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Null-controllability of linear parabolic-transport systems

Karine Beauchard*, Armand Koenig†, Kévin Le Balch‡

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Abstract

Over the past two decades, the controllability of several examples of parabolic-hyperbolic systems has been investigated. The present article is the beginning of an attempt to find a unified framework that encompasses and generalizes the previous results.

We consider constant coefficients heat-transport systems with coupling of order zero and one, with a locally distributed control in the source term, posed on the one dimensional torus.

We prove the null-controllability, in optimal time (the one expected because of the transport component) when there is as much controls as equations. When the control acts only on the transport (resp. parabolic) component, we prove an algebraic necessary and sufficient condition, on the coupling term, for the null controllability.

The whole study relies on a careful spectral analysis, based on perturbation theory. The proof of the negative result in small time uses holomorphic functions technics. The proof of the positive result in large time relies on a spectral decomposition into low, and asymptotically parabolic or hyperbolic frequencies.

Keywords: parabolic-transport systems, null-controllability, observability.

MSC 2010: 93B05, 93B07, 93C20, 35M30.

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1 Introduction

1.1 Parabolic-transport systems

We consider the linear control system

$$\begin{cases} \partial_t f - B\partial_x^2 f + A\partial_x f + Kf = Mu1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ f(0, \cdot) = f_0 & \text{in } \mathbb{T}, \end{cases} \quad (\text{Sys})$$

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where

- $T > 0$, $\mathbb{T} = \mathbb{R}/(2\pi\mathbb{Z})$, ω is a nonempty open subset of \mathbb{T} , $d \in \mathbb{N}^*$, $m \in \{1, \dots, d\}$, $A, B, K \in \mathbb{R}^{d \times d}$, $M \in \mathbb{R}^{d \times m}$,
- the state is $f : [0, T] \times \mathbb{T} \rightarrow \mathbb{R}^d$,
- the control is $u : [0, T] \times \mathbb{T} \rightarrow \mathbb{R}^m$.

We assume

$$d = d_1 + d_2 \text{ with } 1 \leq d_1 < d, 1 \leq d_2 < d, \quad (\text{H.1})$$

$$B = \begin{pmatrix} 0 & 0 \\ 0 & D \end{pmatrix}, \text{ with } D \in \mathbb{R}^{d_2 \times d_2}, \quad (\text{H.2})$$

$$\Re(\text{Sp}(D)) \subset (0, \infty). \quad (\text{H.3})$$

Introducing the analogue block decomposition for the $d \times d$ matrices A and K , the $d \times m$ matrix M and the function f ,

$$A = \begin{pmatrix} A' & A_{12} \\ A_{21} & A_{22} \end{pmatrix}, \quad K = \begin{pmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{pmatrix}, \quad M = \begin{pmatrix} M_1 \\ M_2 \end{pmatrix}, \quad f(t, x) = \begin{pmatrix} f_1(t, x) \\ f_2(t, x) \end{pmatrix},$$

we see that the system **(Sys)** couples a transport equation on f_1 with a parabolic equation on f_2

$$\begin{cases} (\partial_t + A' \partial_x + K_{11})f_1 + (A_{12} \partial_x + K_{12})f_2 = M_1 u 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - D \partial_x^2 + A_{22} \partial_x + K_{22})f_2 + (A_{21} \partial_x + K_{21})f_1 = M_2 u 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (f_1, f_2)(0, \cdot) = (f_{01}, f_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (1)$$

We make the following hypothesis on the matrix A'

$$A' \text{ is diagonalizable with } \text{Sp}(A') \subset \mathbb{R}. \quad (\text{H.4})$$

We will prove later, with vector valued Fourier series and a careful spectral analysis, that for every $f_0 \in L^2(\mathbb{T}, \mathbb{C}^d)$ and $u \in L^2((0, T) \times \mathbb{T}, \mathbb{C}^m)$, there exists a unique solution $f \in C^0([0, T], L^2(\mathbb{T})^d)$ of **(Sys)** (see Section 2.2.3). In this article, we are interested in the null controllability of **(Sys)**.

Definition 1. The system **(Sys)** is null-controllable on ω in time T if for every $f_0 \in L^2(\mathbb{T}; \mathbb{C}^d)$, there exists a control $u \in L^2((0, T) \times \mathbb{T}, \mathbb{C}^m)$ supported on $[0, T] \times \omega$ such that the solution f of **(Sys)** satisfies $f(T, \cdot) = 0$.

We aim at

- identifying the minimal time for null controllability,
- controlling the system with a small number of controls $m < d$,
- understanding the influence of the algebraic structure (A, B, K, M) on the above properties.

1.2 Statement of the results

1.2.1 Control on any component, minimal time

Our first result identifies the minimal time, when the control acts on each of the d equations.

Theorem 2. *We assume that ω is a strict open subset of \mathbb{T} . We also assume (H.1)–(H.4) and that the control matrix is $M = I_d$ (and so $m = d$). We define¹*

$$\ell(\omega) := \sup\{|I|; I \text{ connected component of } \mathbb{T} \setminus \omega\}, \quad (2)$$

$$\mu_* = \min\{|\mu|; \mu \in \text{Sp}(A')\},$$

and

$$T^* = \begin{cases} \frac{\ell(\omega)}{\mu_*} & \text{if } \mu_* > 0, \\ +\infty & \text{if } \mu_* = 0. \end{cases} \quad (3)$$

Then

¹If $I \subset \mathbb{R}$ is measurable, we note $|I|$ its Lebesgue measure.

- i) the system (Sys) is not null-controllable on ω in time $T < T^*$,
- ii) the system (Sys) is null-controllable on ω in any time $T > T^*$.

In particular, when ω is an interval of \mathbb{T} and $\mu_* > 0$, then the minimal time for null controllability is $T^* = \frac{2\pi - |\omega|}{\mu_*}$.

Actually, the controls may be more regular than in Definition 1: we construct controls of the form $u = (u_1, u_2)$ where $u_1 \in L^2((0, T) \times \omega)^{d_1}$ and $u_2 \in C_c^\infty((0, T) \times \omega)^{d_2}$.

The proof of Theorem 2 relies on a spectral decomposition: for high frequencies, the spectrum splits into a parabolic part and a hyperbolic part.

The negative result in time $T < T^*$ is expected, because of the transport component of the system, but its proof is not obvious. Indeed, because of the coupling with a parabolic component, in general, there does not exist pure transport solutions to the system (Sys), concentrated outside $(0, T) \times \omega$ (see Section 3.1 for more precision). Our proof consists in disproving the equivalent observability inequality on solutions of the adjoint system, built on non trivial finite sums of hyperbolic eigenfunctions. Their existence is proved by holomorphic functions technics developed by the second author [17].

The proof of the positive result, in time $T > T^*$ relies on an adaptation, to systems with arbitrary size, of the strategy introduced by Lebeau and Zuazua [20] to control the system of linear thermoelasticity, that couples a scalar heat equation and a scalar wave equation. By projecting the dynamics onto appropriate eigenspaces, the system is decomposed into 3 weakly coupled systems. The first one behaves like a transport system, its controllability is handled by hyperbolic methods from [1]. The second one behaves like a parabolic system, its controllability is handled by the Lebeau-Robbiano method. The third one, associated to low frequencies, has finite dimension; its controllability is handled by a compactness/uniqueness argument.

The null controllability of the system (Sys) in time $T = T^*$ is an open problem.

1.2.2 Control on the hyperbolic component

Our second result concerns controls acting on the whole transport component, $M_1 = I_{d_1}$, but not on the parabolic component, $M_2 = 0$. To get an aesthetic necessary and sufficient algebraic condition for null controllability, we also assume that the diffusion is given by $D = I_{d_2}$, the coupling is realized exclusively by the transport term $A_{21}\partial_x f_1$, i.e. $K_{21} = 0$ and there is no zero order term in the parabolic dynamics, i.e. $K_{22} = 0$, which corresponds to the system

$$\begin{cases} (\partial_t + A'\partial_x + K_{11})f_1 + (A_{12}\partial_x + K_{12})f_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + A_{22}\partial_x)f_2 + A_{21}\partial_x f_1 = 0 & \text{in } (0, T) \times \mathbb{T}. \end{cases} \quad (4)$$

By integrating with respect to the space variable the second equation of (4), we see that, for being steered to zero, an initial condition $f_0 = (f_{01}, f_{02}) \in L^2(\mathbb{T})^{d_1} \times L^2(\mathbb{T})^{d_2}$ has to satisfy

$$\int_{\mathbb{T}} f_{02}(x) dx = 0. \quad (5)$$

For any vector subspace E of $L^1(\mathbb{T})$ we denote by E_m the vector subspace made of functions $f \in E$ with zero mean value, i.e. $\int_{\mathbb{T}} f(x) dx = 0$.

Theorem 3. *We assume (H.1)–(H.4), $D = I_{d_2}$, $m = d_1$, $M_1 = I_{d_1}$, $M_2 = 0$, $K_{21} = 0$ and $K_{22} = 0$. Let T^* be defined by (3). The following statements are equivalent:*

- For every $T > T^*$ and $f_0 = (f_{01}, f_{02}) \in L^2(\mathbb{T})^{d_1} \times L_m^2(\mathbb{T})^{d_2}$, there exists $u_1 \in L^2((0, T) \times \omega)^{d_1}$ such that the solution of (4) satisfies $f(T) = 0$.
- The couple of matrices (A_{22}, A_{21}) satisfies the Kalman rank condition:

$$\text{Span}\{A_{22}^j A_{21} X_1; X_1 \in \mathbb{C}^{d_1}, 0 \leq j \leq d_2 - 1\} = \mathbb{C}^{d_2}. \quad (6)$$

With the same proof, similar statements can be proved for the following systems:

$$\begin{cases} (\partial_t + A'\partial_x + K_{11})f_1 + (A_{12}\partial_x + K_{12})f_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + K_{22})f_2 + K_{21}f_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \end{cases} \quad (7)$$

with arbitrary initial conditions $f_0 \in L^2(\mathbb{T})^d$ and Kalman rank condition on (K_{22}, K_{21}) (see Section 5),

$$\begin{cases} (\partial_t + A'\partial_x + K_{11})f_1 + (A_{12}\partial_x + K_{12})f_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + A_{22}\partial_x)f_2 + K_{21}f_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \end{cases} \quad (8)$$

with arbitrary initial conditions $f_0 \in L^2(\mathbb{T})^d$ and Kalman rank condition on (A_{22}, K_{21}) ,

$$\begin{cases} (\partial_t + A'\partial_x + K_{11})f_1 + (A_{12}\partial_x + K_{12})f_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + K_{22})f_2 + A_{21}\partial_x f_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \end{cases} \quad (9)$$

with initial conditions $f_0 \in L^2(\mathbb{T})^d$ satisfying (5) and Kalman rank condition on (K_{22}, A_{21}) .

The proof of the controllability of (4) uses 2 ingredients. The first ingredient is a strengthened version of Theorem 2 with smoother controls, more precisely, the associated observability inequality with observation of negative Sobolev norms of the parabolic component. The second ingredient is a cascade structure (or Brunovski form) of the system (4) ensured by the Kalman condition, to eliminate the observation of the parabolic component.

Proving an algebraic necessary and sufficient condition for null controllability of (Sys), involving both matrices D , A and K is an open problem. In the context of parabolic systems, this difficulty already appeared, see [3] and [11].

1.2.3 Control on the parabolic component

Our third result concerns controls acting on the whole parabolic component, $M_2 = I_{d_2}$, but not on the hyperbolic component of the system, $M_1 = 0$. To get an aesthetic necessary and sufficient condition for null controllability, we also assume that the coupling is realized exclusively by the transport term $A_{12}\partial_x f_2$, i.e. $K_{12} = 0$, and there is no zero order term in the hyperbolic dynamics, i.e. $K_{11} = 0$. This corresponds to the system

$$\begin{cases} (\partial_t + A'\partial_x)f_1 + A_{12}\partial_x f_2 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - D\partial_x^2 + A_{22}\partial_x + K_{22})f_2 + (A_{21}\partial_x + K_{21})f_1 = u_2 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (f_1, f_2)(0, \cdot) = (f_{01}, f_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (10)$$

By integrating with respect to the space variable the first equation of (10), we see that, for being steered to zero, an initial condition $f_0 = (f_{01}, f_{02}) \in L^2(\mathbb{T})^{d_1} \times L^2(\mathbb{T})^{d_2}$ has to satisfy

$$\int_{\mathbb{T}} f_{01}(x) dx = 0 \quad (11)$$

i.e. $f_0 = (f_{01}, f_{02}) \in L_m^2(\mathbb{T})^{d_1} \times L^2(\mathbb{T})^{d_2}$.

We need to adapt the notion of null controllability, because null controllable initial conditions necessarily have a regular hyperbolic component. Indeed, in (10), the source term $A_{12}\partial_x f_2$ entering the hyperbolic equation on f_1 — that has to serve as an indirect control for f_1 — is smooth, because of the parabolic smoothing on f_2 . Such a smooth source term cannot steer to zero non-smooth initial conditions.

Theorem 4. *Let ω be an open interval of \mathbb{T} . We assume (H.1)–(H.4), $m = d_2$, $M_1 = 0$, $M_2 = I_{d_2}$, $K_{11} = 0$ and $K_{12} = 0$. Let T^* be defined by (3). The following statements are equivalent.*

- For every $T > T^*$ and $f_0 = (f_{01}, f_{02}) \in H_m^{d_1+1}(\mathbb{T})^{d_1} \times H^{d_1+1}(\mathbb{T})^{d_2}$ there exists $u_2 \in L^2((0, T) \times \omega)^{d_2}$ such that the solution of (10) satisfies $f(T) = 0$.
- The couple of matrices (A', A_{12}) satisfies the Kalman rank condition:

$$\text{Span}\{(A')^j A_{12} X_2; X_2 \in \mathbb{C}^{d_2}, 0 \leq j \leq d_2 - 1\} = \mathbb{C}^{d_2}. \quad (12)$$

In Theorem 4, we assume that the open set of control ω is an interval because the proof uses [1, Lemma 2.6] (see Lemma 55 below). The generalisation of this result to a general open set ω of \mathbb{T} is not known.

A similar statement can be obtained with the same proof, when $K_{11} = 0$, $A_{12} = 0$ under Kalman rank condition on (A', K_{12}) .

The proof of Theorem 4 follows essentially the same strategy as the one of Theorem 3: a strengthened version of Theorem 2 and a cascade structure ensured by Kalman condition. The regularity assumption on the hyperbolic component allows the elimination of the observation of the hyperbolic component.

After Theorem 4, two problems are still open:

- the characterization of null controllable initial conditions: it may be a larger space than $H_m^{d_1+1}(\mathbb{T})^{d_1} \times H^{d_1+1}(\mathbb{T})^{d_2}$, see Section 7,
- the algebraic necessary and sufficient condition for null controllability, involving both matrices A and K . In the context of parabolic systems, this difficulty already appeared, see [3] and [11].

1.3 Organization of the article

Section 2 is dedicated to preliminary results concerning the spectral analysis of $-B\partial_x^2 + A\partial_x + K$ on \mathbb{T} , the well posedness of (Sys) and the Hilbert uniqueness method.

In Section 3, we prove the negative null controllability result in time $T < T^*$ of Theorem 2.

In Section 4, we prove the positive null controllability result in time $T > T^*$ of Theorem 2.

In Section 5, we explain how to adapt this proof to get the null controllability in time $T > T^*$ of system (7). The interest of this section is to introduce the proof strategy of Theorem 3 and Theorem 4, in a less technical framework.

Then, in Section 6, we prove Theorem 3 and in Section 7, we prove Theorem 4.

In Appendix A, we prove a technical result about operators on holomorphic functions, used in Section 3.

1.4 Bibliographical comments

1.4.1 Wave equation with structural damping

We consider the 1D wave equation with structural damping and control h

$$\partial_t^2 y - \partial_x^2 y - \partial_t \partial_x^2 y + b \partial_t y = h(t, x), \quad (13)$$

where $b \in \mathbb{R}$. This equation can be splitted in a system of the form (Sys) by considering $z := \partial_t y - \partial_x^2 y + (b-1)y$,

$$\begin{cases} \partial_t z + z + (1-b)y = h(t, x), \\ \partial_t y - \partial_x^2 y - z + (b-1)y = 0, \end{cases} \quad (14)$$

i.e. (Sys) with $d = 2$, $d_1 = d_2 = 1$, $m = 1$,

$$f = \begin{pmatrix} z \\ y \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \quad A = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}, \quad K = \begin{pmatrix} 1 & 1-b \\ -1 & b-1 \end{pmatrix}, \quad M = \begin{pmatrix} 1 \\ 0 \end{pmatrix}. \quad (15)$$

Rosier and Rouchon [25] studied the equation (13) on a 1D-interval, $x \in (0, 1)$, with a boundary control at $x = 1$ and $h = 0$. This is essentially equivalent to take (13) with $x \in (0, 1)$, Dirichlet boundary conditions at $x = 0$ and $x = 1$, and a source term of the form $h(t, x) = u(t)p(x)$, where p is a fixed profile and u is a scalar control. The authors prove that this equation is not controllable.

By Theorem 2, we extend this negative result to general controls h (i.e. without separate variables) for periodic boundary conditions. Here, $A' = 0$, $\mu_* = 0$, $T^* = +\infty$, the system (14) is not controllable even with an additional control in the second equation.

In [25], the authors prove that this system is not even spectrally controllable, because of an accumulation point in the spectrum. Indeed, by the moment method, a control that would steer the system from an eigenstate to another one would have a Fourier transform vanishing on a set with an accumulation point, which is not possible for an holomorphic function.

Martin, Rosier and Rouchon [22], studied the null-controllability of the equation (13) on the 1D torus, $x \in \mathbb{T}$, with moving controls, i.e. $h(t, x) = u(t, x)1_{\omega+ct}$ with $c \in \mathbb{R}^*$. By the change of variable $x \mapsto (x - ct)$, this is equivalent to study the null controllability of the system

$$\begin{cases} \partial_t z - c\partial_x z + z + (1-b)y = u(t, x)1_\omega(x), \\ \partial_t y - c\partial_x y - \partial_x^2 y - z + (b-1)y = 0 \end{cases} \quad (16)$$

which has the form (Sys) with the same matrices f, B, K as in (15) and

$$A = \begin{pmatrix} -c & 0 \\ 0 & -c \end{pmatrix}.$$

In [22, Theorem 1.2], for $c = 1$, the authors prove that any initial data $(y_0, y_1) \in H^{s+2} \times H^s(\mathbb{T})$ with $s > 15/2$ can be steered to 0 in time $T > 2\pi$ by mean of a control $u \in L^2((0, T) \times \omega)$.

By Theorem 3, we recover this positive null controllability result with a smaller minimal time $T > \ell(\omega)/|c|$ and a weaker regularity assumption on the initial data $(y, \partial_t y)(0) = (y_0, y_1) \in H^2 \times L^2(\mathbb{T})$ for (13). This corresponds to an initial data $(y, z)(0) \in L^2(\mathbb{T})^2$ for (16) because $z(0) = y_1 - \partial_x^2 y_0 + (b-1)y_0$. Actually, Theorem 3 can be applied for $b = 1$ in (16) but an easy adaptation of Theorem 3 gives the same result for every $b \in \mathbb{R}$. We also prove the negative result in time $T < \ell(\omega)/|c|$. Here, $\mu_* = |c|$, $A_{21} = 0$ and $K_{21} = -1$.

The limitations in [22, Theorem 1.2] (regularity and time) are due to the use of controls with separate variables $u(t, x) = u_1(t)u_2(x)$. The proof relies on the moment method and the construction of a biorthogonal family. A key point in both [22] and the present article is a splitting of the spectrum in one parabolic-type part, and one hyperbolic-type part.

Finally, Chaves-Silva, Rosier and Zuazua [9] study the multi-dimensional case of equation (13), $x \in \Omega$, with Dirichlet boundary conditions and locally distributed moving controls $h(t, x) = u(t, x)1_{\omega(t)}(x)$. The control region $\omega(t)$ is assumed to be driven by the flow of an ODE that covers all the domain Ω within the allotted time T . Then, the authors prove the null controllability of any initial data $(y_0, y_1) \in H^2 \cap H_0^1(\Omega) \times L^2(\Omega)$ with a L^2 -control.

In the particular case $\Omega = \mathbb{T}$ with a motion with constant velocity, Theorem 3 gives the same minimal time for the null controllability and also the negative result in smaller time.

The proof strategy in [9] consists in proving Carleman estimates for the parabolic equation and the ODE in (14) with *the same singular weight*, adapted to the geometry of the moving support of the control.

As explained in [9, Section 5.2], the same construction cannot be used with periodic boundary conditions.

In the very recent preprint [14], the authors propose another construction of a weight, to get Carleman estimates for parabolic and transport equations in the torus \mathbb{T}^2 (with the same weight). In the present article, we develop another strategy.

1.4.2 Wave-parabolic systems

Albano and Tataru [2] consider 2×2 parabolic-wave systems with boundary control, where

- the coupling term in the wave equation is given by a second order operator with respect to x ,
- the coupling term in the parabolic equation is given by a first order operator with respect to (t, x) .

This large class contains the linear system of thermoelasticity

$$\begin{cases} \partial_t^2 w - \Delta w + \alpha \Delta \theta = 0, & (t, x) \in (0, T) \times \Omega, \\ \partial_t \theta - \nu \Delta \theta + \beta \partial_t w = 0, & (t, x) \in (0, T) \times \Omega, \\ w(t, x) = u_1(t, x), & (t, x) \in (0, T) \times \partial\Omega, \\ \theta(t, x) = u_2(t, x), & (t, x) \in (0, T) \times \partial\Omega, \end{cases} \quad (17)$$

where $\alpha, \beta, \nu > 0$.

The authors of [2] prove the null controllability in large time of these systems, precisely in any time $T > 2 \sup\{|x|; x \in \Omega\}$ for the system (17). The proof relies on Carleman estimates for the

heat and the wave equation with the same singular weight. This strategy inspired Chaves-Silva, Rosier and Zuazua [9].

Lebeau and Zuazua [20] prove the null-controllability of the linear system of thermoelasticity (17) with a locally distributed control in the source term of the wave equation, under the geometric control condition on (Ω, ω, T) . The method is based on a spectral decomposition. For high frequencies, the spectrum splits into a parabolic part and a hyperbolic part. Projecting the dynamics onto the parabolic/hyperbolic subspaces, the system is decomposed into 2 weakly coupled systems, the first one behaving like a wave equation, the second one like a heat equation. The wave equation is handled by using the microlocal techniques developed for the wave equation [5]. The parabolic equation is treated by using Lebeau and Robbiano's method [19]. The low frequency part is treated by a compactness argument relying on a unique continuation property.

The proof of the positive controllability results in the present article is an adaptation, to coupled transport-parabolic systems *of any size*, of this approach, introduced for a 2×2 wave-parabolic system. The transport equation is handled by using the results from Alabau-Boussouira, Coron and Olive [1].

The framework of systems (Sys) does not cover the system (17) because the order of the coupling terms is too high.

1.4.3 Heat equation with memory

Ivanov and Pandolfi [15] and after them Guerrero and Imanuvilov [13] consider the heat equation with memory

$$\begin{cases} \partial_t y - \Delta y - \int_0^t \Delta y(\tau) d\tau = u1_\omega, & (t, x) \in (0, T) \times \Omega, \\ y(t, x) = 0, & (t, x) \in (0, T) \times \partial\Omega. \end{cases} \quad (18)$$

In 1D, this equation can be splitted into a system of the form (Sys) by considering $v(t, x) = -\int_0^t y_x(\tau) d\tau$:

$$\begin{cases} \partial_t v + \partial_x y = 0, \\ \partial_t y - \partial_x^2 y + v_x = h1_\omega, \\ y(t, 0) = y(t, 1) = v(t, 0) = 0, \end{cases} \quad (19)$$

i.e.

$$f = \begin{pmatrix} v \\ y \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \quad A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad K = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix}.$$

In [15], the authors prove that the heat equation with memory term is not “null-controllable to the rest”. In [13], the authors prove that the scalar equation (18) is not null controllable (whatever $T > 0$). Thus the system (19) is not null controllable.

Theorem 2 proves that, when Dirichlet boundary conditions are replaced by periodic boundary conditions, then system (19) is not null controllable, even with an additional control in the first equation.

2 Preliminary results

We want to understand the operator

$$\mathcal{L} := -B\partial_x^2 + A\partial_x + K \quad (20)$$

with domain

$$D(\mathcal{L}) = \{f \in L^2(\mathbb{T})^d; -B\partial_x^2 f + A\partial_x f + Kf \in L^2(\mathbb{T})^d\} \quad (21)$$

where the derivatives are considered in the distributional sense $\mathcal{D}'(\mathbb{T})$. Throughout the article, we will note e_n the function $x \mapsto e^{inx}$. We remark that applying \mathcal{L} to Xe_n , where $X \in \mathbb{C}^d$, we get

$$\mathcal{L}(Xe_n) = n^2 \left(B + \frac{i}{n} A + \frac{1}{n^2} K \right) Xe_n. \quad (22)$$

Thus, if we define $E(z)$ the following perturbation of B

$$\forall z \in \mathbb{C}, \quad E(z) = B + zA - z^2K, \quad (23)$$

then \mathcal{L} acts on the Fourier side as a multiplication by $n^2 E(i/n)$.

In Section 2.1, we apply the perturbation theory to the matrices $E(z)$ near $z = 0$: the spectrum of $E(z)$ splits into 2 parts: one close to zero that defines the hyperbolic component, one close to the spectrum of D that defines the parabolic component. In Section 2.2, we deduce the dissipation of the parabolic component and the boundedness of the hyperbolic component. Thanks to these estimates, we prove the well-posedness of System (Sys). Finally, in Section 2.3, we recall the Hilbert Uniqueness Method.

2.1 Perturbation theory

If we want to understand the semigroup $e^{t\mathcal{L}}$, we need to know the spectrum and the eigenvectors of $E(z)$. Here, we relate the spectral properties of $E(z)$ to those of A and B , in the limit $z \rightarrow 0$. This is instrumental in all the article. Our proofs are essentially self-contained, but the reader unfamiliar with the analytic perturbation theory in finite dimension may read [16, Ch. II §1 and §2].

For $r > 0$ and $m \in \mathbb{N}^*$, we define $\mathcal{O}_r^{m \times m}$ as the set of holomorphic functions in the complex disk $D(0, r)$ with values in $\mathbb{C}^{m \times m}$. Our first result is the following one.

Proposition 5. *There exist $r > 0$ and a matrix-valued holomorphic function $P^h \in \mathcal{O}_r^{m \times m}$ such that*

- i) $P^h(0) = \begin{pmatrix} I_{d_1} & 0 \\ 0 & 0 \end{pmatrix}$,
- ii) for all $|z| < r$, $P^h(z)$ is a projection that commutes with $E(z)$,
- iii) in the limit $z \rightarrow 0$, $E(z)P^h(z) = O(z)$.

Proof. The spectrum of $E(z)$ is continuous in z (see [16, Ch. II §1.1]). Let us consider the “0-group” of eigenvalues, i.e. the set of eigenvalues that tend to 0 as $z \rightarrow 0$. Then we note $P^h(z)$ the sum of the projections onto the eigenspace² of $E(z)$ associated with eigenvalues in the 0-group along the other eigenspaces. Another way to define $P^h(z)$ is to choose $R = \frac{1}{2} \min_{\lambda \in \text{Sp}(D)} |\lambda|$ and r small enough so that for $|z| < r$, there is no eigenvalues of $E(z)$ on the circle $\partial D(0, R)$. Then, we define (see [16, Ch. II, Eq. (1.16)])

$$P^h(z) = -\frac{1}{2i\pi} \int_{\partial D(0, R)} (E(z) - \zeta I_d)^{-1} d\zeta. \quad (24)$$

In the terminology of Kato, $P^h(z)$ is the “total projection for the 0-group”. Then, according to [16, Ch. II §1.4], $P^h(z)$ is the projection onto the sum of eigenspaces associated to eigenvalues of $E(z)$ lying inside $D(0, R)$ along the other eigenspaces. It is holomorphic in $|z| < r$. For $z = 0$, the formula (24) that defines $P^h(0)$ becomes

$$P^h(0) = -\frac{1}{2i\pi} \int_{\partial D(0, R)} (B - \zeta I_d)^{-1} d\zeta.$$

Then, $P^h(0)$ is the projection onto the eigenspace of B associated to the eigenvalue 0 along the other eigenspaces (see [16, Ch. II §1.4]). So, according to the hypotheses (H.2–H.3) on the blocks of B , $P^h(0) = \begin{pmatrix} I_{d_1} & 0 \\ 0 & 0 \end{pmatrix}$. This proves i).

According to the definition (24), $P^h(z)$ commutes with $E(z)$. This proves ii). Then we have

$$P^h(0)E(0) = E(0)P^h(0) = BP^h(0) = 0,$$

which, along with the holomorphy of P^h , proves iii). □

We say that P^h is the “projection on the hyperbolic branches”. We note $P^p(z) = I_d - P^h(z)$, which we call the “projection on the parabolic branches”, and satisfies properties analog to P^h :

Proposition 6. *The matrix-valued function P^p is in $\mathcal{O}_r^{m \times m}$ and*

²We stress that when we talk about “eigenspace”, we mean “generalized eigenspace” (or, in the terminology of Kato, algebraic eigenspace), i.e. the space of generalized eigenvectors.

- i) $P^P(0) = \begin{pmatrix} 0 & 0 \\ 0 & I_{d_2} \end{pmatrix}$,
- ii) for all $|z| < r$, $P^P(z)$ is a projection that commutes with $E(z)$,
- iii) in the limit $z \rightarrow 0$, $E(z)P^P(z) = B + O(z)$.

We will need to split the hyperbolic branches further.

Proposition 7. *There exist $r > 0$ and a family of matrix-valued holomorphic functions $(P_\mu^h)_{\mu \in \text{Sp}(A')} \in (\mathcal{O}_r^{d \times d})^{\text{Sp}(A')}$ satisfying*

- i) for all $\mu \in \text{Sp}(A')$ and $|z| < r$, $P_\mu^h(z)$ is a non-zero projection that commutes with $E(z)$,
- ii) for all $|z| < r$, $P^h(z) = \sum_{\mu \in \text{Sp}(A')} P_\mu^h(z)$ and for all $\mu \neq \mu'$, $P_\mu^h(z)P_{\mu'}^h(z) = 0$,
- iii) for every $\mu \in \text{Sp}(A')$, there exists $R_\mu^h \in \mathcal{O}_r^{d \times d}$ such that

$$\forall |z| < r, E(z)P_\mu^h(z) = \mu z P_\mu^h(z) + z^2 R_\mu^h(z).$$

Remark 8. For $\mu \in \text{Sp}(A')$, the projection P_μ^h is holomorphic and thus continuous in $D(0, r)$. Therefore, the rank of $P_\mu^h(z)$, which is its trace, does not depend on $|z| < r$ (the $P_\mu^h(z)$ even are similar, see [16, Ch. I, §4.6, Lem. 4.10]). In the same vein, the ranks of $P^h(z)$ and $P^P(z)$ do not depend on z .

Proof. The proof is essentially the “reduction process” of Kato [16, Ch. II §2.3]. According to Prop. 5, P^h is holomorphic and $P^h(z)E(z) = O(z)$. Then we define

$$E^{(1)}(z) = z^{-1}E(z)P^h(z) = z^{-1}P^h(z)E(z),$$

which is holomorphic in $|z| < r$. Note that we have according to Kato [16, Ch. II Eq. (2.38)]

$$E^{(1)}(0) = P^h(0)E(0)P^h(0) = \begin{pmatrix} A' & 0 \\ 0 & 0 \end{pmatrix}.$$

Let us assume for the moment that 0 is not an eigenvalue of A' . Then, for $\mu \in \text{Sp}(A')$, we define $P_\mu^h(z)$ the total projection on the μ -group of eigenvalues of $E^{(1)}(z)$. Said otherwise, and according to the definition of $E^{(1)}(z)$, $P_\mu^h(z)$ is the total projection on the μz -group of eigenvalues of $E(z)$. The projection $P_\mu^h(z)$ is defined and holomorphic for z small enough according to [16, Ch. II, §1.4].

Since for z small enough, $P_\mu^h(z)$ is the projection on some eigenspaces of $E^{(1)}(z)$ associated with non-zero eigenvalues,

$$\text{Im}(P_\mu^h(z)) \subset \text{Im}(E^{(1)}(z)) \subset \text{Im}(P^h(z)),$$

with the last inclusion coming from the definition of $E^{(1)}(z)$. Thus $P_\mu^h(z)$ is a subprojection of $P^h(z)$. Moreover, $P_\mu^h(z)$ commutes with $E^{(1)}(z)$, so it commutes with $E(z)$. This proves Item *i*) in the case $0 \notin \text{Sp}(A')$.

For $\mu \neq \nu$, $P_\mu^h(z)$ and $P_\nu^h(z)$ are the projections on some sums of eigenspaces associated with different eigenvalues, so $P_\mu^h(z)P_\nu^h(z) = 0$. Let us note for convenience $Q^h(z) = \sum_{\mu \in \text{Sp}(A')} P_\mu^h(z)$. Then, for z small, $Q^h(z)$ is the projection on all the eigenspaces of $E^{(1)}(z)$ associated with non-zero eigenvalues. According to the definition of $E^{(1)}(z)$, this proves that $Q^h(z)$ is a subprojection of $P^h(z)$. Let us check that $Q^h(z)$ and $P^h(z)$ have the same rank. This will prove that for all z small enough, $Q^h(z) = P^h(z)$. The rank of $Q^h(z)$, which is its trace, does not depend on z . The same is true for $P^h(z)$. For $z = 0$, we have $E^{(1)}(0) = \begin{pmatrix} A' & 0 \\ 0 & 0 \end{pmatrix}$, so by using the fact that $0 \notin \text{Sp}(A')$,

$$Q^h(0) = \begin{pmatrix} I_{d_1} & 0 \\ 0 & 0 \end{pmatrix} = P^h(0).$$

This proves that for all z small enough, $Q^h(z) = P^h(z)$, and in turn finishes the proof of Item *ii*) in the case where $0 \notin \text{Sp}(A')$.

If $0 \in \text{Sp}(A')$, then we add $\alpha z I$ to $E(z)$ for some $\alpha \in \mathbb{C}$. This amounts to adding $\alpha P^{\text{h}}(z)$ to $E^{(1)}(z)$. This only shifts the eigenvalues of the restriction of $E^{(1)}(z)$ to $\text{Im}(P^{\text{h}}(z))$ (but not of its restriction to $\text{Im}(I_d - P^{\text{h}}(z))$) by α , while leaving the eigenprojections unchanged. Thus, choosing α so that $0 \notin \alpha + \text{Sp}(A')$, we get the Items *i*) and *ii*) in the case $0 \in \text{Sp}(A')$.

We still need to prove the asymptotics of Item *iii*). Since A' is diagonalizable, so is $E^{(1)}(0) = \begin{pmatrix} A' & 0 \\ 0 & 0 \end{pmatrix}$. So, there is no nilpotent part in the spectral decomposition of $E^{(1)}(0)$. That is to say, for all $\mu \in \text{Sp}(A')$,

$$E^{(1)}(0)P_\mu^{\text{h}}(0) = \mu P_\mu^{\text{h}}(0).$$

Since $z \mapsto E^{(1)}(z)P_\mu^{\text{h}}(z)$ is holomorphic, we have

$$E^{(1)}(z)P_\mu^{\text{h}}(z) = \mu P_\mu^{\text{h}}(z) + O(z).$$

Finally, we multiply by z to come back to $E(z)$, which gives us

$$E(z)P_\mu^{\text{h}}(z) = \mu z P_\mu^{\text{h}}(z) + O(z^2). \quad \square$$

2.2 Estimates on Fourier components and well-posedness

2.2.1 Dissipation of the parabolic component

The goal of this section is the proof of the following result.

Proposition 9. *There exist $r, K_{\text{p}}, c_{\text{p}} > 0$ such that for every $|z| < r$, $\tau > 0$ and $X \in \text{Im}(P^{\text{p}}(z))$,*

$$|e^{-E(z)\tau} X| \leq K_{\text{p}} e^{-c_{\text{p}}\tau} |X|.$$

Proof. By using Proposition 6, for $|z| \leq r$, we denote by $E^{\text{p}}(z)$ the restriction of $E(z)$ to the vector subspace $\text{Im}[P^{\text{p}}(z)]$, which is an endomorphism of $\text{Im}[P^{\text{p}}(z)]$.

By assumption (H.3), there exists $c > 0$ such that $\Re(\text{Sp}(D)) \subset (c, \infty)$. There exists an open disk Ω in the complex plane such that $\text{Sp}(D) \subset \Omega$ and $\min\{\Re(z); z \in \Omega\} > c$. Then, by continuity of the spectrum, for r small enough, we have, for every $|z| \leq r$, $\text{Sp}(E^{\text{p}}(z)) \subset \Omega$.

Step 1: Cauchy formula. We prove the following equality between endomorphisms of $\text{Im}[P^{\text{p}}(z)]$

$$\forall |z| \leq r, \tau \in \mathbb{R}, \quad e^{-E^{\text{p}}(z)\tau} = \frac{1}{2\pi i} \int_{\partial\Omega} e^{-\tau\xi} (\xi I - E^{\text{p}}(z))^{-1} d\xi, \quad (25)$$

where I is the identity on $\text{Im}[P^{\text{p}}(z)]$. The right hand side is well defined because $\partial\Omega \cap \text{Sp}(E^{\text{p}}(z)) = \emptyset$. Let us denote it by $\phi(\tau)$. Then

$$\begin{aligned} \phi'(\tau) &= \frac{-1}{2\pi i} \int_{\partial\Omega} e^{-\tau\xi} \xi (\xi I - E^{\text{p}}(z))^{-1} d\xi \\ &= \frac{-1}{2\pi i} \int_{\partial\Omega} e^{-\tau\xi} ((\xi I - E^{\text{p}}(z)) + E^{\text{p}}(z)) (\xi I - E^{\text{p}}(z))^{-1} d\xi. \end{aligned}$$

By the Cauchy formula, $\int_{\partial\Omega} e^{-\tau\xi} d\xi = 0$ thus $\phi'(\tau) = -E^{\text{p}}(z)\phi(\tau)$. Moreover $\phi(0) = I$ because all the eigenvalues of $E^{\text{p}}(z)$ are inside Ω (see [16, Ch. I, Problem 5.9]). Thus $\phi(\tau) = e^{-\tau E^{\text{p}}(z)}$.

Step 2: Estimate. We deduce from (25) the following equality between endomorphisms of \mathbb{C}^d

$$\forall |z| \leq r, \tau \in \mathbb{R}, \quad e^{-E(z)\tau} P^{\text{p}}(z) = \frac{1}{2\pi i} \int_{\partial\Omega} e^{-\tau\xi} (\xi I_d - E(z))^{-1} P^{\text{p}}(z) d\xi. \quad (26)$$

Note that, if r is small enough, then the eigenvalues of $E(z)$ are either inside Ω (parabolic branch) or close to 0 (hyperbolic branch), for instance in $\{\Re(\xi) < c/2\}$. Thus $(\xi I_d - E(z))$ is invertible on \mathbb{C}^d for every $\xi \in \partial\Omega$ and the above right hand side is well defined.

We deduce from (26) that

$$\left| e^{-E(z)\tau} P^{\text{p}}(z) \right| \leq \frac{1}{2\pi} \int_{\partial\Omega} e^{-\tau\Re(\xi)} \left| (\xi I_d - E(z))^{-1} P^{\text{p}}(z) \right| d\xi.$$

The map $(\xi, z) \in \partial\Omega \times \overline{D}(0, r) \mapsto \left| (\xi I_d - E(z))^{-1} P^{\text{p}}(z) \right|$ is continuous on a compact set thus bounded. Thus there exists a positive constant K such that, for every $|z| < r$ and $\tau > 0$, $\left| e^{-E(z)\tau} P^{\text{p}}(z) \right| \leq K e^{-c\tau}$. \square

2.2.2 Boundedness of the transport component

The goal of this section is to prove the following result.

Proposition 10. *There exists $r, K_h, c_h > 0$ such that for every $x \in [-r, r] \setminus \{0\}$, $t \in \mathbb{R}$ and $X \in \text{Im}(P^h(ix))$,*

$$\left| \exp\left(\frac{t}{x^2}E(ix)\right)X \right| \leq K_h e^{c_h|t|}|X|.$$

Proof. Let r be as in Proposition 7, $x \in [-r, r] \setminus \{0\}$, $t \in \mathbb{R}$, $\mu \in \text{Sp}(A')$ and $Y \in \text{Im}[P_\mu^h(ix)]$. Taking into account that $\text{Im}[P_\mu^h(ix)]$ is stable by $E(ix)$, we get

$$\exp\left(\frac{t}{x^2}E(ix)\right)Y = \exp\left(\frac{t}{x^2}E(ix)P_\mu^h(ix)\right)Y = \exp\left(\frac{t}{x^2}(i\mu x P_\mu^h(ix) - x^2 R_\mu^h(ix))\right)Y.$$

Note that $P_\mu^h(ix)$ and $R_\mu^h(ix)$ commute because $P_\mu^h(ix)$ and $E(ix)$ commute and $E(ix)P_\mu^h(ix) = i\mu x P_\mu^h(ix) - x^2 R_\mu^h(ix)$. Thus, by using that $i\mu/x \in i\mathbb{R}$, we obtain

$$\left| \exp\left(\frac{t}{x^2}E(ix)\right)Y \right| = \left| e^{i\mu t/x} \exp(-tR_\mu^h(ix))Y \right| \leq e^{c_\mu|t|}|Y|,$$

where $c_\mu = \max\{|R_\mu^h(z)|; z \in \overline{D}(0, r)\}$. We conclude for $X \in \text{Im}[P^h(ix)]$ that

$$\begin{aligned} \left| \exp\left(\frac{t}{x^2}E(ix)\right)X \right| &\leq \sum_{\mu \in \text{Sp}(A')} \left| \exp\left(\frac{t}{x^2}E(ix)\right)P_\mu^h(ix)X \right| \\ &\leq \sum_{\mu \in \text{Sp}(A')} e^{c_\mu|t|}|P_\mu^h(ix)X| \leq K e^{c|t|}|X| \end{aligned}$$

with $c = \max\{c_\mu; \mu \in \text{Sp}(A')\}$ and $K = \max\left\{\sum_{\mu \in \text{Sp}(A')} |P_\mu^h(z)|; z \in \overline{D}(0, r)\right\}$. \square

2.2.3 Well-posedness

By gathering the results of the previous two subsections, we can prove that the heat-transport system (Sys) is well-posed. We define the Fourier coefficients of $f \in L^2(\mathbb{T})^d$ by

$$\forall n \in \mathbb{Z}, \hat{f}(n) = \frac{1}{2\pi} \int_{\mathbb{T}} f(t) e^{-int} dt \in \mathbb{C}^d.$$

We consider the operator \mathcal{L} defined by (20) and (21). By Bessel-Parseval identity and the fact that $\mathcal{L}(Xe_n) = n^2 E(i/n)Xe_n$,

$$D(\mathcal{L}) = \left\{ f \in L^2(\mathbb{T})^d; \sum_{n \in \mathbb{Z}} \left| n^2 E\left(\frac{i}{n}\right) \hat{f}(n) \right|^2 < \infty \right\}. \quad (27)$$

The goal of this section is to prove the following result.

Proposition 11. *$-\mathcal{L}$ generates a C^0 semi-group of bounded operators on $L^2(\mathbb{T}^d)$.*

This result will ensure well posedness of (Sys) in the following sense.

Definition 12. Let $T > 0$, $f_0 \in L^2(\mathbb{T})^d$ and $u \in L^2(Q_T)^d$. The solution of (Sys) is the function $f \in C^0([0, T]; L^2(\mathbb{T})^d)$ defined for $t \in [0, T]$ by

$$f(t) = e^{-t\mathcal{L}} f_0 + \int_0^t e^{-(t-\tau)\mathcal{L}} u(\tau) d\tau.$$

Moreover, $f(t)$ satisfies the estimate

$$\forall 0 \leq t \leq T, \|f(t)\|_{L^2(\mathbb{T})} \leq C(\|f_0\|_{L^2(\mathbb{T})} + \|u\|_{L^2([0, T] \times \mathbb{T}^d)}), \quad (28)$$

where C depends on T but not on f_0 and u . We will also note $S(t, f_0, u) := f(t)$ this solution.

Proof. We deduce from Proposition 9 and Proposition 10 that for every $x \in [-r, r] \setminus \{0\}$, $t > 0$ and $X \in \mathbb{C}^d$,

$$\begin{aligned} \left| \exp\left(-\frac{t}{x^2}E(ix)\right)X \right| &\leq \left| \exp\left(-E(ix)\frac{t}{x^2}\right)P^p(ix)X \right| + \left| \exp\left(-\frac{t}{x^2}E(ix)\right)P^h(ix)X \right| \\ &\leq K_p e^{-c_p t x^{-2}} |P^p(ix)X| + K_h e^{c_h t} |P^h(ix)X| \\ &\leq K e^{c_h t} |X| \end{aligned} \quad (29)$$

where $K = \max\{K_p |P^p(ix)| + K_h |P^h(ix)|; x \in [-r, r]\}$.

For $f \in L^2(\mathbb{T}^d)$ and $t \in [0, \infty)$ we define

$$S(t) = \sum_{n \in \mathbb{Z}} e^{-tn^2 E(\frac{i}{n})} \hat{f}(n) e_n.$$

By Bessel Parseval equality and (29) with $x = 1/n$, $S(t)$ is a bounded operator on $L^2(\mathbb{T}^d)$, because the number of $n \in \mathbb{Z}$ such that $\frac{1}{n} \notin [-r, r]$ is finite. The semi-group properties $S(0) = I$ and $S(t+s) = S(t)S(s)$ are clearly satisfied. For $f \in D(\mathcal{L})$, we have, by Bessel Parseval equality

$$\left\| \left(\frac{S(t) - I}{t} + \mathcal{L} \right) f \right\|_{L^2(\mathbb{T}^d)}^2 = \sum_{n \in \mathbb{Z}} \left| \left(\frac{e^{-tn^2 E(\frac{i}{n})} - I_d}{t} - n^2 E\left(\frac{i}{n}\right) \right) \hat{f}(n) \right|^2.$$

In the right hand side, each term of the series converges to zero when $[t \rightarrow 0]$ and, thanks to (29), is dominated for every $t \in [0, 1]$ and $n > 1/r$ by

$$\left| \left(\int_0^1 e^{-t\theta n^2 E(\frac{i}{n})} d\theta - I_d \right) n^2 E\left(\frac{i}{n}\right) \hat{f}(n) \right|^2 \leq (K e^{c_h} + 1)^2 \left| n^2 E\left(\frac{i}{n}\right) \hat{f}(n) \right|^2,$$

which can be summed over $n \in \mathbb{Z}$ because $f \in D(\mathcal{L})$, see (27). By the dominated convergence theorem, the sum of the series converges to zero. \square

Remark 13. We can see from this proof that the semi-group $e^{-t\mathcal{L}}$ is strongly continuous on any $H^s(\mathbb{T}^d)$ for any $s \geq 0$, i.e. we have

$$\|e^{-t\mathcal{L}} f_0\|_{H^s(\mathbb{T}^d)} \leq K e^{c_h t} \|f_0\|_{H^s(\mathbb{T}^d)}.$$

2.3 Adjoint system and observability

The null-controllability of a linear system is equivalent to a dual notion called ‘‘observability’’. We have the following general, abstract result (see [10, Lemma 2.48]).

Lemma 14. *Let H_1 , H_2 and H_3 be three Hilbert spaces. Let $\Phi_2: H_2 \rightarrow H_1$ and $\Phi_3: H_3 \rightarrow H_1$ be continuous linear maps. Then*

$$\text{Im}(\Phi_2) \subset \text{Im}(\Phi_3)$$

if and only if there exists $C > 0$ such that

$$\forall h_1 \in H_1, \|\Phi_2^* h_1\|_{H_2} \leq C \|\Phi_3^* h_1\|_{H_3}.$$

From Lemma 14, see [10, Theorem 2.44], we deduce the following result.

Proposition 15. *Given $T > 0$, the system (Sys) is null-controllable on ω in time T if and only if there exists $C > 0$ such that for every $g_0 \in L^2(\mathbb{T}; \mathbb{C}^d)$, the solution g to the equation*

$$\begin{cases} \partial_t g - B^{\text{tr}} \partial_x^2 g - A^{\text{tr}} \partial_x g + K^{\text{tr}} g = 0 & \text{in } (0, T) \times \mathbb{T}, \\ g(0, \cdot) = g_0 & \text{in } \mathbb{T}. \end{cases} \quad (30)$$

satisfies

$$\|g(T, \cdot)\|_{L^2(\mathbb{T}; \mathbb{C}^d)}^2 \leq C \int_0^T \int_{\omega} |M^* g(t, x)|^2 dt dx. \quad (31)$$

Note that the solutions of the adjoint system (30) are of the form³

$$g(t, x) = \sum_{n \in \mathbb{Z}} e^{-tn^2 E(\frac{i}{n})^*} \widehat{g}_0(n) e^{inx}. \quad (32)$$

Moreover, we have a spectral theory for the adjoint system that is similar to Prop. 5–7. We just have to take the adjoint of each formulas of these Propositions.

Remark 16. As for the semi-group $e^{-t\mathcal{L}}$ (see Remark 13), the dual semi-group $e^{-t\mathcal{L}^*}$ is strongly continuous on any $H^s(\mathbb{T})^d$ for any $s \geq 0$, i.e. we have

$$\|e^{-t\mathcal{L}^*} g_0\|_{H^s(\mathbb{T})^d} \leq K' e^{c't} \|g_0\|_{H^s(\mathbb{T})^d}.$$

3 Obstruction to the null-controllability in small time

3.1 Motivation and strategy

The goal of this section is to prove the first point of Theorem 2, by disproving the observability inequality (31) on an appropriate solution of (30)

The first idea is to build a solution of (30) on an eigenfunction g_0 of the operator \mathcal{L}^* , but these eigenfunctions are of the form Xe_n , with $X \in \mathbb{C}^d$ and do not concentrate, thus they do not disprove the observability inequality.

The second idea is to use the same kind of solution as for disproving the observability of the transport equation $(\partial_t + A'\partial_x)f_1(t, x) = 0$ in time $T < T^* = \frac{\ell(\omega)}{\mu_*}$. Namely functions of the form $f_1(t, x) = X\rho(x - \mu_*t)$ where $X \in \mathbb{C}^{d_1}$ satisfies $A'X = \mu X$ and ρ is a compactly supported fonction such that $\cup_{t \in [0, T]}(\text{supp}(\rho) + \mu_*t)$ does not intersect ω . But unless there exists an eigenvector of A^* in the kernel of B^* , such concentrated pure transport solutions of (30) do not exist (see Proposition 17 below).

Yet another possible approach would be to show some propagation of singularities. But we expect the coupling between the parabolic equation and the transport equation to significantly complicate the matter, compared to the strategy used for the wave equation by Burq and Gérard [8].

Because of this, we adopt another strategy: we adapt the method used by the second author for the Grushin equation [17]. It provides a proof which is elementary to anyone knowing the basics of holomorphic functions (Cauchy integral formula and its consequences) and Runge's theorem (that we recall). It provides the existence of solutions of the (full) adjoint system (30) that are perturbations, in some sense, of the solutions of the uncoupled transport equation $(\partial_t + A'\partial_x)f_1(t, x) = 0$.

Proposition 17. *Let us assume that the $d \times d^2$ matrix*

$$(B \mid AB \mid \dots \mid A^{d-1}B)$$

has rank = d, or, equivalently, that there is no eigenvector of A^ in the kernel of B^* (see for instance [6, Lemma 1]). Let $\mu \in \mathbb{R}$ and $T > 0$. There exists $C = C(\mu, T) > 0^4$ such that every solution of the adjoint system (30) of the form $g(t, x) = g_0(x - \mu t)$ satisfies $\|g(T, \cdot)\|_{L^2(\mathbb{T})^d} \leq C\|g\|_{L^2([0, T] \times \omega)^d}$.*

This statement shows that, for a dense set of matrices (A, B) pure transport solutions of the adjoint system (30) cannot be used to disprove the observability inequality (31), and thus the null controllability of (Sys).

Proof. Let us note Sol_μ the set of solutions of the adjoint system (30) of the form $g_0(x - \mu t)$. Remark that according to the expression (32) of the solutions of the adjoint system, the relation $g_0 \in Sol_\mu$ is equivalent to

$$\forall n \neq 0, nE\left(\frac{i}{n}\right)^* \widehat{g}_0(n) = i\mu \widehat{g}_0(n). \quad (33)$$

³When we write $E(z)^*$, it is to be understood as $(E(z))^*$. We will use the same notation for $P_\mu^h(z)^*$ etc.

⁴With the help of Proposition 7, we could even prove that $C(\mu, T)$ can be chosen independently of μ .

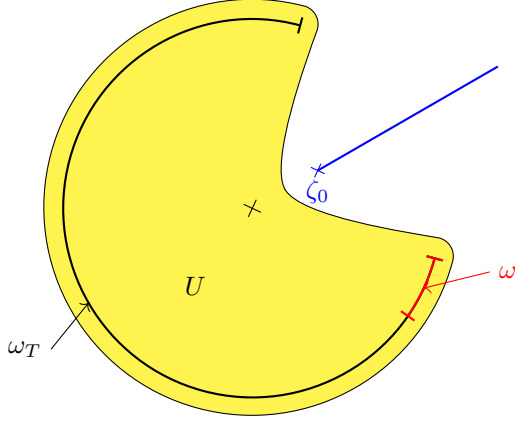


Figure 1 – In yellow, an example of the domain U . The black circle arc is ω_T (once we identify \mathbb{T} with the complex unit circle). The null-controllability of the parabolic-transport system implies that we can estimate the $L^2(D(0,1))$ norm of complex polynomials by their $L^\infty(U)$ norm. But if $T < T^*$, then ω_T is not the whole unit circle, and we can choose U such that $D(0,1) \not\subset U$. Then, we can find a sequence of polynomials that converges to $\zeta \mapsto (\zeta - \zeta_0)^{-1}$ away from the blue line.

We claim that Sol_μ is finite dimensional. Indeed, if it is infinite dimensional, then, according to the relation (33), there is infinitely many n such that $i\mu$ is an eigenvalue of $nE(i/n)$. Let $(X_{n_k})_{k \geq 0}$ be an associated sequence of eigenvectors, chosen such that $|X_{n_k}| = 1$. Since the unit sphere of \mathbb{C}^d is compact, we may assume that (X_{n_k}) converges to some X with $|X| = 1$. Then we have

$$n_k B^* X_{n_k} - iA^* X_{n_k} + \frac{1}{n_k} K^* X_{n_k} = n_k E\left(\frac{i}{n_k}\right)^* X_{n_k} = i\mu X_{n_k} \xrightarrow{k \rightarrow +\infty} i\mu X.$$

And since $-iA^* X_{n_k} + (n_k)^{-1} K^* X_{n_k} \xrightarrow{k \rightarrow +\infty} -iA^* X$, we must have $B^* X = 0$ and $A^* X = -\mu X$. But this is in contradiction with the hypothesis of the Proposition. Therefore Sol_μ is finite dimensional.

So, according to the description (33) of Sol_μ , there exists $N > 0$ such that every solution of the adjoint system (30) of the form $g_0(x - \mu t)$ has no frequencies higher than N : $Sol_\mu \subset \text{Span}\{e_n, |n| < N\}$. But finite linear combination of exponentials have the unique continuation property.⁵ So the expressions $\|g_0(\cdot - \mu T)\|_{L^2(\mathbb{T})^d}$ and $\|g_0(x - \mu t)\|_{L^2([0,T] \times \omega)^d}$ both define a norm on Sol_μ . Since Sol_μ is finite dimensional, these two norms are equivalent. This proves the claimed inequality. \square

3.2 Construction of a counterexample to the observability inequality

First, note that it is sufficient to work with an open interval ω . Indeed, otherwise, ω is contained in an open interval $\tilde{\omega}$ of \mathbb{T} such that $\ell(\omega) = \ell(\tilde{\omega})$ and the negative result for the large control support $\tilde{\omega}$ implies the negative result for the small control support ω . Thus, in the whole section, ω is an open interval of \mathbb{T} and $T \in (0, T^*)$ is fixed.

Let $\mu \in \text{Sp}(A')$ with minimum absolute value. First, we prove the following estimate.

Proposition 18. *Let U be a open domain, star-shaped with respect to 0, that contains $\omega_T := \bigcup_{0 \leq t \leq T} (\bar{\omega} - \mu t)$ (where $\bar{\omega} - \mu t$ is to be understood as the rotation of $\bar{\omega}$ by an angle of $-\mu t$, see figure 1).*

There exist an integer N and a constant $C > 0$ such that if the system (Sys) is null-controllable on ω in time T , then for all polynomials $p(z) = \sum_{n > N} a_n z^n$ with a zero of order at least N at 0, we have

$$\|p\|_{L^2(D(0,1))} \leq C \|p\|_{L^\infty(U)}. \quad (34)$$

Proof. According to Proposition 7, there exist $r > 0$, a projection-valued function P_μ^h and a matrix-valued function R_μ^h that are holomorphic on $D(0, r)$ such that for every $|z| < r$,

$$P_\mu^h(z)E(z) = E(z)P_\mu^h(z) = \mu z P_\mu^h(z) + z^2 R_\mu^h(z). \quad (35)$$

⁵For instance because they are entire functions, and entire functions have the unique continuation property.

Let $\varphi_0 \neq 0$ in the range of $P_\mu^h(0)^*$. To disprove the observability inequality (31), we look at solutions $g(t, x)$ of the system (30) with initial conditions of the form $g(0, x) = \sum_{n>r^{-1}} a_n e^{inx} P_\mu^h(i/n)^* \varphi_0$. To avoid irrelevant summability issues, we will assume that all sums are finite. Since on the range of $P_\mu^h(z)$, $E(z)$ acts as $\mu z + z^2 R_\mu^h(z)$ (see Eq. (35)), we have

$$\begin{aligned} g(t, x) &= \sum_{n>r^{-1}} a_n e^{inx} e^{-tn^2 E(\frac{i}{n})^*} P_\mu^h\left(\frac{i}{n}\right)^* \varphi_0 \\ &= \sum_{n>r^{-1}} a_n e^{in(x+\mu t)} e^{tR_\mu^h(\frac{i}{n})^*} P_\mu^h\left(\frac{i}{n}\right)^* \varphi_0. \end{aligned}$$

So, if we define for $0 \leq t \leq T$ and $n > r^{-1}$,

$$\gamma_t(n) = e^{tR_\mu^h(\frac{i}{n})^*} P_\mu^h\left(\frac{i}{n}\right)^*, \quad (36)$$

we rewrite $g(t, x)$ as

$$g(t, x) = \sum_{n>r^{-1}} a_n e^{in(x+\mu t)} \gamma_t(n) \varphi_0.$$

If the term $\gamma_t(n)$ was equal to one, then $g(t, x)$ would just be the solution to an uncoupled transport equation, therefore it would be easy to disprove (31). To treat this term, we will use the following lemma, that we prove in Section 3.3.

Lemma 19. *Let U be as in Proposition 18. There exist an integer $N > 0$ and a constant $C > 0$ such that for every polynomial function $\zeta \in \mathbb{C} \mapsto \sum_{n>N} a_n \zeta^n \in \mathbb{C}$ with a zero of order N at 0, for every $0 \leq \tau \leq T$,*

$$\left\| \sum_{n>N} a_n \zeta^n \gamma_\tau(n) \right\|_{L^\infty(\omega_T)} \leq C \left\| \sum_{n>N} a_n \zeta^n \right\|_{L^\infty(U)}. \quad (37)$$

From now on, we assume that $a_n = 0$ for $n \leq N$. For $(t, x) \in [0, T] \times \omega$, we note $\zeta(t, x) = e^{i(x+\mu t)}$ which belongs to ω_T . Then

$$g(t, x) = \sum_{n>N} a_n \zeta(t, x)^n \gamma_t(n) \varphi_0.$$

Let $(t, x) \in [0, T] \times \omega$. By applying Lemma 19 with $\tau = t$, we have

$$|g(t, x)| \leq C \left\| \sum_{n>N} a_n \zeta^n \right\|_{L^\infty(U)}.$$

So the right-hand side of the observability inequality (31) satisfies

$$\|g\|_{L^2([0, T] \times \omega)}^2 \leq 2\pi T \|g\|_{L^\infty([0, T] \times \omega)}^2 \leq 2\pi T C^2 \left\| \sum_{n>N} a_n \zeta^n \right\|_{L^\infty(U)}^2. \quad (38)$$

We now lower bound the left hand-side of the observability inequality (31). Thanks to Parseval's identity, we have

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})}^2 = \left\| \sum_{n>N} a_n e^{in(x+\mu T)} \gamma_T(n) \varphi_0 \right\|_{L^2(\mathbb{T})}^2 = 2\pi \sum_{n>N} |a_n|^2 |\gamma_T(n) \varphi_0|^2. \quad (39)$$

The map $z \mapsto R_\mu^h(\bar{z})^*$ is holomorphic in $D(0, r)$. In particular, $C_1 := \sup_{|z| \leq r/2} |R_\mu^h(z)^*|$ is finite. So, we have for $n \geq 2r^{-1}$,

$$|(e^{-TR_\mu^h(\frac{i}{n})^*})^{-1}| = |e^{TR_\mu^h(\frac{i}{n})^*}| \leq e^{C_1 T}. \quad (40)$$

Moreover, φ_0 is in the range of $P_\mu^h(0)^*$ and P_μ^h is holomorphic in $D(0, r)$, so there exists $r' > 0$ sufficiently small such that for $|z| < r'$,

$$|P_\mu^h(z)^* \varphi_0| \geq |\varphi_0|/2 =: c. \quad (41)$$

By gathering (40) and (41), we have for $n \geq N' := \lfloor \max(2r^{-1}, r'^{-1}) \rfloor + 1$,

$$|\gamma_T(n)\varphi_0| = \left| e^{-TR_\mu^h(\frac{i}{n})^*} P_\mu^h\left(\frac{i}{n}\right)^* \varphi_0 \right| \geq e^{-C_1 T} c =: c'.$$

So, assuming $a_n = 0$ for $n \leq N'$, we have by plugging the previous lower bound into Parseval's identity (39)

$$\left\| \sum_{n>N} a_n \zeta^n \right\|_{L^2(D(0,1))}^2 = \pi \sum_{n>N} \frac{|a_n|^2}{n+1} \leq \frac{\pi}{c'} \sum_{n>N} \frac{|a_n|^2}{n+1} |\gamma_T(n)\varphi_0|^2 \leq \frac{1}{2c'} \|g(T, \cdot)\|_{L^2(\mathbb{T})}^2. \quad (42)$$

Thus, thanks to the lower bound (42) and the upper bound (38), the observability inequality (31) implies

$$\left\| \sum_{n>N} a_n \zeta^n \right\|_{L^2(D(0,1))}^2 \leq C \|g(T, \cdot)\|_{L^2(\mathbb{T})}^2 \leq C' \|g\|_{L^2([0,T] \times \omega)}^2 \leq C'' \left\| \sum_{n>N} a_n \zeta^n \right\|_{L^\infty(U)}^2,$$

which concludes the proof of Proposition 18. \square

Let us check that the inequality of Proposition 18 does not hold. We will use Runge's theorem (see for instance Rudin's textbook [26, Thm. 13.9]) to construct a counterexample.

Proposition 20 (Runge's theorem). *Let U be a connected, simply connected open subset of \mathbb{C} and f be a holomorphic function on U . Then, there exists a sequence $(p_k)_{k \geq 0}$ of polynomials that converges uniformly on every compact subset of U to f .*

Proof of Theorem 2.i. Let ω be an open interval of \mathbb{T} and $T \in (0, T^*)$. Let ω_T be as in Proposition 18. By definition of T^* , ω_T is not the whole unit circle, thus we can find an open bounded domain U that is star-shaped with respect to 0 and that does not contain $D(0, 1)$ (see Fig. 1).

With such a choice of U , there exists a complex number $\zeta_0 \in D(0, 1)$ which is non-adherent to U . Then, according to Runge's theorem, there exists a sequence of polynomials (\tilde{p}_k) that converges uniformly on every compact subset of $\mathbb{C} \setminus (\zeta_0[1, +\infty))$ to $\zeta \mapsto (\zeta - \zeta_0)^{-1}$. Let us define $p_k(\zeta) = \zeta^{N+1} \tilde{p}_k(\zeta)$. Then, the sequence (p_k) is a counterexample to the inequality on complex polynomials (34). Indeed, since $\zeta^{N+1}(\zeta - \zeta_0)^{-1}$ is bounded on U , (p_k) is uniformly bounded on U , thus, the right-hand side of the inequality (34) is bounded. But since ζ_0 is in $D(0, 1)$, $\zeta^{N+1}(\zeta - \zeta_0)^{-1}$ has infinite L^2 -norm in $D(0, 1)$, and thanks to Fatou's Lemma, $\|p_k\|_{L^2(D(0,1))}$ tends to $+\infty$ as $k \rightarrow +\infty$. \square

3.3 Estimate on some operators on polynomial functions

Here, we prove Lemma 19. In essence, we have to estimate quantities of the form $\sum \gamma_n a_n \zeta^n$ in function of $\sum a_n \zeta^n$, in some appropriate norm. This is stated in Theorem 23, which is a variant of a theorem that the second author proved when studying Grushin's equation (see [17, Thm. 18]).

Definition 21. Let E be a Banach space. Let $R > 0$ and $\Delta_R := \{z \in \mathbb{C}, \Re(z) > R\}$. We define $\mathcal{S}_R(E)$ as the set of functions γ from Δ_R to E that are holomorphic with subexponential growth, i.e. such that for all $\varepsilon > 0$,

$$p_\varepsilon(\gamma) = \sup_{z \in \Delta_R} |\gamma(z)| e^{-\varepsilon|z|} < +\infty. \quad (43)$$

We endow $\mathcal{S}_R(E)$ with the topology of the seminorms p_ε for $\varepsilon > 0$.

If E is the space $\mathbb{C}^{d \times d}$ of linear maps of \mathbb{C}^d , we will note $\mathcal{S}_R^{d \times d} := \mathcal{S}_R(\mathcal{L}(\mathbb{C}^d))$. We will sometimes call elements of $\mathcal{S}_R^{d \times d}$ *symbols*.

Remark 22. If $n \leq R$, i.e. if n is not in the domain of definition of $\gamma \in \mathcal{S}_R(E)$, we will set for convenience $\gamma(n) = 0$.

We introduce $\mathcal{O}(\mathbb{C})$ the space of entire functions $f: \mathbb{C} \rightarrow \mathbb{C}$, endowed with its usual topology, i.e. the topology of the uniform convergence on compact subsets.

Theorem 23. Let $R > 0$ and $\gamma \in \mathcal{S}_R^{d \times d}$. Let H_γ be the operator on vector-valued entire functions defined by

$$H_\gamma: \sum_{n>R} a_n \zeta^n \in \mathcal{O}(\mathbb{C})^d \mapsto \sum_{n>R} \gamma(n) a_n \zeta^n \in \mathcal{O}(\mathbb{C})^d. \quad (44)$$

Then, the operator H_γ is continuous on $\mathcal{O}(\mathbb{C})^d$. Moreover, the map $\gamma \in \mathcal{S}_R^{d \times d} \mapsto H_\gamma \in \mathcal{L}(\mathcal{O}(\mathbb{C})^d)$ satisfies the following continuity-like estimate: for each compact subset K of \mathbb{C} and each neighborhood V of K that is star-shaped with respect to 0, there exist a constant $C > 0$ and a seminorm p_ε of $\mathcal{S}_R^{d \times d}$ such that for every entire function f :

$$\|H_\gamma(f)\|_{L^\infty(K)} \leq C p_\varepsilon(\gamma) \|f\|_{L^\infty(V)}. \quad (45)$$

A variant of this Theorem was proved in the case $d = 1$ by the second author [17, Thm. 18]. The proof follows the same lines in the general case. We provide it in Appendix A.

Now, we turn to the proof of Lemma 19 which is basically an application of Theorem 23.

Proof of Lemma 19. Let us define $\tilde{\gamma}_\tau(z) = e^{t R_\mu^h(i/\bar{z})^*} P_\mu^h(i/\bar{z})^*$, so that $\gamma_\tau(n) = \tilde{\gamma}_\tau(n)$ (see the definition of γ_t Eq. (36)), and thus for every $(a_n) \in \mathbb{C}^{\mathbb{N}}$,

$$\sum_{n>N} \gamma_\tau(n) a_n \varphi_0 \zeta^n = H_{\tilde{\gamma}_\tau} \left(\sum_{n>N} a_n \zeta^n \varphi_0 \right). \quad (46)$$

Let us check that $(\tilde{\gamma}_\tau)_{0 \leq \tau \leq T}$ is a bounded family of $\mathcal{S}_R^{d \times d}$ for some $R > 0$. Since R_μ^h and P_μ^h are holomorphic on $D(0, r)$, $\tilde{\gamma}_\tau$ is holomorphic on $\{|z| > r^{-1}\}$, and in particular in $\{\Re(z) > r^{-1}\}$. So, for $|z| > 2r^{-1}$ and $0 \leq \tau \leq T$, we have

$$|\tilde{\gamma}_\tau(z)| \leq e^{T \sup_{|z| < r/2} |R_\mu^h(z)|} \sup_{|z| < r/2} |P_\mu^h(z)| < +\infty.$$

Thus, with $R = 2r^{-1}$, γ_τ is in $\mathcal{S}_R^{d \times d}$, and since the previous bound is uniform in $0 \leq \tau \leq T$, the family $(\gamma_\tau)_{0 \leq \tau \leq T}$ is bounded in $\mathcal{S}_R^{d \times d}$.

Let us also remind that U is star-shaped with respect to 0, and that $\omega_T \subset U$. All the conditions of Theorem 23 are satisfied, so we can apply the estimate (45) with $K = \omega_T$ and $V = U$:

$$\|H_{\tilde{\gamma}_\tau} \left(\sum_{n>N} a_n \varphi_0 \zeta^n \right)\|_{L^\infty(\omega_T)} \leq C \left\| \sum_{n>N} a_n \varphi_0 \zeta^n \right\|_{L^\infty(U)} = C \left\| \sum_{n>N} a_n \zeta^n \right\|_{L^\infty(U)}, \quad (47)$$

where C that depends neither on the polynomial $\sum a_n \zeta^n$, neither on $0 \leq \tau \leq T$ because the family $(\tilde{\gamma}_\tau)_{0 \leq \tau \leq T}$ is bounded. This, combined with (46), proves the inequality (37) and concludes the proof of Lemma 19. \square

4 Large time null-controllability

The goal of this section is to prove the point (ii) of Theorem 2. An adapted decomposition of $L^2(\mathbb{T})^d$ is introduced in Section 4.1. The control strategy is presented in Section 4.2. Projecting the dynamics onto the parabolic/hyperbolic subspaces, the system is decomposed into 2 weakly coupled systems, the first one behaving like a transport equation, the second one like a heat equation. The transport equation is handled in Section 4.3 by using the methods developed in [1]. The parabolic equation is treated in Section 4.4 by adapting the Lebeau-Robbiano method [19] to systems with arbitrary size. The low frequency part is treated by a compactness argument and a unique continuation property in Section 4.5.

In the whole Section 4, the parameter $r > 0$ is assumed to be small enough so that Propositions 5, 6, 7, 9 and 10 hold.

4.1 An adapted decomposition of $L^2(\mathbb{T})^d$

Proposition 24. *Let $n_0 \in \mathbb{N}$ be such that $\frac{1}{n_0} < r$. We have the following decomposition*

$$L^2(\mathbb{T})^d = F^0 \oplus F^p \oplus F^h, \quad (48)$$

where

$$F^0 := \bigoplus_{|n| \leq n_0} \mathbb{C}^d e_n, \quad (49)$$

$$F^p := \bigoplus_{|n| > n_0} \operatorname{Im} \left(P^p \left(\frac{i}{n} \right) \right) e_n, \quad (50)$$

$$F^h := \bigoplus_{|n| > n_0} \operatorname{Im} \left(P^h \left(\frac{i}{n} \right) \right) e_n. \quad (51)$$

Moreover the projections Π^0 , Π^p , Π^h and Π defined by

$$\begin{aligned} L^2(\mathbb{T})^d &= F^0 \oplus F^p \oplus F^h \\ \Pi^0 &= I_{F^0} + 0 + 0 \\ \Pi^p &= 0 + I_{F^p} + 0 \\ \Pi^h &= 0 + 0 + I_{F^h} \\ \Pi &= 0 + I_{F^p} + I_{F^h} = \Pi^p + \Pi^h \end{aligned}$$

are bounded operators on $L^2(\mathbb{T})^d$.

Proof. The function $z \in D(0, r) \mapsto P^p(z)$ is continuous thus there exists $C > 0$ such that, for every $z \in \bar{D}(0, 1/n_0)$, $|P^p(z)| \leq C$. Let $f \in L^2(\mathbb{T})^d$. We deduce from

$$\sum_{|n| > n_0} \left| P^p \left(\frac{i}{n} \right) \hat{f}(n) \right|^2 \leq C^2 \sum_{|n| > n_0} |\hat{f}(n)|^2 \leq C^2 \|f\|_{L^2(\mathbb{T})^d}^2 \quad (52)$$

and Bessel-Parseval identity that the series $\sum P^p \left(\frac{i}{n} \right) \hat{f}(n) e_n$ converges in $L^2(\mathbb{T})^d$. Using $I_d = P^p(z) + P^h(z)$, we get the decomposition

$$f = \sum_{n \in \mathbb{Z}} \hat{f}(n) e_n = \sum_{|n| \leq n_0} \hat{f}(n) e_n + \sum_{|n| > n_0} P^p \left(\frac{i}{n} \right) \hat{f}(n) e_n + \sum_{|n| > n_0} P^h \left(\frac{i}{n} \right) \hat{f}(n) e_n$$

with convergent series in $L^2(\mathbb{T})^d$. This proves $L^2(\mathbb{T})^d = F^0 + F^p + F^h$. The sum is direct because $(e_n)_{n \in \mathbb{Z}}$ is orthogonal and $\operatorname{Im}(P^p(z)) \cap \operatorname{Im}(P^h(z)) = \{0\}$ when $|z| < r$. The linear mappings Π^0 and Π are orthogonal projections, thus bounded operators on $L^2(\mathbb{T})^d$. We deduce from Bessel-Parseval identity and (52) that Π^p is a bounded operator on $L^2(\mathbb{T})^d$ and so is $\Pi^h = \Pi - \Pi^p$. \square

The operator \mathcal{L} defined in (20) maps $D(\mathcal{L}) \cap F^0 = F^0$ into F^0 thus we can define an operator \mathcal{L}^0 on F^0 by $D(\mathcal{L}^0) = D(\mathcal{L}) \cap F^0$ and $\mathcal{L}^0 = \mathcal{L}|_{F^0}$. Moreover, $-\mathcal{L}^0$ generates a C^0 -semi-group of bounded operators on F^0 and $e^{-t\mathcal{L}^0} = e^{-t\mathcal{L}}|_{F^0}$. For the same reasons, we can define an operator \mathcal{L}^p on F^p by $D(\mathcal{L}^p) = D(\mathcal{L}) \cap F^p$ and $\mathcal{L}^p = \mathcal{L}|_{F^p}$, that generates a C^0 -semi-group of bounded operators on F^p : $e^{-t\mathcal{L}^p} = e^{-t\mathcal{L}}|_{F^p}$. Finally, we can define an operator \mathcal{L}^h on F^h by $D(\mathcal{L}^h) = D(\mathcal{L}) \cap F^h$ and $\mathcal{L}^h = \mathcal{L}|_{F^h}$, that generates a C^0 -semi-group of bounded operators on F^h : $e^{-t\mathcal{L}^h} = e^{-t\mathcal{L}}|_{F^h}$.

Proposition 25. *The operator $-\mathcal{L}^0$ generates a C^0 group $(e^{-t\mathcal{L}^0})_{t \in \mathbb{R}}$ of bounded operators on F^0 . The operator $-\mathcal{L}^h$ generates a C^0 group $(e^{-t\mathcal{L}^h})_{t \in \mathbb{R}}$ of bounded operators on F^h*

Proof. We just need to check that $e^{-t\mathcal{L}}$ defines a bounded operator of F^0 and F^h when $t < 0$. It is clear for F^0 because it has finite dimension. For F^h , one may proceed as in the proof of Proposition 11, noticing that the estimate of Proposition 10 is valid for any $t \in \mathbb{R}$. \square

For the duality method, we will need the dual decomposition of (48), i.e.

$$\begin{aligned} L^2(\mathbb{T})^d &= F^0 \oplus \widetilde{F}^p \oplus \widetilde{F}^h, \\ \text{where } \widetilde{F}^p &:= \text{Im}((\Pi^p)^*), \quad \widetilde{F}^h := \text{Im}((\Pi^h)^*). \end{aligned} \quad (53)$$

By using the definitions of F^p and F^h in (50) and (51) and the fact that $(e_n)_{n \in \mathbb{Z}}$ is an Hilbert basis of $L^2(\mathbb{T})$, we get

$$\widetilde{F}^p = \bigoplus_{|n| > n_0} \text{Im} \left(P^p \left(\frac{i}{n} \right)^* \right) e_n, \quad (54)$$

$$\widetilde{F}^h = \bigoplus_{|n| > n_0} \text{Im} \left(P^h \left(\frac{i}{n} \right)^* \right) e_n. \quad (55)$$

Moreover,

$$(e^{-t\mathcal{L}})^* f = e^{-t\mathcal{L}^*} f = \sum_{n \in \mathbb{Z}} e^{-tn^2 E(\frac{i}{n})^*} \widehat{f}(n) e_n \quad (56)$$

and the spaces F^0 , \widetilde{F}^p and \widetilde{F}^h are stable by $e^{t\mathcal{L}^*}$.

4.2 Control strategy

Let T^* be as in (3) and T, T' be such that

$$T^* < T' < T. \quad (57)$$

In this section, we consider controls u of the form

$$u := (u_h, u_p)^{\text{tr}} \in \mathbb{C}^{d_1} \times \mathbb{C}^{d_2}, \quad (58)$$

where

$$\begin{aligned} \text{supp}(u_h) &\subset [0, T'] \times \overline{\omega}, & \text{supp}(u_p) &\subset [T', T] \times \overline{\omega}, \\ u_h &\in L^2((0, T') \times \mathbb{T})^{d_1}, & u_p &\in L^2((T', T) \times \mathbb{T})^{d_2}. \end{aligned} \quad (59)$$

The control u_h is intended to control the hyperbolic component of the system and the control u_p the parabolic component.

The control strategy for system (Sys) consists in

- first proving the null controllability in time T in a subspace of $L^2(\mathbb{T})^d$ with finite codimension,
- then using a unique continuation argument, to get the full null controllability.

The first step of this strategy is given by the following statement.

Proposition 26. *There exists a closed subspace \mathcal{G} of $L^2(\mathbb{T})^d$ with finite codimension and a continuous operator*

$$\begin{aligned} \mathcal{U}: \mathcal{G} &\rightarrow L^2((0, T') \times \omega)^{d_1} \times C_c^\infty((T', T) \times \omega)^{d_2} \\ f_0 &\mapsto (u_h, u_p), \end{aligned}$$

that associates with each $f_0 \in \mathcal{G}$ a pair of controls $\mathcal{U}f_0 = (u_h, u_p)$ such that

$$\forall f_0 \in \mathcal{G}, \quad \Pi S(T; f_0, \mathcal{U}f_0) = 0. \quad (60)$$

By ‘‘continuous operator’’, we mean that, for every $s \in \mathbb{N}$, the map $\mathcal{U}: \mathcal{G} \mapsto L^2((0, T') \times \omega)^{d_1} \times H_0^s((T', T) \times \omega)^{d_2}$ is continuous: there exists $C_s > 0$ such that

$$\forall f_0 \in \mathcal{G}, \quad \|u_h\|_{L^2((0, T') \times \omega)^{d_1}} + \|u_p\|_{H_0^s((T', T) \times \omega)^{d_2}} \leq C_s \|f_0\|_{L^2(\mathbb{T})^d}.$$

The proof strategy of Proposition 26 consists in splitting the problem in two parts:

- for any initial data f_0 and parabolic control u_p , steer the hyperbolic high frequencies to zero at time T (Proposition 27),
- for any initial data f_0 and hyperbolic control u_h , steer the parabolic high frequencies to zero at time T (Proposition 28).

Proposition 27. *If n_0 (in Eq. (49–50)) is large enough, there exists a continuous operator*

$$\begin{aligned} \mathcal{U}^h : L^2(\mathbb{T})^d \times L^2((T', T) \times \omega)^{d_2} &\rightarrow L^2((0, T') \times \omega)^{d_1} \\ (f_0, u_p) &\mapsto u_h, \end{aligned}$$

such that for every $(f_0, u_p) \in L^2(\mathbb{T})^d \times L^2((T', T) \times \omega)^{d_2}$,

$$\Pi^h S(T; f_0, (\mathcal{U}^h(f_0, u_p), u_p)) = 0.$$

Proposition 28. *If n_0 is large enough, there exists a continuous operator*

$$\begin{aligned} \mathcal{U}^p : L^2(\mathbb{T})^d \times L^2((0, T') \times \omega)^{d_1} &\rightarrow C_c^\infty((T', T) \times \omega)^{d_2} \\ (f_0, u_h) &\mapsto u_p, \end{aligned}$$

such that for every $(f_0, u_h) \in L^2(\mathbb{T})^d \times L^2((0, T') \times \omega)^{d_1}$,

$$\Pi^p S(T; f_0, (u_h, \mathcal{U}^p(f_0, u_h))) = 0.$$

Admitting that Proposition 27 and Proposition 28 hold, we can now prove Proposition 26.

Proof. We observe that the relation $\Pi S(T; f_0, (u_h, u_p)) = 0$ holds if the two following equations are simultaneously satisfied

$$\begin{aligned} u_h &= \mathcal{U}^h(f_0, u_p) = \mathcal{U}_1^h(f_0) + \mathcal{U}_2^h(u_p), \\ u_p &= \mathcal{U}^p(f_0, u_h) = \mathcal{U}_1^p(f_0) + \mathcal{U}_2^p(u_h). \end{aligned} \tag{61}$$

If we set

$$C := \mathcal{U}_1^p + \mathcal{U}_2^p \mathcal{U}_1^h : L^2(\mathbb{T})^d \rightarrow C_c^\infty((T', T) \times \mathbb{T})^{d_2},$$

then solving system (61) is equivalent to

$$\text{find } u_p \in C_c^\infty((T', T) \times \mathbb{T})^{d_2}, \text{ such that } C f_0 = (I - \mathcal{U}_2^p \mathcal{U}_2^h) u_p. \tag{62}$$

The operator $\mathcal{U}_2^p \mathcal{U}_2^h$ is compact on $L^2((T', T) \times \mathbb{T})^{d_2}$ because it takes values in $C_c^\infty((T', T) \times \mathbb{T})^{d_2}$. Thus, by Fredholm's alternative (see [7, Thm. 6.6]), there exist $N \in \mathbb{N}$ and l_1, \dots, l_N continuous linear forms on $L^2((T', T) \times \mathbb{T})^{d_2}$ such that the equation (62) has a solution $u_p \in L^2((T', T) \times \mathbb{T})^{d_2}$ if and only if

$$\forall j \in \{1, \dots, N\}, l_j(C f_0) = 0. \tag{63}$$

Under these conditions (63), the equation (62) has a solution $u_p = L(f_0)$ given by a continuous map $L: \mathcal{G} \rightarrow L^2((T', T) \times \mathbb{T})^{d_2}$ defined on the closed vector subspace of $L^2(\mathbb{T})^d$ defined by

$$\mathcal{G} := \{f_0 \in L^2(\mathbb{T})^d ; l_j(C f_0) = 0, 1 \leq j \leq N\}. \tag{64}$$

Then $L(f_0) = u_p = \mathcal{U}_2^p \mathcal{U}_2^h u_p + C f_0$ belongs to $C_c^\infty((T', T) \times \omega)$. We get the conclusion with

$$\forall f_0 \in \mathcal{G}, \mathcal{U}(f_0) := (\mathcal{U}^h(f_0, L(f_0)), L(f_0)). \quad \square$$

Proposition 27 is proved in Section 4.3. Proposition 28 is proved in Section 4.4. The unique continuation argument to control the low frequencies is presented in Section 4.5.

4.3 Control of the hyperbolic high frequencies

The goal of this subsection is to prove Proposition 27. We remind that $T > T' > T^*$ and that the control $u = (u_h, u_p)$ satisfies (59).

4.3.1 Reduction to an exact controllability problem

The goal of this paragraph is to transform the null-controllability problem of Proposition 27 into an exact controllability problem associated with an hyperbolic system. Precisely, we will get Proposition 27 as a corollary of the following result.

Proposition 29. *If n_0 (in Eq. (49–50)) is large enough, then, for every $T' > T^*$, there exists a continuous operator*

$$\begin{aligned} \underline{\mathcal{U}}_{T'}^h: F^h &\rightarrow L^2((0, T') \times \omega)^{d_1} \\ f_{T'} &\mapsto u_h, \end{aligned}$$

such that for every $f_{T'} \in F^h$,

$$\Pi^h S\left(T'; 0, (\underline{\mathcal{U}}_{T'}^h(f_{T'}), 0)\right) = f_{T'}.$$

Proposition 29 will be proved in Section 4.3.2. Now, we prove Proposition 27 thanks to Proposition 29.

Proof of Proposition 27. Let $(f_0, u_p) \in L^2(\mathbb{T})^d \times L^2((T', T) \times \omega)^{d_2}$. We have to find $u_h \in L^2((0, T') \times \omega)^{d_1}$ such that

$$\Pi^h S(T; f_0, (u_h, u_p)) = 0,$$

or, equivalently,

$$\Pi^h S(T; 0, (u_h, 0)) = -\Pi^h S(T; f_0, (0, u_p)). \quad (65)$$

According to the well-posedness of the system (Sys) and the continuity of the projection Π^h (Definition 12 and Proposition 24), the linear map

$$(f_0, u_p) \mapsto -\Pi^h S(T; f_0, (0, u_p)), \quad (66)$$

is continuous from $L^2(\mathbb{T})^d \times L^2((T', T) \times \omega)^{d_2}$ into F^h , equipped with the $L^2(\mathbb{T})^d$ -norm. Since u_h is supported in $(0, T') \times \omega$ by (59), we have

$$\Pi^h S(T; 0, (u_h, 0)) = e^{-(T-T')\mathcal{L}^h} \Pi^h S(T'; 0, (u_h, 0)). \quad (67)$$

As pointed out in Proposition 25, $e^{t\mathcal{L}^h}$ is well-defined for all $t \in \mathbb{R}$. Therefore, by using (66) and (67), (65) is equivalent to

$$\Pi^h S(T'; 0, (u_h, 0)) = -e^{(T-T')\mathcal{L}^h} \Pi^h S(T; f_0, (0, u_p)) \in F^h. \quad (68)$$

We get the conclusion with

$$\mathcal{U}^h(f_0, u_p) = \underline{\mathcal{U}}_{T'}^h\left(-e^{(T-T')\mathcal{L}^h} \Pi^h S(T; f_0, (0, u_p))\right). \quad \square$$

4.3.2 Exact controllability of the hyperbolic part

The goal of this section is to prove Proposition 29. By the Hilbert Uniqueness Method, Proposition 29 is equivalent to the following observability inequality (it is an adaptation of [10, Thm. 2.42]).

Proposition 30. *If n_0 is large enough, there exists a constant $C > 0$ such that for every $g_0 \in \widetilde{F}^h$, the solution g of (30) satisfies*

$$\|g_0\|_{L^2(\mathbb{T})^d}^2 \leq C \int_0^{T'} \int_{\omega} |g_1(t, x)|^2 dt dx, \quad (69)$$

where g_1 denotes the first d_1 components of g .

Proof. Let $g_0 \in \widetilde{F}^{\text{h}}$. By using the definition (55) of \widetilde{F}^{h} , g_0 decomposes as follows

$$g_0 = \sum_{\mu \in \text{Sp}(A')} \sum_{|n| > n_0} P_\mu^{\text{h}}\left(\frac{i}{n}\right)^* \widehat{g}_0(n) e_n. \quad (70)$$

Then, the solution g of (30) is

$$g(t) = \sum_{\mu \in \text{Sp}(A')} G_\mu(t) \quad \text{where} \quad G_\mu(t) = \sum_{|n| > n_0} e^{-tn^2 E(\frac{i}{n})^*} P_\mu^{\text{h}}\left(\frac{i}{n}\right)^* \widehat{g}_0(n) e_n. \quad (71)$$

Let $\mu \in \text{Sp}(A')$.

Step 1: We prove the existence of $C_1 = C_1(T') > 0$, independent of g_0 , such that

$$\|G_\mu(0, \cdot)\|_{L^2(\mathbb{T}^d)} \leq C_1 (\|G_\mu\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T}^d)}) \quad (72)$$

where $q_{T'} = (0, T') \times \omega$ and

$$\|g_0\|_{H^{-1}(\mathbb{T}^d)} = \left(\sum_{|n| > n_0} \frac{|\widehat{g}_0(n)|^2}{n^2} \right)^{1/2}. \quad (73)$$

By using *i)* and *iii)* of Proposition 7, we have

$$e^{-tn^2 E(\frac{i}{n})^*} P_\mu^{\text{h}}\left(\frac{i}{n}\right)^* = e^{-tn^2 (\mu \frac{i}{n} + (\frac{i}{n})^2 R_\mu^{\text{h}}(\frac{i}{n}))^*} P_\mu^{\text{h}}\left(\frac{i}{n}\right)^* = e^{t\mu in + tR_\mu^{\text{h}}(\frac{i}{n})^*} P_\mu^{\text{h}}\left(\frac{i}{n}\right)^*,$$

which leads to

$$\partial_t G_\mu - \mu \partial_x G_\mu - R_\mu^{\text{h}}(0)^* G_\mu = S_\mu \quad \text{in } (0, T') \times \mathbb{T}, \quad (74)$$

where

$$S_\mu(t) = \sum_{|n| > n_0} \left(R_\mu^{\text{h}}\left(\frac{i}{n}\right)^* - R_\mu^{\text{h}}(0)^* \right) e^{t\mu in + tR_\mu^{\text{h}}(\frac{i}{n})^*} P_\mu^{\text{h}}\left(\frac{i}{n}\right)^* \widehat{g}_0(n) e_n. \quad (75)$$

By regularity of $z \mapsto R_\mu^{\text{h}}(z)$, Bessel-Parseval identity and (73) there exists $C = C(T') > 0$, independent of g_0 , such that

$$\|S_\mu\|_{L^\infty((0, T'), L^2(\mathbb{T}^d))} \leq C \|g_0\|_{H^{-1}(\mathbb{T}^d)}. \quad (76)$$

By (74), the function \widetilde{G}_μ defined by

$$\widetilde{G}_\mu(t, x) = e^{tR_\mu^{\text{h}}(0)^*} G_\mu(t, x) \quad (77)$$

solves

$$\begin{cases} \partial_t \widetilde{G}_\mu - \mu \partial_x \widetilde{G}_\mu = e^{tR_\mu^{\text{h}}(0)^*} S_\mu & \text{in } (0, T') \times \mathbb{T}, \\ \widetilde{G}_\mu(0, \cdot) = G_\mu(0, \cdot) & \text{in } \mathbb{T}. \end{cases} \quad (78)$$

We introduce the solution G_μ^{b} of

$$\begin{cases} \partial_t G_\mu^{\text{b}} - \mu \partial_x G_\mu^{\text{b}} = 0 & \text{in } (0, T') \times \mathbb{T}, \\ G_\mu^{\text{b}}(0, \cdot) = G_\mu(0, \cdot) & \text{in } \mathbb{T}. \end{cases} \quad (79)$$

Using the Duhamel formula for system (78) and the estimate (76), we obtain

$$\|\widetilde{G}_\mu - G_\mu^{\text{b}}\|_{L^\infty((0, T'), L^2(\mathbb{T}^d))} \leq C \|e^{tR_\mu^{\text{h}}(0)^*} S_\mu\|_{L^1((0, T'), L^2(\mathbb{T}^d))} \leq C \|g_0\|_{H^{-1}(\mathbb{T}^d)} \quad (80)$$

where $C = C(T') > 0$ is independent of g_0 . The time $T_\mu := \ell(\omega)/|\mu|$ is the minimal time for the observability of the system (79) on ω (see for instance [1, Theorem 2.2]). Indeed, for any $T'' > T_\mu$,

$$\mathbb{T} \subset \{x - \mu t; (t, x) \in [0, T''] \times \omega\}.$$

Since $T' > T_\mu$, there exists $C = C(T', \omega) > 0$, independent of g_0 , such that

$$\|G_\mu(0, \cdot)\|_{L^2(\mathbb{T})^d} \leq C \|G_\mu^\flat\|_{L^2(q_{T'})^d}.$$

By the triangular inequality, (77) and (80), we deduce that

$$\|G_\mu(0, \cdot)\|_{L^2(\mathbb{T})^d} \leq C \left(\|\tilde{G}_\mu\|_{L^2(q_{T'})^d} + \|\tilde{G}_\mu - G_\mu^\flat\|_{L^2(q_{T'})^d} \right) \leq C (\|G_\mu\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T})^d})$$

which ends the first step.

Step 2: We prove the existence of $C_2 = C_2(T', \omega) > 0$, independent of g_0 , such that

$$\|G_\mu(0, \cdot)\|_{L^2(\mathbb{T})^d} \leq C_2 (\|P_\mu^h(0)^* g\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T})^d}). \quad (81)$$

Taking into account that the projection $P_\lambda^h(z)$ commutes with $E(z)$ we deduce from (71) that for any $\lambda \in \text{Sp}(A')$,

$$G_\lambda(t) = \sum_{|n| > n_0} P_\lambda^h\left(\frac{i}{n}\right)^* e^{-tn^2 E(\frac{i}{n})^*} P_\lambda^h\left(\frac{i}{n}\right)^* \hat{g}_0(n) e_n$$

thus,

$$\begin{aligned} & G_\mu(t) - P_\mu^h(0)^* g(t) \\ &= \sum_{|n| > n_0} \left(P_\mu^h\left(\frac{i}{n}\right)^* - P_\mu^h(0)^* \right) e^{-tn^2 E(\frac{i}{n})^*} P_\mu^h\left(\frac{i}{n}\right)^* \hat{g}_0(n) e_n \\ &\quad - \sum_{\lambda \in \text{Sp}(A') \setminus \{\mu\}} \sum_{|n| > n_0} P_\mu^h(0)^* \left(P_\lambda^h\left(\frac{i}{n}\right)^* - P_\lambda^h(0)^* \right) e^{-tn^2 E(\frac{i}{n})^*} P_\lambda^h\left(\frac{i}{n}\right)^* \hat{g}_0(n) e_n \end{aligned} \quad (82)$$

because, for $\lambda \neq \mu$, $P_\mu^h(0)^* P_\lambda^h(0)^* = 0$. By using the regularity of $z \mapsto P_\lambda^h(z)$, Bessel-Parseval identity and (73), we obtain $C = C(T') > 0$ independent of g_0 such that

$$\|G_\mu - P_\mu^h(0)^* g\|_{L^\infty((0, T'), L^2(\mathbb{T})^d)} \leq C \|g_0\|_{H^{-1}(\mathbb{T})^d}.$$

We deduce from Step 1, the triangular inequality and the previous estimate that

$$\begin{aligned} \|G_\mu(0, \cdot)\|_{L^2(\mathbb{T})^d} &\leq C (\|G_\mu\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T})^d}) \\ &\leq C (\|P_\mu^h(0)^* g\|_{L^2(q_{T'})^d} + \|G_\mu - P_\mu^h(0)^* g\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T})^d}) \\ &\leq C (\|P_\mu^h(0)^* g\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T})^d}). \end{aligned}$$

which ends Step 2.

Step 3: Conclusion. For every $\mu \in \text{Sp}(A')$, we have $P_\mu^h(0)^* = P_\mu^h(0)^* P^h(0)^*$ thus

$$\|P_\mu^h(0)^* g\|_{L^2(q_{T'})^d} \leq |P_\mu^h(0)^*| \|P^h(0)^* g\|_{L^2(q_{T'})^d} \leq C \|g_1\|_{L^2(q_{T'})^d}.$$

Using (71), the triangular inequality, Step 2 and the previous inequality, we obtain

$$\|g_0\|_{L^2(\mathbb{T})^d} \leq \sum_{\mu \in \text{Sp}(A')} \|G_\mu(0, \cdot)\|_{L^2(\mathbb{T})^d} \leq C (\|g_1\|_{L^2(q_{T'})^d} + \|g_0\|_{H^{-1}(\mathbb{T})^d}). \quad (83)$$

From this estimate and the compact embedding $L^2(\mathbb{T}) \hookrightarrow H^{-1}(\mathbb{T})$, a classical compactness-uniqueness argument gives the observability inequality (69) (see for instance [12, Lemma 2.1 and Remark 2.2]).

Indeed, by Peetre's lemma (see [23, Lemma 3]), we have from (83) that

$$N_{T'} := \{g_0 \in \tilde{F}^h; g_1 = 0 \text{ in } (0, T') \times \omega\},$$

has finite-dimension. Moreover, from [23, Lemma 4], to prove (69), we only need to show that $N_{T'}$ is reduced to zero. First, by definition, we remark that $N_{T'}$ decreases as T' increases. By a small

perturbation of T' , we may therefore assume that $N_T = N_{T'}$ for $T - T'$ small, in which case $N_{T'}$ is stable by $e^{-t\mathcal{L}^{*h}}$ where \mathcal{L}^{*h} is the restriction of \mathcal{L}^* to \widetilde{F}^h . Then, if $N_{T'}$ is not reduced to zero, it contains an eigenfunction of \mathcal{L}^{*h} , i.e. a function of the form Xe_n where $X \in \mathbb{C}^d$, $|n| > n_0$ and $X = P^h\left(\frac{i}{n}\right)X$. By definition of $N_{T'}$, the first components of that eigenfunction vanishes on ω i.e. $X_1 = 0$, or equivalently $P^h(0)X = 0$. Thus

$$|X| = \left| \left(P^h\left(\frac{i}{n}\right) - P^h(0) \right) X \right| \leq \frac{C}{|n|} |X|$$

where $C > 0$ does not depend on n . For a large enough choice of n_0 , this is impossible. \square

4.4 Control of the parabolic high frequencies

The goal of this subsection is to prove Proposition 28. We recall that T and T' are chosen such that $T^* < T' < T$ and the control u is such that (58) and (59) hold.

The strategy is the following one: identify the equation satisfied by the last d_2 components of the parabolic equation (30) with the help of the asymptotics of Proposition 7, then construct smooth controls by adapting the Lebeau-Robbiano's method to systems.

In this section, for every vector $\varphi \in \mathbb{C}^d$, we will note φ_1 its first d_1 components and φ_2 its last d_2 components.

4.4.1 Reduction to a null-controllability problem

The goal of this paragraph is to transform the null-controllability problem of Proposition 28 into a null-controllability problem associated to a parabolic system. Precisely, we will prove that Proposition 28 is a consequence of the following result.

Proposition 31. *If n_0 is large enough, then for every $T > 0$, there exists a continuous operator*

$$\begin{aligned} \underline{\mathcal{U}}_T^p: F^p &\rightarrow C_c^\infty((0, T) \times \omega)^{d_2} \\ f_0 &\mapsto u_p, \end{aligned}$$

such that for every $f_0 \in F^p$,

$$\Pi^p S(T; f_0, (0, \underline{\mathcal{U}}_T^p(f_0))) = 0.$$

Proposition 31 will be proved thanks to an adaptation of Lebeau-Robbiano's method in Section 4.4.4, after two sections of preliminary results. Now we prove Proposition 28 thanks to Proposition 31.

Proof of Proposition 28. Let $(f_0, u_h) \in L^2(\mathbb{T}^d) \times L^2((0, T') \times \omega)^{d_1}$. We have to find $u_p \in C_c^\infty((T', T) \times \omega)^{d_2}$ such that

$$\Pi^p S(T; f_0, (u_h, u_p)) = 0, \tag{84}$$

or equivalently,

$$\Pi^p S(T; 0, (0, u_p)) = -\Pi^p S(T; f_0, (u_h, 0)). \tag{85}$$

In view of the support of the controls (Eq. (59)), the equality (85) is equivalent to

$$\Pi^p S(T - T'; 0, (0, u_p(\cdot + T'))) = -e^{-(T-T')\mathcal{L}^p} \Pi^p S(T'; f_0, (u_h, 0)), \tag{86}$$

or

$$\Pi^p S\left(T - T'; \Pi^p S(T'; f_0, (u_h, 0)), (0, u_p(\cdot + T'))\right) = 0. \tag{87}$$

By using Definition 12 and Proposition 24, we see that the mapping $(f_0, u_h) \mapsto \Pi^p S(T'; f_0, (u_h, 0))$ is continuous from $L^2(\mathbb{T}^d) \times L^2((0, T') \times \omega)^{d_1}$ into F^p . Thus we get the conclusion with

$$\forall t \in (T', T), \mathcal{U}^p(f_0, u_h)(t) = \underline{\mathcal{U}}_{(T-T')}^p\left(\Pi^p S(T'; f_0, (u_h, 0))\right)(t - T'). \quad \square$$

4.4.2 Equation satisfied by the parabolic components of the free system

We begin by proving that if g is in $\widetilde{F}^{\mathbb{P}}$ then we can compute the first d_1 components of g from the last d_2 . This will allow us to write an uncoupled equation for these components.

Proposition 32. *If z is small enough, there exists a matrix $G(z)$ such that for every $\varphi \in \mathbb{C}^d$,*

$$\varphi \in \text{Im}(P^{\mathbb{P}}(z)^*) \iff \varphi_1 = G(z)\varphi_2.$$

Moreover, G is holomorphic in z and $G(0) = 0$.

Proof. We write

$$P^{\mathbb{P}}(z)^* = \begin{pmatrix} p_{11}(z) & p_{12}(z) \\ p_{21}(z) & p_{22}(z) \end{pmatrix}.$$

Since $P^{\mathbb{P}}(z)^*$ is a projection, φ is in $\text{Im}(P^{\mathbb{P}}(z)^*)$ if and only if

$$\begin{cases} p_{11}(z)\varphi_1 + p_{12}(z)\varphi_2 = \varphi_1 \\ p_{21}(z)\varphi_1 + p_{22}(z)\varphi_2 = \varphi_2. \end{cases}$$

In particular, if $\varphi \in \text{Im}(P^{\mathbb{P}}(z)^*)$, then $(I_{d_1} - p_{11}(z))\varphi_1 = p_{12}(z)\varphi_2$. And since $P^{\mathbb{P}}(0)^* = \begin{pmatrix} 0 & 0 \\ 0 & I_{d_2} \end{pmatrix}$ (see Proposition 6), $p_{11}(0) = 0$, and so, if z is small enough, $|p_{11}(z)| < 1$ and $I_{d_1} - p_{11}(z)$ is invertible.

In that case, $\varphi_1 = (I_{d_1} - p_{11}(z))^{-1}p_{12}(z)\varphi_2$. This proves that the map

$$\varphi \in \text{Im}(P^{\mathbb{P}}(z)^*) \mapsto \varphi_2 \in \mathbb{C}^{d_2}$$

is one-to-one. But the rank of $P^{\mathbb{P}}(z)^*$ does not depend on z (Remark 8), and so it is always d_2 . So the previous map is bijective. We note $G(z)$ the first d_1 component of its inverse. Note that we have $G(z) = (I_{d_1} - p_{11}(z))^{-1}p_{12}(z)$. Then, if $\varphi \in \text{Im}(P^{\mathbb{P}}(z)^*)$, we have

$$\varphi = (\varphi_1, \varphi_2) = (G(z)\varphi_2, \varphi_2).$$

To prove the converse, note that the inverse of $\varphi \in \text{Im}(P^{\mathbb{P}}(z)^*) \mapsto \varphi_2$ is $\varphi_2 \in \mathbb{C}^{d_2} \mapsto (G(z)\varphi_2, \varphi_2)$. \square

Increasing n_0 if necessary, we may assume that for $|n| > n_0$, $G(i/n)$ is well-defined. Then, we define the (bounded) operator G from $L^2(\mathbb{T}, \mathbb{C}^{d_2})$ to $L^2(\mathbb{T}, \mathbb{C}^{d_1})$ by

$$G\left(\sum_{n \in \mathbb{Z}} \varphi_{n,2} e_n\right) = \sum_{|n| > n_0} G\left(\frac{i}{n}\right) \varphi_{n,2} e_n. \quad (88)$$

Then, according to the definition of $\widetilde{F}^{\mathbb{P}}$, we have the following corollary that allows us to compute the first d_1 components from the last d_2 .

Corollary 33. *For every $g \in (F^0)^\perp$ (the space of functions with no components along frequencies less than n_0), we have the equivalence $g \in \widetilde{F}^{\mathbb{P}} \Leftrightarrow g_1 = Gg_2$.*

The Corollary 33 makes it easy to write an equation on the last d_2 components of the adjoint system (30) if the initial condition is in $\widetilde{F}^{\mathbb{P}}$.

Proposition 34. *We define the operator \mathfrak{D} by*

$$D(\mathfrak{D}) = H^2(\mathbb{T})^{d_2}, \quad \mathfrak{D} = D^{\text{tr}} \partial_x^2 + A_{22}^{\text{tr}} \partial_x - K_{22}^{\text{tr}} + A_{12}^{\text{tr}} \partial_x G - K_{12}^{\text{tr}} G. \quad (89)$$

Let $g_0 \in \widetilde{F}^{\mathbb{P}}$ and $g(t) = e^{-t\mathcal{L}^*} g_0$. Then, for all $t \geq 0$, $g_1(t) = Gg_2(t)$ and g_2 satisfies the following equation

$$\partial_t g_2(t, x) - \mathfrak{D}g_2(t, x) = 0 \quad \text{in } (0, T) \times \mathbb{T}. \quad (90)$$

Proof. The function g satisfies the system

$$(\partial_t - B^{\text{tr}}\partial_x^2 - A^{\text{tr}}\partial_x + K^{\text{tr}})g(t, x) = 0 \quad \text{in } (0, T) \times \mathbb{T}.$$

If we take the last d_2 components of this system, we get, in $(0, T) \times \mathbb{T}$,

$$(\partial_t - D^{\text{tr}}\partial_x^2 - A_{22}^{\text{tr}}\partial_x + K_{22}^{\text{tr}})g_2(t, x) - (A_{12}^{\text{tr}}\partial_x - K_{12}^{\text{tr}})g_1(t, x) = 0. \quad (91)$$

But for all $t \in [0, T]$, $g(t, \cdot) \in \widetilde{F}^{\text{p}}$, so, according to Corollary 33, $g_1(t) = Gg_2(t)$. Substituting this inside the equation (91) gives the stated equation (90). \square

4.4.3 Smooth control of a finite number of parabolic vectorial components

For $N > n_0$ we introduce

$$F_N^{\text{p}} := \bigoplus_{n_0 < |n| \leq N} \text{Im} \left(P^{\text{p}} \left(\frac{\mathbf{i}}{n} \right) \right) e_n, \quad (92)$$

$$F_{>N}^{\text{p}} := \bigoplus_{|n| > N} \text{Im} \left(P^{\text{p}} \left(\frac{\mathbf{i}}{n} \right) \right) e_n.$$

and the projection Π_N^{p} defined by

$$\begin{aligned} L^2(\mathbb{T})^d &= F^0 \oplus F_N^{\text{p}} \oplus F_{>N}^{\text{p}} \oplus F^{\text{h}} \\ \Pi_N^{\text{p}} &= 0 + I_{F_N^{\text{p}}} + 0 + 0 \end{aligned}$$

which is a bounded operator on $L^2(\mathbb{T})^d$ (composition of the bounded operator Π^{p} with an orthogonal projection). The goal of this section is to prove the following result.

Proposition 35. *There exists $\mathcal{C} > 0$ such that, for every $T \in (0, 1]$ and $N > n_0$, there exists a linear map⁶*

$$\mathcal{K}_{T, N}: F^{\text{p}} \rightarrow C_0^\infty((0, T) \times \omega)$$

such that, for every $f_0 \in F^{\text{p}}$ and $s \in \mathbb{N}$

$$\Pi_N^{\text{p}} S \left(T; f_0, (0, \mathcal{K}_{T, N}(f_0)) \right) = 0,$$

$$\|\mathcal{K}_{T, N}(f_0)\|_{H_0^s((0, T) \times \mathbb{T})} \leq \frac{\mathcal{C}}{T^{s+1}} N^{2s} e^{cN} \|f_0\|_{L^2(\mathbb{T})^d}.$$

Proof. Let $f_0 \in F^{\text{p}}$. Throughout this proof, we will note $E_2(n)$ the $d_2 \times d_2$ matrices defined by

$$\forall |n| > n_0, \quad E_2(n) := D^{\text{tr}} - \frac{\mathbf{i}}{n} A_{22}^{\text{tr}} + \frac{1}{n^2} K_{22}^{\text{tr}} - \left(\frac{\mathbf{i}}{n} A_{12}^{\text{tr}} - \frac{1}{n^2} K_{12}^{\text{tr}} \right) G \left(\frac{\mathbf{i}}{n} \right).$$

Step 1: We prove that $u_2 \in C_0^\infty((0, T) \times \omega)$ satisfies $\Pi_N^{\text{p}} S(T; f_0, (0, u_2)) = 0$ if and only if u_2 solves the following moments problem in \mathbb{C}^{d_2}

$$\begin{aligned} \forall n_0 < |n| \leq N, \quad \int_0^T \int_\omega e^{-n^2(T-t)E_2(n)^*} u_2(t, x) e^{-inx} dx dt &= F_n \\ \text{where } F_n &= -e^{-n^2 T E_2(n)^*} \left(G \left(\frac{\mathbf{i}}{n} \right)^* \widehat{f}_{01}(n) + \widehat{f}_{02}(n) \right) \end{aligned} \quad (93)$$

and $E_2(n)^* = \overline{E_2(n)}^{\text{tr}}$.

We first recall that, if P is a projection operator on \mathbb{R}^d and $x \in \text{Im}(P)$, then

$$(x = 0) \Leftrightarrow (\forall z \in \text{Im}(P^*), \langle x, z \rangle = 0)$$

⁶The space $C_0^\infty((0, T) \times \omega)$ means that the function is supported on $[0, T] \times K$ where K is a compact subset of ω , and all the derivatives vanish on ω at time $t = 0$ and $t = T$.

because $|x|^2 = \langle x, x \rangle = \langle Px, x \rangle = \langle x, P^*x \rangle$.

As a consequence, the relation $\Pi_N^p S(T; f_0, (0, u_2)) = 0$ is equivalent to

$$\forall g_T \in \widetilde{F}_N^p, \langle S(T; f_0, (0, u_2)), g_T \rangle = 0 \quad (94)$$

where $\langle \cdot, \cdot \rangle$ is the scalar product of $L^2(\mathbb{T}, \mathbb{C}^d)$ and

$$\widetilde{F}_N^p := \bigoplus_{n_0 < |n| \leq N} \text{Im} \left(P^p \left(\frac{i}{n} \right)^* \right) e_n.$$

For $g_T \in \widetilde{F}_N^p$, we denote by $g(t) = e^{-\mathcal{L}^*(T-t)} g_T$ the solution of the adjoint system (30). Then, by Proposition 34, $g = (g_1, g_2)$, where $g_1 = G(g_2)$ and

$$\langle S(T; f_0, (0, u_2)), g_T \rangle = \langle f_0, g(0) \rangle + \int_0^T \int_\omega \langle u_2(t, x), g_2(t, x) \rangle dx dt.$$

where the first 2 scalar products are in $L^2(\mathbb{T})^d$ and the last one is in \mathbb{C}^{d_2} . By Corollary 33, the assertion (94) is equivalent to

$$\forall g_2^T \in L^2(\mathbb{T}, \mathbb{C}^{d_2}), \int_0^T \int_\omega \langle u_2(t, x), g_2(t, x) \rangle dx dt = -\langle f_0, (G(g_2^0), g_2^0) \rangle,$$

where $g_2(t) = e^{-\mathfrak{D}(T-t)} g_2^T$ and $g_2^0 = g_2(0)$. By considering $g_2^T = X e_n$ with $X \in \mathbb{C}^{d_2}$ and $n_0 < |n| \leq N$, we obtain

$$g_2(t) = e^{-n^2(T-t)E_2(n)} X e_n \text{ and } G(g_2^0) = G \left(\frac{i}{n} \right) e^{-n^2 T E_2(n)} X e_n.$$

The previous property is equivalent to

$$\begin{aligned} \forall n_0 < |n| \leq N, \forall X \in \mathbb{C}^{d_2}, \int_0^T \int_\omega \langle u_2(t, x), e^{-n^2(T-t)E_2(n)} X \rangle e^{-inx} dx dt \\ = -\langle f_{01}, G(i/n) e^{-n^2 T E_2(n)} X e_n \rangle - \langle f_{02}, e^{-n^2 T E_2(n)} X e_n \rangle \end{aligned}$$

or, equivalently,

$$\begin{aligned} \forall n_0 < |n| \leq N, \forall X \in \mathbb{C}^{d_2}, \left\langle \int_0^T \int_\omega e^{-n^2(T-t)E_2(n)^*} u_2(t, x) e^{-inx} dx dt, X \right\rangle \\ = -\left\langle e^{-n^2 T E_2(n)^*} G(i/n)^* \widehat{f}_{01}(n) + e^{-n^2 T E_2(n)^*} \widehat{f}_{02}(n), X \right\rangle \end{aligned}$$

which proves (93).

Step 2: Solving the moment problem. We look for a solution $u_2 \in C_0^\infty((0, T) \times \omega)$ of the moment problem (93) of the form

$$u_2(t, x) = \rho(t, x) v_2(t, x) \quad (95)$$

where $v_2 \in C^\infty((0, T) \times \mathbb{T})^{d_2}$ and $\rho \in C_0^\infty((0, T) \times \omega)$ is a scalar function with an appropriate support. More precisely, let

- $\widehat{\omega}$ be an open subset such that $\widehat{\omega} \subset\subset \omega$ and $\rho_2 \in C_c^\infty(\omega, \mathbb{R}_+)$ such that $\rho_2 = 1$ on $\widehat{\omega}$,
- $\rho_1 \in C^\infty([0, 1], \mathbb{R}_+)$ such that $\rho_1(0) = \rho_1(1) = 0$ and

$$\exists C_0 > 0, \forall \gamma > 0, \int_0^1 \rho_1(\tau) e^{-\gamma \tau} d\tau \geq \frac{1}{C_0} e^{-C_0 \sqrt{\gamma}}. \quad (96)$$

For instance, we may consider ρ_1 such that $\rho_1(\tau) = \rho_1(1 - \tau) = e^{-\frac{1}{\tau}}$ for $\tau \in (0, 1/4)$. Indeed, for every $\gamma > 0$, the change of variable $s = \sqrt{\gamma}\tau$ gives

$$\int_0^1 \rho_1(\tau) e^{-\gamma\tau} d\tau \geq \frac{1}{\sqrt{\gamma}} \int_0^{\sqrt{\gamma}/4} e^{-\sqrt{\gamma}\phi(s)} ds$$

where $\phi(s) = \frac{1}{s} + s$. The function ϕ takes its minimal value at $s_* = 1$ and $\phi''(1) = 2 > 0$ thus, by Laplace's method (see [24, Chapitre 9, Théorème VI.1]),

$$\int_0^2 e^{-\sqrt{\gamma}\phi(s)} ds \underset{\gamma \rightarrow \infty}{\sim} \frac{\sqrt{\pi}}{\sqrt[4]{\gamma}} e^{-2\sqrt{\gamma}}.$$

which proves (96) for a large enough constant C_0 .

Then we choose $\rho(t, x) = \rho_1((T - t)/T)\rho_2(x)$. We also look for v_2 of the form

$$v_2(t, x) = \sum_{n_0 < |k| \leq N} e^{-k^2(T-t)E_2(k)} V_k e^{ikx} \quad \text{where } V_k \in \mathbb{C}^{d_2}. \quad (97)$$

The construction of v_2 will use the following algebraic result.

Lemma 36. *There exists $C > 0$ such that, for every $N > n_0$ and $T \in (0, 1]$ the matrix A in $\mathbb{C}^{(2(N-n_0)d_2) \times (2(N-n_0)d_2)}$, defined by blocks $A = (A_{n,k})_{\substack{n_0 < |n| \leq N \\ n_0 < |k| \leq N}}$ by*

$$A_{n,k} = \int_0^T \int_{\omega} e^{-n^2(T-t)E_2(n)^*} e^{-k^2(T-t)E_2(k)} e^{i(k-n)x} \rho(t, x) dx dt \in \mathbb{C}^{d_2 \times d_2},$$

is invertible and

$$\forall F \in \mathbb{C}^{2(N-n_0)d_2}, \quad |A^{-1}F| \leq \frac{C}{T} e^{CN} |F|,$$

where $|\cdot|$ is the hermitian norm on $\mathbb{C}^{2(N-n_0)d_2}$.

Remark 37. For instance, when $N = n_0 + 2$, then A is given by

$$A = \begin{pmatrix} A_{-n_0-2, -n_0-2} & A_{-n_0-2, -n_0-1} & A_{-n_0-2, n_0+1} & A_{-n_0-2, n_0+2} \\ A_{-n_0-1, -n_0-2} & A_{-n_0-1, -n_0-1} & A_{-n_0-1, n_0+1} & A_{-n_0-1, n_0+2} \\ A_{n_0+1, -n_0-2} & A_{n_0+1, -n_0-1} & A_{n_0+1, n_0+1} & A_{n_0+1, n_0+2} \\ A_{n_0+2, -n_0-2} & A_{n_0+2, -n_0-1} & A_{n_0+2, n_0+1} & A_{n_0+2, n_0+2} \end{pmatrix}.$$

For $X \in \mathbb{C}^{4d_2}$ with block decomposition

$$X = \begin{pmatrix} X_{-n_0-2} \\ X_{-n_0-1} \\ X_{n_0+1} \\ X_{n_0+2} \end{pmatrix}$$

where $X_k \in \mathbb{C}^{d_2}$ for every $n_0 < |k| \leq n_0 + 2$, we have

$$AX = \begin{pmatrix} \sum_{n_0 < |k| \leq n_0+2} A_{-n_0-2, k} X_k \\ \sum_{n_0 < |k| \leq n_0+2} A_{-n_0-1, k} X_k \\ \sum_{n_0 < |k| \leq n_0+2} A_{n_0+1, k} X_k \\ \sum_{n_0 < |k| \leq n_0+2} A_{n_0+2, k} X_k \end{pmatrix}.$$

Thus $\langle X, AX \rangle = \sum_{n_0 < |n|, |k| \leq n_0+2} X_n^* A_{n,k} X_k$.

Proof of Lemma 36. The proof relies on the following spectral inequality, due to Lebeau and Robbiano (see [19] and also [18, Thm. 5.4]):

$$\exists C_1 > 0, \forall N \in \mathbb{N}, \forall (a_n)_{n \in \mathbb{Z}} \in \mathbb{C}^{\mathbb{Z}}, \sum_{n=-N}^{+N} |a_n|^2 \leq C_1 e^{C_1 N} \int_{\widehat{\omega}} \left| \sum_{n=-N}^{+N} a_n e^{inx} \right|^2 dx. \quad (98)$$

By summing the components, the same inequality holds when a_n is a vector, $a_n \in \mathbb{C}^{d_2}$, and $|\cdot|$ denotes the hermitian norm on \mathbb{C}^{d_2} .

Let $N > n_0$ and $X \in \mathbb{C}^{2(N-n_0)d_2}$ written by blocks $X = (X_k)_{n_0 < |k| \leq N}$ with $X_k \in \mathbb{C}^{d_2}$. Then, by using the definition of A , ρ , the properties of ρ_2 and the above spectral inequality in vectorial form, we obtain

$$\begin{aligned} \langle AX, X \rangle &= \sum_{n_0 < |n|, |k| \leq N} X_n^* A_{n,k} X_k \\ &= \int_0^T \int_{\omega} \left| \sum_{n_0 < |k| \leq N} e^{-k^2(T-t)E_2(k)} X_k e^{ikx} \right|^2 \rho(t, x) dx dt \\ &\geq \int_0^T \int_{\widehat{\omega}} \left| \sum_{n_0 < |k| \leq N} e^{-k^2(T-t)E_2(k)} X_k e^{ikx} \right|^2 \rho_1 \left(\frac{T-t}{T} \right) dx dt \\ &\geq \frac{e^{-C_1 N}}{C_1} \int_0^T \sum_{n_0 < |k| \leq N} \left| e^{-k^2(T-t)E_2(k)} X_k \right|^2 \rho_1 \left(\frac{T-t}{T} \right) dt. \end{aligned}$$

There exists $c > 0$ such that, for every $|k| > n_0$, $|E_2(k)| \leq c$. Then,

$$\forall |k| > n_0, \tau > 0, Y \in \mathbb{C}^{d_2}, |e^{E_2(k)\tau} Y| \leq e^{c\tau} |Y|.$$

Then, by considering $\tau = k^2(T-t)$ and $Y = \exp(-k^2(T-t)E_2(k))X_k$, we obtain

$$\forall |k| > n_0, t \in (0, T), \left| e^{-k^2(T-t)E_2(k)} X_k \right| \geq e^{-ck^2(T-t)} |X_k|.$$

Therefore, by using the change of variable $\tau = \frac{T-t}{T}$ and (96), we get

$$\begin{aligned} \langle AX, X \rangle &\geq \frac{T e^{-C_1 N}}{C_1} \sum_{n_0 < |k| \leq N} |X_k|^2 \int_0^T e^{-2ck^2 T \tau} \rho_1(\tau) d\tau \\ &\geq \frac{T e^{-C_1 N}}{C_1 C_0} \sum_{n_0 < |k| \leq N} |X_k|^2 e^{-C_0 k \sqrt{2cT}} \\ &\geq \frac{T}{C_1 C_0} e^{-(C_1 + C_0 \sqrt{2cT})N} |X|^2. \end{aligned}$$

The above relation, valid for any $X \in \mathbb{C}^{2(N-n_0)d_2}$ proves that any eigenvalue of A is positive, thus A is invertible. Moreover, for any $F \in \mathbb{C}^{2(N-n_0)d_2} \setminus \{0\}$, the vector $X = A^{-1}F$ satisfies

$$\frac{T}{C_1 C_0} e^{-(C_1 + C_0 \sqrt{2cT})N} |X|^2 \leq \langle AX, X \rangle = \langle F, X \rangle \leq |F| |X|.$$

Thus

$$|X| \leq \frac{C_1 C_0}{T} e^{(C_1 + C_0 \sqrt{2cT})N} |F|.$$

This gives the conclusion with $\mathcal{C} = \max\{C_1 C_0; C_1 + C_0 \sqrt{2c}\}$. \square

Now, let us come back to the proof of Proposition 35. For such a control of the form given by equations (95) and (97), the moment problem (93) writes

$$\forall n_0 < |n| \leq N, \sum_{n_0 < |k| \leq N} A_{n,k} V_k = F_n$$

or equivalently $AV = F$ with the notations of Lemma 36. Thus, it is sufficient to take $V = A^{-1}F$. By the definition of F in (93), and Bessel-Parseval identity there exists $C_2 > 0$ independent of (T, N) such that

$$|F| = \left(\sum_{n_0 < |n| \leq N} |F_n|^2 \right)^{1/2} \leq C_2 \|f_0\|_{L^2(\mathbb{T})^d}.$$

Thus, by Lemma 36

$$|V| = \left(\sum_{n_0 < |k| \leq N} |V_k|^2 \right)^{1/2} \leq \frac{C_2 \mathcal{C}}{T} e^{cN} \|f_0\|_{L^2(\mathbb{T})^d}. \quad (99)$$

Step 3: Estimates on u_2 . Let $s \in \mathbb{N}^*$. By (95) and the definition of ρ , there exists $C = C(\rho, s) > 0$ such that

$$\|u_2\|_{H^s((0,T) \times \omega)} \leq \frac{C}{T^s} \|v_2\|_{H^s((0,T) \times \mathbb{T})}. \quad (100)$$

For any $s_1, s_2 \in \mathbb{N}$ such that $s_1 + s_2 \leq s$ we have,

$$\partial_t^{s_1} \partial_x^{s_2} v_2(t, x) = \sum_{n_0 < |k| \leq N} k^{2s_1} E_2(k)^{s_1} e^{-k^2(T-t)E_2(k)} V_k(ik)^{s_2} e^{ikx}.$$

By Bessel-Parseval identity, we have

$$\begin{aligned} \|\partial_t^{s_1} \partial_x^{s_2} v_2\|_{L^2((0,T) \times \mathbb{T})}^2 &= \int_0^T \sum_{n_0 < |k| \leq N} \left| k^{2s_1+s_2} E_2(k)^{s_1} e^{-k^2(T-t)E_2(k)} V_k \right|^2 dt \\ &\leq C \int_0^T \sum_{n_0 < |k| \leq N} k^{4s} \left| e^{-k^2(T-t)E_2(k)} V_k \right|^2 dt \end{aligned}$$

By working as in the proof of Proposition 9, we obtain, for n_0 large enough, positive constants $K_p, c_p > 0$ such that

$$\begin{aligned} \|\partial_t^{s_1} \partial_x^{s_2} v_2\|_{L^2((0,T) \times \mathbb{T})}^2 &\leq C \sum_{n_0 < |k| \leq N} k^{4s} K_p^2 \int_0^T e^{-2c_p k^2(T-t)} dt |V_k|^2 \\ &\leq \frac{CK_p^2}{2c_p} \sum_{n_0 < |k| \leq N} k^{4s-2} |V_k|^2 \leq \frac{CK_p^2}{c_p} N^{4s-1} |V|^2 \end{aligned}$$

By (99),

$$\|\partial_t^{s_1} \partial_x^{s_2} v_2\|_{L^2((0,T) \times \mathbb{T})} \leq \sqrt{\frac{C}{c_p}} K_p N^{2s-1/2} \frac{C_2 \mathcal{C}}{T} e^{cN} \|f_0\|_{L^2(\mathbb{T})^d}.$$

This provides a constant $C > 0$ independant of (T, N) such that

$$\|v_2\|_{H^s((0,T) \times \mathbb{T})} \leq \frac{C}{T} N^{2s-1/2} e^{cN} \|f_0\|_{L^2(\mathbb{T})^d}$$

and (100) gives the expected estimate on u in H^s . \square

4.4.4 Lebeau-Robbiano's method

The goal of this section is to prove Proposition 31. Let $T > 0$. We fix $\delta \in (0, T/2)$ and $\rho \in (0, 1)$. For $\ell \in \mathbb{N}^*$, we set $N_\ell = 2^\ell$, $T_\ell = A2^{-\rho\ell}$ where $A > 0$ is such that $2 \sum_{\ell=1}^{\infty} T_\ell = T - 2\delta$. Let $f_0 \in F^{\mathbb{P}}$. We define

$$\begin{cases} f_1 = e^{-\delta \mathcal{L}^{\mathbb{P}}} f_0, \\ g_\ell = \Pi^{\mathbb{P}} S(T_\ell; f_\ell, u_\ell) \text{ where } u_\ell = (0, K_{T_\ell, N_\ell}(f_\ell)), \\ f_{\ell+1} = e^{-T_\ell \mathcal{L}^{\mathbb{P}}} g_\ell, \end{cases}$$

where K_{T_ℓ, N_ℓ} is the control operator introduced in Proposition 35. By construction $\Pi_{N_\ell}^p g_\ell = 0$ and therefore, by Proposition 9

$$\begin{aligned} \|f_{\ell+1}\|_{L^2(\mathbb{T})^d}^2 &= \|e^{-T_\ell \mathcal{L}^p} g_\ell\|_{L^2(\mathbb{T})^d}^2 = \sum_{|n| > N_\ell} \left| e^{-n^2 E(i/n) T_\ell} \widehat{g}_\ell(n) \right|^2 \\ &\leq \sum_{|n| > N_\ell} K_p^2 e^{-2n^2 c_p T_\ell} |\widehat{g}_\ell(n)|^2 \leq K_p^2 e^{-2c_p N_\ell^2 T_\ell} \|g_\ell\|_{L^2(\mathbb{T})^d}^2. \end{aligned}$$

By the semi-group property proved in Proposition 11, there exists positive constants K and c such that

$$\forall f \in L^2(\mathbb{T})^d, t \geq 0 \quad \|e^{-t\mathcal{L}} f\|_{L^2(\mathbb{T})^d} \leq K e^{ct} \|f\|_{L^2(\mathbb{T})^d}.$$

Then, according to the triangle inequality and Cauchy-Schwarz inequality,

$$\begin{aligned} \|g_\ell\|_{L^2(\mathbb{T})^d} &\leq \|S(T_\ell; f_\ell, u_\ell)\| \leq K e^{cT_\ell} \|f_\ell\|_{L^2(\mathbb{T})^d} + \int_0^{T_\ell} K e^{c(T_\ell-t)} \|u_\ell(t)\|_{L^2(\mathbb{T})} dt \\ &\leq K e^{cT_\ell} \left(\|f_\ell\|_{L^2(\mathbb{T})^d} + \sqrt{T_\ell} \|u_\ell\|_{L^2((0, T_\ell) \times \omega)} \right), \end{aligned}$$

and by Proposition 35

$$\|u_\ell\|_{L^2((0, T_\ell) \times \omega)} \leq \frac{C}{T_\ell} e^{cN_\ell} \|f_\ell\|_{L^2(\mathbb{T})^d}. \quad (101)$$

Thus

$$\|g_\ell\|_{L^2(\mathbb{T})^d} \leq K e^{cT_\ell} \left(1 + \frac{C}{\sqrt{T_\ell}} e^{cN_\ell} \right) \|f_\ell\|_{L^2(\mathbb{T})^d}.$$

By setting

$$m_\ell = K_p e^{-c_p N_\ell^2 T_\ell} K e^{cT_\ell} \left(1 + \frac{C}{\sqrt{T_\ell}} e^{cN_\ell} \right),$$

we get

$$\|f_{\ell+1}\|_{L^2(\mathbb{T})^d} \leq m_\ell \|f_\ell\|_{L^2(\mathbb{T})^d}.$$

It is easy to see that there exists $C_1, C_2 > 0$ such that $m_\ell \leq C_1 e^{-C_2 2^{(2-\rho)\ell}}$. Thus $\|f_\ell\|_{L^2(\mathbb{T})^d} \rightarrow 0$ and more precisely there exists positive constants $C_3, C_4 > 0$ such that

$$\|f_\ell\|_{L^2(\mathbb{T})^d} \leq C_3 \exp\left(-C_4 2^{(2-\rho)\ell}\right) \|f_0\|_{L^2(\mathbb{T})^d}.$$

Moreover, from (101),

$$\sum_{\ell=1}^{\infty} \|u_\ell\|_{L^2((0, T_\ell) \times \omega)}^2 \leq C \sum_{\ell=1}^{\infty} \frac{e^{cN_\ell}}{T_\ell} C_3 \exp(-C_4 2^{(2-\rho)\ell}) \|f_0\|_{L^2(\mathbb{T})^d} < \infty. \quad (102)$$

We set $a_0 = \delta$, $a_2 = \delta + 2T_1$, \dots , $a_\ell = a_{\ell-1} + 2T_\ell$. We have $a_\ell \rightarrow (T - \delta)$ as $\ell \rightarrow \infty$. Then, for any $f_0 \in F^p$, we define the control

$$\underline{\mathcal{U}}_T^p(f_0)(t, x) = \begin{cases} K_{T_\ell, N_\ell}(f_\ell)(t - a_{\ell-1}) & \text{for } a_{\ell-1} \leq t \leq a_{\ell-1} + T_\ell, \\ 0 & \text{for } a_{\ell-1} + T_\ell \leq t \leq a_{\ell-1} + 2T_\ell = a_\ell, \\ 0 & \text{for } T - \delta \leq t \leq T. \end{cases}$$

Then, $\underline{\mathcal{U}}_T^p(f_0) \in C_0^\infty((\delta, T - \delta) \times \omega)^{d_2}$ because all its derivatives vanish at times $t = a_\ell$. Thus $\underline{\mathcal{U}}_T^p(f_0) \in C_c^\infty((0, T) \times \omega)^{d_2}$.

By (102), $\underline{\mathcal{U}}_T^p(f_0) \in L^2((0, T) \times \omega)^d$ thus $S(T - \delta; f_0, \underline{\mathcal{U}}_T^p(f_0))$ is the limit, in $L^2(\mathbb{T})^d$, as $\ell \rightarrow \infty$, of the sequence $S(a_\ell; f_0, \underline{\mathcal{U}}_T^p(f_0))$. As a consequence, $\Pi^p S(T - \delta; f_0, \underline{\mathcal{U}}_T^p(f_0))$ is the limit in $L^2(\mathbb{T})$ of the sequence $\Pi^p S(a_\ell; f_0, \underline{\mathcal{U}}_T^p(f_0)) = f_{\ell+1}$. Finally,

$$\Pi^p S(T; f_0, \underline{\mathcal{U}}_T^p(f_0)) = \Pi^p S(T - \delta; f_0, \underline{\mathcal{U}}_T^p(f_0)) = 0.$$

By Proposition 35, for any $s \in \mathbb{N}^*$,

$$\|\underline{\mathcal{U}}_T^p(f_0)\|_{H^s((0,T) \times \omega)} \leq \underbrace{\sum_{\ell=1}^{\infty} \frac{C}{T^{\ell s+1}} N_{\ell}^{2s} e^{CN_{\ell}} C_3 \exp(-C_4 2^{(2-\rho)\ell})}_{< \infty} \|f_0\|_{L^2(\mathbb{T})^d}.$$

This concludes the proof of Proposition 31. \square

4.5 Control of the low frequencies

The goal of this subsection is to prove Theorem 2. Let $T > T^*$ where T^* is defined in (3). Then, there exists $T' > 0$ such that (57) holds. Let \mathcal{G} and \mathcal{U} be as in Proposition 26.

Without loss of generality, we may assume that $F_0 \subset \mathcal{G}$ by the following procedure. Let W be a complement of $\mathcal{G} \cap F^0$ in F^0 . Then W is a complement of \mathcal{G} in $\mathcal{G} + F^0$, and we extend \mathcal{U} to $\mathcal{G} \oplus W$ by setting $\mathcal{U}(f_0) = 0$ for every $f_0 \in W$.

Implicitly, \mathcal{G} is equipped with the topology of the $L^2(\mathbb{T})^d$ -norm. The operator S is defined in Definition 12.

We introduce the vector subspace of $L^2(\mathbb{T})^d$ defined by

$$\mathcal{F}_T = \{f_0 \in L^2(\mathbb{T})^d; \exists u \in L^2((0, T') \times \omega)^{d_1} \times C_c^\infty((T', T) \times \omega)^{d_2} / S(T; f_0, u) = 0\}.$$

Step 1: We prove that \mathcal{F}_T is a closed subspace of $L^2(\mathbb{T})^d$ with finite codimension.

For $f_0 \in \mathcal{G}$, the function $S(T; f_0, \mathcal{U}f_0)$ belongs to F^0 , thus

$$\mathcal{K}(f_0) := -e^{T\mathcal{L}^0} S(T; f_0, \mathcal{U}f_0) \quad (103)$$

is well defined in F^0 by Proposition 25. Then, \mathcal{K} is a compact operator on \mathcal{G} because it has finite rank. By the Fredholm alternative, $(I + \mathcal{K})(\mathcal{G})$ is a closed subspace of \mathcal{G} and there exists a closed subspace \mathcal{G}' of \mathcal{G} , with finite codimension in \mathcal{G} , such that $(I + \mathcal{K})$ is a bijection from \mathcal{G}' to $(I + \mathcal{K})(\mathcal{G})$. Note that \mathcal{G}' is also a closed subspace with finite codimension in $L^2(\mathbb{T})^d$.

For any $f_0 \in \mathcal{G}'$, by using that $\mathcal{K}(f_0) \in F^0$ and (103), we obtain

$$S(T, \mathcal{K}(f_0), 0) = e^{-T\mathcal{L}} \mathcal{K}(f_0) = e^{-T\mathcal{L}^0} \mathcal{K}(f_0) = -S(T, f_0, \mathcal{U}f_0)$$

thus

$$S(T, f_0 + \mathcal{K}(f_0), \mathcal{U}f_0) = S(T, f_0, \mathcal{U}f_0) + S(T, \mathcal{K}(f_0), 0) = 0.$$

This proves that \mathcal{F}_T contains $(I + \mathcal{K})(\mathcal{G}')$, which is a closed subspace with finite codimension in $L^2(\mathbb{T})^d$. Therefore, there exists a finite dimensional subspace F_{\sharp}^{\perp} of $L^2(\mathbb{T})^d$ such that $\mathcal{F}_T = (I + \mathcal{K})(\mathcal{G}') \oplus F_{\sharp}^{\perp}$. This gives the conclusion of Step 1.

Step 2: We prove that, up to a possibly smaller choice of $T > T^$, there exists $\delta > 0$ such that $\mathcal{F}_{T'} = \mathcal{F}_T$ for every $T' \in [T, T + \delta]$. When $0 < T' < T''$, by extending controls defined on $(0, T')$ by zero on (T', T'') , we see that $\mathcal{F}_{T'} \subset \mathcal{F}_{T''}$. Thus, the map $T' \mapsto \text{codim}(\mathcal{F}_{T'})$ is decreasing and takes integer values. As a consequence the discontinuities on $(T^*, T + 1]$ are isolated. If T is not such a discontinuity point, then there exists $\delta > 0$ such that $\text{codim}(\mathcal{F}_{T'}) = \text{codim}(\mathcal{F}_T)$ for every $T' \in [T, T + \delta]$. In case T is such a discontinuity point, one may replace T by a smaller value, still such that $T > T^*$, for which this holds.*

Step 3: We prove that $(e^{-t\mathcal{L}^} \mathcal{F}_T^{\perp})^{\perp} \subset \mathcal{F}_T$ for every $t \in (0, \delta)$. Let $t \in (0, \delta)$ and $g_0 \in L^2(\mathbb{T})^d$ be such that $\langle g_0, e^{-t\mathcal{L}^*} f_0 \rangle = 0$ for every $f_0 \in \mathcal{F}_T^{\perp}$. Then $\langle e^{-t\mathcal{L}} g_0, f_0 \rangle = 0$ for every $f_0 \in \mathcal{F}_T^{\perp}$, i.e. $e^{-t\mathcal{L}} g_0 \in (\mathcal{F}_T^{\perp})^{\perp}$. By Step 1, \mathcal{F}_T is a closed subspace of $L^2(\mathbb{T})^d$ thus $(\mathcal{F}_T^{\perp})^{\perp} = \mathcal{F}_T$. Therefore $e^{-t\mathcal{L}} g_0 \in \mathcal{F}_T$. By definition of \mathcal{F}_T , this implies that $g_0 \in \mathcal{F}_{T+t}$. By Step 2, we get $g_0 \in \mathcal{F}_T$, which ends the proof of Step 3.*

⁷If $f \in \mathcal{G} + F^0$, we write it as $f_{\mathcal{G}} + f_{F_0}$, and in turn we decompose f_{F_0} along the sum $F_0 = \mathcal{G} \cap F_0 \oplus W$: $f_{F_0} = f_{\mathcal{G} \cap F_0} + f_W \in \mathcal{G} + W$. So $f = (f_{\mathcal{G}} + f_{\mathcal{G} \cap F_0}) + f_W$. This proves that $\mathcal{G} + F_0 = \mathcal{G} + W$. Moreover, if $f \in \mathcal{G} \cap W$, since $W \subset F_0$, we have $f \in \mathcal{G} \cap F_0 \cap W$, which is $\{0\}$. So the sum $\mathcal{G} + W$ is direct.

Step 4: We prove that \mathcal{F}_T^\perp is left invariant by $e^{-t\mathcal{L}^*}$, i.e. $\mathcal{F}_T^\perp = e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp$ for every $t > 0$. The subspace $e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp$ is closed in $L^2(\mathbb{T})^d$ because it has finite dimension. Thus $\left((e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp)^\perp\right)^\perp = e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp$ and we deduce from Step 3 that, for every $t \in (0, \delta)$, $\mathcal{F}_T^\perp \subset e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp$. Taking into account that $\dim(e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp) \leq \dim(\mathcal{F}_T^\perp)$, we obtain $\mathcal{F}_T^\perp = e^{-t\mathcal{L}^*}\mathcal{F}_T^\perp$ for every $t \in (0, \delta)$. By the semi-group property, this equality holds for every $t > 0$.

Step 5: We prove the existence of $N \in \mathbb{N}$ such that any $f_0 \in \mathcal{F}_T^\perp$ can be written

$$f_0 = \sum_{k \leq N} \varphi_k e_k \quad \text{with } \varphi_k \in \mathbb{C}^d. \quad (104)$$

Let $S(t)^*$ be the restriction of the semigroup $e^{t\mathcal{L}^*}$ to \mathcal{F}_T^\perp , i.e. $S(t)^* = e^{-t\mathcal{L}^*}|_{\mathcal{F}_T^\perp}$. Then $S(t)^* = e^{tM}$ where M is a matrix such that $\mathcal{L}^*f_0 = Mf_0$ for every $f_0 \in \mathcal{F}_T^\perp$. But then $\ker(M - \bar{\lambda})^j = \ker(\mathcal{L}^* - \bar{\lambda})^j \cap \mathcal{F}_T^\perp$. The Kernel decomposition theorem applied to M , and the structure of the generalized eigenspaces of \mathcal{L}^* gives the conclusion of Step 4.

Step 6: We prove that any element of $L^2(\mathbb{T})^d$ can be steered to \mathcal{F}_T in an arbitrary short time, i.e. for every $\varepsilon > 0$ and $f_0 \in L^2(\mathbb{T})^d$, there exists $u \in L^2((0, T') \times \omega)^{d_1} \times C_c^\infty((T', T) \times \omega)^{d_2}$ such that $S(\varepsilon; f_0, u) \in \mathcal{F}_T$. By the Hilbert Uniqueness Method, it is sufficient to prove an observability inequality for $S(t)^*$. By using the finite-dimensionality of \mathcal{F}_T^\perp , it is equivalent to prove that the following unique continuation property holds: if $f(t, \cdot) = e^{tM}f_0$ with $f = 0$ in $(0, \varepsilon) \times \omega$, then $f_0 = 0$. By using the spectral inequality of Lebeau-Robbiano, i.e. (98) and (104), we readily get the result.

Step 7: Conclusion. Step 5 implies the controllability of the system in any time $\tau > T$. As T is an arbitrary time such that $T > T^*$, this concludes the null-controllability in any time $T > T^*$. \square

By a duality argument, we obtain the following result, that will be used in the next sections.

Corollary 38. *For every $T > T^*$ and $s \in \mathbb{N}$, there exists $C_{T,s} > 0$ such that, for every $g_0 \in L^2(\mathbb{T})^d$ the solution $g(t) = e^{-t\mathcal{L}^*}g_0 = (g_1, g_2)(t)$ of the adjoint system (30) satisfies*

$$\|g(T)\|_{L^2(\mathbb{T})^d} \leq C_{T,s} (\|g_1\|_{L^2(q_T)^{d_1}} + \|g_2\|_{H^{-s}(q_T)^{d_2}}),$$

where $q_T = (0, T) \times \omega$.

We will use the following standard lemma that gives a canonical isometry between $H^{-s}(\Omega)$ and $H_0^s(\Omega)$.

Lemma 39. *Let Ω be an open subset of \mathbb{R}^d or a compact manifold (possibly with boundary). Let $s \geq 0$ and $\iota_s: H_0^s(\Omega) \rightarrow L^2(\Omega)$ be the inclusion map⁸. The map $\iota_s^*: L^2(\Omega) \rightarrow H_0^s(\Omega)$ extends to a bijective isometry from $H_0^s(\Omega)$ to $H^{-s}(\Omega)$.*

Proof. The map ι_s^* is defined on $L^2(\Omega)$ by

$$\forall f \in L^2(\Omega), \forall v \in H_0^s(\Omega), \langle \iota_s^* f, v \rangle_{H_0^s} = \langle f, v \rangle_{L^2}. \quad (105)$$

Thus, for every $f \in L^2(\Omega)$,

$$|\iota_s^* f|_{H_0^s} = \sup_{|v|_{H_0^s}=1} \langle \iota_s^* f, v \rangle_{H_0^s} = \sup_{|v|_{H_0^s}=1} \langle f, v \rangle_{L^2} = |f|_{H^{-s}},$$

where we used the definition of $H^{-s}(\Omega)$ as the dual of $H_0^s(\Omega)$ with respect to the pivot space $L^2(\Omega)$ (see for instance [27, Sec. 2.9]). Since $L^2(\Omega)$ is dense in $H^{-s}(\Omega)^d$, this proves that ι_s^* extends by continuity to $H^{-s}(\Omega)$.

This extension is an isometry from $H^{-s}(\Omega)$ onto its range. As such it is injective and its range is closed. To prove it is bijective, we check that its range is dense, i.e. that its orthogonal is zero.

If $g_0 \in H_0^s(\Omega)$ is orthogonal to $\text{Im}(\iota_s^*)$, then, according to the definition of ι_s^* (Eq. (105)) g_0 is orthogonal in $L^2(\Omega)$ to $H_0^s(\Omega)$. But $H_0^s(\Omega)$ is dense in $L^2(\Omega)$, so $g_0 = 0$. Thus $\text{Im}(\iota_s^*)^\perp = \{0\}$. \square

⁸We recall that $H_0^s(\Omega)$ is the closure of $C_c^\infty(\Omega)$ for the H^s -norm, and that $H^{-s}(\Omega)$ is the dual of $H_0^s(\Omega)$ with respect to the pivot space $L^2(\Omega)$.

Proof of Corollary 38. We apply the duality Lemma 14 with

$$\Phi_2: f_0 \in L^2(\mathbb{T})^d \mapsto f(T, \cdot) \in L^2(\mathbb{T})^d,$$

where f is the solution to the system (Sys) with initial data f_0 and control $u = 0$, and

$$\Phi_3: u = (u_1, u_2) \in L^2(q_T)^{d_1} \times H_0^s(q_T)^{d_2} \mapsto f(T, \cdot) \in L^2(\mathbb{T})^d,$$

where f is the solution to the system (Sys) with initial data $f_0 = 0$ and control u . The null-controllability result proved above is equivalent to the inclusion $\text{Im}(\Phi_2) \subset \text{Im}(\Phi_3)$, thus to the existence of $C > 0$ such that for every $g_T \in L^2(\mathbb{T})^d$,

$$\|\Phi_2^*(g_T)\|_{L^2(\mathbb{T})^d} \leq C \|\Phi_3^*(g_T)\|_{L^2(q_T)^{d_1} \times H_0^s(q_T)^{d_2}}. \quad (106)$$

We compute the adjoint operators of Φ_2 and Φ_3 thanks to the duality relation between the solution f of (Sys) and the solution $\varphi(\cdot) = g(T - \cdot)$ of the adjoint system (30):

$$\langle f(T), \varphi(T) \rangle_{L^2(\mathbb{T})^d} = \langle f(0), \varphi(0) \rangle_{L^2(\mathbb{T})^d} + \int_0^T \int_\omega \langle u(t, x), \varphi(t, x) \rangle dt dx \quad (107)$$

$$= \langle f(0), \varphi(0) \rangle_{L^2(\mathbb{T})^d} + \int_0^T \int_\omega \langle u_1(t, x), \varphi_1(t, x) \rangle + \langle u_2(t, x), \varphi_2(t, x) \rangle dt dx. \quad (108)$$

First, we have $\Phi_2^*(g_T) = (e^{-T\mathcal{L}})^* g_T = e^{-T\mathcal{L}^*} g_T$. To compute Φ_3^* , we introduce the input-output operator $\mathcal{F}_T: u \in L^2(q_T)^d \mapsto f(T, \cdot) \in L^2(\mathbb{T})^d$, where f is the solution of (Sys) with initial condition $f_0 = 0$ and right-hand side u . By (107), $\mathcal{F}_T^*(g_T)$ is the restriction of $e^{(t-T)\mathcal{L}^*} g_T$ to $[0, T] \times \omega$. We have $\Phi_3 = \mathcal{F}_T \circ (I, \iota_s)$, where (I, ι_s) stands for the inclusion map $L^2(q_T)^{d_1} \times H_0^s(q_T)^{d_2} \rightarrow L^2(q_T)^d$. Thus, according to Lemma 39, the right-hand side of the inequality (106) is

$$\|(I, \iota_s^*) \circ \mathcal{F}_T^*(g_T)\|_{L^2(q_T)^{d_1} \times H_0^s(q_T)^{d_2}} = \|\mathcal{F}_T^*(g_T)\|_{L^2(q_T)^{d_1} \times H^{-s}(q_T)^{d_2}},$$

which gives the conclusion. \square

5 Hyperbolic control: coupling of order zero

The goal of this section is to prove the following result on the system

$$\begin{cases} (\partial_t + A' \partial_x + K_{11})f_1 + (A_{12} \partial_x + K_{12})f_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + K_{22})f_2 + K_{21}f_1 = 0 & \text{in } (0, T) \times \mathbb{T}. \end{cases} \quad (109)$$

Theorem 40. *We assume (H.1)–(H.4), $D = I_{d_2}$, $m = d_1$, $M_1 = I_{d_1}$, $M_2 = 0$, $A_{21} = 0$ and $A_{22} = 0$. Let T^* be defined by (3). The following statements are equivalent.*

- The system (109) is null controllable in any time $T > T^*$.
- The couple of matrices (K_{22}, K_{21}) satisfies the Kalman rank condition:

$$\text{Span}\{K_{22}^j K_{21} X_1; X_1 \in \mathbb{C}^{d_1}, 0 \leq j \leq d_2 - 1\} = \mathbb{C}^{d_2}. \quad (110)$$

The interest of this theorem is that its proof is essentially the same as the one of Theorems 3 and 4 (that will be done in the next sections) but it is less technical.

In Section 5.1, we prove that the Kalman condition (110) is necessary for the null controllability of System (109). In Section 5.2, we prove that the Kalman condition (110) is sufficient for the null controllability of System (109), first in the case $d_1 = 1$ (i.e. with one hyperbolic line in the system) where the cascade structure (or Brunovski form) is easy to handle, then in the general case $d_1 > 1$ which is more delicate to write.

5.1 The Kalman condition is necessary

If the null controllability property for (109) holds, then, by considering the Fourier components of the solution and the control, we obtain the null controllability, for every $n \in \mathbb{Z} \setminus \{0\}$, of the system

$$\begin{cases} X_1(t)' + (inA' + K_{11})X_1(t) + (inA_{12} + K_{12})X_2(t) = v_1(t), \\ X_2'(t) + (n^2I_{d_2} + K_{22})X_2(t) + K_{21}X_1(t) = 0, \end{cases}$$

with state $X(t) = (X_1, X_2)(t) \in \mathbb{C}^{d_1} \times \mathbb{C}^{d_2}$ and control $v_1 \in L^2(0, T)^{d_1}$. This requires the null controllability of the control system

$$X_2'(t) + (n^2I_{d_2} + K_{22})X_2(t) + K_{21}X_1(t) = 0,$$

with state $X_2(t) \in \mathbb{C}^{d_2}$ and control $X_1 \in L^2(0, T)^{d_1}$, i.e. the Kalman rank condition (see for instance [10, Thm. 1.16])

$$\text{Span}\{(n^2I_{d_2} + K_{22})^j K_{21}v_1; v_1 \in \mathbb{C}^{d_1}, j \in \{0, \dots, d_2 - 1\}\} = \mathbb{C}^{d_2},$$

that can equivalently be written in the form (110).

5.2 The Kalman condition is sufficient

In this section, we explain how to complete the proof of Theorem 2 to prove that the Kalman rank condition (110) implies the null controllability of (109) in time $T > T^*$, in Theorem 40.

First, we treat the case $d_1 = 1$ then we generalize to the case $d_1 > 1$.

From now and until end of this subsection, C will denote positive constants which will vary from line to line. For $1 \leq i \leq 2$ and $1 \leq j \leq d_i$, we denote by v_i^j the j -th component of a vector $v_i \in \mathbb{C}^{d_i}$.

5.2.1 The case of one hyperbolic component: $d_1 = 1$

By using the Hamilton-Cayley's theorem, we know that there exist $c_0, \dots, c_{d_2-1} \in \mathbb{R}$ such that

$$K_{22}^{d_2} = c_0 I_{d_2} + c_1 K_{22} + \dots + c_{d_2-1} K_{22}^{d_2-1}. \quad (111)$$

By using the Kalman condition (110), the matrix P defined as follows

$$P := (K_{21}, K_{22}K_{21}, \dots, K_{22}^{d_2-1}K_{21}), \quad (112)$$

is invertible. We set

$$\widehat{K}_{22} := \begin{pmatrix} 0 & \dots & \dots & 0 & c_0 \\ 1 & 0 & \dots & \vdots & c_1 \\ 0 & \ddots & \ddots & \vdots & c_2 \\ \vdots & \ddots & \ddots & 0 & \vdots \\ 0 & \dots & 0 & 1 & c_{d_2-1} \end{pmatrix} \quad \text{and} \quad \widehat{K}_{21} := \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}. \quad (113)$$

From (111), (112), (113), we check that we have the following relations

$$K_{22}P = P\widehat{K}_{22} \quad \text{and} \quad K_{21} = P\widehat{K}_{21}, \quad \text{i.e.} \quad \widehat{K}_{22} = P^{-1}K_{22}P \quad \text{and} \quad \widehat{K}_{21} = P^{-1}K_{21}.$$

The function $w = (w_1, w_2) = (f_1, P^{-1}f_2)$ solves

$$\begin{cases} (\partial_t + A'\partial_x + K_{11})w_1 + (A_{12}P\partial_x + K_{12}P)w_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + \widehat{K}_{22})w_2 + \widehat{K}_{21}w_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (w_1, w_2)(0, \cdot) = (w_{01}, w_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (114)$$

The system (114) is a ‘‘cascade system’’. Indeed, roughly speaking the control u_1 directly controls the component w_1 , the component w_1 indirectly controls the component w_2 in the second equation

through the coupling term w_1 , the component w_2^1 indirectly controls the component w_2^2 in the third equation through the coupling term w_2^1 , ... the component $w_2^{d_2-1}$ indirectly controls the component $w_2^{d_2}$ in the last equation through the coupling term $w_2^{d_2-1}$.

The adjoint system of (114) is

$$\begin{cases} \left(\partial_t - A'^{\text{tr}} \partial_x + K_{11}^{\text{tr}} \right) g_1 + \widehat{K}_{21}^{\text{tr}} g_2 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ \left(\partial_t - \partial_x^2 + \widehat{K}_{22}^{\text{tr}} \right) g_2 + \left(-(A_{12}P)^{\text{tr}} \partial_x + (K_{12}P)^{\text{tr}} \right) g_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (g_1, g_2)(0, \cdot) = (g_{01}, g_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (115)$$

From Corollary 38, we know that for every $g_0 \in L^2(\mathbb{T})^d$, the solution g of (115) satisfies

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})} \leq C(\|g_1\|_{L^2(q_T)} + \|g_2\|_{H^{-2d_2+1}(q_T)}). \quad (116)$$

By using the fact that \widehat{K}_{22} is a companion matrix, see (113), we have that for every $i \in \{2, \dots, d_2\}$, the i -th equation of (115) is

$$\partial_t g_2^{i-1} - \partial_x^2 g_2^{i-1} + g_2^i + b_{i-1} \partial_x g_1 + a_{i-1} g_1 = 0, \text{ with } (a_{i-1}, b_{i-1}) \in \mathbb{R}^2$$

Then we deduce

$$\|g_2^i\|_{H^{-2i+1}(q_T)} \leq C(\|g_2^{i-1}\|_{H^{-2(i-1)+1}(q_T)} + \|g_1\|_{L^2(q_T)}). \quad (117)$$

Here, we have used in particular that

$$\|(\partial_t - \partial_x^2) g_2^{i-1}\|_{H^{-2i+1}(q_T)} \leq C \|g_2^{i-1}\|_{H^{-2(i-1)+1}(q_T)}$$

and

$$\|b_{i-1} \partial_x g_1 + a_{i-1} g_1\|_{H^{-2i+1}(q_T)} \leq C \|g_1\|_{L^2(q_T)}.$$

Then, we deduce from (116) and (117) that

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})} \leq C(\|g_1\|_{L^2(q_T)} + \|g_2^1\|_{H^{-1}(q_T)}). \quad (118)$$

By using the fact that \widehat{K}_{21} is the first vector of the canonical basis of \mathbb{R}^{d_2} , see (113), the first equation of (115) is

$$\partial_t g_1 - A' \partial_x g_1 + K_{11} g_1 + g_2^1 = 0.$$

Then, we obtain that

$$\|g_2^1\|_{H^{-1}(q_T)} \leq C \|g_1\|_{L^2(q_T)}. \quad (119)$$

So, we deduce from (118) and (119) the observability inequality

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})^d}^2 \leq C \int_0^T \int_{\omega} |g_1(t, x)|^2 dx dt,$$

in the case $d_1 = 1$. This concludes the proof of Theorem 40 in the case $d_1 = 1$ by duality.

5.2.2 The case of several hyperbolic components: $d_1 > 1$

In this section, we deal with the general problem of null-controllability of (109). To this aim, we introduce $K_{21}^i \in \mathbb{R}^{d_2}$ the i -th column of the matrix K_{21} ($1 \leq i \leq d_1$), i.e.

$$K_{21} = \left(K_{21}^1 | K_{21}^2 | \dots | K_{21}^{d_1} \right),$$

From the Kalman rank condition (110), we construct an adapted basis of \mathbb{C}^{d_2} .

Lemma 41. *There exist $r \in \{1, \dots, d_2\}$ and sequences $(l_j)_{1 \leq j \leq r} \subset \{1, 2, \dots, d_1\}$ and $(s_j)_{1 \leq j \leq r} \subset \{1, 2, \dots, d_2\}$ with $\sum_{j=1}^r s_j = d_2$, such that*

$$\mathcal{B} = \bigcup_{j=1}^r \left\{ K_{21}^{l_j}, K_{22} K_{21}^{l_j}, \dots, K_{22}^{s_j-1} K_{21}^{l_j} \right\}$$

is a basis of \mathbb{C}^{d_2} . Moreover, for every j , with $1 \leq j \leq r$, there exist $\alpha_{k,s_j}^i \in \mathbb{R}$ ($1 \leq i \leq j$, $1 \leq k \leq s_j$) such that

$$K_{22}^{s_j} K_{21}^{l_j} = \sum_{i=1}^j \left(\alpha_{1,s_j}^i K_{21}^{l_i} + \alpha_{2,s_j}^i K_{22} K_{21}^{l_i} + \cdots + \alpha_{s_i,s_j}^i K_{22}^{s_i-1} K_{21}^{l_i} \right). \quad (120)$$

For a proof of this lemma, see [3, Lemma 3.1].

Let \mathcal{B} the basis of \mathbb{C}^{d_2} provided by Lemma 41 and P be the matrix whose columns are the elements of \mathcal{B} , i.e.

$$P := \left(K_{21}^{l_1} | K_{22} K_{21}^{l_1} | \cdots | K_{22}^{s_1-1} K_{21}^{l_1} | \cdots | K_{21}^{l_r} | \cdots | K_{22}^{s_r-1} K_{21}^{l_r} \right).$$

Let us observe that the basis \mathcal{B} has been constructed in such a way that (120) is satisfied.

Let the matrices $C_{ii} \in \mathbb{R}^{s_i \times s_i}$ and $C_{ij} \in \mathbb{R}^{s_i \times s_j}$, $1 \leq i < j \leq r$, be defined by

$$C_{ii} = \begin{pmatrix} 0 & 0 & 0 & \cdots & \alpha_{1,s_i}^i \\ 1 & 0 & 0 & \cdots & \alpha_{2,s_i}^i \\ 0 & 1 & 0 & \cdots & \alpha_{3,s_i}^i \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 & \alpha_{s_i,s_i}^i \end{pmatrix} \text{ and } C_{ij} = \begin{pmatrix} 0 & \cdots & 0 & \alpha_{1,s_j}^i \\ \vdots & \ddots & \vdots & \alpha_{2,s_j}^i \\ 0 & \cdots & 0 & \alpha_{s_i,s_j}^i \end{pmatrix}. \quad (121)$$

We set

$$\widehat{K}_{22} := \begin{pmatrix} C_{11} & C_{12} & \cdots & C_{1r} \\ 0 & C_{22} & \cdots & C_{2r} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & C_{rr} \end{pmatrix} \text{ and } \widehat{K}_{21} := P^{-1} K_{21}. \quad (122)$$

From (120), (122) and (121), by denoting $P_i := \left(K_{21}^{l_i} | K_{22} K_{21}^{l_i} | \cdots | K_{22}^{s_i-1} K_{21}^{l_i} \right)$, we have

$$\begin{aligned} K_{22} P_i &= \left(K_{22} K_{21}^{l_i} | K_{22}^2 K_{21}^{l_i} | \cdots | K_{22}^{s_i} K_{21}^{l_i} \right) \\ &= \left(K_{22} K_{21}^{l_i} \left| K_{22}^2 K_{21}^{l_i} \right| \cdots \left| \sum_{k=1}^i \left(\alpha_{1,s_i}^k K_{21}^{l_k} + \alpha_{2,s_i}^k K_{22} K_{21}^{l_k} + \cdots + \alpha_{s_k,s_i}^k K_{22}^{s_k-1} K_{21}^{l_k} \right) \right| \right) \\ &= \left(0 \left| \cdots \right| 0 \left| \sum_{k=1}^{i-1} \left(\alpha_{1,s_i}^k K_{21}^{l_k} + \alpha_{2,s_i}^k K_{22} K_{21}^{l_k} + \cdots + \alpha_{s_k,s_i}^k K_{22}^{s_k-1} K_{21}^{l_k} \right) \right| \right) \\ &\quad + \left(K_{22} K_{21}^{l_i} \left| K_{22}^2 K_{21}^{l_i} \right| \cdots \left| \left(\alpha_{1,s_i}^i K_{21}^{l_i} + \alpha_{2,s_i}^i K_{22} K_{21}^{l_i} + \cdots + \alpha_{s_i,s_i}^i K_{22}^{s_i-1} K_{21}^{l_i} \right) \right| \right) \\ &= P_1 C_{1i} + P_2 C_{2i} + \cdots + P_i C_{ii}. \end{aligned}$$

Then, we obtain

$$K_{22} P = P \widehat{K}_{22} \text{ and } P e_{S_i} = K_{21}^{l_i}, \quad 1 \leq i \leq r, \quad (123)$$

where e_{S_i} is the S_i -element of the canonical basis of \mathbb{R}^n with $S_i = 1 + \sum_{j=1}^{i-1} s_j$. In the following, we will also use the notation $S_{r+1} := d_2 + 1$.

We argue as in the previous subsection. We perform the same change of variable $w = (w_1, w_2) = (f_1, P^{-1} f_2)$, we consider the solution g of the adjoint system

$$\begin{cases} \left(\partial_t - A^{\text{tr}} \partial_x + K_{11}^{\text{tr}} \right) g_1 + \widehat{K}_{21}^{\text{tr}} g_2 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ \left(\partial_t - \partial_x^2 + \widehat{K}_{22}^{\text{tr}} \right) g_2 + \left(-(A_{12} P)^{\text{tr}} \partial_x + (K_{12} P)^{\text{tr}} \right) g_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (g_1, g_2)(0, \cdot) = (g_{01}, g_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (124)$$

From Corollary 38, we recall that the solution g of (124) satisfies

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})} \leq C \left(\|g_1\|_{L^2(Q_T)} + \|g_2\|_{H^{-2m+1}(Q_T)} \right), \text{ with } m = \max_{1 \leq i \leq r} s_i. \quad (125)$$

Then, we use the coupling terms in the system (124) in order to get rid of the term $\|g_2\|_{H^{-2m+1}(q_T)}^2$ in the right hand side of the inequality (125).

From the cascade form of the matrix \widehat{K}_{22} , see (122), more precisely from the cascade form of the block matrix C_{ii} and the form of the matrices $C_{1,i}, \dots, C_{i-1,i}$, see (121), the equations of the adjoint system (124) are

$$\begin{aligned} \forall i \in \{1, \dots, r\}, \forall j \in \{S_i, \dots, S_{i+1} - 2\}, \\ \partial_t g_2^j - \partial_x^2 g_2^j + g_2^{j+1} + \sum_{k=1}^{d_1} b_{i,j}^k \partial_x g_1^k + a_{i,j}^k g_1^k = 0, \quad (a_{i,j}^k, b_{i,j}^k) \in \mathbb{R}^2. \end{aligned} \quad (126)$$

To simplify, we will denote by H^k , $k \in \mathbb{Z}^-$, the space $H^k(q_T)$.

We deduce successively from (126) with $j = S_{i+1} - 2, S_{i+1} - 3, \dots, S_{i+1} - 2 - (s_i - 2) = S_i$, the following estimates

$$\begin{aligned} \left\| g_2^{S_{i+1}-1} \right\|_{H^{-2s_i+1}(q_T)} &\leq C \left(\left\| g_2^{S_{i+1}-2} \right\|_{H^{-2(s_i-1)+1}(q_T)} + \|g_1\|_{L^2(q_T)} \right) \\ &\leq C \left(\left\| g_2^{S_{i+1}-3} \right\|_{H^{-2(s_i-2)+1}(q_T)} + \|g_1\|_{L^2(q_T)} \right) \\ &\leq \dots \\ &\leq C \left(\left\| g_2^{S_{i+1}-2-(s_i-2)} \right\|_{H^{-1}(q_T)} + \|g_1\|_{L^2(q_T)} \right). \end{aligned}$$

So, we have for every $i \in \{1, \dots, r\}$ and $j \in \{S_i + 1, \dots, S_{i+1} - 1\}$,

$$\left\| g_2^j \right\|_{H^{-2m+1}(q_T)} \leq C \left(\left\| g_2^{S_i} \right\|_{H^{-1}(q_T)} + \|g_1\|_{L^2(q_T)} \right). \quad (127)$$

Then, by using (122) and (123), we have $\widehat{K}_{21}^{l_i} = P^{-1} K_{21}^{l_i} = e_{S_i}$. Consequently, the l_i -th equation of the adjoint system (124) is

$$\partial_t g_1^{l_i} + \sum_{k=1}^{d_1} a_{l_i,k} \partial_x g_1^k + b_{l_i,k} g_1^k + g_2^{S_i} = 0, \quad (a_{l_i,k}, b_{l_i,k}) \in \mathbb{R}^2.$$

Then, we obtain

$$\left\| g_2^{S_i} \right\|_{H^{-1}(q_T)} \leq C \|g_1\|_{L^2(q_T)}. \quad (128)$$

By gathering (127) and (128), we obtain

$$\forall i \in \{1, \dots, r\}, \forall j \in \{S_i, \dots, S_{i+1} - 1\}, \left\| g_2^j \right\|_{H^{-2m+1}(q_T)} \leq C \|g_1\|_{L^2(q_T)}. \quad (129)$$

By using that $\{S_1, \dots, S_2 - 1, S_2, \dots, S_3 - 1, \dots, S_r, \dots, S_{r+1} - 1\} = \{1, \dots, d_2\}$, we finally deduce from (129) and (125) the observability inequality

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})^d}^2 \leq C \int_0^T \int_{\omega} |g_1(t, x)|^2 dx dt.$$

This concludes the proof of Theorem 40 in the case $d_1 > 1$ by duality.

6 Hyperbolic control: coupling of order one

The goal of this section is to prove Theorem 3. The requirement of the Kalman rank condition (6) for null-controllability is an adaptation of the proof given in Section 5.1. Now, we explain

how to complete the proof of Theorem 2 to prove that the Kalman condition is sufficient for null controllability. We set

$$\mathbf{F}_2 := L^2(\mathbb{T})^{d_1} \times L_m^2(\mathbb{T})^{d_2} = \left\{ f_0 = (f_{01}, f_{02}) \in L^2(\mathbb{T})^d ; \int_{\mathbb{T}} f_{02}(x) dx = 0 \right\}. \quad (130)$$

We only give the proof in the case $d_1 = 1$. The case $d_1 > 1$ is an easy adaptation of the case $d_1 = 1$ and the arguments already presented for coupling terms of order zero in Section 5.2.2.

6.1 A special observability inequality

The goal of this section is to prove the following observability inequality.

Proposition 42. *There exists $C > 0$ such that for every $g_0 \in \mathbf{F}_2$, the solution of the adjoint system (30) satisfies*

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})}^2 \leq C \left(\|g_1\|_{L^2(q_T)}^2 + \|\partial_x^{d_2} g_2\|_{H^{-2d_2+1}(q_T)}^2 \right). \quad (131)$$

In order to prove Proposition 42, by a duality argument, it is sufficient to establish the following null-controllability result.

Proposition 43. *For every $f_0 \in \mathbf{F}_2$, there exists $u \in L^2(q_T)^{d_1} \times (H_0^{2d_2-1}(q_T))^{d_2}$ such that $S(T, f_0, (u_h, \partial_x^{d_2} u_p)) = 0$.*

Proof of the equivalence between Proposition 42 and Proposition 43. We apply Lemma 14 with

$$\Phi_2: f_0 \in \mathbf{F}_2 \mapsto f(T, \cdot) \in \mathbf{F}_2,$$

where f is the solution to the system (Sys) with initial data f_0 and control $u = 0$, and

$$\Phi_3: u = (u_1, u_2) \in L^2(q_T)^{d_1} \times H_0^{2d_2-1}(q_T)^{d_2} \mapsto f(T, \cdot) \in \mathbf{F}_2,$$

where f is the solution to the system (Sys) with initial data $f_0 = 0$ and control $(u_1, \partial_x^{d_2} u_2)$. Note that by integrating the second equation of the system (1), we see that a control of the form $(u_1, \partial_x^{d_2} u_2)$ cannot change the mean of the parabolic component. This justifies that Φ_2 and Φ_3 do indeed take values in \mathbf{F}_2 .

The null-controllability result of Proposition 43 is equivalent to the existence of $C > 0$ such that for every $g_T \in L^2(\mathbb{T})^d$,

$$\|\Phi_2^*(g_T)\|_{\mathbf{F}_2} \leq C \|\Phi_3^*(g_T)\|_{L^2(q_T)^{d_1} \times H_0^{2d_2-1}(q_T)^{d_2}}. \quad (132)$$

We have $\Phi_2^*(g_T) = (e^{-T\mathcal{L}})^* g_T = e^{-T\mathcal{L}^*} g_T$. We claim that the right-hand side of the inequality (132) satisfies

$$\|\Phi_3^*(g_T)\|_{L^2(q_T)^{d_1} \times H_0^{2d_2-1}(q_T)^{d_2}} = \|(g_1, (-1)^{d_2} \partial_x^{d_2} g_2)\|_{L^2(q_T)^{d_1} \times H^{-2d_2+1}(q_T)^{d_2}}, \quad (133)$$

where $g = e^{-(T-t)\mathcal{L}^*} g_T$. This will prove that the inequality (132) is exactly the observability inequality (131).

We write Φ_3 as

$$\Phi_3 = \mathcal{F}_T \circ (I, \partial_x^{d_2}) \circ (I, \iota_{2d_2-1}),$$

where $\mathcal{F}_T: L^2(\mathbb{T})^d \rightarrow L^2(\mathbb{T})^d$ is the input-output operator introduced in the proof of Corollary 38, $\partial_x^{d_2}$ is seen as an unbounded operator on $L^2(\mathbb{T})^{d_2}$ with domain $H^{d_2}(\mathbb{T})^{d_2}$, and $\iota_{2d_2-1}: H^{2d_2-1}(\mathbb{T})^{d_2} \rightarrow L^2(\mathbb{T})^{d_2}$ is the inclusion map (see Lemma 39). Note that while Φ_3 written this way looks like an unbounded operator (because $\partial_x^{d_2}$ is), we have $\text{Im}(\iota_{2d_2-1}) \subset D(\partial_x^{d_2})$, so that the composition of operators above is indeed a continuous operator. So, we have

$$\Phi_3^* = (I, \iota_{2d_2-1}^*) \circ (I, (\partial_x^{d_2})^*) \circ \mathcal{F}_T^* = (I, \iota_{2d_2-1}^*) \circ (I, (-1)^{d_2} \partial_x^{d_2}) \circ \mathcal{F}_T^*.$$

Since $\iota_{2d_2-1}^*$ is an isometry between $H_0^{2d_2-1}$ and H^{-2d_2+1} (see Lemma 39), this proves the relation (133). \square

First, we show that the null-controllability result of Proposition 43 is true at the high-frequency level, i.e. we prove the following adaptation of Proposition 26.

Proposition 44. *There exists a closed subspace \mathcal{G}^\diamond of $L^2(\mathbb{T})^d$ with finite codimension and a continuous operator*

$$\begin{aligned} \mathcal{U}^\diamond: \mathcal{G}^\diamond &\rightarrow L^2((0, T') \times \omega)^{d_1} \times C_c^\infty((T', T) \times \omega)^{d_2} \\ f_0 &\mapsto (u_h, u_p), \end{aligned}$$

that associates with each $f_0 \in \mathcal{G}^\diamond$ a pair of controls $\mathcal{U}^\diamond f_0 = (u_h, u_p)$ such that

$$\forall f_0 \in \mathcal{G}^\diamond, \quad \Pi S(T; f_0, (u_h, \partial_x^{d_2} u_p)) = 0. \quad (134)$$

In order to prove Proposition 44, it is enough to prove Proposition 28 with parabolic control of the form $\partial_x^{d_2} u_p$. Thus, by using Section 4.4.1, it is sufficient to show the following adaptation of Proposition 31.

Proposition 45. *If n_0 is large enough, then for every $T > 0$, there exists a continuous operator*

$$\begin{aligned} \underline{\mathcal{U}}_T^{\text{P}, \diamond}: F^{\text{P}} &\rightarrow C_c^\infty((0, T) \times \omega)^{d_2} \\ f_0 &\mapsto u_p, \end{aligned}$$

that associates with each $f_0 \in F^{\text{P}}$ a control $\underline{\mathcal{U}}_T^{\text{P}, \diamond} f_0 = u_p$ such that

$$\Pi^{\text{P}} S(T; f_0, (0, \partial_x^{d_2} u_p)) = 0.$$

Proof. Let $f_0 \in F^{\text{P}}$ and f_0^\diamond be such that $\partial_x^{d_2} f_0^\diamond = f_0$. Note that f_0^\diamond is well-defined because $\int_{\mathbb{T}} f_0(x) dx = 0$. We know from Proposition 31 that there exists $u_p \in C_c^\infty((0, T) \times \omega)^{d_2}$ such that the solution f^\diamond of (Sys) with initial data f_0^\diamond and control $(0, u_p)$ satisfies

$$\Pi^{\text{P}} f^\diamond(T, \cdot) = 0.$$

Then, by setting $f := \partial_x^{d_2} f^\diamond$ and by applying $\partial_x^{d_2}$ to the system (Sys) satisfied by f^\diamond , we deduce that f is the solution of (Sys) with initial data f_0 and control $(0, \partial_x^{d_2} u_p)$ and satisfies

$$\Pi^{\text{P}} f(T, \cdot) = 0,$$

because $\partial_x^{d_2}$ and Π^{P} commute.

We get the conclusion of the proof of Proposition 45 with the continuous operator $\underline{\mathcal{U}}_T^{\text{P}, \diamond}(f_0) = \underline{\mathcal{U}}_T^{\text{P}}(f_0^\diamond)$ where $\underline{\mathcal{U}}_T^{\text{P}}$ is the operator defined in Proposition 31. \square

Secondly, we have to show that the null-controllability result of Proposition 43 is true at the low frequency-level, as we have already shown for Theorem 2 in Section 4.5. All the steps of Section 4.5 remain unchanged except the Step 6. Indeed, the unique continuation argument transforms into: if $f(t, \cdot) = e^{tM} f_0$ with $(f_1, \partial_x^{d_2} f_2) = (0, 0)$ in $(0, \varepsilon) \times \omega$ then $(f_{01}, \partial_x^{d_2} f_{02}) = (0, 0)$ thanks to the spectral inequality of Lebeau-Robbiano (98), that is to say, $f_0 = 0$ because $\int_{\mathbb{T}} f_{02}(x) dx = 0$.

This concludes the proof of Proposition 43 thus the proof of Proposition 42. \square

6.2 The case of one hyperbolic component: $d_1 = 1$

By the Hamilton-Cayley's theorem, there exist $c_0, \dots, c_{d_2-1} \in \mathbb{R}$ such that

$$A_{22}^{d_2} = c_0 I_{d_2} + c_1 A_{22} + \dots + c_{d_2-1} A_{22}^{d_2-1}.$$

By using the Kalman condition (6), the matrix P defined as follows

$$P := (A_{21}, A_{22} A_{21}, \dots, A_{22}^{d_2-1} A_{21}),$$

is invertible. By setting

$$\widehat{A}_{22} := \begin{pmatrix} 0 & \dots & \dots & 0 & c_0 \\ 1 & 0 & \dots & \vdots & c_1 \\ 0 & \ddots & \ddots & \vdots & c_2 \\ \vdots & \ddots & \ddots & 0 & \vdots \\ 0 & \dots & 0 & 1 & c_{d_2-1} \end{pmatrix} \text{ and } \widehat{A}_{21} := \begin{pmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix}, \quad (135)$$

we check that we have the following relations

$$A_{22}P = P\widehat{A}_{22} \text{ and } A_{21} = P\widehat{A}_{21}, \text{ i.e. } \widehat{A}_{22} = P^{-1}A_{22}P \text{ and } \widehat{A}_{21} = P^{-1}A_{21}.$$

Then, by setting $w = (w_1, w_2) = (f_1, P^{-1}f_2)$, we have

$$\begin{cases} (\partial_t + A'\partial_x + K_{11})w_1 + (A_{12}P\partial_x + K_{12}P)w_2 = u_1 1_\omega & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 + \widehat{A}_{22}\partial_x)w_2 + \widehat{A}_{21}\partial_x w_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (w_1, w_2)(0, \cdot) = (w_{01}, w_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (136)$$

The system (136) is a ‘‘cascade system’’ with coupling terms of order one in the spatial variable.

The adjoint system of (136) is

$$\begin{cases} (\partial_t - A'^{\text{tr}}\partial_x + K_{11}^{\text{tr}})g_1 - \widehat{A}_{21}^{\text{tr}}\partial_x g_2 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (\partial_t - \partial_x^2 - \widehat{A}_{22}^{\text{tr}}\partial_x)g_2 + \left(- (A_{12}P)^{\text{tr}}\partial_x + (K_{12}P)^{\text{tr}}\right)g_1 = 0 & \text{in } (0, T) \times \mathbb{T}, \\ (g_1, g_2)(0, \cdot) = (g_{01}, g_{02}) & \text{in } \mathbb{T}. \end{cases} \quad (137)$$

We know from Proposition 42 that the solution g of (137) satisfies

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})} \leq C(\|g_1\|_{L^2(q_T)} + \|\partial_x^{d_2} g_2\|_{H^{-2d_2+1}(q_T)}). \quad (138)$$

By using the fact that \widehat{A}_{22} is a companion matrix, see (113), for every $i \in \{2, \dots, d_2\}$, the i -th equation of (137) is

$$\partial_t g_2^{i-1} - \partial_x^2 g_2^{i-1} + \partial_x g_2^i + b_{i-1}\partial_x g_1 + a_{i-1}g_1 = 0, \quad (a_{i-1}, b_{i-1}) \in \mathbb{R}^2. \quad (139)$$

Then, by applying ∂_x^{i-1} to (139) with $i \in \{2, \dots, d_2\}$, we get that there exists $C > 0$ such that

$$\|\partial_x^i g_2^i\|_{H^{-2i+1}(q_T)} \leq C(\|(\partial_t - \partial_x^2)\partial_x^{i-1} g_2^{i-1}\|_{H^{-2i+1}(q_T)} + \|(b_{i-1}\partial_x^i + a_{i-1}\partial_x^{i-1})g_1\|_{H^{-2i+1}(q_T)}),$$

therefore we have

$$\|\partial_x^i g_2^i\|_{H^{-2i+1}(q_T)} \leq C(\|\partial_x^{i-1} g_2^{i-1}\|_{H^{-2(i-1)+1}(q_T)} + \|g_1\|_{L^2(q_T)}). \quad (140)$$

Then, we deduce from (138) and (140) that

$$\begin{aligned} \|g(T, \cdot)\|_{L^2(\mathbb{T})} &\leq C(\|g_1\|_{L^2(q_T)} + \|\partial_x^{d_2} g_2\|_{H^{-2d_2+1}(q_T)}) \\ &\leq C\left(\|g_1\|_{L^2(q_T)} + \sum_{i=1}^{d_2} \|\partial_x^i g_2^i\|_{H^{-2i+1}(q_T)}\right) \\ &\leq C(\|g_1\|_{L^2(q_T)} + \|\partial_x g_2^1\|_{H^{-1}(q_T)}). \end{aligned} \quad (141)$$

By using the fact that \widehat{A}_{21} is the first vector of the canonical basis of \mathbb{R}^{d_2} , see (135), the first equation of (137) is

$$\partial_t g_1 - A'\partial_x g_1 + K_{11}g_1 + \partial_x g_2^1 = 0.$$

Then, we obtain that

$$\|\partial_x g_2^1\|_{H^{-1}(q_T)} \leq C\|g_1\|_{L^2(q_T)}. \quad (142)$$

So, we deduce from (141) and (142) the observability inequality

$$\|g(T, \cdot)\|_{L^2(\mathbb{T})} \leq C\|g_1\|_{L^2(q_T)},$$

which concludes the proof of Theorem 3 in the case $d_1 = 1$. \square

7 Parabolic control

The goal of this section is to prove Theorem 4 and to illustrate the necessity of a regularity assumption on the initial condition.

7.1 A regularity assumption is necessary

We consider for $\lambda \in \mathbb{R}^*$ the system

$$\begin{cases} \partial_t \tilde{f}_1 + \lambda \partial_x \tilde{f}_1 + \partial_x \tilde{f}_2 = 0, & \text{in } (0, T) \times \mathbb{T}, \\ \partial_t \tilde{f}_2 - \partial_x^2 \tilde{f}_2 + \lambda \partial_x \tilde{f}_2 = v(t, x), & \text{in } (0, T) \times \mathbb{T}, \end{cases} \quad (143)$$

i.e. $\omega = \mathbb{T}$, $d = 2$, $m = 1$,

$$A = \begin{pmatrix} \lambda & 1 \\ 0 & \lambda \end{pmatrix}, \quad A' = (\lambda), \quad B = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \quad M = \begin{pmatrix} 0 \\ 1 \end{pmatrix},$$

that satisfies (H.3), (H.4) and the Kalman condition (12) because $A_{12} = 1$. By Theorem 4, any initial condition $f_0 = (f_{01}, f_{02}) \in H_m^2 \times H^2(\mathbb{T})$ is null controllable. The following statement illustrates that

- a regularity assumption on f_{01} is necessary for the null controllability
- the one given by Theorem 4 is sufficient but may not be necessary.

Proposition 46. *An initial condition $f_0 = (f_{01}, f_{02}) \in L_m^2(\mathbb{T}) \times L^2(\mathbb{T})$ is null controllable with $v \in L^2((0, T) \times \mathbb{T})$ if and only if $f_{01} \in H^1(\mathbb{T})$.*

Remark 47. Similar problems of regularity between initial data and control have already been noticed in the context of transport systems, see [1, Remark 5].

Proof. In the proof, we use the notation $Q_T = (0, T) \times \Omega$.

The change of variable

$$\tilde{f}_j(t, x) = f_j(t, x - \lambda t), \quad v(t, x) = u(t, x - \lambda t)$$

leads to

$$\begin{cases} \partial_t f_1 - \partial_x f_2 = 0, & \text{in } (0, T) \times \mathbb{T}, \\ \partial_t f_2 - \partial_x^2 f_2 = u(t, x), & \text{in } (0, T) \times \mathbb{T}. \end{cases} \quad (144)$$

The null controllability of $(\tilde{f}_1, \tilde{f}_2)$ with control $v \in L^2(Q_T)$ is equivalent to the null controllability of (f_1, f_2) with control $u \in L^2(Q_T)$. On Fourier components, equation (144) gives the ordinary differential equations

$$\begin{cases} \frac{d}{dt} \hat{f}_1(t, n) = in \hat{f}_2(t, n), \\ \frac{d}{dt} \hat{f}_2(t, n) = -n^2 \hat{f}_2(t, n) + \hat{u}(t, n). \end{cases} \quad (145)$$

Let $f_0 = (f_{01}, f_{02}) \in L_m^2(\mathbb{T}) \times L^2(\mathbb{T})$. The solution writes

$$\hat{f}_2(t, n) = \hat{f}_{02}(n) e^{-n^2 t} + \int_0^t e^{-n^2(t-\tau)} \hat{u}(\tau, n) d\tau,$$

$$\begin{aligned} \hat{f}_1(t, n) &= \hat{f}_{10}(n) + in \int_0^t \hat{f}_2(\tau, n) d\tau \\ &= \hat{f}_{01}(n) + \frac{i}{n} (1 - e^{-n^2 T}) \hat{f}_{02}(n) + in \int_0^t \hat{u}(\tau, n) \frac{1 - e^{-n^2(t-\tau)}}{n^2} d\tau. \end{aligned}$$

thus the relation $f(T) = 0$ is equivalent to the moment problem

$$\begin{cases} \int_0^T e^{-n^2(T-\tau)} \hat{u}(\tau, n) d\tau = -\hat{f}_{02}(n) e^{-n^2 T}, & \forall n \in \mathbb{Z}, \\ \int_0^T \hat{u}(\tau, n) d\tau = in \hat{f}_{01}(n) - \hat{f}_{02}(n), & \forall n \in \mathbb{Z} \setminus \{0\}. \end{cases} \quad (146)$$

Note that the assumption $\int_{\mathbb{T}} f_{01} = 0$ implies $\int_{\mathbb{T}} f_1(t) = 0$ for every $t > 0$ thus the null controllability of this component does not require any condition on the control u .

Necessary condition: We assume $f_0 = (f_{01}, f_{02})$ null controllable with a control $u \in L^2(Q_T)$ and we prove that $f_{01} \in H^1(\mathbb{T})$. By the Bessel-Parseval equality and Cauchy-Schwarz inequality,

$$\begin{aligned} \|u\|_{L^2(Q_T)}^2 &= \sum_{n \in \mathbb{Z}} \int_0^T |\widehat{u}(t, n)|^2 dt \\ &\geq \sum_{n \in \mathbb{Z}} \frac{1}{T} \left| \int_0^T \widehat{u}(t, n) dt \right|^2 \\ &\geq \sum_{n \in \mathbb{Z}} \frac{1}{T} \left| in\widehat{f}_{01}(n) - \widehat{f}_{02}(n) \right|^2 = \frac{1}{T} \|\partial_x f_{01} - f_{02}\|_{L^2(\mathbb{T})}^2 \end{aligned}$$

thus $f_{01} \in H^1(\mathbb{T})$.

Sufficient condition: We assume $f_0 = (f_{01}, f_{02}) \in H_m^1 \times L^2(\mathbb{T})$ and we construct a control $u \in L^2((0, T) \times \mathbb{T})$ that steers this initial condition to 0.

Let G_n be the Grammian matrix, in $L^2(0, T)$, of the family $(w_{1,n}, w_{2,n})$ where $w_{1,n}: \tau \mapsto ne^{-n^2(T-\tau)}$ and $w_{2,n}: \tau \mapsto 1$, i.e. $(G_n)_{i,j} = \int_0^T w_{i,n}(\tau)w_{j,n}(\tau) d\tau$ for every $1 \leq i, j \leq 2$. Then G_n is invertible for every $n \in \mathbb{Z} \setminus \{0\}$ (because it is the Grammian matrix of a linearly independent family) and, when $|n| \rightarrow \infty$,

$$G_n \sim \begin{pmatrix} 1/2 & 1/n \\ 1/n & T \end{pmatrix}$$

thus there exists $C > 0$ such that, for every $n \in \mathbb{Z} \setminus \{0\}$, $\|G_n^{-1}\| \leq C$. We take

$$u(\tau, x) = -\frac{1}{T}\widehat{f}_{02}(0) + \sum_{n \in \mathbb{Z} \setminus \{0\}} (\alpha_n w_{1,n}(\tau) + \beta_n w_{2,n}(\tau))e^{inx}$$

where

$$\begin{pmatrix} \alpha_n \\ \beta_n \end{pmatrix} := G_n^{-1} \begin{pmatrix} -n\widehat{f}_{02}(n)e^{-n^2T} \\ in\widehat{f}_{01}(n) - \widehat{f}_{02}(n) \end{pmatrix}. \quad (147)$$

Then, by Bessel-Parseval equality, we have for various positive constants C depending on T ,

$$\begin{aligned} \|u\|_{L^2(Q_T)}^2 &= \frac{1}{T} |\widehat{f}_{02}(0)|^2 + \int_0^T \sum_{n \in \mathbb{Z} \setminus \{0\}} |\alpha_n w_{1,n}(t) + \beta_n w_{2,n}(t)|^2 dt \\ &\leq \frac{1}{T} |\widehat{f}_{02}(0)|^2 + C \sum_{n \in \mathbb{Z} \setminus \{0\}} (|\alpha_n|^2 + |\beta_n|^2) \\ &\leq \frac{1}{T} |\widehat{f}_{02}(0)|^2 + C \sum_{n \in \mathbb{Z} \setminus \{0\}} \left(|n\widehat{f}_{02}(n)e^{-n^2T}|^2 + |in\widehat{f}_{01}(n) - \widehat{f}_{02}(n)|^2 \right) \\ &\leq C \left(\|f_{01}\|_{H^1(\mathbb{T})}^2 + \|f_{02}\|_{L^2(\mathbb{T})}^2 \right) < \infty. \end{aligned}$$

Thus $u \in L^2(Q_T)$. Note that the moment problem (146) can equivalently be written

$$\begin{aligned} \int_0^T \widehat{u}(\tau, n) d\tau &= -\widehat{f}_{02}(0), \\ \int_0^T w_{1,n}(\tau) \widehat{u}(\tau, n) d\tau &= -n\widehat{f}_{02}(n)e^{-n^2T}, & \forall n \in \mathbb{Z} \setminus \{0\}, \\ \int_0^T w_{2,n}(\tau) \widehat{u}(\tau, n) d\tau &= in\widehat{f}_{01}(n) - \widehat{f}_{02}(n), & \forall n \in \mathbb{Z} \setminus \{0\}. \end{aligned} \quad (148)$$

Thus, by (147), u solves (146). \square

7.2 Proof of Theorem 4

The Kalman rank condition (12) is a necessary condition for null-controllability of (10) by the same arguments as in Section 5.1. Thus we only explain how to complete the proof of Theorem 2 to prove that it is a sufficient condition for null-controllability of (10). We introduce the space

$$\mathbf{F}_1 := H_m^{d_1+1}(\mathbb{T})^{d_1} \times H^{d_1+1}(\mathbb{T})^{d_2}, \quad (149)$$

equipped with the scalar product of $H^{d_1+1}(\mathbb{T})^d$ and the space

$$\widetilde{\mathbf{F}}_1 := L_m^2(\mathbb{T})^{d_1} \times L^2(\mathbb{T})^{d_2}, \quad (150)$$

equipped with the scalar product of $L^2(\mathbb{T})^d$.

The null-controllability of the system (10) in \mathbf{F}_1 with control of the form $(0, u_2) \in \{0\}^{d_1} \times L^2(q_T)^{d_2}$ is equivalent to the following observability inequality: for every $T > T^*$, there exists $C > 0$ such that, for every $g_0 \in \widetilde{\mathbf{F}}_1$, the solution of the adjoint system (30) satisfies

$$\|g(T, \cdot)\|_{H^{-(d_1+1)}(\mathbb{T})^d}^2 \leq C \int_0^T \int_\omega |g_2(t, x)|^2 dx dt. \quad (151)$$

where $g_2(t, x) \in \mathbb{C}^{d_2}$ is made of the last d_2 components of $g(t, x)$.

Proof of the equivalence between the null-controllability in \mathbf{F}_1 and the observability inequality (151). We apply the duality Lemma 14 with

$$\Phi_2: f_0 \in \mathbf{F}_1 \mapsto e^{-T\mathcal{L}} f_0 \in \widetilde{\mathbf{F}}_1,$$

$$\Phi_3: u_2 \in L^2(q_T)^{d_2} \mapsto S(T; 0, (0, u_2)) \in \widetilde{\mathbf{F}}_1.$$

Note that the mean value of the d_1 first components is indeed zero. The null-controllability result in \mathbf{F}_1 is equivalent to the inclusion $\text{Im}(\Phi_2) \subset \text{Im}(\Phi_3)$, thus to the existence of a constant $C > 0$ such that for every $g_T \in \widetilde{\mathbf{F}}_1$

$$\|\Phi_2^*(g_T)\|_{H^{d_1+1}(\mathbb{T})^d} \leq C \|\Phi_3^*(g_T)\|_{L^2(q_T)^{d_2}}. \quad (152)$$

We compute the adjoint operators of Φ_2 and Φ_3 thanks to the duality relation between the solution f of (Sys) and the solution $\varphi(\cdot) = g(T - \cdot)$ of the adjoint system (30):

$$\langle f(T), \varphi(T) \rangle_{L^2(\mathbb{T})^d} = \langle f(0), \varphi(0) \rangle_{L^2(\mathbb{T})^d} + \int_0^T \int_\omega \langle u_2(t, x), \varphi_2(t, x) \rangle dt dx. \quad (153)$$

First, $\Phi_3^*(g_T)$ is the restriction of the d_2 -last components of $e^{(t-T)\mathcal{L}^*} g_T$ to $[0, T] \times \omega$. Then, by (153) and Lemma 39 (working as in the proof of Corollary 38), the left-hand side of (152) is

$$\|\Phi_2^*(g_T)\|_{H^{d_1+1}(\mathbb{T})^d} = \|e^{-T\mathcal{L}^*} g_T\|_{H^{-(d_1+1)}(\mathbb{T})^d}.$$

Thus the inequality (152) is indeed the observability inequality (151). \square

By using the strategy developed in Section 6, we claim that, in the case $d_2 = 1$, it is sufficient to prove the following result in order to prove the observability inequality (151).

Proposition 48. *For every $T > T^*$, there exists $C > 0$ such that for every $g_0 \in \widetilde{\mathbf{F}}_1$, the solution g of the adjoint system (30) satisfies*

$$\|g(T, \cdot)\|_{H^{-(d_1+1)}(\mathbb{T})^d}^2 \leq C \left(\|\partial_x^{d_1} g_1\|_{H^{-(d_1+1)}(q_T)}^2 + \|g_2\|_{L^2(q_T)}^2 \right). \quad (154)$$

The observability inequality (154) has to be compared to the observability inequality (131) in Section 6. Roughly speaking, the term $\|\partial_x^{d_1} g_1\|_{H^{-(d_1+1)}(q_T)}$ comes from the fact that we will perform $(d_1 - 1)$ steps of elimination, each of them “costs” one derivative (instead of two in Section 6.2) because we will use transport equations which are of order one in time and space (instead of parabolic equations which are of order two in space variable). The last step of elimination “costs” two derivatives because we will use a heat equation which is of order one in time and two in space. This explains the number $(d_1 - 1) + 2 = d_1 + 1$ derivatives. By adapting the arguments of Section 5.2.2, we can also treat the case $d_2 > 1$.

In order to prove Proposition 48, by duality (a simple adaptation of the proof that Proposition 42 and Proposition 43 are equivalent), it is sufficient to establish the following null-controllability result.

Proposition 49. *For every $f_0 \in \mathbf{F}_1$, there exists $u = (u_h, u_p) \in (H_0^{2d_1+1}(q_T))^{d_1} \times L^2(q_T)^{d_2}$ such that $S(T, f_0, (\partial_x^{d_1} u_h, u_p)) = 0$.*

The proof of this result is an adaptation of the proof of Theorem 2:

- we prove that parabolic high frequencies are null-controllable,
- we prove that hyperbolic high frequencies are null-controllable,
- we combine these two propositions to prove that high frequencies are null-controllable,
- we finally deal with low frequencies.

For the first point, we just need a special case of the corresponding result that was used in the proof of Theorem 2, i.e. Proposition 28.

Proposition 50. *If n_0 is large enough, there exists a continuous operator*

$$\begin{aligned} \mathcal{U}^{p,\sharp}: \mathbf{F}_1 \times H_0^{2d_1+1}((0, T') \times \omega)^{d_1} &\rightarrow C_c^\infty((T', T) \times \omega)^{d_2} \\ (f_0, u_h) &\mapsto u_p, \end{aligned}$$

that associates with any $(f_0, u_h) \in \mathbf{F}_1 \times H_0^{2d_1+1}((0, T') \times \omega)^{d_1}$ a control $u_p = \mathcal{U}^{p,\sharp}(f_0, u_h)$ such that

$$\Pi^p S(T; f_0, (\partial_x^{d_1} u_h, u_p)) = 0.$$

Proof. Proposition 50 is a consequence of Proposition 28 because $\mathbf{F}_1 \times H_0^{2d_1+1}((T', T) \times \omega)^{d_2}$ is continuously embedded in $L^2(\mathbb{T})^d \times L^2((T', T) \times \omega)^{d_2}$ and $\partial_x^{d_1} u_h \in L^2((0, T') \times \omega)^{d_1}$ for every $u_h \in H_0^{2d_1+1}((0, T') \times \omega)^{d_1}$. \square

For the second point, we will prove the following adaptation of Proposition 27.

Proposition 51. *If n_0 is large enough, there exists a continuous operator*

$$\begin{aligned} \mathcal{U}^{h,\sharp}: \mathbf{F}_1 \times H_0^{2d_1+1}((T', T) \times \omega)^{d_2} &\rightarrow H_0^{2d_1+1}((0, T') \times \omega)^{d_1} \\ (f_0, u_p) &\mapsto u_h, \end{aligned}$$

that associates with any $(f_0, u_p) \in \mathbf{F}_1 \times H_0^{2d_1+1}((T', T) \times \omega)^{d_2}$ a control $u_h = \mathcal{U}^{h,\sharp}(f_0, u_p)$ such that

$$\Pi^h S(T; f_0, (\partial_x^{d_1} u_h, u_p)) = 0. \tag{155}$$

While the ideas of the proof are the same as for Proposition 27, the proof of this Proposition is technically more delicate, as we have to build regular controls, and, on the observability side, deal with the (slightly impractical) H_0^s and H^{-s} norms. We postpone the proof to the next subsection. For now, let us assume Proposition 51 holds true, and finish the proof of Theorem 4.

We now combine Propositions 50 and 51 with the Fredholm alternative, as in the proof of Proposition 26, to prove that high frequencies are null-controllable. That is to say, we get the following adaptation of Proposition 26.

Proposition 52. *There exists a closed subspace \mathcal{G}^\sharp of \mathbf{F}_1 with finite codimension and a continuous operator*

$$\begin{aligned} \mathcal{U}^\sharp: \mathcal{G}^\sharp &\rightarrow H_0^{2d_1+1}(q_T)^{d_1} \times H_0^{2d_1+1}(q_T)^{d_2} \\ f_0 &\mapsto (u_h, u_p), \end{aligned}$$

that associates with each $f_0 \in \mathcal{G}^\sharp$ a pair of controls $\mathcal{U}^\sharp f_0 = (u_h, u_p)$ such that

$$\forall f_0 \in \mathcal{G}^\sharp, \Pi S(T; f_0, (\partial_x^{d_1} u_h, u_p)) = 0. \quad (156)$$

The last step consists in showing that the null-controllability result of Proposition 49 is true at the low frequency-level, as we have already shown for Theorem 2 in Section 4.5. All the steps of Section 4.5 remain unchanged except the Step 6. Indeed, the unique continuation argument transforms into: if $f(t, \cdot) = e^{tM} f_0$ with $(\partial_x^{d_1} f_1, f_2) = (0, 0)$ in $(0, \varepsilon) \times \omega$ then $(\partial_x^{d_1} f_{01}, f_{02}) = (0, 0)$ thanks to the spectral inequality of Lebeau-Robbiano (98), that is to say, $f_0 = 0$ because $\int_{\mathbb{T}} f_{01}(x) dx = 0$.

This concludes the proof of Proposition 49 thus the proof of Proposition 48. \square

7.3 Proof of Proposition 51

The proof of Proposition 51 is an adaptation of the one of Proposition 27, with the following changes:

- we deal with the fact that we want a control of the form $(\partial_x^{d_1} u_h, 0)$,
- we adapt the duality argument to take into account the regularity of the controls that we want (it involves some H^{-s} norms),
- we adapt all the inequalities to replace the relevant L^2 norms by H^{-s} norms,
- to build regular controls of the simple transport equation $\partial_t f + \mu \partial_x f = 0$, we use [1].

Step 1: reduction to an exact controllability problem. We claim that in order to prove Proposition 51, we only have to prove the following exact controllability result.

Proposition 53. *If n_0 is large enough, then for every $T' > T^*$, there exists a continuous operator*

$$\begin{aligned} \underline{\mathcal{U}}_{T'}^{\text{h}, \sharp}: F^{\text{h}} \cap H^{2d_1+1}(\mathbb{T})^d &\rightarrow H_0^{2d_1+1}(q_{T'})^{d_1} \\ f_{T'} &\mapsto u_h, \end{aligned}$$

that associates with any $f_{T'} \in F^{\text{h}} \cap H^{2d_1+1}(\mathbb{T})^d$, a control $\underline{\mathcal{U}}_{T'}^{\text{h}, \sharp}(f_{T'}) = u_h$ such that

$$\Pi^{\text{h}} S(T'; 0, (u_h, 0)) = f_{T'}.$$

Indeed, by the choice of support in time of the controls, and by the reversibility of $e^{-t\mathcal{L}^{\text{h}}}$ (see Section 4.3.1 for the details), the relation (155) is equivalent to

$$\Pi^{\text{h}}(S(T'; 0, (\partial_x^{d_1} u_h, 0))) = -e^{(T-T')\mathcal{L}^{\text{h}}} \Pi^{\text{h}} S(T; f_0, (0, u_p)).$$

Note that functions in F^{h} have zero mean (see the definition of F^{h} Eq. (51)). Thus, $\partial_x^{d_1}$ is invertible on F^{h} , and its inverse $\partial_x^{-d_1}$ is, on the Fourier side, the multiplication by $(in)^{-d_1}$. Moreover, the operator ∂_x commute with Π^{h} and the semi-group $e^{-t\mathcal{L}}$. So the relation (155) is equivalent to

$$\Pi^{\text{h}}(S(T'; 0, (u_h, 0))) = -\partial_x^{-d_1} e^{(T-T')\mathcal{L}^{\text{h}}} \Pi^{\text{h}} S(T; f_0, (0, u_p)) =: K(f_0, u_p). \quad (157)$$

So, if Proposition 53 holds, we may choose (assuming it makes sense)

$$u_h := \underline{\mathcal{U}}_{T'}^{\text{h}, \sharp}(K(f_0, u_p)).$$

Thus, to end this first step, we just have to check that the right-hand side $K(f_0, u_p)$ of (157) is indeed in $F^{\text{h}} \cap H^{2d_1+1}(\mathbb{T})^d$.

The projection Π^h has range F^h , and $e^{t\mathcal{L}^h}$ sends F^h to itself, as do $\partial_x^{-d_1}$. So $K(f_0, u_p)$ belongs to F^h .

The group $e^{t\mathcal{L}^h}$ sends every $H^s(\mathbb{T})^d$ into itself (see Remark 13). Since Π^h is just the multiplication on the Fourier side by $P^h(i/n)$, the operator Π^h also sends every $H^s(\mathbb{T})^d$ into itself. Thus, we just have to check that $S(T, f_0, (0, u_p)) = e^{-T\mathcal{L}}f_0 + S(T, 0, (0, u_p)) \in H^{d_1+1}(\mathbb{T})^d$ because $\partial_x^{-d_1}$ sends $H^{d_1+1}(\mathbb{T})^d$ into $H^{2d_1+1}(\mathbb{T})^d$.

- The function f_0 belongs to $H^{d_1+1}(\mathbb{T})$ by hypothesis, so $e^{-T\mathcal{L}}f_0$ also belongs to $H^{d_1+1}(\mathbb{T})$ (see Remark 13).
- The parabolic control u_p belongs to $H_0^{2d_1+1}((T', T) \times \omega)^{d_2}$ by hypothesis, thus for almost every $t \in (0, T)$, $(0, u_p)(t, \cdot)$ belongs to $H^{2d_1+1}(\mathbb{T})$ and thus

$$S(T; 0, (0, u_p)) = \int_0^T e^{-(T-t)\mathcal{L}}(0, u_p)(t) dt \in H^{2d_1+1}(\mathbb{T})^d.$$

This concludes this first step.

Step 2: Observability inequality associated to the controllability problem of Proposition 53. Let

$$\Phi_2 := \Pi^h \circ \iota_{2d_1+1}: H^{2d_1+1}(\mathbb{T})^d \rightarrow L^2(\mathbb{T})^d$$

be the restriction of Π^h to $H^{2d_1+1}(\mathbb{T})^d$ and

$$\Phi_3 := \Pi^h \circ \mathcal{F}_{T'} \circ (\iota_{2d_1+1}, 0): H_0^{2d_1+1}(q_{T'})^{d_1} \rightarrow L^2(\mathbb{T})^d,$$

where $(\iota_{2d_1+1}, 0)$ stands for the map $u_h \in H_0^{2d_1+1}(q_{T'})^{d_1} \mapsto (u_h, 0) \in L^2(q_{T'})^d$. Note that Φ_2 and Φ_3 are continuous.

The controllability problem of Proposition 53 is equivalent to the inclusion $\text{Im}(\Phi_2) \subset \text{Im}(\Phi_3)$. Therefore, according to the duality Lemma 14, it is equivalent to the following inequality: there exists $C > 0$ such that for every $g_0 \in L^2(\mathbb{T})^d$, $\|\Phi_2^* g_0\|_{H^{2d_1+1}(\mathbb{T})^d} \leq C \|\Phi_3^* g_0\|_{H_0^{2d_1+1}(q_{T'})^d}$. Since Π^h is a projection on \widetilde{F}^h , since $\mathcal{F}_{T'}^* g_0$ is the restriction of the first d_1 components of $e^{-(T'-t)\mathcal{L}^*} g_0$ to $q_{T'}$, and since ι_s^* is an isometry between H_0^s and H^{-s} ,⁹ this inequality reads: there exists $C > 0$ such that for every $g_0 \in \widetilde{F}^h$, the solution $g = e^{-t\mathcal{L}^*} g_0$ of the adjoint system (30) satisfies

$$\|g_0\|_{H^{-2d_1-1}(\mathbb{T})^d} \leq C \|g_1\|_{H^{-2d_1-1}(q_{T'})^{d_1}}, \quad (158)$$

where g_1 are the first d_1 components of g .

Let $g_0 \in \widetilde{F}^h$. For the remaining of this proof, we use the notations of Section 4.3.2, and in particular we introduce the decompositions (70) and (71). In the following arguments, the constants C do not depend on g_0 .

Step 3: We prove the observability inequality (158) assuming that, for every $\mu \in \text{Sp}(A')$, there exists $C > 0$ such that the solution G_μ^b of (79) satisfies

$$\|G_\mu(0, \cdot)\|_{H^{-(2d_1+1)}(\mathbb{T})} = \|G_\mu^b(0, \cdot)\|_{H^{-(2d_1+1)}(\mathbb{T})} \leq C \|G_\mu^b\|_{H^{-(2d_1+1)}(q_T)}. \quad (159)$$

We will prove (159) in Step 3.

We proceed as in the proof given in Section 4.3.2. By the explicit expression (75) of S_μ and Bessel-Parseval identity, there exists $C = C(T')$ independent of g_0 such that

$$\|S_\mu\|_{L^\infty((0, T'), H^{-(2d_1+1)}(\mathbb{T})^d)} \leq C \|g(0, \cdot)\|_{H^{-(2d_1+2)}(\mathbb{T})^d}. \quad (160)$$

Using the Duhamel formula, we obtain that the function \widetilde{G}_μ defined by (77) satisfies

$$\begin{aligned} & \|\widetilde{G}_\mu - G_\mu^b\|_{L^\infty((0, T'), H^{-(2d_1+1)}(\mathbb{T})^d)} \\ & \leq C \|e^{tR_\mu^h(0)^*} S_\mu\|_{L^1((0, T'), H^{-(2d_1+1)}(\mathbb{T})^d)} \leq C \|g_0\|_{H^{-(2d_1+2)}(\mathbb{T})^d}. \end{aligned} \quad (161)$$

⁹See Lemma 39, and also recall that because \mathbb{T} has no boundary $H_0^s(\mathbb{T}) = H^s(\mathbb{T})$.

By (159), the triangular inequality, (77) and (161), we deduce that

$$\begin{aligned} \|G_\mu(0, \cdot)\|_{H^{-(2d_1+1)}(\mathbb{T})^d} &\leq C \left(\|\tilde{G}_\mu\|_{H^{-(2d_1+1)}(q_{T'})^d} + \|\tilde{G}_\mu - G_\mu^b\|_{H^{-(2d_1+1)}(q_{T'})^d} \right) \\ &\leq C \left(\|G_\mu\|_{H^{-(2d_1+1)}(q_{T'})^d} + \|g_0\|_{H^{-(2d_1+2)}(\mathbb{T})^d} \right). \end{aligned} \quad (162)$$

Using Bessel-Parseval identity and the decomposition (82), we obtain

$$\|G_\mu - P_\mu^h(0)^*g\|_{L^\infty((0, T'), H^{-(2d_1+1)}(\mathbb{T})^d)} \leq C \|g_0\|_{H^{-(2d_1+2)}(\mathbb{T})^d}. \quad (163)$$

We deduce from (162), the triangular inequality and (163) that

$$\|G_\mu(0, \cdot)\|_{H^{-(2d_1+1)}(\mathbb{T})^d} \leq C \left(\|P_\mu^h(0)^*g\|_{H^{-(2d_1+1)}(q_{T'})^d} + \|g_0\|_{H^{-(2d_1+2)}(\mathbb{T})^d} \right).$$

Taking into account that $P_\mu^h(0)^* = P_\mu^h(0)^*P^h(0)^*$, we get¹⁰

$$\|P_\mu^h(0)^*g\|_{H^{-(2d_1+1)}(q_{T'})^d} \leq |P_\mu^h(0)^*| \|P^h(0)^*g\|_{H^{-(2d_1+1)}(q_{T'})^d} \leq C \|g_1\|_{H^{-(2d_1+1)}(q_{T'})^{d_1}}.$$

Using (71), the triangular inequality and the previous two estimates, we obtain

$$\begin{aligned} &\|g_0\|_{H^{-(2d_1+1)}(\mathbb{T})^d} \\ &\leq \sum_{\mu \in \text{Sp}(A')} \|G_\mu(0, \cdot)\|_{H^{-(2d_1+1)}(\mathbb{T})^d} \leq C \left(\|g_1\|_{H^{-(2d_1+1)}(q_{T'})^{d_1}} + \|g_0\|_{H^{-(2d_1+2)}(\mathbb{T})^d} \right). \end{aligned} \quad (164)$$

Proceeding as in the end of the proof given in Section 4.3.2, the inequality (164), together with a compactness-uniqueness argument, end Step 2.

Step 4: We prove that the solution G_μ^b of (79) satisfies (159). By duality, it is actually enough to prove the following exact-controllability result.

Proposition 54. *Let $\omega = (a, b)$ and $T' > \frac{2\pi-(b-a)}{|\mu|}$. For every $(f_0, f_{T'}) \in (H^{2d+1}(\mathbb{T})^d)^2$, there exists $u \in H_0^{2d_1+1}(q_T)^d$ such that the solution f of*

$$\begin{cases} \partial_t f + \mu \partial_x f = u 1_\omega & \text{in } Q_{T'}, \\ f(0, \cdot) = f_0 & \text{in } \mathbb{T}, \end{cases} \quad (165)$$

satisfies $f(T', \cdot) = f_{T'}$.

To prove Proposition 54, we will use the following lemma, which is an easy adaptation of [1, Lemma 2.6].

Lemma 55. *Let $\omega = (a, b)$ and $T' > \frac{2\pi-(b-a)}{|\mu|}$. Then, there exists $\delta > 0$ small enough and a cut-off function $\eta \in C^\infty([0, T'] \times [0, 2\pi])$ with*

$$\eta = 0 \text{ in } [0, T'] \times [0, 2\pi] \setminus ((\delta, T' - \delta) \times (a + \delta, b - \delta)), \quad (166)$$

such that, for every $x \in [0, 2\pi]$,

$$Q_x := \int_0^{T'} \eta(s, x + \mu s) ds \neq 0. \quad (167)$$

Remark 56. We assumed that the function η is extended by 2π -periodicity in the spatial variable.

Now, we give the proof of Proposition 54 thanks to Lemma 55.

¹⁰Remark that if K is a matrix and $f \in (H^{-s})^d$, then $\|Kf\|_{H^{-s}} \leq |K| \|f\|_{H^{-s}}$. Indeed, noting $\langle \cdot, \cdot \rangle$ the duality between H_0^s and H^{-s} , we have for every $g \in H_0^s$, $\langle Kf, g \rangle = \langle f, K^*g \rangle \leq \|f\|_{H^{-s}} \|K^*g\|_{H_0^s} \leq \|f\|_{H^{-s}} |K^*| \|g\|_{H_0^s}$, and taking the supremum over $\|g\|_{H_0^s} = 1$, we do have $\|Kf\|_{H^{-s}} \leq |K^*| \|f\|_{H^{-s}}$.

Proof of Proposition 54. We take the control

$$u(t, x) = \eta(t, x) Q_{x-\mu t}^{-1} (f_{T'}(x) - f_0(x - \mu t)). \quad (168)$$

We easily check that the control u belongs to $H_0^k(q_T)$ by using the support of η (166), and the regularity of the three functions η , $f_{T'}$ and f_0 . Let f be the solution of (165) with initial data f_0 and control u defined in (168). We just have to check that f satisfies $f(T', \cdot) = f_{T'}$. We write the solution along the characteristic, that is to say

$$\frac{d}{dt} f(t, x + \mu t) = u(t, x + t) = \eta(t, x + \mu t) Q_x^{-1} (f_{T'}(x + \mu t) - f_0(x)).$$

By integrating in space between 0 and T' and by using the definition of Q_x (167), we obtain

$$f(T', \cdot + \mu T') - f(0, \cdot) = f_{T'}(\cdot + \mu T') - f_0(\cdot),$$

then $f(T', \cdot) = f_{T'}$ which concludes the proof of Proposition 54. \diamond

This ends the proof of Proposition 53. \square

Appendix A Proof of the estimate on some operators on polynomials

Proof. To prove Theorem 23, it is enough to prove the estimate (45). Let K and V be as in Theorem 23.

Let us fix $R' > 0$ large enough so that $\bar{V} \subset D(0, R')$. Let f be any entire function that we write $f(z) = \sum f_n z^n$. According to Cauchy's integral formula, we have $f_n = \frac{1}{2i\pi} \oint_{\partial D(0, R')} \zeta^{-n-1} f(\zeta) d\zeta$. Then,

$$\begin{aligned} H_\gamma(f)(z) &= \sum_n \gamma(n) f_n z^n \\ &= \sum_n \gamma(n) \frac{1}{2i\pi} \oint_{\partial D(0, R')} \frac{f(\zeta)}{\zeta^{n+1}} z^n d\zeta \\ &= \oint_{\partial D(0, R')} \frac{1}{2i\pi \zeta} K_\gamma\left(\frac{z}{\zeta}\right) f(\zeta) d\zeta, \end{aligned} \quad (169)$$

with

$$K_\gamma(\zeta) := \sum \gamma(n) \zeta^n. \quad (170)$$

According to the subexponential growth of $\gamma(n)$, the Taylor series in (170) converges for $|z| < 1$. We will prove that it can be analytically extended to $\mathbb{C} \setminus [1, +\infty)$.

Proposition 57. *Let $\gamma \in \mathcal{S}_R^{d \times d}$. Then, K_γ can be extended to a holomorphic function on $\mathbb{C} \setminus [1, +\infty)$. Moreover, $\gamma \in \mathcal{S}_R^{d \times d} \mapsto K_\gamma \in \mathcal{O}(\mathbb{C} \setminus [1, +\infty))^d$ is continuous, i.e. for every compact subset K of $\mathbb{C} \setminus [1, +\infty)$, there exist $C > 0$ and a seminorm p_ε of $\mathcal{S}_R^{d \times d}$ such that for every $\gamma \in \mathcal{S}_R^{d \times d}$,*

$$\|K_\gamma\|_{L^\infty(K)} \leq C p_\varepsilon(\gamma). \quad (171)$$

Let us finish the proof of Theorem 23 before proving Proposition 57. Let us remind that V is a neighborhood of K that is star-shaped with respect to 0. So, we can choose V' a smooth, open, star-shaped with respect to 0 neighborhood of K such that $V' \subset V$. Let $c = \partial V'$ with clockwise orientation. Since V' is star-shaped with respect to 0, for $z \in V'$ and $\zeta \in c$, we never have $z/\zeta \in [1, +\infty)$, so $K(z/\zeta)$ is well-defined. This justifies the change of integration path in the expression of H_γ as a kernel operator (169) from $\partial D(0, R')$ to c . Therefore, we have

$$\begin{aligned} |H_\gamma(f)(z)| &= \frac{1}{2\pi} \left| \oint_c \frac{1}{\zeta} K_\gamma\left(\frac{z}{\zeta}\right) f(\zeta) d\zeta \right| \\ &\leq \frac{\text{length}(c)}{2\pi} \sup_{\zeta \in c} |\zeta|^{-1} \sup_{z \in K, \zeta \in c} \left| K_\gamma\left(\frac{z}{\zeta}\right) \right| \|f\|_{L^\infty(c)}. \end{aligned}$$

According to the estimation (171) on the kernel K_γ applying with the compact $K \leftarrow K' := \{z/\zeta ; (z, \zeta) \in K \times c\}$, there exists $C > 0$ and $\varepsilon > 0$ independent of γ such that

$$\sup_{z \in K, \zeta \in c} \left| K_\gamma \left(\frac{z}{\zeta} \right) \right| \leq Cp_\varepsilon(\gamma).$$

So,

$$|H_\gamma(f)(z)| \leq C'p_\varepsilon(\gamma)\|f\|_{L^\infty(c)} \leq C'p_\varepsilon(\gamma)\|f\|_{L^\infty(V)}.$$

This is the inequality (45) we wanted to prove. \square

Proposition 57 was essentially already proved by Lindelöf [21, Ch. V], and then slightly generalized by Arakelyan in [4] and rediscovered by the second author in [17]. We will use here Lindelöf's method, based on the Residue theorem, instead of the method based on the Poisson summation formula in [17].

Proof of Prop. 57. Let U be a bounded open subset of $\mathbb{C} \setminus [1, +\infty)$. We note K the closure of U . We want to extend K_γ to a holomorphic function on U and prove the estimate (171).

First, since the Taylor series $\sum \gamma(n)z^n$ defining $K_\gamma(z)$ converges for $|z| < 1$, it is enough to do so for every bounded subset U of $\mathbb{C} \setminus \mathbb{R}_+$.

The idea is to chose the right path Γ so that thanks to the Residue Theorem, $K_\gamma(z)$ is equal to

$$\sum_{n > R} \gamma(n)z^n = \frac{1}{2i\pi} \int_{\Gamma} \frac{\gamma(\zeta)z^\zeta}{e^{2i\pi\zeta} - 1} d\zeta. \quad (172)$$

and then prove that the right hand side of (172) is defined for $z \in \mathbb{C} \setminus \mathbb{R}_+$.

Step 1: the estimate on the integrand. As a technical preparation, we prove an elementary estimate on $g_z(\zeta) := z^\zeta(e^{2i\pi\zeta} - 1)^{-1}$. We claim that for every $\delta > 0$, there exists $C_\delta > 0$ such that if for every ζ such that $\text{distance}(\zeta, \mathbb{Z}) \geq \delta > 0$ and $z \in \mathbb{C} \setminus \mathbb{R}_+$,

$$\begin{aligned} |g_z(\zeta)| &\leq C_\delta e^{\Re(\zeta) \ln|z| - |\Im(\zeta)| \arg(z)} && \text{if } \Im(z) > 0, \\ |g_z(\zeta)| &\leq C_\delta e^{\Re(\zeta) \ln|z| - |\Im(\zeta)|(2\pi - \arg(z))} && \text{if } \Im(z) < 0, \end{aligned} \quad (173)$$

where we chose $\arg(z) \in (0, 2\pi)$.

If $\text{distance}(\zeta, \mathbb{Z}) > \delta$, we have

$$\begin{aligned} |e^{2i\pi\zeta} - 1|^{-1} &\leq C_\delta && \text{if } \Im(\zeta) > 0, \\ |e^{2i\pi\zeta} - 1|^{-1} &\leq C_\delta e^{2\pi\Im(\zeta)} && \text{if } \Im(\zeta) < 0. \end{aligned}$$

Then since $z^\zeta = e^{\zeta \ln(z)}$, we have

$$|z^\zeta| = e^{\Re(\zeta \ln(z))} = e^{\Re(\zeta) \ln|z| - \Im(\zeta) \arg(z)}.$$

By gathering these two upper-bounds, we deduce (173).

The choice of the path Γ . We see from the estimate (173) that for the integral to converge, we need to minimize $\Re(\zeta)$ along the integration path. We choose R' between R and $[R] + 1$ (so that R' is not an integer) and we choose the path Γ to be $\{R' - it, t \in \mathbb{R}\}$.

Step 2: the Residue theorem. We first prove that the integral representation (172) of K_γ holds for $|z| < 1$, $z \notin [0, 1)$.

For $k \in \mathbb{N}^*$, let Γ_k be the positively oriented boundary of the half-disk $\{|\zeta - R'\| < k, \Re(\zeta) > R'\}$ (see Fig. 2).

Note that $(e^{2i\pi\zeta} - 1)^{-1}$ has residues 1 at every $\zeta \in \mathbb{Z}$. Then, according to the Residue theorem, we have for every $k \in \mathbb{N}^*$, and $z \in \mathbb{C}$,

$$\sum_{R' < n < R'+k} \gamma(n)z^n = \frac{1}{2i\pi} \oint_{\Gamma_k} \frac{\gamma(\zeta)z^\zeta}{e^{2i\pi\zeta} - 1} d\zeta. \quad (174)$$

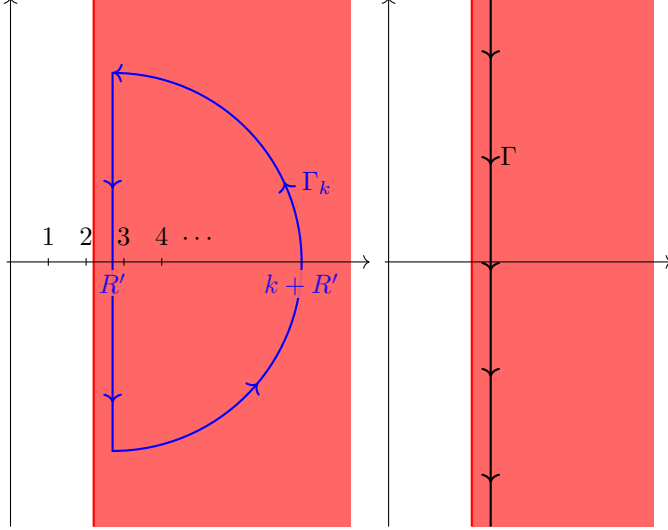


Figure 2 – In red, the domain of definition of γ . In blue, the integration path for the Residue theorem in (174). By taking k (the radius of the half-circle) going to $+\infty$, we prove that the integral on the “half-circle” part of Γ_k tends to 0. So the integral on Γ_k tends to the integral on the vertical line $\Gamma = \{\Re(\zeta) = R'\}$ in black in the right figure.

For $|z| < 1$, $z \notin [0, 1)$, we want to take the limit $k \rightarrow +\infty$. To that end, we prove the integral on the “half-circle” part of γ_k tends to 0 as $k \rightarrow +\infty$. Note that all paths Γ_k stay at distance $\delta > 0$ from \mathbb{Z} , so we can apply the estimate (173). Note also that for such z , we have

$$c_z := \min(-\ln|z|, -\arg(z), \arg(z) - 2\pi) > 0.$$

So, for every $\varepsilon > 0$ and $\Re(\zeta) > 0$, we have the estimate on the integrand

$$|\gamma(\zeta)g_z(\zeta)| \leq C_\delta |\gamma(\zeta)| e^{-c_z(\Re(\zeta) + |\Im(\zeta)|)} \leq C_\delta p_\varepsilon(\gamma) e^{-(c_z - \varepsilon)|\zeta|},$$

where we used that $|\zeta| \leq |\Re(\zeta)| + |\Im(\zeta)|$ and the definition of the seminorms of $\mathcal{S}_R^{d \times d}$ for the second inequality.

We take $\varepsilon = c_z/2$. So, if $\zeta = R' + ke^{i\theta}$ is in the “half-circle” part of γ_k , we have

$$|\gamma(\zeta)g_z(\zeta)| \leq C_\delta e^{R'c_z/2} p_\varepsilon(\gamma) e^{-(c_z/2)k}.$$

So we have the following upper-bound, valid for every $k \in \mathbb{N}^*$ and $\varepsilon > 0$:

$$\left| \int_{\substack{|\zeta - R'| = k \\ \Re(\zeta) > R'}} \gamma(\zeta)g_z(\zeta) d\zeta \right| \leq C_\delta p_\varepsilon(\gamma) \pi k e^{-(c_z/2)k}.$$

We see that this integral decays exponentially as $k \rightarrow +\infty$.

Coming back to the residue theorem of (174), the left-hand side has a limit for $k \rightarrow +\infty$. So, the right-hand side also has a limit for $k \rightarrow +\infty$, and since the integral on the half-disk tends to 0, we do have

$$\sum_{n > R} \gamma(n)z^n = \frac{1}{2i\pi} \oint_{\Gamma} \frac{\gamma(\zeta)z^\zeta}{e^{2i\pi\zeta} - 1} d\zeta,$$

which is what we wanted.

Step 3: the integral representation defines a holomorphic function for $z \notin \mathbb{R}_+$. We again use the upper bound (173) on g_z . Let $z \notin \mathbb{R}_+$ and $\zeta = R' - it$ in the integration path. We also define $c'_z = \min(\arg(z), 2\pi - \arg(z)) > 0$. We have according to the upper-bound (173)

$$|\gamma(\zeta)g_z(\zeta)| \leq C_\delta p_\varepsilon(\gamma) |\zeta|^{R'} e^{-(c'_z - \varepsilon)|t|}. \quad (175)$$

So, the integrand in (172) is indeed integrable with respect to t . Moreover, this upper-bound is uniform in $\sigma < \arg(z) < 2\pi - \sigma$ for every $\sigma > 0$. So, the integral in (172) is holomorphic in $\mathbb{C} \setminus \mathbb{R}_+$ by the theorem of holomorphy under the integral sign.

Step 4: continuity with respect to γ . We want to prove that for every compact set X of $\mathbb{C} \setminus [1, +\infty)$, there exists $C > 0$ and $\varepsilon > 0$ such that for every $\gamma \in \mathcal{S}_R^{d \times d}$,

$$\|K_\gamma\|_{L^\infty(X)} \leq Cp_\varepsilon(\gamma). \quad (176)$$

As we saw in the previous steps, the case $z \in [0, 1)$ cannot be handled with the integral representation. This is a minor inconvenience. To circumvent it, we write X as a union $X_1 \cup X_2$ of a compact subset X_1 of $D(0, 1)$ and of a compact subset X_2 of $\mathbb{C} \setminus \mathbb{R}_+$, and we estimate $\|K_\gamma\|_{L^\infty(X_1)}$ and $\|K_\gamma\|_{L^\infty(X_2)}$ separately.

We start with $\|K_\gamma\|_{L^\infty(X_2)}$. There exists $\sigma > 0$ such that $X_2 \subset \{\sigma < \arg(z) < 2\pi - \sigma\}$. Then, with the notation of the previous step, for every $z \in X_2$, we have

$$c'_z = \min(\arg(z), 2\pi - \arg(z)) > \sigma.$$

Then, according to the upper bound (175) of the previous step, we have for every $\varepsilon < \sigma$ and $z \in X_2$:

$$|K_\gamma(z)| \leq \frac{2C_\delta p_\varepsilon(\gamma)}{\sigma - \varepsilon}.$$

Estimating $\|K_\gamma\|_{L^\infty(X_1)}$ is done by bounding termwise the series defining $K_\gamma(z)$: if $|z| < e^\varepsilon$, we have

$$|K_\gamma(z)| \leq p_\varepsilon(\gamma) \sum_{n>R} |z|^n e^{\varepsilon n} = p_\varepsilon(\gamma) \frac{|z|^{[R]+1}}{1 - |z|e^\varepsilon}.$$

This proves that $\gamma \mapsto K_\gamma$ is continuous, and concludes the proof of Prop. 57. \square

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