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Abstract: *We interpret the usual Cayley transform of linear (infinite-dimensional) state space systems as a numerical integration scheme of Crank–Nicholson type. This turns out to be equivalent to an approximation procedure of the Laplace transform. The convergence properties of such an approximation are investigated.*

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1 Introduction and motivation

Let U and X be separable Hilbert spaces. Let $S = \left[\begin{smallmatrix} A\&B \\ C\&D \end{smallmatrix}\right]$ be a system node in the sense of [8], whose input and output space are U, and the state space is X. An additional space $V := \left\{ \left[\begin{smallmatrix} x \\ u \end{smallmatrix}\right] \in \left[\begin{smallmatrix} X \\ U \end{smallmatrix}\right] : A_{-1}x + Bu \in X \right\}$ is defined as usual, and it is equipped with the natural norm making it a Hilbert space. Then, as is well-known, the Cauchy problem

$$\begin{cases} x'(t) = A_{-1}x(t) + Bu(t), \quad t \geq 0, \\ x(0) = x_0 \end{cases} \tag{1.1}$$

is uniquely solvable for any input $u \in C^2(\mathbb{R}_+; U)$ and initial state $x_0 \in X$ for which the compatibility condition $\left[\begin{smallmatrix} x_0 \\ u(0) \end{smallmatrix}\right] \in V$ holds. Moreover, then also $\left[\begin{smallmatrix} x(\cdot) \\ u(\cdot) \end{smallmatrix}\right] \in C(\mathbb{R}_+; V)$, and hence the output relation $y(t) = C\&D \left[\begin{smallmatrix} x(t) \\ u(t) \end{smallmatrix}\right]$ is well defined for all $t \geq 0$ as $C\&D \in \mathcal{L}(V; U)$. These and many other facts can be found in [8, Section 2].

The system node $\left[\begin{smallmatrix} A\&B \\ C\&D \end{smallmatrix}\right]$ is *energy preserving* if the following energy balance holds for all $T > 0$

$$\langle x(T), x(T)\rangle_X^2 + \int_0^T \langle y(t), y(t)\rangle_Y^2 dt = \langle x_0, x_0\rangle_X^2 + \int_0^T \langle u(t), u(t)\rangle_U^2 dt, \tag{1.2}$$

where u, x, y and x_0 are as in (1.1). For any energy preserving S, the semigroup generator A is maximally dissipative and $\mathbb{C}_+ \subset \rho(A)$. If both $S = \left[\begin{smallmatrix} A\&B \\ C\&D \end{smallmatrix}\right]$ and its *dual node* $S^d = \left[\begin{smallmatrix} [A\&B]^d \\ [C\&D]^d \end{smallmatrix}\right]$ are energy-preserving, then $\left[\begin{smallmatrix} A\&B \\ C\&D \end{smallmatrix}\right]$ is called *conservative*; see [8, Definitions 3.1 and 4.1]. Conservative system nodes are known in classical operator theory as *operator colligations* or *Livšic – Brodskiĭ nodes*. A wide classical literature exists for them but the practical linear systems content might sometimes be hard to understand. See e.g. Brodskiĭ [4, 6, 5], Livšic [12], Livšic and Yantsevich [11], Sz.-Nagy and Foiaş [15], Smuljan [13], and Helton [3]. An up-to-date, comprehensive reference for operator nodes is Staffans [14]. The general conservative case is treated in Malinen, Staffans and Weiss [8], and the special case of *boundary control* systems are described in [7, 9].

For simplicity, it will be henceforth assumed that all system nodes treated in this paper are conservative, even though most of the results could be given in a more general setting. For the same reason, we assume that $U = \mathbb{C}$, i.e. the signals $u(\cdot)$ and $y(\cdot)$ in (1.1) are scalar valued, even though everything would still remain true (with similar proofs) even if U was a separable Hilbert space.

Let us assume, for a moment, that we are treating the matrix case. Then the dynamical equations take the usual form

$$\begin{cases} x'(t) = Ax(t) + Bu(t), \\ y(t) = Cx(t) + Du(t), \quad t \geq 0, \\ x(0) = x_0. \end{cases} \tag{1.3}$$

where $A \in \mathbb{C}^{n\times n}$, $B \in \mathbb{C}^{n\times 1}$, $C \in \mathbb{C}^{1\times n}$, and $D \in \mathbb{C}$. Let $h > 0$ be a *discretization parameter.* We can carry out a slightly nonstandard time discretization of (1.3) and obtain an approximation of Crank–Nicholson type

$$\begin{cases} \frac{x(jh)-x((j-1)h)}{h} & \approx A\frac{x(jh)+x((j-1)h)}{2} + Bu(jh), \\ y(jh) & \approx C\frac{x(jh)+x((j-1)h)}{2} + Du((j-1)h), \quad j \geq 1, \\ x(0) & = x_0. \end{cases}$$

Clearly, this induces the discrete time dynamics

$$\begin{cases} \frac{x_j^{(h)}-x_{j-1}^{(h)}}{h} & = A\frac{x_j^{(h)}+x_{j-1}^{(h)}}{2} + B\frac{u_j^{(h)}}{\sqrt{h}}, \\ \frac{y_j^{(h)}}{\sqrt{h}} & = C\frac{x_j^{(h)}+x_{j-1}^{(h)}}{2} + D\frac{u_j^{(h)}}{\sqrt{h}}, \quad j \geq 1, \\ x_0^{(h)} & = x_0, \end{cases} \tag{1.4}$$

where loosely speaking $u_j^{(h)}/\sqrt{h}$ is an approximation of $u(jh)$. We hope very much that $y_j^{(h)}/\sqrt{h}$ would be close to $y(jh)$ — at least under some exceptionally happy circumstances. After some easy computations, equations (1.4) take the form

$$\begin{cases} x_j^{(h)} & = A_\sigma x_{j-1}^{(h)} + B_\sigma u_j^{(h)}, \\ y_j^{(h)} & = C_\sigma x_{j-1}^{(h)} + D_\sigma u_j^{(h)}, \quad j \geq 1, \\ x_0^{(h)} & = x_0, \end{cases} \tag{1.5}$$

where $A_\sigma := (\sigma + A)(\sigma - A)^{-1}$, $B_\sigma := \sqrt{2\sigma}(\sigma - A)^{-1}B$, $C_\sigma := \sqrt{2\sigma}C(\sigma - A)^{-1}$ and $D_\sigma := D + C(\sigma - A)^{-1}B$ with $\sigma := 2/h$.

Even though the computation leading to (1.5) was carried out in the matrix setting, exactly the same transformation can be done for any system node $S = \left[\begin{smallmatrix} A\&B \\ C\&D \end{smallmatrix}\right]$. We simply define the *discrete time linear system* (henceforth, DLS) described by the operator quadruple

$$\phi_\sigma = \begin{bmatrix} A_\sigma & B_\sigma \\ C_\sigma & D_\sigma \end{bmatrix} = \begin{bmatrix} (\sigma + A)(\sigma - A)^{-1} & \sqrt{2\sigma}(\sigma - A_{-1})^{-1}B \\ \sqrt{2\sigma}C(\sigma - A)^{-1} & \mathbf{G}(\sigma) \end{bmatrix} \tag{1.6}$$

for any $\sigma > 0$ (or even for any $\sigma \in \mathbb{D}$, $\mathbb{D}$ being the unit disk, but we shall not use this in this paper). Here $\mathbf{G}(\cdot)$ denotes the transfer function of S, and it is defined by $\mathbf{G}(s) = C\&D \left[\begin{smallmatrix} (s-A_{-1})^{-1}B & I \end{smallmatrix}\right]^T$ for all $s \in \mathbb{C}_+$.

In system theory, the transformation $S \mapsto \phi_\sigma$ is called *Cayley transform* of continuous time systems to discrete time systems. By some computations, it can be checked that the discrete time transfer function $\mathbf{D}_\sigma(\cdot)$ of ϕ_σ satisfies

$$\mathbf{D}_\sigma(z) := D_\sigma + zC_\sigma(I - zA_\sigma)^{-1}B_\sigma = \mathbf{G}\left(\frac{1-z}{1+z}\sigma\right). \tag{1.7}$$

We say that the DLS ϕ_σ of type (1.5) is *conservative* if the defining block matrix $\left[\begin{smallmatrix} A_\sigma & B_\sigma \\ C_\sigma & D_\sigma \end{smallmatrix}\right]$ is unitary. Then the discrete time balance equation

$$\sum_{j=1}^{N} \|x_j\|^2 - \sum_{j=1}^{N} \|x_{j-1}\|^2 = \sum_{j=1}^{N} \|u_{j-1}\|^2 - \sum_{j=1}^{N} \|y_{j-1}\|^2$$

is satisfied for all $N \geq 1$, where the sequences $\{u_j\}$, $\{x_j\}$ and $\{y_j\}$ satisfy (1.5). Studying the approximation scheme (1.4) might not be well motivated, unless the following proposition did not hold:

Proposition 1. *Let the system node* $S = \left[\begin{smallmatrix} A\&B \\ C\&D \end{smallmatrix}\right]$ *and the DLS* $\phi_\sigma = \left[\begin{smallmatrix} A_\sigma & B_\sigma \\ C_\sigma & D_\sigma \end{smallmatrix}\right]$ *be connected by* (1.6)*. Then S is (continuous time) conservative (passive) if and only if ϕ_σ is (discrete time) conservative (resp., passive).*

There exists an extensive literature on the Cayley transform of systems, and we shall not try to make a full account of it here. See e.g. Ober and Montgomery-Smith [10]. A nice piece of work, parallelling our approach, is Arov and Gavrilyuk [1].

2 Approximation of the input/output mapping

In this section, we describe the discretization (1.5) of dynamical system (1.1) in operator theory language.

2.1 Spaces and transforms.

The norm of the usual Hardy space $H^2(\mathbb{C}_+)$ is given by

$$\|\Phi\|^2_{H^2(\mathbb{C}_+)} = \sup_{x>0} \frac{1}{2\pi} \int_{-\infty}^{\infty} |\Phi(x+yi)|^2 \, dy.$$

As usual, the Laplace transform is defined

$$(\mathcal{L}f)(s) = \int_0^\infty e^{-st} f(t)\, dt \qquad \text{for all} \qquad s \in \mathbb{C}_+, \tag{2.1}$$

and it maps $L^2(\mathbb{R}_+) \to H^2(\mathbb{C}_+)$ unitarily. The norm of $H^2(\mathbb{D})$ is given by $\|\phi\|^2_{H^2(\mathbb{D})} = \sum_{j\geq 0} |\phi_j|^2$ if $\phi(z) = \sum_{j \geq 0} \phi_j z^j$, which makes the Z-transform unitary from $\ell^2(\mathbb{Z}_+) \to H^2(\mathbb{D})$. If, say, $f \in C_c(\mathbb{R})$ in (2.1), then $(\mathcal{L}f)(s)$ is well defined for all $s \in i\mathbb{R}$, too. We then call the function $i\omega \mapsto (\mathcal{L}f)(i\omega)$ the Fourier transform of f.

From now on, denote by $\mathbf{D}_\sigma : H^2(\mathbb{D}) \to H^2(\mathbb{D})$ the multiplication operator defined by $(\mathbf{D}_\sigma \tilde{u})(z) = \mathbf{D}_\sigma(z)\tilde{u}(z)$ for all $z \in \mathbb{D}$ and $\sigma > 0$. Similarly, denote by $\mathbf{G} : H^2(\mathbb{C}_+) \to H^2(\mathbb{C}_+)$ the multiplication operator satisfying $(\mathbf{G}\hat{u})(s) = \mathbf{G}(s)\hat{u}(s)$ for all $s \in \mathbb{C}_+$[2]. It follows immediately that (1.7) takes the form of the similarity transformation

$$\mathbf{G} = \mathcal{C}_\sigma^{-1} \mathbf{D}_\sigma \mathcal{C}_\sigma, \tag{2.2}$$

where the *composition operator* is defined by $(\mathcal{C}_\sigma F)(z) := F(\frac{1-z}{1-z}\sigma)$ for all $z \in \mathbb{D}$ and $F : \mathbb{C}_+ \to \mathbb{C}$. Trivially $(\mathcal{C}_\sigma^{-1} f)(s) := f(\frac{s-\sigma}{s+\sigma})$ for all $s \in \mathbb{C}_+$ and $f : \mathbb{D} \to \mathbb{C}$.

[2] Then $\mathbf{D}_\sigma$ and $\mathbf{G}$ are unitarily equivalent to the input/output mappings of ϕ_σ and S, respectively.

Proposition 2. *The mapping $f \mapsto F$ given by $F(s) = \frac{\sqrt{2/\sigma}}{1+s/\sigma} f(\frac{s-\sigma}{s+\sigma})$ is unitary from $H^2(\mathbb{D})$ onto $H^2(\mathbb{C}_+)$. In particular, the operator $\mathcal{M}_\sigma \mathcal{C}_\sigma^{-1} : H^2(\mathbb{D}) \to H^2(\mathbb{C}_+)$ is unitary, where $\mathcal{M}_\sigma : H(\mathbb{C}_+) \to H(\mathbb{C}_+)$ denotes the multiplication operator by $\frac{\sqrt{2/\sigma}}{1+s/\sigma}$.*

Proof. This follows as soon as it is shown that for each $\sigma > 0$, the sequence $\left\{ \frac{\sqrt{2/\sigma}}{1+s/\sigma} \left(\frac{s-\sigma}{s+\sigma}\right)^j \right\}_{j \geq 0}$ is an orthonormal basis for $H^2(\mathbb{C}_+)$. □

2.2 Discretizing operators.

By T_σ we denote a discretizing (or sampling) bounded linear operator $T_\sigma : L^2(\mathbb{R}_+) \to H^2(\mathbb{D})$. The adjoint T_σ^* of T_σ maps then $H^2(\mathbb{D}) \to L^2(\mathbb{R}_+)$, and it is typically an interpolating operator. In this paper, we define T_σ is by

$$(T_\sigma u)(z) = \sum_{j \geq 1} u_j^{(h)} z^j \quad \text{where} \quad \frac{u_j^{(h)}}{\sqrt{h}} = \frac{1}{h} \int_{(j-1)h}^{jh} u(t)\, dt, \tag{2.3}$$

with $h = 2/\sigma$; see (1.4) and (1.5). Then the adjoint T_σ^* is given by

$$\left(T_\sigma^* \tilde{v}\right)(t) = \frac{1}{\sqrt{h}} \sum_{j \geq 1} v_j \chi_{[(j-1)h, jh]}(t) \tag{2.4}$$

where $\tilde{v}(z) = \sum_{j \geq 0} v_j z^j \in H^2(\mathbb{D})$ and $\chi_I(\cdot)$ denotes the characteristic function of the interval I.

It is worth noticing that the operator $T_\sigma : L^2(\mathbb{R}_+) \to H^2(\mathbb{D})$ is a coisometry. This can be seen as follows:

$$\begin{aligned} \|T_\sigma^* \tilde{v}\|^2_{L^2(\mathbb{R}_+)} &= \frac{1}{h} \int_0^\infty |\sum_{j \geq 1} v_j \chi_{[(j-1)h, jh]}|^2\, dt = \frac{1}{h} \int_0^\infty \sum_{j \geq 1} |v_j|^2 \chi_{[(j-1)h, jh]}\, dt \\ &= \frac{1}{h} \sum_{j \geq 1} |v_j|^2 \int_0^\infty \chi_{[(j-1)h, jh]}\, dt = \sum_{j \geq 1} |v_j|^2 = \|\tilde{v}\|^2_{H^2(\mathbb{D})}. \end{aligned} \tag{2.5}$$

2.3 Approximation of the Laplace transform.

Let us now use the discrete time trajectories of (1.5) to approximate the continuous time dynamics in (1.3).

Let $u \in L^2(\mathbb{R}_+)$ be arbitrary. In the operator notation, the output of the discretized dynamics (1.5) (after interpolation by T_σ^* back to a continuous time signal) is given by $T_\sigma^* \mathbf{D}_\sigma T_\sigma u$. The output of continuous time dynamics (1.3) is given by $\mathcal{L}^* \mathbf{G} \mathcal{L} u$. Our first task is to show that at least for some nice $u \in L^2(\mathbb{R}_+)$ and $T > 0$ we have convergence

$$\|T_\sigma^* \mathbf{D}_\sigma T_\sigma u - \mathcal{L}^* \mathbf{G} \mathcal{L} u\|_{L^2([0,T])} \to 0 \tag{2.6}$$

at some speed as $\sigma \to \infty$. By Proposition 2 and equation (2.2) we see that

$$\begin{aligned} T_\sigma^* \mathbf{D}_\sigma T_\sigma &= T_\sigma^* \left(\mathcal{C}_\sigma \mathcal{M}_\sigma^{-1}\right) \cdot \mathbf{G} \cdot \left(\mathcal{M}_\sigma \mathcal{C}_\sigma^{-1}\right) T_\sigma \\ &= T_\sigma^* \left(\mathcal{M}_\sigma \mathcal{C}_\sigma^{-1}\right)^{-1} \cdot \mathbf{G} \cdot \left(\mathcal{M}_\sigma \mathcal{C}_\sigma^{-1}\right) T_\sigma = \left(\mathcal{M}_\sigma \mathcal{C}_\sigma^{-1} T_\sigma\right)^* \cdot \mathbf{G} \cdot \left(\mathcal{M}_\sigma \mathcal{C}_\sigma^{-1} T_\sigma\right) \end{aligned}$$

since the multiplication operator $\mathcal{M}_\sigma$ commutes with $\mathbf{G}$. Hence by (2.6), we are led to inquire whether the operators $L_\sigma := \mathcal{M}_\sigma \mathcal{C}_\sigma^{-1} T_\sigma$ are close (on compact intervals) to the Laplace transform $\mathcal{L}$ when σ is large. This, indeed, appears to be true to some extent [3].

Proposition 3. *For any $u \in C_c(\mathbb{R}_+)$ and $s \in \mathbb{C}_+$, we have $(\mathcal{L}u)(s) = \lim_{\sigma\to\infty} (L_\sigma u)(s)$ where L_σ is defined as above.*

Proof. Defining T_σ by (2.3) we get

$$\begin{aligned} (L_\sigma u)(s) &= \frac{\sqrt{2/\sigma}}{1+s/\sigma} \sum_{j\geq 1} \left(\frac{1}{h} \int_{(j-1)h}^{jh} u(t)\, dt \right) \left(\frac{\sigma - s}{\sigma + s} \right)^j \qquad (2.7) \\ &= \frac{1}{1+s/\sigma} \sum_{j\geq 1} \left(\int_0^\infty \chi_{[(j-1)h, jh]}(t) \left(\frac{\sigma - s}{\sigma + s} \right)^j u(t)\, dt \right) \\ &= \int_0^\infty K_{s,\sigma}(t) u(t)\, dt, \end{aligned}$$

where $\sigma = 2/h$ and

$$K_{s,\sigma}(t) = \frac{1}{1+s/\sigma} \sum_{j\geq 1} \chi_{[(j-1)h, jh]}(t) \left(1 - \frac{2s}{s+\sigma} \right)^j. \qquad (2.8)$$

Now, if j is such that $t \in [(j-1)h, jh]$, then we obtain from the previous

$$K_{s,\sigma}(t) \approx \frac{1}{1+s/\sigma} \left(1 - \frac{s}{s/2 + \sigma/2} \right)^{(\sigma/2)\cdot t} \to e^{-st} \text{ as } \sigma \to \infty.$$

We conclude that $\lim_{\sigma\to\infty} K_{s,\sigma}(t) = e^{-st}$ for all $s \in \mathbb{C}_+$ and $t \geq 0$. Moreover, for each fixed $s \in \mathbb{C}_+$ and $\sigma \geq 2|s|$ we have

$$\begin{aligned} |K_{s,\sigma}(t)| &\leq 2 \cdot \left(1 + \frac{2|s|}{\sigma - |s|} \right)^{(\sigma/2)\cdot t} \\ &\leq 2 \cdot \left(1 + \frac{2|s|}{\sigma - |s|} \right)^{(\sigma - |s|)t/2} \cdot \left(1 + \frac{2|s|}{\sigma - |s|} \right)^{|s|t/2} \leq 2 \left(e\sqrt{3} \right)^{|s|t}. \end{aligned}$$

The proposition now follows from the Lebesgue dominated convergence theorem, as the integrand in (2.7) is has a compact support. □

The purpose of this paper is to give stronger versions of Proposition 3.

[3]Note that by Proposition 2 and equality (2.5), we see that each $L_\sigma : L^2(\mathbb{R}_+) \to H^2(\mathbb{C}_+)$ is a coisometry. The Laplace transform, in its turn, is an unitary mapping between the same spaces. Hence, the convergence of $L_\sigma \to \mathcal{L}$ must be rather weak.

3 A pointwise convergence estimate

Our main result will be given in this section. Theorem 1 provides a uniform speed estimate for the convergence of $(L_\sigma u)(i\omega) \to (\mathcal{L}u)(i\omega)$ for $i\omega \in K$ where $K \subset i\mathbb{R}$ is compact.

Before that some new definitions and notations must be given: Let $I_j = ((j-1)h, jh] = (t_{j-1}, t_j]$ and $t_{j-1/2} = \frac{1}{2}(t_{j-1} + t_j)$. For $u \in L^2(\mathbb{R}_+)$, let $I_{h,s}u$ be the piecewise constant interpolating function, defined by

$$(I_{h,s}u)(t) = \bar{u}_{j,h} + \frac{c_j(h,s)}{h}(t - t_{j-1/2}), \quad t \in I_j, \tag{3.1}$$

where $\bar{u}_{j,h} = \frac{1}{h}\int_{I_j} u(t)\,dt$ and the defining sequence $\{c_j(h,s)\}_{j\geq 1}$ (depending on two parameters h and s) will be later chosen in a particular way. Let P_h denote the orthogonal projection in $L^2(\mathbb{R}_+)$ onto the subspace of functions that are constant on each interval I_j. Then clearly for all $u \in L^2(\mathbb{R}_+)$, $j \geq 1$ and $t \in I_j$ we have $(P_h u)(t) = \bar{u}_{j,h}$.

Theorem 1. *Let $h > 0$, $\sigma = 2/h$, $T = Jh$ for some $J \in \mathbb{N}$, $u \in C_c(\mathbb{R}_+) \cap H^1(\mathbb{R}_+)$, and assume that* $\operatorname{supp}(u) := \{t \in \mathbb{R} : u(t) \neq 0\} \subset [0, T]$.

(i) *Then the sequence $\{c_j(h,s)\}_{j\geq 1}$ can be chosen so that $(L_\sigma - \mathcal{L})(I_{h,s}u)(s) = 0$ for all $s \in \overline{\mathbb{C}_+}$.*

(ii) *For any such choice of the sequence $\{c_j(h,s)\}_{j\geq 1}$, we have*

$$\begin{aligned} &|(L_\sigma u)(s) - (\mathcal{L}u)(s)| \\ &\leq \frac{hT^{1/2}|s|}{\pi}\left(\|I_{h,s}u - P_h u\|_{L^2([0,T])} + \frac{h}{\pi}|u|_{H^1([0,T])}\right) \end{aligned} \tag{3.2}$$

for all $s \in \overline{\mathbb{C}_+}$.

(iii) *The sequence $\{c_j(h,s)\}_{j\geq 1}$ in claim* (i) *can be chosen* optimally *so that*

$$\|I_{h,s}u - P_h u\|_{L^2([0,T])} \leq \frac{15}{218}\left(h^{-1/2}T^{-1/2} + \frac{|s|}{6e}\right)\|P_h u\|_{L^2([0,T])}$$

for a given $s \in i\mathbb{R}$, $T \geq 1$ if $9h \leq T^{2/3}e^{-\frac{4}{3}|s|T}$. Furthermore, then

$$\begin{aligned} &|(L_\sigma u)(s) - (\mathcal{L}u)(s)| \\ &\leq \frac{3h^{1/2}|s|}{100}\|u\|_{L^2([0,T])} + \frac{2hT^{1/2}|s|^2}{1000}\|u\|_{L^2([0,T])} \\ &+ \frac{h^2T^{1/2}|s|}{10}|u|_{H^1([0,T])}. \end{aligned} \tag{3.3}$$

Proof. Let us first make some general observations. By a simple argument, $\|P_h u\|^2_{L^2(\mathbb{R}_+)} = h\sum_{j\geq 1}\bar{u}^2_{j,h}$. Clearly for all $t \in I_j$

$$(I_{h,s}u - P_h u)(t) = \frac{c_j(h,s)}{h}(t - t_{j-1/2}).$$

Since for any $b > a$ we have

$$\frac{1}{(b-a)^2}\int_a^b \left(t - \frac{b+a}{2}\right)^2 = \frac{b-a}{12},$$

it follows that

$$\|I_{h,s}u - P_h u\|^2_{L^2([0,T])} = \sum_{j=1}^{J} \frac{c_j(h,s)^2}{h^2}\int_{t_{j-1}}^{t_j} (t - t_{j-1/2})^2\, dt \tag{3.4}$$
$$= \frac{h}{12}\sum_{j=1}^{J} c_j(h,s)^2.$$

In claim (i) we want to determine the sequence $\{c_j(h,s)\}_{j\geq 1}$ so as to satisfy $(L_\sigma - \mathcal{L})(I_{h,s}u)(s) = 0$ for given h and s. After some computations, we see that this is equivalent to requiring that $\{c_j(h,s)\}_{j\geq 1}$ satisfies

$$\sum_{j=1}^{J} \bar{u}_{j,h} I_j^{(0)}(h,s) + \sum_{j=1}^{J} c_j(h,s) J_j(h,s) = 0, \tag{3.5}$$

where for $s \in \overline{\mathbb{C}_+} \setminus \{0\}$

$$I_j^{(0)}(h,s) := \int_{I_j} \left[\frac{1}{1+s/\sigma}\left(\frac{\sigma - s}{\sigma + s}\right)^j - e^{-st}\right] dt \tag{3.6}$$
$$= \frac{2}{\sigma + s}\left(\frac{\sigma - s}{\sigma + s}\right)^j + \frac{1}{s}\left[e^{-sjh} - e^{-s(j-1)h}\right],$$

and

$$J_j(h,s) := I_j^{(1)}(h,s) - (j - 1/2)h \cdot I_j^{(0)}(h,s) \tag{3.7}$$
$$= \frac{1}{s^2}\left[e^{-sjh} - e^{-s(j-1)h}\right] + \frac{h}{2s}\left[e^{-sjh} + e^{-s(j-1)h}\right],$$

together with

$$I_j^{(1)}(h,s) := \int_{I_j} \left[\frac{1}{1+s/\sigma}\left(\frac{\sigma - s}{\sigma + s}\right)^j - e^{-st}\right] t\, dt$$
$$= \frac{(2j-1)h}{\sigma + s}\left(\frac{\sigma - s}{\sigma + s}\right)^j + \left(\frac{jh}{s} + \frac{1}{s^2}\right)\left[e^{-sjh} - e^{-s(j-1)h}\right] + \frac{h}{s}e^{-s(j-1)h}.$$

It is clear that (3.5) has a huge number of solutions $\{c_j(h,s)\}_{j=1}^J$ for any fixed s and h, and most of the functions $(h,s) \mapsto c_j(h,s)$ need not even be continuous.

Claim (ii) is to be treated next. Recalling (2.7), (2.8) and (3.1)

$$
\begin{aligned}
&(L_\sigma u)(s) - (\mathcal{L}u)(s) = \int_0^T (K_{s,\sigma}(t) - e^{-st})u(t)\,dt \\
&= \int_0^T (K_{s,\sigma}(t) - e^{-st})(u(t) - (I_{h,s}u)(t))\,dt \\
&= \sum_{j=1}^J \int_{t_{j-1}}^{t_j} (K_{s,\sigma}(t) - e^{-st})(u(t) - \bar{u}_{j,h})\,dt \\
&- \sum_{j=1}^J \frac{c_j(h,s)}{h} \int_{t_{j-1}}^{t_j} (K_{s,\sigma}(t) - e^{-st})(t - t_{j-1/2})\,dt = I - II.
\end{aligned}
\tag{3.8}
$$

Let us first give an estimate to the term II. By the Poincare inequality, Proposition 6, we obtain for all $j = 1, \ldots, J$

$$
\|(I - P_h)(K_{s,\sigma} - e^{-s(\cdot)})\|_{L^2(I_j)} \le \frac{h}{\pi}|K_{s,\sigma} - e^{-s(\cdot)}|_{H^1(I_j)} = \frac{h}{\pi}|e^{-s(\cdot)}|_{H^1(I_j)},
$$

where the equality follows because the function $K_{s,\sigma}$ is constant on each interval I_j. By the mean value theorem we get for $s \in \mathbb{C}_+$ and $0 \le a < b < \infty$,

$$
\begin{aligned}
&|e^{-s(\cdot)}|^2_{H^1([a,b])} = \int_a^b |\frac{d}{dt}e^{-st}|^2\,dt = \frac{|s|^2}{2\mathrm{Re}\, s}\left(e^{-2a\mathrm{Re}\, s} - e^{-2b\mathrm{Re}\, s}\right) \\
&\le \frac{|s|^2}{2\mathrm{Re}\, s} \cdot 2\mathrm{Re}\, s e^{-2\xi\mathrm{Re}\, s}(b-a) \le (b-a)|s|^2 e^{-2a\mathrm{Re}\, s}.
\end{aligned}
$$

Hence $|e^{-s(\cdot)}|_{H^1(I_j)} \le h^{1/2}|s|e^{-(j-1)h\mathrm{Re}\, s}$ and this estimate is seen to hold also for all $s \in \overline{\mathbb{C}_+}$. We now conclude that $|e^{-s(\cdot)}|_{H^1([0,T])} \le T^{1/2}|s|$ and

$$
\|(I - P_h)(K_{s,\sigma} - e^{-s(\cdot)})\|_{L^2(I_j)} \le \frac{h^{3/2}|s|}{\pi} \tag{3.9}
$$

for all $s \in \overline{\mathbb{C}_+}$. Using (3.9) we have

$$
\begin{aligned}
II =& \sum_{j=1}^J \int_{t_{j-1}}^{t_j} (K_{s,\sigma}(t) - e^{-st}) \cdot \frac{c_j(h,s)}{h}(t - t_{j-1/2})\,dt \qquad (3.10)\\
=& \sum_{j=1}^J \int_{t_{j-1}}^{t_j} \left((I - P_h)\left(K_{s,\sigma} - e^{-s(\cdot)}\right)\right)(t) \cdot \frac{c_j(h,s)}{h}(t - t_{j-1/2})\,dt \\
\le& \sum_{j=1}^J \frac{h^{3/2}|s|}{\pi} \cdot \left[\frac{c_j(h,s)^2}{h^2}\int_{t_{j-1}}^{t_j}(t - t_{j-1/2})^2\,dt\right]^{1/2} \\
\le& \left(\sum_{j=1}^J \frac{h^3|s|^2}{\pi^2}\right)^{1/2} \cdot \left(\sum_{j=1}^J \frac{c_j(h,s)^2}{h^2}\int_{t_{j-1}}^{t_j}(t - t_{j-1/2})^2\,dt\right)^{1/2} \\
\le& \frac{h^{3/2}|s|}{\pi} J^{1/2} \cdot \|I_{h,s}u - P_h u\|_{L^2([0,T])} = \frac{hT^{1/2}|s|}{\pi}\|I_{h,s}u - P_h u\|_{L^2([0,T])}
\end{aligned}
$$

where the Schwarz inequality has been used twice, and the second to last step is by (3.4).

It remains to estimate term I in (3.8). In this case, since P_h maps on piecewise constant functions and each $u(t) - \bar{u}_{j,h}$ has zero mean on subintervals I_j, we obtain by the inequalities of Schwarz and Poincare, together with (3.9)

$$
\begin{aligned}
II \leq & \sum_{j=1}^{J} \int_{t_{j-1}}^{t_j} \left((I - P_h)\left(K_{s,\sigma} - e^{-s(\cdot)}\right)\right)(t)(u(t) - \bar{u}_{j,h})\, dt \\
\leq & \sum_{j=1}^{J} \frac{h^{3/2}|s|}{\pi} \cdot \frac{h}{\pi}|u|_{H^1(I_j)} \leq \frac{h^{5/2}|s|}{\pi^2} \sum_{j=1}^{J} |u|_{H^1(I_j)} \qquad (3.11) \\
\leq & \frac{h^{5/2}|s|}{\pi^2} \left(\sum_{j=1}^{J} 1\right)^{1/2} \left(\sum_{j=1}^{J} |u|^2_{H^1(I_j)}\right)^{1/2} = \frac{h^2 T^{1/2}|s|}{\pi^2}|u|_{H^1([0,T])}.
\end{aligned}
$$

Estimate (3.2) follows from combining (3.10) and (3.11) with (3.8).

To prove claim (iii), we shall minimise $\frac{h}{12}\sum_{j\geq 1} c_j(h,s)^2$ under the constraint (3.5), see (3.4) for motivation. We form the Langrange function

$$
\begin{aligned}
& L(c_1, \ldots, c_k \ldots, c_J, \lambda) \\
& = \frac{h}{12}\sum_{j=1}^{J} c_j^2 + \lambda \left(\sum_{j=1}^{J} \bar{u}_{j,h} I_j^{(0)}(h,s) + \sum_{j=1}^{J} c_j J_j(h,s)\right),
\end{aligned}
$$

and compute its (unique) critical point giving the minimum. We obtain

$$
\begin{cases}
\frac{\partial L}{\partial c_k} = \frac{h}{6} c_k + \lambda J_k(h,s) = 0 \quad \text{for } 1 \leq k \leq J, \\
\sum_{j=1}^{J} \bar{u}_{j,h} I_j^{(0)}(h,s) + \sum_{j=1}^{J} c_j J_j(h,s) = 0.
\end{cases}
$$

Solving this gives the minimising sequence

$$
c_k = c_k(h,s) = -\frac{6\lambda}{h} J_k(h,s) = -\frac{\sum_{j=1}^{J} \bar{u}_{j,h} I_j^{(0)}(h,s)}{\sum_{j=1}^{J} J_j(h,s)^2} J_k(h,s),
$$

for all $1 \leq k \leq J$, and then for the minimum value

$$
\begin{aligned}
\frac{h}{12}\sum_{j=1}^{J} c_j(h,s)^2 &= \frac{h}{12}\left(\frac{\sum_{j=1}^{J} \bar{u}_{j,h} I_j^{(0)}(h,s)}{\sum_{j=1}^{J} J_j(h,s)^2}\right)^2 \sum_{k=1}^{J} J_k(h,s)^2 \\
&= \frac{h}{12} \frac{\left(\sum_{j=1}^{J} \bar{u}_{j,h} I_j^{(0)}(h,s)\right)^2}{\sum_{j=1}^{J} J_j(h,s)^2}.
\end{aligned}
$$

Hence, choosing the operator $I_{h,s}$ in (3.4) optimally gives

$$
\|I_{h,s}u - P_h u\|_{L^2([0,T])} \leq \frac{\left(\sum_{j=1}^{J} I_j^{(0)}(h,s)^2\right)^{1/2}}{\left(\sum_{j=1}^{J} J_j(h,s)^2\right)^{1/2}} \frac{\|P_h u\|_{L^2([0],)}}{2\sqrt{3}}
$$

since $\|P_h u\|_{L^2([0,T])} = \left(h \sum_{j=1}^{J} \bar{u}_{j,h}^2\right)^{1/2}$. We must now attack (3.6) and (3.7) to estimate the required two square sums, and the resulting long computations will be done in separate subsections 3.1 and 3.2. As a final result, we get by Propositions 4 and 5

$$\frac{\left(\sum_{j=1}^{J} I_j^{(0)}(h,s)^2\right)^{1/2}}{\left(\sum_{j=1}^{J} J_j(h,s)^2\right)^{1/2}} \leq \frac{5}{218}\left(3h^{-1/2}T^{-1/2} + h^{1/2}|s|^2T^{1/2}\right)$$

assuming that $9h \leq T^{2/3}e^{-\frac{4}{3}|s|T}$. But then

$$h^{1/2}|s|^2T^{1/2} \leq \frac{|s|}{3} \cdot |s|T^{5/6}e^{-\frac{2}{3}|s|T} \leq \frac{|s|}{3} \cdot |s|Te^{-\frac{2}{3}|s|T} \leq \frac{|s|}{2e},$$

since $\max_{r\geq 0} re^{-\frac{2}{3}r} = 3/(2e)$. Noting that the norm of the orthogonal projection P_h is 1, the proof of 1 is now complete. □

3.1 Estimation of (3.7)

In this subsection, we shall estimate the square sum of

$$J_j(h,s) = \frac{1}{s^2}\left[e^{-sjh} - e^{-s(j-1)h}\right] + \frac{h}{2s}\left[e^{-sjh} + e^{-s(j-1)h}\right] \tag{3.12}$$

from below and above. For the first term on the left of (3.12) we obtain

$$\begin{aligned}
&\frac{1}{s^2}\left[e^{-sjh} - e^{-s(j-1)h}\right] = \frac{1}{s^2}\left[\sum_{k\geq 0}\frac{(-sjh)^k}{k!} - \sum_{k\geq 0}\frac{(-s(j-1)h)^k}{k!}\right] \\
&= \frac{1}{s^2}\left[-sh + \sum_{k\geq 2}\frac{(-sh)^k(j^k-(j-1)^k)}{k!}\right] \\
&= -\frac{h}{s} + \sum_{k\geq 2}\frac{(j^k-(j-1)^k)}{k!}(-s)^{k-2}h^k.
\end{aligned}$$

For the latter term in (3.12) we get

$$\begin{aligned}
&\frac{h}{2s}\left[e^{-sjh} + e^{-s(j-1)h}\right] = \frac{h}{s}\sum_{k\geq 0}\frac{(-s)^k(j^k+(j-1)^k)}{2k!}h^k \\
&= \frac{h}{s} - \sum_{k\geq 2}\frac{(j^{k-1}+(j-1)^{k-1})}{2(k-1)!}(-s)^{k-2}h^k.
\end{aligned}$$

Hence, for all $s \in \overline{\mathbb{C}_+} \setminus \{0\}$

$$J_j(h,s) = \sum_{k\geq 2}\frac{d_k(j)}{2k!}(-s)^{k-2}h^k$$

where the coefficient polynomials satisfy (by the binomial theorem)

$$\begin{aligned} d_k(j) &= 2\left(j^k - (j-1)^k\right) - k\left(j^{k-1} + (j-1)^{k-1}\right) \\ &= \sum_{m=0}^{k-3} \binom{k}{m} (k-m-2)(-1)^{k-m} j^m \quad \text{for} \quad k \geq 3 \end{aligned}$$

and $d_2(j) = 0$. Hence $d_k(j)$ is a polynomial of degree $k-3$ in variable j. Finally, we get

$$J_j(h,s) = \sum_{k\geq 3} \sum_{m=0}^{k-3} \frac{k-m-2}{2m!(k-m)!} (-j)^m s^{k-2} h^k.$$

Let us compute an upper estimate for

$$\|\{J_j(h,s)\}_j\|_{\ell^2} := \left(\sum_{j=1}^{J} J_j(h,s)^2 \right)^{1/2}.$$

By the triangle inequality

$$\begin{aligned} &\|\{J_j(h,s)\}_j\|_{\ell^2} \\ &\leq |s^{-2}| \cdot \sum_{k\geq 3} \sum_{m=0}^{k-3} \frac{k-m-2}{2m!(k-m)!} |sh|^k \left(\sum_{j=1}^{J} j^{2m} \right)^{1/2} \\ &\leq |s^{-2}| \cdot \sum_{k\geq 3} \sum_{m=0}^{k-3} \frac{k-m-2}{2m!(k-m)!} |sh|^k \cdot \frac{J^{m+1/2}}{\sqrt{2m+1}} \\ &\leq \frac{1}{2} |s| T^{1/2} h^{5/2} \cdot \sum_{k\geq 3} \sum_{m=0}^{k-3} \frac{k-m-2}{2\sqrt{2m+1}\, m!(k-m)!} |s|^{k-3} T^m h^{k-m-3}. \end{aligned}$$

Noting that for $k-3 \geq m \geq 0$ we have $\frac{k-m-2}{\sqrt{2m+1}\, m!(k-m)!} \leq \frac{1}{m!(k-m-3)!}$ and $|s|^{k-3} T^m h^{k-m-3} = |sh|^{k-3} \cdot (T/h)^m$, we may estimate the sum term above

$$\begin{aligned} &\sum_{k\geq 3} \sum_{m=0}^{k-3} \frac{k-m-2}{2\sqrt{2m+1}\, m!(k-m)!} |s|^{k-3} T^m h^{k-m-3} \\ &\leq \sum_{k\geq 3} \left(\frac{|sh|^{k-3}}{(k-3)!} \sum_{m=0}^{k-3} \binom{k-3}{m} \left(\frac{T}{h}\right)^m \right) \\ &\leq \sum_{k\geq 3} \frac{|sh|^{k-3}}{(k-3)!} \left(1 + \frac{T}{h}\right)^{k-3} = e^{|s|(h+T)}. \end{aligned}$$

We now conclude for all $h, T > 0$ and $s \in \overline{\mathbb{C}_+} \setminus \{0\}$ that

$$\|\{J_j(h,s)\}_{j=1}^{J}\|_{\ell^2} \leq \frac{1}{2} |s| T^{1/2} h^{5/2} e^{|s|(h+T)}. \tag{3.13}$$

In addition to estimate (3.13) a lower bound can also be obtained: Decompose

$$
\begin{aligned}
J_j(h,s) &= \sum_{k=3}^{\infty}\sum_{m=0}^{k-3} \frac{k-m-2}{2m!(k-m)!}(-j)^m s^{k-2}h^k \\
&= \sum_{k=3}^{\infty}\left(\frac{1}{2(k-3)!3!}(-j)^{k-3}s^{k-2}h^k + \sum_{m=0}^{k-4} \frac{k-m-2}{2m!(k-m)!}(-j)^m s^{k-2}h^k \right) \\
&= \sum_{k=3}^{\infty} \frac{1}{2(k-3)!3!}(-j)^{k-3}s^{k-2}h^k + \sum_{k=4}^{\infty}\sum_{m=0}^{k-4} \frac{k-m-2}{2m!(k-m)!}(-j)^m s^{k-2}h^k
\end{aligned}
$$

so that by the triangle inequality

$$
\begin{aligned}
\left\|\{J_j(h,s)\}_{j=1}^J\right\|_{\ell^2} \geq & \left\|\left\{ \sum_{k=3}^{\infty} \frac{1}{2(k-3)!3!}(-j)^{k-3}s^{k-2}h^k \right\}_{j=1}^J\right\|_{\ell^2} \\
& - \left\|\left\{ \sum_{k=4}^{\infty}\sum_{m=0}^{k-4} \frac{k-m-2}{2m!(k-m)!}(-j)^m s^{k-2}h^k \right\}_{j=1}^J\right\|_{\ell^2}.
\end{aligned}
\tag{3.14}
$$

For the first term in the right hand side of (3.14) we have

$$
\begin{aligned}
& \left\|\left\{ \sum_{k=3}^{\infty} \frac{1}{2(k-3)!3!}(-j)^{k-3}s^{k-2}h^k \right\}_{j=1}^J\right\|_{\ell^2} \\
&= \left\|\left\{ \frac{1}{12}sh^3 \sum_{k=3}^{\infty} \frac{1}{(k-3)!}(-j)^{k-3}s^{k-3}h^{k-3} \right\}_{j=1}^J\right\|_{\ell^2} \\
&= \frac{1}{12}|s|h^3 \cdot \left\|\{e^{-jsh}\}_{j=1}^J\right\|_{\ell^2}
\end{aligned}
\tag{3.15}
$$

where

$$
\begin{aligned}
\left\|\{e^{-jsh}\}_{j=1}^J\right\|_{\ell^2} &= \sum_{j=1}^{J} |e^{-jsh}|^2 \\
&= \begin{cases} J = h^{-1}T, & \text{when } \operatorname{Re} s = 0 \\ e^{-2h\operatorname{Re} s}\frac{1-e^{-2(J+1)h\operatorname{Re} s}}{1-e^{-2h\operatorname{Re} s}}, & \text{when } \operatorname{Re} s > 0. \end{cases}
\end{aligned}
\tag{3.16}
$$

For the latter term in (3.14) we have a similar upper estimate to (3.13). Indeed,

$$\begin{aligned}
&\|\left\{\sum_{k=4}^{\infty}\sum_{m=0}^{k-4}\frac{k-m-2}{2m!(k-m)!}(-j)^m s^{k-2}h^k\right\}_{j=1}^{J}\|_{\ell^2}\\
\leq&\sum_{k=4}^{\infty}\sum_{m=0}^{k-4}\frac{k-m-2}{2m!(k-m)!}|s|^{k-2}h^k\frac{J^{m+1/2}}{\sqrt{2m+1}}\\
=&\sum_{k=4}^{\infty}\sum_{m=0}^{k-4}\frac{k-m-2}{2m!(k-m)!}|s|^{k-2}h^k h^{-m-1/2}T^{m+1/2}\\
=&|s|^2h^{7/2}\sum_{k=4}^{\infty}\sum_{m=0}^{k-4}\frac{k-m-2}{2m!(k-m)!}|s|^{k-4}h^{k-m-4}T^m\\
\leq&|s|h^{7/2}e^{|s|(h+T)}.
\end{aligned}\tag{3.17}$$

As a conclusion we can now state

Proposition 4. *Let $J_j(h,s)$ be defined through* (3.12)*. Then for any $s\in i\mathbb{R}$, $T,h>0$ satisfying $T=Jh$, $J\in\mathbb{N}$ and $9h\leq T^{2/3}e^{-\frac{4}{3}|s|T}$ we have*

$$\|\{J_j(h,s)\}_{j=1}^{J}\|_{\ell^2}\geq\frac{5}{109}Th^2|s|.\tag{3.18}$$

Proof. It is clear that (3.18) is satisfied for $s=0$. For $s\in i\mathbb{R}\setminus\{0\}$ it follows from (3.14) and (3.15) – (3.17) that for all $s\in i\mathbb{R}\setminus\{0\}$, $h,T>0$ satisfying $T=Jh$ for $J\in\mathbb{N}$ that the estimate

$$\left\|\{J_j(h,s)\}_{j=1}^{J}\right\|_{\ell^2}\geq\left(\frac{T}{12}-h^{3/2}e^{|s|(h+T)}\right)h^2|s|$$

holds. Since always $h\leq T$, we have $h^{3/2}e^{|s|(h+T)}\leq h^{3/2}e^{2|s|T}\leq\frac{T}{27}$ provided that $h\leq\frac{T^{2/3}}{9}e^{-\frac{4}{3}|s|T}$. The claim follows from this. □

3.2 Estimation of (3.6)

In this subsection, we compute an upper estimate for

$$\|\left\{I_j^{(0)}(h,s)\right\}_{j=1}^{J}\|_{\ell^2}:=\left(\sum_{j=1}^{J}I_j^{(0)}(h,s)^2\right)^{1/2}.$$

Writing $\tau=sh$ and recalling $\sigma=2/h$, we get for $s\in\overline{\mathbb{C}_+}$

$$\begin{aligned}
I_j^{(0)}(h,s)=&\frac{2}{\sigma+s}\left(\frac{\sigma-s}{\sigma+s}\right)^j+\frac{1}{s}\left(e^{-sjh}-e^{-s(j-1)h}\right)\\
=&\frac{2}{\sigma+s}\left(\left(\frac{\sigma-s}{\sigma+s}\right)^j-e^{-sjh}\right)+\left(\frac{2}{\sigma+s}-\frac{1}{s}(e^{sh}-1)\right)e^{-sjh}\\
=&\frac{2h}{2+\tau}\left(\left(\frac{2-\tau}{2+\tau}\right)^j-e^{-\tau j}\right)+\left(\frac{2h}{2+\tau}-\frac{h}{\tau}(e^{\tau}-1)\right)e^{-\tau j}.
\end{aligned}$$

Let $\Omega \subset \overline{\mathbb{C}_+}$ be any set. Then for any $\tau \in \Omega$ we have

$$\begin{aligned}
|I_j^{(0)}(h,s)| \leq & \left|\frac{2h}{2+\tau}\right| \left|\left(\frac{2-\tau}{2+\tau}\right)^j - e^{-\tau j}\right| + \left|\frac{2h}{2+\tau} - \frac{h}{\tau}(e^\tau - 1)\right| \left|e^{-\tau j}\right| \\
\leq & \left|\frac{2h}{2+\tau}\right| \left|\left(\frac{2-\tau}{2+\tau}\right) - e^{-\tau}\right| \left|\sum_{k=1}^{j-1} \left(\frac{2-\tau}{2+\tau}\right)^k e^{-\tau(j-k-1)}\right| \\
& + \left|\frac{2h}{2+\tau} - \frac{h}{\tau}(e^\tau - 1)\right| \\
\leq & h|\tau| \left(C_\Omega \left|\frac{2j\tau^2}{2+\tau}\right| + C'_\Omega\right)
\end{aligned}$$

where the constants are given by

$$C_\Omega = \sup_{\tau\in\Omega} \left|\frac{1}{\tau^3}\left(\frac{2-\tau}{2+\tau} - e^{-\tau}\right)\right| \text{ and } C'_\Omega = \sup_{\tau\in\Omega} \left|\frac{1}{\tau}\left(\frac{2}{2+\tau} - \frac{1}{\tau}(e^\tau - 1)\right)\right|.$$

This implies for all $h \geq 0$ and $\tau = sh \in \Omega$

$$\begin{aligned}
\left\|\left\{I_j^{(0)}(h,s)\right\}_{j=1}^J\right\|_{\ell^2} \leq & C_\Omega \frac{2h|\tau|^3}{|2+h|} \left(\sum_{j=1}^J j^2\right)^{1/2} + C'_\Omega h|\tau| \left(\sum_{j=1}^J 1\right)^{1/2} \\
\leq & C_\Omega h^4 |s|^3 \left(\frac{1}{3}J^3 + \frac{1}{2}J^2 + \frac{1}{6}J\right)^{1/2} + C'_\Omega h^2 |s| J^{1/2} \qquad (3.19) \\
\leq & C_\Omega h^{5/2}|s|^3 T^{3/2} + C'_\Omega h^{3/2}|s| T^{1/2}
\end{aligned}$$

by the facts that $T = Jh$ and $J \geq 1$. We now have to choose the set Ω in a clever way, so that the resulting estimate is properly "fine tuned" according to Proposition 4.

Proposition 5. *Let* $I_j^{(0)}(h,s)$ *be defined through* (3.6). *Then for any* $s \in i\mathbb{R}$, $T \geq 1, h > 0$ *satisfying* $T = Jh$, $J \in \mathbb{N}$ *and* $9h \leq T^{2/3}e^{-\frac{4}{3}|s|T}$ *we have*

$$\left\|\left\{I_j^{(0)}(h,s)\right\}_{j=1}^J\right\|_{\ell^2} \leq \frac{1}{2}h^{5/2}|s|^3 T^{3/2} + \frac{3}{2}h^{3/2}|s|T^{1/2} \qquad (3.20)$$

Proof. Since we assume (motivated by Proposition 4) that $9h \leq T^{2/3}e^{-\frac{4}{3}|s|T}$, we have

$$|\tau| = |s|h \leq \frac{|s|T^{2/3}}{9} e^{-\frac{4}{3}|s|T} \leq \frac{|s|T}{9} e^{-\frac{4}{3}|s|T} \leq \frac{1}{12e},$$

since $\max_{r\geq 0} re^{-\frac{4}{3}r} = 3/(4e)$. Hence, we are invited to estimate the constants C_Ω and C'_Ω for the set $\Omega := [-i/(12e), i/(12e)]$. By computing the Taylor series, we see that

$$\begin{aligned}
C_\Omega \leq & \sum_{j\geq 0} \left|\frac{1}{2^{j+2}} - \frac{1}{(j+3)!}\right| \cdot \left(\frac{1}{12e}\right)^j < \sum_{j\geq 0} \frac{1}{2^{j-1}} \cdot \left(\frac{1}{12e}\right)^j \\
= & \frac{6e}{24e-1} < \frac{1}{2}.
\end{aligned}$$

Similarly

$$C'_\Omega \leq \sum_{j\geq 0} \left| \left(-\frac{1}{2}\right)^{j+1} - \frac{1}{(j+2)!} \right| \cdot \left(\frac{1}{12e}\right)^j < \sum_{j\geq 0} \frac{1}{2^j} \cdot \left(\frac{1}{12e}\right)^j$$
$$= \frac{24e}{24e-1} < \frac{3}{2}.$$

But now (3.19) implies (3.20). □

3.3 Determination of the isoperimetric constant

In this section we give a basic interpolation estimate used several times in the proofs.

Proposition 6. *Assume that $u \in H^1(I_j)$. Then*

$$||u - \bar{u}||_{L^2(I_j)} \leq \frac{h}{\pi} |u|_{H^1(I_j)}$$

Proof. Let $I_{ref} = (0, 1]$ and define the bilinear forms $a(u, v) = \int_{I_{ref}} u'(v')^* \, dt$ and $b(u, v) = \int_{I_{ref}} uv^* \, dt$ where the asterisk denotes complex conjugation. Furthermore, let

$$V = \{v \in H^1(I_{ref}) \mid \int_{I_{ref}} v(t) \, dt = 0\}$$

and

$$\lambda_1 = \inf_{v\in V, v\neq 0} \frac{a(v, v)}{b(v, v)} \in \mathbb{R}^+$$

By Rayleigh's theorem, λ_1 is the smallest eigenvalue of the problem: Find $u \in V$ such that

$$a(u, v) = \lambda b(u, v) \quad \forall v \in V. \tag{3.21}$$

Solution to (3.21) can be sought for using the Euler equations for the eigenpair (λ, u). By standard calculus the first eigenpair is found to be $(\lambda_1, u_1) = (\pi^2, \cos(\pi t))$. It follows that $b(v, v) \leq \frac{1}{\lambda_1} a(v, v)$, that is $||v||^2_{L^2(I_{ref})} \leq \frac{1}{\pi^2} |v|^2_{H^1(I_{ref})}$ for any $v \in V$. Let now $u \in H^1(I_{ref})$ and set $v = u - \bar{u} \in V$ implying

$$||u - \bar{u}||^2_{L^2(I_{ref})} \leq \frac{1}{\pi^2} |u - \bar{u}|^2_{H^1(I_{ref})} = \frac{1}{\pi^2} |u|^2_{H^1(I_{ref})} \tag{3.22}$$

For the general interval $I_j = (t_{j-1}, t_j]$ a standard scaling argument with $\hat{u}(\tau) = u((t - t_{j-1})/h)$ and $\tau = (t - t_{j-1})/h \in I_{ref}$ gives

$$||u - \bar{u}||^2_{L^2(I_j)} = h||\hat{u} - \bar{\hat{u}}||^2_{L^2(I_{ref})} \leq \frac{1}{\pi^2} h |\hat{u}|^2_{H^1(I_{ref})} = \frac{1}{\pi^2} h^2 |u|^2_{H^1(I_j)} \tag{3.23}$$

implying

$$||u - \bar{u}||_{L^2(I_j)} \leq \frac{1}{\pi} h |u|_{H^1(I_j)}. \tag{3.24}$$

□

4 Weak and strong convergence

We first show that Theorem 1 implies that $L_\sigma \to \mathcal{L}$ in weak operator topology. Using this, it is then shown in Theorem 2 that the convergence is, in fact, strong.

Indeed, it follows from Theorem 1 that $(L_\sigma u)(i\omega) \to (\mathcal{L}u)(i\omega)$ uniformly in the compact subsets $i\omega \in K \subset i\mathbb{R}$ for any $u \in C_c(\mathbb{R}_+) \cap H^1(\mathbb{R}_+)$. Hence, for finite linear combinations s (also called simple functions) of characteristic functions χ_K of compact intervals $K \subset i\mathbb{R}$ we have $\langle s, L_\sigma u\rangle_{L^2(i\mathbb{R})} \to \langle s, \mathcal{L}u\rangle_{L^2(i\mathbb{R})}$. Since $\|L_\sigma\|_{\mathcal{L}(L^2(\mathbb{R}_+);H^2(\mathbb{C}_+))} \leq 1$ and simple functions are dense in $L^2(i\mathbb{R})$, it follows that

$$\langle v, L_\sigma u\rangle_{K^2(i\mathbb{R})} \to \langle v, \mathcal{L}u\rangle_{H^2(i\mathbb{R})} \text{ as } \sigma \to \infty \tag{4.1}$$

for all $u \in C_c(\mathbb{R}) \cap H^1(\mathbb{R}_+)$ and $v \in L^2(i\mathbb{R}_+)$. Another density argument implies finally that (4.1) holds even for all $u \in L^2(\mathbb{R}_+)$ and $v \in L^2(i\mathbb{R}_+)$.

We recall a result from elementary functional analysis:

Proposition 7. *Let H be a Hilbert space, and assume that $u_j \to u$ weakly in H. If $\|u_j\|_H \to \|u\|_H$, then $u_j \to u$ in the norm of H.*

Proof. $\langle u_j - u, u_j - u\rangle_H = \langle u_j, u_j\rangle_H - \langle u, u\rangle_H - \langle u, u_j - u\rangle_H - \langle u_j - u, u\rangle_H = \|u_j\|_H^2 - \|u\|_H^2 - 2\mathrm{Re}\,\langle u, u_j - u\rangle_H$. □

Theorem 2. *We have $\|L_\sigma u - \mathcal{L}u\|_{H^2(\mathbb{C}_+)} \to 0$ for any $u \in L^2(\mathbb{R}_+)$. Moreover, $\|L_\sigma^* v - \mathcal{L}^* v\|_{L^2(\mathbb{R}_+)} \to 0$ for any $v \in H^2(\mathbb{C}_+)$.*

Proof. Adjoining (4.1) shows that $L_\sigma^* v \to \mathcal{L}^* v$ weakly. Since L_σ is a coisometry by Proposition 2 and (2.5), we have

$$\|L_\sigma^* v\|_{L^2(\mathbb{R}_+)}^2 = \langle L_\sigma L_\sigma^* v, v\rangle_{H^2(\mathbb{C}_+)}^2 = \|v\|_{H^2(\mathbb{C}_+)}^2.$$

Now Proposition 7 implies the latter part of this Theorem.

To show the first part, we have to work a bit harder to verify that $\|L_\sigma u\|_{L^2(i\mathbb{R})} \to \|u\|_{L^2(\mathbb{R}_+)} = \|\mathcal{L}u\|_{L^2(i\mathbb{R})}$. Suppose that $h = 2/\sigma > 0$ and $u \in L^2(\mathbb{R}_+)$ is such that $u(t) = \overline{u}_{j,h} := \int_{((j-1)h,jh]} u(t)\,dt$ for all $t \in I_j := ((j-1)h, jh]$ — in other words, this is simply $u = P_h u$. For such u

$$\|u\|_{L^2(\mathbb{R}_+)}^2 = \sum_{j\geq 1} \int_{I_j} |u(t)|^2\,dt = h\|\{\overline{u}_{j,h}\}_{j\geq 0}\|_{\ell^2}^2.$$

By the definition of the discretizing operator T_σ, we have

$$\|T_\sigma u\|_{H^2(\mathbb{D})}^2 = \sum_{j\geq 1} \left(\frac{1}{\sqrt{h}} \int_{I_j} |u(t)|^2\,dt\right)^2 = h \sum_{j\geq 1} |\overline{u}_{j,h}|^2 = \|u\|_{L^2(\mathbb{R}_+)}^2.$$

Hence, we have $\|T_\sigma P_h u\|_{H^2(\mathbb{D})} = \|P_h u\|_{L^2(\mathbb{R}_+)}$ for all $u \in L^2(\mathbb{R}_+)$ where $\sigma = 2/h$. Also note that $T_\sigma u = T_\sigma P_h u$ for all $u \in L^2(\mathbb{R}_+)$ provided that $\sigma = 2/h$.

We now have for any $u \in L^2(\mathbb{R}_+)$

$$\begin{aligned}
&\big| \|T_\sigma u\|_{H^2(\mathbb{D})} - \|u\|_{L^2(\mathbb{R}_+)} \big| \\
&\leq \big| \|T_\sigma u\|_{H^2(\mathbb{D})} - \|T_\sigma P_h u\|_{H^2(\mathbb{D})} \big| + \big| \|T_\sigma P_h u\|_{H^2(\mathbb{D})} - \|P_h u\|_{L^2(\mathbb{R}_+)} \big| \\
&+ \big| \|P_h u\|_{L^2(\mathbb{R}_+)} - \|u\|_{L^2(\mathbb{R}_+)} \big| = \big| \|P_h u\|_{L^2(\mathbb{R}_+)} - \|u\|_{L^2(\mathbb{R}_+)} \big|
\end{aligned}$$

where again $\sigma = 2/h$. Since the projections $P_h \to I$ strongly in $L^2(\mathbb{R}_+)$ as $h \to 0$, we conclude that $\|T_\sigma u\|_{H^2(\mathbb{D})} \to \|u\|_{L^2(\mathbb{R}_+)}$ and hence $\|L_\sigma u\|_{H^2(\mathbb{C}_+)} \to \|u\|_{L^2(\mathbb{R}_+)}$ as $\sigma \to \infty$, see Proposition 2. The first claim of this theorem follows from this, Proposition 7 and (4.1). □

Using Theorem 2 we can show that the output of integration scheme (1.5) converges to the output of continuous time dynamics (1.3) for *input/output stable* systems S. These are systems for which $\mathbf{G}(\cdot) \in H^\infty(\mathbb{C}_+)$ or, equivalently, $\mathbf{G} \in \mathcal{L}(H^2(\mathbb{C}_+))$. To understand the formulation of the following theorem, we refer back to Section 2.

Theorem 3. *For any $u \in L^2(\mathbb{R}_+)$ and $\mathbf{G} \in H^\infty(\mathbb{C}_+)$, we have*

$$\|T_\sigma^* \mathbf{D}_\sigma T_\sigma u - \mathcal{L}^* \mathbf{G} \mathcal{L} u\|_{L^2(\mathbb{R}_+)} \to 0 \tag{4.2}$$

as $\sigma \to \infty$.

Proof. As noted just before Proposition 3, we have $T_\sigma^* \mathbf{D}_\sigma T_\sigma = L_\sigma^* \mathbf{G} L_\sigma$. Then we get for all $\sigma > 0$

$$\begin{aligned}
&\|L_\sigma^* \mathbf{G} L_\sigma u - \mathcal{L}^* \mathbf{G} \mathcal{L} u\|_{L^2(\mathbb{R}_+)} \leq \|(L_\sigma^* - \mathcal{L}^*)\, \mathbf{G}\, (L_\sigma u - \mathcal{L} u)\|_{L^2(\mathbb{R}_+)} \\
&+ \|(L_\sigma^* - \mathcal{L}^*)\, \mathbf{G} \mathcal{L} u\|_{L^2(\mathbb{R}_+)} + \|\mathcal{L}^* \mathbf{G}\, (L_\sigma u - \mathcal{L} u)\|_{L^2(\mathbb{R}_+)}.
\end{aligned}$$

Now (4.2) follows by Theorem 2. □

5 A counterexample

We complete this paper by reviewing estimate (2.6) in the special case when $\mathbf{G}(s) = I$ for all $s \in \mathbb{C}_+$. It indicates that Theorem 3 cannot be improved by a speed estimate for convergence.

In this special case it follows from the very definitions that $L_\sigma^* \mathbf{G} L_\sigma = T_\sigma^* T_\sigma = P_{2/\sigma}$ where the orthogonal projection P_h is defined as in Section 3. Since $\mathcal{L}^* \mathcal{L} = \mathcal{I}$ on all of $L^2(\mathbb{R}_+)$, we should give an estimate to

$$\|u - P_h u\|_{L^2([0,T])} \quad \text{for a family of functions} \quad u \in L^2(\mathbb{R}_+).$$

It is, of course, true that $P_h u \to u$ as $h \to 0$ for all $u \in L^2(\mathbb{R}_+)$. However, there cannot be a uniform speed estimate of type

$$\|u - P_h u\|_{L^2([0,T])} \leq C_u h^\alpha \tag{5.1}$$

where $C_u < \infty$ for *all* $u \in L^2([0,T])$. If it were so, then for any $0 < \beta < \alpha$ we would have $\|h^{-\beta}(I - P_h)u\|_{L^2([0,T])} \leq C_u h^{\alpha-\beta} \to 0$ as $h \to 0$, for all $u \in L^2([0,T])$. By the uniform boundedness principle,

$$\sup_{h>0} \|h^{-\beta}(I - P_h)\|_{L^2([0,T])} =: M < \infty$$

and hence $\|(I - P_h)\|_{\mathcal{L}(L^2([0,T]))} \leq M h^\beta$ for all $h > 0$.

Making now h small enough, we see that then the norm of the orthogonal projection $(I - P_h)|L^2([0,T])$ is strictly less than 1; this implies that $I|L^2([0,T]) = P_h|L^2([0,T])$. But $P_h|L^2([0,T])$ is a finite rank operator, and the uniform speed estimate (5.1) cannot hold by contradiction. The same conclusion holds, if h^α in (5.1) is replaced by *any* increasing continuous function $\phi(h)$ satisfying $\phi(0) = 0$.

It should also be noted that for functions $u \in L^2(\mathbb{R}_+)$ that possess certain smoothness properties such a speed estimate can be obtained. See [2] for a further discussion on what is obtainable and what is not.

6 Conclusions

The operators L_σ for $\sigma > 0$ have been introduced just before Proposition 3 with aid of the Cayley transformation (1.7). It is shown in Theorem 2 that the operators L_σ provide an approximation to Laplace transform for a wide class of functions. In addition, Theorem 3 shows that for I/O-stable linear systems, the convergence extends to the input/output relation of the system. All this can be anticipated since the Cayley transform actually corresponds to the slightly “unorthodox”, conservativity-preserving discretization (1.5) of the dynamical equations (1.3) (or their infinite-dimensional analogue e.g. in [8, Proposition 2.5]).

Theorem 3 gives no estimate on the speed of the convergence with respect to the sampling parameter $h = 2/\sigma$. If we had some decay

$$\mathbf{G}(s) \to 0 \quad \text{as} \quad |s| \to \infty \tag{6.1}$$

at some speed, then we could effectively restrict our analysis to compact subsets of $i\mathbb{R}$. Then the speed estimate of Theorem 1 could show up in (4.2) in some form. Unfortunately, (6.1) is not a generic property of $\mathbf{G} \in H^\infty(\mathbb{C}_+)$ – hence it is not a generic property of the transfer functions of conservative systems either.

In the time domain, the same problem appears because the sampling operator T_σ cannot detect above a certain cutoff frequency: there are always high-frequency signals carrying substantial energy that a given discretized system cannot capture. To achieve a speed estimate in (4.2), one could assume either

(i) that the high frequencies are damped by the linear system itself (e.g. by a property like (6.1)), or

(ii) that the high frequencies have a small amplitude in the signal u (e.g. an assumption such as $u \in H^1(\mathbb{R}_+)$ in Theorem 1).

The approximation of the state trajectory $x(\cdot)$ by the discrete trajectories $\{x_j^{(h)}\}_{j\geq 0}$ solving (1.5) has not been studied here. This will be carried out in a future paper on the state space approximation for conservative systems.

Remark 1. *We remark that practically all of the results presented in this paper hold if the input space of the node S is a separable Hilbert space instead of $\mathbb{C}$.*

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