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COMMENTS ON OBSERVABILITY AND STABILIZATION OF MAGNETIC SCHRÖDINGER EQUATIONS

KAÏS AMMARI, MOURAD CHOULLI, AND LUC ROBBIANO

ABSTRACT. We are mainly interested in extending the known results on observability inequalities and stabilization for the Schrödinger equation to the magnetic Schrödinger equation. That is in presence of a magnetic potential. We establish observability inequalities and exponential stabilization by extending the usual multiplier method, under the same geometric condition to that needed for the Schrödinger equation. We also prove, with the help of elliptic Carleman inequalities, logarithmic stabilization results through a resolvent estimate. Although the approach is classical, these results on logarithmic stabilization seem to be new even for the Schrödinger equation.

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1. Introduction

1.1. **State of art.** Observability inequalities for the Schrödinger equation were established by Machtyngier [23] by the multiplier method. The corresponding exponential stabilization results are due to Machtyngier and Zuazua [24]. Under the so-called geometric control condition, Lebeau [20] showed that the Schrödinger

equation is exactly controlable (or equivalently exactly observable) for an arbitrary fixed time (see also Phung [33], Laurent [19] and Dehman, Gérard and Lebeau [13] for the nonlinear case). In the case of a square, Ramdani, Takahashi, Tenenbaum and Tucsnak [34] obtained an observability inequality by a spectral method which is build on the fact that observability is equivalent to an observability resolvent estimate, known also as Hautus test. This equivalence was first proved by Burq and Zworski [10] (see also Miller [31]).

The case of Schrödinger equation on spheres and Zoll manifolds was studied in Macià [25], Marcià and Rivière [26, 27]. While the Schrödinger equation on the torus and the disk was considered by Anantharaman, Fermanian-Kammerer and Macià [1], Anantharaman and M. Léautaud [4], Anantharaman, M. Léautaud and Macià [2], Anantharaman and Macià [3].

Exact observability inequalities for the (magnetic) wave equation can transferred to observability inequalities for the (magnetic) Schrödinger equation and vice versa via a transmutation method (see Miller [31] and references therein) or by an abstract framework consisting in transforming a second order evolution equation into a first order evolution equation (see [36] for more details). There is wide literature on control, observability and stabilization for the wave equation. We only quote the following few reference [6, 11, 14, 15, 18, 35].

1.2. Main notations. Denote by dx the Lebesgue measure on \mathbb{R}^d , $d \geq 1$, and $d\sigma$ the Lebesgue measure on a submanifold S of \mathbb{R}^k of dimension $k - 1$. Let X be an open subset of \mathbb{R}^d and $Y = (X, d\mu)$, $Y = (S, d\mu)$ or $Y = (X \times S, d\mu)$, where $d\mu = dx$ if $Y = X$, $d\mu = d\sigma$ if $Y = S$ and $d\mu = dx \otimes d\sigma$ if $Y = X \times S$.

For $f, g \in L^2(Y) = L^2(Y, \mathbb{C})$ and $E \subset Y$ is measurable, we set

$$(f|g)_{0,E} = \int_E f \bar{g} d\mu,$$

$$\|f\|_{0,E} = \left(\int_E |f|^2 d\mu \right)^{1/2}$$

and, if in addition $f \in H^1(Y) = H^1(Y, \mathbb{C})$, let

$$\|f\|_{1,E} = \left(\|f\|_{0,E}^2 + \sum_{j=1}^d \|\partial_j f\|_{0,E}^2 \right)^{1/2}.$$

Similarly, for $F, G \in L^2(Y, \mathbb{C}^\ell)$, $\ell \geq 1$, we define

$$(F|G)_{0,E} = \int_E F \cdot \bar{G} d\mu,$$

$$\|F\|_{0,E} = \left(\int_E |F|^2 d\mu \right)^{1/2}.$$

For simplicity sake's, the real part of $(\cdot|\cdot)_{0,E}$ is denoted by $\langle \cdot | \cdot \rangle_{0,E}$.

Finally, for $f \in L^\infty(X, \mathbb{R}^\ell)$, $\ell \geq 1$, we set

$$\|f\|_\infty = \| |f| \|_{L^\infty(X, \mathbb{R})}.$$

Throughout this text, Ω is a C^∞ bounded domain of \mathbb{R}^n , $n \geq 1$, with boundary Γ . Let ν denotes the outward unit normal vector field on Γ .

Henceforth $\mathbf{a} = (a_1, \dots, a_n) \in W^{1,\infty}(\Omega, \mathbb{R}^n)$ is a fixed vector field. We define the magnetic Laplacian and the magnetic gradient respectively by

$$\Delta_{\mathbf{a}} = \sum_{j=1}^n (\partial_j + i a_j)^2 = \Delta + 2i\mathbf{a} \cdot \nabla + i \operatorname{div}(\mathbf{a}) - |\mathbf{a}|^2$$

and

$$\nabla_{\mathbf{a}} = \nabla + i\mathbf{a}.$$

We shall also need the notation

$$\partial_{\nu_{\mathbf{a}}} = \nabla_{\mathbf{a}} \cdot \nu = \partial_{\nu} + i\mathbf{a} \cdot \nu.$$

The following identities will be useful in the sequel. There are obtained by making integrations by parts

$$(1.1) \quad (\Delta_{\mathbf{a}} f | g)_{0,\Omega} = -(\nabla_{\mathbf{a}} f | \nabla_{\mathbf{a}} g)_{0,\Omega} + (\partial_{\nu_{\mathbf{a}}} f | g)_{0,\Gamma}, \quad f \in H^2(\Omega), \quad g \in H^1(\Omega),$$

$$(1.2) \quad (\Delta_{\mathbf{a}} f | g)_{0,\Omega} = (f | \Delta_{\mathbf{a}} g)_{0,\Omega}, \quad f, g \in H^2(\Omega) \cap H_0^1(\Omega).$$

Let Λ be a nonempty open subset of Γ and

$$(1.3) \quad \mathcal{H} = \{u \in H^1(\Omega); u = 0 \text{ on } \Lambda\}.$$

The Poincaré constant of \mathcal{H} will be denoted by $\varkappa(\mathcal{H})$:

$$\|u\|_{0,\Omega} \leq \varkappa(\mathcal{H}) \|\nabla u\|_{0,\Omega}, \quad u \in \mathcal{H}.$$

1.3. Magnetic gradient semi-norm. Consider on $H_0^1(\Omega) = H_0^1(\Omega, \mathbb{C})$ the semi-norm

$$f \in H_0^1(\Omega) \mapsto \|\nabla_{\mathbf{a}} f\|_{0,\Omega}.$$

By the fundamental relation of Jaffe-Taubes [17]

$$|\nabla|f|| \leq |\nabla_{\mathbf{a}} f| \quad \text{a.e. in } \Omega.$$

As a consequence of this relation, we deduce that $\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ defines a norm on $H_0^1(\Omega)$. This norm is not in general equivalent to the natural norm $\|\nabla \cdot\|_{0,\Omega}$ on $H_0^1(\Omega)$. For simplicity sake's, even it is not always necessary, we assume that \mathbf{a} is chosen in such a way that $\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ is equivalent to $\|\nabla \cdot\|_{0,\Omega}$. This is achieved for instance if 0 is not an eigenvalue of the $\Delta_{\mathbf{a}}$, under Dirichlet boundary condition. We refer to [8, Proposition 3.1] for a proof and other equivalent conditions.

Note that if $\|\mathbf{a}\|_{\infty}$ is sufficiently small then $\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ and $\|\nabla \cdot\|_{0,\Omega}$ are equivalent on $H_0^1(\Omega)$. Indeed, if $\varkappa = \varkappa(H_0^1(\Omega))$, then

$$(1.4) \quad \frac{1}{\sqrt{2}}(1 - \sqrt{2}\|\mathbf{a}\|_{\infty}\varkappa)\|\nabla u\|_{0,\Omega} \leq \|\nabla_{\mathbf{a}} u\|_{0,\Omega} \leq \sqrt{2}(1 + \|\mathbf{a}\|_{\infty}\varkappa)\|\nabla u\|_{0,\Omega}.$$

Whence, under the smallness condition

$$(1.5) \quad \|\mathbf{a}\|_{\infty} < \frac{1}{\varkappa\sqrt{2}},$$

$\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ and $\|\nabla \cdot\|_{0,\Omega}$ are equivalent on $H_0^1(\Omega)$.

More generally, if \mathcal{H} is of the form (1.3) and $\|\mathbf{a}\|_{\infty} < \frac{1}{\varkappa(\mathcal{H})\sqrt{2}}$, then $\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ and $\|\nabla \cdot\|_{0,\Omega}$ are equivalent on \mathcal{H} .

1.4. IBVP's for the magnetic Schrödinger operator. Consider Γ_0 and Γ_1 two disjoint nonempty open subsets of Γ so that $\Gamma = \overline{\Gamma_0} \cup \overline{\Gamma_1}$.

From now on, we assume

(i) $0 \leq c \in L^\infty(\Omega)$ and there exist ω , an open subset of Ω , and $c_0 > 0$ so that $c \geq c_0$ a.e. in ω .

(ii) $0 \leq d \in L^\infty(\Gamma_0)$ and there exist γ_0 , an open subset of Γ_0 , and $d_0 > 0$ so that $d \geq d_0$ a.e. on γ_0 .

We deal with systems governed by IBVP's for the magnetic Schrödinger operator with different types of dampings. The first system we consider is given by the IBVP

$$(1.6) \quad \begin{cases} iu_t + \Delta_{\mathbf{a}}u + ic(x)u = 0 & \text{in } \Omega \times (0, +\infty), \\ u = 0 & \text{on } \Gamma \times (0, +\infty), \\ u(\cdot, 0) = u_0. \end{cases}$$

As a consequence of (1.2) we obtain that the unbounded operator $A : L^2(\Omega) \rightarrow L^2(\Omega)$ given by $Au = \Delta_{\mathbf{a}}u$ and $D(A) = H^2(\Omega) \cap H_0^1(\Omega)$ is self-adjoint.

From inequality (1.1)

$$\langle Au|u \rangle_0 = -\|\nabla_{\mathbf{a}}u\|_0^2 \leq 0, \quad u \in D(A).$$

As a non negative self-adjoint densely defined operator, A is m-dissipative. Then so is $A_0 = iA$ and, consequently, A_0 generates a strongly continuous group e^{tA_0} .

Let $A_1 = -i\Delta_{\mathbf{a}} - c$ with domain $D(A_1) = D(A_0)$. As a bounded perturbation of A_0 , A_1 generates also a strongly continuous group e^{tA_1} .

For $u_0 \in L^2(\Omega)$, define the energy for the system (1.6) by

$$\mathcal{E}_{u_0}^1(t) = \frac{1}{2} \|e^{tA_1}u_0\|_{0,\Omega}^2.$$

If $u(t) = e^{tA_1}u_0$, we get by using identity (1.1)

$$\frac{d}{dt} \|u(t)\|_{0,\Omega}^2 = 2\Re(u'(t), u(t))_{0,\Omega} = 2\Re [i\|\nabla_{\mathbf{a}}u(t)\|_{0,\Omega}^2 - \|\sqrt{c}u(t)\|_{0,\Omega}^2], \quad t > 0.$$

Hence

$$\frac{d}{dt} \mathcal{E}_{u_0}^1(t) = -\|\sqrt{c}u(t)\|_{0,\Omega}^2, \quad t > 0.$$

Therefore $t \rightarrow \mathcal{E}_{u_0}^1(t)$ is decreasing when $u_0 \neq 0$. We can then address the question to know how fast this energy decay. This issue will be one of our objectives in the coming sections.

The second system is associated with an IBVP with boundary damping.

$$(1.7) \quad \begin{cases} iu_t + \Delta_{\mathbf{a}}u = 0 & \text{in } \Omega \times (0, +\infty), \\ \partial_{\nu_{\mathbf{a}}}u + du_t = 0 & \text{on } \Gamma_0 \times (0, +\infty), \\ u = 0 & \text{on } \Gamma_1 \times (0, +\infty), \\ u(\cdot, 0) = u_0. \end{cases}$$

Introduce

$$V = \{u \in H^1(\Omega); u|_{\Gamma_1} = 0\}.$$

Then, as we have seen before, under the smallness condition

$$(1.8) \quad \|\mathbf{a}\|_\infty < \frac{1}{\kappa(V)\sqrt{2}},$$

$\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ and $\|\nabla \cdot\|_{0,\Omega}$ are equivalent on V . In particular, V endowed with the norm $\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$ is a Hilbert space.

Consider the unbounded operator $A_2 : V \rightarrow V$ given by

$$A_2 = i\Delta_{\mathbf{a}} \text{ and } D(A_2) = \{u \in V; \Delta_{\mathbf{a}} u \in V \text{ and } \partial_{\nu_{\mathbf{a}}} u + id\Delta_{\mathbf{a}} u = 0 \text{ on } \Gamma_0\}.$$

Applying one more time (1.1) twice in order to derive, for $u, v \in D(A_2)$,

$$(1.9) \quad \begin{aligned} \langle \nabla_{\mathbf{a}}(\Delta_{\mathbf{a}} u) | \nabla_{\mathbf{a}} v \rangle_{0, \Omega} &= -(\Delta_{\mathbf{a}} u | \Delta_{\mathbf{a}} v)_{0, \Omega} + (\Delta_{\mathbf{a}} u | \partial_{\nu_{\mathbf{a}}} v)_{0, \Gamma_0} \\ &= -(\Delta_{\mathbf{a}} u | \Delta_{\mathbf{a}} v)_{0, \Omega} + i(d\Delta_{\mathbf{a}} u | \Delta_{\mathbf{a}} v)_{0, \Gamma_0}, \\ &= \langle \nabla_{\mathbf{a}} u | \nabla_{\mathbf{a}}(\Delta_{\mathbf{a}} v) \rangle_{0, \Omega}. \end{aligned}$$

Whence $-iA_2$ is self-adjoint and

$$\langle \nabla_{\mathbf{a}}(-iA_2) | \nabla_{\mathbf{a}} u \rangle_{0, \Omega} = -\|\Delta_{\mathbf{a}} u\|_{0, \Omega}^2 \leq 0.$$

Hence A_2 is the generator of strongly continuous group e^{tA_2} .

The energy associated to the system (1.7) is given by

$$\mathcal{E}_{u_0}^2(t) = \frac{1}{2} \|\nabla_{\mathbf{a}} e^{tA_2} u_0\|_{0, \Omega}^2, \quad u_0 \in V.$$

We obtain by applying (1.9), where $u(t) = e^{tA_2} u_0$, $u_0 \in V$,

$$\begin{aligned} \langle \nabla_{\mathbf{a}}(A_2 u(t)) | \nabla_{\mathbf{a}} u(t) \rangle_{0, \Omega} &= -i\|\Delta_{\mathbf{a}} u(t)\|_{0, \Omega}^2 - \|\sqrt{d}\Delta_{\mathbf{a}} u\|_{0, \Gamma_0}^2 \\ &= -i\|\Delta_{\mathbf{a}} u(t)\|_{0, \Omega}^2 - \|\sqrt{d}u'(t)\|_{0, \Gamma_0}^2, \quad t > 0, \end{aligned}$$

and then

$$\begin{aligned} \frac{d}{dt} \mathcal{E}_{u_0}^2(t) &= \langle \nabla_{\mathbf{a}} u(t) | \nabla_{\mathbf{a}} u'(t) \rangle_{0, \Omega} = \langle \nabla_{\mathbf{a}}(A_2 u(t)) | \nabla_{\mathbf{a}} u(t) \rangle_{0, \Omega} \\ &= -\|\sqrt{d}\Delta_{\mathbf{a}} u\|_{0, \Gamma_0}^2 = -\|\sqrt{d}u'(t)\|_{0, \Gamma_0}^2, \quad t > 0. \end{aligned}$$

Here again, we see that $t \mapsto \mathcal{E}_{u_0}^2(t)$ is decreasing whenever $u_0 \neq 0$.

The third system is again an IBVP with a boundary damping

$$(1.10) \quad \begin{cases} iu_t + \Delta_{\mathbf{a}} u = 0 & \text{in } \Omega \times (0, +\infty), \\ \partial_{\nu_{\mathbf{a}}} u - idu = 0 & \text{on } \Gamma_0 \times (0, +\infty), \\ u = 0 & \text{on } \Gamma_1 \times (0, +\infty), \\ u(\cdot, 0) = u_0. \end{cases}$$

Define the unbounded operator $A_3 : L^2(\Omega) \rightarrow L^2(\Omega)$ given by

$$A_3 = i\Delta_{\mathbf{a}} \text{ and } D(A_3) = \{u \in V; \Delta_{\mathbf{a}} u \in L^2(\Omega) \text{ and } \partial_{\nu_{\mathbf{a}}} u - idu = 0 \text{ on } \Gamma_0\}.$$

In light of identity (1.2), for $u, v \in D(A_3)$, we have

$$(1.11) \quad \begin{aligned} (\Delta_{\mathbf{a}} u | v)_{0, \Omega} &= -(\nabla_{\mathbf{a}} u | \nabla_{\mathbf{a}} v)_{0, \Omega} + i(du | v)_{0, \Gamma_0} \\ &= (u, \Delta_{\mathbf{a}} v)_{0, \Omega}, \end{aligned}$$

from which we deduce that $-iA_3$ is self-adjoint and

$$\langle -iA_3 u, u \rangle_{0, \Omega} = -\|\nabla_{\mathbf{a}} u\|_{0, \Omega}^2.$$

That is $-iA_3 \leq 0$. We repeat the same argument for A_2 in order to derive that A_3 generates a strongly continuous group e^{tA_3} .

The energy corresponding to the system (1.10) is

$$\mathcal{E}_{u_0}^3(t) = \frac{1}{2} \|e^{tA_3} u_0\|_{0, \Omega}^2, \quad u_0 \in L^2(\Omega).$$

In light of (1.11), one gets

$$\frac{d}{dt} \mathcal{E}_{u_0}^3(t) = -\|\sqrt{d}u(t)\|_{0, \Gamma_0}^2, \quad t > 0,$$

where $u(t) = e^{tA_3}u_0$, $u_0 \in L^2(\Omega)$.

One more time, we observe that, if $u_0 \neq 0$ then $t \mapsto \mathcal{E}_{u_0}^3(t)$ is decreasing.

If $\overline{\Gamma_0} \cap \overline{\Gamma_1} \neq \emptyset$, we do not have necessarily $D(A_j) \subset H^2(\Omega)$. In order to avoid this case, we assume in the rest of this text, even if it is not always necessary, that $\overline{\Gamma_0} \cap \overline{\Gamma_1} = \emptyset$.

Prior to give sufficient condition guaranteeing that $D(A_j) \subset H^2(\Omega)$, $j = 2, 3$, we introduce, for $s \in \mathbb{R}$ and $1 \leq r \leq \infty$,

$$B_{s,r}(\mathbb{R}^{n-1}) := \{w \in \mathcal{S}'(\mathbb{R}^{n-1}); (1 + |\xi|^2)^{s/2} \widehat{w} \in L^r(\mathbb{R}^{n-1})\},$$

where $\mathcal{S}'(\mathbb{R}^{n-1})$ is the space of tempered distributions on \mathbb{R}^{n-1} and \widehat{w} is the Fourier transform of w . Endowed with its natural norm

$$\|w\|_{B_{s,r}(\mathbb{R}^{n-1})} := \|(1 + |\xi|^2)^{s/2} \widehat{w}\|_{L^r(\mathbb{R}^{n-1})},$$

$B_{s,r}(\mathbb{R}^{n-1})$ is a Banach space (it is noted that $B_{s,2}(\mathbb{R}^{n-1})$ is merely the usual Sobolev space $H^s(\mathbb{R}^{n-1})$). By using local charts and a partition of unity, we construct $B_{s,r}(\Gamma)$ from $B_{s,r}(\mathbb{R}^{n-1})$ similarly as $H^s(\Gamma)$ is built from $H^s(\mathbb{R}^{n-1})$.

The main interest in these spaces is that the multiplication by a function from $B_{s,1}(\Gamma_1)$, $s \geq 0$, defines a bounded operator on $H^s(\Gamma_1)$ (see [12, Theorem 2.1]).

Additionally to the previous conditions on \mathbf{a} and d , we assume in the sequel $\mathbf{a} \cdot \nu \in B_{1/2,1}(\Gamma_1)$ and there exists $\mathbf{d} \in B_{1/2,1}(\Gamma_1)$ so that $d = \mathbf{d}|_{\Gamma_1}$.

Under these supplementary assumptions, for $u \in D(A_j)$, $j = 2, 3$, $\partial_\nu u \in H^{1/2}(\Gamma_1)$ and, since

$$[2i\mathbf{a} \cdot \nabla + i\operatorname{div}(\mathbf{a}) - |\mathbf{a}|^2] u \in L^2(\Omega),$$

the usual H^2 -regularity for the Laplacian with mixed boundary conditions entail $u \in H^2(\Omega)$. Whence, $D(A_j) \subset H^2(\Omega)$, $j = 1, 2, 3$.

Remark 1.1. 1) Let $\psi \in W^{2,\infty}(\Omega, \mathbb{R})$ and denote by A_j^ψ , $j = 1, 2, 3$, the operator A_j in which we substituted \mathbf{a} by $\mathbf{a} + \nabla\psi$. Straightforward computations give

$$e^{-i\psi} \nabla_{\mathbf{a}} e^{i\psi} = \nabla_{\mathbf{a} + \nabla\psi}, \quad e^{-i\psi} \Delta_{\mathbf{a}} e^{i\psi} = \Delta_{\mathbf{a} + \nabla\psi}$$

and then

$$(1.12) \quad e^{tA_j^\psi} = e^{-i\psi} e^{tA_j} e^{i\psi}, \quad j = 1, 2, 3.$$

In particular,

$$\|e^{tA_j^\psi}\|_{\mathcal{B}(H)} = \|e^{tA_j}\|_{\mathcal{B}(H)}, \quad H = L^2(\Omega) \text{ for } j = 1, 3 \text{ and } H = V \text{ if } j = 2.$$

Let $\mathcal{E}_{u_0}^{j,\psi}$ the energy corresponding to A_j^ψ , with $u_0 \in L^2(\Omega)$, $j = 1, 3$ and $u_0 \in V$ for $j = 2$. In light of (1.12), we have

$$\mathcal{E}_{u_0}^{j,\psi} = \mathcal{E}_{e^{i\psi}u_0}^j, \quad j = 1, 2, 3.$$

2) Assume $n = 1$ and let $\Omega = (0, 1)$. Denote by A_j^0 the operator A_j when $\mathbf{a} = 0$, $j = 1, 2, 3$. Using that $\psi(x) = \int_0^x \mathbf{a}(t)dt$ satisfies $\partial_x \psi = \mathbf{a}$, we get from 1)

$$e^{tA_j} = e^{-i\psi} e^{tA_j^0} e^{i\psi} \quad \text{and} \quad \mathcal{E}_{u_0}^j = \mathcal{E}_{e^{i\psi}u_0}^{0,j}, \quad j = 1, 2, 3.$$

Here $\mathcal{E}_{u_0}^{0,j}$ is the energy corresponding to A_j^0 , $j = 1, 2, 3$. Therefore, all the results existing in the literature without the presence of magnetic potential can be transferred to the magnetic case.

3) According to [36, Theorem 6.7.5 and Proposition 6.8.2], observability inequalities for magnetic Schrödinger equations yield observability inequalities for magnetic wave equations and conversely.

1.5. Outline. The rest of this text is organized as follows. Section 2 is devoted to establish logarithmic decay of each of the energies $\mathcal{E}_{u_0}^j$, $j = 1, 2, 3$. The main step consists in proving a resolvent estimate via elliptic Carleman inequalities. Logarithmic energy decay is obtained by using an abstract theorem guaranteeing such decay when the resolvent satisfies some estimates. Note that in the actual section we do not impose any geometric condition on the subregion where the control acts. We revisit in section 3 the multiplier method with the objective to extend the existing results for the Schrödinger equation to the magnetic Schrödinger equation, provided that the magnetic potential satisfies certain conditions. In section 3, we need the usual geometric conditions on the control subregion. Namely, the boundary control region must contain a part of the boundary enlightened by a point in the space. For the internal control region, its boundary must contain again a part of the boundary enlightened by a point in the space. In the last section, we added supplementary comments. Precisely, we give an exponential stabilization estimate based on a direct application of a Carleman inequality and an observability inequality in a product space.

2. Logarithmic stabilization

We firstly recall some interior Carleman estimates as well as boundary Carleman estimates. For this last case we have several estimates depending on the a priori knowledge we have on traces. Next, we apply these inequalities in order to get resolvent estimates on imaginary axis, yielded to obtain energy decay of logarithmic type.

2.1. Carleman estimates. Carleman estimates can be viewed as weighted energy estimates with a large parameter. The crucial assumption is the sub-ellipticity condition introduced in this context by Hörmander [16].

Henceforth

$$X = (-2, 2) \times \Omega \text{ and } L = (-2, 2) \times \Gamma.$$

Denote by P an elliptic operator of order 2, with smooth coefficients. Denote its principal symbol by $p(y, \eta)$. For operators we consider in this text, we have $p(y, \eta) = |\eta|^2$.

Set, for $\varphi \in \mathcal{C}^\infty(\mathbb{R}^{n+1}, \mathbb{R})$,

$$p_\varphi(y, \eta, \tau) = p(y, \eta + i\tau d\varphi(y)).$$

Here d is the exterior derivative.

Definition 2.1. Let \mathcal{O} be a bounded open set in \mathbb{R}^{n+1} and $\varphi \in \mathcal{C}^\infty(\mathbb{R}^{n+1}, \mathbb{R})$. We say that (P, φ) satisfies the sub-ellipticity condition in $\overline{\mathcal{O}}$ if $|\nabla\varphi| > 0$ in $\overline{\mathcal{O}}$ and

$$(2.1) \quad p_\varphi(y, \eta, \tau) = 0, (y, \eta) \in \overline{\mathcal{O}} \times \mathbb{R}^{n+1}, \tau > 0 \Rightarrow \{\Im p_\varphi, \Re p_\varphi\}(y, \eta, \tau) > 0,$$

where $\{\cdot, \cdot\}$ is the usual Poisson bracket.

Remark 2.1. Note that the sub-ellipticity condition is not really too restrictive. To see that, pick $\psi \in \mathcal{C}^\infty(\mathbb{R}^{n+1}, \mathbb{R})$ such that $\nabla\psi(y) \neq 0$ for every $y \in \overline{\mathcal{O}}$. Then $\varphi(y) = e^{\lambda\psi(y)}$ satisfies obviously the sub-ellipticity property in $\overline{\mathcal{O}}$ if λ is chosen

sufficiently large. This gives a method to construct a weight function having the sub-ellipticity property in $\overline{\mathcal{O}}$ but other choices could be possible.

2.1.1. Interior Carleman estimate. The following Carleman estimate is classical and we can find a proof in Hörmander [16, Theorem 8.3.1].

Theorem 2.1. *Let U be an open subset of X and assume that (P, φ) obeys to the sub-ellipticity condition in \overline{U} . Then there exist $C > 0$ and $\tau_0 > 0$, such that*

$$(2.2) \quad \tau^3 \|e^{\tau\varphi} f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,X}^2 \leq C \|e^{\tau\varphi} Pf\|_{0,X}^2,$$

for all $\tau \geq \tau_0$, $f \in \mathcal{C}_0^\infty(U)$.

Remark 2.2. This theorem still holds if we substitute P by P plus a first order operator Q having bounded coefficients. For that it is enough to observe that

$$\|e^{\tau\varphi} Pf\|_{0,X} \leq \|e^{\tau\varphi}(P+Q)f\|_{0,X} + \|e^{\tau\varphi}Qf\|_{0,X}$$

and that the term $\|e^{\tau\varphi}Qf\|_{0,X}$ can be absorbed by the left hand side of (2.2), by modifying τ_0 if necessary.

2.1.2. Boundary Carleman estimates. For simplicity sake's, we use in the sequel the notation

$$Y = (-2, 2) \times \overline{\Omega}.$$

Let $y_0 \in L$ and \mathcal{O} be a neighborhood of y_0 in $(-2, 2) \times \mathbb{R}^n$. We say that $f \in \overline{\mathcal{C}_0^\infty}(\mathcal{O}|_X)$ if there exists $g \in \mathcal{C}_0^\infty(\mathcal{O})$ such that $f = g|_Y$. In particular $f \in \mathcal{C}^\infty(Y)$. This definition allows functions with non null traces on ∂X but with null traces on $\partial(\mathcal{O} \cap X) \setminus L$. The following theorem is proved in [22, Proposition 1].

Theorem 2.2. *Let $y_0 \in \partial X$ and \mathcal{O} a neighborhood of y_0 in $(-2, 2) \times \mathbb{R}^n$ and assume that (P, φ) satisfies the sub-ellipticity condition in $\overline{\mathcal{O} \cap X}$. We also assume that $\partial_\nu \varphi(y) \neq 0$ in $\overline{\partial\mathcal{O} \cap \partial X}$. Then there exist $C > 0$ and $\tau_0 > 0$, such that*

$$\begin{aligned} & \tau^3 \|e^{\tau\varphi} f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,L}^2 \\ & \leq C (\|e^{\tau\varphi} Pf\|_{0,X}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,L}^2 + \tau \|e^{\tau\varphi} \partial_\nu f\|_{0,L}^2), \end{aligned}$$

for all $\tau \geq \tau_0$, $f \in \overline{\mathcal{C}_0^\infty}(\mathcal{O}|_X)$.

This Carleman estimate is useful when we know Dirichlet and Neumann traces of f on a part of the boundary. It allows to estimate the function f in an interior domain by its Dirichlet and Neumann traces on a part of the boundary and Pf .

The two next theorems only assume that the knowledge of the Dirichlet trace or Neumann trace. They allow to estimate the function f up to the boundary by Pf and a priori knowledge of f in a small domain contained in X .

Henceforth, ∇_T denotes the tangential gradient on Σ . The following theorem is proved in [21, Proposition 1]

Theorem 2.3. *Let $y_0 \in \partial X$ and \mathcal{O} a neighborhood of y_0 in $(-2, 2) \times \mathbb{R}^n$, assume that (P, φ) satisfies the sub-ellipticity condition in $\overline{\mathcal{O} \cap X}$ and $\partial_\nu \varphi(y) < 0$ on $\overline{\partial\mathcal{O} \cap \partial X}$. Then there exist $C > 0$ and $\tau_0 > 0$, such that*

$$\begin{aligned} & \tau^3 \|e^{\tau\varphi} f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \partial_\nu f\|_{0,L}^2 \\ & \leq C (\|e^{\tau\varphi} Pf\|_{0,X}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,L}^2 + \tau \|e^{\tau\varphi} \nabla_T f\|_{0,L}^2), \end{aligned}$$

for all $\tau \geq \tau_0$, $f \in \overline{\mathcal{C}_0^\infty}(\mathcal{O}|_X)$.

The following theorem is a consequence of [22, Lemma 4].

Theorem 2.4. *Let $y_0 \in \partial X$ and \mathcal{O} a neighborhood of y_0 in $(-2, 2) \times \mathbb{R}^n$, assume that (P, φ) satisfies the sub-ellipticity condition in $\overline{\mathcal{O} \cap X}$ and $\partial_\nu \varphi(y) < 0$ on $\overline{\partial \mathcal{O} \cap \partial X}$. Then there exist $C > 0$ and $\tau_0 > 0$, such that*

$$\begin{aligned} & \tau^3 \|e^{\tau\varphi} f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,X}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,L}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,L}^2 \\ & \leq C (\|e^{\tau\varphi} P f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \partial_\nu f\|_{0,L}^2), \end{aligned}$$

for all $\tau \geq \tau_0$, $f \in \overline{\mathcal{C}_0^\infty}(\mathcal{O}|_X)$.

2.1.3. Global Carleman estimates. We can patch together the interior and boundary Carleman estimates to obtain a global one. The global Carleman estimate we obtain will be very useful to tackle the stabilization issue for system (1.6).

Theorem 2.5. *Let Z be a open subset of X and assume that (P, φ) satisfies the sub-ellipticity condition in $Y \setminus Z$. Assume moreover that $\partial_\nu \varphi(y) < 0$ in L . Then there exist $C > 0$ and $\tau_0 > 0$, such that*

$$\begin{aligned} & C (\tau^3 \|e^{\tau\varphi} f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \partial_\nu f\|_{0,L}^2) \\ & \leq \|e^{\tau\varphi} P f\|_{0,X}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,L}^2 + \tau \|e^{\tau\varphi} \nabla_T f\|_{0,L}^2 \\ & \quad + \|e^{\tau\varphi} f\|_{0,Z}^2 + \|e^{\tau\varphi} \nabla f\|_{0,Z}^2, \end{aligned}$$

for all $\tau \geq \tau_0$, $f \in \mathcal{C}^\infty(\overline{X})$.

We now state a theorem that we will use to deal with stabilization issue for systems (1.7) and (1.10)

Set

$$L_j = (-2, 2) \times \Gamma_j, \quad j = 0, 1.$$

Theorem 2.6. *Let Λ an open subset of L_0 . Assume that (P, φ) satisfies the sub-ellipticity condition in Y and $\partial_\nu \varphi(y) < 0$ in $L \setminus \Lambda$. Then there exist $C > 0$ and $\tau_0 > 0$, such that*

$$\begin{aligned} & C (\tau^3 \|e^{\tau\varphi} f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,X}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,L}^2 + \tau \|e^{\tau\varphi} \nabla f\|_{0,L}^2) \\ & \leq \|e^{\tau\varphi} P f\|_{0,X}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,L_1}^2 + \tau \|e^{\tau\varphi} \nabla_T f\|_{0,L_1}^2 \\ & \quad + \tau \|e^{\tau\varphi} \partial_\nu f\|_{0,L_0 \setminus \Lambda}^2 + \tau^3 \|e^{\tau\varphi} f\|_{0,\Lambda}^2 + \tau \|e^{\tau\varphi} \partial_\nu f\|_{0,\Lambda}^2, \end{aligned}$$

for all $\tau \geq \tau_0$, $f \in \mathcal{C}^\infty(\overline{X})$.

The assumptions on the weight function may impose some constraints on the topology of Ω . In Theorem 2.5, if φ satisfies $\partial_\nu \varphi(y) < 0$ in L , φ has a maximum in X , thus we have to impose that this maximum belongs to Z . In Theorem 2.6, we need $\nabla \varphi \neq 0$ in Y . This is always possible as long as we do not assume that $\partial_\nu \varphi$ is of constant sign on Z . However one can construct weight functions φ obeying to the assumptions of the preceding theorems.

Proposition 2.1. *Let Z an open subset of X . There exists $\psi \in \mathcal{C}^\infty(\overline{X})$ such that $\partial_\nu \psi < 0$ on L and $\nabla \psi \neq 0$ in $Y \setminus Z$.*

Proposition 2.2. *Let Λ be an open subset of L_0 . There exists $\psi \in \mathcal{C}^\infty(\overline{X})$ such that $\partial_\nu \psi < 0$ on $L \setminus \Lambda$ and $\nabla \psi \neq 0$ in Y .*

To prove the existence of such functions ψ , we first construct ψ in a neighborhood of L (resp. $L \setminus \Lambda$). Next, we extend this function to Y and approximate the extended function by a Morse function. Finally, we *push* the singularities in Z along paths to singularities in a point in Z (resp. in the exterior of X along paths passing through Λ). We refer to Milnor [32] and Fursikov-Imanuvilov [14] for a proof. One can then check that $\varphi = e^{\lambda\psi}$ possesses the assumptions of Theorem 2.5 (resp. Theorem 2.6) for ψ constructed in Proposition 2.1 (resp. Proposition 2.2).

2.2. Stabilization by a resolvent estimate. The resolvent set of an operator B will be denoted by $\rho(B)$.

The following abstract theorem is the key tool in establishing the logarithmic stabilization for each of the three systems we are interested in.

Theorem 2.7. *Let B be the generator of a continuous semigroup e^{tB} on a Hilbert space H . Assume that*

(i) $\sup_{t \geq 0} \|e^{tB}\|_{\mathcal{B}(H)} < \infty,$

(ii) $i\mathbb{R} \subset \rho(B),$

(iii) $\|(B - i\mu)^{-1}\|_{\mathcal{B}(H)} \leq Ce^{K\sqrt{|\mu|}}, \mu \in \mathbb{R},$ for some constants $C > 0$ and $K > 0.$

Then there exists a constant $C_1 > 0,$ such that

$$\|e^{tB}f\|_H \leq \frac{C_1}{\ln^{2k}(2+t)} \|f\|_{D(B^k)}, \quad f \in D(B^k)$$

or equivalently

$$\|e^{tB}B^{-k}\|_{\mathcal{B}(H)} \leq \frac{C_1}{\ln^{2k}(2+t)}.$$

This result is a particular case of [7, Theorem 1.5].

2.2.1. Interior damping. We deal in this subsection with the system (1.6). Specifically we are going to apply Theorem 2.7 with $B = A_1$ and $H = L^2(\Omega)$. We have

Theorem 2.8. *For every $\mu \in \mathbb{R}, A_1 - i\mu$ is invertible and*

(i) $\|(A_1 - i\mu)^{-1}\|_{\mathcal{B}(L^2(\Omega))} \leq Ce^{K\sqrt{|\mu|}}, \mu \in \mathbb{R},$ for some constants $C > 0$ and $K > 0,$

(ii) *there exists a constant $C_1 > 0,$ such that*

$$\|e^{tA_1}u_0\|_{\mathcal{B}(L^2(\Omega))} \leq \frac{C_1}{\ln^{2k}(2+t)} \|u_0\|_{D(A_1^k)}, \quad u_0 \in D(A_1^k).$$

Proof. Let us first consider the resolvent equation $(A_1 - i\mu)u = g, g \in L^2(\Omega)$. Changing g by $-ig,$ we are lead to solve

$$(2.3) \quad \Delta_{\mathbf{a}}u + icu - \mu u = g.$$

Multiplying this equation by \bar{u} and integrating on $\Omega,$ we have

$$(\Delta_{\mathbf{a}}u|u)_{0,\Omega} + i(cu|u)_{0,\Omega} - \mu(u|u)_0 = (g|u)_{0,\Omega},$$

We obtain by applying (1.1)

$$(2.4) \quad -\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 + i(cu|u)_{0,\Omega} - \mu\|u\|_0^2 = (g|u)_{0,\Omega}.$$

Taking the real part of this equation, we obtain

$$-\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 = \langle g|u \rangle_{0,\Omega}.$$

If $\mu \geq 0$, this estimate entails

$$\|\nabla_{\mathbf{a}}u\|_{0,\Omega} \leq \|g\|_{0,\Omega}$$

and hence

$$\|u\|_{0,\Omega} \leq \varkappa k \|g\|_{0,\Omega}, \quad \mu \geq 0.$$

Here \varkappa is the Poincaré constant of $H_0^1(\Omega)$ and k is a constant so that $\|\nabla w\|_{0,\Omega} \leq k \|\nabla_{\mathbf{a}}w\|_{0,\Omega}$, for each $w \in H_0^1(\Omega)$. In other words, we proved the resolvent estimate when $\mu \geq 0$.

Next, simple computations show that $(iA_1)^* = iA_1 + 2ic$. Whence

$$\text{ind}(iA_1 + \mu) = -\text{ind}(iA_1 + 2ic + \mu) = -\text{ind}(iA_1 + \mu)$$

and then $\text{ind}(iA_1 + \mu) = 0$. Therefore, $A_1 - i\mu$ is invertible if and only if it is injective.

To prove that $A_1 - i\mu$ is injective, take, for $g = 0$, the imaginary part of equation (2.4) in order to obtain that $u = 0$ in ω . Hence $\Delta_{\mathbf{a}}u + icu - \mu u = 0$ in Ω and $u = 0$ in ω . Then, by the unique continuation property, $u = 0$ in Ω .

We complete the proof by establishing the resolvent estimate when $\mu < 0$. By continuity argument, we are reduced to prove the resolvent estimate for large $|\mu|$. To do that, we obtain, by taking again the imaginary part of equation (2.4),

$$(2.5) \quad c_0 \|u\|_{0,\omega}^2 \leq \|u\|_{0,\Omega} \|g\|_{0,\Omega}.$$

Now are now going to apply a Carleman inequality to estimate $\|u\|_{0,\Omega}$ in term of $\|u\|_{0,\omega}$. To this end, define $f(s, x) = e^{\alpha s}u(x)$, where $\alpha = \sqrt{-\mu}$. Since u is the solution of (2.3), we easily get that f satisfies

$$(2.6) \quad \partial_s^2 f + \Delta_{\mathbf{a}}f + icf = e^{s\alpha}g.$$

Fix $\omega' \Subset \omega$ and set

$$X_1 = (-1, 1) \times \Omega \text{ and } X_2 = (-1/2, 1/2) \times \omega'.$$

Pick $\chi \in \mathcal{C}_0^\infty(\mathbb{R})$, such that $\chi(s) = 1$ for $|s| \leq 3/4$ and $\chi(s) = 0$ for $|s| \geq 1$. We put

$$\varphi(s, x) = e^{\lambda(-\beta s^2 + \psi(x))},$$

where ψ satisfies Proposition 2.1 and $\beta > 0$ fixed in what follows. The critical points of $-\beta s^2 + \psi(x)$ are located in X_2 . Then for λ sufficiently large (but fixed from now on) (P, φ) satisfies the sub-ellipticity condition according to Remark 2.1, with $P = \partial_s^2 + \Delta_{\mathbf{a}} + ic$. We can apply Theorem 2.5, with χf instead of f . We obtain as χf satisfies the Dirichlet boundary condition

$$(2.7) \quad \tau^3 \|e^{\tau\varphi}\chi f\|_{0,X}^2 + \tau \|e^{\tau\varphi}\nabla(\chi f)\|_{0,X}^2 \lesssim \|e^{\tau\varphi}(\partial_s^2(\chi f) + \Delta_{\mathbf{a}}(\chi f) + ic\chi f)\|_{0,X}^2 \\ + \|e^{\tau\varphi}f\|_{0,X_2}^2 + \|e^{\tau\varphi}\nabla f\|_{0,X_2}^2.$$

Here and until the end of this proof, $Q_1 \lesssim Q_2$ means that $Q_1 \leq CQ_2$, for some generic constant C , only depending on Ω , ψ , \mathbf{a} and c .

We have

$$\partial_s^2(\chi f) + \Delta_{\mathbf{a}}(\chi f) + ia\chi f = e^{s\alpha}\chi g + 2\partial_s\chi\partial_s f + f\partial_s^2\chi.$$

As $\partial_s\chi$ is supported in the set $\{s \in \mathbb{R}, 3/4 \leq |s| \leq 1\}$, we get

$$(2.8) \quad \|e^{\tau\varphi}(2\partial_s\chi\partial_s f + f\partial_s^2\chi)\|_{0,X}^2 \lesssim \alpha e^{C_1\tau+2\alpha} \|u\|_{0,\Omega}^2,$$

with $C_1 = e^{\lambda(-9\beta/16 + \max_\Omega \psi)}$.

On the other hand

$$(2.9) \quad \|e^{\tau\varphi} f\|_{0, X_2}^2 + \|e^{\tau\varphi} \nabla f\|_{0, X_2}^2 \lesssim \alpha e^{\tau C_3 + 2\alpha} \|u\|_{1, \omega'}^2,$$

$$(2.10) \quad \|e^{\tau\varphi} \chi f\|_{0, \Omega}^2 \lesssim e^{\tau C_3 + 2\alpha} \|g\|_{0, \Omega}^2.$$

where $C_3 = 2e^{\lambda \max_{\Omega} \psi}$.

Inequalities (2.8), (2.9) and (2.10) in (2.7) yield

$$(2.11) \quad \tau^3 \|e^{\tau\varphi} \chi f\|_{0, X}^2 + \tau \|e^{\tau\varphi} \nabla(\chi f)\|_{0, X}^2 \lesssim \alpha e^{\tau C_3 + 2\alpha} (\|u\|_{1, \omega'}^2 + \|g\|_{0, \Omega}^2) + \alpha e^{C_1 \tau + 2\alpha} \|u\|_{0, \Omega}^2.$$

Let $\chi_0^2 \in \mathcal{C}_0^\infty(\omega)$ where $\chi_0 = 1$ on ω' . We multiply (2.3) by $\chi_0^2 \bar{u}$ and we make an integration by parts. We obtain

$$\|\nabla u\|_{0, \omega'}^2 \lesssim \alpha \|u\|_{0, \omega}^2 + \|g\|_{0, \Omega}^2$$

for which we deduce

$$(2.12) \quad \tau^3 \|e^{\tau\varphi} \chi f\|_{0, X}^2 + \tau \|e^{\tau\varphi} \nabla(\chi f)\|_{0, X}^2 \lesssim \alpha^2 e^{\tau C_3 + 2\alpha} (\|u\|_{0, \omega}^2 + \|g\|_{0, \Omega}^2) + \alpha e^{C_1 \tau + 2\alpha} \|u\|_{0, \Omega}^2.$$

In the set $X \cap \{(s, x); |s| \leq 1/2\}$, $\chi = 1$ and

$$\varphi \geq e^{\lambda(-\beta/4 + \min_{\Omega} \psi)}.$$

Then $e^{2\tau\varphi} \geq e^{\tau C_2}$, where

$$C_2 = 2e^{\lambda(-\beta/4 + \min_{\Omega} \psi)}.$$

Fix then β sufficiently large in such a way that $C_1 < C_2 < C_3$. From (2.12) we thus obtain

$$e^{\tau C_2 + \alpha} \|u\|_{0, \Omega}^2 \lesssim \alpha^2 e^{\tau C_3 + 2\alpha} (\|u\|_{0, \omega}^2 + \|g\|_{0, \Omega}^2) + \alpha e^{C_1 \tau + 2\alpha} \|u\|_{0, \Omega}^2.$$

Taking $\tau = \gamma\alpha = \gamma\sqrt{|\mu|}$ with γ sufficiently large, there exist $C_4, C_5 > 0$ such that

$$\|u\|_{0, \Omega}^2 \lesssim e^{C_4 \alpha} (\|u\|_{0, \omega}^2 + \|g\|_{0, \Omega}^2) + e^{-C_5 \alpha} \|u\|_{0, \Omega}^2.$$

For α sufficiently large, we have

$$\|u\|_{0, \Omega}^2 \lesssim e^{C_4 \alpha} (\|u\|_{0, \Omega}^2 + \|g\|_{0, \Omega}^2).$$

From (2.5) we have

$$\|u\|_{0, \Omega}^2 \leq K e^{C_4 \alpha} (\|u\|_{0, \Omega} \|g\|_{0, \Omega} + \|g\|_{0, \Omega}^2).$$

As

$$K e^{C_4 \alpha} \|u\|_{0, \Omega} \|g\|_{0, \Omega} \leq \|u\|_{0, \Omega}^2 / 2 + e^{2C_4 \alpha} \|g\|_{0, \Omega}^2,$$

we obtain

$$\|u\|_{0, \Omega}^2 \lesssim e^{2C_4 \alpha} \|g\|_{0, \Omega}^2,$$

which is exactly the expected resolvent estimate. \square

2.2.2. *Boundary damping.* Similarly to the first system, we have for (1.7) the following result.

Theorem 2.9. *For every $\mu \in \mathbb{R}$, $A_2 - i\mu$ is invertible and*

- (i) $\|(A_2 - i\mu)^{-1}\|_{\mathcal{B}(V)} \leq Ce^{K\sqrt{|\mu|}}$, $\mu \in \mathbb{R}$, for some constants $C > 0$ and $K > 0$,
- (ii) *there exists a constant $C_1 > 0$, such that*

$$\|e^{tA_2}u_0\|_V \leq \frac{C_1}{\ln^{2k}(2+t)} \|u_0\|_{D(A_2^k)}, \quad u_0 \in D(A_2^k).$$

Proof. We are going to prove that $B = A_2$ obeys to the conditions of Theorem 2.7 when $H = V$. As in the preceding proof, we solve the resolvent equation: for $g \in V$, find $u \in D(A_2)$ satisfying

$$(A_2 - i\mu)u = g.$$

Substituting g by $-ig$, we are reduced the following equation: find $u \in D(A_2)$ so that

$$(2.13) \quad \Delta_{\mathbf{a}}u - \mu u = g.$$

Multiply this equation by \bar{u} and integrate over Ω in order to get

$$(\Delta_{\mathbf{a}}u|u)_{0,\Omega} - \mu(u|u)_{0,\Omega} = (g|u)_{0,\Omega},$$

In combination with (1.1), this identity yields

$$-\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 + (\partial_{\nu_A}u|u)_{0,\Gamma_0} = (g|u)_{0,\Omega}.$$

As $\partial_{\nu_A}u = -id\Delta_{\mathbf{a}}u$ and $\Delta_{\mathbf{a}}u = \mu u + g$ on Γ_0 , we have

$$(2.14) \quad -\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 - i\mu\|\sqrt{d}u\|_{0,\Gamma_0} = (g|u)_{0,\Omega} + i(dg|u)_{0,\Gamma_0}.$$

Taking the real part, we get

$$(2.15) \quad -\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 = \langle g|u \rangle_{0,\Omega} + \langle idg|u \rangle_{0,\Gamma_0}.$$

For $\mu \geq 0$, we have

$$\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 + \mu\|u\|_{0,\Omega}^2 \leq \|g\|_{0,\Omega}\|u\|_{0,\Omega} + \|d\|_{\infty}\|g\|_{0,\Gamma_0}\|u\|_{0,\Gamma_0}.$$

We know that $\|\nabla_{\mathbf{a}} \cdot \|_{0,\Omega}$ is equivalent to the natural norm of V induced by that on $H_0^1(\Omega)$. Therefore, the trace operator $\mathbf{tr} : V \rightarrow L^2(\Gamma_0)$ is bounded when V is endowed with norm $\|\nabla_{\mathbf{a}} \cdot \|_{0,\Omega}$.

Thus, we have

$$\begin{aligned} \|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 + \mu\|u\|_{0,\Omega}^2 &\leq \varkappa_1^2\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega} + \|d\|_{\infty}\|\mathbf{tr}\|\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega} \\ &\leq (\varkappa_1^2 + \|d\|_{\infty}\|\mathbf{tr}\|^2)\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}, \end{aligned}$$

where $\|\mathbf{tr}\|$ denotes the norm of \mathbf{tr} in $\mathcal{B}(V, L^2(\Gamma_0))$ and \varkappa_1 is the Poincaré constant of V . In particular

$$(2.16) \quad \|\nabla_{\mathbf{a}}u\|_{0,\Omega} \leq (\varkappa_1^2 + \|d\|_{\infty}\|\mathbf{tr}\|^2)\|\nabla_{\mathbf{a}}g\|_{0,\Omega}$$

This is nothing but the resolvent estimate for $\mu \geq 0$.

Now as iA_2 is self-adjoint, $\text{ind}(iA_2 + \mu) = 0$ for any $\mu \in \mathbb{R}$. Then $A_2 - i\mu$ will be invertible if we show that it is injective. If $\mu \neq 0$, take $g = 0$ and then the imaginary part in part (2.14) to get $u = 0$ on γ_0 yielding $\partial_{\nu}u = 0$ on γ_0 . Whence $u = 0$ by the unique continuation property. Obviously, $g = 0$ and $\mu = 0$ entail $\nabla_{\mathbf{a}}u = 0$ and then $u = 0$.

To complete the proof, it remains to prove the resolvent estimate for $\mu < 0$. As in the preceding proof it is enough to establish such an estimate for $|\mu|$ large. To this end, taking one more time the imaginary part of (2.14), we obtain

$$(2.17) \quad -\mu \|\sqrt{d}u\|_{0,\Gamma_0}^2 = -\langle ig|u \rangle_{0,\Omega} + \langle dg|u \rangle_{0,\Gamma_0}.$$

From (2.17), we get by using the continuity of the trace operator \mathbf{tr} and $|\mu| \geq 1$,

$$(2.18) \quad d_0 \|u\|_{0,\gamma_0}^2 \leq \|d\|_\infty \|\mathbf{tr}\|^2 \|\nabla_{\mathbf{a}}g\|_{0,\Omega} \|\nabla_{\mathbf{a}}u\|_{0,\Omega}.$$

Next we proceed as in the preceding theorem. We first use a Carleman inequality to estimate $\|\nabla_{\mathbf{a}}u\|_{0,\Omega}$ by $\|u\|_{0,\Gamma_0}$. Set $f(s, x) = e^{\alpha s}u(x)$, where $s \in (-2, 2)$ and $\alpha = \sqrt{-\mu}$. Then it is straightforward to check that f satisfies

$$(2.19) \quad Pf = \partial_s^2 f + \Delta_{\mathbf{a}}f = e^{s\alpha}g.$$

Recall that

$$X = (-2, 2) \times \Omega, \quad X_1 = (-1, 1) \times \Omega$$

and define

$$\ell_0 = (-1/2, 1/2) \times \gamma_0.$$

Let $\chi \in \mathcal{C}_0^\infty(\mathbb{R})$, such that $\chi(s) = 1$ for $|s| \leq 3/4$ and $\chi(s) = 0$ for $|s| \geq 1$. We set

$$\varphi(s, x) = e^{\lambda(-\beta s^2 + \psi(x))},$$

where ψ satisfies Proposition 2.2 and $\beta > 0$ fixed in what follows. The function $-\beta s^2 + \psi(x)$ has no critical point in X . Then for λ sufficiently large (but fixed from now on) (P, φ) satisfies the sub-ellipticity condition of Remark 2.1.

In the rest of this proof $Q_1 \lesssim Q_2$ means $Q_1 \leq CQ_2$, for some generic constant C , only depending on n, Ω, \mathbf{a} and d .

We can apply Theorem 2.6, with χf instead of f . As χf satisfies Dirichlet boundary condition on Γ_1 and as $\partial_{\nu_{\mathbf{a}}} = \partial_\nu + i\mathbf{a}$, we get $\tau^3 \|e^{\tau\varphi}f\|_{0,\ell_0}^2 + \tau \|e^{\tau\varphi}\partial_\nu f\|_{0,\ell_0}^2$ is equivalent to $\tau^3 \|e^{\tau\varphi}f\|_{0,\ell_0}^2 + \tau \|e^{\tau\varphi}\partial_{\nu_{\mathbf{a}}}f\|_{0,\ell_0}^2$. Then

$$(2.20) \quad \begin{aligned} \tau^3 \|e^{\tau\varphi}\chi f\|_{0,X}^2 + \tau \|e^{\tau\varphi}\nabla(\chi f)\|_{0,X}^2 &\lesssim \|e^{\tau\varphi}P(\chi f)\|_{0,X}^2 \\ &+ \tau \|e^{\tau\varphi}\partial_{\nu_{\mathbf{a}}}f\|_{0,L_0 \setminus \ell_0}^2 + \tau^3 \|e^{\tau\varphi}f\|_{0,\ell_0}^2 + \tau \|e^{\tau\varphi}\partial_{\nu_{\mathbf{a}}}f\|_{0,\ell_0}^2. \end{aligned}$$

We recall the constants defined in the previous section,

$$(2.21) \quad \begin{aligned} C_1 &= 2e^{\lambda(-9\beta/16 + \sup_\Omega \psi)}, \\ C_2 &= 2e^{\lambda(-\beta/4 + \min_\Omega \psi)}, \\ C_3 &= 2e^{\lambda \sup_\Omega \psi(x)}. \end{aligned}$$

Similarly to the previous section, we have

$$(2.22) \quad \begin{aligned} \|e^{\tau\varphi}P(\chi f)\|_{0,X}^2 &\lesssim e^{2\alpha + C_3\tau} \|\nabla_{\mathbf{a}}g\|_{0,\Omega}^2 + e^{2\alpha + C_1\tau} \|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2, \\ \|e^{\tau\varphi}f\|_{0,\ell_0}^2 &\lesssim e^{2\alpha + C_3\tau} \|u\|_{0,\gamma_0}^2 \lesssim e^{2\alpha + C_3\tau} \|\nabla_{\mathbf{a}}g\|_{0,\Omega} \|\nabla_{\mathbf{a}}u\|_{0,\Omega}, \end{aligned}$$

from (2.18). The two other terms of the right hand side of (2.20) may be estimated by $\|e^{\tau\varphi}\partial_{\nu_{\mathbf{a}}}f\|_{0,L_0}^2$. We have

$$(\partial_{\nu_A}f)|_{L_0} = e^{\alpha s}(\partial_{\nu_A}u)|_{\Gamma_0} = -ide^{\alpha s}(\Delta_{\mathbf{a}}u)|_{\Gamma_0} = -ide^{\alpha s}(g + \mu u)|_{\Gamma_0}.$$

Whence

$$(2.23) \quad \begin{aligned} \|e^{\tau\varphi}\partial_{\nu_{\mathbf{a}}}f\|_{0,L_0}^2 &\lesssim e^{2\alpha+C_3\tau}(\|g\|_{0,\Gamma_0}^2 + |\mu|^2\|d^{1/2}u\|_{0,\Gamma_0}^2) \\ &\lesssim e^{2\alpha+C_3\tau}(\|\nabla_{\mathbf{a}}g\|_{0,\Omega}^2 + \alpha^4\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}). \end{aligned}$$

On the other hand, it is straightforward to check

$$(2.24) \quad \tau^3\|e^{\tau\varphi}\chi f\|_{0,X}^2 + \tau\|e^{\tau\varphi}\nabla(\chi f)\|_{0,X}^2 \gtrsim \tau^3\|e^{\tau\varphi}f\|_{0,(-1/2,1/2)\times\Omega}^2$$

$$(2.25) \quad \begin{aligned} &+ \tau\|e^{\tau\varphi}\nabla f\|_{0,(-1/2,1/2)\times\Omega}^2 \\ &\gtrsim e^{\alpha+\tau C_2}(\|u\|_{0,\Omega}^2 + \|\nabla u\|_{0,\Omega}^2). \end{aligned}$$

Inequalities (2.20) and (2.22) to (2.24) yield

$$\begin{aligned} e^{\alpha+\tau C_2}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 &\lesssim e^{2\alpha+C_3\tau}(\|\nabla_{\mathbf{a}}g\|_{0,\Omega}^2 + \alpha^4\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}) + \alpha e^{2\alpha+C_1\tau}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2. \end{aligned}$$

As we have done in the preceding proof, taking β sufficiently large, we have $C_1 < C_2 < C_3$ and, for $\tau = \gamma\alpha$ with γ sufficiently large, we find $C_4 > 0$ and $C_5 > 0$ so that

$$\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 \leq C e^{C_4\alpha}(\|\nabla_{\mathbf{a}}g\|_{0,\Omega}^2 + \alpha^4\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}) + C e^{-C_5\alpha}\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2.$$

Choose α sufficiently large in such a way that $C e^{-C_5\alpha} \leq 1/4$. Then

$$C\alpha^4 e^{C_4\alpha}\|\nabla_{\mathbf{a}}g\|_{0,\Omega}\|\nabla_{\mathbf{a}}u\|_{0,\Omega} \leq C^2\alpha^8 e^{2C_4\alpha}\|\nabla_{\mathbf{a}}g\|_{0,\Omega}^2 + \|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2/2.$$

The last two estimates entail

$$(2.26) \quad \|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 \leq C e^{C\alpha}\|\nabla_{\mathbf{a}}g\|_{0,\Omega}^2.$$

The proof is then complete. \square

We move now to the system (1.10) for which we aim to prove the following theorem.

Theorem 2.10. *For every $\mu \in \mathbb{R}$, $A_3 - i\mu$ is invertible and*

- (i) $\|(A_3 - i\mu)^{-1}\|_{\mathcal{B}(L^2(\Omega))} \leq C e^{K\sqrt{|\mu|}}$, $\mu \in \mathbb{R}$, for some constants $C > 0$ and K ,
- (ii) there exists a constant $C_1 > 0$, such that

$$\|e^{tA_3}u_0\|_{0,\Omega} \leq \frac{C_1}{\ln^{2k}(2+t)}\|u_0\|_{D(A_3^k)}, \quad u_0 \in D(A_3^k).$$

Proof. As in the preceding two proofs, we first solve the resolvent equation: for $g \in L^2(\Omega)$, find $u \in D(A_3)$ so that

$$(2.27) \quad \Delta_{\mathbf{a}}u - \mu u = g.$$

With the help of identity (1.1), we get

$$-\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 + (\partial_{\nu_{\mathbf{A}}}u|u)_{0,\Gamma_0} = (g|u)_{0,\Omega}.$$

As $\partial_{\nu_{\mathbf{A}}}u = idu$, we have

$$(2.28) \quad -\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 + i\|\sqrt{d}u\|_{0,\Gamma_0}^2 = (g|u)_{0,\Omega}.$$

Take the real part of each side in order to derive

$$(2.29) \quad -\|\nabla_{\mathbf{a}}u\|_{0,\Omega}^2 - \mu\|u\|_{0,\Omega}^2 = \langle g|u \rangle_{0,\Omega}.$$

When $\mu \geq 0$, we obtain

$$(2.30) \quad \|\nabla_{\mathbf{a}}u\|_{0,\Omega} \leq \|g\|_{0,\Omega}.$$

This and Poincaré inequality on V imply the resolvent estimate when $\mu \geq 0$.

As for A_2 , since iA_3 is self adjoint $\text{ind}(iA_3 + \mu) = 0$ and then $A_3 - i\mu$ is invertible since it is injective. This last fact is again a consequence of a unique continuation property.

Next assume that $\mu < 0$. We get by taking the imaginary part of each side of (2.28)

$$\|\sqrt{d}u\|_{0,\Gamma_0}^2 = -\langle ig|u\rangle_{0,\Omega}.$$

Hence

$$(2.31) \quad d_0 \|u\|_{0,\gamma_0}^2 \leq \|g\|_{0,\Omega} \|u\|_{0,\Omega}.$$

In this proof \lesssim has the same meaning as in the proof of Theorem 2.9.

With the notations of the preceding proof, we have

$$(2.32) \quad \begin{aligned} \|e^{\tau\varphi} P(\chi f)\|_{0,X}^2 &\lesssim e^{2\alpha+C_3\tau} \|g\|_{0,\Omega}^2 + \alpha e^{2\alpha+C_1\tau} \|u\|_{1,\Omega}^2 \\ \|e^{\tau\varphi} f\|_{0,L_0}^2 &\lesssim e^{2\alpha+C_3\tau} \|u\|_{L^2(\gamma_0)}^2 \lesssim e^{2\alpha+C_3\tau} \|g\|_{0,\Omega} \|u\|_{0,\Omega}, \end{aligned}$$

where we used (2.31).

The two other terms of the right hand side of (2.20) are estimated by $\|e^{\tau\varphi} \partial_{\nu_a} f\|_{0,L_0}^2$. We have

$$(\partial_{\nu_a} f)|_{L_0} = e^{\alpha s} (\partial_{\nu_a} u)|_{\Gamma_0} = i d e^{\alpha s} u|_{\Gamma_0}.$$

Whence, using (2.31), we get

$$(2.33) \quad \begin{aligned} \|e^{\tau\varphi} \partial_{\nu_a} f\|_{0,L_0}^2 &\lesssim e^{2\alpha+C_3\tau} \|\sqrt{d}u\|_{0,\Gamma_0}^2 \\ &\lesssim e^{2\alpha+C_3\tau} \|g\|_{0,\Omega} \|u\|_{0,\Omega}. \end{aligned}$$

On the other hand,

$$(2.34) \quad \begin{aligned} \tau^3 \|e^{\tau\varphi} \chi f\|_{0,X}^2 + \tau \|e^{\tau\varphi} \nabla(\chi f)\|_{0,X}^2 &\gtrsim \tau^3 \|e^{\tau\varphi} f\|_{0,(-1/2,1/2)\times\Omega}^2 \\ &\quad + \tau \|e^{\tau\varphi} \nabla f\|_{0,(-1/2,1/2)\times\Omega}^2 \\ &\gtrsim e^{\alpha+\tau C_2} (\|u\|_{0,\Omega}^2 + \|\nabla u\|_{0,\Omega}^2). \end{aligned}$$

Estimates (2.20) and (2.32) to (2.34), imply

$$(2.35) \quad e^{\alpha+\tau C_2} \|u\|_{1,\Omega}^2 \lesssim e^{2\alpha+C_3\tau} (\|g\|_{0,\Omega}^2 + \|g\|_{0,\Omega} \|u\|_{0,\Omega}) + e^{2\alpha+C_1\tau} \|u\|_{1,\Omega}^2.$$

Similarly to the proof of the preceding theorem, we can take β large enough in order to ensure that $C_1 < C_2 < C_3$ and, for $\tau = \gamma\alpha$ with γ sufficiently large, there exist $C_4 > 0$ and $C_5 > 0$ so that

$$\|u\|_{1,\Omega}^2 \leq C e^{C_4\alpha} (\|g\|_{0,\Omega}^2 + \|g\|_{0,\Omega} \|u\|_{0,\Omega}) + C e^{-C_5\alpha} \|u\|_{1,\Omega}^2.$$

Pick α large enough in such a way that $C e^{-C_5\alpha} \leq 1/4$. Then

$$C e^{C_4\alpha} \|g\|_{0,\Omega} \|u\|_{0,\Omega} \leq C^2 e^{2C_4\alpha} \|g\|_{0,\Omega}^2 + \|u\|_{0,\Omega}^2/2.$$

The two last estimates yield

$$(2.36) \quad \|u\|_{0,\Omega}^2 \leq \|u\|_{1,\Omega}^2 \leq C e^{C\alpha} \|g\|_{0,\Omega}^2,$$

That is we proved the resolvent estimate for $\mu < 0$. \square

3. Exponential stabilization

3.1. **Observability inequalities.** In this section, we use the following notation

$$Q = \Omega \times (0, T), \quad \Sigma = \Gamma \times (0, T) \quad \text{and} \quad \Sigma_j = \Gamma_j \times (0, T), \quad j = 0, 1.$$

Following Lions and Magenes notation, the anisotropic Sobolev space $H^{2,1}(Q)$ is given by

$$H^{2,1}(Q) = L^2((0, T), H^2(\Omega)) \cap H^1((0, T), L^2(\Omega)).$$

We use frequently in the sequel the following Green's formula

$$(3.1) \quad ((\partial_j + ia_j)u|v)_{0,\Omega} = -(u|(\partial_j + ia_j)u)_{0,\Omega} + (u|v\nu_j)_{0,\Gamma}.$$

The following proposition is a key tool in the multiplier method.

Proposition 3.1. *Let $\aleph \in C^2(\overline{Q}, \mathbb{R}^n)$, $u \in H^{2,1}(Q)$ and set*

$$f = i\partial_t u + \Delta_{\mathbf{a}} u.$$

Then

$$\begin{aligned} & \langle \nabla_{\mathbf{a}} u \cdot \nu | \aleph \cdot \nabla_{\mathbf{a}} u \rangle_{0,\Sigma} - \frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \aleph \cdot \nu)_{0,\Sigma} \\ & \quad + \frac{1}{2} (\operatorname{div}(\aleph)u | \nabla_{\mathbf{a}} u \cdot \nu)_{0,\Sigma} - \frac{i}{2} (u(\aleph \cdot \nu) | \partial_t u)_{0,\Sigma} \\ & \quad = \langle D\aleph \nabla_{\mathbf{a}} u | \nabla_{\mathbf{a}} u \rangle_{0,Q} + \frac{1}{2} (u \nabla \operatorname{div}(\aleph) | \nabla_{\mathbf{a}} u)_{0,Q} \\ & \quad + \frac{i}{2} (u \partial_t \aleph | \nabla_{\mathbf{a}} u)_{0,Q} - \frac{i}{2} [(u \aleph | \nabla_{\mathbf{a}} u)_{0,\Omega}]_0^T dx \\ & \quad + \langle f \aleph | \nabla_{\mathbf{a}} u \rangle_{0,Q} + \frac{1}{2} (\operatorname{div}(\aleph)u | f)_{0,Q}. \end{aligned}$$

Here $D\aleph = (\partial_k \aleph_\ell)$ is the Jacobian matrix of \aleph .

Proof. For simplicity sake's, we use in this proof the following notation

$$d_j = \partial_j + ia_j \quad \text{and} \quad \overline{d}_j = \partial_j - ia_j.$$

First step. We prove

$$(3.2) \quad \begin{aligned} & \langle \Delta_{\mathbf{a}} u | \aleph \cdot \nabla_{\mathbf{a}} u \rangle_{0,Q} = -\langle D\aleph \nabla_{\mathbf{a}} u | \nabla_{\mathbf{a}} u \rangle_{0,Q} \\ & \quad + \frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \operatorname{div}(\aleph))_{0,Q} - \frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \aleph \cdot \nu)_{0,\Sigma} + \langle \nabla_{\mathbf{a}} u \cdot \nu | \aleph \cdot \nabla_{\mathbf{a}} u \rangle_{0,\Sigma}. \end{aligned}$$

From Green's formula (3.1), we have

$$(3.3) \quad \begin{aligned} & (\Delta_{\mathbf{a}} u | \aleph \cdot \nabla_{\mathbf{a}} u)_{0,\Omega} = \sum_{j,k=1}^n (d_j^2 u \aleph_k | d_k u)_{0,\Omega} \\ & \quad = - \sum_{j,k=1}^n (d_j u | d_j (\aleph_k d_k u))_{0,\Omega} + \sum_{j,k=1}^n (d_j u \nu_j | \aleph_k d_k u)_{0,\Gamma} \\ & \quad = - \sum_{j,k=1}^n (d_j u | d_j (\aleph_k d_k u))_{0,\Omega} + (\nabla_{\mathbf{a}} u \cdot \nu | \aleph \cdot \nabla_{\mathbf{a}} u)_{0,\Gamma}. \end{aligned}$$

Elementary calculations show

$$d_j (\aleph_k d_k u) = \partial_j \aleph_k d_k u + \aleph_k d_j d_k u.$$

Therefore

$$(d_j u | d_j (\aleph_k d_k u))_{0,\Omega} = (\partial_j \aleph_k d_j u | d_k u)_{0,\Omega} + (d_j u \aleph_k | d_j d_k u)_{0,\Omega}.$$

Hence

$$(3.4) \quad \sum_{i,k=1}^n (d_j u | d_j (\aleph_k d_k u))_{0,\Omega} = (D \aleph \nabla_{\mathbf{a}} u | \nabla_{\mathbf{a}} u)_{0,\Omega} + \sum_{i,k=1}^n (d_j u \aleph_k | d_j d_k u)_{0,\Omega}.$$

Introduce the auxiliary function $v_j = d_j u$. Then

$$d_j u \overline{d_j d_k u} = v_j \overline{d_k v_j} = v_j \partial_k \overline{v_j} - i a_j |v_j|^2$$

and then

$$\Re[d_j u \overline{d_j d_k u}] = \Re[v_j \partial_k \overline{v_j}] = \frac{1}{2} (v_j \partial_k \overline{v_j} + \overline{v_j} \partial_k v_j) = \frac{1}{2} \partial_k |v_j|^2 = \frac{1}{2} \partial_k |d_j u|^2.$$

Whence

$$\begin{aligned} \sum_{i,j=1}^n \langle \aleph_k d_j u | d_j d_k u \rangle_{0,\Omega} &= \frac{1}{2} (\nabla |\nabla_{\mathbf{a}} u|^2 | \aleph)_{0,\Omega} \\ &= -\frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \operatorname{div}(\aleph))_{0,\Omega} + \frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \aleph \cdot \nu)_{0,\Gamma}. \end{aligned}$$

This and (3.4) lead

$$\begin{aligned} \sum_{j,k=1}^n \langle \aleph_k d_j u | d_j (\aleph_k d_k u) \rangle_{0,\Omega} &= (D \aleph \nabla_{\mathbf{a}} u | \nabla_{\mathbf{a}} u)_{0,\Omega} \\ &\quad - \frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \operatorname{div}(\aleph))_{0,\Omega} + \frac{1}{2} (|\nabla_{\mathbf{a}} u|^2 | \aleph \cdot \nu)_{0,\Gamma}. \end{aligned}$$

Combine this identity with the real part of (3.3) and integrate with respect to t in order to get the expected identity.

Second step. We have

$$\begin{aligned} 2\Re [i \partial_t u (\aleph \cdot \overline{\nabla_{\mathbf{a}} u})] &= i \partial_t u (\aleph \cdot \overline{\nabla_{\mathbf{a}} u}) - i \partial_t \overline{u} (\aleph \cdot \nabla_{\mathbf{a}} u) \\ &= i [\partial_t u (\aleph \cdot \overline{\nabla u}) - \partial_t \overline{u} (\aleph \cdot \nabla u)] + (\aleph \cdot \mathbf{a}) (\partial_t u \overline{u} + u \partial_t \overline{u}) \\ &= i [\partial_t u (\aleph \cdot \overline{\nabla u}) - \partial_t \overline{u} (\aleph \cdot \nabla u)] + (\aleph \cdot \mathbf{a}) \partial_t |u|^2. \end{aligned}$$

An integration by parts with respect to t gives

$$(\aleph \cdot \mathbf{a} | \partial_t |u|^2)_{0,(0,T)} = -(\partial_t \aleph \cdot \mathbf{a} | |u|^2)_{0,(0,T)} + [(\aleph \cdot \mathbf{a}) |u|^2]_0^T.$$

Therefore

$$(3.5) \quad \begin{aligned} (i \partial_t u \aleph | \nabla_{\mathbf{a}} u)_{0,Q} &= \frac{i}{2} [(\partial_t u \aleph | \nabla u)_{0,Q} - (\nabla u | \partial_t u \aleph)_{0,Q}] \\ &\quad - \frac{1}{2} (\partial_t \aleph \cdot \mathbf{a} | |u|^2)_{0,Q} + \frac{1}{2} [(\aleph \cdot \mathbf{a} | |u|^2)_{0,\Omega}]_0^T. \end{aligned}$$

Next we calculate the first term in the right hand side of the identity above. Integrating with respect to t , we find

$$(\partial_t u | \aleph \cdot \nabla u)_{0,(0,T)} = -(u | \partial_t \aleph \cdot \nabla u)_{0,(0,T)} - (u | \aleph \cdot \partial_t \nabla u)_{0,(0,T)} + [u (\aleph \cdot \overline{\nabla u})]_0^T.$$

On the other hand, Green's formula yields

$$(u \aleph | \partial_t \nabla u)_{0,Q} = -(\operatorname{div}(\aleph) u | \partial_t u)_{0,Q} - (\aleph \cdot \nabla u | \partial_t u)_{0,Q} + ((\aleph \cdot \nu) u | \partial_t u)_{0,\Sigma}.$$

Hence

$$(3.6) \quad \frac{i}{2} [(\partial_t u \aleph | \nabla u)_{0,Q} - (\nabla u | \partial_t u \aleph)_{0,Q}] = -\frac{i}{2} (u \partial_t \aleph | \nabla u)_{0,Q} + \frac{i}{2} (\operatorname{div}(\aleph) u | \partial_t u)_{0,Q} \\ + \frac{i}{2} [u \aleph | \nabla u]_{0,\Omega}^T dx - \frac{i}{2} (u(\aleph \cdot \nu) | \partial_t u)_{0,\Sigma}.$$

Step three. We calculate the term $(\operatorname{div}(\aleph) u | \partial_t u)_{0,Q}$ in (3.6). Using $i \partial_t u = -\Delta_{\mathbf{a}} u + f$, we find

$$(3.7) \quad i(\operatorname{div}(\aleph) u | \partial_t u)_{0,Q} = (\operatorname{div}(\aleph) u | \Delta_{\mathbf{a}} u)_{0,Q} - (\operatorname{div}(\aleph) u | f)_{0,Q}.$$

But

$$(3.8) \quad (\operatorname{div}(\aleph) u | \Delta_{\mathbf{a}} u)_{0,Q} = \sum_{j=1}^n (\operatorname{div}(\aleph) u | d_j d_j u)_{0,Q} \\ = -\sum_{j=1}^n (d_j (\operatorname{div}(\aleph) u) | d_j u)_{0,Q} + \sum_{j=1}^n (\operatorname{div}(\aleph) u \nu_j | d_j u)_{0,\Sigma} \\ = -\sum_{j=1}^n (\operatorname{div}(\aleph) d_j u | d_j u)_{0,Q} - \sum_{j=1}^n (\partial_j \operatorname{div}(\aleph) u | d_j u)_{0,Q} \\ + \sum_{j=1}^n (\operatorname{div}(\aleph) u \nu_j | d_j u)_{0,\Sigma} \\ = -(\operatorname{div}(\aleph) | |\nabla_{\mathbf{a}} u|^2)_{0,Q} - (u \nabla (\operatorname{div}(\aleph)) | \nabla_{\mathbf{a}} u)_{0,Q} \\ + (\operatorname{div}(\aleph) u | \nabla_{\mathbf{a}} u \cdot \nu)_{0,\Sigma}.$$

A combination of (3.5) to (3.8) entails

$$(3.9) \quad \langle i \partial_t u \aleph | \nabla_{\mathbf{a}} u \rangle_{0,Q} = -\frac{i}{2} (\partial_t \aleph | \nabla u)_{0,Q} - \frac{1}{2} (\operatorname{div}(\aleph) | |\nabla_{\mathbf{a}} u|^2)_{0,Q} \\ - \frac{1}{2} (u \nabla (\operatorname{div}(\aleph)) | \nabla_{\mathbf{a}} u)_{0,Q} - \frac{1}{2} (\mathbf{a} \cdot \partial_t \aleph | |u|^2)_{0,Q} \\ + \frac{1}{2} (\operatorname{div}(\aleph) u | f)_{0,Q} \\ + \frac{i}{2} [(u \aleph | \nabla u)_{0,\Omega}]_0^T dx + \frac{1}{2} [(u \aleph | u \mathbf{a})_{0,\Omega}]_0^T dx \\ + \frac{1}{2} (\operatorname{div}(\aleph) u | \nabla_{\mathbf{a}} u \cdot \nu)_{0,\Sigma} - \frac{i}{2} (u(\aleph \cdot \nu) | \partial_t u)_{0,\Sigma}.$$

We put together the first and the fourth terms of the right hand side of this inequality. We obtain

$$-\frac{i}{2} (u \partial_t \aleph | \nabla u)_{0,Q} - \frac{1}{2} (\partial_t \aleph u | u \mathbf{a})_{0,Q} = -\frac{i}{2} (u \partial_t \aleph | \nabla_{\mathbf{a}} u)_{0,Q}.$$

Similarly, we put together the sixtieth and the ninetieth terms for the right hand of (3.9). We get

$$\frac{i}{2} [(u \aleph | \nabla u)_{0,\Omega}]_0^T dx + \frac{1}{2} [(u \aleph | u \mathbf{a})_{0,\Omega}]_0^T dx = \frac{i}{2} [(u \aleph | \nabla_{\mathbf{a}} u)_{0,\Omega}]_0^T dx.$$

Then (3.9) becomes

$$\begin{aligned}
(3.10) \quad \langle i\partial_t u \aleph | \nabla_{\mathbf{a}} u \rangle_{0,Q} &= -\frac{i}{2} (\partial_t \aleph | \nabla_{\mathbf{a}} u \rangle_{0,Q} - \frac{1}{2} (\operatorname{div}(\aleph) | |\nabla_{\mathbf{a}} u|^2 \rangle_{0,Q} \\
&\quad - \frac{1}{2} (u \nabla(\operatorname{div}(\aleph)) | \nabla_{\mathbf{a}} u \rangle_{0,Q} \\
&\quad + \frac{1}{2} (\operatorname{div}(\aleph) u | f \rangle_{0,Q} \\
&\quad + \frac{i}{2} [(u \aleph | \nabla_{\mathbf{a}} u)_{0,\Omega}]_0^T dx \\
&\quad + \frac{1}{2} (\operatorname{div}(\aleph) u | \nabla_{\mathbf{a}} u \cdot \nu \rangle_{0,\Sigma} - \frac{i}{2} (u(\aleph \cdot \nu) | \partial_t u \rangle_{0,\Sigma}).
\end{aligned}$$

Step four. We complete the proof by noting the expected identity follows from (3.2), (3.10) and

$$\Re [i\partial_t u \aleph \cdot \overline{\nabla_{\mathbf{a}} u}] + \Re [\Delta_{\mathbf{a}} u \aleph \cdot \overline{\nabla_{\mathbf{a}} u}] = \Re [f \aleph \cdot \overline{\nabla_{\mathbf{a}} u}].$$

□

Bearing in mind that $D(A_0) = H_0^1(\Omega) \cap H^2(\Omega)$, we derive that, for $u_0 \in D(A_0)$,

$$u(t) = e^{tA_0} u_0 \in C([0, T], D(A_0)) \cap C^1([0, T], L^2(\Omega)) \subset H^{2,1}(Q).$$

Corollary 3.1. *There exists a constant $C = C_1 + C_2\sqrt{T} > 0$, the constants C_1 and C_2 only depend on Ω , so that, for any $u_0 \in D(A_0)$ and $u(t) = e^{tA_0} u_0$, we have*

$$(3.11) \quad \|\nabla_{\mathbf{a}} u\|_{0,\Sigma} \leq C \|\nabla_{\mathbf{a}} u_0\|_{0,\Omega}.$$

Proof. We firstly note that according to [8, Lemma 3.2],

$$(3.12) \quad \|u(\cdot, t)\|_{0,\Omega} = \|u_0\|_{0,\Omega} \quad \text{and} \quad \|\nabla_{\mathbf{a}} u(\cdot, t)\|_{0,\Omega} = \|\nabla_{\mathbf{a}} u_0\|_{0,\Omega}, \quad 0 \leq t \leq T.$$

Let us choose $\aleph \in C^\infty(\overline{\Omega}, \mathbb{R}^n)$ as an extension of ν . In that case the left hand side of the identity in Proposition 3.1 is equal to the square of the left hand side of (3.11). While the right hand of the identity in Proposition 3.1 is bounded by the square of the right hand side of (3.11). This a consequence of Cauchy-Schwarz's inequality and (3.12). □

In the rest of this section, $x_0 \in \mathbb{R}^n$ is fixed, $m = m(x) = x - x_0$, $x \in \mathbb{R}^n$ and

$$\Gamma_0 = \{x \in \Gamma; m(x) \cdot \nu(x) > 0\}.$$

Observe that in the present case the condition $\overline{\Gamma_0} \cap \overline{\Gamma_1} = \emptyset$ is satisfied for instance if $\Omega = \Omega_0 \setminus \Omega_1$, with $\Omega_1 \Subset \Omega_0$, Ω_j star-shaped with respect to $x_0 \in \Omega_1$ and $\Gamma_j = \partial\Omega_j$, $j = 0, 1$.

Proposition 3.2. *There exists a constant $C > 0$, only depending on Ω and T , so that, for any $u_0 \in D(A_0)$ and $u(t) = e^{tA_0} u_0$, we have*

$$(3.13) \quad \|\nabla_{\mathbf{a}} u_0\|_{0,\Omega} \leq C \|\nabla_{\mathbf{a}} u\|_{0,\Sigma_0} = C \|\partial_{\nu_{\mathbf{a}}} u\|_{0,\Sigma_0}.$$

Sketch of the proof. Take $\aleph = m$ in the identity of Proposition 3.1. We get

$$(m \cdot \nu | |\partial_{\nu_{\mathbf{a}}} u|^2 \rangle_{0,\Sigma} = \|\nabla_{\mathbf{a}} u\|_{0,Q}^2 - \frac{i}{2} [(um | \nabla_{\mathbf{a}} u)_{0,\Omega}]_0^T.$$

Whence, in light of (3.12),

$$T \|\nabla_{\mathbf{a}} u_0\|_{0,\Omega}^2 \leq (m \cdot \nu | |\partial_{\nu_{\mathbf{a}}} u|^2 \rangle_{0,\Sigma_0} + \frac{1}{2} \left| [(um | \nabla_{\mathbf{a}} u)_{0,\Omega}]_0^T \right|.$$

But, for $0 < \epsilon < T$, there exists a constant $C_\epsilon > 0$, independent on T , so that

$$\frac{1}{2} \left| [(um|\nabla_{\mathbf{a}}u)_{0,\Omega}]_0^T \right| \leq \epsilon \|\nabla_{\mathbf{a}}u_0\|_{0,\Omega}^2 + C_\epsilon \|u_0\|_{0,\Omega}^2,$$

where we used again (3.12). Hence

$$(T - \epsilon) \|\nabla_{\mathbf{a}}u_0\|_{0,\Omega}^2 \leq \|m\|_\infty \|\partial_{\nu_{\mathbf{a}}}u\|_{0,\Sigma_0}^2 + C_\epsilon \|u_0\|_{0,\Omega}^2.$$

As $\|\nabla_{\mathbf{a}}\cdot\|_{0,\Omega}$ and $\|\nabla\cdot\|_{0,\Omega}$ are equivalent on $H_0^1(\Omega)$, we can repeat the compactness argument in [23, Proposition 2.1] to complete the proof. \square

Let \mathcal{O} and $\tilde{\mathcal{O}}$ be two open C^∞ bounded subsets of \mathbb{R}^n so that $\tilde{\mathcal{O}} \Subset \mathcal{O}$ and $\bar{\Gamma}_0 \subset \tilde{\mathcal{O}} \cap \Gamma$. Set then $\omega = \mathcal{O} \cap \Omega$, $\tilde{\omega} = \tilde{\mathcal{O}} \cap \Omega$ and assume in addition that $\Omega \setminus \tilde{\omega} \neq \emptyset$.

Proposition 3.3. *There exists a constant $C > 0$, only depending on Ω , T , Ω and Γ_0 , so that, for any $u_0 \in D(A_0)$ and $u(t) = e^{tA_0}u_0$, we have*

$$(3.14) \quad \|u_0\|_{0,\Omega} \leq C \|u\|_{0,Q_\omega}.$$

Here $Q_\omega = \omega \times (0, T)$.

Sketch of the proof. Fix $0 < \delta < T$. Let $\nu_e \in C^\infty(\bar{\Omega}, \mathbb{R}^n)$ be an extension of ν , $0 \leq \phi \in C_0^\infty(0, T)$ satisfying $\phi = 1$ in $[\delta, T - \delta]$, and $\psi \in C_0^\infty(\mathbb{R}^n)$ so that $\text{supp}(\psi) \cap \Omega \subset \tilde{\omega}$ and $\psi = 1$ on Γ_0 .

We have from Proposition 3.2 with $\aleph = \nu_e \phi \psi$, in which $(0, T)$ is substituted by $(\delta, T - \delta)$,

$$(3.15) \quad \|\nabla_{\mathbf{a}}u_0\|_{0,\Omega} = \|\nabla_{\mathbf{a}}u(\cdot, \delta)\|_{0,\Omega} \leq C \|\partial_{\nu_{\mathbf{a}}}u\|_{0,\Gamma_0 \times (\delta, T - \delta)} \leq C \|(\aleph \cdot \nu) \partial_{\nu_{\mathbf{a}}}u\|_{0,\Sigma}.$$

As in the proof of Corollary 3.1, we obtain by applying Proposition 3.1, where $Q_{\tilde{\omega}} = \tilde{\omega} \times (0, T)$,

$$(3.16) \quad C \|(\aleph \cdot \nu) \partial_{\nu_{\mathbf{a}}}u\|_{0,\Sigma} \leq \|\nabla_{\mathbf{a}}u\|_{0,Q_{\tilde{\omega}}} + \|u\|_{0,Q_{\tilde{\omega}}}.$$

On the other hand, using $\Delta_{\mathbf{a}}u(\cdot, t) = -i\partial_t u(\cdot, t)$ in Ω and Caccioppoli's inequality in order to obtain

$$(3.17) \quad C \|\nabla_{\mathbf{a}}u\|_{0,Q_{\tilde{\omega}}} \leq \|u\|_{0,Q_\omega} + \|\partial_t u\|_{L^2((0,T), H^{-1}(\omega))}.$$

Inequalities (3.16) and (3.17) at hand, we can mimic the interpolation argument in the end of the proof of [23, Proposition 3.1] to complete the proof. \square

3.2. Stabilization by an internal damping.

Theorem 3.1. *There exists a constant $\varrho > 0$, depending only on Ω , T , Ω and Γ_0 so that*

$$\mathcal{E}_{u_0}^1(t) \leq e^{-\varrho t} \mathcal{E}_{u_0}^1(0), \quad u_0 \in L^2(\Omega).$$

Proof. By density it is enough to give the proof when $u_0 \in D(A_0)$. Fix then $u_0 \in L^2(\Omega)$ and let $u(t) = e^{tA_1}u_0$. We decompose u into two terms, $u = v + w$, with

$$v(t) = e^{tA_0}u_0 \quad \text{and} \quad w(t) = -i \int_0^t e^{(t-s)A_0} c u(s) ds.$$

As $\mathcal{E}_{u_0}^1$ is non increasing, we have

$$\mathcal{E}_{u_0}^1(t) \leq \mathcal{E}_{u_0}^1(0) = \frac{1}{2} \|u_0\|_{0,\Omega}^2.$$

Hence

$$\mathcal{E}_{u_0}^1(t) \leq C \|v\|_{0,Q_\omega}^2 \leq C \|\sqrt{c}u\|_{0,Q_\omega}^2 + C \|w\|_{0,Q_\omega}^2$$

by Proposition 3.3. Whence, using that $c \geq c_0 > 0$ a.e. in ω ,

$$(3.18) \quad \mathcal{E}_{u_0}^1(t) \leq C \|\sqrt{c}v\|_{0,Q}^2 \leq C \|\sqrt{c}u\|_{0,Q}^2 + C \|w\|_{0,Q}^2.$$

On the other hand, it is straightforward to check that

$$\|w\|_{0,Q}^2 \leq \|cu\|_{0,Q}^2 \leq \|c\|_\infty \|\sqrt{c}u\|_{0,Q}^2.$$

This and (3.18) entail

$$\mathcal{E}_{u_0}^1(t) \leq C \|\sqrt{c}u\|_{0,Q}^2 = -C \frac{d}{dt} \mathcal{E}_{u_0}^1(t).$$

Or equivalently

$$\frac{d}{dt} \mathcal{E}_{u_0}^1(t) \leq -C^{-1} \mathcal{E}_{u_0}^1(t).$$

This yields the expected inequality in a straightforward manner. \square

3.3. Stabilization by a boundary damping. In this subsection we take $d(x) = m(x) \cdot \nu(x)$, $x \in \Gamma_0$, which satisfies obviously the assumption required in Section 1.

Let $u_0 \in V$ and recall the $\mathcal{E}_{u_0}^2(t) = \frac{1}{2} \|\nabla_{\mathbf{a}} e^{tA_2} u_0\|_{0,\Omega}^2$ satisfies

$$\frac{d}{dt} \mathcal{E}_{u_0}^2(t) = -\|\sqrt{m \cdot \nu} u'(t)\|_{0,\Gamma_0} = -\|\sqrt{m \cdot \nu} \Delta_{\mathbf{a}}(t)\|_{0,\Gamma_0}, \quad t > 0.$$

Here $u(t) = e^{tA_2} u_0$.

Introduce,

$$\mathcal{E}_{u_0}^2(t) = \Im(u(t)|m \cdot \nabla u(t))_{0,\Omega}.$$

Lemma 3.1. *For any $u_0 \in V$ and $u(t) = e^{tA_2} u_0$, we have, where $t > 0$,*

$$(3.19) \quad \frac{d}{dt} \mathcal{E}_{u_0}^2(t) = 2\langle \Delta_{\mathbf{a}} u | m \cdot \nabla u(t) \rangle_{0,\Omega} - n \|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2 - \langle (n+i)(m \cdot \nu) u(t) | u'(t) \rangle_{0,\Gamma_0}.$$

Proof. By density it is sufficient to give the proof when $u_0 \in D(A_2)$. In that case, we have

$$\frac{d}{dt} \mathcal{E}_{u_0}^2(t) = \Im [(u'(t) | m \cdot \nabla u(t))_{0,\Omega} + (u(t) | m \cdot \nabla u'(t))_{0,\Omega}].$$

An integration by parts yields

$$\begin{aligned} (u(t) | m \cdot \nabla u'(t))_{0,\Omega} &= -(\operatorname{div}(u(t)m) | u'(t))_{0,\Omega} + (u(t)(m \cdot \nu) | u'(t))_{0,\Gamma} \\ &= -n(u(t) | u'(t))_{0,\Omega} - (m \cdot \nabla u(t) | u'(t))_{0,\Omega} + (u(t)(m \cdot \nu) | u'(t))_{0,\Gamma}. \end{aligned}$$

Hence

$$\begin{aligned} \frac{d}{dt} \mathcal{E}_{u_0}^2(t) &= \Im [(u'(t) | m \cdot \nabla u(t))_{0,\Omega} - n(u(t) | u'(t))_{0,\Omega}] \\ &\quad - \Im [(\nabla u(t) \cdot m | u'(t))_{0,\Omega} + (u(t)(m \cdot \nu) | u'(t))_{0,\Gamma}]. \end{aligned}$$

Since

$$(u'(t) | m \cdot \nabla u(t))_{0,\Omega} - (\nabla u(t) \cdot m | u'(t))_{0,\Omega} = 2i \Im (u'(t) | m \cdot \nabla u(t))_{0,\Omega},$$

we obtain

$$\frac{d}{dt} \mathcal{E}_{u_0}^2(t) = 2 \Im (u'(t) | m \cdot \nabla u(t))_{0,\Omega} - n \Im (u(t), u'(t))_{0,\Omega} + \Im (u(t)(m \cdot \nu) | u'(t))_{0,\Gamma}.$$

But $u'(t) = i \Delta_{\mathbf{a}} u(t)$. Therefore

$$\frac{d}{dt} \mathcal{E}_{u_0}^2(t) = 2 \langle \Delta_{\mathbf{a}} u | m \cdot \nabla u(t) \rangle_{0,\Omega} - n \langle u(t), \Delta_{\mathbf{a}}(t) \rangle_{0,\Omega} + \Im (u(t)(m \cdot \nu) | u'(t))_{0,\Gamma}.$$

This and

$$\langle \Delta_{\mathbf{a}} u(t), u(t) \rangle_{0,\Omega} = -\|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2 + \langle \partial_{\nu_{\mathbf{a}}} u(t) | u(t) \rangle_{0,\Gamma}$$

entail

$$(3.20) \quad \begin{aligned} \frac{d}{dt} \mathcal{E}_{u_0}^2(t) &= 2\langle \Delta_{\mathbf{a}} u | m \cdot \nabla u(t) \rangle_{0,\Omega} - n\|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2 \\ &\quad + n\langle \partial_{\nu_{\mathbf{a}}} u(t) | u(t) \rangle_{0,\Gamma} + \Im(u(t)(m \cdot \nu) | u'(t))_{0,\Gamma}. \end{aligned}$$

Using that $\partial_{\nu_{\mathbf{a}}} u = -(m \cdot \nu)u'(t)$ on Γ_0 and $u = 0$ on Γ_1 , we get

$$n\langle \partial_{\nu_{\mathbf{a}}} u(t) | u(t) \rangle_{0,\Gamma} + \Im(u(t)(m \cdot \nu) | u'(t))_{0,\Gamma} = -\langle (n+i)(m \cdot \nu)u(t) | u'(t) \rangle_{0,\Gamma_0}.$$

In (3.20), this identity yields

$$\begin{aligned} \frac{d}{dt} \mathcal{E}_{u_0}^2(t) &= 2\langle \Delta_{\mathbf{a}} u(t) | m \cdot \nabla u(t) \rangle_{0,\Omega} - n\|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2 \\ &\quad - \langle (n+i)(m \cdot \nu)u(t) | u'(t) \rangle_{0,\Gamma_0}, \end{aligned}$$

which is the expected inequality. \square

In the sequel, $\varkappa_1 = \varkappa(V)$, the Poincaré constant of V .

Lemma 3.2. *Assume that $\|\mathbf{a}\|_{\infty} \leq \frac{1}{2\varkappa_1}$. Then, for any $u \in D(A_2)$, we have*

$$(3.21) \quad \begin{aligned} \langle \Delta_{\mathbf{a}} u, m \cdot \nabla u \rangle_{0,\Omega} &\leq \frac{n-2}{2}(1 + \delta(\|\mathbf{a}\|_{\infty}))\|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2 \\ &\quad + \langle \partial_{\nu} u | m \cdot \nabla u \rangle_{0,\Gamma_0} - \frac{1}{2}(|\nabla u|^2 | m \cdot \nu)_{0,\Gamma_0}, \end{aligned}$$

where the function δ , depending only on Ω and Γ_0 , satisfies $\delta(\rho) \rightarrow 0$ as $\rho \rightarrow 0$.

Proof. By simple integration by parts, we have

$$(3.22) \quad \langle \nabla u | \nabla(m \cdot \nabla u) \rangle_{0,\Omega} = -\frac{n-2}{2}\|\nabla u\|_{0,\Omega}^2 + \frac{1}{2}(|\nabla u|^2 | m \cdot \nu)_{0,\Gamma}.$$

But

$$(3.23) \quad \begin{aligned} \langle \Delta_{\mathbf{a}} u, m \cdot \nabla u \rangle_{0,\Omega} &= \langle \Delta u | m \cdot \nabla u \rangle_{0,\Omega} - 2\Im(\mathbf{a} \cdot \nabla u | m \cdot \nabla u)_{0,\Omega} \\ &\quad + \langle [i\operatorname{div}(\mathbf{a}) - |\mathbf{a}|^2]u | m \cdot \nabla u \rangle_{0,\Omega}. \end{aligned}$$

Integrating by parts, the first term in the right hand side of inequality (3.23) in order to get

$$\langle \Delta u | m \cdot \nabla u \rangle_{0,\Omega} = -\langle \nabla u | \nabla(m \cdot \nabla u) \rangle_{0,\Omega} + \langle \partial_{\nu} u | m \cdot \nabla u \rangle_{0,\Gamma}.$$

This identity combined with (3.22) yields

$$(3.24) \quad \begin{aligned} \langle \Delta u | m \cdot \nabla u \rangle_{0,\Omega} &= \frac{n-2}{2}\|\nabla u\|_{0,\Omega}^2 + \langle \partial_{\nu} u | m \cdot \nabla u \rangle_{0,\Gamma} - \frac{1}{2}(|\nabla u|^2 | m \cdot \nu)_{0,\Gamma} \\ &= \frac{n-2}{2}(\|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2 + 2\Im(u | \mathbf{a} \cdot \nabla u)_{0,\Omega} - \|\mathbf{a}|u\|_{0,\Omega}^2) \\ &\quad + \langle \partial_{\nu} u | m \cdot \nabla u \rangle_{0,\Gamma} - \frac{1}{2}(|\nabla u|^2 | m \cdot \nu)_{0,\Gamma}. \end{aligned}$$

Under the assumption on \mathbf{a} , straightforward computations show

$$\|\nabla u\|_{0,\Omega} \leq 2\|\nabla_{\mathbf{a}} u\|_{0,\Omega}$$

and

$$\|u\|_{0,\Omega} \leq 2\varkappa_1\|\nabla_{\mathbf{a}} u\|_{0,\Omega}.$$

These inequalities enable us to derive from (3.24)

$$(3.25) \quad \langle \Delta u | m \cdot \nabla u \rangle_{0,\Omega} \leq \frac{n-2}{2}(1+\delta_0) \|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2 + \langle \partial_\nu u | m \cdot \nabla u \rangle_{0,\Gamma} \\ - \frac{1}{2} (|\nabla u|^2 |m \cdot \nu|)_{0,\Gamma},$$

where

$$\delta_0 = 4(2\kappa_1 + \kappa_1^2) \|\mathbf{a}\|_\infty.$$

Similarly, we have

$$(3.26) \quad | -2\Im(\mathbf{a} \cdot \nabla u | m \cdot \nabla u)_{0,\Omega} + \Re([i \operatorname{div}(\mathbf{a}) - |\mathbf{a}|^2] u | m \cdot \nabla u)_{0,\Omega} | \\ \leq \frac{n-2}{2} \delta_1 \|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2,$$

the constant $\delta_1 = \delta_1(\|\mathbf{a}\|_\infty)$ is so that $\delta_1(\rho) \rightarrow 0$ as $\rho \rightarrow 0$.

In light of (3.25) and (3.26), we get from (3.23)

$$(3.27) \quad \langle \Delta_{\mathbf{a}} u, m \cdot \nabla u \rangle_{0,\Omega} \leq \frac{n-2}{2}(1+\delta) \|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2 + \langle \partial_\nu u | m \cdot \nabla u \rangle_{0,\Gamma} \\ - \frac{1}{2} (|\nabla u|^2 |m \cdot \nu|)_{0,\Gamma}.$$

Here $\delta = \delta_0 + \delta_1$.

On the other hand,

$$(3.28) \quad \langle \partial_\nu u | m \cdot \nabla u \rangle_{0,\Gamma_1} - \frac{1}{2} (|\nabla u|^2 |m \cdot \nu|)_{0,\Gamma_1} \\ = (|\partial_\nu u|^2 |m \cdot \nu|)_{0,\Gamma_1} - \frac{1}{2} (|\partial_\nu u|^2 |m \cdot \nu|)_{0,\Gamma_1} \\ = \frac{1}{2} (|\partial_\nu u|^2 |m \cdot \nu|)_{0,\Gamma_1} \leq 0.$$

A combination of (3.27) and (3.28) yields

$$\langle \Delta_{\mathbf{a}} u, m \cdot \nabla u \rangle_{0,\Omega} \leq \frac{n-2}{2}(1+\delta) \|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2 \\ + \langle \partial_\nu u | m \cdot \nabla u \rangle_{0,\Gamma_0} - \frac{1}{2} (|\nabla u|^2 |m \cdot \nu|)_{0,\Gamma_0}.$$

The proof is then complete. \square

Theorem 3.2. *There exists $0 < \varsigma \leq \frac{1}{2\kappa_1}$, depending on x_0 and Ω , with the property that, if $\|\mathbf{a}\|_\infty \leq \varsigma$ and $\mathbf{a} = 0$ on Γ_0 , then there exists two constants $C > 0$ and $\varrho > 0$, depending only on x_0 and Ω , so that*

$$\mathcal{E}_{u_0}^2(t) \leq C e^{-\varrho t} \mathcal{E}_{u_0}^2(0), \quad u_0 \in V.$$

Proof. Let $u_0 \in V$ and set $u(t) = e^{tA_2} u_0$. Since $\mathbf{a} = 0$ on Γ_0 , we have

$$\langle \partial_\nu u(t) | m \cdot \nabla u(t) \rangle_{0,\Gamma_0} = -\langle (m \cdot \nu) u'(t) | m \cdot \nabla u(t) \rangle_{0,\Gamma_0}.$$

This inequality and (3.21) entail

$$2\langle \Delta_{\mathbf{a}} u, m \cdot \nabla u \rangle_{0,\Omega} \leq (n-2)(1+\delta(\|\mathbf{a}\|_\infty)) \|\nabla_{\mathbf{a}} u\|_{0,\Omega}^2 \\ - 2\langle (m \cdot \nu) u'(t) | m \cdot \nabla u(t) \rangle_{0,\Gamma_0} - \langle m \cdot \nu | |\nabla u|^2 \rangle_{0,\Gamma_0}.$$

Using this inequality in (3.19), we get

$$(3.29) \quad \begin{aligned} \frac{d}{dt} \mathcal{E}_{u_0}^2(t) &\leq -\|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2 - 2\langle (m \cdot \nu) u'(t) | m \cdot \nabla u(t) \rangle_{0,\Gamma_0} \\ &\quad - \langle m \cdot \nu | |\nabla u|^2 \rangle_{0,\Gamma_0} - \langle (n+i)u(t) | u'(t) \rangle_{0,\Gamma_0}, \end{aligned}$$

provided that $\delta \leq \frac{1}{n-2}$. This last condition is satisfied whenever $\|\mathbf{a}\|_\infty \leq \varsigma$, for some $0 < \varsigma \leq \frac{1}{2\kappa_1}$.

Define, for $\epsilon > 0$,

$$\mathcal{E}_{u_0}^{2,\epsilon} = \mathcal{E}_{u_0}^2 + \epsilon \mathcal{E}_{u_0}^2.$$

From inequality (3.29), we have

$$(3.30) \quad \begin{aligned} \frac{d}{dt} \mathcal{E}_{u_0}^{2,\epsilon}(t) &\leq -\epsilon \mathcal{E}_{u_0}^2(t) - (m \cdot \nu | |u'(t)|^2)_{0,\Gamma_0} \\ &\quad - \epsilon [2\langle (m \cdot \nu) u'(t) | m \cdot \nabla u(t) \rangle_{0,\Gamma_0} + \langle m \cdot \nu | |\nabla u|^2 \rangle_{0,\Gamma_0} + \langle (n+i)u(t) | u'(t) \rangle_{0,\Gamma_0}]. \end{aligned}$$

Let $\|\mathbf{tr}\|$ be the norm of the trace operator

$$u \in V \rightarrow \sqrt{m \cdot \nu} u|_{\Gamma_0} \in L^2(\Gamma_0),$$

when V is endowed with the norm $\|\nabla_{\mathbf{a}} \cdot\|_{0,\Omega}$. Then

$$(3.31) \quad \begin{aligned} ((m \cdot \nu)(n+i)u(t) | u'(t))_{0,\Gamma_0} &\leq \frac{\|\mathbf{tr}\|^2}{2} (n^2 + 1) \|\sqrt{m \cdot \nu} u'(t)\|_{0,\Gamma_0}^2 \\ &\quad + \frac{1}{2\|\mathbf{tr}\|^2} \|\sqrt{m \cdot \nu} u(t)\|_{0,\Gamma_0}^2 \\ &\leq \frac{\|\mathbf{tr}\|}{2} (n^2 + 1) \|\sqrt{m \cdot \nu} u'(t)\|_{0,\Gamma_0}^2 + \frac{1}{2} \|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2. \end{aligned}$$

Also,

$$(3.32) \quad 2|u'(t)(m \cdot \nabla \overline{u(t)})| \leq \|m\|_\infty^2 |u'(t)|^2 + |\nabla u(t)|^2.$$

If $\vartheta = \frac{\|\mathbf{tr}\|}{2} (n^2 + 1) + \|m\|_\infty^2$, then inequalities (3.31) and (3.32) in (3.30) entail

$$\frac{d}{dt} \mathcal{E}_{u_0}^{2,\epsilon}(t) \leq -\frac{\epsilon}{2} \mathcal{E}_{u_0}^2(t) - (1 - \epsilon\vartheta) \|\sqrt{m \cdot \nu} u'(t)\|_{0,\Gamma_0}^2.$$

That is

$$(3.33) \quad \frac{d}{dt} \mathcal{E}_{u_0}^{2,\epsilon}(t) \leq -\frac{\epsilon}{2} \mathcal{E}_{u_0}^2(t) \quad \text{if } 1 - \epsilon\vartheta \geq 0.$$

On the other hand, as

$$\mathcal{E}_{u_0}^2(t) \leq 2\kappa_1 \|m\|_\infty \|\nabla_{\mathbf{a}} u(t)\|_{0,\Omega}^2 = 2\kappa \|m\|_\infty \mathcal{E}_{u_0}^2(t),$$

we have

$$\mathcal{E}_{u_0}^{2,\epsilon}(t) \leq (1 + 2\kappa_1 \|m\|_\infty) \mathcal{E}_{u_0}^2(t).$$

This in (3.33) yields

$$\frac{d}{dt} \mathcal{E}_{u_0}^{2,\epsilon}(t) \leq -\epsilon\mu \mathcal{E}_{u_0}^{2,\epsilon}(t), \quad 0 < \epsilon \leq \epsilon_0 = \frac{1}{\vartheta}.$$

Here $\mu = \frac{1}{2+4\kappa_1 \|m\|_\infty}$. Hence

$$\mathcal{E}_{u_0}^{2,\epsilon}(t) \leq e^{-\epsilon\mu t} \mathcal{E}_{u_0}^{2,\epsilon}(0)$$

But

$$(1 - 2\kappa_1 \|m\|_\infty) \mathcal{E}_{u_0}^2(t) \leq \mathcal{E}_{u_0}^{2,\epsilon}(t) \leq (1 + 2\kappa_1 \|m\|_\infty) \mathcal{E}_{u_0}^2(t).$$

Therefore

$$\mathcal{E}_{u_0}^2(t) \leq \frac{1 + 2\kappa_1 \|m\|_\infty}{2} e^{-\epsilon t} \mathcal{E}_{u_0}^2(0), \quad 0 < \epsilon \leq \min\left(\epsilon_0, \frac{1}{4\kappa_1 \|m\|_\infty}\right).$$

The proof is then complete. \square

4. Additional comments

4.1. Exponential stabilization via a Carleman inequality. Assume that ω can be chosen in such a way that there exists $\psi \in C^4(\overline{\Omega})$ satisfying

$$\psi > 0 \text{ in } \overline{\Omega}, \quad \nabla \psi \neq 0 \text{ in } \overline{\Omega} \setminus \omega, \quad \partial_\nu \psi \leq 0 \text{ on } \Gamma$$

and the following pseudo-convexity condition: there exists $\varpi > 0$ so that

$$|\nabla \psi(x) \cdot \xi|^2 + \nabla^2 \psi(x) \xi \cdot \bar{\xi} \geq \varpi |\xi|^2, \quad x \in \overline{\Omega} \setminus \omega, \quad \xi \in \mathbb{C}^n.$$

Here where $\nabla^2 \psi = (\partial_{ij} \psi)$.

Note that since $\nabla^2 \psi$ is symmetric, $\nabla^2 \psi \xi \cdot \bar{\xi}$ is real.

We call this condition on ω by (\mathcal{G}) .

Let us provide a domain ω obeying to condition (\mathcal{G}) . In fact, any neighborhood ω of Γ in Ω possesses this property. To see that, pick ω a neighborhood of Γ in Ω , x_0 an arbitrary point in $\mathbb{R}^n \setminus \overline{\Omega}$ and $0 \leq \chi \in C_0^\infty(\Omega)$ satisfying $\chi = 1$ in a neighborhood of $\overline{\Omega} \setminus \omega$. Then it is obvious to check that $\psi(x) = 1 + \chi(x)|x - x_0|^2$ satisfies all the conditions listed in (\mathcal{G}) . This construction can be improved to include domains satisfying the condition for the exponential stabilization discussed in the multiplier method. To this end, fix again x_0 an arbitrary point in $\mathbb{R}^n \setminus \overline{\Omega}$ and set

$$\Gamma_0 = \{x \in \Gamma; \nu(x) \cdot (x - x_0) > 0\}.$$

Pick ω a neighborhood of Γ_0 in Ω and let $0 \leq \chi \in C_0^\infty(\Omega)$ with $\chi = 1$ in a neighborhood of $\overline{\Omega} \setminus \omega$ and $\text{supp}(\chi) \cap \overline{\Gamma_0} = \emptyset$. A straightforward computations show that $\psi(x) = 1 + \chi(x)|x - x_0|^2$ fulfills condition (\mathcal{G}) .

Substituting, if necessary, ψ by $\psi + C$, for some large constant C , we can assume that

$$\psi > \frac{2}{3} \|\psi\|_\infty \text{ in } \overline{\Omega}.$$

In the sequel, the two functions θ and φ , defined on Q , are given by

$$\theta(x, t) = \frac{e^{\lambda \psi(x)}}{t(T-t)}, \quad \varphi(x, t) = \frac{e^{2\lambda \|\psi\|_\infty} - e^{\lambda \psi(x)}}{t(T-t)}.$$

Here λ is a parameter to be specified later.

Let

$$\mathcal{H} = \{w \in L^2((0, T), H_0^1(\Omega)); i\partial_t + \Delta_{\mathbf{a}} \in L^2(Q)\}.$$

A straightforward modification of the proof [29, Corollary 3.2] gives

Lemma 4.1. *There are three constants $\lambda_0 \geq 1$, $s_0 \geq 1$ and $C_0 > 0$ such that for all $\lambda \geq \lambda_0$, $s \geq s_0$ and $w \in \mathcal{H}$, it holds*

$$\begin{aligned} & \|\sqrt{\lambda s \theta} e^{-s\varphi} \nabla_{\mathbf{a}} w\|_{0,Q} + \|\lambda^2 s \theta \sqrt{s \theta} e^{-s\varphi} w\|_{0,Q} \\ & \leq C_0 \left(\|e^{-s\varphi} (i\partial_t + \Delta_{\mathbf{a}}) w\|_{0,Q} + \|\sqrt{\lambda s \theta} e^{-s\varphi} \nabla_{\mathbf{a}} w\|_{0,Q_\omega} + \|\lambda^2 s \theta \sqrt{s \theta} e^{-s\varphi} w\|_{0,Q_\omega} \right). \end{aligned}$$

Pick $u_0 \in D(A_0)$ and let $u(t) = e^{tA_0}u_0$. Taking into account that

$$\|u(t)\|_0 = \|u_0\|_{0,\Omega} \quad \text{and} \quad \|\nabla_{\mathbf{a}}u(t)\|_{0,\Omega} = \|\nabla_{\mathbf{a}}u_0\|_{0,\Omega},$$

we obtain by applying Lemma 4.1 the following observability inequality

Corollary 4.1. *There exists a constant $C > 0$, depending on Ω , \mathbf{a} , ω and T , so that for any $u_0 \in D(A_0)$ and $u(t) = e^{tA_0}u_0$, we have*

$$(4.1) \quad \|\nabla_{\mathbf{a}}u_0\|_{0,\Omega} \leq C (\|\nabla_{\mathbf{a}}u\|_{0,Q_\omega} + \|u\|_{0,Q_\omega}).$$

This observability inequality at hand, we can proceed similarly to the proof of Theorem 3.1 in order to get the following theorem.

Theorem 4.1. *Assume that $\omega \ni \omega_0$ where ω_0 obeys to the condition (\mathcal{G}) . Then there exists a constant $\varrho > 0$, depending only on Ω , T , ω , so that*

$$\mathcal{E}_{u_0}^1(t) \leq e^{-\varrho t} \mathcal{E}_{u_0}^1(0), \quad u_0 \in L^2(\Omega).$$

Remark 4.1. As in Theorem 3.1, one step in the proof consists in establishing the following observability inequality

$$\|u_0\|_{0,\Omega} \leq C \|e^{tA_0}u_0\|_{0,Q_\omega}, \quad u_0 \in L^2(\Omega).$$

According to [30, Theorem 5.1], under the assumption of Theorem 4.1, this inequality is equivalent to the following the so-called observability resolvent estimate: there exists two constants \aleph_0 and \aleph_1 , depending on Ω , ω and \mathbf{a} so that, for any $\mu \in \mathbb{R}$ and $u \in D(A_0)$, we have

$$\|u\|_{0,\Omega}^2 \leq \aleph_0 \|(A_0 - i\mu)u\|_0^2 + \aleph_1 \|u\|_{0,\omega}^2.$$

4.2. Observability inequality in a product space. We consider the case in which $\Omega = \Omega_1 \times \Omega_2$, with Ω_j a C^∞ bounded domain of \mathbb{R}^{n_j} , $j = 1, 2$ and $n_1 + n_2 = n$. Assume that

$$\mathbf{a}(x_1, x_2) = (\mathbf{a}_1(x_1), \mathbf{a}_2(x_2)) \in \mathbb{R}^{n_1} \oplus \mathbb{R}^{n_2}, \quad (x_1, x_2) \in \Omega.$$

where \mathbf{a}_j satisfies the same assumptions as \mathbf{a} when Ω is substituted by Ω_j , $j = 1, 2$. Denote by $A_{0,j}$ the operator A_0 when $\Omega = \Omega_j$ and \mathbf{a} is substituted by \mathbf{a}_j , $j = 1, 2$.

For $u_{0,j} \in L^2(\Omega_j)$, $j = 1, 2$, it is not hard to check that

$$(4.2) \quad e^{tA_0}(u_{0,1} \otimes u_{0,2}) = e^{tA_{0,1}}u_{0,1} \otimes e^{tA_{0,2}}u_{0,2}.$$

Let ω_1 be an open subset of Ω_1 , $Q_{\omega_1} = \omega_1 \times (0, T)$, $\omega = \omega_1 \times \Omega_2$ and $Q_\omega = \omega \times (0, T)$.

Following a simple idea in [10], we have

Theorem 4.2. *Assume that there exists a constant $C > 0$ so that the following observability inequality holds*

$$(4.3) \quad \|u_{0,1}\|_{0,\Omega_1}^2 \leq C \|e^{tA_{0,1}}u_{0,1}\|_{0,Q_{\omega_1}}, \quad u_{0,1} \in L^2(\Omega_1).$$

Then

$$\|u_0\|_{0,\Omega}^2 \leq C \|e^{tA_0}u_0\|_{0,Q_\omega}, \quad u_0 \in L^2(\Omega).$$

Proof. Denote by $(\phi_k)_{k \geq 1}$ an orthonormal basis consisting of eigenfunctions of $A_{0,2}$. For $u_0 \in L^2(\Omega)$, we have

$$u_0(x_1, x_2) = \sum_{k \geq 1} \psi_k(x_1) \phi_k(x_2).$$

Here

$$\psi_k(x_1) = (u(x_1, \cdot)|\phi_k)_{0, \Omega_2} \in L^2(\Omega_1), \quad k \geq 1$$

In light of (4.2) we have, where $(i\lambda_k) \subset i\mathbb{R}$ is the sequence of eigenvalues of $A_{0,2}$,

$$e^{tA_0}u_0(x_1, x_2) = \sum_{k \geq 1} e^{i\lambda_k t} e^{tA_{0,1}} \psi_k(x_1) \phi_k(x_2).$$

We get by applying Parseval's identity

$$\|e^{tA_0}u_0\|_{0, \Omega}^2 = \sum_{k \geq 1} \|e^{tA_{0,1}}\psi_k\|_{0, \Omega_1}^2 = \sum_{k \geq 1} \|\psi_k\|_{0, \Omega_1}^2 = \|u_0\|_{0, \Omega}^2$$

and

$$(4.4) \quad \|e^{tA_0}u_0\|_{0, \omega}^2 = \sum_{k \geq 1} \|e^{tA_{0,1}}\psi_k\|_{0, \omega_1}^2.$$

On other hand, apply observability inequality (4.3) in order to obtain

$$\|u_0\|_{0, \Omega}^2 = \sum_{k \geq 1} \|\psi_k\|_{0, \Omega_1}^2 \leq C \sum_{k \geq 1} \|e^{tA_{0,1}}\psi_k\|_{0, Q_{\omega_1}}^2.$$

This and (4.4) entail

$$\|u_0\|_{0, \Omega}^2 \leq C \|e^{tA_0}u_0\|_{0, Q_{\omega}}^2.$$

This is the expected inequality. \square

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