}(xM(x)y(x))\right)dx\\
&=-\int_0^1\eta_\parallel\left(\frac{f'(x)}{x}y(x)+\frac{f(x)}{x}y_x(x)\right)\frac{d}{dx}(xM(x)y(x))\,dx\\
&=-\int_0^1\eta_\parallel\left(\frac{f'(x)}{x}y(x)+\frac{f(x)}{x}y_x(x)\right)\Big(M(x)y(x)\\
&\qquad\qquad +xM_x(x)y(x)+xM(x)y_x(x)\Big)dx\\
&=-\int_0^1\eta_\parallel\left(\frac{f'(x)M(x)}{x}+f'(x)M_x(x)\right)y(x)^2dx\\
&-\int_0^1\eta_\parallel\left(f(x)M(x)\right)y_x(x)^2dx\\
&-\int_0^1\eta_\parallel\left(f'(x)M(x)+\frac{f(x)M(x)}{x}+f(x)M_x(x)\right)y(x)y_x(x)dx\\
&=-\int_0^1\eta_\parallel\left(\frac{f'(x)M(x)}{x}+f'(x)M_x(x)\right)y(x)^2dx\\
&-\int_0^1\eta_\parallel\left(f(x)M(x)\right)y_x(x)^2dx\\
&+\tfrac12\int_0^1\eta_\parallel\Big(f''(x)M(x)+f'(x)M_x(x)+\frac{xf'(x)-f(x)}{x^2}M(x)\\
&+\frac{f(x)}{x}M_x(x)+f'(x)M_x(x)+f(x)M_{xx}(x)\Big)y(x)^2dx\\
&+\tfrac12\int_0^1\eta_{\parallel,x}\left(f'(x)M(x)+\frac{f(x)M(x)}{x}+f(x)M_x(x)\right)y(x)^2dx\\
&=\tfrac12\int_0^1 y(x)^2b_1\left(x,\frac{d}{dx}\right)M(x)dx+\tfrac12\int_0^1 y_x(x)^2c_1(x)M(x)dx.\end{aligned}$$

where we have used that $\lim_{x\to0} f(x)/x = \lim_{x\to0} f'(x)/1 = 0$ and $y(1) = 0$.
Performing integration by parts on the second term, we have

$$\begin{aligned}&\dot V_2(z) = \int_0^1 f(x)Z_{1,x}(x)y(x)^2dx+\int_0^1 f(x)Z_1(x)y(x)y_x(x)dx\\
&=\int_0^1\left(f(x)Z_{1,x}(x)-\tfrac12 f'(x)Z_1(x)-\tfrac12 f(x)Z_{1,x}(x)\right)y(x)^2dx\\
&=\int_0^1\left(\tfrac12 f(x)\frac{d}{dx}-\tfrac12 f'(x)\right)Z_1(x)y(x)^2dx\\
&=\tfrac12\int_0^1 y(x)^2b_2\left(x,\frac{d}{dx}\right)Z_1(x)dx\end{aligned}$$

where we have used that $y(0) = y(1) = 0$.
Performing integration by parts on the third term, we have

$$\begin{aligned}&\dot V_3(z) = \int_0^1 f(x)y(x)\frac{d}{dx}\left(\eta_\parallel\frac{d}{dx}(Z_2(x)y(x))\right)dx\\
&=-\int_0^1\eta_\parallel y(x)\left(f'(x)y(x)\right)\left(Z_{2,x}(x)y(x)+Z_2(x)y_x(x)\right)dx\\
&-\int_0^1\eta_\parallel y(x)\left(f(x)y_x(x)\right)\left(Z_{2,x}(x)y(x)+Z_2(x)y_x(x)\right)dx\\
&=-\int_0^1\eta_\parallel\left(f'(x)Z_{2,x}(x)y(x)\right)y(x)^2+\eta_\parallel\left(f(x)Z_2(x)\right)y_x(x)^2dx\\
&-\int_0^1\eta_\parallel\left(f'(x)Z_2(x)+f(x)Z_{2,x}(x)\right)y(x)y_x(x)dx\\
&=-\int_0^1\eta_\parallel\left(f'(x)Z_{2,x}(x)\right)y(x)^2+\eta_\parallel\left(f(x)Z_2(x)\right)y_x(x)^2dx\\
&+\tfrac12\int_0^1\eta_\parallel\left(f''(x)Z_2(x)+2f'(x)Z_{2,x}(x)+f(x)Z_{2,xx}(x)\right)y(x)^2dx\\
&+\tfrac12\int_0^1\eta_{\parallel,x}\left(f'(x)Z_2(x)+f(x)Z_{2,x}(x)\right)y(x)^2dx\\
&=-\int_0^1\eta_\parallel\left(f(x)Z_2(x)\right)y_x(x)^2dx\\
&+\tfrac12\int_0^1\eta_\parallel\left(f''(x)Z_2(x)+f(x)Z_{2,xx}(x)\right)y(x)^2dx\\
&+\tfrac12\int_0^1\eta_{\parallel,x}\left(f'(x)Z_2(x)+f(x)Z_{2,x}(x)\right)y(x)^2dx\\
&=\tfrac12\int_0^1 y(x)^2b_3\left(x,\frac{d}{dx}\right)Z_2(x)dx+\tfrac12\int_0^1 y_x(x)^2c_2(x)Z_2(x)dx\end{aligned}$$

where we have used $y(0) = 0$ and $y(1) = 0$. Combining the three terms, we obtain

$$\begin{aligned}\dot V(z) =& \int_0^1 y_x(x)^2\left(\frac{1}{\mu_0a^2}c_1M(x)+c_2Z_2(x)\right)dx\\&+\tfrac12\int_0^1 y(x)^2\left(\frac{1}{\mu_0a^2}b_1M(x)+b_2Z_1(x)+b_3Z_2(x)\right)dx\end{aligned}$$

where the dependencies of b_i and c_i are suppressed for clarity. Since $M(x) > 0$ for $x \in [0,1]$ and $z \neq 0$, then $y \neq 0$. Hence we conclude that if the conditions of the theorem are satisfied then $\dot V(z) < 0$ for $z \neq 0$. Thus we can conclude on the asymptotic stability of the system described by (6) with the controller (8).

The conditions of the theorem may be tested using sum-of-squares optimization. The theorem uses a notion of duality and full-state feedback synthesis which was introduced in Peet and Papachristodoulou [2009]. Note that there are several limitations of this main result. In particular, it gives no bound on the current amplitude of the control signal, nor does it attempt to constrain the controller to a Gaussian shape. The bound on the control signal amplitude can be implemented using a constraint of the form

$$K_1(x)\psi_{x,ref}(x) = R_0^{-1}\eta_{\|}^{-1}Z_1(x)M(x)^{-1}\psi_{x,ref}(x) \leq 10^7 A$$

for some error reference profile, $\psi_{x,ref}$. This will lead to a functional constraint of the form

$$Z_1(x) \leq R_0\,\eta_{\|}(x)M(x) * 10^7 A,$$

which can be included via SOSTOOLS.

4. DISCRETIZATION OF THE SYSTEM MODEL

In a tokamak, a number of radio-frequency (RF) antennas act as actuators for providing the external non-inductive current deposits. These RF-antennas are tuned to the electron cyclotron and/or ion cyclotron frequencies. It was shown in Witrant et al. [2007] that the current deposited by the RF-antennas can be approximated by Gaussian curves. To implement the proposed controller we would search for polynomials $M(x), Z_1(x)$ and $Z_2(x)$, using SOSTOOLS, satisfying theorem 3 and construct the controller of the form given in (8). The next step would involve fitting a Gaussian to the control input and then the RF-antennas would be commanded to provide the desired Gaussian shaped current deposits.

For the purposes of an in-silico implementation, we will employ the following method. Once we have designed a controller satisfying Theorem 3, we would like to simulate the dynamics under realistic operating conditions in order to verify convergence. To do this we discretize the controlled model in space to get a system of coupled ODEs and solve them using MATLAB. Since we have Dirichlet boundary conditions $\psi_x(0,t) = a$ and $\psi_x(1,t) = b$, we will be discretizing the interior of the spatial domain, which in this case is $(0,1)$. Spatial domain is discretized with N uniformly-spaced interior points with distance Δx between them. The first and the N^{th} point are located at the distance $\Delta x/2$ from the left and right boundary of the domain, respectively. Then the grid size, Δx, is calculated as $\Delta x = 1/N$. The discrete variables of the function $u(x,t)$ are calculated at $x_j = (j-1/2)\Delta x$ for $j = 1,\cdots,N$.

Expanding (6) with the controller (8) one can easily observe that we will obtain an equation of the form

$$\dot{\psi}_x(x,t) = \underbrace{\alpha(x)\psi_x}_{1} + \underbrace{\beta(x)\frac{\partial\psi_x}{\partial x}}_{2} + \underbrace{\gamma(x)\frac{\partial^2\psi_x}{\partial x^2}}_{3}, \qquad (11)$$

where $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ are the relevant coefficients.

We will now describe the scheme used for the discretization of Eq. (11). We denote the values of the functions $\psi_x(x,t)$, $\alpha(x)$, $\beta(x)$ and $\gamma(x)$ at the grid points x_j as $\psi_{x,j}(t)$, α_j, β_j and γ_j, respectively. Then the spatial discretization of the first term is simply

$$L[\alpha(x)\,\psi_x] = \alpha_j\psi_{x,j}(t), \qquad (12)$$

for the second term we use upwind-differentiation scheme in order to ensure stability:

$$L\left[\beta(x)\frac{\partial\psi_x}{\partial x}\right] = \begin{cases} \dfrac{\beta_j}{\Delta x}\left(\psi_{x,j}(t) - \psi_{x,j-1}(t)\right) & \text{if}\,\beta_j < 0 \\ \dfrac{\beta_j}{\Delta x}\left(\psi_{x,j+1}(t) - \psi_{x,j}(t)\right) & \text{if}\,\beta_j \geq 0 \end{cases}, \qquad (13)$$

and the third term is discretized with the second-order central difference scheme

$$L\left[\gamma(x)\frac{\partial^2\psi_x}{\partial x^2}\right] = \frac{\gamma_j}{\Delta x^2}\left(\psi_{x,j+1}(t) - 2\psi_{x,j}(t) + \psi_{x,j-1}(t)\right). \qquad (14)$$

With the help of Eqs. (12)–(14), the spatial discretization of Eq. (11) becomes

$$L[\dot{\psi}_{x,j}(t)] = \left[\, e_{j1}\;\; e_{j2}\;\; e_{j3} \,\right] \begin{bmatrix} \psi_{x,j-1}(t) \\ \psi_{x,j}(t) \\ \psi_{x,j+1}(t) \end{bmatrix}, \qquad (15)$$

where

$$e_{j1} = -\frac{\beta_j}{\Delta x} + \frac{\gamma_j}{\Delta x^2}, e_{j2} = \alpha_j + \frac{\beta_j}{\Delta x} - 2\frac{\gamma_j}{\Delta x^2}, \quad e_{j3} = \frac{\gamma_j}{\Delta x^2}, \qquad (16)$$

if $\beta_j < 0$, and

$$e_{j1} = \frac{\gamma_j}{\Delta x^2}, e_{j2} = \alpha_j - \frac{\beta_j}{\Delta x} - 2\frac{\gamma_j}{\Delta x^2}, \quad e_{j3} = \frac{\beta_j}{\Delta x} + \frac{\gamma_j}{\Delta x^2}, \qquad (17)$$

if $\beta_j \geq 0$.

Boundary conditions: Note that Eqs. (13)–(17) are only valid for the points $j = 2\ldots N-1$, and not for $j = 1$ and $j = N$, since, first, equations at $j = 1$ and $j = N$ require the values at the the domain boundaries $\psi_{x,0}(t)$ and $\psi_{x,N+1}(t)$ and, second, the discretization stencil must be changed to accommodate the fact that $j = 1$ and $j = N$ are spaced only $\Delta x/2$ from the boundaries, and not Δx. The boundary values are available from the Dirichlet boundary conditions $\psi_{x,0}(t) = a$ and $\psi_{x,N+1}(t) = b$. Spatial discretization of the second term at the point $j = 1$ given by Eq. (13) will be modified as

$$L\left[\beta(x)\frac{\partial\psi_x}{\partial x}\right] = \begin{cases} \dfrac{\beta_1}{\Delta x/2}\left(\psi_{x,1}(t) - \psi_{x,0}(t)\right) & \text{if}\,\beta_1 < 0 \\ \dfrac{\beta_1}{\Delta x}\left(\psi_{x,2}(t) - \psi_{x,1}(t)\right) & \text{if}\,\beta_1 \geq 0 \end{cases} \qquad (18)$$

and similarly for $j = N$. Spatial discretization of the third term at the point $j = 1$ given by Eq. (14) is

$$L\left[\gamma(x)\frac{\partial^2\psi_x}{\partial x^2}\right] = \frac{\gamma_j}{\Delta x/2 + \Delta x/4}\left(\psi'_{x,3/2}(t) - \psi'_{x,1/2}(t)\right) = \frac{\gamma_j}{\Delta x/2 + \Delta x/4}\left(\frac{\psi_{x,1}(t) - \psi_{x,0}(t)}{\Delta x/2} + \frac{\psi_{x,2}(t) - \psi_{x,1}(t)}{\Delta x}\right) \qquad (19)$$

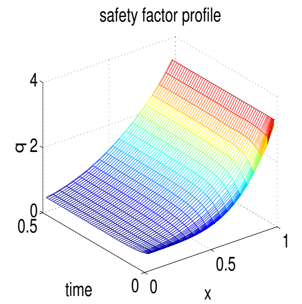
where $\psi'_{x,1/2}$ and $\psi'_{x,3/2}$ denote spatial derivative of ψ_x at the midpoints of the intervals $[x_0,x_1]$ and $[x_1,x_2]$, respectively. Similar discretizaton can be constructed for $j = N$.

5. SIMULATION

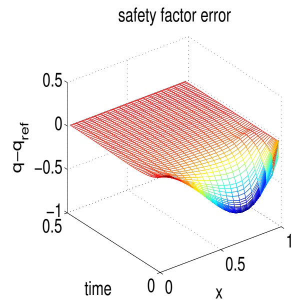
For the purpose of simulation, the following values are taken from the data of the Tore Supra tokamak: $I_p = 0.6MA$ and $B_{\phi_0} = 1.9T$, where I_p is the plasma current and B_{ϕ_0} is the toroidal magnetic field at the plasma center.

Given a q-profile, the corresponding ψ_x-profile, for $x \in (0,1)$, can be computed using (1), where $a = .72\ m$ for Tore Supra. The boundary values for ψ_x are calculated using the magnetic center location, which is $R_0 = 2.38\ m$ and the equations (3) and (4) to get

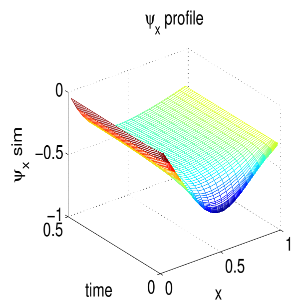
$$\psi_x(0,t) = 0 \text{ and } \psi_x(1,t) = -0.2851. \qquad (20)$$



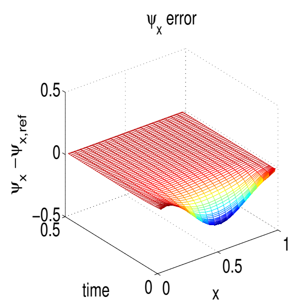
(a) Time evolution of the safety factor profile or the q-profile.



(b) Time evolution of the q-profile Error, $q(x,t) - q_{ref}(x)$. Here x is the normalized spatial variable.



(c) Time evolution of ψ_x-profile corresponding to the q-profile in Fig. 1(a).



(d) ψ_x-profile error, $\psi_x - \psi_{x,ref}$. Here $\psi_{x,ref}$ is obtained from the reference q-profile, q_{ref}.

Fig. 1. Time evolution of safety-factor and ψ_x profiles and their corresponding error profiles

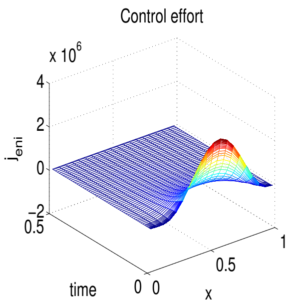


Fig. 2. External non-inductive current deposit, $j_{eni}(x,t)$.

Even though we used steady-state $\eta_{\|}$ for controller synthesis, in order for a realistic controller simulation we use time-varying $\eta_{\|}$ data for shot TS 35109. Time evolution of the pertinent variables is presented in Figs. 1–2.

6. CONCLUSIONS

In this paper we present a methodology to synthesize full-state feedback controllers for the stabilization of the safety factor profile using *sum-of-squares* polynomials. This methodology is based on a dual version of the Lyapunov inequality.

Future works will aim at expanding the presented approach to synthesize controllers implementable on operational tokamaks. This would entail the inclusion of more sophisticated Lyapunov functions, realistic models with time-varying plasma resistivity and bootstrap current, Gaussian shaped controller outputs and the ability to stabilize time-varying reference safety-factor profiles.

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