

Stability results for infinite-dimensional linear control systems subject to saturations

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Abstract—This article deals with the stability analysis and the derivation of ISS-Lyapunov functions for infinite-dimensional linear systems subject to saturations. Two cases are considered: 1) the saturation acts in the same space as the control space; 2) the saturation acts in another space, especially a Banach space. For the first case, an explicit ISS-Lyapunov function can be derived. For the second case, we prove the global asymptotic stability of the origin when considering all weak solutions.

I. INTRODUCTION

In recent decades, a great deal of effort has been dedicated to the development of tools for the analysis of systems with a saturated control in a finite-dimensional framework (see [23], for a nice introduction to the topic as well as the main techniques used). It is well known, in the finite-dimensional framework, that without any Lyapunov stability property for the open-loop system, the origin cannot be globally asymptotically stable when closing the loop with a saturated feedback law. Moreover, even if the open-loop system is Lyapunov stable, simply saturating a stabilizing feedback can lead to undesirable behavior for the asymptotic stability of the closed-loop system (see e.g., [5]). In these cases, the feedback-law has to be designed taking into account the nonlinearity (see e.g. the famous nested saturation solution given in [24] for the chain of integrators and generalized in [22], and [13] for another solution based on optimization).

To the best of our knowledge, analysis of infinite-dimensional systems subject to saturations started with [20] and [18] and it is only very recently that appeared other works such as [12] and [17]. In [20] and [18], global asymptotic stability of the closed-loop system is tackled using nonlinear semigroup theory. Moreover [12] and [17] use similar results, but for a wider class of saturations. In [11], a nonlinear partial differential equation, namely the Korteweg-de Vries equation, is considered and some Lyapunov arguments are used to conclude on the global

asymptotic stability of the closed-loop system. Finally, some nonlinear open-loop abstract control systems are studied in [10], where a LaSalle Invariance Principle is applied to prove global asymptotic stability.

A system subject to disturbances is said to be input-to-state stable (for short ISS) if its state is bounded by the norm of the disturbances. It implies that the state is bounded if the disturbances are bounded, and converges to 0 if the disturbances goes to 0. Such a notion, introduced in [21] for finite-dimensional systems, is an important tool to design robust feedback laws or even observers. This kind of properties has been studied for finite-dimensional control systems subject to saturations (see e.g., [1]). Note that the ISS notion has been extended for infinite-dimensional systems (see e.g., [16], [6] and [14]).

The aim of this paper is to study linear infinite-dimensional systems subject to saturations and disturbances, therefore to analyse the asymptotic stability and to find ISS-Lyapunov functions for such systems. Two cases are considered: 1) the saturation acts in the same space as the control space; 2) the saturation acts in another space, especially a Banach space. For the first case, we provide an ISS-Lyapunov function inspired by [9]. For the second case, we just prove the global asymptotic stability of the origin, when considering all weak solutions of the nonlinear infinite-dimensional system.

The paper is organized as follows. In Section II, the problem is stated, some useful definitions are introduced and the main result is provided. In Section III, some definitions and technical lemmas are given together with the proof of the main result. Some numerical simulation are collected in Section IV for the linearized Korteweg-de Vries equation. Finally, Section V collects some concluding remarks.

II. PROBLEM STATEMENT AND MAIN RESULTS

A. Some remarks on the linear system

Let H and U be real Hilbert spaces equipped with the scalar product $\langle \cdot, \cdot \rangle_H$ and $\langle \cdot, \cdot \rangle_U$, respectively. Let $A : D(A) \subset H \rightarrow H$ be a (possibly unbounded) linear operator whose domain $D(A)$ is dense in H . Suppose that A generates a strongly continuous semigroup of linear contractions denoted by e^{tA} . Let $B : U \rightarrow H$ be a bounded operator. The operators A^* and B^* denote the adjoint operators of A and B , respectively. The aim of this paper is to study the following abstract control system

$$\begin{cases} \frac{d}{dt}z = Az + Bu, \\ z(0) = z_0. \end{cases} \quad (1)$$

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Suppose that we have the output $y = B^*z$. Therefore, in this case, a natural feedback law for (1) is $u = -B^*z$. One needs the following assumption.

Assumption 1. [Linear feedback law] The feedback law $u = -B^*z$ makes the origin of the closed-loop system

$$\begin{cases} \frac{d}{dt}z = (A - BB^*)z, \\ z(0) = z_0. \end{cases} \quad (2)$$

globally exponentially stable.

It is easy to see that, under Assumption 1, $A - BB^*$ generates a strongly continuous semigroup of contractions (see [18] for a precise proof of this result). In the remaining sections of this paper, the following notation will be used.

$$\tilde{A} := A - BB^* \quad (3)$$

Let us denote the strongly continuous semigroup of contractions generated by \tilde{A} by $e^{t\tilde{A}}$.

From [4, Theorem 5.1.3, page 217], Assumption 1 holds if and only if there exist a self-adjoint and definite positive operator $P \in \mathcal{L}(H)$ and a positive value C such that

$$\langle \tilde{A}z, Pz \rangle_H + \langle Pz, \tilde{A}z \rangle_H \leq -C\|z\|_H^2, \quad \forall z \in D(\tilde{A}), \quad (4)$$

where $D(\tilde{A})$ is the domain of \tilde{A} (by (3) and the boundedness of B , it coincides with the domain of A). In other words, this inequality implies that there exists a Lyapunov function for the closed-loop system (2), given by

$$V(z) := \langle Pz, z \rangle_H. \quad (5)$$

B. Saturation functions

In this section, the case where the feedback law is bounded is studied. As explained in introduction, the feedback laws rely on the use of a saturation function defined next.

Definition 1. [Saturation functions on S] Let S be a real Banach space equipped with the norm $\|\cdot\|_S$. Assume moreover that (U, S) is a rigged Hilbert space. In other words, S is a dense subspace of U and the following inclusions hold

$$S \subseteq U \subseteq S'. \quad (6)$$

In particular, the duality pairing between S and S' is compatible with the inner product on U , in the sense that

$$(v, u)_{S' \times S} = \langle v, u \rangle_U, \quad \forall u \in S \subset U, \quad \forall v \in U = U' \subset S'. \quad (7)$$

A function $\sigma : S \rightarrow S$ is said to be a saturation function on S admissible for U if it satisfies the following properties

1. For any $s \in S$, the following holds

$$\|\sigma(s)\|_S \leq 1; \quad (8)$$

2. For any $s, \tilde{s} \in S$, the following holds

$$\langle \sigma(s) - \sigma(\tilde{s}), s - \tilde{s} \rangle_U \geq 0; \quad (9)$$

3. For any $s, \tilde{s} \in S$, there exists a positive value k such that the following holds

$$\|\sigma(s) - \sigma(\tilde{s})\|_U \leq k\|s - \tilde{s}\|_U; \quad (10)$$

4. There exist positive values

and

such that, for any $s \in U$, the following holds

$$\|\sigma(s) - s\|_{S'} \leq \langle \sigma(s), s \rangle_U. \quad (11)$$

5. There exists a positive value C_0 such that, for any $s, \tilde{s} \in U$, the following holds

$$\langle s, \sigma(s + \tilde{s}) - \sigma(s) \rangle_U \leq C_0\|\tilde{s}\|_U. \quad (12)$$

Example 1. [Examples of saturations] Here are examples of saturations borrowed from [23] or [20].

1. Suppose that $S := L^\infty(0, 1)$ and $U = L^2(0, 1)$. In this case, S' is the space of Radon measures. It contains strictly the space $L^1(0, L)$. In particular, the norm of S' is identified by the norm of $L^1(0, L)$. Hence, (U, S) is a rigged Hilbert space.

The classical saturation, which is used in practice, can be defined as follows:

$$\begin{aligned} L^\infty(0, 1) &\rightarrow L^\infty(0, 1), \\ s &\mapsto \text{sat}_{L^\infty(0,1)}(s), \end{aligned} \quad (13)$$

where

$$\text{sat}_{L^\infty(0,1)}(s)(x) = \text{sat}_{\mathbb{R}}(s(x)) \quad (14)$$

and

$$\text{sat}_{\mathbb{R}}(s) := \begin{cases} -1 & \text{if } s \leq -1, \\ s & \text{if } -1 \leq s \leq 1, \\ 1 & \text{if } s \geq 1, \end{cases} \quad (15)$$

All the items of Definition 1 are proved in [7] and [23].

2. Suppose that $S := U$. The saturation, studied in [20], [8] and [11], is defined as follows, for all $s \in U$

$$\text{sat}_U(s) := \begin{cases} s & \text{if } \|s\|_U \leq 1, \\ \frac{s}{\|s\|_U} & \text{if } \|s\|_U \geq 1. \end{cases} \quad (16)$$

It may be proven that sat_U satisfies all items of Definition 1 for an admissible saturation map.

C. Discussion on the well-posedness

1) *Case without disturbance:* We aim at studying the following closed-loop system

$$\begin{cases} \frac{d}{dt}z = Az - B\sigma(B^*z) := A_\sigma z, \\ z(0) = z_0, \end{cases} \quad (17)$$

where the operator A_σ is defined as follows

$$\begin{aligned} A_\sigma : D(A_\sigma) \subset H &\rightarrow H \\ z &\mapsto A_\sigma z, \end{aligned} \quad (18)$$

with $D(A_\sigma) = D(A)$.

From [19, Lemma 2.1., Part IV, Page 165.], we have the following proposition

Proposition 1. [Well-posedness] The operator A_σ generates a strongly continuous semigroup of contractions, which we denote by $(W_\sigma(t))_{t \geq 0}$. Hence, there exists a unique strong

solution to (17) and, for all $z_0 \in D(A_\sigma)$, the following functions

$$t \mapsto \|W_\sigma(t)z_0\|_H, \quad t \mapsto \|A_\sigma W_\sigma(t)z_0\|_H \quad (19)$$

are nonincreasing.

2) *Case with disturbance:* In this paper, we will also consider the case with a perturbation. The system under consideration is the following

$$\begin{cases} \frac{d}{dt}z = Az - B\sigma(B^*z + d), \\ z(0) = z_0, \end{cases} \quad (20)$$

where $d : \mathbb{R}_{\geq 0} \rightarrow U$ is the perturbation. Note that d belongs to $\mathfrak{U} := L^2((0, \infty); U)$. For this system, we study only weak solution.

Let us introduce two notions related to stability.

Definition 2. [Global asymptotic stability and ISS property]

1. The origin of (17) is globally asymptotically stable, if there exists a class \mathcal{KL} function β such that for any weak solution $z(\cdot)$ to (17), it holds

$$\|z(t)\|_H \leq \beta(\|z(0)\|_H, t), \quad \forall t \geq 0;$$

2. A positive definite function $V : H \rightarrow \mathbb{R}_{\geq 0}$ is said to be an ISS-Lyapunov function with respect to d if there exist two class \mathcal{K}_∞ functions α and ρ such that, for any weak solution to (20)

$$\frac{d}{dt}V(z) \leq -\alpha(\|z\|) + \rho(\|d\|_U).$$

D. Input-to-state stability result

We are now in position to state our main result. Here is its statement.

Theorem 1. Suppose that Assumption 1 holds and let $P \in \mathcal{L}(H)$ be the self-adjoint and positive operator $P \in \mathcal{L}(H)$ satisfying (4). Let σ be a saturation function satisfying all the items of Definition 1. Then, the following holds.

1. If $S = U$, there exists an ISS-Lyapunov function for (20).
2. If $S \neq U$, assume that the following holds, for any $s \in D(A)$,

$$\|B^*s\|_S \leq c_S \|s\|_{D(A)}. \quad (21)$$

Then, the origin of (17) is globally asymptotically for any weak solution.

III. PROOF OF THE MAIN RESULT

A. Definitions and technical lemmas

Before proving Theorem 1, let us give some useful definitions and results to prove Theorem 1, especially the case where $S \neq U$. When $S \neq U$, the properties given in Definition 1 do not hold when considering weak solutions. Therefore, the following result is needed to link the attractivity for strong and weak solutions. Note that its proof, which relies on a density argument, can be found in [8] and [10].

Lemma 1. Let $(W_\sigma(t))_{t \geq 0}$ be a strongly continuous semigroup of contractions on H , a Hilbert space. Let $D(A)$ be dense in H . If for all $z_0 \in D(A)$, the following holds

$$\lim_{t \rightarrow +\infty} \|W_\sigma(t)z_0\|_H = 0, \quad (22)$$

then, for all $z_0 \in H$,

$$\lim_{t \rightarrow +\infty} \|W_\sigma(t)z_0\|_H = 0. \quad (23)$$

Thanks to this latter lemma, proving the global asymptotic stability of the origin of (17) for every weak solution reduces to proving it for every strong solution to (17). We need another definition of stability before proving the global asymptotic stability.

Definition 3. The origin of (17) is said to be semi-globally exponentially stable if, for any positive value r and any initial condition satisfying $\|z_0\|_{D(A_\sigma)} \leq r$, there exist two positive values $\mu := \mu(r)$ and $K := K(r)$ such that, for every strong solution to (17)

$$\|W_\sigma(t)z_0\|_H \leq K e^{-\mu t} \|z_0\|_H, \quad \forall t \geq 0, \quad (24)$$

where $(W_\sigma(t))_{t \geq 0}$ is the strongly continuous semigroup of contractions generated by the operator A_σ .

This definition is inspired by [11]. One has also the following result, whose proof is omitted due to lack of space.

Lemma 2. If the origin of (17) is semi-globally exponentially stable, then it is globally asymptotically stable.

B. Proof of Theorem 1

Proof of Theorem 1: We split the proof of Theorem 1 into two cases. Firstly, we prove Item 1. of Theorem 1 and then Item 2. Indeed, the Lyapunov functions considered in both cases are different.

Case 1: $S = U$.

Let us consider the following candidate Lyapunov function

$$\begin{aligned} V_1(z) &:= \langle Pz, z \rangle_H + \frac{2M}{3} \|z\|_H^3 \\ &= V(z) + \frac{2M}{3} \|z\|_H^3, \end{aligned} \quad (25)$$

where $P \in \mathcal{L}(H)$ is defined in (4) and M is a sufficiently large positive value that will be chosen later. This function, inspired by [9], is clearly positive definite and tends to infinity if the H -norm of z does. Firstly applying Cauchy-Schwarz inequality, one has, along the strong solutions to (20),

$$\begin{aligned} \frac{d}{dt}V(z) &= \langle Pz, \tilde{A}z \rangle_H + \langle P\tilde{A}z, z \rangle_H \\ &\quad + \langle PB(B^*z - \sigma(B^*z)), z \rangle_H \\ &\quad + \langle Pz, B(B^*z - \sigma(B^*z)) \rangle_H \\ &\quad + \langle PB(\sigma(B^*z) - \sigma(B^*z + d)), z \rangle_H \\ &\quad + \langle z, PB(\sigma(B^*z) - \sigma(B^*z + d)) \rangle_H \\ &\leq -C\|z\|_H^2 + 2\|B^*z\|_U \|P\|_{\mathcal{L}(H)} \|B^*z - \sigma(B^*z)\|_U \\ &\quad + 2\langle \sigma(B^*z) - \sigma(B^*z + d), B^*Pz \rangle_U, \\ &\leq -C\|z\|_H^2 + 2\|B^*z\|_U \|P\|_{\mathcal{L}(H)} \|B^*z - \sigma(B^*z)\|_U \\ &\quad + 2k\|d\|_U \|B^*\|_{\mathcal{L}(H,U)} \|P\|_{\mathcal{L}(H)} \|z\|_H, \end{aligned}$$

where (4) and Item 3. of Definition 1 have been used to get this inequality. Using Item 4. of Definition 1, Cauchy-Schwarz inequality and the fact that B^* is bounded in U yields

$$\begin{aligned} \frac{d}{dt}V(z) &\leq - \left(C - \frac{\|B^*\|_{\mathcal{L}(H,U)}^2 \|P\|_{\mathcal{L}(H)}^2}{\varepsilon_1} \right) \|z\|_H^2 \\ &\quad + 2\|B^*z\|_U \|P\|_{\mathcal{L}(H)} \|B^*z - \sigma(B^*z)\|_U \\ &\quad + k^2 \varepsilon_1 \|d\|_U^2, \\ &\leq - \left(C - \frac{\|B^*\|_{\mathcal{L}(H,U)}^2 \|P\|_{\mathcal{L}(H)}^2}{\varepsilon_1} \right) \|z\|_H^2 \\ &\quad + 2\|B^*\|_{\mathcal{L}(H,U)} \|P\|_{\mathcal{L}(H)} \|z\|_H (\langle \sigma(B^*z), B^*z \rangle_U \\ &\quad + \langle B^*z, \sigma(B^*z) \rangle_U) \\ &\quad + k^2 \varepsilon_1 \|d\|_U^2 \\ &\leq - \left(C - \frac{\|B^*\|_{\mathcal{L}(H,U)}^2 \|P\|_{\mathcal{L}(H)}^2}{\varepsilon_1} \right) \|z\|_H^2 \\ &\quad + 2\|B^*\|_{\mathcal{L}(H,U)} \|P\|_{\mathcal{L}(H)} \|z\|_H (\langle \sigma(B^*z), B^*z \rangle_U \\ &\quad + \langle B^*z, \sigma(B^*z) \rangle_U) + k^2 \varepsilon_1 \|d\|_U^2, \end{aligned}$$

where ε_1 is a positive value that will be selected later. Secondly, using the dissipativity of the operator A_σ , Item 5. of Definition 1 and Young inequality, one has

$$\begin{aligned} \frac{2M}{3} \frac{d}{dt} \|z\|_H^3 &= M \|z\|_H (\langle Az, z \rangle_H + \langle z, Az \rangle_H) \\ &\quad - 2M \|z\|_H \langle B\sigma(B^*z + d), z \rangle_H \\ &\leq - 2M \|z\|_H (\langle \sigma(B^*z), B^*z \rangle_U \\ &\quad + \langle \sigma(B^*z) - \sigma(B^*z + d), B^*z \rangle_U) \\ &\leq - 2M \|z\|_H (\langle \sigma(B^*z), B^*z \rangle_U) \\ &\quad + 2MC_0 \|z\|_H \|d\|_U \\ &\leq - 2M \|z\|_H (\langle \sigma(B^*z), B^*z \rangle_U) \\ &\quad + \frac{2MC_0}{\varepsilon_2} \|z\|_H^2 + 2MC_0 \varepsilon_2 \|d\|_U^2, \end{aligned}$$

where ε_2 is a positive value that has to be selected. Hence, if one chooses M , ε_1 and ε_2 as follows

$$\begin{cases} M \geq 2\|B^*\|_{\mathcal{L}(H,U)} \|P\|_{\mathcal{L}(H)}, \\ \frac{2MC_0}{\varepsilon_2} + \frac{\|B^*\|_{\mathcal{L}(H,U)}^2 \|P\|_{\mathcal{L}(H)}^2}{\varepsilon_1} \leq C, \end{cases}$$

one obtains

$$\begin{aligned} \frac{d}{dt}V_1(z) &\leq - \left(C - \frac{2M}{\varepsilon_2} - \frac{\|B^*\|_{\mathcal{L}(H,U)}^2 \|P\|_{\mathcal{L}(H)}^2}{\varepsilon_1} \right) \|z\|_H^2 \\ &\quad + (C_0 2M \varepsilon_2 + k^2 \varepsilon_1) \|d\|_U^2. \end{aligned}$$

With an appropriate choice of ε_1 and ε_2 , it concludes the proof of Item 1. of Theorem 1.

Case 2: $S \neq U$. In the case where $S \neq U$, we will prove that the origin of (17) is semi-globally exponentially stable. Using Lemma 2, it proves that the origin of (17) is globally asymptotically stable.

Pick a positive value r . Consider any strong solution to (17) starting from z_0 satisfying

$$\|z_0\|_{D(A)} \leq r. \quad (26)$$

Now, focus on the following Lyapunov function

$$\begin{aligned} V_2(z) &:= \langle Pz, z \rangle_H + \tilde{M}r \|z\|_H^2 \\ &= V(z) + \tilde{M}r \|z\|_H^2 \end{aligned} \quad (27)$$

where \tilde{M} is a sufficiently large positive value that will be selected later.

Firstly, using Assumption 1, one has

$$\begin{aligned} \frac{d}{dt}V(z) &= \langle Pz, \tilde{A}z \rangle_H + \langle P\tilde{A}z, z \rangle_H \\ &\quad + \langle PB(B^*z - \sigma(B^*z)), z \rangle_H \\ &\quad + \langle Pz, B(B^*z - \sigma(B^*z)) \rangle_H \\ &\leq -C \|z\|_H^2 + \langle B^*z - \sigma(B^*z), B^*Pz \rangle_U \\ &\quad + \langle B^*Pz, B^*z - \sigma(B^*z) \rangle_U. \end{aligned}$$

Since (U, S) is a rigged Hilbert space, one has the following equality

$$\begin{aligned} \langle B^*z - \sigma(B^*z), B^*Pz \rangle_U + \langle B^*Pz, B^*z - \sigma(B^*z) \rangle_U &= \\ 2\langle B^*z - \sigma(B^*z), B^*Pz \rangle_{S' \times S}. \end{aligned}$$

Hence, applying Cauchy-Schwarz's inequality, one obtains

$$\frac{d}{dt}V(z) \leq -C \|z\|_H^2 + 2\|B^*Pz\|_S \|B^*z - \sigma(B^*z)\|_{S'}$$

Using Item 4. of Definition 1 yields

$$\begin{aligned} \frac{d}{dt}V(z) &\leq -C \|z\|_H^2 \\ &\quad + 4c_S \|Pz\|_{D(A)} (\langle B^*z, \sigma(B^*z) \rangle_U), \end{aligned} \quad (28)$$

where, in the second line, it has been used the assumption given in (21).

Now, using (26) together with the monotonicity of the function in (19), along the strong solutions to (17), we have

$$\|W_\sigma(t)z_0\|_{D(A)} \leq \|z_0\|_{D(A)}. \quad (29)$$

Therefore, noticing that $\|Pz\|_{D(A)} := \|Pz\|_H + \|PAz\|_H \leq \|P\|_{\mathcal{L}(H)} \|z\|_{D(A)}$, and using (28) and (21), one obtains

$$\begin{aligned} \frac{d}{dt}V(z) &\leq -C \|z\|_H^2 \\ &\quad + 4c_S r \|P\|_{\mathcal{L}(H)} (\langle z, B\sigma(B^*z) \rangle_H). \end{aligned}$$

Moreover, one has, using the dissipativity of the operator A

$$\begin{aligned} \frac{d}{dt}\tilde{M}r \|z\|_H^2 &= \tilde{M}r \langle Az, z \rangle_H + \langle z, Az \rangle_H \\ &\quad - \tilde{M}r (\langle z, B\sigma(B^*z) \rangle_H + \langle B\sigma(B^*z), z \rangle_H) \\ &\leq -4\tilde{M}r (\langle z, B\sigma(B^*z) \rangle_H). \end{aligned}$$

Hence, if one selects \tilde{M} such that

$$\tilde{M} > 2c_S \|P\|_{\mathcal{L}(H)},$$

it follows

$$\frac{d}{dt}V_2(z) \leq -C \|z\|_H^2. \quad (30)$$

Note that, from (27), we have, for all $z \in H$,

$$\tilde{M}r \|z\|_H^2 \leq V_2(z) \leq (\|P\|_{\mathcal{L}(H)} + \tilde{M}r) \|z\|_H^2 \quad (31)$$

It yields

$$\frac{d}{dt} V_2(z) \leq - \frac{C}{\|P\|_{\mathcal{L}(H)} + \tilde{M}r} V_2(z) \quad (32)$$

Applying Grönwall's inequality, one obtains

$$V_2(W_\sigma(t)z_0) \leq e^{-\mu t} V_2(z_0), \quad \forall t \geq 0, \quad (33)$$

where $\mu := \frac{C}{\|P\|_{\mathcal{L}(H)} + \tilde{M}r}$.

Therefore, using (31) yields

$$\|W_\sigma(t)z_0\|_H^2 \leq \frac{\|P\|_{\mathcal{L}(H)} + \tilde{M}r}{\tilde{M}r} e^{-\mu t} \|z_0\|_H^2. \quad (34)$$

Hence, the origin of (17) is semi-globally exponentially stable for any strong solution to (17). It yields that the origin is globally asymptotically stable from Lemma 2. Moreover, using Lemma 1, the origin of (17) is globally asymptotically stable for any weak solution to (17). Therefore, this concludes the proof of Item 2. of Theorem 1. \square

IV. EXAMPLE: A KORTEWEG-DE VRIES EQUATION

A. Applying Theorem 1

The Korteweg-de Vries equation (for short KdV) describes long waves in water of relatively shallow depth. It has been deeply studied in recent decades (see e.g., [2] for a nice introduction to the KdV equation in the context of the control).

The linearized version of the controlled KdV equation can be written as follows

$$\begin{cases} z_t + z_x + z_{xxx} = u, & (t, x) \in \mathbb{R}_{\geq 0} \times [0, L], \\ z(t, 0) = z(t, L) = 0, & t \in \mathbb{R}_{\geq 0} \\ z_x(t, L) = 0, & t \in \mathbb{R}_{\geq 0} \\ z(0, x) = z_0(x), & x \in [0, L]. \end{cases} \quad (35)$$

Given

$$H = U = L^2(0, L),$$

$$D(A) := \{z \in H^3(0, L) \mid z(0) = z(L) = z'(L) = 0\},$$

one can describe (35) as an abstract control system with the following operators

$$A : z \in D(A) \subset H \mapsto -z' - z''' \in H, \quad B = I_H, \quad (36)$$

where I_H denotes the identity operator for H . A simple computation shows that

$$\langle Az, z \rangle_H \leq 0, \quad \langle A^*z, z \rangle_H \leq 0.$$

These inequalities together with the fact that A is a closed operator allow us to apply the Lümer-Phillips theorem. Therefore, A generates a strongly continuous semigroup of contractions.

If one sets $u = -B^*z = -z$, then Assumption 1 holds. Indeed, the associated Lyapunov function is

$$V(z) = \frac{1}{2} \|z\|_H^2. \quad (37)$$

Its derivative along the solutions to (35) satisfies

$$\frac{d}{dt} V(z) \leq -V(z). \quad (38)$$

Therefore, the operator P given by (4) reduces to the identity.

Now, focus on the case where the control is saturated and where $S \neq U$. Let $S = L^\infty(0, L)$ and σ be given by (13). In [12], the following lemma has been proved

Lemma 3. *[[12], Lemma 4.] There exists a positive value Δ such that, for all $z \in D(A)$,*

$$\|z\|_{H_0^1(0, L)} \leq \Delta \|z\|_{D(A)}. \quad (39)$$

Using the above mentioned result together with the fact that the space $H_0^1(0, L)$ is continuously embedded in $L^\infty(0, L)$, one obtains that

$$\|z\|_S \leq \Delta \|z\|_{D(A)}. \quad (40)$$

Since $B^* = I_H$, one has

$$\|B^*z\|_S \leq \Delta \|z\|_{D(A)}. \quad (41)$$

Therefore, (21) holds for the linear Korteweg-de Vries equation (35).

Finally, since all the properties needed to apply Theorem 1 hold, this proves that the origin of

$$\begin{cases} z_t + z_x + z_{xxx} = -\text{sat}_{L^\infty(0, L)}(z), & (t, x) \in \mathbb{R}_{\geq 0} \times [0, L], \\ z(t, 0) = z(t, L) = 0, & t \in \mathbb{R}_{\geq 0} \\ z_x(t, L) = 0, & t \in \mathbb{R}_{\geq 0} \\ z(0, x) = z_0(x), & x \in [0, L], \end{cases} \quad (42)$$

is globally asymptotically stable.

B. Numerical simulations

Let us discretize the PDE (43) by means of finite difference method (see e.g. [15] for an introduction on the numerical scheme of a generalized Korteweg-de Vries equation). The time and the space steps are chosen such that the stability condition of the numerical scheme is satisfied.

By applying Theorem 1 Case 2, we know that the origin of (43) is globally asymptotically stable. A natural question is to inspect if Case 1 applies, that is, if

$$\begin{cases} z_t + z_x + z_{xxx} = -\text{sat}_{L^\infty(0, L)}(z + d), & (t, x) \in \mathbb{R}_{\geq 0} \times [0, L], \\ z(t, 0) = z(t, L) = 0, & t \in \mathbb{R}_{\geq 0} \\ z_x(t, L) = 0, & t \in \mathbb{R}_{\geq 0} \\ z(0, x) = z_0(x), & x \in [0, L], \end{cases} \quad (43)$$

is ISS with respect to d . To check that on numerical simulations, we choose $L = 2\pi$, $T = 9$, $z_0(x) = (1 - \cos(x))$ for all $x \in [0, 2\pi]$ and $d(t) = 0.05 \cos(t)$. Let us numerically compute the corresponding solution to (43).

Figure 1 (top) gives the time-evolution of this solution to (43), where the convergence property could be checked. Since the disturbance is bounded, one can check that the solution is also, which is one of the property of ISS. Figure 1 illustrates the Lyapunov function $\|z\|_{L^2(0, L)}^2$ with respect

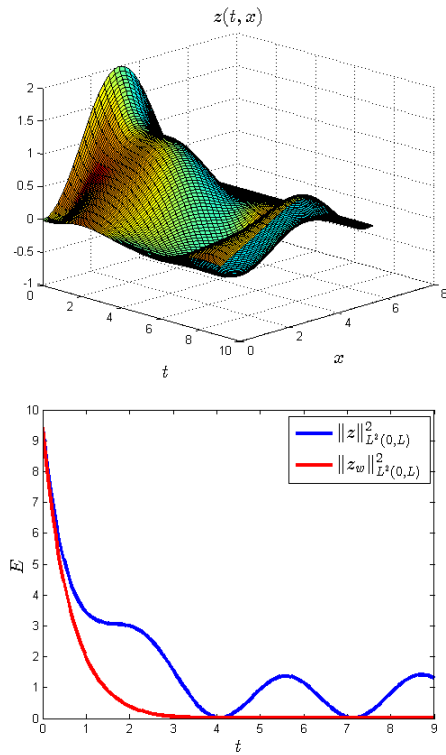


Fig. 1. Top: time-evolution of the solution to (43). Down: L^2 -norm of the solution to (43) (in blue) and of the solution to (43) without saturation and without perturbation (in red).

to the time and the solution without perturbation and without saturation. One can see that the L^2 -norm of the solution to (43) is bounded, and thus that the origin of (43) seems to be ISS with respect to d .

V. CONCLUSION

In this paper, the analysis of a stabilizing feedback law modified via a saturation function has been tackled using Lyapunov theory for infinite-dimensional systems. The saturation under consideration might render the feedback-law bounded in another space than the one where the origin is stabilized. Assuming a stabilizability property and depending on the set where the saturation acts, an ISS property has been derived, or a weaker property, as the global asymptotic stability of the origin in the infinite-dimension nonlinear system.

For future research lines, it would be interesting to prove an ISS property for both case of Theorem 1 and to study the case of unbounded control operators as considered for instance in [3], [25] or [17]. The case of nonlinear open-loop systems, as it is considered in [10], could be also challenging.

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REFERENCES

- [1] R. Azouit, A. Chaillet, Y. Chitour, and L. Greco, "Strong iISS for a class of systems under saturated feedback," *Automatica*, vol. 71, pp. 272–280, 2016.
- [2] E. Cerpa, "Control of a Korteweg-de Vries equation: a tutorial," *Mathematical Control and Related Fields*, vol. 4(1), pp. 45–99, 2014.
- [3] R. Curtain and G. Weiss, "Exponential stabilization of well-posed systems by colocated feedback," *SIAM Journal on Control and Optimization*, vol. 45, no. 1, pp. 273–297, 2006.
- [4] R. Curtain and H. Zwart, *An Introduction to Infinite-Dimensional Systems Theory*. Springer-Verlag, New York, 1995.
- [5] A. T. Fuller, "In-the-large stability of relay and saturating control systems with linear controllers," *International Journal of Control*, vol. 10, no. 4, pp. 457–480, 1969.
- [6] I. Karafyllis and M. Krstic, "ISS with respect to boundary disturbances for 1-D parabolic PDEs," *IEEE Transactions on Automatic Control*, vol. 61, no. 12, pp. 3712–3724, 2016.
- [7] H. Khalil, *Nonlinear Systems Second Edition*, S. . Schuster, Ed. Prentice Hall, Inc., 1996.
- [8] I. Lasiecka and T. I. Seidman, "Strong stability of elastic control systems with dissipative saturating feedback," *Systems & Control Letters*, vol. 48, pp. 243–252, 2003.
- [9] W. Liu, Y. Chitour, and E. Sontag, "On finite-gain stabilizability of linear systems subject to input saturation," *SIAM Journal on Control and Optimization*, vol. 34, no. 4, pp. 1190–1219, 1996.
- [10] S. Marx, V. Andrieu, and C. Prieur, "Cone-bounded feedback laws for m -dissipative operators on Hilbert spaces," *Mathematics of Control, Signals and Systems*, vol. to appear, 2017.
- [11] S. Marx, E. Cerpa, C. Prieur, and V. Andrieu, "Global stabilization of a Korteweg-de Vries equation with a saturating distributed control," *SIAM Journal on Control and Optimization*, vol. 55, no. 3, pp. 1452–1480, 2017.
- [12] —, "Stabilization of a linear Korteweg-de Vries with a saturated internal control," in *Proceedings of the European Control Conference*, Linz, AU, July 2015, pp. 867–872.
- [13] A. Megretski, " L_2 BIBO output feedback stabilization with saturated control," in *Proc. 13th IFAC world congress*, vol. 500, 1996, pp. 435–440.
- [14] A. Mironchenko and F. Wirth, "Characterizations of input-to-state stability for infinite-dimensional systems," *Accepted to IEEE Transactions on Automatic Control*, 2017.
- [15] A. F. Pazoto, M. Sepúlveda, and O. V. Villagrán, "Uniform stabilization of numerical schemes for the critical generalized Korteweg-de Vries equation with damping," *Numer. Math.*, vol. 116, no. 2, pp. 317–356, 2010.
- [16] C. Prieur and F. Mazenc, "ISS Lyapunov functions for time-varying hyperbolic partial differential equations," in *Decision and Control and European Control Conference (CDC-ECC), 2011 50th IEEE Conference on*. IEEE, 2011, pp. 4915–4920.
- [17] C. Prieur, S. Tarbouriech, and J. M. G. da Silva Jr, "Wave equation with cone-bounded control laws," *IEEE Trans. on Automat. Control*, vol. 61(11), pp. 3452–3463, 2016.
- [18] T. I. Seidman and H. Li, "A note on stabilization with saturating feedback," *Discrete Contin. Dyn. Syst.*, vol. 7, no. 2, pp. 319–328, 2001.
- [19] R. Showalter, *Monotone operators in Banach space and nonlinear partial differential equations*. Mathematical Surveys and Monographs, 1997.
- [20] M. Slemrod, "Feedback stabilization of a linear control system in Hilbert space with an a priori bounded control," *Mathematics of Control, Signals and Systems*, vol. 2(3), pp. 847–857, 1989.
- [21] E. Sontag, "Smooth stabilization implies coprime factorization," *IEEE transactions on automatic control*, vol. 34, no. 4, pp. 435–443, 1989.
- [22] H. Sussmann and Y. Yang, "On the stabilizability of multiple integrators by means of bounded feedback controls," *Technical Report SYCON-91-01*, vol. Rutgers Center for Systems and Control, 1991.
- [23] S. Tarbouriech, G. Garcia, J. G. da Silva Jr, and I. Queinnec, *Stability and Stabilization of Linear Systems with Saturating Actuators*, S. Verlag, Ed. Springer-Verlag, 2011.
- [24] A. R. Teel, "Global stabilization and restricted tracking for multiple integrators with bounded controls," *Systems & Control Letters*, vol. 18, pp. 165–171, 1992.
- [25] M. Tucsnak and G. Weiss, *Observation and control for operator semigroups*. Springer, 2009.