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Lyapunov stability analysis of a string equation coupled with an ordinary differential system

Matthieu Barreau, Alexandre Seuret, Frédéric Gouaisbaut and Lucie Baudouin

Abstract—This paper considers the stability problem of a linear time invariant system in feedback with a string equation. A new Lyapunov functional candidate is proposed using augmented states which enriches and encompasses the classical functionals proposed in the literature. It results in tractable stability conditions expressed in terms of linear matrix inequalities. This methodology follows from the application of the Bessel inequality together with Legendre polynomials. Numerical examples illustrate the potential of our approach through three scenarios: a stable ODE perturbed by the PDE, an unstable open-loop ODE and an unstable closed-loop ODE stabilized by the PDE.

Index Terms—String equation, Ordinary differential equation, Lyapunov functionals, LMI.

I. INTRODUCTION

This paper presents a novel approach to assess stability of a heterogeneous system composed of the interconnection of a partial differential equation (PDE), more precisely a damped string equation, with a linear ordinary differential equation (ODE). While the topic of stability and control of PDE systems has a rich literature between applied mathematics [7], [16] and automatic control [18]; the stability analysis (and the control) of such a coupled system belongs to a recent research area. To cite a few related results, one can refer to [4], [5], [23] where an ODE is interconnected with a transport equation, to [25] for a heat equation, to [13] for the wave equation and to [27] for the beam equation.

Generally, the PDE is viewed as a perturbation to be compensated e.g. using a backstepping method proposed by [14], where infinite dimensional controllers are provided to cope with the undesirable effect of the PDE. Another interesting point of view relies on the converse approach: the ODE system can be seen as a finite dimensional boundary controller for the PDE (see [10], [20], [21]). A last strategy describes a robust control approach, aiming at characterizing the robustness of the interconnection [11].

In the present paper, we consider a damped string equation, i.e. a stable one-dimensional wave equation which is perturbed at its boundary by a stable or unstable ODE. The proposed method to assess stability is inspired by the recent developments on the stability analysis of time-delay systems based on Bessel inequality and Legendre polynomials [24]. Since time-delay systems represent a particular class of systems coupling a transport PDE with a classical ODE system (see for instance [2]), the main motivation of this work is to show how this methodology can be adapted to a larger class of PDE/ODE systems as demonstrated with the heat equation in [1].

Compared to the literature on coupled PDE/ODE systems, the proposed methodology aims at designing a new Lyapunov functional, integrating some cross-terms merging the ODE's and the PDE's usual terms. This new class of Lyapunov functional encompasses the classical notion of energy usually proposed in the literature by offering more flexibility. Hence, it allows us to guarantee stability for a larger set of systems, for instance, instable open-loop ODE and, for the first time to the best of our knowledge, even an unstable closed-loop ODE.

The paper is organized as follows. The next section formulates the problem and provides some general results on the existence of solutions and equilibrium. In Section 3, after a modeling phase inspired by the Riemann coordinates, a generic form of Lyapunov functionals is introduced, and its associate analysis leads to a first stability theorem. Then, in Section 4, an extension using Bessel inequality is provided. Finally, Section 5 discusses the results on three examples. The last section draws some conclusion and perspectives.

Notations: In this paper, Ω is the closed set $[0, 1]$ and $\mathbb{R}^+ = [0, +\infty)$. Then, $(x, t) \mapsto u(x, t)$ is a multi-variable function from $\Omega \times \mathbb{R}^+$ to \mathbb{R} . The notation u_t stands for $\frac{\partial u}{\partial t}$. We also use the notations $L^2 = L^2(\Omega; \mathbb{R})$ and for the Sobolev spaces: $H^n = \{z \in L^2; \forall m \leq n, \frac{\partial^m z}{\partial x^m} \in L^2\}$. The norm in L^2 is $\|z\|^2 = \int_{\Omega} |z(x)|^2 dx$. For any square matrices A, B , the operations ‘He’ and ‘diag’ are defined as follows: $\text{He}(A) = A + A^\top$ and $\text{diag}(A, B) = \begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}$. A symmetric positive definite matrix P of $\mathbb{R}^{n \times n}$ belongs to the set \mathbb{S}_+^n or we write more simply $P \succ 0$.

II. PROBLEM STATEMENT

We consider the coupled system described by

$$\dot{X}(t) = AX(t) + Bu(1, t), \quad t \geq 0, \quad (1a)$$

$$u_{tt}(x, t) = c^2 u_{xx}(x, t), \quad x \in \Omega, t \geq 0, \quad (1b)$$

$$u(0, t) = KX(t), \quad t \geq 0, \quad (1c)$$

$$u_x(1, t) = -c_0 u_t(1, t), \quad t \geq 0, \quad (1d)$$

$$u(x, 0) = u^0(x), \quad u_t(x, 0) = v^0(x), \quad x \in \Omega, \quad (1e)$$

$$X(0) = X^0, \quad (1f)$$

with the initial conditions $X^0 \in \mathbb{R}^n$ and $(u^0, v^0) \in H^1 \times L^2$ such that equations (1c) and (1d) are respected. They are then called “compatibles” with the boundary conditions. A, B and K are time-invariant matrices of appropriate size.

Remark 1: When no confusion is possible, parameter t may be omitted and so do the domains of definition.

This system can be viewed as an interconnection in feedback between a linear time invariant system (1a) and an infinite dimensional system modeled by a string equation (1b). The latter is a one dimension hyperbolic PDE, representing the

evolution of a wave of speed $c > 0$ and amplitude u . To keep the content clear, the dimension of $x \mapsto u(x, \cdot)$ is assumed to be one but the calculus are done as if it was a vector of any dimension. The measure is the state u at $x = 1$ which is the end of the string and the control is a Dirichlet actuation (equation (1c)) because it affects directly the state u and not its derivative. To be well-posed, another boundary condition must be added. It is defined at $x = 1$ by $u_x(1) = -c_0 u_t(1)$. This is a well-known damping condition for $c_0 > 0$ (see for example [15]). A potential application would be the control of a drilling system as presented in [3]. The control is given at one end and the measure is done at the other end of the drilling pit.

More generally, this system can be seen either as the control of the PDE by a finite dimensional dynamic control law generated by an ODE [6] or on the contrary the robustness of a linear closed loop system with a control signal conveyed by a damped string equation. On the first scenario, both the ODE and the PDE are stable and the stability of the coupled system is studied. The second case is with an unstable but stabilizable ODE and the PDE is still stable. Finally, this paper focuses on the stability analysis of *closed-loop* coupled system (1). This differs from the backstepping methodology presented in [13] where infinite dimensional control laws are designed to ensure stability of a cascaded ODE-PDE systems.

A. Existence and regularity of solutions

This subsection is dedicated to the existence and regularity of solutions (X, u) to system (1). We consider the classical norm on the Hilbert space $\mathcal{H} = \mathbb{R}^n \times H^1 \times L^2$:

$$\|(X, u, v)\|_{\mathcal{H}}^2 = |X|_n^2 + \|u\|^2 + c^2 \|u_x\|^2 + \|v\|^2.$$

This norm can be seen as the sum of the energy of the ODE system and the one of the PDE.

Remark 2: A more natural norm for space \mathcal{H} would be $|X|_n^2 + \|u\|^2 + \|u_x\|^2 + \|v\|^2$ which is equivalent to $\|\cdot\|_{\mathcal{H}}^2$. The norm used here makes the calculus easier in the sequel.

Once the space is defined, we can model System (1) using the following linear unbounded operator $T : \mathcal{D}(T) \rightarrow \mathcal{H}$:

$$T \begin{pmatrix} X \\ u \\ v \end{pmatrix} = \begin{pmatrix} AX + Bu(1) \\ v \\ c^2 u_{xx} \end{pmatrix} \text{ and}$$

$$\mathcal{D}(T) = \{(X, u, v) \in \mathcal{H}, u(0) = KX, u_x(1) = -c_0 v(1)\}.$$

This operator T is said to be dissipative with respect to a norm if its time-derivative along the trajectories generated by T is strictly negative. The aim of this paper is then to find an equivalent norm to $\|\cdot\|_{\mathcal{H}}$ which allows us to refine the dissipativity analysis of T . This equivalent norm is derived from a general formulation of a Lyapunov functional, whose parameters are chosen using a semi-definite programming optimization process.

Beforehand, from the semi-group theory, we propose the following result on the existence of solutions for (1).

Proposition 1: If there exists a norm on \mathcal{H} for which the linear operator T is dissipative with $A + BK$ non singular, then there exists a unique solution (X, u, u_t) of system (1) with initial conditions $(X^0, u^0, v^0) \in \mathcal{H}$ compatible with the

boundary conditions. Moreover, the solution has the following regularity property: $(X, u, u_t) \in C(0, +\infty, \mathcal{H})$.

Proof: This proof follows the same lines than in [19]. Applying Lumer-Phillips theorem (p103 from [26]), as the norm is dissipative, it is enough to show that for all $\lambda \in (0, \lambda_{max})$ with $\lambda > 0$, the application $\mathcal{D}(T) \subset \mathcal{R}(\lambda I - T)$ where \mathcal{R} is the range operator. This is quite technical and has already been done by Morgül in [19] for a slightly different system considering a Neumann actuation. Let $(r, g, h) \in \mathcal{H}$, we want to show that for this system, there exists $(X, u, v) \in \mathcal{D}(T)$ for which the following set of equation is verified:

$$\lambda X - AX - Bu(1) = r, \quad (2a)$$

$$\lambda u(x) - v(x) = g(x), \quad (2b)$$

$$\lambda v(x) - c^2 u_{xx}(x) = h(x), \quad (2c)$$

for all $x \in (0, 1)$ and a given $\lambda > 0$. Using equations (2b), (2c) and the boundary conditions, we get:

$$\forall x \in (0, 1), \quad u(x) = 2k_1 \sinh(\lambda c^{-1} x) + KX e^{-\lambda c^{-1} x} + G(x),$$

where $G(x) = \int_0^x \frac{\lambda g(s) + h(s)}{\lambda c} \sinh\left(\frac{\lambda}{c}(s-x)\right) ds$. $k_1 \in \mathbb{R}$ is a constant to be determined. Taking its derivative at the boundary we get:

$$u_x(1) = 2\lambda c^{-1} k_1 \cosh(\lambda c^{-1}) - \lambda c^{-1} KX e^{-\lambda c^{-1}} + G_1,$$

with $G_1 \in \mathbb{R}$ known. We also have $u_x(1) + c_0 v(1) = 0$, leading to $u(1) = G_2 + KX f(\lambda c^{-1})$ with $G_2 \in \mathbb{R}$ and $f(y) = \left(1 - \frac{(cc_0 - 1) \sinh(y)}{2(\cosh(y) + cc_0 \sinh(y))}\right) e^{-y}$. Then using (2a), we get:

$$(\lambda I_n - (A + BK f(\lambda c^{-1}))) X = r + BG_2.$$

Since $f(\lambda c^{-1})$ tends to 1 when λ tends to 0 and $A + BK$ is non singular, there exists $\lambda_{max} > 0$ such that $A + BK f(\lambda_{max} c^{-1})$ is non singular and

$$\forall \lambda \in (0, \lambda_{max}), \quad \det(\lambda I_n - (A + BK f(\lambda c^{-1}))) \neq 0.$$

Then, there is a unique $X \in \mathbb{R}^n$ for a given $(r, f, h) \in \mathcal{H}$. We immediately get that (X, u, v) is in $\mathcal{D}(T)$. The for $\lambda \in (0, \lambda_{max})$, $\mathcal{D}(T) \subset \mathcal{R}(\lambda I - T)$. The regularity property falls from Theorem 4.1.6 of [26]. \square

B. Equilibrium point

An equilibrium $x_{eq} = (X_e, u_e, v_e) \in \mathcal{D}(T)$ of System (1) is such that $T x_{eq} = 0_{\mathcal{H}}$, i.e. it verifies the following equations:

$$0 = AX_e + Bu_e(1), \quad (3a)$$

$$0 = c^2 \partial_{xx} u_e(x), \quad x \in (0, 1), \quad (3b)$$

$$v_e(x) = 0, \quad x \in (0, 1), \quad (3c)$$

$$u_e(0) = KX_e, \quad (3d)$$

$$\partial_x u_e(1) = 0. \quad (3e)$$

Using equation (3b), we get u_e as a first order polynomial in x but in accordance to equation (3e), u_e is a constant function. Then, using equation (3d), we get $u_e = KX_e$. Equation (3a) and the previous statement lead to: $(A + BK) X_e = 0$. We get then the following proposition:

Proposition 2: An equilibrium $(X_e, u_e, v_e) \in \mathcal{H}$ of System (1) verifies $(A + BK) X_e = 0$, $u_e = KX_e$, $v_e = 0$. Moreover,

if $A + BK$ is not singular, system (1) admits a unique equilibrium $(X_e, u_e, v_e) = (0_{n,1}, 0, 0) = 0_{\mathcal{H}}$.

Remark 3: In the previous subsection, we showed that $A + BK$ must be not singular to get uniqueness of the solution. This requirement is also related to the existence of a unique equilibrium.

III. A FIRST STABILITY ANALYSIS BASED ON MODIFIED RIEMANN COORDINATES

This part is dedicated to the construction of a Lyapunov functional candidate. We introduce therefore a new structure based on variables directly related to the states of System (1).

A. Modified Riemann coordinates

The PDE considered in System (1) is of second order in time. As we want to use some tools already designed for first order systems, we propose to define some new states using modified Riemann coordinates, which satisfy a set of coupled first order PDEs and diagonalize the operator. Let us introduce these coordinates, defined as follows:

$$\chi(x) = \begin{bmatrix} u_t(x) + cu_x(x) \\ u_t(1-x) - cu_x(1-x) \end{bmatrix} = \begin{bmatrix} \chi^+(x) \\ \chi^-(1-x) \end{bmatrix}.$$

The introduction of such variables is not new and the reader can refer to articles [22], [3] or [8] and references therein about Riemann invariants. χ^+ and χ^- are eigenfunctions of equation (1b) associated respectively to the eigenvalues c and $-c$. Therefore, using $\chi^-(1-x)$, the previous equation leads to a transport PDE for $x \in \Omega$:

$$\forall t \geq 0, \forall x \in \Omega, \quad \chi_t(x, t) = c\chi_x(x, t). \quad (4)$$

Remark 4: The norm of the modified state χ can be directly related to the norm of the functions u_t and u_x . Indeed simple calculations and a change of variables give:

$$\|\chi\|^2 = 2(\|u_t\|^2 + c^2\|u_x\|^2). \quad (5)$$

Remark 5: This manipulation does not aim at providing an equivalent formulation for System (1) but at identifying a manner to build a Lyapunov functional for System (1).

The second step is to understand how the extra-variable χ interacts with the ODE of System (1). Hence, we notice:

$$\begin{aligned} \dot{X} &= AX + B(u(1) - u(0) + KX), \\ &= (A + BK)X + B \int_0^1 u_x(x) dx. \end{aligned}$$

To express the last integral term using χ , we note that:

$$2c \int_0^1 u_x(x) dx = \int_0^1 \chi^+(x) dx - \int_0^1 \chi^-(x) dx.$$

This expression allows us to rewrite the ODE system as $\dot{X} = (A + BK)X + \tilde{B}\tilde{\mathfrak{X}}_0$ where $\tilde{\mathfrak{X}}_0 = \int_0^1 \chi(x) dx$ and $\tilde{B} = \frac{1}{2c}B[1 \ -1]$. The extra-state $\tilde{\mathfrak{X}}_0$ follows the dynamics:

$$\dot{\tilde{\mathfrak{X}}}_0 = c \int_0^1 \chi_x(x) dx = c[\chi(1) - \chi(0)].$$

The ODE dynamic can then be enriched by considering an extended system where $\tilde{\mathfrak{X}}_0$ is viewed as a new dynamical state:

$$\dot{X}_0 = \begin{bmatrix} A+BK & \tilde{B} \\ 0_{2,n} & 0_2 \end{bmatrix} X_0 + \begin{bmatrix} 0_{n,2} \\ cI_2 \end{bmatrix} (\chi(1) - \chi(0)), \quad (6)$$

with $X_0 = [X^\top \ \tilde{\mathfrak{X}}_0^\top]^\top$. Beware that X_0 is not the initial ODE data X^0 .

Hence, associated to the original system (1), we propose a set of equation (4)-(6). They are linked to System (1) but enriched by extra dynamics aiming at representing the interconnection between the extended finite dimensional system and the two transport equations. Nevertheless, these two systems are not equivalent. The transport equation gives trajectories of u_t and u_x but u can be defined within a constant. The second set of equations just induces a formulation for a Lyapunov functional candidate which is developed in the subsection below.

B. Lyapunov functional and stability analysis

The main idea is to rely on the auxiliary variables satisfying equations (4) and (6) to define a Lyapunov functional for the original system (1). The associated Lyapunov function of ODE (6) is a simple quadratic term on the state $X_0^\top P_0 X_0$, with $P_0 \in \mathbb{S}_+^{n+2}$. It introduces automatically a cross-term between the ODE and the original PDE through X_0 . Hence, the auxiliary equations of the previous part shows a coupling between a finite dimensional LTI system and an infinite dimension PDE seen as a transport equation. For the infinite dimensional part, inspired from the literature on time-delay systems [2], [8], we provide a Lyapunov functional:

$$\mathcal{V}(u) = \int_0^1 \chi^\top(x) (S + xR) \chi(x) dx,$$

with $S, R \in \mathbb{S}_+^2$. The use of the modified Riemann coordinates enables us to consider full matrices S and R . As the transport described by the variable χ is going backward, R is multiplied by x . Thereby, we propose a Lyapunov functional for system (1) expressed with the extended state variable X_0 :

$$V_0(X_0, u) = X_0^\top P_0 X_0 + \mathcal{V}(u). \quad (7)$$

This Lyapunov functional is actually made up of three terms:

- 1) A quadratic term in X introduced by the ODE;
- 2) A functional \mathcal{V} for the stability of the string equation;
- 3) A cross-term between $\tilde{\mathfrak{X}}_0$ and X described by the extended state X_0 .

The idea is that this last contribution is of interesting since we may consider the stability of System (1) with an unstable ODE part, stabilized thanks to the string equation. At this stage, a stability theorem can be derived using the Lyapunov functional V_0 .

Theorem 1: Consider the system defined in (1) with a given speed c , a viscous damping $c_0 > 0$ with initial conditions $(X^0, u^0, v^0) \in \mathcal{H}$ compatible with the boundary conditions. Assume there exist $P_0 \in \mathbb{S}_+^{n+2}$ and $S, R \in \mathbb{S}_+^2$ such that the linear matrix inequality $\Psi_0 < 0$ holds where

$$\Psi_0 = \text{He} \left(Z_0^\top P_0 F_0 \right) - c\tilde{R}_0 + c(H_0^\top (S + R)H_0 - G_0^\top S G_0) \quad (8)$$

$$\begin{aligned}
F_0 &= \begin{bmatrix} I_{n+2} & 0_{n+2,2} \end{bmatrix}, & Z_0 &= \begin{bmatrix} \mathcal{N}_0^\top & c(H_0 - G_0)^\top \end{bmatrix}^\top, \\
\mathcal{N}_0 &= \begin{bmatrix} A+BK & \tilde{B} & 0_{n,2} \end{bmatrix}, & \tilde{R}_0 &= \text{diag}(0_n, R, 0_2), \\
G_0 &= \begin{bmatrix} 0_{2,n+2} & g \end{bmatrix} + \begin{bmatrix} -K \\ 0_{1,n} \end{bmatrix} \mathcal{N}_0, & g &= - \begin{bmatrix} 0 \\ 1+cc_0 & 0 \end{bmatrix}, \\
H_0 &= \begin{bmatrix} 0_{2,n+2} & h \end{bmatrix} + \begin{bmatrix} 0_{1,n} \\ K \end{bmatrix} \mathcal{N}_0, & h &= \begin{bmatrix} 1-cc_0 & 0 \\ 0 & -1 \end{bmatrix}.
\end{aligned} \tag{9}$$

Then there exists a unique solution to System (1) and it is exponentially stable in the sense of norm $\|\cdot\|_{\mathcal{H}}$ i.e. there exist $\gamma \geq 1, \delta > 0$ such that the following estimate holds:

$$\forall t > 0, \|(X(t), u(t), u_t(t))\|_{\mathcal{H}}^2 \leq \gamma e^{-\delta t} \|(X^0, u^0, v^0)\|_{\mathcal{H}}^2. \tag{10}$$

Remark 6: Condition $\Psi_0 \prec 0$ includes a necessary condition given by $e_3^\top \Psi_0 e_3 \prec 0$, with $e_3 = [0_{n,n+2} \ I_2]^\top$, which is $h^\top(S+R)h - g^\top Sg \prec 0$. This inequality is guaranteed if and only if the matrix $g^{-1}h$ has its eigenvalues inside the unit cycle of the complex plan, i.e. $c_0 > 0$, which is consistent with the result on exponential stability presented in [12].

C. Proof of Theorem 1

The proof of stability is presented below.

1) *Preliminaries:* As a first step of this proof, let us introduce the following lemma that will be useful in the sequel.

Lemma 1: The following inequality holds:

$$\|u\|^2 \leq 2\|u_x\|^2 + 2|u(0)|^2, \quad \forall u \in H^1.$$

Proof: Since $u_x \in L^2(\Omega)$, Young and Jensen inequalities imply that for all $x \in \Omega$:

$$u(x)^2 = \left(\int_0^x u_s(s) ds - u(0) \right)^2 \leq 2 \int_0^x u_s^2(s) ds + 2|u(0)|^2. \quad \square$$

The proof of Theorem 1 consists in explaining how the fulfillment of LMI condition presented in Theorem 1 implies there exist a functional V and three positive scalars $\varepsilon_1, \varepsilon_2$ and ε_3 such that the following inequalities hold:

$$\begin{aligned}
\varepsilon_1 \|(X, u, u_t)\|_{\mathcal{H}}^2 &\leq V(X, u) \leq \varepsilon_2 \|(X, u, u_t)\|_{\mathcal{H}}^2, \\
\dot{V}(X, u) &\leq -\varepsilon_3 \|(X, u, u_t)\|_{\mathcal{H}}^2.
\end{aligned} \tag{11}$$

The next paragraphs aim at proving (11) in order to obtain the convergence of the state to the equilibrium.

2) *Well-posedness:* If the conditions of Theorem 1 are satisfied, then the inequality $\Psi_0(1, 1) = e_1^\top \Psi_0 e_1 \prec 0$ holds where $e_1 = [I_n \ 0_{n,4}]^\top$. After some simplifications, we get $\text{He}((A+BK)^\top Q) \prec 0$, for some matrix Q depending on R, S and P_0 . This strict inequality requires that $A+BK$ is not singular and, in light of Propositions 1 and 2, the problem is indeed well-posed and $0_{\mathcal{H}}$ is the unique equilibrium point. Furthermore, note that since Q is not necessarily symmetric, matrix $A+BK$ does not have to be Hurwitz.

3) *Existence of ε_1 :* The LMI conditions, $P_0 \succ 0, S \succ 0$ and $R \succ 0$ mean that there exists $\varepsilon_1 > 0$, such that for all $x \in [0, 1]$:

$$\begin{aligned}
P_0 &\succeq \varepsilon_1 \text{diag}(I_{n+2} + 2K^\top K, 0_2), \\
S + xR &\succeq S \succeq \varepsilon_1 \frac{2+c^2}{2c^2} I_2.
\end{aligned}$$

These inequalities lead to:

$$\begin{aligned}
V_0(X_0, u) &\geq \varepsilon_1 \left(|X|_n^2 + |KX|^2 + \frac{2+c^2}{2c^2} \|\chi\|^2 \right) \\
&\quad + \int_0^1 \chi^\top(x) \left(S + xR - \varepsilon_1 \frac{2+c^2}{2c^2} I_2 \right) \chi(x) dx \\
&\geq \varepsilon_1 \left(|X|_n^2 + |KX|^2 + \frac{2+c^2}{2c^2} \|\chi\|^2 \right).
\end{aligned}$$

Noting the boundary condition (1c) and norm equality (5), it becomes

$$\begin{aligned}
V_0(X_0, u) &\geq \varepsilon_1 \left(|X|_n^2 + \|u\|^2 + \|u_t\|^2 + c^2 \|u_x\|^2 \right) \\
&\quad + \frac{2\varepsilon_1}{c^2} \|u_t\|^2 + \varepsilon_1 \left(2\|u_x\|^2 + 2|u(0)|^2 - \|u\|^2 \right).
\end{aligned}$$

Then, we apply Lemma 1 to ensure that the last term is positive so that it yields $V_0(X_0, u) \geq \varepsilon_1 \|(X, u, u_t)\|_{\mathcal{H}}^2$, which ends the proof of existence of ε_1 .

4) *Existence of ε_2 :* Since $P_0 \in \mathbb{S}_+^{n+2}$ and $S, R \in \mathbb{S}_+^2$, there exists $\varepsilon_2 > 0$ such that for $x \in (0, 1]$:

$$\begin{aligned}
P_0 &\preceq \text{diag}(\varepsilon_2 I_n, \frac{\varepsilon_2}{4} I_2), \\
S + xR &\preceq S + R \preceq \frac{\varepsilon_2}{4} I_2.
\end{aligned}$$

From equation (7), we get:

$$\begin{aligned}
V_0(X_0, u) &\leq \varepsilon_2 \left(|X|_n^2 + \frac{1}{4} \mathfrak{X}_0^\top \mathfrak{X}_0 + \frac{1}{4} \|\chi\|^2 \right) \\
&\quad + \int_0^1 \chi^\top(x) \left(S + xR - \frac{\varepsilon_2}{4} I_2 \right) \chi(x) dx \tag{12} \\
&\leq \varepsilon_2 \left(|X|_n^2 + \frac{1}{2} \|\chi\|^2 \right)
\end{aligned}$$

where we have used Jensen's inequality which ensures that $\mathfrak{X}_0^\top \mathfrak{X}_0 \leq \|\chi\|^2$. The proof of the existence of ε_2 ends by using norm equality (5) so that we get:

$$V_0(X_0, u) \leq \varepsilon_2 \left(|X|_n^2 + \|u_t\|^2 + c^2 \|u_x\|^2 \right) \leq \varepsilon_2 \|(X, u, u_t)\|_{\mathcal{H}}^2.$$

5) *Existence of ε_3 :* Differentiating V_0 in (7) along the trajectories of system (1) leads to

$$\dot{V}_0(X_0, u) = \text{He} \left(\begin{bmatrix} \dot{X} \\ \dot{\mathfrak{X}}_0 \end{bmatrix}^\top P_0 \begin{bmatrix} X \\ \mathfrak{X}_0 \end{bmatrix} \right) + \dot{V}(u).$$

Our goal is to expressed an upper bound of \dot{V}_0 thanks to the extended vector ξ_0 defined as follows:

$$\xi_0 = \begin{bmatrix} X^\top & \mathfrak{X}_0^\top & u_t(1) & cu_x(0) \end{bmatrix}^\top. \tag{13}$$

Let us first concentrate on \dot{V} . Equation (4) yields:

$$\dot{V}(u) = 2c \int_0^1 \chi_x^\top(x, t) (S + xR) \chi(x, t) dx. \tag{14}$$

Integrating by parts the last expression leads to:

$$\begin{aligned}
\dot{V}(u) &= c \left(\chi^\top(1) (S + R) \chi(1) - \chi^\top(0) S \chi(0) \right. \\
&\quad \left. - \int_0^1 \chi^\top(x) R \chi(x) dx \right). \tag{15}
\end{aligned}$$

Then we note that $\dot{X} = \mathcal{N}_0 \xi_0$, $\dot{\mathfrak{X}}_0 = c(H_0 - G_0) \xi_0$, $\chi(1) = H_0 \xi_0$, $\chi(0) = G_0 \xi_0$, with ξ_0 defined in (13) and the matrices above in equation (9). We get $X_0 = F_0 \xi_0$ and $\dot{X}_0 = Z_0 \xi_0$

and the resulting expression for \dot{V}_0 is obtained:

$$\dot{V}_0(X_0, u) = \xi_0^\top (\text{He}(Z_0^\top P_0 F_0) + cH_0^\top (S+R)H_0 - cG_0^\top S G_0) \xi_0 - c \int_0^1 \chi^\top(x) R \chi(x) dx. \quad (16)$$

Then, using the definition of matrix Ψ_0 given in (8), the previous expression can be rewritten as follows:

$$\dot{V}_0(X_0, u) = \xi_0^\top \Psi_0 \xi_0 + c \tilde{\mathfrak{X}}_0^\top R \tilde{\mathfrak{X}}_0 - c \int_0^1 \chi^\top(x) R \chi(x) dx. \quad (17)$$

Since $R \succ 0$ and $\Psi_0 \prec 0$, there exists $\varepsilon_3 > 0$ such that:

$$R \succeq \frac{\varepsilon_3}{2c} \frac{2+c^2}{c^2} I_2, \quad (18a)$$

$$\Psi_0 \preceq -\varepsilon_3 \text{diag} \left(I_n + 2K^\top K, \frac{2+c^2}{2c^2} I_2, 0_2 \right). \quad (18b)$$

Using (18b) and the boundary condition $u(0) = KX$, equation (17) becomes:

$$\begin{aligned} \dot{V}_0(X_0, u) \leq & -\varepsilon_3 \left(|X_n^2| + 2|u(0)|^2 + \frac{2+c^2}{2c^2} \|\chi\|^2 \right) \\ & + c \tilde{\mathfrak{X}}_0^\top \left(R - \frac{\varepsilon_3}{2c} \frac{2+c^2}{c^2} I_2 \right) \tilde{\mathfrak{X}}_0 \\ & - c \int_0^1 \chi^\top(x) \left(R - \frac{\varepsilon_3}{2c} \frac{2+c^2}{c^2} I_2 \right) \chi(x) dx \end{aligned}$$

So that we get by application of Jensen's inequality:

$$\dot{V}_0(X_0, u) \leq -\varepsilon_3 \left(|X_n^2| + 2|u(0)|^2 + \frac{2+c^2}{2c^2} \|\chi\|^2 \right). \quad (19)$$

The most important part of the proof lies in the following trick. Since (5) holds, we get:

$$\begin{aligned} \dot{V}_0(X_0, u) \leq & -\varepsilon_3 \|(X, u, u_t)\|_{\mathcal{H}}^2 - \varepsilon_3 \frac{2}{c^2} \|u_t\|^2 \\ & - \varepsilon_3 (2|u(0)|^2 + 2\|u_x\|^2 - \|u\|^2). \end{aligned}$$

Moreover, Lemma 1 ensures that the last term of the previous expression is negative so that we have $\dot{V}_0(X_0, u) \leq -\varepsilon_3 \|(X, u)\|_{\mathcal{H}}^2$, which concludes this proof of existence.

6) *Conclusion:* Finally, there exist $\varepsilon_1, \varepsilon_2, \varepsilon_3 > 0$ such that equation (11) holds for a functional V_0 . Hence $V_0(\cdot)$ is an equivalent norm of $\|\cdot\|_{\mathcal{H}}$ which is strictly decreasing. It means, according to Propositions 1 and 2, that there exists a unique solution to System (1) converging in \mathcal{H} to the solution equilibrium $0_{\mathcal{H}}$. These conditions also bring : $\forall t > 0, \dot{V}_0(X_0, u) + \frac{\varepsilon_3}{\varepsilon_2} V_0(X_0, u) \leq 0$ and

$$\|(X(t), u(t), u_t(t))\|_{\mathcal{H}}^2 \leq \frac{\varepsilon_2}{\varepsilon_1} e^{-\frac{\varepsilon_3}{\varepsilon_2} t} \|(X^0, u^0, v^0)\|_{\mathcal{H}}^2,$$

which shows the exponential convergence of all trajectories of system (1) to the unique equilibrium $0_{\mathcal{H}}$. In other words, the solution to System (1) is exponentially stable.

Remark 7: It is also worth noting that LMI (8) is affine with respect to matrices A, B , which allows us, in a straightforward manner, to extend this theorem to uncertain ODE systems subject, for instance, to polytopic-type uncertainties.

IV. EXTENDED STABILITY ANALYSIS

A. Main motivation

In the previous analysis, we have proposed an auxiliary system presented in (6) helping us to define a new Lyapunov

functional for System (1). The notable aspect is that the term $\tilde{\mathfrak{X}}_0 = \int_0^1 \chi(x) dx$ appears naturally in the dynamics of System (1). In light of the previous work on integral inequalities by [24], this term can also be interpreted as the projection of the modified state χ over the set of constant functions in the sense of the canonical inner product in L^2 . One may therefore enrich system (6) by additional projections of χ over the next Legendre polynomials, as one can read in [24] in the context of time-delay systems. The family of shifted Legendre polynomials, denoted $\{\mathcal{L}_k\}_{k \in \mathbb{N}}$ and defined over $(0, 1)$ by $\mathcal{L}_k(x) = (-1)^k \sum_{l=0}^k (-1)^l \binom{k}{l} \binom{k+l}{l} x^l$ with $\binom{k}{l} = \frac{k!}{l!(k-l)!}$, forms an orthogonal family respect to the L^2 inner product (see [9] for more details).

B. Preliminaries

The previous discussion leads us to define additional vectors for any function χ in L^2 :

$$\forall k \in \mathbb{N}, \quad \tilde{\mathfrak{X}}_k = \int_0^1 \chi(x) \mathcal{L}_k(x) dx,$$

and the augmented vector X_N , for $N \in \mathbb{N}$, as follows:

$$X_N = \begin{bmatrix} X^\top & \tilde{\mathfrak{X}}_0^\top & \dots & \tilde{\mathfrak{X}}_N^\top \end{bmatrix}^\top. \quad (20)$$

Following the same methodology as for Theorem 1, this specific structure leads us to introduce a new Lyapunov functional, inspired from (7), with $P_N \in \mathbb{S}_+^{n+2(N+1)}$:

$$V_N(X_N, u) = X_N^\top P_N X_N + \mathcal{V}(u). \quad (21)$$

In order to follow the same procedure, several technical extensions are required. Indeed, the stability conditions issued from the functional V_0 are coming from Jensen's inequality and an explicit expression of the time derivative of $\tilde{\mathfrak{X}}_0$. Therefore, it is necessary to provide an extended version of the Jensen inequality and of this differentiation rule. These technical steps are summarized in the two following lemmas.

Lemma 2: For any function $\chi \in L^2$ and symmetric positive matrix $R \in \mathbb{S}_+^2$, the following Bessel-like integral inequality holds for all $N \in \mathbb{N}$:

$$\int_0^1 \chi^\top(x) R \chi(x) dx \geq \sum_{k=0}^N (2k+1) \tilde{\mathfrak{X}}_k^\top R \tilde{\mathfrak{X}}_k. \quad (22)$$

This inequality includes Jensen's inequality as the particular case $N = 0$, which was one of the key element in the proof of Theorem 1. This comment allows us to assert that the previous lemma is the appropriate extension of the Jensen's inequality to address the stability analysis using the new Lyapunov functional (21) with the augmented state X_N .

The proof is based on the expansion of the positive scalar $\|R^{1/2} \chi_N\|^2$ where $\chi_N(x) = \chi(x) - \sum_{k=0}^N (2k+1) \tilde{\mathfrak{X}}_k \mathcal{L}_k(x)$ can be interpreted as the error approximation between function χ and its orthogonal projection over the family $\{\mathcal{L}_k\}_{k \leq N}$.

The next lemma is concerned by the differentiation of $\tilde{\mathfrak{X}}_k$.
Lemma 3: For any function $\chi \in L^2$, the following expression holds for any N in \mathbb{N} :

$$\begin{bmatrix} \dot{\tilde{\mathfrak{X}}}_0 \\ \vdots \\ \dot{\tilde{\mathfrak{X}}}_N \end{bmatrix} = c \mathbb{1}_N \chi(1) - c \bar{\mathbb{1}}_N \chi(0) - c L_N \begin{bmatrix} \tilde{\mathfrak{X}}_0 \\ \vdots \\ \tilde{\mathfrak{X}}_N \end{bmatrix},$$

where

$$L_N = \begin{bmatrix} \ell_{0,0} I_2 & \cdots & 0_2 \\ \vdots & \ddots & \vdots \\ \ell_{N,0} I_2 & \cdots & \ell_{N,N} I_2 \end{bmatrix}, \mathbb{1}_N = \begin{bmatrix} I_2 \\ \vdots \\ I_2 \end{bmatrix}, \bar{\mathbb{1}}_N = \begin{bmatrix} I_2 \\ \vdots \\ (-1)^N I_2 \end{bmatrix}, \quad (23)$$

where $\ell_N^{k,j} = (2j+1)(1-(-1)^{j+k})$ if $j \leq k$ and 0 otherwise.

Proof: The proof of this lemma is presented in the appendix of this paper because of its technical nature. \square

C. Main result

Taking advantage of the previous lemmas, the following extension to Theorem 1, using the augmented vector X_N , is stated:

Theorem 2: Consider the system defined in (1) for a given speed $c > 0$, a viscous damping $c_0 > 0$ with initial conditions $(X^0, u^0, v^0) \in \mathcal{H}$ compatible with the boundary conditions. Assume that for a given integer $N \in \mathbb{N}$, there exist $P_N \in \mathbb{S}_+^{n+2(N+1)}$ and $S, R \in \mathbb{S}_+^2$ such that inequality

$$\Psi_N = \text{He} \left(Z_N^\top P_N F_N \right) - c \tilde{R}_N + c \left(H_N^\top (S+R) H_N - G_N^\top S G_N \right) \prec 0 \quad (24)$$

holds, where

$$\begin{aligned} F_N &= \begin{bmatrix} I_{n+2N+2} & 0_{n+2N+2,2} \end{bmatrix}, Z_N = \begin{bmatrix} \mathcal{N}_N^\top & c Z_N^\top \end{bmatrix}^\top, \\ \mathcal{N}_N &= \begin{bmatrix} A+BK & \tilde{B} & 0_{n,2(N+1)} \end{bmatrix}, \\ Z_N &= \mathbb{1}_N H_N + \bar{\mathbb{1}}_N G_N - \begin{bmatrix} 0_{2N+2,n} & L_N & 0_{2N+2,2} \end{bmatrix}, \\ G_N &= \begin{bmatrix} 0_{2,n+2N+2} & g \end{bmatrix} + \begin{bmatrix} -K \\ 0_{1,n} \end{bmatrix} \mathcal{N}_N, \\ H_N &= \begin{bmatrix} 0_{2,n+2N+2} & h \end{bmatrix} + \begin{bmatrix} 0_{1,n} \\ K \end{bmatrix} \mathcal{N}_N, \\ \tilde{R} &= \text{diag}(0_n, R, 3R, \dots, (2N+1)R, 0_2), \end{aligned} \quad (25)$$

and where matrices L_N , $\mathbb{1}_N$ and $\bar{\mathbb{1}}_N$ are given in (23). Then, the coupled infinite dimensional system (1) is exponentially stable in the sense of norm $\|\cdot\|_{\mathcal{H}}^2$ and there exist $\gamma > 1$ and $\delta > 0$ such that the energy estimate (10) holds.

Remark 8: Remark 6 also applies for this theorem. That means c_0 must be strictly positive. In other words, these theorems cannot ensure the stability if the PDE is undamped.

Remark 9: Note that Theorem 2 with $N = 0$ leads exactly to the same conditions as presented in Theorem 1.

Remark 10: Following [24] which shows that this methodology introduces a hierarchy in the case of time-delay systems, we also have the same characteristic. In other words, the sets

$$\mathcal{C}_N = \left\{ c > 0 \text{ s.t. } \exists P_N \in \mathbb{S}_+^{n+2(N+1)}, S, R \in \mathbb{S}_+^2, \Psi_N \prec 0 \right\}$$

which represents the set of parameters c such that the LMI of Theorem 2 is feasible for a given system (1) and for a given $N \in \mathbb{N}$ satisfy the following inclusion $\mathcal{C}_N \subseteq \mathcal{C}_{N+1}$. That means, if there exists a solution to Theorem 2 at an order N_0 , then there also exists a solution for any order $N \geq N_0$. The proof is very similar to the one given in [24]. We can proceed by induction with $P_{N+1} = \begin{bmatrix} P_N & 0 \\ 0 & \varepsilon I_2 \end{bmatrix}$ and a sufficiently small $\varepsilon > 0$. Then, $\Psi_N \prec 0 \Rightarrow \Psi_{N+1} \prec 0$. The calculus are tedious and technical and we do not intend to give them in this article.

D. Proof of Theorem 2

The proof of dissipativity follows the same line as in Theorem 1 and consists in proving the existence of positive

scalars $\varepsilon_1, \varepsilon_2$ and ε_3 such that the functional V_N verifies the inequalities given in (11).

1) *Well-posedness:* Using a similar reasoning as in Theorem 1, a necessary condition for LMI (24) to be verified is that $A+BK$ is non singular. Then, according to Propositions 1 and 2, the problem is well-posed and $0_{\mathcal{H}}$ is the unique equilibrium.

2) *Existence of ε_1 :* It strictly follows the same line as in Theorem 1 and is therefore omitted.

3) *Existence of ε_2 :* Since $P_N, S, R \succ 0$, there exists $\varepsilon_2 > 0$ such that:

$$\begin{aligned} P_N &\preceq \text{diag} \left(\varepsilon_2 I_n, \frac{\varepsilon_2}{4} \text{diag} \{ (2k+1) I_n \}_{k \in (0, N)} \right), \\ (S+xR) &\preceq S+R \preceq \frac{\varepsilon_2}{4} I_2, \quad \forall x \in (0, 1). \end{aligned}$$

From equation (21), we get:

$$\begin{aligned} V_N(X_N, u) &\leq \varepsilon_2 |X|_n^2 + \frac{\varepsilon_2}{4} \left(\sum_{k=0}^N (2k+1) \mathfrak{X}_k^\top \mathfrak{X}_k + \|\chi\|^2 \right) \\ &\leq \varepsilon_2 \left(|X|_n^2 + \frac{1}{2} \|\chi\|^2 \right). \end{aligned}$$

While the first inequality is guaranteed by the constraint $(S+xR) \preceq \frac{\varepsilon_2}{4} I_2$, for all $x \in (0, 1)$, the second estimate results from the application of Bessel inequality (22). Therefore, following the same procedure as in the proof of Theorem 1 after equation (12), there indeed exists $\varepsilon_2 > 0$ such that $V_N(X_N, u) \leq \varepsilon_2 \|(X, u)\|_{\mathcal{H}}^2$.

4) *Existence of ε_3 :* Differentiating V_N defined in (21) along the trajectories of system (1) leads to:

$$\dot{V}_N(X_N, u) = \text{He} \left(\begin{bmatrix} \dot{X} \\ \dot{\mathfrak{X}}_0 \\ \vdots \\ \dot{\mathfrak{X}}_N \end{bmatrix}^\top P_N \begin{bmatrix} X \\ \mathfrak{X}_0 \\ \vdots \\ \mathfrak{X}_N \end{bmatrix} \right) + \dot{V}(u).$$

The goal here is to find an upper bound of \dot{V}_N using the following extended state: $\xi_N = \begin{bmatrix} X_N^\top & u_t(1) & cu_x(0) \end{bmatrix}^\top$. Using equation (15) and Lemma 3, we note that $X_N = F_N \xi_N$, $\dot{X}_N = Z_N \xi_N$, $\chi(1) = H_N \xi_N$, $\chi(0) = G_N \xi_N$ where the matrices F_N, Z_N, H_N, G_N are given in (25). Then we can write:

$$\begin{aligned} \dot{V}_N(X_N, u) &= \xi_N^\top \Psi_N \xi_N + c \sum_{k=0}^N \mathfrak{X}_k^\top (2k+1) R \mathfrak{X}_k \\ &\quad - c \int_0^1 \chi^\top(x) R \chi(x) dx. \end{aligned} \quad (26)$$

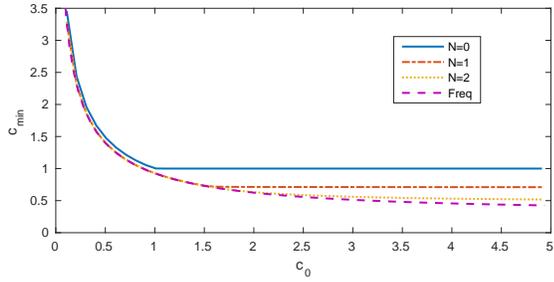
Since $R \succ 0$ and $\Psi_N \prec 0$, there exists $\varepsilon_3 > 0$ such that:

$$\begin{aligned} R &\succeq \frac{\varepsilon_3}{2c} \frac{2+c^2}{c^2} I_2, \\ \Psi_N &\preceq -\varepsilon_3 \text{diag} \left(I_n + K^\top K, \right. \\ &\quad \left. \frac{2+c^2}{2c^2} \text{diag} \{ I_2, 3I_2, \dots, (2N+1)I_2 \}, 0_2 \right). \end{aligned} \quad (27)$$

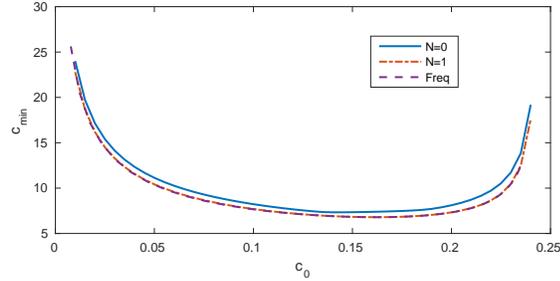
Using (27) and Bessel's inequality, equation (26) becomes:

$$\dot{V}_N(X_N, u) \leq -\varepsilon_3 \left(|X|_n^2 + 2|u(0)|^2 + \frac{2+c^2}{2c^2} \|\chi\|^2 \right),$$

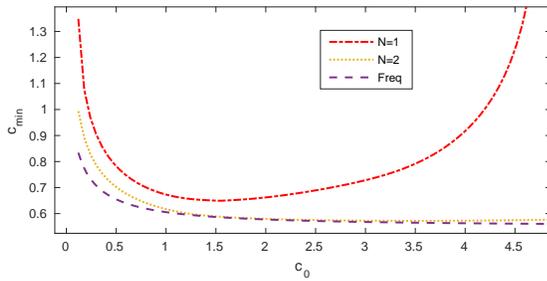
which is similar to equation (19) in the proof of Theorem 1. Therefore, following the same procedure, we obtain $\dot{V}_N(X_N, u) \leq -\varepsilon_3 \|(X, u)\|_{\mathcal{H}}^2$.



(a) System (28)



(b) System (29)



(c) System (30)

Fig. 1: Minimum wave speed c_{min} as a function of c_0 for System (1) to be stable. The values for A , B and K are given by equations (28), (29) or (30).

5) *Conclusion*: There exist $\varepsilon_1, \varepsilon_2$ and ε_3 positive reals such that inequalities (11) are satisfied and the exponential stability of system (1) is therefore guaranteed.

V. EXAMPLES

Three examples of stability for System (1) are provided here. In each case, $A + BK$ is not singular and therefore, there is a unique equilibrium. The solver used for the LMIs is `sd3` with the `YALMIP` toolbox [17].

A. Problem (1) with A and $A + BK$ Hurwitz

In this first part, the considered system is defined as follows:

$$A = \begin{bmatrix} -2 & 1 \\ 0 & -1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad K = \begin{bmatrix} 0 & -2 \end{bmatrix}. \quad (28)$$

Matrices A and $A + BK$ are Hurwitz. The ODE and the PDE are then stable if they are not coupled. As shown in Figure 1a, there exists a minimum wave speed called here c_{min} which is function of the damping c_0 for the system to be stable.

The phenomenon induced by the coupling can be understood as the robustness of the ODE to a disturbance generated by a wave equation. Intuitively, if the wave speed is large enough, the perturbation tends to 0 fast enough for the ODE

to keep its stability behavior. Another important thing to notice is the hierarchy property i.e. the decrease of c_{min} as N increases. The curve denoted ‘‘Freq’’ is obtained using a frequential analysis and displays the exact stability area. This exact method will be explained in another paper but do not use Lyapunov arguments. For this example, as N increases, the stability area is converging to the exact one.

B. Problem (1) with $A + BK$ Hurwitz and A with unstable eigenvalues.

This time, the system is described by the following matrices:

$$A = \begin{bmatrix} 2 & 1 \\ 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad K = \begin{bmatrix} -10 & 2 \end{bmatrix}. \quad (29)$$

As A is not Hurwitz, we are studying the stabilization of the ODE through a communication modeled by the wave equation. For the same reason than before, the wave must be fast enough for the control not to be too much delayed but also with a moderated damping to transfer the state variable X through the PDE equation. Intuitively, we are lead to introduce a trade-off between c_{min} and c_0 , introducing then a c_{0max} as it is possible to see in Figure 1b.

Some numerical simulations have been done on this example. Figure 1b shows that for System (29) with $c_0 = 0.15$, the minimum wave speed is $c_{min} = 6.83$. The numerical stability can also be seen in Figure 2 and indeed, the system is at the boundary of the stable area in Figure 2b and unstable for smaller values of c . The results coming from the exact criterion and Theorem 2 are close even for small N . That means the stability area provided with $N = 1$ is a good estimation of the maximum stability set.

C. Problem (1) with A and $A + BK$ not Hurwitz.

Consider an open loop unstable system defined by:

$$A = \begin{bmatrix} 0 & 1 \\ -2 & 0.1 \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad K = \begin{bmatrix} 1 & 0 \end{bmatrix}. \quad (30)$$

Gain K has been chosen such that the closed loop is also unstable. Surprisingly, the proposed algorithm give some couples (c, c_0) for which the whole System (1) is stable. The results are depicted in Figure 1c. Notice that for Theorem 1 (or Theorem 2 with $N = 0$), the LMIs do not give any stability results. For $N \geq 1$, there is a stability area for which the slope of the right asymptotic branch is decreasing at each order. Hence, it appears that the introduction of the string equation in the feedback loop helps the stabilization of the closed loop system. For $N = 1$, the stability area is quite far from the maximum one but as N increases, this gap reduces significantly.

VI. CONCLUSION

A hierarchy of stability criteria has been provided for the stability of systems described by the interconnection between a finite dimensional linear system and an infinite dimensional ODE modeled by a string PDE. The proposed methodology relies on an extensive use of Bessel’s inequality which allows us to design a new an accurate Lyapunov functional. This new class encompasses the classical notion of energy proposed in that case. In particular, the stability of the closed-loop or open-loop system is not a requirement anymore. Future works will include the study of robustness of this approach and controller design.

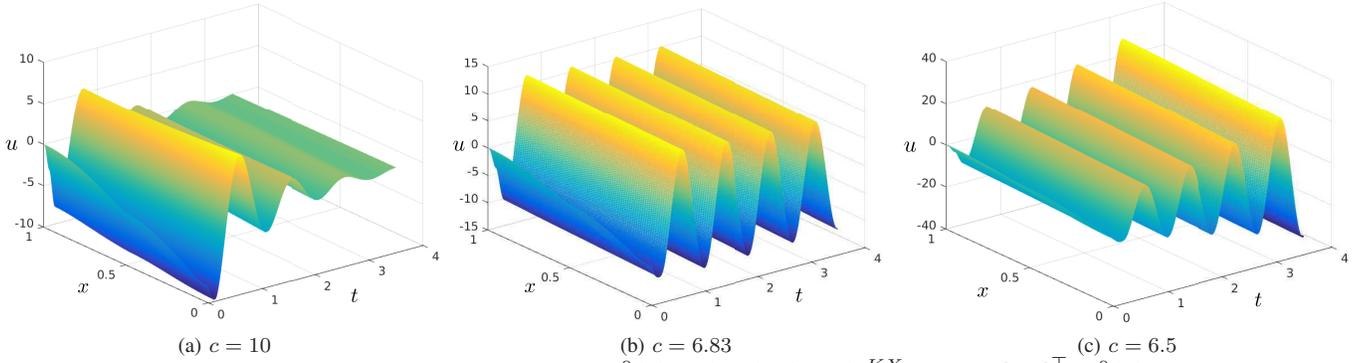


Fig. 2: Chart of u for system (29) with the parameters: $u^0(x) = (\cos(\pi x) + 1) \frac{KX_0}{2}$, $X_0 = [1 \ 1]^\top$, $v^0(x) = 0$ and $c_0 = 0.15$ for 3 values of c . These results are obtained using Euler forward as a numerical scheme.

APPENDIX

A. Proof of Lemma 3

For a given integer k in \mathbb{N} , the differentiating of $\dot{\mathfrak{X}}_k$ along the trajectories of (4) yields $\dot{\mathfrak{X}}_k = c \int_0^1 \chi_x(x) \mathcal{L}_k(x) dx$. Then, integrating by parts, we get

$$\dot{\mathfrak{X}}_k = c \left([\chi(x) \mathcal{L}_k(x)]_0^1 - \int_0^1 \chi(x) \mathcal{L}'_k(x) dx \right). \quad (31)$$

In order to derive the expression of $\dot{\mathfrak{X}}_k$, we will use the following properties of the Legendre polynomials. On the one hand, the values of Legendre polynomials at the boundaries of $[0 \ 1]$ are given by $\mathcal{L}_k(0) = (-1)^k$ and $\mathcal{L}_k(1) = 1$. On the other hand, the Legendre polynomials verifies the following differentiation rule for $k > 0$:

$$\frac{d}{dx} \mathcal{L}_k(x) = \sum_{j=0}^{k-1} (2j+1) (1 - (-1)^{j+k}) \mathcal{L}_j(x)$$

Hence, injecting these expressions into (31) leads to:

$$\dot{\mathfrak{X}}_k = c (\chi(1, t) - (-1)^k \chi(0)) - c \sum_{j=0}^N \ell_N^{k,j} \mathfrak{X}_j$$

where the coefficient $\ell_N^{k,j}$ are defined in equation (23). The end of the proof consists in gathering the previous expression from $k = 1$ to $k = N$, leading to the definition of matrices L_N , $\mathbb{1}_N$ and $\bar{\mathbb{1}}_N$ given in (23).

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