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A VARIATIONAL APPROACH TO APPROXIMATE CONTROLS FOR SYSTEM WITH ESSENTIAL SPECTRUM : APPLICATION TO MEMBRANAL ARCH

ARNAUD MÜNCH

ABSTRACT. We address the numerical approximation of boundary controls for systems of the form $\mathbf{y}'' + \mathbf{A}_M \mathbf{y} = \mathbf{0}$ which models dynamical elastic shell structure. The membranal operator \mathbf{A}_M is self-adjoint and of mixed order, so that it possesses a non empty and bounded essential spectrum $\sigma_{ess}(\mathbf{A}_M)$. Consequently, the controllability does not hold uniformly with respect to the initial data. Thus the numerical computation of controls by the way of dual approaches and gradient methods may fail, even if the initial data belongs to the orthogonal of the space spanned by the eigenfunctions associated with $\sigma_{ess}(\mathbf{A}_M)$. In that work, we adapt a variational approach introduced in [Pablo Pedregal, *Inverse Problems* (26) 015004 (2010)] for the wave equation and obtain a robust method of approximation. This approach does not require any information on the spectrum of the operator \mathbf{A}_M . We also show that it allows to extract, from any initial data $(\mathbf{y}^0, \mathbf{y}^1)$, a controllable component for the mixed order system. We illustrate these properties with some numerical experiments in the full controllability context as well as a partial controllability one.

Key Words. Controllability, Shell equation, Essential spectrum, Variational approach.

1. INTRODUCTION

This work is a contribution to the boundary controllability of the hyperbolic system

$$(1.1) \quad \begin{cases} \mathbf{y}_\epsilon'' + \mathbf{A}_M \mathbf{y}_\epsilon + \epsilon^2 \mathbf{A}_F \mathbf{y}_\epsilon = \mathbf{0}, & (\xi, t) \in q_T = \omega \times (0, T) \\ (\mathbf{y}_\epsilon(\xi, 0), \mathbf{y}_\epsilon'(\xi, 0)) = (\mathbf{y}^0, \mathbf{y}^1), & \xi \in \omega, \end{cases}$$

which models the vibration of an elastic shell-type structure occupying, in local coordinates, the domain $\omega \times]-\epsilon/2, \epsilon/2[$. $\omega \subset \mathbb{R}^2$ denotes the bounded mid-surface of the shell and $\mathbf{y}_\epsilon = (y_{\epsilon, \alpha}, y_{\epsilon, 3})$ the local displacement field decomposed into the tangential $\mathbf{y}_{\epsilon, \alpha} = (y_{\epsilon, 1}, y_{\epsilon, 2})$ and the normal $y_{\epsilon, 3}$ components. ϵ is the constant thickness of the shell and $\xi = (\xi_1, \xi_2) \in \omega$. \mathbf{A}_M and \mathbf{A}_F denote the membranal and flexural operator respectively, associated with the map defining the mid-surface ω . System (1.1) is referred to in the literature as the Koiter shell model, derived from the three dimensional elasticity system via kinematical assumptions (see [4, 5, 6, 26]).

The boundary controllability problem of (1.1) consists to drive the initial condition $(\mathbf{y}^0, \mathbf{y}^1)$ - assumed to belong in a suitable space - to a target $(\mathbf{y}_T^0, \mathbf{y}_T^1)$ at a time T large enough through a control $\mathbf{v} = (\mathbf{v}_\alpha, v_3)$ acting on $\Sigma_T = \Sigma \times (0, T)$, $\Sigma \subset \partial\omega$. The controllability of system (1.1) strongly relies on the spectral property of the operator $\mathbf{A}^\epsilon := \mathbf{A}_M + \epsilon^2 \mathbf{A}_F$.

For any $\epsilon > 0$ fixed, the operator \mathbf{A}^ϵ enjoys suitable compactness properties, so that the multiplier method leads to positive controllability results ([9, 20]). On the other hand, when ϵ goes to zero, the system degenerates, under some assumption on $\text{Ker}(\mathbf{A}_M)$ ([27]), into the following system

$$(1.2) \quad \begin{cases} \mathbf{y}'' + \mathbf{A}_M \mathbf{y} = \mathbf{0}, & (\xi, t) \in q_T \\ (\mathbf{y}(\xi, 0), \mathbf{y}'(\xi, 0)) = (\mathbf{y}^0, \mathbf{y}^1), & \xi \in \omega. \end{cases}$$

The controllability of the limit system (1.2) is much more involved because \mathbf{A}_M is a mixed order operator and possesses a non empty essential spectrum [14]. Precisely, it is shown in [11] that, for

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such operator, the controllability does not hold uniformly with respect to the data $(\mathbf{y}^0, \mathbf{y}^1)$. For instance, in [2], for any $a, \alpha \in \mathbb{R}$, $a \leq \alpha^2$, $\omega = (0, 1)^2$, the mixed order and self-adjoint operator

$$\mathbf{A}_M = \begin{pmatrix} -\Delta & -\alpha \partial_\xi \\ \alpha \partial_\xi & a \end{pmatrix}$$

for which $\sigma_{ess}(\mathbf{A}_M) = [a - \alpha^2, a]$ is considered. It is shown that the controllability only hold for initial data spanned by the eigenfunctions associated to the discrete spectrum $\sigma_d(\mathbf{A}_M)$. The proof is based on the explicit expression of the spectrum $\sigma(\mathbf{A}_M)$ and the use of 2-D Ingham type theorem [16].

In [22], we provide numerical experiments for the system (1.1) in the one dimensional case, that is, $\omega = (0, 1)$ and the simpler but still very instructive operator \mathbf{A}_M defined by

$$(1.3) \quad \mathbf{A}_M = \begin{pmatrix} -\partial_{\xi\xi}^2 & -c\partial_\xi \\ c\partial_\xi & c^2 \end{pmatrix}$$

and $D(\mathbf{A}_M) = (H^2(\omega) \cap H_0^1(\omega)) \times H^1(\omega)$ for which $\sigma_{ess}(\mathbf{A}_M) = \{0\}$. This operator enters in the modelization of an elastic arch of length one and constant curvature $c > 0$. The experiments exhibit the loss of compactness in the transition shell-membrane, as $\epsilon \rightarrow 0$. Precisely, the controls $(v_\epsilon)_{\epsilon > 0}$ (obtained by dual arguments and minimization of conjugate functions) are not uniformly bounded with respect to $\epsilon > 0$. In the case $\epsilon = 0$, the practical computation of boundary controls for (1.2) remains a challenge, unless a precise description of the discrete spectrum is known.

We present in this work a different approach based on variational arguments inspired from [24], that allows to obtain control associated to the controllable part of the initial data $(\mathbf{y}^0, \mathbf{y}^1)$. It is interesting to note that such approach does not require any information on $\sigma(\mathbf{A}_M)$. It consists first in introducing a class of functions satisfying *a priori* the boundary conditions in space and time - in particular the controllability condition at time T - and then find among this class one element satisfying the state equation of (1.2).

The paper is organized as follow. In Section 2, we use standard dual arguments and analyze some Dirichlet controllability properties of (1.2) with \mathbf{A}_M defined by (1.3). Two distinct cases are considered: the full controllability case which requires the equality $(\mathbf{y}(T), \mathbf{y}'(T)) = (\mathbf{y}_T^0, \mathbf{y}_T^1)$ at the final time and a relaxed situation, where we simply require that $(y_1(T), y_1'(T)) = (y_{1T}^0, y_{1T}^1)$. In both cases, we characterize the class of initial data which are controllable. In Section 3, we enrich this analysis with some careful numerical experiments, obtained thanks to a precise description of $\sigma(\mathbf{A}_M)$. Then, in Section 4 we show how to adapt [24] to the operator (1.3) in these two situations. Section 5, additional numerical experiments highlight that this variational approach allows to extract from any data $(\mathbf{y}^0, \mathbf{y}^1)$ its controllable part. We conclude with some perspectives in Section 6.

2. CONTROL PROBLEMS

Let us define the spaces $\mathbf{H} = L^2(\omega) \times L^2(\omega)$, $\mathbf{V} = H_0^1(\omega) \times L^2(\omega)$ and $\mathbf{V}' = H^{-1}(\omega) \times L^2(\omega)$ so that one has the usual situation $\mathbf{V} \subset \mathbf{H} \equiv \mathbf{H}' \subset \mathbf{V}'$ with \mathbf{H} as a pivot space.

The Dirichlet controllability problem for (1.3) reads as follows: for any $T > 0$ large enough, any $(\mathbf{y}^0, \mathbf{y}^1), (\mathbf{y}_T^0, \mathbf{y}_T^1) \in \mathbf{H} \times \mathbf{V}'$, find a control $v \in L^2(\Sigma_T)$, $\Sigma_T = \{1\} \times (0, T)$ such that the unique solution $\mathbf{y} \in C([0, T], \mathbf{H}) \cap C^1([0, T], \mathbf{V}')$ of

$$(2.1) \quad \begin{cases} y_1'' - (y_{1,1} + cy_3)_{,1} = 0, & (\xi, t) \in q_T \\ y_3'' + c(y_{1,1} + cy_3) = 0, & (\xi, t) \in q_T \\ y_1(0, t) = 0, \quad y_1(1, t) = v(t), & t \in (0, T) \\ (\mathbf{y}(\xi, 0), \mathbf{y}'(\xi, 0)) = (\mathbf{y}^0, \mathbf{y}^1), & \xi \in \omega, \end{cases}$$

satisfies $(\mathbf{y}(\cdot, T), \mathbf{y}'(\cdot, T)) = (\mathbf{y}_T^0, \mathbf{y}_T^1)$ in ω . In (2.1), $y_{1,1}(\xi, t)$ stands for $\partial y_1(\xi, t)/\partial \xi$.

We also consider a weaker (relaxed) version which consists, under the same hypothesis, to find a control $v \in L^2(\Sigma_T)$ such that simply $(y_1(T), y_1'(T)) = (y_{T,1}^0, y_{T,1}^1)$: this is the so-called *partial controllability* of system (2.1). In both cases, since y_3 belongs only to $L^2(\omega)$, there is one (boundary) control v for the two components of \mathbf{y} . (2.1) models the control of an elastic arch of length one and curvature c . The map $\varphi : \bar{\omega} \rightarrow \mathbb{R}^2$ which describes the circular line of length one

and curvature c is $\varphi(\xi) = (c^{-1} \sin(c\xi), c^{-1} \cos(c\xi))$. $\xi \in \omega$ is the curvilinear abscissae. We refer to [22] for details on the geometrical description.

2.1. Spectral property of the homogeneous system. The homogeneous adjoint problem associated with (2.1) is as follows: for any $(\phi^0, \phi^1) \in \mathbf{V} \times \mathbf{H}$, find the solution ϕ of

$$(2.2) \quad \begin{cases} \phi'' + \mathbf{A}_M \phi = \mathbf{0}, & (\xi, t) \in q_T \\ \phi_1(0, \cdot) = \phi_1(1, \cdot) = 0, & t \in (0, T) \\ (\phi(\xi, 0), \phi'(\xi, 0)) = (\phi^0, \phi^1), & \xi \in \omega. \end{cases}$$

Introducing the bilinear and symmetric form $b_M(\phi, \mathbf{v}) = (\phi_{1,1} + c\phi_3)(v_{1,1} + cv_3)$, integrations by part then lead to the relation $\int_{\omega} \mathbf{A}_M \phi \cdot \mathbf{v} d\xi = \int_{\omega} b_M(\phi, \mathbf{v}) d\xi - [(\phi_{1,1} + c\phi_3)v_1]_0^1$ for all $\phi \in \mathbf{V}$ and all $\mathbf{v} \in H^1(\omega) \times L^2(\omega)$. Then, from the Lions-Magenes theory [19] we have the following result.

Proposition 2.1. *For all $(\phi^0, \phi^1) \in \mathbf{V} \times \mathbf{H}$, there exists a unique weak solution $\phi \in C(0, T; \mathbf{V}) \cap C^1(0, T; \mathbf{H})$ that satisfies the variational problem*

$$\int_{\omega} \phi'' \cdot \mathbf{v} d\xi + \int_{\omega} b_M(\phi, \mathbf{v}) d\xi = 0, \quad \forall \phi \in \mathbf{V}.$$

Moreover, the mapping $(\phi^0, \phi^1) \rightarrow (\phi(t), \phi'(t))$ is continuous : there exists a constant $C > 0$ such that $|\phi(t)|_{\mathbf{V}}^2 + |\phi'(t)|_{\mathbf{H}}^2 \leq C(|\phi^0|_{\mathbf{V}}^2 + |\phi^1|_{\mathbf{H}}^2)$, for all $t \in (0, T)$.

The natural energy E of the arch, denoted by $E(t, \phi) = \frac{1}{2} \int_{\omega} (|\phi'|^2 + b_M(\phi, \phi)) d\xi$, $t \in (0, T)$, is constant along all the trajectories, that is, $E(t, \phi) = E_0 = \frac{1}{2} \int_{\omega} (|\phi^1|^2 + b_M(\phi^0, \phi^0)) d\xi$, for all $(\phi^0, \phi^1) \in \mathbf{V} \times \mathbf{H}$ and $t > 0$.

A simple computation gives that the eigenvalues of

$$\mathbf{A}_M \psi = \lambda \psi, \quad \xi \in \omega, \quad \psi_1 = 0, \quad \xi \in \partial\omega$$

are $\sigma(\mathbf{A}_M) = \{0, \lambda_k = c^2 + (k\pi)^2, k \geq 0\}$. Since

$$\text{Ker } \mathbf{A}_M = \{v_{\zeta} = (-c\zeta, \zeta_1) \in \mathbf{H}, \zeta \in H_0^1(\omega)\}$$

and the eigenfunctions associated with λ_0 and λ_k , $k > 0$ are respectively :

$$\mathbf{v}_0 = (0, 1), \quad \mathbf{v}_k = \left(\sin(k\pi\zeta), \frac{c}{k\pi} \cos(k\pi\zeta) \right),$$

one deduces that the essential spectrum $\sigma_{ess}(\mathbf{A}_M) = 0$. Let us also remark that an orthogonal basis in \mathbf{H} of $\text{Ker } \mathbf{A}_M$ is

$$\mathbf{w}_k = \left(-\frac{c}{k\pi} \sin(k\pi\zeta), \cos(k\pi\zeta) \right), \quad k \geq 1$$

and that $\{\mathbf{w}_k, \mathbf{v}_0, \mathbf{v}_k\}$ is an orthogonal basis in \mathbf{H} . This permits to expand the weak solution of the system (2.2) in term of a Fourier serie as follows, setting $\mu_k = \sqrt{\lambda_k}$, $k \geq 0$:

$$(2.3) \quad \phi(\cdot, t) = \sum_{k \geq 1} (a_k + b_k t) \mathbf{w}_k + (A_0 \cos(\mu_0 t) + B_0 \sin(\mu_0 t)) \mathbf{v}_0 + \sum_{k \geq 1} (A_k \cos(\mu_k t) + B_k \sin(\mu_k t)) \mathbf{v}_k$$

where the coefficients $a_k, b_k, A_0, B_0, A_k, B_k$ are determined from the expansion of the initial data:

$$\phi^0 = \sum_{k \geq 1} a_k \mathbf{w}_k + A_0 \mathbf{v}_0 + \sum_{k \geq 1} A_k \mathbf{v}_k, \quad \phi^1 = \sum_{k \geq 1} b_k \mathbf{w}_k + \mu_0 B_0 \mathbf{v}_0 + \sum_{k \geq 1} \mu_k B_k \mathbf{v}_k.$$

The assumption $(\phi^0, \phi^1) \in \mathbf{V} \times \mathbf{H}$ implies that

$$\sum_{k \geq 1} (a_k^2 + A_k^2) < \infty, \quad \sum_{k \geq 1} (ca_k + k\pi A_k)^2 < \infty, \quad \sum_{k \geq 1} (b_k^2 + \lambda B_k^2) < \infty.$$

Observe that if $\phi^0, \phi^1 \in \text{Ker } \mathbf{A}_M$ then $\phi(\cdot, t) \in \text{Ker } \mathbf{A}_M$. Similarly, if $\phi^0 \in \text{Ker } \mathbf{A}_M$ and $\phi^1 = \mathbf{0}$, then $\phi(\cdot, t) = \phi^0$ for all $t > 0$.

We now introduce the orthogonal of the subspace $\text{Ker } \mathbf{A}_M$ in \mathbf{H} :

$$\mathbf{H}^{\perp} = \left\{ \psi = (\psi_1, \psi_3) \in \mathbf{H}, \int_{\omega} (\psi_1 \phi_1 + \psi_3 \phi_3) d\xi = 0, \forall (\phi_1, \phi_3) \in \text{Ker } \mathbf{A}_M \right\}.$$

From the definition of $\text{Ker } \mathbf{A}_M$, we get that $\mathbf{H}^\perp = \{(\psi_1, \psi_3) \in \mathbf{H}, c\psi_1 + \psi_{3,1} = 0 \text{ in } H^{-1}(\omega)\}$ and then

$$(2.4) \quad \mathbf{H}^\perp = \{\mathbf{v} = (\psi_{,1}, -c\psi) \in \mathbf{H}, \psi \in H^1(\omega)\}.$$

The subspace \mathbf{H}^\perp is generated by \mathbf{v}_k , $k \geq 0$. We denote with \mathbf{V}^\perp the orthogonal in \mathbf{V} of $\text{Ker } \mathbf{A}_M$; it is also generated, in \mathbf{V} , by \mathbf{v}_k , $k \geq 0$. At last, let us remark that the energy $E(t, \phi) = E(0, \phi)$ defines a norm over $\mathbf{V}^\perp \times \mathbf{H}^\perp$. Moreover, if $(\phi^0, \phi^1) \in \mathbf{V}^\perp \times \mathbf{H}^\perp$ then $\phi(\cdot, t) \in \mathbf{V}^\perp$ for all t .

2.2. Observability inequality and controllability results. From standard dual arguments [18], the control property of (2.1) is related to the existence of two constants $C_1, C_2 > 0$ such that, for $T > 0$ large enough, the solution of (2.2) satisfies

$$C_1 \|(\phi^0, \phi^1)\|_{\mathbf{V} \times \mathbf{H}}^2 \leq \int_0^T b_M(\phi, \phi)(1, t) dt \leq C_2 \|(\phi^0, \phi^1)\|_{\mathbf{V} \times \mathbf{H}}^2 \quad \forall (\phi^0, \phi^1) \in \mathbf{V} \times \mathbf{H}.$$

Since $0 \in \sigma(\mathbf{A}_M)$, the left inequality (called the observability inequality) can not hold for all $(\phi^0, \phi^1) \in \mathbf{V} \times \mathbf{H}$. It suffices to take $\phi^0, \phi^1 \in \text{Ker } \mathbf{A}_M$ so that $b_M(\phi, \phi) = 0$ for all $t > 0$. We have the following result.

Proposition 2.2. *Let $c > 0$, $\gamma^*(c) = \min(2c, \sqrt{c^2 + \pi^2} - c)$. For all $T > T^*(c) \equiv 2\pi/\gamma^*(c)$, there exist two strictly positive constants $C_1(c)$ and $C_2(c)$ such that*

$$(2.5) \quad C_1(c) \|(\phi^0, \phi^1)\|_{\mathbf{V} \times \mathbf{H}}^2 \leq \int_0^T (\phi_{1,1}(1, t) + c\phi_3(1, t))^2 dt \leq C_2(c) \|(\phi^0, \phi^1)\|_{\mathbf{V} \times \mathbf{H}}^2$$

for all $(\phi^0, \phi^1) \in \mathbf{V}^\perp \times \mathbf{H}^\perp$.

Relation (2.5) is equivalent to the existence of two positive constants C_1, C_2 such that

$$(2.6) \quad C_1(c) E_0(\phi) \leq \int_0^T (\phi_{1,1} + c\phi_3)^2(1, t) dt \leq C_2(c) E_0(\phi), \quad \forall (\phi^0, \phi^1) \in \mathbf{V}^\perp \times \mathbf{H}^\perp.$$

These inequalities may be obtained from a direct application of the following Ingham's theorem on Nonharmonic series (see [16] for recent developments) :

Theorem 2.3. *Let $K \in \mathbb{Z}$ and $(w_k)_{k \in K}$ be a family of real numbers satisfying the uniform gap condition $\gamma = \inf_{k \neq n} |w_k - w_n| > 0$. If I is a bounded interval of length $|I| > 2\pi/\gamma$, then there exist two positives constants C_1, C_2 such that*

$$C_1 \sum_{k \in K} |x_k|^2 \leq \int_I |x(t)|^2 dt \leq C_2 \sum_{k \in K} |x_k|^2$$

for all functions given by the sum $x(t) = \sum_{k \in K} x_k e^{i w_k t}$ with square-summable complex coefficients x_k .

Proof of Proposition 2.2. One finds $E(0, \phi) = \frac{c^2}{2}(A_0^2 + B_0^2) + \frac{1}{2} \sum_{k=1}^{\infty} \lambda_k (A_k^2 + B_k^2)$. On the other hand, one has

$$\begin{aligned} (\phi_{1,1} + c\phi_3)(1, t) &= c(A_0 \cos(\mu_0 t) + B_0 \sin(\mu_0 t)) + \sum_{k \geq 1} (-1)^k \frac{\mu_k^2}{k\pi} (A_k \cos(\mu_k t) + B_k \sin(\mu_k t)) \\ &= \frac{1}{2} \sum_{k \geq 1} (-1)^k \frac{\mu_k^2}{k\pi} (A_k + iB_k) e^{-i\mu_k t} + \frac{c}{2} (A_0 + iB_0) e^{-i\mu_0 t} \\ &\quad + \frac{c}{2} (A_0 - iB_0) e^{i\mu_0 t} + \frac{1}{2} \sum_{k \geq 1} (-1)^k \frac{\mu_k^2}{k\pi} (A_k - iB_k) e^{i\mu_k t} \end{aligned}$$

so that $\phi_{1,1}(1, t) + c\phi_3(1, t) = \sum_{k \in \mathbb{Z}, k \neq 0} x_k e^{i\Lambda_k t}$ with

$$\Lambda_k = \begin{cases} -\mu_{-(k+1)} & \text{for } k < -1 \\ -\mu_0 & \text{for } k = -1 \\ \mu_0 & \text{for } k = 1 \\ \mu_{k-1} & \text{for } k > 1 \end{cases}$$

and

$$x_k = \begin{cases} \frac{1}{2}(-1)^{-(k+1)} \frac{\mu_{-(k+1)}^2}{-(k+1)\pi} (A_{-(k+1)} + iB_{-(k+1)}) & \text{for } k < -1 \\ \frac{c}{2}(A_0 + iB_0) & \text{for } k = -1 \\ \frac{c}{2}(A_0 - iB_0) & \text{for } k = 1 \\ \frac{1}{2}(-1)^{(k-1)} \frac{\mu_{(k-1)}^2}{(k-1)\pi} (A_{(k-1)} - iB_{(k-1)}) & \text{for } k > 1. \end{cases}$$

We then apply Theorem 2.3 with $I = (0, T)$, $K = \mathbb{Z} \setminus \{0\}$ and the sequence $(w_k)_k = (\Lambda_k)_k = (\dots, -\mu_2, -\mu_1, -\mu_0, \mu_0, \mu_1, \mu_2, \dots)$ to obtain that there exist two positives constants $C_1(c)$ and $C_2(c)$ such that (2.6) holds for all $r > 0$, under the condition $T > 2\pi/\gamma$ with $\gamma = \min(\mu_0 - (-\mu_0), \inf_{k \in \mathbb{N}} |\mu_k - \mu_{k-1}|)$. From the concavity of the square root function, we deduce that $|\mu_1 - \mu_0| \leq |\mu_{k+1} - \mu_k|$ for all $k \geq 0$ leading to T^* defined in Proposition 2.2.

The lower bound value T^* of controllability may be precised as follows

$$T^*(c) = \frac{\pi}{c} \mathcal{X}_{(c \leq \pi/\sqrt{8})} + \frac{2\pi}{\sqrt{c^2 + \pi^2} - c} \mathcal{X}_{(c > \pi/\sqrt{8})}$$

and reaches its minimum when $c = \pi/\sqrt{8}$ for which $T^*(c) = \sqrt{8}$. We observe that the minimal time of controllability T^* goes to infinity, almost linearly, as c goes to infinity. Remark that in practice, c is not greater than 2π for which the arch is a closed circle. Moreover, the time of controllability blows up as the curvature c of the arch goes to zero. This is due to the eigenvalue λ_0 which vanishes with c . Therefore, one can not expect a uniform convergence of the control with respect to c . Precisely, if the initial condition is $(\phi^0, \phi^1) = (v_0, \mu_0 v_0)$ so that $\phi_{1,1}(1, t) + c\phi_3(1, t) = c(A_0 \cos(\mu_0 t) + B_0, \sin(\mu_0 t))$ we obtain explicitly

$$\begin{aligned} \int_0^T (\phi_{1,1} + c\phi_3)^2(1, t) dt &= \mu_0^2 \left(A_0^2 \frac{\cos(\mu_0 T) \sin(\mu_0 T) + \mu_0 T}{2\mu_0} \right. \\ &\quad \left. + B_0^2 \frac{\mu_0 T - \cos(\mu_0 T) \sin(\mu_0 T)}{2\mu_0} + A_0 B_0 \frac{\sin^2(\mu_0 T)}{\mu_0} \right) \\ &= \mu_0^2 \left(A_0^2 \left[T + O(\mu_0^2) \right] + B_0^2 \left[\frac{T^3}{3} \mu_0^2 + O(\mu_0^4) \right] + A_0 B_0 \left[T^2 \mu_0 + O(\mu_0^3) \right] \right) \end{aligned}$$

and $E_0(\phi) = \mu_0^2(A_0^2 + B_0^2)/2$, so that

$$2 \min\left(T, \frac{T^3}{3} c^2\right) E_0(\phi) \leq \int_0^T (\phi_{1,1} + c\phi_3)^2(1, t) dt \leq 2 \max\left(T, \frac{T^3}{3} c^2\right) E_0(\phi).$$

The constant $C_1(c)$ goes to zero as c goes to zero unless $T = \mathcal{O}(c^{-1})$. Consequently, the observability inequality is not uniform with respect to c for an arbitrarily shallow arch. The observability is uniform if and only if $B_0 = 0$, i.e. in this case if $\phi_3^1 = 0$.

If we denote by \mathbf{H}_K , resp. \mathbf{V}_K , the closed subspace of \mathbf{H} , resp. \mathbf{V} , generated by v_k , for all $k \geq 1$, we have the following result.

Proposition 2.4. *Let $c > 0$ and $\gamma^{**}(c) = \sqrt{c^2 + 4\pi^2} - \sqrt{c^2 + \pi^2}$. For all $T > T^{**}(c) \equiv 2\pi/\gamma^{**}(c)$, there exist two positive constants C_1, C_2 independent of c such that (2.5) holds for all $(\phi^0, \phi^1) \in \mathbf{V}_K \times \mathbf{H}_K$.*

The lower bound T^{**} is now a monotonous increasing function of c such that $\lim_{c \rightarrow 0} T^{**}(c) = 2$, lower bound for the wave equation controlled at one extremity. We also have that $2 < T^{**}(c) < T^*(c)$ for all $c > 0$.

We are now in a position to give the corresponding controllability results assuming, without loss of generality since the problem is linear, that the target is zero, i.e. $(y_T^0, y_T^1) = (0, 0)$. Integrations by part provide that v is a control for the system (2.1) if and only if

$$(2.7) \quad \int_0^T (\phi_{1,1} + c\phi_3)(1, t) v(t) dt = \langle (\phi^0, \phi^1), (y^1, -y^0) \rangle_{\mathbf{V} \times \mathbf{H}, \mathbf{V}' \times \mathbf{H}}.$$

with $\langle (\phi^0, \phi^1), (\mathbf{y}^1, -\mathbf{y}^0) \rangle_{\mathbf{V} \times \mathbf{H}, \mathbf{V}' \times \mathbf{H}} := \langle \phi^0, \mathbf{y}^1 \rangle_{\mathbf{V}, \mathbf{V}'} - \langle \phi^1, \mathbf{y}^0 \rangle_{\mathbf{H}, \mathbf{H}}$.

We then introduce the continuous and convex functional $\mathcal{J} : \mathbf{V} \times \mathbf{H} \rightarrow \mathbb{R}$ defined by

$$(2.8) \quad \mathcal{J}(\phi^0, \phi^1) = \frac{1}{2} \int_0^T (\phi_{1,1} + c\phi_3)^2(1, t) dt - \langle (\phi^0, \phi^1), (\mathbf{y}^1, -\mathbf{y}^0) \rangle_{\mathbf{V} \times \mathbf{H}, \mathbf{V}' \times \mathbf{H}}.$$

If \mathcal{J} is coercive, then \mathcal{J} admits a unique minimum and the control of minimal L^2 -norm is given by $v(t) = (\phi_{1,1} + c\phi_3)(1, t)$, for all $t \in (0, T)$. Remark first that \mathcal{J} is only coercive in $\mathbf{V}^\perp \times \mathbf{H}^\perp$ for $T > T^*(c)$. Furthermore, if $(\mathbf{y}^0, \mathbf{y}^1)$ belongs to $\text{Ker} \mathbf{A}_M$, then

$$\langle (\phi^0, \phi^1), (\mathbf{y}^1, -\mathbf{y}^0) \rangle_{\mathbf{V} \times \mathbf{H}, \mathbf{V}' \times \mathbf{H}} = 0, \quad \forall (\phi^0, \phi^1) \in \mathbf{V}^\perp \times \mathbf{H}^\perp$$

and from the characterization (2.7), the control is zero; in this case, the solution \mathbf{y} remains in $\text{Ker} \mathbf{A}_M$ for all $t > 0$ but is not controlled! Hence, we consider \mathbf{y}^0 , resp. \mathbf{y}^1 in a dual of \mathbf{H}^\perp , resp. \mathbf{V}^\perp . Precisely, we take $\mathbf{y}^0 \in \mathbf{H}^\perp$ and $\mathbf{y}^1 \in \mathbf{V}^{\perp'}$ where $\mathbf{V}^{\perp'} \subset \mathbf{V}'$ is the orthogonal of $\text{Ker} \mathbf{A}_M$ in the duality $\langle \cdot, \cdot \rangle_{\mathbf{V}, \mathbf{V}'}$. Let us explicit remark that $\mathbf{V}^{\perp'}$ is the closure of \mathbf{V}^\perp in \mathbf{V}' . We have, as a consequence of Proposition 2.2

Theorem 2.5. *Let $c > 0$. For any $T > T^*(c)$ and any initial data $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H}^\perp \times \mathbf{V}^{\perp'}$, there exists a control function $v \in L^2(0, T)$ which drives to rest at time T the solution \mathbf{y} of (2.1) associated with $(\mathbf{y}^0, \mathbf{y}^1)$. Moreover, the control of minimal L^2 -norm is given by $v = (\phi_{1,1} + c\phi_3)(1, \cdot)$ where ϕ is solution of (2.2) and associated with (ϕ^0, ϕ^1) minimum of \mathcal{J} defined by (2.8) over $\mathbf{V}^\perp \times \mathbf{H}^\perp$.*

Remark 2.6. *The non controllable modes $\mathbf{w}_k \in \text{Ker} \mathbf{A}_M$, $k \geq 1$, do not correspond to modes of arbitrarily small energy. Precisely, for $(\mathbf{y}^0, \mathbf{y}^1) = \sum_{k \geq 1} (a_k, b_k) \mathbf{w}_k$, the norm of the solution at time $t = T$ is (since the control v has no effect on \mathbf{w}_k)*

$$\|\mathbf{y}(T)\|_{\mathbf{V}}^2 = \sum_{k \geq 1} (a_k + b_k T)^2 \left(c^2 + \frac{\lambda_k}{(k\pi)^2} \right), \quad \|\mathbf{y}'(T)\|_{\mathbf{H}}^2 = \frac{1}{2} \sum_{k \geq 1} b_k^2 \frac{\lambda_k}{(k\pi)^2}$$

and different from zero. Consequently, approximate controllability for the system (2.1) does not hold anymore.

Let us note \mathbf{V}'_K the closure of \mathbf{V}_K in \mathbf{V}' . As a consequence of Proposition 2.4, we have :

Theorem 2.7. *Let $c > 0$. For any $T > T^{**}(c)$ and any initial data $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H}_K \times \mathbf{V}'_K$, there exists a control function $v \in L^2(0, T)$ which drives to rest at time T the solution \mathbf{y} of (2.1) associated with $(\mathbf{y}^0, \mathbf{y}^1)$. Moreover, the control of minimal L^2 -norm is given by $v = (\phi_{1,1} + c\phi_3)(1, \cdot)$ where ϕ is solution of (2.2) and associated with (ϕ^0, ϕ^1) minimum of \mathcal{J} defined by (2.8) over $\mathbf{V}_K \times \mathbf{H}_K$. Finally, this control converges weakly in $L^2(0, T)$ as c goes to zero toward the control of minimal L^2 -norm which drives to rest the solution \bar{y} of the wave equation: $\bar{y}'' - \bar{y}_{,11} = 0$ in q_T , $(\bar{y}(\xi, 0), \bar{y}'(\xi, 0)) = (y_1^0, y_1^1)$.*

As $c \rightarrow 0$, the state equation of (2.1) degenerates into two uncoupled equations : the wave equation $y_1'' - y_{1,11} = 0$ controlled by v and $y_3'' = 0$. The uniform controllability holds here, because, as $c \rightarrow 0$, the initial condition $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H}_K \times \mathbf{V}'_K$ degenerates into $((y_1^0, 0), (y_1^1, 0))$, so that at the limit the component y_3 solution of the Cauchy problem $y_3''(\xi, t) = 0$, $t > 0$, $(y_3(\xi, 0), y_3'(\xi, 0)) = (0, 0)$ vanishes.

Remark 2.8. *Another natural control for (2.1) consists in acting on the longitudinal strain $y_{1,1} + cy_3$ of the arch. Thus, in the case $v(t) = (y_{1,1} + cy_3)(1, t)$ (corresponding to a Neuman control), we get similar controllability results. In particular, $\sigma(\mathbf{A}_M) = \{0, \lambda_k, k \geq 1\}$ with $0 \in \sigma_{ess}(\mathbf{A}_M)$ (we recall that the essential spectrum does not depend on the boundary condition).*

2.3. Uniform partial controllability. We now emphasize that the partial controllability do hold uniformly with respect to the data. For any $T > 0$ large enough, $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H} \times \mathbf{V}'$, (y_0^T, y_1^T) in $L^2(\omega) \times H^{-1}(\omega)$, we study the existence of a control function $v \in L^2(0, T)$ such that the tangential displacement y_1 of (2.1) satisfies the condition

$$(2.9) \quad (y_1(\cdot, T), y_1'(\cdot, T)) = (y_T^0, y_T^1) \quad \text{in } \omega.$$

We want to control only y_1 , the normal component y_3 being free. We refer to [17] for a similar - but different - treatment in a case where $\sigma_{ess}(\mathbf{A}_M) \in \mathbb{R}_+^*$. Eliminating the variable y_3 , one may reformulate the problem; y_3 solution of the ordinary differential equation $y_3'' + c^2 y_3 = -c y_{1,1}$ takes the expression

$$(2.10) \quad y_3(\xi, t) = y_3^0(\xi) \cos(ct) + \frac{y_3^1(\xi)}{c} \sin(ct) - \int_0^t \sin(c(t-u)) y_{1,1}(\xi, u) du.$$

Assuming to simplify the notation that $y_3^0 = y_3^1 = 0$ in ω , and reporting (2.10) in the first equation of (2.1), we obtain that y_1 is solution of the following integro-differential equation

$$(2.11) \quad y_1''(\xi, t) - y_{1,11}(\xi, t) + c \int_0^t \sin(c(t-u)) y_{1,11}(\xi, u) du = 0, \quad (\xi, t) \in q_T$$

submitted to the boundary and initial condition

$$(2.12) \quad y_1(0, t) = 0, \quad y_1(1, t) = v(t), \quad t \in (0, T), \quad (y_1(\cdot, 0), y_1'(\cdot, 0)) = (y_1^0, y_1^1) \quad \xi \in \omega.$$

For any $v \in L^2(0, T)$, the well-posedness of the problem (2.11-2.12) is a consequence of the well-posedness of the full system considered in the previous section. This system, not reversible in time, is reminiscent of systems with memory ([18], tome 2, chapter 7). The crucial difference is the presence of an essential spectrum.

We consider the homogeneous adjoint problem

$$(2.13) \quad \begin{cases} z''(\xi, t) - z_{,11}(\xi, t) + c \int_t^T \sin(c(u-t)) z_{,11}(\xi, u) du = 0, & (\xi, t) \in q_T \\ z(0, t) = z(1, t) = 0, & t \in (0, T) \\ (z(\cdot, T), z'(\cdot, T)) = (z^0, z^1), & \xi \in \omega \end{cases}$$

and put

$$G_z^*(\xi, t) = \int_t^T \sin(c(u-t)) z(\xi, u) du.$$

Then, proceeding as the previous section, the controls are formally characterized by the following equality

$$(2.14) \quad \int_0^1 [y_1'(\cdot, T) z(\cdot, T) - y_1(\cdot, T) z'(\cdot, T)] d\xi + \int_0^T v(t) \left(z_{,1}(1, t) - c G_{z_{,1}}^*(1, t) \right) dt = 0.$$

Defining the application $\mu : H_1^0(\omega) \times L^2(\omega) \rightarrow H^{-1}(\omega) \times L^2(\omega)$, $\mu\{z^0, z^1\} = \{y_1^1, -y_1^0\}$, (2.14) is equivalent to

$$\langle \mu\{z^0, z^1\}, \{z^0, z^1\} \rangle_{(H^{-1} \times L^2), (H_0^1 \times L^2)} = \int_0^T y(1, t) \left(z_{,1,1}(1, t) - c G_{z_{,1,1}}^*(1, t) \right) dt$$

and the controllability problem is reduced to the injectivity of the application μ , i.e. the existence of $C > 0$ such that

$$\|(z^0, z^1)\|_{H_0^1 \times L^2}^2 \leq C \int_0^T (z_{,1}(1, t) - c G_{z_{,1}}^*(1, t))^2 dt, \quad \forall (z^0, z^1) \in H_0^1(\omega) \times L^2(\omega).$$

If this inequality holds, the control of minimal L^2 -norm is given by

$$v(t) = z_{,1}(1, t) - c G_{z_{,1}}^*(1, t), \quad t \in (0, T).$$

Once again, this question may be addressed via a spectral analysis. Since $z \in C([0, T]; H_0^1(\omega))$, we assume that the solution z of the adjoint problem (2.13) can be written as

$$z(\xi, t) = \sum_{k \geq 1} f_k(t) \sin(k\pi\xi)$$

with $(z(\xi, T), z'(\xi, T)) = (z^0(\xi), z^1(\xi)) = \sum_{k \geq 1} (f_k^T, f_k^{T'}) \sin(k\pi\xi) \in H_0^1(\omega) \times L^2(\omega)$ so that $\sum_{k \geq 0} (k\pi)^2 (f_k^T)^2 < \infty$ and $\sum_{k \geq 0} (f_k^{T'})^2 < \infty$. From (2.13), f_k solves the equation

$$(2.15) \quad f_k''(t) + (k\pi)^2 f_k(t) - c(k\pi)^2 \int_t^T \sin(c(u-t)) f_k(u) du = 0, \quad \forall k \geq 1.$$

Then, derivating twice in time this equality, we get

$$f_k^{(4)}(t) + (k\pi)^2 f_k''(t) + r^{-3}(k\pi)^2 \int_t^T \sin(c(u-t)) f_k(u) du - c^2(k\pi)^2 f_k(t) = 0, \quad k \geq 1$$

and then using (2.15), we eliminate the integral term to obtain the fourth order ODE :

$$f_k^{(4)}(t) + ((k\pi)^2 + c^2) f_k^{(2)}(t) = 0, \quad \forall k \geq 1$$

so that

$$f_k(t) = C_k^{(1)} + C_k^{(2)}(t-T) + C_k^{(3)} \cos(\mu_k(t-T)) + C_k^{(4)} \sin(\mu_k(t-T)), \quad \forall k \geq 1.$$

We recall that $\mu_k = \sqrt{c^2 + (k\pi)^2}$. Reporting this expression in the second order ordinary differential equation (2.15), we obtain that

$$C_k^{(3)} = C_k^{(1)} \frac{(k\pi)^2}{c^2}, \quad C_k^{(4)} = C_k^{(2)} \frac{(k\pi)^2}{c^2 \mu_k}, \quad \forall k \geq 1.$$

Finally, from $f_k(T) = f_k^T$ and $f_k'(T) = f_k^{T'}$, we obtain the following expression

$$f_k(t) = \frac{c^2}{\lambda_k} f_k^T + \frac{c^2}{\lambda_k} f_k^{T'}(t-T) + \frac{(k\pi)^2}{\lambda_k} f_k^T \cos(\mu_k(t-T)) + \frac{(k\pi)^2}{\lambda_k^{3/2}} f_k^{T'} \sin(\mu_k(t-T))$$

and the expression of the adjoint solution

$$(2.16) \quad z(\xi, t) = \sum_{k \geq 1} \left(\frac{c^2}{\lambda_k} f_k^T + \frac{c^2}{\lambda_k} f_k^{T'}(t-T) + \frac{(k\pi)^2}{\lambda_k} f_k^T \cos(\mu_k(t-T)) + \frac{(k\pi)^2}{\lambda_k^{3/2}} f_k^{T'} \sin(\mu_k(t-T)) \right) \sin(k\pi\xi).$$

As in the previous section, the Fourier expansion of the adjoint solution is expressed in terms of two sums: the first one linear in time is associated with the sequence $\{\lambda_k^-\}_{k \geq 0}$, $\lambda_k^- = 0 \in \sigma_{ess}(\mathbf{A}_M)$, for all $k \geq 1$. The second one, periodic and bounded in time, corresponds to the discrete spectrum $\{\lambda_k^+\}_{k \geq 1} = \{\lambda_k\}_{k \geq 1}$. The fundamental difference here, with respect to the expansion (2.3), comes from the fact that the coefficient of these sums are related each other.

Using (2.16), we now evaluate the quantity $v(t) = z_{,1}(1, t) - cG_{z_{,1}}^*(1, t)$. We have

$$v(t) = \sum_{k \geq 1} (-1)^k (k\pi) \left(f_k(t) - c \int_t^T \sin(c(u-t)) f_k(u) du \right)$$

and from (2.15)

$$(2.17) \quad v(t) = \sum_{k \geq 1} (-1)^{k+1} \frac{f_k''(t)}{(k\pi)} = \sum_{k \geq 1} (-1)^k k\pi \left(f_k^T \cos(\mu_k(t-T)) + \frac{f_k^{T'}}{\mu_k} \sin(\mu_k(t-T)) \right).$$

Therefore

$$\int_0^T v(t)^2 dt = \frac{1}{4} \int_0^T \left(\sum_{k \geq 1} \left[a_k e^{i\mu_k(t-T)} + \overline{a_k} e^{-i\mu_k(t-T)} \right] \right)^2 dt = \frac{1}{4} \int_0^T \left(\sum_{k \geq 1} \left[a_k e^{-i\mu_k s} + \overline{a_k} e^{i\mu_k s} \right] \right)^2 ds$$

with $a_k = (-1)^k (k\pi) (f_k^T - i\mu_k^{-1} f_k^{T'})$ for all $k \geq 1$ and then

$$\int_0^T v(t)^2 dt = \frac{1}{4} \int_0^T \left(\sum_{k \in \mathbb{Z}, k \neq 0} A_k e^{i\Lambda_k s} \right)^2 ds$$

with $(A_k, \Lambda_k) = (\overline{a_k}, \mu_k)$ if $k > 0$ and $(A_k, \Lambda_k) = (\overline{a_{-k}}, -\mu_k)$ if $k < 0$. We then can apply the Ingham type Theorem 2.3 with $K = \mathbb{Z} \setminus \{0\}$ to get the equivalence

$$\int_0^T v(t)^2 dt \approx \sum_{k \in \mathbb{Z}, k \neq 0} |A_k|^2$$

under the condition $T > 2\pi/\gamma$ with $\gamma = \inf_{k, p \in \mathbb{Z}, k \neq p} |\Lambda_p - \Lambda_k|$. We easily obtain that $\gamma = \sqrt{c^2 + 4\pi^2} - \sqrt{c^2 + \pi^2} = \gamma^{**}(c)$ so that $2\pi/\gamma = T^{**}(c)$. Finally, the sum

$$\sum_{k \in \mathbb{Z}} |A_k|^2 = 2 \sum_{k > 0} (k\pi)^2 \left((f_k^T)^2 + \frac{(f_k^{T'})^2}{\lambda_k} \right)$$

is equivalent to the $H_0^1 \times L^2$ norm of the data (z^0, z^1) :

$$\|(z^0, z^1)\|_{H_0^1(\omega) \times L^2(\omega)}^2 \approx \frac{1}{2} \sum_{k \geq 1} \left((k\pi)^2 (f_k^T)^2 + (f_k^{T'})^2 \right)$$

We therefore conclude that the map μ is an isomorphism from $H_0^1(\omega) \times L^2(\omega)$ into $L^2(\omega) \times H^{-1}(\omega)$. Thus, in the partial controllability case, the property holds uniformly with respect to the initial data (y_1^0, y_1^1) and c .

Theorem 2.9. *For any $T > T^{**}(c)$, and any $(y^0, y^1), (y_T^0, y_T^1) \in L^2(\omega) \times H^{-1}(\omega)$, there exists a control function $v \in L^2(0, T)$ which drives the solution (y^0, y^1) to the target (y_T^0, y_T^1) at time T . The control of minimal L^2 -norm is given by*

$$v(t) = z_{1,1}(1, t) - cG_{z_{1,1}}^*(1, t), \quad t \in (0, T)$$

where z is the solution of the adjoint system (2.13) who initial state (z^0, z^1) minimizes the coercive and convex functional $\mathcal{I} : H_0^1(\omega) \times L^2(\omega) \rightarrow \mathbb{R}$:

$$\mathcal{I}(z^0, z^1) = \frac{1}{2} \int_0^T \left(z_{1,1}(1, t) - cG_{z_{1,1}}^*(1, t) \right)^2 dt - \langle (z^0, z^1), (y_T^1, -y_T^0) \rangle_{(H_0^1, L^2) \times (H^{-1}, L^2)}.$$

3. NUMERICAL EXPERIMENTS I

From duality arguments, the determination of controls for (2.1) is reduced to the minimization of the functional \mathcal{J} - defined in (2.8)- over $\mathbf{V}^\perp \times \mathbf{H}^\perp$ (resp. $\mathbf{V}_K \times \mathbf{H}_K$), for any initial data $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H}^\perp \times \mathbf{V}'^\perp$ and $T > T^*(c)$ (resp. $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H}_K \times \mathbf{V}'_K$ and $T > T^{**}(c)$). The minimization provides the control of minimal $L^2(\Sigma_T)$ -norm: indeed, we have

$$\inf_{(\phi^0, \phi^1)} \mathcal{J}(\phi^0, \phi^1) = - \inf_{v \in \mathcal{C}} \frac{1}{2} \|v\|_{L^2(\Sigma_T)}^2$$

with $\mathcal{C} = \{v \in L^2(\Sigma_T), v\text{-null control for system (2.1)}\}$. Since \mathcal{J} is coercive over $\mathbf{V}^\perp \times \mathbf{H}^\perp$, the conjugate gradient algorithm is commonly used in such situation (see [13] and [22] for details). At each iteration, a projection of the descent direction on the orthogonal of $\text{Ker} \mathbf{A}_M$ is needed (in order to enforce that the minimizer belongs to $\mathbf{V}^\perp \times \mathbf{H}^\perp$). Without this projection (which requires a precise characterization of the orthogonal of the kernel), the algorithm do not converge, even when $(\mathbf{y}^0, \mathbf{y}^1) \in \mathbf{H}^\perp \times \mathbf{V}'^\perp$. This is partially due to the high sensibility of controllability with respect to discretization (see [13] chapter 6, [21] and the references therein).

Now, if we start with an initial condition which is not in $\mathbf{V}^\perp \times \mathbf{H}^\perp$, then the residual of the algorithm (provided a careful projection just mentioned) first decreases (the method stabilizes the controllable part) then diverge. Since the Fourier decomposition of the solution is explicitly known here, it is simpler to solve directly the optimal condition associated to \mathcal{J} with respect to the coefficient A_k, B_k of ϕ^0, ϕ^1 expressed as follows:

$$(3.1) \quad (\phi_N^0, \phi_N^1) = (A_0, \mu_0 B_0) \mathbf{v}_0 + \sum_{k=1}^N (A_k, \mu_k B_k) \mathbf{v}_k$$

with $N \in \mathbb{N}$ large enough. This reduces the controllability problem to the inversion of a positive symmetric matrix of order $2N$. Up to the truncation of the Fourier series, this method (used in [10] for hemispherical cap) is exact. The corresponding control permits to stabilize at time T large enough the components of the data $(\mathbf{y}^0, \mathbf{y}^1)$ which are in $\mathbf{H}^\perp \times \mathbf{V}'^\perp$ and leaves uncontrolled the remaining components. If such components are presents, the solution at time T is not stabilized but fulfills the relation $y_{1,1}(\xi, T) + cy_3(\xi, T) = 0$ (i.e. $\mathbf{y}(\cdot, T) \in \text{Ker} \mathbf{A}_M$).

3.1. Non uniform exact controllability. We consider arbitrarily the following initial condition

$$(3.2) \quad \mathbf{y}^0 = \alpha \mathbf{v}_0 + \mathbf{v}_1 \quad \mathbf{y}^1 = \alpha \mu_0 \mathbf{v}_0 + \mu_2 \mathbf{v}_2$$

with $\alpha \in \{0, 1\}$. Note that we consider only low frequencies modes in order to avoid some spurious numerical effect (analyzed in [21] in the case of the wave equation). The control obtained with $\alpha = 1$, $c = \pi/2$ and $T = 3.5 > T^*(c) \approx 3.2552$ is given on Figure 1-left. In order to have a smooth control at time $t = 0$ and at time $t = T$, we impose that the control v is of the form

$v(\xi, t) = \rho(t)(\phi_{1,1}(\xi, t) + c\phi_3(\xi, t))$ where $\rho \in C_c^1([0, T]; [0, 1])$ is a compact support function. We take $\rho(t) = \sin^2(\pi t/T)$. The corresponding energy and kinetic energy are given on Figure 1-right. The controlled and uncontrolled solution \mathbf{y} are depicted on Figure 2 and 3 respectively. The evolution of the arch in the cartesian ¹ plane (O, x_1, x_2) with respect to the time is finally described on Figure 4.

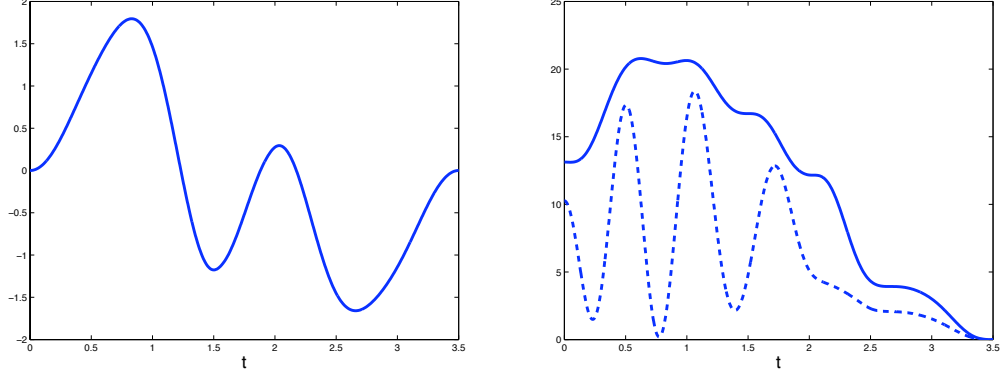


FIGURE 1. **Left:** Control of minimal $L^2(\Sigma_T)$ -norm v vs. $t \in (0, T)$; **Right:** Energy (solid line) and kinetic energy (dashed line) vs. $t \in (0, T)$.

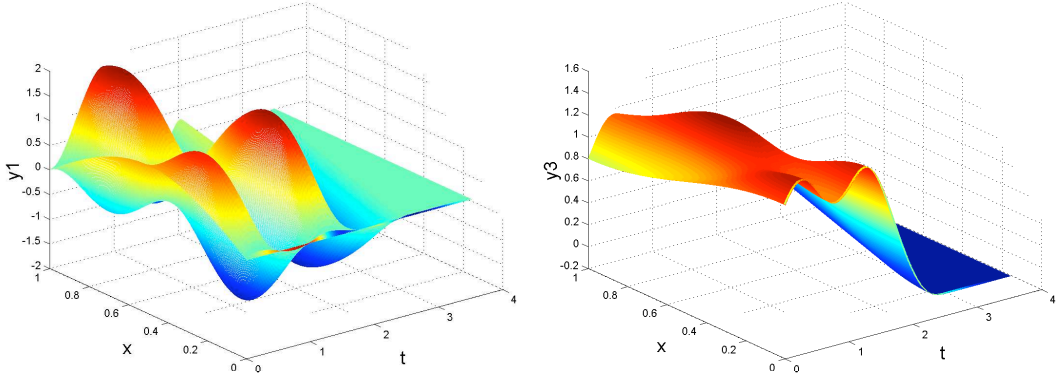


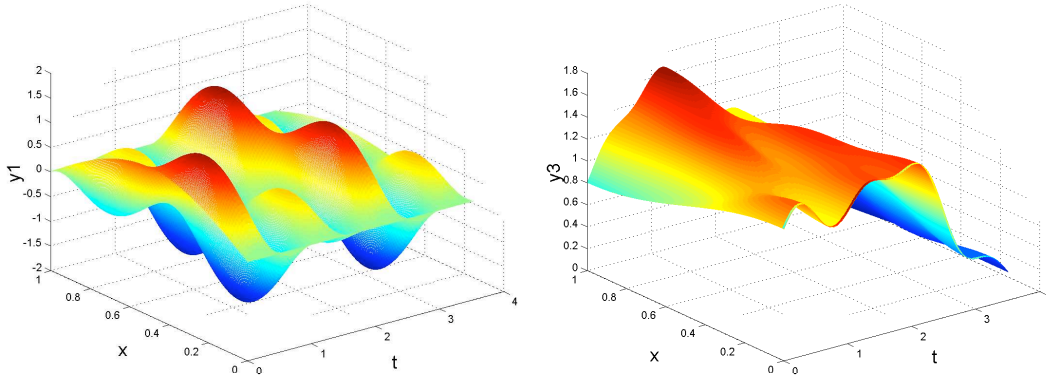
FIGURE 2. Controlled solution $\mathbf{y} = (y_1, y_3)$

Let us now analyze the behavior of the control with respect to c . For $\alpha = 1$, Table 1 gives the value of L^2 -norm of v for several value of c . As expected from the definition of $T^*(c)$, these value suggest that the norm of the control is not uniformly bounded with respect to c . Similarly, the behavior of the ratio $\|v\|_{L^2(0,T)}^2 / \|(\phi^0, \phi^1)\|_{\mathbf{V} \times \mathbf{H}}^2$ of order $O(c^2)$ which appears in the observability constant indicates that the functional \mathcal{J} is not uniformly coercive. On the contrary, when the

	$c = \pi$	$c = \pi/4$	$c = \pi/16$	$c = \pi/64$	$c = \pi/256$
# Iteration	8	8	9	7	8
$\ v\ _{L^2(0,T)}$	1.415	1.601	4.823	15.791	59.220
$E(0)/E(T)$	2.51×10^{-5}	4.47×10^{-7}	3.12×10^{-6}	3.26×10^{-5}	4.49×10^{-4}
$\frac{\ v\ _{L^2(0,T)}^2}{\ (\phi^0, \phi^1)\ _{\mathbf{V} \times \mathbf{H}}^2}$	5.33×10^{-1}	7.95×10^{-2}	1.67×10^{-3}	9.86×10^{-5}	6.18×10^{-6}

TABLE 1. $\alpha = 1$ - Evolution of the L^2 -norm of the control vs. the curvature c .

¹We recall that the displacement \mathbf{Y} in the global cartesian frame $(O, \mathbf{e}_1, \mathbf{e}_2)$ is given by $Y(\mathbf{x}, t) = y_1(\xi, t)\boldsymbol{\tau} + y_3(\xi, t)\boldsymbol{\nu}$ where the tangential and normal vector are defined by $\boldsymbol{\tau} = (\cos(c\xi), -\sin(c\xi))$ and $\boldsymbol{\nu} = (\sin(c\xi), \cos(c\xi))$ (see [5, 22]).


FIGURE 3. Free (uncontrolled) solution $\mathbf{y} = (y_1, y_3)$

constant are eliminated in y_3^0 and y_3^1 (corresponding to $\alpha = 0$ in (3.2)), a uniform behavior with respect to c is recovered in agreement with Theorem 2.7 (see Table 2). Moreover, we then check as c goes to 0, the convergence of v toward the control $v_{c=0}$ associated with the wave equation (see Table 3).

	$c = \pi$	$c = \pi/4$	$c = \pi/16$	$c = \pi/64$	$c = \pi/256$
# Iteration	5	4	4	4	4
$\ v\ _{L^2(0,T)}$	0.823	0.692	0.679	0.678	0.678
$E(0)/E(T)$	1.12×10^{-6}	8.47×10^{-8}	4.28×10^{-6}	2.83×10^{-7}	1.05×10^{-7}
$\frac{\ v\ _{L^2(0,T)}^2}{\ (\phi^0, \phi^1)\ _{V \times H}^2}$	2.019	1.565	1.515	1.5126	1.5124

TABLE 2. $\alpha = 0$ - Evolution of the L^2 -norm of the control vs. the curvature c .

	$c = \pi$	$c = \pi/4$	$c = \pi/16$	$c = \pi/64$	$c = \pi/256$
$\frac{\ v - v_{c=0}\ _{L^2(0,T)}}{\ v_{c=0}\ _{L^2(0,T)}}$	1.679	1.24×10^{-1}	7.87×10^{-3}	5.77×10^{-4}	4.28×10^{-5}

TABLE 3. $\alpha = 0$ - Evolution of $\|v - v_{c=0}\|_{L^2(0,T)}$ vs. the curvature c - $\|v - v_{c=0}\|_{L^2(0,T)} / \|v_{c=0}\|_{L^2(0,T)} \approx O(c^2)$.

We insist on the fact that the practical computation of controls by the standard dual approach is feasible only thank to the precise characterization of the subspace of controllable initial data. For general operator for which the spectrum is in general unknown, such approach is not effective.

3.2. Uniform partial controllability. We now minimize the functional \mathcal{I} defined in Theorem 2.9. Since the controllability is uniform one may use here the conjugate gradient algorithm (without any use of projection). We assume that the initial condition are zero and use as a target for the tangential displacement y_1 , the initial condition in (3.2):

$$(3.3) \quad (y_T^0(\xi), y_T^1(\xi)) = (\sin(\pi\xi), \mu_2 \sin(2\pi\xi)), \quad \xi \in \omega.$$

According to (2.10), the state of y_3 at time $t = T$ is then

$$(3.4) \quad (y_3(\xi, T), y_3'(\xi, T)) = \left(- \int_0^T \sin(c(T-u)) y_{1,1}(\xi, u) du, -c \int_0^T \cos(c(T-u)) y_{1,1}(\xi, u) du \right).$$

From the analysis performed in the previous section, the partial control v is such that both $(y_T^0, y_3(\cdot, T)), (y_T^1, y_3'(\cdot, T))$ belong to $(\text{Ker } \mathbf{A}_M)^\perp$. We take $T = 3.5$ and $c = \pi/2$. Table 4 reports the L^2 -norm of the control with respect to c . We check that the minimal L^2 -norm of the control which drives the solution of (2.1) from $(\mathbf{0}, \mathbf{0})$ to $(y_T^0, y_3(\cdot, T)), (y_T^1, y_3'(\cdot, T))$ is lower than the control which drives the solution from $(\mathbf{y}^0, \mathbf{y}^1)$ to $(\mathbf{0}, \mathbf{0})$. Moreover, as c goes to zero, the limit value is different from the one in Table 2. The corresponding control and energy are

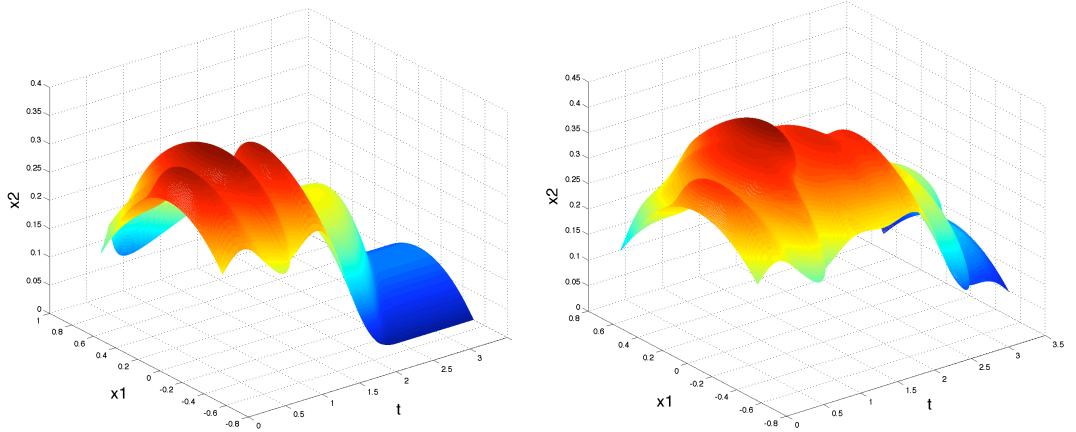


FIGURE 4. Evolution of the controlled (**left**) and uncontrolled (**right**) arch in the plane (O, x_1, x_2) vs. $t \in (0, T)$.

	$c = \pi$	$c = \pi/4$	$c = \pi/16$	$c = \pi/64$	$c = \pi/256$
$\ v\ _{L^2(0,T)}$	7.83×10^{-1}	6.17×10^{-1}	6.08×10^{-1}	6.07×10^{-1}	6.07×10^{-1}

TABLE 4. Evolution of the L^2 -norm of the partial control vs. the curvature c .

depicted on Figure 5. The evolution of the controlled component y_1 is described on Figure 6-Left. We check the simulation by computing the norm $\|y_1(T) - y_T^0\|_{L^2(\omega)} \approx 4.31 \times 10^{-5}$ and that $\|y_1'(T) - y_T^1\|_{H^{-1}(\omega)} \approx 7.32 \times 10^{-4}$ (we remind that, for any $f \in H^{-1}(\omega)$, $\|f\|_{H^{-1}(\omega)} = \|\tilde{f}\|_{H_0^1(\omega)}$ where $\tilde{f} = \tilde{f}(f)$ is the solution of $-\Delta \tilde{f} = f$ in ω , $\tilde{f} = 0$ on $\partial\omega$). The corresponding evolution of the (free) component y_3 is described on Figure 6-Right.

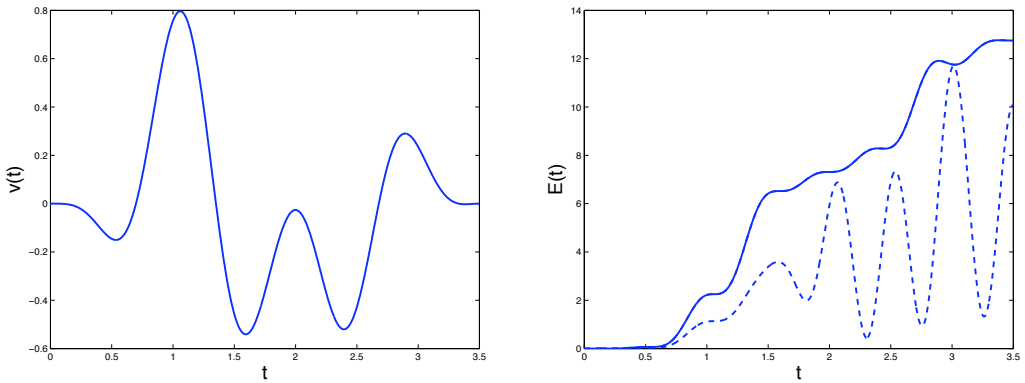


FIGURE 5. **left**: Partial control v vs. $t \in (0, T)$; **right**: Energy (solid line) and kinetic energy (dashed line) vs. $t \in (0, T)$.

4. A VARIATIONAL APPROACH

We now describe an approach which does not make use of the spectral representation of the operator but still allows to approximate exact or partial controls for system (2.1). The main idea of that (variational) method, as introduced in [24], consists in setting up an error functional which measures the deviation of functions from being a solution of the underlying system, and minimizing such error over the class of feasible functions that comply with initial, boundary, and final conditions.

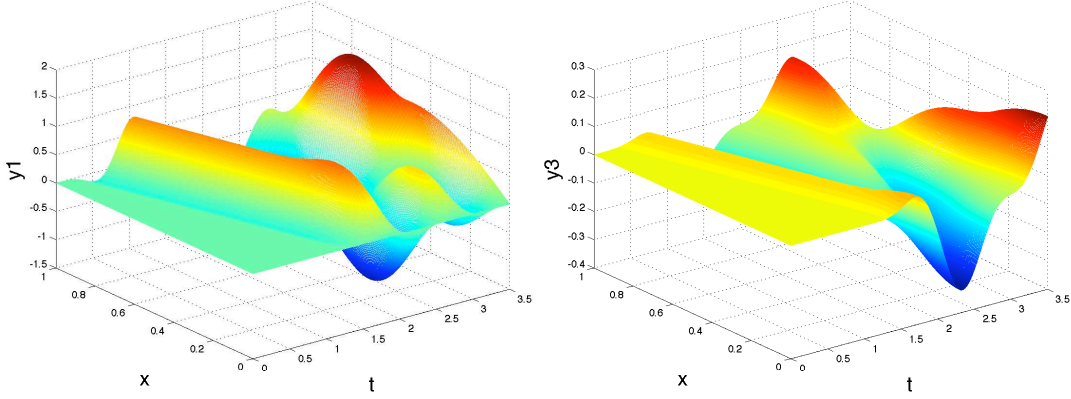


FIGURE 6. Evolution of the controlled component y_1 vs. t (**left**) and corresponding evolution of the component y_3 (**right**), starting from $(\mathbf{0}, \mathbf{0})$.

4.1. **Variational approach.** Consider the convex class of functions

$$(4.1) \quad \mathcal{A} = \left\{ \mathbf{y} \in H^2(0, T; H^1(\omega)) \times H^2(0, T; L^2(\omega)) : (\mathbf{y}(\xi, 0), \mathbf{y}'(\xi, 0)) = (\mathbf{y}^0, \mathbf{y}^1), \right. \\ \left. (\mathbf{y}(\xi, T), \mathbf{y}'(\xi, T)) = (\mathbf{0}, \mathbf{0}), \xi \in \omega, y_1(0, t) = 0, t \in (0, T) \right\}$$

assumed non empty. This requirement simply demands some compatibility with the vanishing boundary data for $\xi = 0$, precisely, $y_1^0(0) = 0$, and that \mathbf{y}^0 , as the trace of an $H^2(H^1)$ function over q_T be slightly more regular than $L^2(\omega)$. For any $\mathbf{y} \in \mathcal{A}$, we define its corrector \mathbf{u} over q_T as the unique solution in $H^1(q_T)$ of the elliptic system

$$(4.2) \quad \begin{cases} -u_1'' - u_{1,11} = -y_1'' + (y_{1,1} + cy_3)_{,1}, & (\xi, t) \in q_T \\ -u_3'' - u_{3,11} + c^2 u_3 = -y_3'' - c(y_{1,1} + cy_3), & (\xi, t) \in q_T \\ \mathbf{u}(0, t) = \mathbf{u}(1, t) = 0, & t \in (0, T) \\ \mathbf{u}'(\xi, 0) = \mathbf{u}'(\xi, T) = 0, & t \in (0, T). \end{cases}$$

Then, we define the following quadratic minimization problem :

$$(4.3) \quad \inf_{\mathbf{y} \in \mathcal{A}} E(\mathbf{y}) = \frac{1}{2} \iint_{q_T} (|\mathbf{u}'|^2 + |\mathbf{u}_{,1}|^2 + c^2 |u_3|^2) d\xi dt$$

where $\mathbf{u} = \mathbf{u}(\mathbf{y})$ is the corrector function associated with \mathbf{y} . It turns that if (and only if) the infimum is attained in \mathcal{A} and is equal to 0, then the corresponding minimizer $\mathbf{y} \in \mathcal{A}$ is a solution of the system (2.1) (since then $\mathbf{u} = \mathbf{0}$). Therefore, such solution \mathbf{y} is a controlled solution of the system and a boundary control v is simply obtained by taking the trace of y_1 at $\xi = 1$: $v(t) = y_1(t), t \in (0, T)$. In that case, the control, as a trace of an $H^2(H^1)$ function is slightly more regular than $L^2(0, T)$.

Therefore, it amounts proving that, first, the infimum of the error E functional is attained, and second, that it vanishes. The first can be proved in a general framework using the quadratic nature of E and the linear dependance of \mathbf{u} with respect to \mathbf{y} (we refer to [23, 24]). The second may be obtained, as we will see, by writing down the optimality conditions of E . Note also that these two points are also the consequence of the controllability property proved in Section 2.2, when the initial data $(\mathbf{y}^0, \mathbf{y}^1)$ to be controlled belongs to the orthogonal of $\text{Ker}(\mathbf{A}_M)$ and are the restriction at $t = 0$ of $H^2(H^1) \times H^2(L^2)$ functions.

Let us turn to optimality. We introduce the set of admissible variations of \mathbf{y} as follows:

$$(4.4) \quad \mathcal{A}_0 = \left\{ \mathbf{Y} \in H^2(0, T; H^1(\omega)) \times H^2(0, T; L^2(\omega)) : (\mathbf{Y}(\xi, 0), \mathbf{Y}'(\xi, 0)) = (\mathbf{0}, \mathbf{0}), (\mathbf{Y}(\xi, T), \right. \\ \left. \mathbf{Y}'(\xi, T)) = (\mathbf{0}, \mathbf{0}), \xi \in \omega, Y_1(0, t) = 0, t \in (0, T) \right\}$$

and then define the variation of $E(\mathbf{y})$, $\mathbf{y} \in \mathcal{A}$ in the direction $\mathbf{Y} \in \mathcal{A}_0$

$$\langle E'(\mathbf{y}), \mathbf{Y} \rangle = \lim_{\eta \rightarrow 0} \frac{E(\mathbf{y} + \eta \mathbf{Y}) - E(\mathbf{y})}{\eta}.$$

We obtain that

$$(4.5) \quad \langle E'(\mathbf{y}), \mathbf{Y} \rangle = \iint_{q_T} (u' \mathbf{U}' + \mathbf{u}_{,1} \mathbf{U}_{,1} + c^2 u_3 U_3) dx dt$$

where $\mathbf{U} \in H_{0,x}^1(q_T)$ is the corrector function associated with $\mathbf{Y} \in \mathcal{A}_0$, that is, the solution of

$$(4.6) \quad \begin{cases} -U_1'' - U_{1,11} = -Y_1'' + (Y_{1,1} + cY_3)_{,1}, & (\xi, t) \in q_T \\ -U_3'' - U_{3,11} + c^2 U_3 = -Y_3'' - c(Y_{1,1} + cY_3), & (\xi, t) \in q_T \\ \mathbf{U}(0, t) = \mathbf{U}(1, t) = 0, & t \in (0, T) \\ \mathbf{U}'(\xi, 0) = \mathbf{U}'(\xi, T) = 0, & t \in (0, T). \end{cases}$$

Multiplying the state equations (4.6) by \mathbf{u} , integrating by parts, and taking into account the boundary conditions on \mathbf{v} and \mathbf{Y} , we transform (4.5) into

$$(4.7) \quad \langle E'(\mathbf{y}), \mathbf{Y} \rangle = - \int_{q_T} \left(\mathbf{Y}'' \mathbf{u} + (Y_{1,1} + cY_3)(u_{1,1} + cu_3) \right) d\xi dt, \forall \mathbf{Y} \in \mathcal{A}_0.$$

Now, let us assume that $\mathbf{y} \in \mathcal{A}$ is a minimizer for E , so that $\langle E'(\mathbf{y}), \mathbf{Y} \rangle = 0$ for all $\mathbf{Y} \in \mathcal{A}_0$. This equality implies that \mathbf{u} satisfies the equation

$$(4.8) \quad \begin{cases} u_1'' - (u_{1,1} + cu_3)_{,1} = 0, & (\xi, t) \in q_T \\ u_3'' + c(u_{1,1} + cu_3) = 0, & (\xi, t) \in q_T \\ u_{1,1} + cu_3 = 0, & (\xi, t) \in \Sigma_T, \end{cases}$$

in addition to the boundary conditions $\mathbf{u}(0, t) = \mathbf{u}(1, t) = 0$ for $t \in (0, T)$ and $\mathbf{u}'(\xi, 0) = \mathbf{u}'(\xi, T) = 0$ for $\xi \in (0, 1)$. For $T > T^*(c)$, this implies that $\mathbf{u} = 0$ in q_T , as a consequence of Proposition 2.2. Notice that this argument, within the framework of Proposition 2.2, implies that critical points of E can only occur at zero error.

We insist on the fact that this approach relies on minimization of the error functional, and does not make use of duality argument nor introduce any dual variable. We also emphasize that this approach is reminiscent of least square type method introduced to solve non linear system (see [?], ch. 7).

Remark 4.1. *There are many ways to define the corrector \mathbf{u} . One may for instance, replace the state equation of (4.2) by*

$$(4.9) \quad \begin{cases} y_1'' - u_1'' - (y_{1,1} + u_{1,1} + cy_3)_{,1} = 0 & (\xi, t) \in q_T \\ y_3'' - u_3'' + c(y_{1,1} + cy_3 + cu_3) = 0 & (\xi, t) \in q_T \\ u_1(0, t) = u_1(1, t) = 0, & t \in (0, T), \\ u'(\xi, 0) = u'(\xi, T) = 0, & \xi \in \omega \end{cases}$$

The procedure is the same, with now $\mathbf{u} \in H^1(q_T) \times H^1(0, T; L^2(\omega))$, u_3 being simply solution of an ODE of second order in time.

Remark 4.2. *The partial controllability considered in Section 2.3 may be addressed in a similar way. It suffices to relax the conditions on y_3 at time T in \mathcal{A} and work with:*

$$(4.10) \quad \mathcal{A}_p = \left\{ \mathbf{y} \in H^2(0, T; H^1(\omega)) \times H^2(0, T; L^2(\omega)) : (\mathbf{y}(\xi, 0), \mathbf{y}'(\xi, 0)) = (\mathbf{y}^0, \mathbf{y}^1), \right. \\ \left. (y_1(\xi, T), y_1'(\xi, T)) = (0, 0), \xi \in \omega, y_1(0, t) = 0, t \in (0, T) \right\}.$$

Remark 4.3. *Let us assume that the initial datum $(\mathbf{y}^0, \mathbf{y}^1)$ has a component in $\text{Ker } \mathbf{A}_M$. In that case, the infimum $E(\mathbf{y})$ is reached over \mathcal{A} but is not zero and the corresponding corrector*

\bar{u} corrector does not vanishes identically over q_T . We note $\mathbf{y} \in \mathcal{A}$ the corresponding minimizer and $v(t) = y_1(1, t)$. Now, we note $\bar{\mathbf{y}}$ the solution of the backward problem

$$\begin{cases} \bar{y}_1'' - \bar{u}_1'' - (\bar{y}_{1,1} + \bar{u}_{1,1} + c\bar{y}_3)_{,1} = 0, & (\xi, t) \in q_T \\ \bar{y}_3'' - \bar{u}_3'' + c(\bar{y}_{1,1} + c\bar{y}_3 + c\bar{u}_3) = 0, & (\xi, t) \in q_T \\ \bar{y}_1 = 0, & (\xi, t) \in \partial\omega \times (0, T) \\ (\bar{\mathbf{y}}(\xi, T), \bar{\mathbf{y}}'(\xi, T)) = (\mathbf{0}, \mathbf{0}), & \xi \in \omega. \end{cases}$$

Then, by linearity of system (2.1), the solution $(\mathbf{y} - \bar{\mathbf{y}})$ of

$$\begin{cases} (\mathbf{y} - \bar{\mathbf{y}})'' + \mathbf{A}_M(\mathbf{y} - \bar{\mathbf{y}}) = 0, & (\xi, t) \in q_T \\ (y_1 - \bar{y}_1)(0, t) = 0, (y_1 - \bar{y}_1)(1, t) = v(t), & (\xi, t) \in \partial\omega \times (0, T) \\ ((\mathbf{y} - \bar{\mathbf{y}})(\cdot, 0), (\mathbf{y} - \bar{\mathbf{y}})'(\cdot, 0)) = (\mathbf{y}^0 - \bar{\mathbf{y}}(\cdot, 0), \mathbf{y}^1 - \bar{\mathbf{y}}(\cdot, 0)), & \xi \in \omega \end{cases}$$

satisfies $((\mathbf{y} - \bar{\mathbf{y}})(\cdot, T), (\mathbf{y} - \bar{\mathbf{y}})'(\cdot, T)) = (\mathbf{0}, \mathbf{0})$. Therefore, we have extract the controllable component $(\mathbf{y}^0 - \bar{\mathbf{y}}(\cdot, 0), \mathbf{y}^1 - \bar{\mathbf{y}}(\cdot, 0))$ from the initial datum $(\mathbf{y}^0, \mathbf{y}^1)$. It is important to note that this does not require any spectral information on the operator \mathbf{A}_M : precisely, at the practical level, the lack of controllability is related to the property $\inf_{\mathbf{y} \in \mathcal{A}} E(\mathbf{y}) \neq 0$.

4.2. Numerical resolution - Conjugate gradient algorithm. Let us describe the procedure to approximate numerically the variational problem is $\min_{\mathbf{y} \in \mathcal{A}} E(\mathbf{y})$. Preliminary, since \mathcal{A} is not an Hilbert space, we consider for any $\bar{\mathbf{y}} \in \mathcal{A}$ the equivalent problem $\min_{\mathbf{z} \in \mathcal{A}_0} E(\bar{\mathbf{y}} + \mathbf{z})$ and we endow the Hilbert space \mathcal{A}_0 with the scalar product

$$(\mathbf{u}, \mathbf{v})_{\mathcal{A}_0} = \iint_{q_T} (\mathbf{u}'' \mathbf{v}'' + \mathbf{u}' \mathbf{v}' + u_{1,1} v_{1,1} + c^2 u_3 v_3) d\xi dt, \quad \forall \mathbf{u}, \mathbf{v} \in \mathcal{A}_0$$

and note that $\|\mathbf{z}\|_{\mathcal{A}_0} = \sqrt{(\mathbf{z}, \mathbf{z})_{\mathcal{A}_0}}$ for all $\mathbf{z} \in \mathcal{A}_0$. We note $E(\bar{\mathbf{y}} + \mathbf{z}) = E_{\bar{\mathbf{y}}}(\mathbf{z})$ so that $\min_{\mathbf{z} \in \mathcal{A}_0} E(\bar{\mathbf{y}} + \mathbf{z}) = \min_{\mathbf{z} \in \mathcal{A}_0} E_{\bar{\mathbf{y}}}(\mathbf{z})$.

The Polak-Ribière version of the conjugate gradient (CG) algorithm to minimize $E_{\bar{\mathbf{y}}}$ over \mathcal{A}_0 is as follows (see [12]): for any $\bar{\mathbf{y}} \in \mathcal{A}$

- *Step 0: Initialization* - Given any $\varepsilon > 0$ and any $\mathbf{z}^0 \in \mathcal{A}_0$, compute the residual $\mathbf{g}^0 \in \mathcal{A}_0$ solution of

$$(\mathbf{g}^0, \mathbf{Y})_{\mathcal{A}_0} = \langle E'_{\bar{\mathbf{y}}}(\mathbf{z}^0), \mathbf{Y} \rangle \quad \forall \mathbf{Y} \in \mathcal{A}_0.$$

If $\|\mathbf{g}^0\|_{\mathcal{A}_0} / \|\mathbf{z}^0\|_{\mathcal{A}_0} \leq \varepsilon$ take $\mathbf{z} = \mathbf{z}^0$ as an approximation of a minimum of $E_{\bar{\mathbf{y}}}$. Otherwise, set $\mathbf{w}^0 = \mathbf{g}^0$.

For $n \geq 0$, assuming $\mathbf{z}^n, \mathbf{g}^n, \mathbf{w}^n$ being known with \mathbf{g}^n and \mathbf{w}^n both different from zero, compute $\mathbf{z}^{n+1}, \mathbf{g}^{n+1}$, and if necessary \mathbf{w}^{n+1} as follows:

- *Step 1: Steepest descent* - Set $\mathbf{z}^{n+1} = \mathbf{z}^n - \lambda_n \mathbf{w}^n$ where $\lambda_n \in \mathbb{R}$ is the solution of the one-dimensional minimization problem

$$(4.11) \quad \text{minimize } E_{\bar{\mathbf{y}}}(\mathbf{z}^n - \lambda \mathbf{w}^n), \quad \text{over } \lambda \in \mathbb{R}.$$

Then, compute the residual $\mathbf{g}^{n+1} \in \mathcal{A}_0$ from the relation

$$(\mathbf{g}^{n+1}, \mathbf{Y})_{\mathcal{A}_0} = \langle E'_{\bar{\mathbf{y}}}(\mathbf{z}^{n+1}), \mathbf{Y} \rangle \quad \forall \mathbf{Y} \in \mathcal{A}_0.$$

- *Step 2: Convergence testing and construction of the new descent direction* - If $\|\mathbf{g}^{n+1}\|_{\mathcal{A}_0} / \|\mathbf{g}^0\|_{\mathcal{A}_0} \leq \varepsilon$ take $\mathbf{z} = \mathbf{z}^{n+1}$; otherwise compute

$$(4.12) \quad \gamma_n = \frac{(\mathbf{g}^{n+1}, \mathbf{g}^{n+1} - \mathbf{g}^n)_{\mathcal{A}_0}}{(\mathbf{g}^n, \mathbf{g}^n)_{\mathcal{A}_0}}, \quad \mathbf{w}^{n+1} = \mathbf{g}^{n+1} + \gamma_n \mathbf{w}^n.$$

Then do $n = n + 1$, and return to step 1.

The following two remarks are in order:

- Since $E_{\bar{\mathbf{y}}}$ is a quadratic functional, one may write

$$\begin{aligned} E_{\bar{\mathbf{y}}}(\mathbf{z}^n - \lambda \mathbf{w}^n) &= E_{\bar{\mathbf{y}}}(\mathbf{z}^n) - \lambda \iint_{q_T} (\mathbf{u}^{n'} \mathbf{W}^{n'} + \mathbf{u}_{,1}^n \mathbf{W}_{,1}^n + c^2 u_3^n W_{,3}) d\xi dt \\ &\quad + \frac{\lambda^2}{2} \iint_{q_T} (|\mathbf{W}_{\mathbf{t}}^n|^2 + |\mathbf{W}_{,1}^n|^2 + c^2 |W_3|) d\xi dt \end{aligned}$$

where \mathbf{u}^n is the corrector of $\bar{\mathbf{y}} + \mathbf{z}^n$ and \mathbf{W}^n is the corrector of \mathbf{w}^n , and solve explicitly the problem (4.11).

- The computation of the residual \mathbf{g}^n is performed as follows. According to the equality

$$(4.13) \quad \langle E'(\mathbf{y}^n), \mathbf{Y} \rangle = - \int_{q_T} \left(\mathbf{Y}'' \mathbf{u}^n + (Y_{1,1} + cY_3)(u_{1,1}^n + cu_3^n) \right) d\xi dt, \forall \mathbf{Y} \in \mathcal{A}_0.$$

$E'(\mathbf{y}^n) \in H^{-2}(q_T)$) may be identified with the linear functional on \mathcal{A}_0 defined by

$$\mathbf{Y} \rightarrow - \int_{q_T} \left(\mathbf{Y}'' \mathbf{u}^n + (Y_{1,1} + cY_3)(u_{1,1}^n + cu_3^n) \right) d\xi dt,$$

It then follows that \mathbf{g}^n is the solution of the following linear variational problem : find $\mathbf{g}^n \in \mathcal{A}_0$ such that

$$\iint_{q_T} (\mathbf{g}^{n''} \mathbf{Y}'' + \mathbf{g}^{n'} \mathbf{Y}' + \mathbf{g}_{,1}^n \mathbf{Y}_{,1} + c^2 g_3^n Y_3) d\xi dt = - \int_{q_T} \left(\mathbf{Y}'' \mathbf{u}^n + (Y_{1,1} + cY_3)(u_{1,1}^n + cu_3^n) \right) d\xi dt,$$

for all $\mathbf{Y} \in \mathcal{A}_0$, where $\mathbf{u}^n \in H_{0,\xi}^1(q_T)$ is the corrector associated with \mathbf{y}^n .

We refer to [23] for details statement in the heat case.

Remark 4.4. *The parameter γ_n given by (4.12) corresponds to the Polak-Ribière version of the conjugate gradient algorithm. In the present quadratic-linear situation, this one should coincide with the Fletcher-Reeves conjugate algorithm for which $\gamma_n = \|\mathbf{g}^{n+1}\|_{\mathcal{A}_0}^2 / \|\mathbf{g}^n\|_{\mathcal{A}_0}^2$ since gradients are conjugate to each other $(\mathbf{g}^m, \mathbf{g}^n)_{\mathcal{A}_0} = 0 \forall m \neq n$. As in the parabolic situation described in [23] the Polak-Ribière version (mainly used in nonlinear situations) allows to reduce the loss of the orthogonality, due to the numerical approximation.*

Once the convergence of the algorithm is reached, up to the threshold ε , we take the trace of u on Σ_T to define an approximation of the control v of (2.1): $v(t) = y_1(1, t)$, $t \in (0, T)$. We next compute an approximation of the controlled solution \mathbf{y} by solving (2.1): the norm $\|(\mathbf{y}(\cdot, T), \mathbf{y}'(\cdot, T))\|_{\mathbf{H} \times \mathbf{V}'}$, that may be seen as an *a posteriori* error, allows to evaluate the efficiency of the approach.

4.3. Numerical approximations. For “large” integers N_x and N_t , we set $\Delta x = 1/N_x$, $\Delta t = T/N_t$, and $h = (\Delta x, \Delta t)$. Let us denote by $\mathcal{P}_{\Delta x}$ the uniform partition of $\bar{\omega}$ associated with Δx , and let us denote by \mathcal{Q}_h the uniform quadrangulation of q_T associated with h , so that $\bar{q}_T = \bigcup_{K \in \mathcal{Q}_h} K$. The following (conformal) finite element approximation of the space $H^2(0, T; H^1(\omega))$ (appearing in \mathcal{A}) is introduced :

$$X_h = \{\varphi_h \in C_{\xi,t}^{0,1}(\bar{q}_T) : \varphi_h|_K \in (\mathbb{P}_{1,\xi} \otimes \mathbb{P}_{3,t})(K) \quad \forall K \in \mathcal{Q}_h\}.$$

Here, $\mathbb{P}_{m,x}$ denotes the space of polynomial functions of order m in the variable x and $C_{\xi,t}^{0,1}(\bar{q}_T)$ is the space of the functions in $C^0(\bar{q}_T)$ that are continuously differentiable with respect to t in \bar{q}_T . The space X_h is also a conformal approximation of $H^2(0, T; L^2(\omega))$. We are thus considering finite elements that C^1 in the variable t . In each quadrangle $K \in \mathcal{Q}_h$, functions to a polynomial of the form $A + B\xi + Ct + D\xi t + Et^2 + Ft^2\xi + Gt^3 + Ht^3\xi$ involving 8 degrees of freedom. This is necessary to enforce the boundary conditions at $t = 0$ and $t = T$ appearing in \mathcal{A} and \mathcal{A}_0 . The space \mathcal{A} is approximated by the finite dimensional space :

$$\mathcal{A} = \left\{ \mathbf{y}_h = (y_{1h}, y_{3h}) \in X_h \times X_h : (\mathbf{y}_h(\xi, 0), \mathbf{y}'_h(\xi, 0)) = (\mathbf{y}_h^0, \mathbf{y}_h^1), \right. \\ \left. (\mathbf{y}_h(\xi, T), \mathbf{y}'_h(\xi, T)) = (\mathbf{0}, \mathbf{0}), \xi \in \omega, y_{1h}(0, t) = 0, t \in (0, T) \right\}.$$

Therefore, for any h , we consider the following problem

$$(4.14) \quad \begin{cases} \text{Minimize} & E_h(\mathbf{y}_h) = \frac{1}{2} \iint_{q_T} (|\mathbf{u}'_h|^2 + |\mathbf{u}_{h,1}|^2 + c^2|u_{3h}|^2) d\xi dt, \\ \text{subject to} & \mathbf{y}_h \in \mathcal{A}_h. \end{cases}$$

According to the conjugate gradient algorithm, this minimization problem is reduced to the resolution of well-posed elliptic problems defined on Q_T in order to compute corrector functions \mathbf{u}_h that we also approximate in $X_h \times X_h$ for the sake of the implementation.

5. NUMERICAL EXPERIMENTS II

We now present some numerical experiments, and highlights the capability of the variational approach to provide controls for system with mixed order operator. We take for simplicity that $\Delta x = \Delta t$, that is we only consider uniform meshes \mathcal{Q}_h .

5.1. Exact controllability. We consider the following initial condition

$$(5.1) \quad \mathbf{y}^0 = \beta(5\mathbf{w}_1 - 2\mathbf{w}_2) + \mathbf{v}_0 + \mathbf{v}_1, \quad \mathbf{y}^1 = \beta(4\mathbf{w}_3 - 2\mathbf{w}_1) + \mu_0\mathbf{v}_0 + \mu_2\mathbf{v}_2$$

with $\beta \in \{0, 1\}$. For $\beta = 0$, $(\mathbf{y}^0, \mathbf{y}^1)$ is controllable and coincides with the datum given by (3.2) (for $\alpha = 1$). For $\beta = 1$, the datum is not controllable due to the components $\mathbf{w}_1, \mathbf{w}_2, \mathbf{w}_3 \in \text{Ker} \mathbf{A}_M$. We then define the functions $F_1(t) = \frac{(T-t)^2(T+2t)}{T^3}$, $F_2(t) = \frac{(T-t)^2 t}{T^2}$ and the function

$$(5.2) \quad \bar{\mathbf{y}}(\xi, t) = F_1(t)\mathbf{y}^0(\xi) + F_2(t)\mathbf{y}^1(\xi), \quad (\xi, t) \in q_T.$$

We easily check that $\bar{\mathbf{y}}$ belongs to \mathcal{A} , in particular $(\bar{\mathbf{y}}(\cdot, 0), \bar{\mathbf{y}}'(\cdot, 0)) = (\mathbf{y}^0, \mathbf{y}^1)$ and $(\bar{\mathbf{y}}(\cdot, T), \bar{\mathbf{y}}'(\cdot, T)) = (\mathbf{0}, \mathbf{0})$.

We take $T = 3.5$, $c = \pi/5$ and use the conjugate gradient algorithm to construct a minimizing sequence for E of the form $\mathbf{y}^n = \bar{\mathbf{y}} + \mathbf{z}^n \in \mathcal{A}$ with $\mathbf{z}^n \in \mathcal{A}_0$. We start with $\mathbf{z}^0 \equiv \mathbf{0}$. We consider the value $\Delta x = \Delta t = 1/80$.

We first give some results in the case $\beta = 0$. Figure 7-Left depicts the evolution (in \log_{10} scale) of the residual $\|\mathbf{g}^n\|_{\mathcal{A}_0}$ and of the cost $E(\mathbf{y}^n)$ with respect to the iteration. After 3000 iterations, we obtain the value $E(\mathbf{y}_h^{3000}) \approx 6.94 \times 10^{-5}$ and $\|\mathbf{g}_h^n\|_{\mathcal{A}_0} \approx 3.16 \times 10^{-5}$. More precisely, we get $(\iint_{q_T} (|u'_{1h}|^2 + |u_{1h,1}|^2) d\xi dt)^{1/2} \approx 1.17 \times 10^{-2}$ and $(\iint_{q_T} (|u'_{3h}|^2 + |u_{3h,1}|^2 + c^2|u_{3h}|^2) d\xi dt)^{1/2} \approx 9.88 \times 10^{-4}$.

Figure 8 and Figure 9 depict the corresponding minimizer (y_{1h}, y_{3h}) and corrector (u_{1h}, u_{3h}) respectively while Figure 7 depicts the trace of the component y_{1h} along $\Sigma_T = \{1\} \times (0, T)$. We obtain $\|y_{1h}\|_{L^2(\Sigma_T)} \approx 1.119$. We check that this value is bigger than the one obtained by the dual method, in Section 3, that is, for $c = \pi/2$, $\|v_h\|_{L^2(\Sigma_T)} \approx 0.753$.

As in the parabolic situation described in [23], the convergence of the algorithm is rather low: however, it provides a satisfactory approximation of a control for the system (2.1). Precisely, if we compute the solution, say \mathbf{y}^* , of the forward system (2.1) with control the trace $y_{1,h}(1, t)$, we have just obtained, we observe that $\|\mathbf{y}_h^*(\cdot, T), \mathbf{y}_h^{*\prime}(\cdot, T)\|_{\mathbf{V} \times \mathbf{H}} \approx 1.40 \times 10^{-3}$.

We now consider the case $\beta = 1$, the other data being unchanged. Figure 10 depicts the evolution of $E_h(\mathbf{y}_h^n)$ and $\|\mathbf{g}_h^n\|_{\mathcal{A}_0}$ (in \log_{10} scale) with respect to n . After 500 iterations, we obtain $\|\mathbf{g}_h^{500}\|_{\mathcal{A}_0} \approx 1.30 \times 10^{-4}$ which indicates that the solution \mathbf{y}_h^{500} obtained is closed to a local minima for E : we recall that the vector \mathbf{g} corresponds to the derivative of E . On the other hand, the value of the cost is $E(\mathbf{y}_h^{500}) \approx 2.28 \times 10^{-2}$ to be compared with the value 6.94×10^{-5} obtained in the case $\beta = 0$. Thus, for this local minimum, the cost does not vanish and $(y_{1h}, y_{3h}) \in \mathcal{A}_h$ is not an approximation of the solution of (2.1). This illustrates the lack of controllability of the data (5.1) for (2.1) and is once again in full agreement with the controllability property of (2.1). Figure 11 gives the corresponding corrector (u_{1h}, u_{3h}) in q_T : we obtain $(\iint_{q_T} (|u'_{1h}|^2 + |u_{1h,1}|^2) d\xi dt)^{1/2} \approx 5.01 \times 10^{-2}$ and $(\iint_{q_T} (|u'_{3h}|^2 + |u_{3h,1}|^2 + c^2|u_{3h}|^2) d\xi dt)^{1/2} \approx 2.07 \times 10^{-1}$.

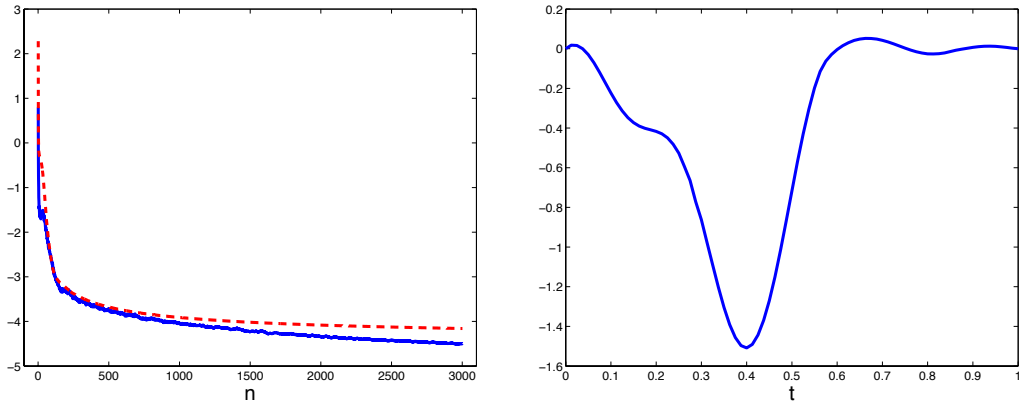


FIGURE 7. $\beta = 0$: $T = 3.5$, $\Delta x = \Delta t = 1/80$ - **Left** : \log_{10} of $E_h(\mathbf{y}_h^n)$ (**dashed line**) and $\log_{10}(\|\mathbf{g}_h^n\|_{\mathcal{A}_0})$ (**full line**) vs. the iteration n of the conjugate gradient algorithm ; **Right** : Trace $y_{1h}(\xi = 1, t)$ vs. $t \in (0, T)$

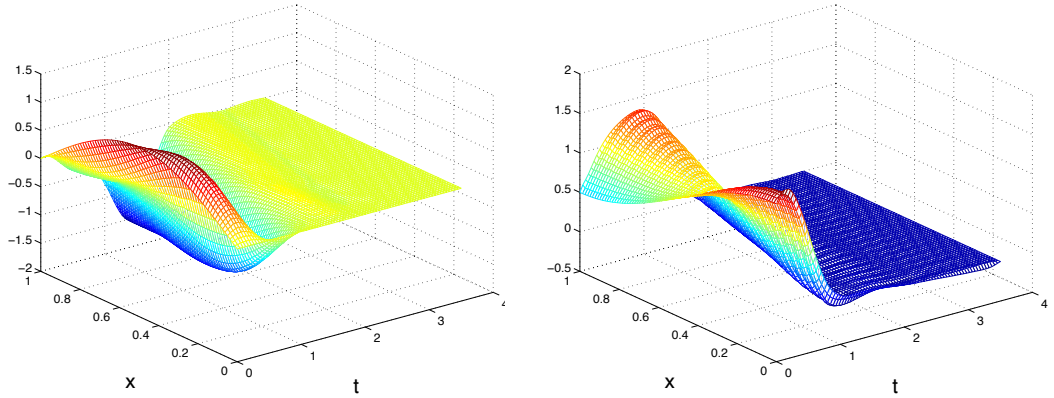


FIGURE 8. $\beta = 0$: Minimizer y_{1h} (**left**) and y_3 (**right**) over q_T .

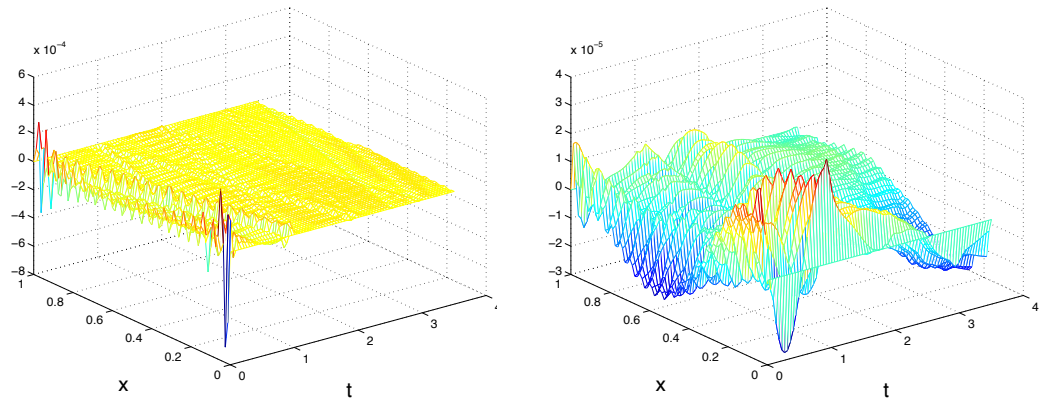


FIGURE 9. $\beta = 0$; Minimizer v_{1h} (**left**) and v_3 (**right**) over q_T .

5.2. Partial uniform controllability. Finally, we illustrate Remark 4.2. We consider the data (5.1) with $\beta = 1$ and work with the relaxed space \mathcal{A}_p defined by (4.10) and larger than \mathcal{A} . The conjugate algorithm remains unchanged.

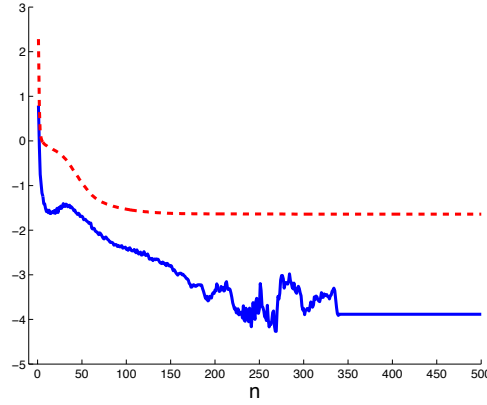


FIGURE 10. $\beta = 1 - T = 3.5$, $\Delta x = \Delta t = 1/80$ - **Left** : \log_{10} of $E_h(\mathbf{y}_h^n)$ (**dashed line**) and $\log_{10}(\|\mathbf{g}_h^n\|_{\mathcal{A}_0})$ (**full line**) vs. the iteration n of the conjugate gradient algorithm ; **Right** : Trace $y_{1h}(\xi = 1, t)$ vs. $t \in (0, T)$.

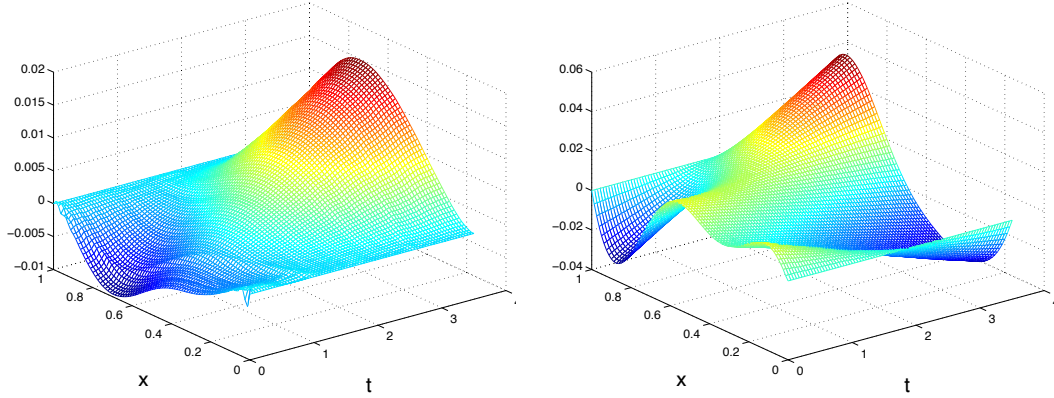


FIGURE 11. $\beta = 1$; Minimizer u_{1h} (**left**) and u_{3h} (**right**) over q_T .

Figure 12-left depicts the evolution of the residu $\|\mathbf{g}_h^n\|_{\mathcal{A}_0}$ and of the cost $E(\mathbf{y}_h^n)$. We observe that after 5000 iterations, these two quantities take small values, precisely $E(\mathbf{y}_h^{5000}) \approx 1.71 \times 10^{-4}$ and $\|\mathbf{g}_h^{5000}\|_{\mathcal{A}_0} \approx 4.44 \times 10^{-5}$. This is in agreement with the partial controllability of 2.1, even for data with components in $\text{Ker} \mathbf{A}_M$. Figure 12-right gives the trace of the controlled component y_{1h} on Σ_T : we get $\|y_{1h}\|_{L^2(\Sigma_T)} \approx 1.124 \times 10^1$. Figure 13 gives the corresponding controlled component y_{1h} and the free component y_{3h} , minimizer for E . At last, Figure 14 gives the corresponding corrector u_{1h} and u_{3h} in q_T : we obtain $(\iint_{q_T} (|u'_{1h}|^2 + |u_{1h,1}|^2) d\xi dt)^{1/2} \approx 1.16 \times 10^{-2}$ and $(\iint_{q_T} (|u'_{3h}|^2 + |u_{3h,1}|^2 + c^2|u_{3h}|^2) d\xi dt)^{1/2} \approx 5.81 \times 10^{-3}$.

6. FINAL REMARKS

The chart which describes the mid-surface of a cylindrical arch of curvature c , as considered along this paper, is given by $\phi(\xi) = (c^{-1} \sin(c\xi), c^{-1} \cos(c\xi))$, $\xi \in \omega$. The corresponding operator is then given by (1.3). For a general chart $\phi(\xi) = (\phi_1(\xi), \phi_2(\xi))$, the operator \mathbf{A}_M is

$$(6.1) \quad \mathbf{A}_M \mathbf{y} = \begin{pmatrix} -\gamma_{11,1}(\mathbf{y}) - 2\gamma_{11}(\mathbf{y})\Gamma_{11}^1 \\ -\gamma_{11}(\mathbf{y})b_{11} \end{pmatrix}, \quad \mathbf{y} = (y_1, y_3)$$

with

$$(6.2) \quad \begin{cases} \gamma_{11}(\mathbf{y}) = y_{1,1} - \Gamma_{11}^1 y_1 - b_{11} y_3, & \Gamma_{11}^1 = t^{-1}(\phi_{1,1}\phi_{1,11} + \phi_{2,1}\phi_{2,11}), \\ t = \phi_{1,1}^2 + \phi_{2,1}^2, & b_{11} = t^{-3/2}(-\phi_{2,1}\phi_{1,11} + \phi_{1,1}\phi_{2,11}). \end{cases}$$

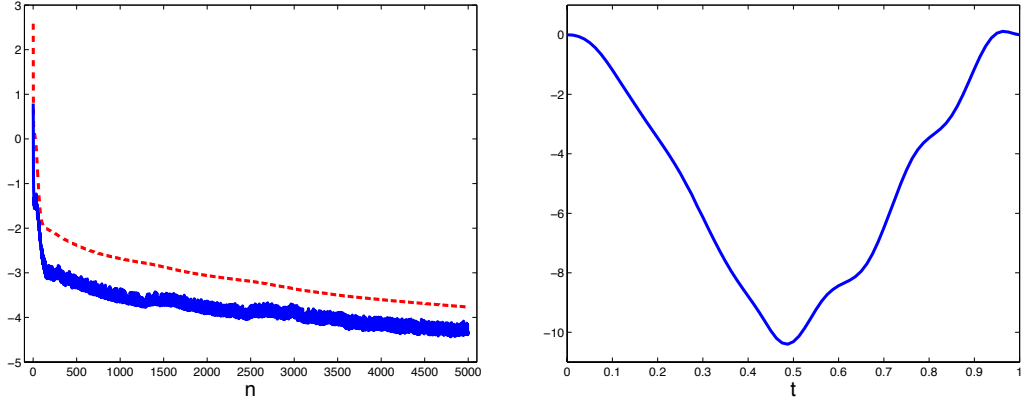


FIGURE 12. $\beta = 1$: $T = 3.5$, $\Delta x = \Delta t = 1/80$ - **Left** : \log_{10} of $E_h(y_h^n)$ (**dashed line**) and $\log_{10}(\|g_h^n\|_{\mathcal{A}_0})$ (**full line**) vs. the iteration n of the conjugate gradient algorithm ; **Right** : Trace $y_{1h}(\xi = 1, t)$ vs. $t \in (0, T)$.

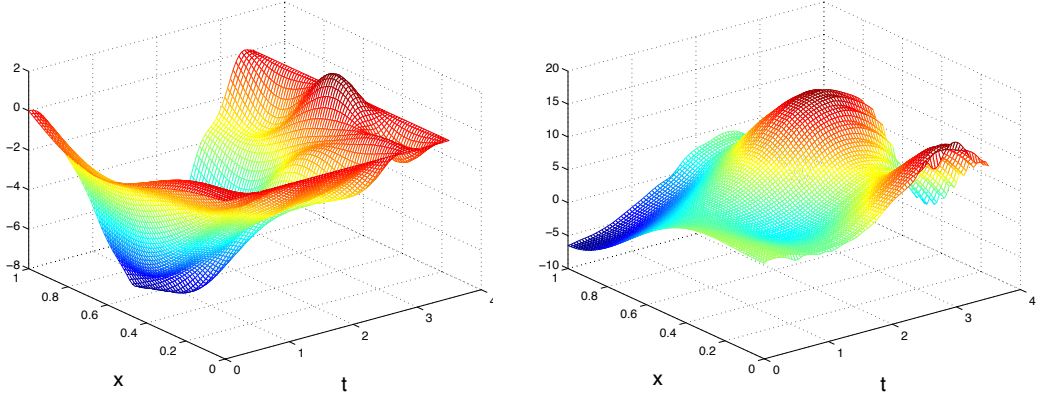


FIGURE 13. $\beta = 0$: Minimizer y_{1h} (**left**) and y_{3h} (**right**) over q_T .

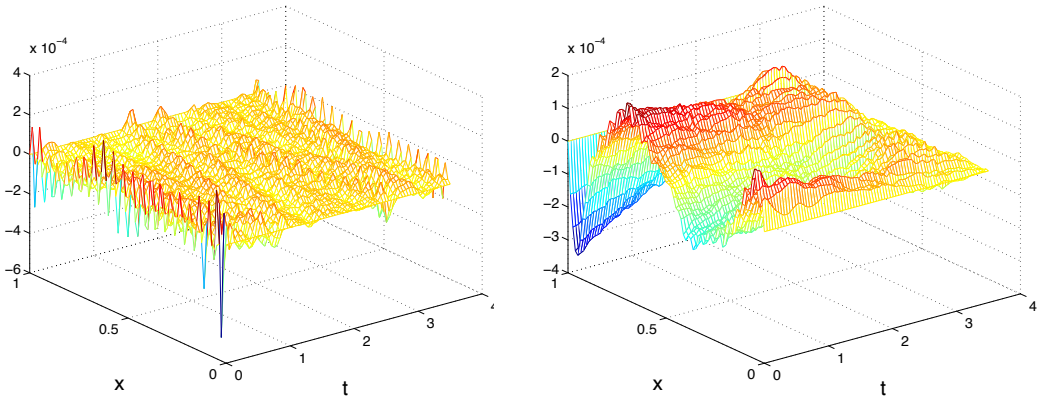


FIGURE 14. $\beta = 0$: Minimizer y_{1h} (**left**) and y_{3h} (**right**) over q_T .

Γ_{11}^1 designates the Christoffel symbol and γ_{11} the longitudinal strain (see [26]). Once again, the kernel is not empty and of infinite dimension - $Ker \mathbf{A}_M = \{v_\zeta = (\zeta, b_{11}^{-1}(\zeta, 1 - \Gamma_{11}^1 \zeta)) \in \mathbf{H}, \zeta \in H_0^1(\omega)\}$ - so that $0 \in \sigma_{ess}(\mathbf{A}_M)$ and the controllability does not hold uniformly with respect to the initial data. But, in this general setting, the spectrum is not explicit so that one can not, *a*

priori, fully characterized the set of initial controllable data and therefore compute controls by duality arguments, as in Section 3. On the other hand, there is no restriction here to apply the variational approach of Section 4.

Similarly, the 3D dimensional situation remains challenging and may be addressed by the variational approach. More precisely, the membranal operator that enters in the modelization of an elastic cylindrical shell - with constant curvature c in one direction and zero curvature in the other direction - is given by

$$(6.3) \quad \mathbf{A}_M = \begin{pmatrix} -a_1 \partial_{\xi_1}^2 - c \partial_{\xi_2}^2 & -(a_2 + a_3) \partial_{\xi_1 \xi_2}^2 & -c a_1 \partial_{\xi_1} \\ -(a_2 + a_3) \partial_{\xi_1 \xi_2}^2 & -a_3 \partial_{\xi_1}^2 - a_1 \partial_{\xi_2}^2 & -c a_2 \partial_{\xi_2} \\ c a_1 \partial_{\xi_1} & c a_2 \partial_{\xi_2} & c^2 a_1 \end{pmatrix}$$

with $a_1 = 8\mu(\lambda + \mu)/(\lambda + 2\mu)$, $a_2 = 4\lambda\mu/(\lambda + 2\mu)$ and $a_3 = 2\mu$. $\lambda, \mu > 0$ denotes the Lamé coefficient. This mixed and self-adjoint operator enters in the framework of [14] and we obtain $\sigma_{ess}(A) = \left[0, \frac{2(3\lambda+2\mu)}{\lambda+\mu}c^2\right]$. Moreover $\text{Ker} \mathbf{A}_M = \emptyset$ and $(0, 0, 1)$ is an eigenfunction associated to $\lambda_0 = c^2 \notin \sigma_{ess}(\mathbf{A}_M)$. The remaining part of the discrete spectrum is unknown (contrary to the operator 1), so that once again the standard method of computation is ineffective.

Let us also note that we may use this variational approach to determine the control of minimal L^2 -norm. It suffices to introduce the Lagrangian

$$L(\mathbf{y}, \lambda) = \|y_1(1, t)\|_{L^2(0, T)}^2 + \lambda E(\mathbf{y})$$

defined over $\mathcal{A} \times \mathbb{R}$, and apply an Uzawa type method, arguing that the set $\{\mathbf{y} \in \mathcal{A}, E(\mathbf{y}) = 0\}$ is convex.

Finally, we mention the recent work [8] where another variational approach is introduced for the approximation of controls.

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