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Sharp control time for viscoelastic bodies^{*}

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Abstract: The evolution in time of a viscoelastic body is described by an equation with memory, which can be seen as a perturbation of the equations of elasticity. This observation is a useful tool in the study of control problems. In this paper, by using moment methods, we compare a viscoelastic system which fills a surface or a solid region (the string case has already been studied) with its elastic counterpart (which is a generalized telegrapher's equation) in order to prove exact controllability of the viscoelastic body as a consequence of the assumed controllability of the associated telegrapher's equation.

Keywords: Controllability and observability, integral equations, linear systems, partial differential equations, heat equations with memory, viscoelasticity.

1 Introduction

We study a control problem for the following equation:

$$\begin{aligned} w_{tt} = & 2cw_t + \nabla \cdot (a(x)\nabla w) + q(x)w + \\ & + \int_0^t M(t-s) \{ \nabla \cdot (a(x)\nabla w(s)) + q(x)w(s) \} \, ds + F(x, t). \end{aligned} \quad (1.1)$$

Here $w = w(x, t)$: $\Omega \times [0, T] \mapsto \mathbb{R}$ where $T > 0$ and $\Omega \subseteq \mathbb{R}^d$, $d \leq 3$.

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Eq (1.1) has several interpretations. For every d , $w(x, t)$ represents the temperature of a thermodynamical system with memory which occupies the region Ω , see [12]. In linear viscoelasticity and when $d = 1$ or $d = 2$, $w(x, t)$ represents the displacement of the point in position x at time t of a body which fills the region Ω (see [31]). If $d = 3$ then a similar interpretation holds for quite special classes of displacements.

Eq. (1.1) has to be supplemented with the initial condition

$$w(\cdot, 0) = w_0, \quad w_t(\cdot, 0) = w_1.$$

A control $f \in L^2_{\text{loc}}(0, +\infty; L^2(\Gamma))$ acts on the boundary of Ω :

$$w(x, t) = f(x, t) \quad x \in \Gamma \subseteq \partial\Omega, \quad w(x, t) = 0 \quad x \in \partial\Omega \setminus \Gamma. \quad (1.2)$$

We stress the fact that the control f is *real valued*.

Note that the arguments of $w = w(x, t)$ are not explicitly indicated unless needed for clarity. We shall write $w(x, t)$ or $w(t)$ or simply w . Furthermore, w does depend on f but also this dependence is not indicated.

We refer to [14] for the following properties of (1.1) (see also [24, Appendix]). Let $f \in L^2(G_T) = L^2(0, T; L^2(\Gamma))$ and $w(\cdot, 0) = \xi \in L^2(\Omega)$, $w_t(\cdot, 0) = \eta \in H^{-1}(\Omega)$. Then, (1.1) admits a unique solution $w(\cdot, t) \in C(0, T; L^2(\Omega)) \cap C^1(0, T; H^{-1}(\Omega))$ and the transformation

$$(\xi, \eta, f) \mapsto (w, w_t)$$

is linear and continuous in the indicated spaces. So, the following definition of controllability is justified:

Definition 1 *System (1.1) is controllable at time T if for every $w_0, \xi \in L^2(\Omega)$ and $w_1, \eta \in H^{-1}(\Omega)$ there exists $f \in L^2(0, T; L^2(\Gamma))$ such that*

$$w(\cdot, T) = \xi \in L^2(\Omega), \quad w_t(\cdot, T) = \eta \in H^{-1}(\Omega).$$

A control f with this property is called a steering control (to the target (ξ, η)).

It is known that controllability of a linear system does not depend on the initial condition or on the affine term F so that we can assume

$$w(x, 0) = 0, \quad w_t(x, 0) = 0, \quad F(x, t) = 0. \quad (1.3)$$

Controllability at time T implies controllability at larger times so that:

Definition 2 *The sharp control time for system (1.1) (with control (1.2)) is the infimum of the set of the times at which the system is controllable.*

The special case of Eq. (1.1) with $M(t) \equiv 0$ is the (generalized) telegrapher's equation:

$$\begin{cases} w_{tt} = 2cw_t + \nabla \cdot (a(x)\nabla w) + q(x)w, \\ w(x, t) = f(x, t) \quad x \in \Gamma, \quad w(x, t) = 0 \quad x \in \partial\Omega \setminus \Gamma. \end{cases} \quad (1.4)$$

The paper [32] proves controllability of (1.4) with *real* controls if Γ is suitably chosen and identifies a Γ -dependent control time. Our goal is the proof that when the telegrapher's equation is controllable at time T then also (1.1) is controllable and conversely:

Theorem 3 *Let $\Omega \in \mathbb{R}^3$ be a bounded region with C^2 boundary and $M(t) \in H_{\text{loc}}^2(0, +\infty)$, $q(x) \in C(\bar{\Omega})$, $a(x) \in C^1(\bar{\Omega})$, with $a(x) > a_0 > 0$ for every $x \in \bar{\Omega}$. Then we have:*

1. *if the telegrapher's equation (1.4) is controllable at time T , then Eq. (1.1) is controllable at any larger time.*
2. *Eq. (1.1) and (1.4) have the same sharp control time.*

Among the different ways in which controllability can be proved, possibly the oldest one is the reduction of a control problem to a moment problem. Theorem 3 when $d = 1$ has been proved via moment methods in [19, 25, 26] and we prove here that moment methods can be used in general.

As an application of our results, we note that controllability can be used to identify external signal using boundary observations, see [27].

Notations. Whenever the notations $\{M_n\}$ and $\{M_n(t)\}$ appear they denote respectively a *bounded* sequence of numbers and a sequence of (continuous) functions which is *bounded* on a (preassigned) interval $[0, T]$, not the same sequences at every occurrence. The special expression of these sequences has no interest in the proofs.

We introduce the notation $(\partial/\partial\nu)$ denotes normal derivative on $\partial\Omega$

$$G_t = \Gamma \times (0, t), \quad \gamma_a \phi = a(x) \frac{\partial \phi}{\partial \nu} \quad \text{on } \partial\Omega \text{ (in particular on } \Gamma).$$

Organization of the paper The goal of the paper is the proof of the two statements in Theorem 3. The proof is in two parts, and requires several preliminaries and ancillary material. Preliminaries are in Section 2: subsection 2.1 presents a transformation of the variable w which does not affect controllability but which simplifies the computations; subsection 2.2 presents information on the theory of moments and Riesz sequences while the properties of the telegrapher's equation are in subsection 2.3.

In Section 3 we prove item 1 of Theorem 3 while equality of the sharp control times (i.e. item 2) is proved in Section 4.

Proofs of ancillary results are in the appendix.

1.1 References and known results

The first results on controllability of viscoelastic systems have been obtained by Leugering (see for example [16, 17]) then followed by several contribution (see for example [15]). Among them, we consider in particular the results in [5, 8, 20, 24]. The paper [20] proves Theorem 3 (even for a nonconvolution kernel. See [28] for an important special case) in the case $q(x) = 0$ and $a(x) = 1$. More important, it explicitly assumes that the control acts on the whole boundary of Ω , $\Gamma = \partial\Omega$. Under these conditions the paper [20] proves controllability, as a consequence of observability of the adjoint system, when $T \geq T_0$, where T_0 is explicitly identified. Controllability via observability of the adjoint system is proved in [8], when the control is distributed in a subregion close to $\partial\Omega$ (the proof is based on Carleman estimates).

An extension of D'Alembert formula is used in [5, Sect. 5] to study controllability to smooth targets of a (one dimensional) thermal system with memory.

The paper [24] uses an operator approach and represents the solutions of (1.1) by using cosine operators (this idea is implicit in previous papers, for example by Leugering). It is proved in [24] that controllability holds for the equation with memory if the corresponding wave equation is controllable but the control time is not explicitly identified.

The papers [5, 8, 24] are concerned with the heat equation with memory so that they study only the controllability of the component $w(t)$, not of the velocity, but at least the arguments in [24] are easily extended to the pair (deformation/velocity).

In conclusion, Theorem 3 extends and completes the results in [5, 8, 20, 24] and furthermore it uses different techniques, which have their independent

interest: the proof uses moment methods and extends to spaces of higher dimension the techniques and results developed in [1, 3, 4, 19, 25, 26, 27, 28].

2 Preliminary information

Let A be the operator in $L^2(\Omega)$,

$$\text{dom } A = H^2(\Omega) \cap H_0^1(\Omega), \quad Aw = \nabla \cdot (a(x)\nabla w) + q(x)w. \quad (2.1)$$

This operator is selfadjoint with compact resolvent and has a sequence $\{-\lambda_n^2\}$ of eigenvalues. Note the sign and the exponent, but this does not imply that $-\lambda_n^2$ is real negative. This property does depend on the sign of $q(x)$. The order of the eigenvalues is taken so that $\{|\lambda_n|\}$ is increasing (eigenvalues with equal modulus are taken in any order) and every eigenvalue is repeated according to its multiplicity (which is finite). It is known (see [23, p. 192]) that there exist N , $m_0 > 0$ and $m_1 > 0$ such that if $n > N$ then λ_n^2 is real and we have:

$$m_0 n^{2/d} < \lambda_n^2 < m_1 n^{2/d}.$$

We shall use the following consequence:

Lemma 4 *If $d \leq 3$ then we have $\sum 1/\lambda_n^4 < +\infty$.*

The space $L^2(\Omega)$ has an orthonormal basis whose elements are eigenvectors of A : $A\phi_n = -\lambda_n^2\phi_n$.

For any $k > 0$ such that $(kI - A)$ is positive, the sequence

$$\left\{ \phi_n \left(\sqrt{k + \lambda_n^2} \right)^{-1} \right\}$$

is an orthonormal basis of $(\text{dom } (kI - A)^{1/2})$ and so $\{\phi_n \sqrt{k + \lambda_n^2}\}$ is an orthonormal basis of $(\text{dom } (kI - A)^{1/2})'$. This space is unitary equivalent to $H^{-1}(\Omega)$ since (from [9, Theorem 1-D]) $(\text{dom } (kI - A)^{1/2}) = H_0^1(\Omega)$. Hence, every $\chi \in H^{-1}(\Omega)$ has the representation

$$\chi = \sum \chi_n \left(\sqrt{k + \lambda_n^2} \right) \phi_n, \quad \{\chi_n\} \in l^2. \quad (2.2)$$

2.1 A preliminary transformation

The computations are simplified if we use a transformation first introduced in [25]. We integrate both the sides of (1.1). Initial conditions and affine term are zero so that we get

$$w_t(t) = 2cw(t) + \int_0^t \tilde{N}(t-s) (\nabla \cdot (a(x)\nabla w(s)) + q(x)w(s)) \, ds$$

with

$$w(0) = 0, \quad w|_{\Gamma}(t) = f(t), \quad w|_{\partial\Omega \setminus \Gamma}(t) = 0, \quad \tilde{N}(t) = 1 + \int_0^t M(s) \, ds.$$

We introduce

$$\theta(x, t) = e^{2\gamma t} w(x, t), \quad \gamma = -M(0)/2 = -\tilde{N}'(0)/2.$$

We see that θ solves the following equation, where $\alpha = c + \gamma$, $N(t) = e^{2\gamma t} \tilde{N}(t)$:

$$\theta_t = 2\alpha\theta(t) + \int_0^t N(t-s) (\nabla \cdot (a(x)\nabla \theta(s)) + q(x)\theta(s)) \, ds \quad (2.3)$$

with conditions

$$\theta(0) = 0 \quad \theta|_{\Gamma}(t) = e^{2\gamma t} f(t), \quad \theta|_{\partial\Omega \setminus \Gamma}(t) = 0$$

(the functions $e^{2\gamma t} f(t)$ will be renamed $f(t)$). The fact that simplifies the computation is:

$$N(0) = 1, \quad N'(0) = 0.$$

Thanks to the equality $w_t = e^{-2\gamma t} (\theta_t - 2\gamma\theta)$, controllability of the pair (w, w_t) is equivalent to controllability of the pair (θ, θ_t) . So, from now on we study the controllability of the pairs (θ, θ_t) where θ solves Eq. (2.3).

Now we compute the derivative of both the sides of Eq. (2.3). We get

$$\begin{aligned} \theta_{tt} &= 2\alpha\theta_t + \nabla \cdot (a(x)\nabla \theta) + q(x)\theta + \\ &+ \int_0^t N(t-s) (\nabla \cdot (a(x)\nabla \theta(s)) + q(x)\theta(s)) \, ds. \end{aligned} \quad (2.4)$$

The telegrapher's equation associated to this system is

$$w_{tt} = 2\alpha w_t + \nabla \cdot (a(x)\nabla w) + q(x)w \quad (2.5)$$

(of course systems (2.5) and (1.4) have the same controllability properties).

We shall prove controllability of the viscoelastic system written in the form (2.3) by comparing it with the telegrapher's equation (2.5). In this study, the following notation will be of frequent use (α is the coefficient in (2.3) and (2.5)):

$$\beta_n = \sqrt{\lambda_n^2 - \alpha^2}. \quad \blacksquare \quad (2.6)$$

2.2 Riesz sequences and moment methods

The study of controllability of linear systems can often be reduced to the solution of suitable *moment problems*. We confine ourselves to consider the special case which is needed in the proof of Theorem 3. Let H be an infinite dimensional, separable (real or complex) Hilbert space (inner product is $\langle \cdot, \cdot \rangle$ and the norm is $|\cdot|$). Let $\{e_n\}$ be a sequence in H . We define $\mathbb{J}: H \mapsto l^2$

$$\text{dom } \mathbb{J} = \{f \in H : \{\langle f, e_n \rangle\} \in l^2\}, \quad \mathbb{J}f = \{\langle f, e_n \rangle\}.$$

The moment problem is the study of $\text{im } \mathbb{J}$. In particular, we are interested to understand whether the sequence of the equations

$$\langle f, e_n \rangle = c_n \quad (2.7)$$

admits a solution f for every $\{c_n\} \in l^2$, and to represent at least one of the solutions. In the proof of Theorem 3 we only use the case $\mathbb{J} \in \mathcal{L}(H, l^2)$. Then we restrict our interest to this case. It is then easy to compute \mathbb{J}^* :

$$\mathbb{J}^*(\{c_n\}) = \sum e_n c_n \quad (2.8)$$

It turns out (see [2, Theorem I.2.1]) that \mathbb{J} is an isomorphism of $\text{cl span}\{e_n\}$ and l^2 if and only if $\{e_n\}$ is a *Riesz sequence*, i.e. if and only if $\{e_n\}$ is the image of an orthonormal basis of a Hilbert space K under a linear bounded and boundedly invertible transformation from K to H .

A Riesz sequence in H which is complete in H is called a *Riesz basis*.

The following result holds (see [33, Th. 9]):

Lemma 5 *The sequence $\{e_n\}$ is a Riesz sequence if and only if there exist numbers $m_0 > 0$ and $m_1 > 0$ such that*

$$m_0 \sum |a_n|^2 \leq \left| \sum a_n e_n \right|_H^2 \leq m_1 \sum |a_n|^2 \quad (2.9)$$

for every finite sequence $\{a_n\}$. If furthermore the sequence $\{e_n\}$ is complete, then it is a Riesz basis.

Every Riesz sequence admits biorthogonal sequences $\{\psi_n\}$ i.e. sequences such that

$$\langle \psi_k, e_n \rangle = \delta_{n,k} = \begin{cases} 1 & \text{if } n = k \\ 0 & \text{if } n \neq k. \end{cases}$$

One (and only one) of these biorthogonal sequences belongs to the closed space spanned by $\{e_n\}$. This biorthogonal sequence is a Riesz sequence too, and the solution of the moment problem (2.7) is

$$f = \sum c_n \psi_n.$$

Let $\{e_n\}$ and $\{z_n\}$ be two sequences in H . We say that they are *quadratically close* if

$$\sum |e_n - z_n|^2 < +\infty$$

and we use the following test (see [30, 33]):

Theorem 6 *Let $\{e_n\}$ be a Riesz sequence in H and let $\{z_n\}$ be quadratically close to $\{e_n\}$. Then we have*

- **Paley-Wiener Theorem:** *there exists N such that $\{z_n\}_{n>N}$ is a Riesz sequence in H ;*
- **Bari Theorem:** *the sequence $\{z_n\}$ is a Riesz sequence if, furthermore, it is ω -independent, i.e. if (here $\{\alpha_n\}$ is a sequence of numbers)*

$$\sum \alpha_n z_n = 0 \implies \{\alpha_n\} = 0.$$

A useful observation (implicitly used in the statement of Theorem 6) is as follows: if $\{z_n\}$ is quadratically close to a Riesz sequence then $\sum \alpha_n z_n$ converges in H if and only if $\{\alpha_n\} \in l^2$ (see [10, Ch. 6]).

The concrete case we are interested in, is the case $H = L^2(0, T; K)$ where K is a second Hilbert space (it will be $K = L^2(\Gamma)$). In this context, we need two special results. For completeness, the proofs are given in the Appendix.

Lemma 7 Let $\mathbb{Z}' = \mathbb{Z} \setminus \{0\}$ and let $\{b_n\}_{n \in \mathbb{Z}'}, \{k_n\}_{n \in \mathbb{Z}'}$ be such that

$$b_{-n} = -b_n, \quad k_n = k_{-n} \in K, \quad |\mathcal{I}m b_n| < L. \quad (2.10)$$

for a suitable number L . If the sequence $\{e^{ib_n t} k_n\}_{n \in \mathbb{Z}'}$ is a Riesz sequence in $L^2(0, 2T, K)$, then the following sequences are Riesz sequences in $L^2(0, T; K)$:

$$\{k_n \cos b_n t\}_{n>0}, \quad \{k_n \sin b_n t\}_{n>0}. \quad (2.11)$$

Now we consider a Riesz basis $\{e_n\}$ in $L^2(0, T; K)$ and a time $T_0 < T$. Then $\{e_n\}$ is complete in $L^2(0, T_0; K)$ but it is not a Riesz sequence since every element of $L^2(0, T_0; K)$ has infinitely many representation as a series $\sum a_n e_n$ (one such representation for every extension which belongs to $L^2(0, T; K)$).

Let \mathbb{J}_0 be the operator from $L^2(0, T_0; K)$ to l^2 given by

$$\mathbb{J}_0 f = \{\langle f, e_n \rangle_{L^2(0, T_0; K)}\}.$$

We prove:

Lemma 8 $\dim [\text{im } \mathbb{J}_0]^\perp = +\infty$.

Finally we note that (2.2) can be written as (β_n is defined in (2.6)):

$$\chi = \sum_{\lambda_n^2 = \alpha^2} \left(\chi_n \sqrt{k + \alpha^2} \right) \phi_n + \sum_{\lambda_n^2 \neq \alpha^2} \left(\frac{\chi_n \sqrt{k + \lambda_n^2}}{\beta_n} \right) [\beta_n \phi_n].$$

It follows that a Riesz basis of $H^{-1}(\Omega)$ is the sequence whose elements are

$$\begin{cases} \phi_n & \text{if } \lambda_n^2 = \alpha^2 \\ \beta_n \phi_n & \text{if } \lambda_n^2 \neq \alpha^2. \end{cases}$$

2.3 The telegrapher's equation

We consider the telegrapher's equation (2.5) associated to Eq. (2.4). Controllability at time T is equivalent to surjectivity of the map $f \mapsto \Lambda_T f = (w(T), w_t(T))$ (from $L^2(G_T)$ to $L^2(\Omega) \times H^{-1}(\Omega)$). By computing Λ_T^* we see that the telegrapher's equation is controllable at time T iff there exist $m = m_T > 0$, $M = M_T > 0$ such that

$$m \left(\|\phi_0\|_{H_0^1(\Omega)}^2 + \|\phi_1\|_{L^2(\Omega)}^2 \right) \leq \int_{G_T} \|\gamma_a \phi\|^2 dG_T \leq M \left(\|\phi_0\|_{H_0^1(\Omega)}^2 + \|\phi_1\|_{L^2(\Omega)}^2 \right). \quad (2.12)$$

Here ϕ denotes the solution of the adjoint system

$$\begin{aligned}\phi_{tt} &= -2\alpha\phi_t + \nabla \cdot (a(x)\nabla\phi) + q(x)\phi, \\ \phi(\cdot, 0) &= \phi_0(x) \in H_0^1(\Omega), \quad \phi_t(\cdot, 0) = \phi_1(x) \in L^2(\Omega), \quad \phi|_{\partial\Omega} = 0.\end{aligned}\tag{2.13}$$

The inequalities (2.12) have the following consequence:

Theorem 9 *Let $T > 0$ and let the telegrapher's equation (2.5) be controllable at time T . Then we have:*

1. *For every target $(\xi, \eta) \in L^2(\Omega) \times H^{-1}(\Omega)$ there exists a unique steering control $f = f^{(\xi, \eta)} \in L^2(G_T)$ of minimal norm. This steering control is a continuous function of (ξ, η) .*
2. *Let $\phi(x)$ be an eigenvector of A . Then $\int_{\Gamma} |\gamma_a \phi|^2 \, d\Gamma \neq 0$.*
3. *The sequence $\{(\gamma_a \phi_n)/\lambda_n\}_{\lambda_n \neq 0}$ is almost normalized in $L^2(\Gamma)$, i.e. there exist $m > 0$ and M such that*

$$0 < m \leq \|(\gamma_a \phi_n)/\lambda_n\|_{L^2(\Gamma)} \leq M.\tag{2.14}$$

Proof. Statement 1 follows since the left inequality in (2.12) is coercivity of the adjoint of the map $f \mapsto (w(T), w'(T))$ (see [18, 22]).

We prove statement 2. Let $A\phi = \lambda\phi$. If $\beta = \sqrt{\lambda^2 - \alpha^2} \neq 0$ then the function $\phi(x, t) = e^{-\alpha t}\phi(x) \sin \beta t$ solves (2.13). The left inequality in (2.12) shows that

$$m\beta^2 \|\phi\|_{L^2(\Omega)}^2 \leq \left[\int_0^T e^{-2\alpha t} \sin^2 \beta t \, dt \right] \int_{\Gamma} |\gamma_a \phi(x)|^2 \, d\Gamma.$$

The result follows since (by definition) the eigenvectors are nonzero.

If $\beta = 0$ a similar argument holds, with $\phi(x, t) = e^{-\alpha t}\phi(x)$.

We prove statement 3 (See [13] for the idea of the proof). Let $\beta_n = \sqrt{\lambda_n^2 - \alpha^2}$. It may be $\beta_n = 0$ in (2.6) only for a finite set of indices. So, in the proof of the asymptotic estimate (2.14) we can assume $\beta_n = \sqrt{\lambda_n^2 - \alpha^2} \neq 0$.

The function $\phi(x, t) = \frac{1}{\beta_n} e^{-\alpha t} \phi_n(x) \sin \beta_n t$ solves Eq. (2.13) with initial conditions

$$\phi(x, 0) = 0, \quad \phi_t(x, 0) = \phi_n(x).$$

By using $\|\phi_n\|_{L^2(\Omega)} = 1$, inequality (2.12) gives

$$m \leq \left[\int_0^T \left(\frac{\lambda_n}{\beta_n} e^{-\alpha t} \sin \beta_n t \right)^2 dt \right] \int_{\Gamma} \left| \frac{\gamma_a \phi_n}{\lambda_n} \right|^2 d\Gamma < M.$$

The result follows since $\lim_{n \rightarrow +\infty} (\lambda_n / \beta_n) = 1$ and

$$\lim_{n \rightarrow +\infty} \int_0^T e^{-2\alpha t} \sin^2 \beta_n t dt = \frac{(1 - e^{-2\alpha T})}{4\alpha}, \quad \lim_{n \rightarrow +\infty} \int_0^T \sin^2 \beta_n t dt = \frac{1}{2}T. \quad \blacksquare$$

2.3.1 Moment method for the telegrapher's equation

The following computations make sense for smooth controls and are then extended to square integrable controls by continuity. Let (ϕ_n) are the eigenvectors of A)

$$w_n(t) = \int_{\Omega} w(x, t) \phi_n(x) dx.$$

Then, $w_n(t)$ solves

$$w_n'' = 2\alpha w_n' - \lambda_n^2 w_n - \int_{\Gamma} (\gamma_a \phi_n) f(x, t) d\Gamma.$$

So, with β_n defined in (2.6), we have

$$w_n(t) = - \int_{G_t} e^{\alpha s} \left[\frac{\gamma_a \phi_n}{\beta_n} \sin \beta_n s \right] \beta_n ds \quad \beta_n \neq 0 \quad (2.15)$$

$$w_n(t) = - \int_{G_t} s e^{\alpha s} [\gamma_a \phi_n] f(x, t - s) dG_t \quad \beta_n = 0 \quad (2.16)$$

(it may be $\beta_n = 0$ for a finite number of indices). So, we have

$$-w(x, t) = \sum \phi_n(x) \int_{G_t} e^{\alpha s} \left[\frac{\gamma_a \phi_n}{\beta_n} \sin \beta_n s \right] f(x, t - s) dG_t, \quad (2.17)$$

$$-w_t(x, t) = \sum \beta_n \phi_n(x) \int_{G_t} e^{\alpha s} \frac{\gamma_a \phi_n}{\beta_n} \left[\frac{\alpha}{\beta_n} \sin \beta_n s + \cos \beta_n s \right] f(x, t - s) dG_t. \quad (2.18)$$

If $\beta_n = 0$ then the corresponding term in (2.17) is replaced with (2.16) while in (2.18) it is replaced with

$$\int_{G_t} (1 + \alpha s) e^{\alpha s} (\gamma_a \phi_n) f(x, t - s) dG_t. \quad (2.19)$$

Equalities (2.17)–(2.18) show that controllability at time T of the telegrapher's equation is equivalent to solvability of the following moment problem

$$\int_{G_T} e^{\alpha s} \left[\frac{\gamma_a \phi_n}{\beta_n} \sin \beta_n s \right] f(x, T - s) \, dG_T = \xi_n \quad (2.20)$$

$$\int_{G_T} e^{\alpha s} \frac{\gamma_a \phi_n}{\beta_n} \left[\frac{\alpha}{\beta_n} \sin \beta_n s + \cos \beta_n s \right] f(x, T - s) \, dG_T = \eta_n \quad (2.21)$$

where $\{\xi_n\}$ and $\{\eta_n\}$ belong to l^2 and f is real.

We noted that when $\beta_n = 0$ the corresponding terms in (2.20) and (2.21) have to be replaced respectively with (2.16) or (2.19). In order to have a unified formulation, we introduce

$$\mathcal{J} = \{n : \beta_n = 0\}$$

(a finite set of indices) and $c_n = \eta_n + i\xi_n$. Then, $\{c_n\}$ is an arbitrary (complex valued) l^2 sequence. The moment problem (2.20)–(2.21) reduces to the following problem where $g(x, s) = e^{\alpha s} f(x, T - s)$ is real:

$$\begin{aligned} \langle g, \bar{e}_n \rangle &= \int_{G_T} e_n(x, s) g(s) \, ds = c_n, \quad n > 0 \\ e_n(x, s) &= \begin{cases} \left(\frac{\gamma_a \phi_n}{\beta_n} \right) \left[e^{i\beta_n s} + \frac{\alpha}{\beta_n} \sin \beta_n s \right], & n \notin \mathcal{J} \\ (1 + \alpha s + is) (\gamma_a \phi_n), & n \in \mathcal{J}. \end{cases} \end{aligned} \quad (2.22)$$

Statement 1 in Theorem 9 is equivalent to the following fact: *for every target $(\xi, \eta) \in L^2(\Omega) \times H^{-1}(\Omega)$ there exists a real steering control f , which depends continuously on (ξ, η) .*

The index n in (2.22) is positive. It is convenient to reformulate the problem with $n \in \mathbb{Z}' = \mathbb{Z} \setminus \{0\}$. We define, for $n < 0$ and $-n \notin \mathcal{J}$:

$$\beta_n = -(\bar{\beta}_{-n}), \quad \phi_n = \phi_{-n}, \quad \lambda_n = \lambda_{-n}. \quad (2.23)$$

This implies $e_{-n} = -\bar{e}_n$ if $-n \notin \mathcal{J}$ and this is the definition of e_{-n} for $-n \in \mathcal{J}$. A real solution f of problem (2.22) (and $n > 0$) exists and depends continuously on the complex sequence $\{c_n\}_{n>0} \in l^2$ if and only if the moment problem

$$\langle f, \bar{e}_n \rangle_{L^2(G_T)} = c_n, \quad n \in \mathbb{Z}' \quad (2.24)$$

admits a complex valued solution $f \in L^2(G_T)$ which depends continuously on (ξ, η) (the proof is the same as in the memory case and it is given in the

Appendix). I.e., controllability of the telegrapher's equation is equivalent to the fact that the moment operator of the sequence $\{\bar{e}_n\}$ is bounded and boundedly invertible. The sequences $\{e_n\}$ and $\{\bar{e}_n\}$ have the same basis properties. So we can state:

Theorem 10 *The telegrapher's equation is controllable in time T if and only if the sequence $\{e_n\}_{n \in \mathbb{Z}'}$ is a Riesz sequence in $L^2(G_T)$ (with complex scalars).*

It has an interest to note that when $\{\xi_n\}$ and $\{\eta_n\}$ are arbitrary in l^2 , the same holds for the sequence $\{\eta_n + i\xi_n - (\gamma/\beta_n)\xi_n\}$, for every number γ . So, Theorem 10 holds as well if the functions e_n in (2.22) are replaced by

$$\left(e^{i\beta_n t} + \frac{\gamma}{\beta_n} \sin \beta_n t \right) \frac{\gamma_a \phi_n}{\beta_n} \quad n \notin \mathcal{J}, \quad (1 + (i + \gamma)s) \gamma_a \phi_n \quad n \in \mathcal{J}$$

where γ is any fixed complex number (possibly $\gamma = 0$).

3 Controllability of the viscoelastic systems

In this section we prove item 1 of Theorem 3. Let θ solve (2.4)) and

$$\theta_n(t) = \int_{\Omega} \theta(x, t) \phi_n(x) \, dx.$$

Then we have

$$\theta'_n = 2\alpha\theta_n - \lambda_n^2 \int_0^t N(t-s)\theta_n(s) \, ds - \int_0^t N(t-s) \left[\int_{\Gamma} (\gamma_a \phi_n) f(x, s) \, d\Gamma \right] \, ds.$$

For every n we introduce the functions $z_n(t)$ which solve

$$z'_n = 2\alpha z_n - \lambda_n^2 \int_0^t N(t-s)z_n(s) \, ds, \quad z_n(0) = 1. \quad (3.1)$$

Hence:

$$\begin{aligned} \theta_n(t) &= - \int_0^t z_n(\tau) \int_0^{t-\tau} N(t-\tau-s) \int_{\Gamma} (\gamma_a \phi_n) f(x, s) \, d\Gamma \, ds \, d\tau = \\ &= - \int_{G_t} \left\{ \int_0^s N(s-\tau) z_n(\tau) \, d\tau \right\} (\gamma_a \phi_n) f(x, t-s) \, dG_t \end{aligned} \quad (3.2)$$

$$\theta'_n(t) = - \int_{G_t} \left[z_n(s) + \int_0^s N'(s-\tau) z_n(\tau) \, d\tau \right] (\gamma_a \phi_n) f(x, t-s) \, dG_t. \quad (3.3)$$

Thanks to continuous dependence of the solutions on the initial data, and regularity when the initial data are smooth (see [14] and [24, Appendix]), the following equalities hold in $C([0, T]; L^2(\Omega))$ and $C([0, T]; H^{-1}(\Omega))$:

$$\theta(t) = \sum_{n=1}^{+\infty} \theta_n(t) \phi_n(x), \quad \theta_t(t) = \sum_{n=1}^{+\infty} \theta'_n(t) \phi_n(x).$$

Let $\{\xi_n\} \in l^2$ and $\{\eta_n\} \in l^2$ be the sequence of the coefficients of the expansions of the targets ξ and η in series of, respectively, $\{\phi_n\}$ and $\{\beta_n \phi_n\}$ ($\beta_n \phi_n$ replaced with ϕ_n if $\beta_n = 0$). We see that controllability at time T is equivalent to the solvability of the following moment problem:

$$\begin{aligned} \int_{G_T} Z_n(t) \frac{\gamma_a \phi_n}{\beta_n} f(x, T-s) dG_T &= c_n = -(\eta_n + i\xi_n), & n \notin \mathcal{J} \\ \int_{G_T} Z_n(t) (\gamma_a \phi_n) f(x, T-s) dG_T &= c_n = -(\eta_n + i\xi_n), & n \in \mathcal{J} \end{aligned} \quad (3.4)$$

where, for $n > 0$,

$$Z_n(t) = \begin{cases} z_n(t) + \int_0^t N'(t-s) z_n(s) ds + i\beta_n \int_0^t N(t-s) z_n(s) ds, & n \notin \mathcal{J}, \\ z_n(t) + \int_0^t N'(t-s) z_n(s) ds + i \int_0^t N(t-s) z_n(s) ds, & n \in \mathcal{J} \end{cases} \quad (3.5)$$

(we recall that if $n \in \mathcal{J}$ then the element $\beta_n \phi_n$ of the basis of $H^{-1}(\Omega)$ has to be replaced with ϕ_n).

It is convenient to reformulate the moment problem with $n \in \mathbb{Z}'$. This is done by using the following definitions:

$$z_{-n}(t) = z_n(t), \quad \phi_{-n}(x) = \phi_n(x), \quad \beta_{-n} = -\bar{\beta}_n, \quad \lambda_{-n} = \lambda_n, \quad n \notin \mathcal{J}.$$

Let

$$\Psi_n = \frac{\gamma_a \phi_n}{\beta_n} \quad n \notin \mathcal{J}, \quad \Psi_n = \gamma_a \phi_n \quad n \in \mathcal{J}. \quad (3.6)$$

Then we have

$$Z_{-n} \Psi_{-n} = -\bar{Z}_n \bar{\Psi}_n, \quad n \notin \mathcal{J}.$$

We symmetrize \mathcal{J} (respect to 0) and we define $Z_{-n} \Psi_{-n}$ when $n \in \mathcal{J}$ by:

$$Z_{-n} \Psi_{-n} = -\bar{Z}_n \bar{\Psi}_n = -\bar{Z}_n \Psi_n \quad \text{if } n \in \mathcal{J}.$$

So, we can consider the moment problem (3.4) with $n \in \mathbb{Z}' = \mathbb{Z} \setminus \{0\}$.

It is proved in the Appendix that $\{Z_n \Psi_n\}_{n \in \mathbb{Z}'}$ is a Riesz sequence if and only if the moment problem (3.4) (with $n > 0$) admits a *real* solution f which is a continuous function of $(\eta_n + i\xi_n) \in l^2$. So, in order to prove the first statement in Theorem 3, we prove:

Theorem 11 *Let the telegrapher's equation (2.5) be controllable at time T . Then, the sequence $\{Z_n(t)\Psi_n\}_{n \in \mathbb{Z}'}$ is a Riesz sequence in $L^2(G_T)$.*

The proof of Theorem 11 is in two steps: we prove that $\{Z_n(t)\Psi_n\}$ is quadratically close to a Riesz sequence and then we prove that it is ω -independent.

3.1 Step 1: closeness to a Riesz sequence

Let

$$K_n(t) = N'(t) + i\beta_n N(t) \quad \text{if } n \notin \mathcal{J}, \quad K_n(t) = N'(t) + iN(t) \quad \text{if } n \in \mathcal{J}.$$

The right hand side of the equality (3.5) is a variation of constants formula, so that (compare (3.1)) $Z_n(t)$ solves

$$Z'_n = 2\alpha Z_n - \lambda_n^2 \int_0^t N(t-s)Z_n(s) \, ds + K_n(t), \quad Z_n(0) = 1. \quad (3.7)$$

Hence also

$$\begin{aligned} Z''_n &= 2\alpha Z'_n - \lambda_n^2 Z_n - \lambda_n^2 \int_0^t N'(t-s)Z_n(s) \, ds + K'_n(t), \\ \begin{cases} Z_n(0) = 1, \\ Z'_n(0) = 2\alpha + i\beta_n \quad (n \notin \mathcal{J}), \quad Z'_n(0) = 2\alpha + i \quad (n \in \mathcal{J}). \end{cases} \end{aligned} \quad (3.8)$$

Then we have the following representation formulas:

if $n \notin \mathcal{J}$ then

$$\begin{aligned} Z_n(t) &= e^{\alpha t} e^{i\beta_n t} + e^{\alpha t} \frac{\alpha}{\beta_n} \sin \beta_n t + \\ &+ \frac{1}{\beta_n} \int_0^t e^{\alpha(t-s)} \sin \beta_n(t-s) \left[K'_n(s) - \lambda_n^2 \int_0^s N'(s-r)Z_n(r) \, dr \right] \, ds, \end{aligned}$$

if $n \in \mathcal{J}$ then

$$\begin{aligned} Z_n(t) &= e^{\alpha t} (1 + (\alpha + i)t) + \\ &+ \int_0^t e^{\alpha(t-s)} (t-s) \left[(N''(s) + iN'(s)) - \alpha^2 \int_0^s N'(r-s)Z_n(s) \, ds \right] \, dr. \end{aligned}$$

We introduce

$$S_n(t) = e^{-\alpha t} Z_n(t)$$

and we see that, for $n \notin \mathcal{J}$,

$$S_n(t) = G_n(t) - \frac{\lambda_n^2}{\beta_n} \int_0^t \sin \beta_n(t-s) \int_0^s (e^{-\alpha(s-r)} N'(s-r)) S_n(r) \, dr \, ds$$

where (in the last integration by parts we use $N'(0) = 0$).

$$\begin{aligned} G_n(t) &= e^{i\beta_n t} + \frac{\alpha}{\beta_n} \sin \beta_n t + \frac{1}{\beta_n} \int_0^t e^{-\alpha s} [N''(s) + i\beta_n N'(s)] \sin \beta_n(t-s) \, ds = \\ &= e^{i\beta_n t} + \frac{\alpha - N'(0)}{\beta_n} \sin \beta_n t + \int_0^t N'(t-s) e^{-\alpha(t-s)} \left[e^{i\beta_n(t-s)} + \frac{\alpha}{\beta_n} \sin \beta_n(t-s) \right] \, ds = \\ &= e^{i\beta_n t} + \frac{\alpha}{\beta_n} \sin \beta_n t + \int_0^t N'(t-s) e^{-\alpha(t-s)} \left(e^{i\beta_n s} + \frac{\alpha}{\beta_n} \sin \beta_n s \right) \, ds. \quad (3.9) \end{aligned}$$

Instead, for $n \in \mathcal{J}$ we have

$$G_n(t) = 1 + (\alpha + i)t + \int_0^t e^{-\alpha(t-s)} N'(t-s) [1 + (\alpha + i)s] \, ds.$$

The linear transformation

$$y \mapsto y(t) + \int_0^t e^{-\alpha(t-s)} N'(t-s) y(s) \, ds$$

is bounded with bounded inverse. So, Theorem 10 and controllability of the telegrapher's equation (2.5) imply that the sequence $\{G_n(t)\Psi_n\}$ is Riesz in $L^2(G_T)$.

We shall need asymptotic estimates of $S_n(t)$ which holds for large n . So we can work with $n \notin \mathcal{J}$. We introduce the notations

$$N_1(t) = e^{-\alpha t} N'(t) \text{ so that } N_1(0) = 0, \quad \mu_n = \frac{\lambda_n^2}{\beta_n^2} \text{ so that } 1 - \mu_n = -\alpha^2/\beta_n^2.$$

An integration by parts gives

$$\begin{aligned} S_n(t) &= G_n(t) - \mu_n \int_0^t N_1(t-r) S_n(r) \, dr + \\ &+ \mu_n \int_0^t \left(\int_0^{t-r} N_1'(t-r-s) \cos \beta_n s \, ds \right) S_n(r) \, dr. \quad (3.10) \end{aligned}$$

Gronwall inequality shows that for every $T > 0$ there exists $M = M_T$ such that

$$|S_n(t)| \leq M \quad t \in [0, T].$$

We integrate by parts again the last integral in (3.10) and we get

$$\begin{aligned} S_n(t) = & G_n(t) - \mu_n \int_0^t N_1(t-r) S_n(r) \, dr + \\ & + \frac{\mu_n}{\beta_n} \int_0^t \left(N_1'(0) \sin \beta_n(t-r) + \int_0^{t-r} N_1''(t-r-s) \sin \beta_n s \, ds \right) S_n(r) \, dr. \end{aligned} \quad (3.11)$$

We introduce

$$E_n(t) = e^{i\beta_n t} + \frac{\alpha}{\beta_n} \sin \beta_n t \quad (\text{if } n \notin \mathcal{J})$$

and we rewrite (3.11) as (\star denotes the convolution)

$$\begin{aligned} (S_n - E_n) + N_1 \star (S_n - E_n) = & \frac{N_1'(0)}{\beta_n} \int_0^t \sin \beta_n(t-r) S_n(r) \, dr + \\ & + \frac{1}{\beta_n} \int_0^t N_1''(s) \int_0^{t-s} \sin \beta_n(t-s-r) S_n(r) \, dr \, ds + \frac{1}{\beta_n^2} M_n(t), \quad (3.12) \\ M_n(t) = & -\alpha^2 \int_0^t N_1(t-r) S_n(r) \, dr + \\ & + \frac{\alpha}{\beta_n} \int_0^t \left[N_1'(0) \sin \beta_n(t-r) + \int_0^{t-r} N_1''(t-r-s) \sin \beta_n s \, ds \right] \, dr. \end{aligned}$$

Note that here we have explicitly written the expression of the functions $M_n(t)$ but this expression does not have a real interest: the important fact is that the sequence $\{M_n(t)\}$ is bounded on (any) interval $[0, T]$. This is the sole property of interest and, as we said already, in the following we use $\{M_n(t)\}$ to denote a sequence of (continuous) functions which is *bounded* (on an interval $[0, T]$), not the same sequence at every occurrence. We shall not write down the explicit expression of the functions $M_n(t)$, which has no role in the proofs.

By using the definition of $E_n(t)$ we see the existence of a sequence $\{M_n(t)\}$ of continuous functions defined for $t \geq 0$, bounded on bounded intervals and such that

$$S_n(t) = e^{i\beta_n t} + \frac{M_n(t)}{\beta_n}. \quad (3.13)$$

Now we compute:

$$\begin{aligned} \int_0^t S_n(r) \sin \beta_n(t-r) \, dr &= \int_0^t \left(e^{i\beta_n r} + \frac{M_n(r)}{\beta_n} \right) \sin \beta_n(t-r) \, dr = \\ &= -\frac{i}{2} t e^{i\beta_n t} + \frac{i}{2\beta_n} \sin \beta_n t + \frac{1}{\beta_n} \int_0^t M_n(r) \sin \beta_n(t-r) \, dr. \end{aligned} \quad (3.14)$$

We observe

$$\frac{i}{\beta_n} t e^{i\beta_n t} = - \int_0^t s e^{i\beta_n s} \, ds + \frac{1}{\beta_n^2} (e^{i\beta_n t} - 1) = - \int_0^t s E_n(s) \, ds + \frac{1}{\beta_n^2} M_n(t).$$

i.e.

$$\begin{aligned} \frac{1}{\beta_n} \int_0^t S_n(r) \sin \beta_n(t-r) \, dr &= -\frac{1}{2} \frac{it}{\beta_n} e^{i\beta_n t} + \frac{1}{\beta_n^2} M_n(t) = \\ &= \frac{1}{2} \int_0^t s E_n(s) \, ds + \frac{1}{\beta_n^2} M_n(t). \end{aligned}$$

We replace this expression in (3.12) and we rewrite the equality as

$$\begin{aligned} (S_n - E_n) + N_1 \star (S_n - E_n) &= \\ &= \frac{N_1'(0)}{2} \int_0^t s E_n(s) \, ds + \frac{1}{2} \int_0^t N_1''(s) \int_0^{t-s} r E_n(r) \, dr \, ds + \frac{1}{\beta_n^2} M_n(t) = \\ &= \frac{1}{2} \int_0^t N_1'(t-r) r E_n(r) \, dr + \frac{1}{\beta_n^2} M_n(t) \end{aligned}$$

(as usual, the functions $M_n(t)$ are not the same at every step).

Let $L(t)$ be the resolvent kernel of $N_1(t)$ so that $L(0) = 0$ and $L(t)$ is twice differentiable. We have

$$\begin{aligned} S_n(t) &= E_n(t) + \frac{1}{2} \int_0^t N_1'(t-s) s E_n(s) \, ds - \\ &\quad - \frac{1}{2} \int_0^t (s E_n(s)) \left[\int_0^{t-s} L(t-s-r) N_1'(r) \, dr \right] \, ds + \frac{1}{\beta_n^2} M_n(t). \end{aligned}$$

In conclusion,

$$\begin{aligned} \Psi_n S_n(t) &= \Psi_n E_n(t) + \frac{1}{2} \int_0^t s \left[N_1'(t-s) - \right. \\ &\quad \left. - \int_0^{t-s} L(t-s-r) N_1'(r) \, dr \right] \Psi_n E_n(s) \, ds + \frac{1}{\beta_n^2} M_n(t) \end{aligned} \quad (3.15)$$

(note that we can replace $\Psi_n M_n(t)$ with $M_n(t)$ since $\{\Psi_n\}$ is bounded in $L^2(\Gamma)$). The sequence whose elements are

$$\Psi_n E_n(t) + \frac{1}{2} \int_0^t s \left[N_1'(t-s) - \int_0^{t-s} L(t-s-r) N_1'(r) dr \right] \Psi_n E_n(s) ds$$

is the image of a Riesz sequence of $L^2(G_T)$ under a linear bounded and boundedly invertible transformation. Hence, it is a Riesz sequence too so that, by using Theorem 6 and Lemma 4, we get:

Theorem 12 *Let the telegrapher's equation (2.5) be controllable at time T . Then, $\{S_n(t)\Psi_n\}_{n \in \mathbb{Z}'}$ is quadratically close to a Riesz sequence in $L^2(G_T)$ and so there exists N such that $\{S_n(t)\Psi_n\}_{|n| > N}$ is a Riesz sequence too.*

In the second step we prove that $\{S_n(t)\Psi_n\}_{n \in \mathbb{Z}'}$ is ω -independent in $L^2(G_T)$ hence it is a Riesz sequence and this completes the proof of the statement 1 in Theorem 3.

3.2 Step 2: ω -independence

We consider the equality

$$\sum_{n \neq 0} \alpha_n S_n(t) \Psi_n = 0 \text{ in } L^2(G_T). \quad (3.16)$$

Theorem 12 implies that $\{\alpha_n\} \in l^2$. Our goal is the proof that $\alpha_n = 0$ for every n . The proof is in three steps:

Step 1 if equality (3.16) holds then $\alpha_n = \gamma_n / \beta_n^3$ where $\{\gamma_n\} \in l^2$.

Step 2 the property of $\{\alpha_n\}$ in **Step 1** is used to prove that $\alpha_n = 0$ for $n > N$ (N is the number in Theorem 12).

Step 3 we finish the proof by proving that $\alpha_n = 0$ also for $n \leq N$.

Now we proceed to realize this program.

Step 1: decaying properties of $\{\alpha_n\}$ In this step we use the short-hand notation

$$H^1 = H^1([0, T]; L^2(\Omega)).$$

We shall use the following lemma (proved in the Appendix).

Lemma 13 *Let a sequence $\{\alpha_n\}$ be such that*

$$\Phi(x, t) = \sum_{n \in \mathbb{Z}'} \alpha_n e^{i\beta_n t} \Psi_n \in H^1 = H^1(0, T; L^2(\Gamma)).$$

If $\{e^{i\beta_n t} \Psi_n\}$ is Riesz on a shorter interval $T - \epsilon$ then, there exists $\{\delta_n\} \in l^2$ such that

$$\alpha_n = \frac{\delta_n}{\beta_n}.$$

We single out from the series (3.16) those terms which correspond to indices in \mathcal{J} (if any). Let

$$F(t) = \sum_{n \in \mathcal{J}} \alpha_n S_n(t) \Psi_n \quad \text{if } \mathcal{J} \neq \emptyset, \quad F(t) = 0 \quad \text{otherwise.}$$

This sum is finite and for the indices in this sum we have

$$S_n(t) = 1 + (\alpha + i)t + \int_0^t (t - r) \left\{ e^{-\alpha r} (N''(r) + iN'(r)) - \right. \quad (3.17)$$

$$\left. -\alpha^2 \int_0^r N_1(r - s) S_n(s) \, ds \right\} \, dr. \quad (3.18)$$

So, $S_n(t)$ does not depend on n when $n \in \mathcal{J}$ and it is of class H^3 : $F(t)$ is a fixed H^3 function (possibly zero).

When, in the next equalities, the index of the series is not explicitly indicated, we intend that it belongs to the set $\mathbb{Z}' \setminus \mathcal{J}$.

Using (3.9) and (3.11) we rewrite (3.16) as

$$\begin{aligned}
& - \sum \alpha_n e^{i\beta_n t} \Psi_n = F(t) + \alpha \sum \frac{\alpha_n}{\beta_n} \Psi_n \sin \beta_n t + \\
& + \int_0^t N_1(t-s) \sum \alpha_n \left(e^{i\beta_n s} + \frac{\alpha}{\beta_n} \sin \beta_n s \right) \Psi_n \, ds - \\
& - \int_0^t N_1(t-r) \sum \alpha_n \mu_n S_n(r) \Psi_n \, dr + \\
& + N_1'(0) \sum \int_0^t \frac{\alpha_n \mu_n}{\beta_n} \sin \beta_n(t-r) S_n(r) \Psi_n \, dr + \\
& + \int_0^t N_1''(s) \sum \frac{\alpha_n \mu_n}{\beta_n} \int_0^{t-s} \sin \beta_n(t-s-r) S_n(r) \Psi_n \, dr \, ds = \\
& = F(t) + f_1 + f_2 + f_3 + f_4 + f_5. \tag{3.19}
\end{aligned}$$

We already know that $F \in H^1$. We prove $f_i \in H^1$ for every i .

The fact that $\{\Psi_n \sin \beta_n s\}$ and $\{\psi_n \cos \beta_n s\}$ are Riesz sequences in $L^2(G_T)$ (see Lemma 7) implies that f_1 and f_2 belong to H^1 .

The series in f_3 converges in $L^2(G_T)$ and $N_1(t)$ is continuously differentiable, so that $f_3 \in H^1$.

We consider the function f_4 , i.e. we consider the series

$$\sum \frac{\alpha_n \mu_n}{\beta_n} \int_0^t \sin \beta_n(t-r) S_n(r) \Psi_n \, dr. \tag{3.20}$$

Using (3.13) and $d \leq 3$ we see that this series converges in $L^2(G_T)$. A formal termwise differentiation gives:

$$\sum \alpha_n \mu_n \int_0^t \cos \beta_n(t-r) S_n(r) \Psi_n \, dr. \tag{3.21}$$

We replace $S_n(r)$ with its expression (3.13) and we get:

$$\sum \alpha_n \mu_n \int_0^t \cos \beta_n(t-s) E_n(s) \Psi_n \, ds - \tag{A}$$

$$-i N'(0) \sum \frac{\alpha_n}{\beta_n} \int_0^t s \cos \beta_n(t-s) e^{i\beta_n s} \Psi_n \, ds + \tag{B}$$

$$+ \sum \frac{\alpha_n}{\beta_n^2} \int_0^t M_n(s) \cos \beta_n(t-s) \, ds. \tag{C}$$

The three series converge: the series **(A)** and **(B)** because the integrand are linear combinations of $\Psi_n \cos \beta_n t$, $\Psi_n \sin \beta_n t$ and $\Psi_n e^{i\beta_n t}$: convergence follows from Lemma 7. Lemma 4 (i.e. $d \leq 3$) shows convergence of the series **(C)**. So we have $f_4 \in H^1$ and its convolution with N_1'' (i.e. f_5) belongs to H^1 too.

In conclusion, using controllability of the telegraph equation in a shorter time,

$$\sum \alpha_n e^{i\beta_n t} \Psi_n \in H^1 \quad \text{hence} \quad \alpha_n = \frac{\delta_n}{\beta_n}, \quad \{\delta_n\} \in l^2.$$

We replace this expression of $\{\alpha_n\}$ in (3.19) and we equate the derivatives of both the sides. We get

$$\begin{aligned} & -i \sum \delta_n e^{i\beta_n t} \Psi_n = F'(t) + \alpha \sum \frac{\delta_n}{\beta_n} \Psi_n \cos \beta_n t + \\ & + \int_0^t N_1'(t-s) \sum \frac{\delta_n}{\beta_n} \left(e^{i\beta_n s} + \frac{\alpha}{\beta_n} \sin \beta_n s \right) \Psi_n \, ds - \\ & - \int_0^t N_1'(t-r) \sum \frac{\delta_n \mu_n}{\beta_n} S_n(r) \Psi_n \, dr + \\ & + N_1'(0) \int_0^t \sum \frac{\delta_n \mu_n}{\beta_n} \cos \beta_n(t-r) S_n(r) \Psi_n \, dr + \\ & + \int_0^t N_1''(s) \int_0^{t-s} \sum \frac{\delta_n \mu_n}{\beta_n} \cos \beta_n(t-s-r) S_n(r) \Psi_n \, dr \, ds. \end{aligned} \quad (3.22)$$

Arguments similar to the previous ones show that every series on the right hand side can be differentiated once more. The term in the second last line is the one that deserves a bit of attention. Its derivative is the sum of the two series

$$\begin{aligned} & N_1'(0) \sum \frac{\delta_n \mu_n}{\beta_n} S_n(t) \Psi_n, \\ & - N_1'(0) \sum \delta_n \mu_n \int_0^t \sin \beta_n(t-r) S_n(r) \Psi_n \, dr. \end{aligned}$$

The first series converges thanks to the first statement in Theorem 12.

We insert (3.13) in the second series and we get

$$\sum \delta_n \mu_n \Psi_n \int_0^t \sin \beta_n(t-r) \left\{ E_n(r) - ir N_1'(0) \frac{1}{\beta_n} e^{i\beta_n r} + \frac{1}{\beta_n^2} M_n(r) \right\} \, dr.$$

Convergence of this series is seen as above. Hence we get

$$\delta_n = \frac{\tilde{\gamma}_n}{\beta_n}, \quad \alpha_n = \frac{\tilde{\gamma}_n}{\beta_n^2}, \quad \{\tilde{\gamma}_n\} \in l^2.$$

Now we iterate this process: we replace δ_n with $\tilde{\gamma}_n/\beta_n$ and we equate the derivatives. We get

$$\tilde{\gamma}_n = \frac{\gamma_n}{\beta_n}, \quad \text{i.e.} \quad \alpha_n = \frac{\gamma_n}{\beta_n^3}, \quad \{\gamma_n\} \in l^2. \quad (3.23)$$

Details of the computations are in the Appendix.

In conclusion, we proved the existence of a sequence $\{\gamma_n\} \in l^2$ such that

$$\alpha_n = \gamma_n \quad \text{if} \quad n \in \mathcal{J}, \quad \alpha_n = \frac{\gamma_n}{\beta_n^3}, \quad \text{if} \quad n \notin \mathcal{J}$$

where α_n are the coefficients in the series (3.16).

Step 2: the sum in (3.16) is finite We recall the definition of $S_n(t)$ in terms of $Z_n(t)$ and we rewrite (3.16) as

$$\sum_{n \in \mathbb{Z}'} \alpha_n \Psi_n Z_n(t) = \sum_{n \in \mathbb{Z}'} \frac{\gamma_n}{\beta_n^3} \Psi_n Z_n(t) = 0 \quad (3.24)$$

The series (3.24) converges uniformly so that:

$$\sum_{n \in \mathbb{Z}'} \alpha_n \Psi_n = \sum_{n \in \mathbb{Z}'} \frac{\gamma_n}{\beta_n^3} \Psi_n = 0. \quad (3.25)$$

Here γ_n/β_n^3 has to be replaced with γ_n if $n \in \mathcal{J}$. We implicitly intend this substitutions also in the next series.

The first statement in Theorem 12, the form of $K_n(t)$, $d \leq 3$ and $\beta_n^2 \asymp \lambda_n^2$ show that the series (3.24) is termwise differentiable. Hence we have:

$$\sum \alpha_n \Psi_n \left\{ -\lambda_n^2 \int_0^t N(t-s) Z_n(s) ds + K_n(t) \right\} = 0.$$

We can distribute the series on the sum and we get

$$\int_0^t N(t-s) \sum_{n \in \mathbb{Z}'} \frac{\gamma_n \lambda_n^2}{\beta_n^3} Z_n(s) \Psi_n ds = \sum_{n \in \mathbb{Z}'} \frac{\gamma_n}{\beta_n^3} K_n(t) \Psi_n. \quad (3.26)$$

Using (3.25) and $K_n(t) = N'(t) + i\beta_n N(t)$ we get

$$\sum \frac{\gamma_n}{\beta_n^3} K_n(t) \Psi_n = iN(t) \sum \frac{\gamma_n}{\beta_n^2} \Psi_n$$

and so

$$\int_0^t N(t-s) \sum_{n \in \mathbb{Z}'} \frac{\gamma_n \lambda_n^2}{\beta_n^3} Z_n(s) \Psi_n \, ds = iN(t) \sum_{n \in \mathbb{Z}'} \frac{\gamma_n}{\beta_n^2} \Psi_n.$$

The property $N(0) \neq 0$ implies a further property of $\{\alpha_n\}$:

$$\sum_{n \in \mathbb{Z}'} \frac{\gamma_n}{\beta_n^2} \Psi_n = \sum_{n \in \mathbb{Z}'} \beta_n \alpha_n \Psi_n = 0 \quad (3.27)$$

and so the right hand side of (3.26) vanishes.

The property $N(0) \neq 0$ used in (3.26) gives:

$$\sum_{n \in \mathbb{Z}'} \alpha_n \lambda_n^2 Z_n(t) \Psi_n = \sum_{n \in \mathbb{Z}'} \frac{\gamma_n \lambda_n^2}{\beta_n^3} Z_n(t) \Psi_n = 0. \quad (3.28)$$

We recall equality (3.24): $\sum_{n \in \mathbb{Z}'} \alpha_n Z_n(t) \Psi_n = 0$. We introduce the finite (possibly empty) set of indices

$$\mathcal{O} = \{n : \lambda_n = 0\}.$$

Note that if $n \in \mathcal{O}$ then $Z_n(t) = \hat{Z}(t)$, the same for every n . We rewrite (3.28) and (3.24) as (the sum on the right side is zero if $\mathcal{O} = \emptyset$):

$$\sum_{n \notin \mathcal{O}} \alpha_n Z_n(t) \Psi_n = - \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n, \quad \sum_{n \notin \mathcal{O}} \alpha_n \lambda_n^2 Z_n(t) \Psi_n = 0. \quad (3.29)$$

Let $k_1 \notin \mathcal{O}$ be an index (of minimal absolute value) for which $\alpha_{k_1} \neq 0$. By combining the equalities in (3.29) we get

$$\sum_{n \notin \mathcal{O}} \left(\alpha_n - \frac{\alpha_n \lambda_n^2}{\lambda_{k_1}^2} \right) Z_n(t) \Psi_n = - \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n.$$

Note that the right hand side is the same as in the first equality of (3.29).

Let

$$\alpha_n^{(1)} = \left(1 - \frac{\lambda_n^2}{\lambda_{k_1}^2} \right) \alpha_n$$

and note that

$$\{\alpha_n^{(1)}\} \in l^2; \quad \begin{cases} \alpha_{k_1}^{(1)} = 0 \text{ if } \lambda_k = \lambda_{k_1} \\ \text{if } \lambda_k \neq \lambda_{k_1} \text{ then } \alpha_k^{(1)} = 0 \end{cases} \iff \alpha_k = 0.$$

So,

$$\begin{cases} \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n \in X_1 = \text{clspan} \{Z_n(t) \Psi_n, \quad n \notin \mathcal{O}, \lambda_n \neq \lambda_{k_1}\} \\ \sum_{\substack{n \notin \mathcal{O} \\ \lambda_n \neq \lambda_{k_1}}} \alpha_n^{(1)} Z_n(t) \Psi_n = - \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n. \end{cases} \quad (3.30)$$

Thanks to $\{\alpha_n^{(1)}\} \in l^2$, we can start a bootstrap argument and repeat this procedure: we find that $\{\lambda_n^3 \alpha_n^{(1)}\} \in l^2$. We fix a second element k_2 (of minimal absolute value) such that $\alpha_{k_2}^{(1)} \neq 0$ and, as above, we get

$$\begin{cases} \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n \in X_2 = \text{clspan} \{Z_n(t) \Psi_n, \quad n \notin \mathcal{O}, \lambda_n \notin \{\lambda_{k_1}, \lambda_{k_2}\}\} \\ \sum_{\substack{n \notin \mathcal{O} \\ \lambda_n \notin \{\lambda_{k_1}, \lambda_{k_2}\}}} \alpha_n^{(2)} Z_n(t) \Psi_n = \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n. \end{cases} \quad (3.31)$$

The new sequence $\{\alpha_n^{(2)}\} \in l^2$ has the property that

$$\begin{cases} \alpha_k^{(2)} = 0 \text{ if } \lambda_k \in \{\lambda_{k_1}, \lambda_{k_2}\} \\ \text{if } \lambda_n \notin \{\lambda_{k_1}, \lambda_{k_2}\} \text{ then } \alpha_n^{(2)} = 0 \end{cases} \iff \alpha_n = 0.$$

The argument can be repeated and we find

$$\sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n \in X_R = \text{clspan} \{Z_n(t) \Psi_n, \quad n \notin \mathcal{O}, \lambda_n \notin \{\lambda_{k_1}, \lambda_{k_2}, \dots, \lambda_{k_R}\}\}$$

for every R , i.e.

Lemma 14 *We have:*

$$\sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n \in \bigcap_R X_R = \{0\}$$

and, after at most $2N$ iteration of the process, we find

$$\sum_{|n| > N} \alpha_n^{(N)} Z_n(t) \Psi_n = 0.$$

If N is large enough, as specified in Theorem 12, we see that

$$\alpha_n^{(N)} = 0 \quad \text{when } |n| > N$$

and the original equality (3.24) involves a finite sum. We rewrite it as

$$\sum_{\substack{|n| \leq K \\ n \notin \mathcal{O}}} \alpha_n Z_n(t) \Psi_n = 0. \quad (3.32)$$

Step 3: we have $\alpha_n = 0$ for every n We use the following lemma:

Lemma 15 *The sequence $\{Z_n(t) \Psi_n(x)\}_{n \notin \mathcal{O}}$ is linearly independent.*

The proof is similar to the proof of the corresponding result in [3, 29] and is omitted. This lemma and (3.32) imply $\alpha_n = 0$ if $n \notin \mathcal{O}$.

In conclusion, Equality (3.24) is in fact

$$0 = \sum_{n \in \mathcal{O}} \alpha_n Z_n(t) \Psi_n = \tilde{Z}(t) \sum_{n \in \mathcal{O}} \alpha_n \Psi_n, \quad \tilde{Z}(t) \neq 0 \quad \text{so that} \quad \sum_{n \in \mathcal{O}} \alpha_n \Psi_n = 0.$$

Finally we prove:

Lemma 16 *If $n \in \mathcal{O}$ then $\alpha_n = 0$.*

Proof. We introduce

$$\Phi(x) = \sum_{n \in \mathcal{O}} \alpha_n \Phi_n(x)$$

which is an eigenfunction of the operator A whose eigenvalue is 0

$$A\Phi(x) = 0.$$

Note that if $\lambda_n = 0$ then $\beta_n = i\alpha$ does not depend on n and so

$$\Psi_n = \begin{cases} \frac{\gamma_a \Phi_n}{\beta_n} = \frac{\gamma_a \Phi_n}{i\alpha} & \text{if } \alpha \neq 0 \\ \gamma_a \Phi_n & \text{if } \alpha = 0. \end{cases}$$

So, in both the cases, we get

$$A\Phi = 0, \quad \gamma_a \Phi = 0.$$

By using statement 2 in Theorem 9, we see that

$$\Phi(x) = \sum \alpha_n \Phi_n(x) = 0.$$

The condition $\alpha_n = 0$ follows, since $\{\Phi_n\}$ is an orthonormal sequence. ■

4 Sharp control time

The results proved up to now show that the sharp control time of the viscoelastic system is not larger than that of the telegrapher's equation. Conversely controllability of (1.1) implies controllability of the telegrapher's equation (2.5). In fact, if Eq. (1.1) is controllable at time T then the moment problem (3.4) is solvable (with continuity) and then the sequence $\{Z_n(t)\Psi_n\}$ is a Riesz sequence in $L^2(0, T; L^2(\Gamma))$. The first statement of Theorem 12 implies the existence of a number N such that for $|n| > N$ the sequence whose elements are described in Theorem 10 is Riesz in $L^2(0, T_0; L^2(\Gamma))$.

This implies that the moment problem (2.20)-(2.21) *for the telegrapher's equation* is solvable for $\{(\xi_n, \eta_n)\} \in L$, where L has *finite codimension*, see [10, p. 323] i.e., the reachable set at time T_0 for the telegrapher's equation has finite codimension. We use Lemma 8 in order to prove that this is not true if the telegrapher's equation is not controllable.

Let $T > T_0$ be any time at which *the telegrapher's equation (2.5) is controllable*.

Let us denote e_n the elements of the sequence described in Theorem 10. By adding elements of $(\text{clspan}\{e_n\})^\perp$, we complete the sequence $\{e_n\}$ to a Riesz *basis* of $L^2(0, T; L^2(\Gamma))$. We denote k_n the added elements.

We consider the operator $\mathbb{J}_0: L^2(0, T_0; L^2(\Gamma)) \mapsto l^2$ given by

$$\mathbb{J}_0 f = \{\langle f, e_n \rangle_{L^2(0, T_0; L^2(\Gamma))}\} \cup \{\langle f, k_n \rangle_{L^2(0, T_0; L^2(\Gamma))}\}.$$

Lemma 8 shows that the codimension of its image is not finite and so we have also

$$\dim L^\perp = \dim \{\langle f, e_n \rangle_{L^2(0, T_0; L^2(\Gamma))}\}^\perp = +\infty.$$

So, the index N cannot exist and the viscoelastic system is not controllable at time T_0 if the telegrapher's equation is not controllable.

The previous negative result proves the second statement in Theorem 3 and it has a clear relation with the following fact, that the speed of propagation of waves in a viscoelastic body is equal to the speed of propagation in the corresponding (memoryless) elastic body, see [6, 7].

5 Appendix: proofs

Ancillary proofs are collected here.

Proofs from Section 2.2

In order to prove Lemma 7 we first note that the transformation

$$\sum \alpha_n e^{ib_n t} k_n \mapsto \sum \alpha_n e^{-ib_n T} e^{ib_n \tau} k_n : \quad L^2(-T, T; K) \mapsto L^2(0, 2T; K)$$

is bounded and boundedly invertible since $\{|\mathcal{I}m b_n|\}$ is bounded. Hence, the assumption is that (2.9) holds for the sequence $\{e^{ib_n t} k_n\}_{n \in \mathbb{Z}'}$ in $L^2(-T, T; K)$. We use Euler formulas and we see that (2.9) holds for the cosine sequences (2.11) in $L^2(0, T; K)$ (the sine sequence is treated analogously). In fact:

$$\begin{aligned} \left\| \sum_{n>0} a_n k_n \cos b_n t \right\|_{L^2(0, T; K)}^2 &= \frac{1}{4} \left\| \sum_{n>0} a_n k_n e^{ib_n t} + \sum_{n>0} a_n k_n e^{-ib_n t} \right\|_{L^2(0, T; K)}^2 = \\ &= \frac{1}{8} \left\| \sum_{n \in \mathbb{Z}'} a_n k_n e^{ib_n t} \right\|_{L^2(-T, T; K)}^2. \end{aligned}$$

In the last equality we put $a_n = a_{-n}$ and we used $-b_n = b_n$, $k_{-n} = k_n$.

Inequalities (2.9) hold by assumption for the right side and so they hold also for the left side.

This proof has been adapted from [11], where it is proved that the opposite implication is false.

Now we prove Lemma 8. We know that

$$(\text{im } \mathbb{J}_0)^\perp = \ker \mathbb{J}_0^* = \left\{ \{c_n\} \in l^2 : \sum c_n e_n = 0 \quad \text{in } L^2(0, T_0; K) \right\}.$$

Every sequence $\{c_n\} \in l^2$ such that $\sum c_n e_n = 0$ in $L^2(0, T_0; K)$ while $\sum c_n e_n \neq 0$ in $L^2(T_0, T; K)$ belongs to $\ker \mathbb{J}_0^*$, and conversely. So, $\dim \ker \mathbb{J}_0^* = +\infty$.

Real and complex solutions of to moment problems

We use (\cdot, \cdot) to denote the integral of a product in $L^2(G_T)$ (so that (f, g) is linear in both the entries) and we use $l^2(\mathbb{N})$ and $l^2(\mathbb{Z}')$ to denote the space of the *complex valued* l^2 sequences, with indices in \mathbb{N} or in \mathbb{Z}' .

Let $e_n = \{\zeta_n + i\hat{\zeta}_n\}$ be a sequence in $L^2(G_T)$ such that $e_n = -\bar{e}_{-n}$ so that

$$\zeta_{-n} = -\zeta_n, \quad \hat{\zeta}_{-n} = \hat{\zeta}_n.$$

We consider the problems

$$(e_n, f) = c_n, \quad \{c_n\} = \{\eta_n + i\xi_n\} \in l^2(\mathbb{N}) \quad (5.1)$$

$$(e_n, g) = d_n = r_n + is_n, \quad \{d_n\} \in l^2(\mathbb{Z}'). \quad (5.2)$$

We prove that if the problem (5.1) has a *real valued* solution $f \in L^2(G_T)$ which depends continuously on $\{c_n\} \in L^2(\mathbb{N})$ then moment problem (5.2) has a *complex valued* solution $g \in L^2(G_T)$, which depends continuously on $\{d_n\} \in l^2(\mathbb{Z}')$, and conversely. Let $g = h + ik$. We separate real and imaginary parts and we see that moment problem (5.2) can be reformulated as

$$\begin{aligned} (\xi_n, h) - (\hat{\zeta}_n, k) &= r_n, & (\zeta_n, k) + (\hat{\zeta}_n, h) &= s_n, \\ (\zeta_n, h) + (\hat{\zeta}_n, k) &= -r_{-n}, & (\zeta_n, k) - (\hat{\zeta}_n, h) &= -s_{-n}. \end{aligned}$$

This is equivalent to the pair of problems (both with arbitrary complex valued l^2 sequences on the right hand side)

$$\begin{aligned} (\zeta_n + i\hat{\zeta}_n, h) &= \frac{1}{2} \{[r_n - r_{-n}] + i[s_n + s_{-n}]\} \quad n \in \mathbb{N}, \quad h \text{ real valued.} \\ (\zeta_n + i\hat{\zeta}_n, k) &= \frac{1}{2} \{[s_n - s_{-n}] - i[r_n + r_{-n}]\} \quad n \in \mathbb{N}, \quad k \text{ real valued.} \end{aligned}$$

So, the solution of (5.2) is the same as the solution of two copies of problem (5.1). This ends the proof. ■

The proof of Lemma 13

We first note that Theorem 12 implies $\{\alpha_n\} \in l^2$ and that in order to prove the formula for $\{\alpha_n\}$ it is sufficient that we prove that it holds for $|n|$ sufficiently large. So, we consider the new function

$$C(x, t) = \sum_{|n| \geq N} \alpha_n e^{i\beta_n t} \Psi_n \in W^{1,2}(0, T+\tilde{h}; L^2(\Gamma)) \quad (5.3)$$

where N is the number specified in Theorem 12. It is known that $C_t(x, t) \in L^2(0, T; L^2(\Gamma))$ is the limit of the incremental quotient:

$$C_t(x, t) = \lim_{h \rightarrow 0} \frac{C(x, t+h) - C(x, t)}{h} = \lim_{h \rightarrow 0} \sum_{|n| > N} \alpha_n \frac{e^{i\beta_n h} - 1}{h} e^{i\beta_n t} \Psi_n.$$

Thanks to the choice of N , there exists $m_0 > 0$ such that

$$\begin{aligned} m_0 \sum_{|n| > N} \left| \alpha_n \beta_n \frac{e^{i\beta_n h} - 1}{\beta_n h} \right|^2 &\leq \left\| \frac{C(x, t+h) - C(x, t)}{h} \right\|_{L^2(0, T; L^2(\Gamma))}^2 \leq \\ &\leq 2 \|C'\|_{L^2(0, T; L^2(\Gamma))}^2. \end{aligned}$$

The last equality holds for h “small”, $|h| < h_0$. We consider $0 < h < h_0$.

Let s be real. There exists $s_0 > 0$ such that:

$$\left| \frac{e^{is} - 1}{s} \right|^2 = \left(\frac{\cos s - 1}{s} \right)^2 + \left(\frac{\sin s}{s} \right)^2 > \frac{1}{2} \quad \text{for } 0 < s < s_0.$$

Then we have, for every $h \in (0, h_0)$,

$$\frac{1}{2} \sum_{\substack{|n| > N \\ \beta_n < s_0/h}} |\alpha_n \beta_n|^2 \leq \sum_{|n| > N} \left| \alpha_n \beta_n \frac{e^{i\beta_n h} - 1}{\beta_n h} \right|^2 \leq \frac{2}{m_0} \|C'\|_{L^2(0,T;L^2(\Gamma))}^2.$$

The limit for $h \rightarrow 0^+$ gives the result.

End of the proof of formula (3.23)

We insert $\delta_n = \tilde{\gamma}_n / \beta_n$ in (3.22) and we equate the derivatives of both the sides. The right hand side is the sum of $F''(t)\Psi_n$ which can be differentiated, and of the following functions \mathbf{S}_1 - \mathbf{S}_5 where

$$\begin{aligned} \mathbf{S}_1 &= -\alpha \sum \frac{\tilde{\gamma}_n}{\beta_n} \Psi_n \sin \beta_n t, & \mathbf{S}_2 &= N'_1(0) \sum \frac{\tilde{\gamma}_n}{\beta_n^2} \Psi_n \left(e^{i\beta_n t} + \frac{\alpha}{\beta_n} \sin \beta_n t \right), \\ \mathbf{S}_3 &= \int_0^t N''_1(t-s) \sum \frac{\tilde{\gamma}_n}{\beta_n^2} \Psi_n \left(e^{i\beta_n s} + \frac{\alpha}{\beta_n} \sin \beta_n s \right) ds. \end{aligned}$$

These functions can be differentiated since $\{\Psi_n \sin \beta_n t\}$ and $\{\Psi_n \cos \beta_n t\}$ are Riesz sequences in $L^2(G_T)$.

The remaining functions are

$$\begin{aligned} \mathbf{S}_4 &= -N'_1(0) \sum \int_0^t \frac{\tilde{\gamma}_n \mu_n}{\beta_n} \sin \beta_n(t-r) \Psi_n S_n(r) dr, \\ \mathbf{S}_5 &= - \int_0^t N''_1(s) \left[\sum \int_0^{t-s} \frac{\tilde{\gamma}_n \mu_n}{\beta_n} \sin \beta_n(t-s-r) \Psi_n S_n(r) dr \right] ds. \end{aligned}$$

The series in \mathbf{S}_4 is $L^2(G_T)$ convergent. Termwise differentiation gives

$$\frac{d}{dt} \int_0^t \sum \frac{\tilde{\gamma}_n \mu_n}{\beta_n} \sin \beta_n(t-r) S_n(r) dr = \int_0^t \sum \tilde{\gamma}_n \mu_n \cos \beta_n(t-r) S_n(r) dr.$$

This series is $L^2(G_T)$ -convergent and so the series in \mathbf{S}_4 belongs to H^1 (compare with the series (3.21)). This implies differentiability of \mathbf{S}_5 .

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