Analysis of a thermo-viscoelastic antiplane contact problem with long-term memory

Chougui Rachid · Lebri Nemira

Abstract We study a mechanical problem modeling the antiplane shear deformation of a cylinder in frictional contact with a rigid foundation. The material is assumed to be thermo-viscoelastic with long-term memory, the process is quasistatic, and the friction is modeled with Tresca's law. The mechanical model is described as a coupled system of a variational elliptic equality for the displacements and a differential heat equation for the temperature. We present a variational formulation of the problem and establish the existence and uniqueness of weak solution in using general results on evolution equations with monotone operators and fixed point arguments.

Keywords thermoviscoelastic materials · quasistatic contact · antiplane problem · variational inequality of evolution · normal compliance · Tresca's friction law · fixed point

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1 Introduction

Some people think that mathematics is an arbitrary creation and the job of mathematicians is to develop abstract theories. In their view, the more abstract and demanding is a theory, the bigger is its value. However, everyday experience shows a somewhat different picture, namely the interest in intellectual activities comes primarily from their practical implication. Nowadays considerable progress has been achieved in the different areas of mathematics and most of it was motivated by applications. Indeed, the abstract character of mathematical tools allows solving wider classes of problems which present a common feature and to provide sign can’t applications in the study of problems arising in sciences, engineering and everyday life.

Antiplane shear deformation problems arise naturally from many real world applications such as rectilinear steady row of simple ideas, interface stress effects of nano-structured materials, structures with cracks, layered composite functional materials 1 and phase transitions in solids. In antiplane shear of the cylindrical body, the displacement is parallel to generators of
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cylinders and is dependent of the axial coordinate. The model of a thermo-viscoelastic body is very complex, in addition to elastic and temperature properties, it takes into account viscous characteristics, (see, [1], [2], [3], [6], [7] and [8]).

The theory of variational inequalities has not been an exception. Indeed, the cross-fertilization between modeling and applications on the one hand and nonlinear mathematical analysis, on the other hand was an important aspect which contributed to its development in the last four decades. Currently, the theory of variational inequalities became a fully mature discipline which deals with existence, uniqueness or non uniqueness, regularity and continuous depend on results, together with numerical approximations and optimal control of the solutions. It provides results which are of considerable theoretical and applied interest.

The aim of this paper is to recall the attention to the great potential of inequalities in mechanics and physics. In the spirit of the classical book of G. Duvaut and J. L. Lions (see, e.g. [5], [7], [9] and [12]), we show how a concrete viscoelastic contact problem leads to a mathematical model which can be solved by using methods of variational inequality theory.

In this paper, we study the frictional contact between a deformable cylinder and a rigid foundation. We consider the case of antiplane shear deformation i.e., the displacement is parallel to the generators of the cylinder and is independent of the axial coordinate. Such kind of problems was studied in a number of papers, in the context of various constitutive laws and contact conditions (see, e.g. [4], [13]-[19]).

The novelty in our work consists in the fact that we model the friction with Tresca’s law and the material’s behavior with a thermo-visco-elastic constitutive law with long-term memory.

The paper is organized as follows. In Sect.2, we describe the mechanical problem, specify the assumptions on the data to derive the variational formulation, and then we state our main existence and uniqueness result. In Sect.3, we give the proof of the claimed result.

2 The variational formulation

We consider a body $B$ identified with a region in $\mathbb{R}^3$, it occupies in a fixed and undistorted reference configuration. We assume that $B$ is a cylinder with generator parallel to the $x_3$-axis with a cross-section which is a regular region in the $x_2x_3$-plane, $Ox_1x_2x_3$ being a cartesian coordinate system. The cylinder is assumed to be sufficiently long, so that end effects in the axial direction are negligible. Thus, $B = \Omega \times (-\infty, +\infty)$. Let $\partial \Omega = \Gamma$ we assume that $\Gamma$ is divided into three disjoint measurable parts $\Gamma_1$, $\Gamma_2$ and $\Gamma_3$ such that the one-dimensional measure of $\Gamma_1$, denoted $\text{mes} \; \Gamma_1$, is strictly positive. We denote by $[0; T]$ the time interval of interest with $T > 0$. The cylinder is clamped on $\Gamma_1 \times (-\infty, +\infty)$ and is in contact with a rigid foundation on $\Gamma_3 \times (-\infty, +\infty)$ during the process. Moreover, the cylinder is subjected
to time-dependent volume forces of density $f_0$ on $B$ and to time-dependent surface tractions of density $f_2$ on $\Gamma_2 \times (-\infty, +\infty)$.

We assume that

$$ f_0 = (0, 0, f_0) \text{ with } f_0 = f_0(x_1, x_2, t) : \Omega \times [0; T] \to \mathbb{R}, \quad (2.1) $$

$$ f_2 = (0, 0, f_2) \text{ with } f_2 = f_2(x_1, x_2, t) : \Gamma \times [0; T] \to \mathbb{R}. \quad (2.2) $$

The body forces (2.1) and the surface tractions (2.2) would be expected to give rise to a deformation of the cylinder whose displacement, denoted by $u$, is independent of $x_3$ and has the form

$$ u = (0, 0, u) \text{ with } u = u(x_1, x_2, t) : \Omega \times [0; T] \to \mathbb{R}. \quad (2.3) $$

Such kind of deformation is called an antiplane shear.

The infinitesimal strain tensor is denoted by $\varepsilon(u) = (\varepsilon_{ij}(u))$ and the stress field by $\sigma = (\sigma_{ij})$. Here and below, in order to simplify the notation, we do not indicate the dependence of various functions on $x_1, x_2$ or $t$.

The material is modeled by the following thermal viscoelastic constitutive law with long-term memory

$$ \sigma = \lambda (tr \varepsilon(u)) I + 2\mu \varepsilon(u) + 2 \int_0^t G(t-s) \varepsilon(u(s)) ds - M_e \theta, \quad (2.4) $$

where $\lambda > 0$ and $\mu > 0$ are the Lamé coefficients, $tr \varepsilon(u) = \sum_{i=1}^{3} \varepsilon_{ii}(u)$, $I$ is the unit tensor in $\mathbb{R}^3$, $G : [0; T] \to \mathbb{R}$ is the relaxation function, $\theta$ is the temperature field and $M_e := (m_{ij})$ represents the thermal expansion tensor and has the form

$$ M_e = \begin{pmatrix} 0 & 0 & M_{e_1} \\ 0 & 0 & M_{e_2} \\ M_{e_1} & M_{e_2} & 0 \end{pmatrix}. $$

We assume that $M_{e_i}(x_1, x_2) : \Omega \to \mathbb{R}$.

In the antiplane context (2.3), keeping in mind (2.4), the stress field becomes

$$ \sigma = \begin{pmatrix} 0 & 0 & \sigma_{13} \\ 0 & 0 & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & 0 \end{pmatrix}, \quad (2.5) $$

where

$$ \sigma_{13} = \sigma_{31} = \mu \partial_{x_1} u + \int_0^t G(t-s) \partial_{x_1} u(s) ds - M_{e_1} \theta, $$

$$ \sigma_{23} = \sigma_{32} = \mu \partial_{x_2} u + \int_0^t G(t-s) \partial_{x_2} u(s) ds - M_{e_2} \theta. $$
Neglecting the inertial term in the equation of motion we obtain the quasi-static approximation for the process. Thus, taking into account (2.5), (2.1) and the previous equalities, the equation of equilibrium reduces to the following scalar equation

$$
\mu \Delta u + \int_0^t \theta(t-s)\Delta u(s)ds + f_0 - \text{div} \theta \mathcal{M}_e = 0 \quad \text{in } \Omega \times (0,T),
$$

whith

$$
\mathcal{M}_e = \begin{pmatrix} M_{e1} \\ M_{e2} \\ 0 \end{pmatrix}.
$$

As the cylinder is clamped on $\Gamma_1 \times (-\infty, +\infty) \times (0,T)$, the displacement field vanishes there. Thus, (2.3) implies

$$
u = 0 \quad \text{on } \Gamma_1 \times (0,T).
$$

Let $\nu$ denote the unit normal on $\Gamma \times (-\infty, +\infty)$. We have

$$
\nu = (\nu_1, \nu_2, 0) \quad \text{with} \quad \nu_i = \nu_i(x_1, x_2) : \Gamma \to \mathbb{R}, \ i = 1, 2. \quad (2.6)
$$

For a vector $\nu$, we denote by $\nu_\nu$ and $\nu_\tau$ its normal and tangential components on the boundary, given by

$$
\nu_\nu = \nu \cdot \nu, \quad \nu_\tau = \nu - \nu_\nu. \quad (2.7)
$$

In (2.7) and every where in this paper “.” represents the inner product on the space $\mathbb{R}^d$, $d = 2$ or 3. Moreover, throughout this paper the notation $|.|$ will designate the Euclidean norm on $\mathbb{R}^d$, and a dot above a function will represent its derivative with respect to the time variable. For a given stress field $\sigma$ we denote by $\sigma_\nu$ and $\sigma_\tau$ the normal and the tangential components on the boundary, that is

$$
\sigma_\nu = (\sigma \nu) \cdot \nu, \quad \sigma_\tau = \sigma \nu - \sigma_\nu. \quad (2.8)
$$

From (2.5) and (2.6), we deduce that the Cauchy stress vector is given by

$$
\sigma \nu = (0, 0, \mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta \mathcal{M}_e \cdot \nu).
$$

From now we use the notation $\partial_\nu u = \partial_{x_1} u \nu_1 + \partial_{x_2} u \nu_2$.

Taking into account the traction boundary condition, $\sigma \nu = f_2$ on $\Gamma_2 \times (0,T)$, it follows from (2.2) and (2.9) that

$$
\mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta \mathcal{M}_e \cdot \nu = f_2 \quad \text{on } \Gamma_2 \times (0,T).
$$
Now, we describe the contact condition on $B = \Omega \times (-\infty, +\infty)$. First, from (2.3) and (2.6) we infer that $u_\nu = 0$, which shows that the contact is bilateral, that is, the contact is kept during all the process. Using now (2.3), (2.6)-(2.8), we conclude that

$$u_\tau = (0, 0, u), \quad \sigma_\tau = (0, 0, \mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta M_e.\nu).$$  \hspace{1cm} (2.10)

We assume that the friction is invariant with respect to the $x_3$ axis and is modeled with Tresca’s friction law, that is

$$\begin{cases}
|\sigma_\tau| \leq g \\
|\sigma_\tau| < g \Rightarrow \dot{u} = 0 \\
|\sigma_\tau| = g \Rightarrow \exists \beta \geq 0, \text{ such that } \sigma_\tau = -\beta \dot{u}_\tau
\end{cases} \hspace{1cm} \text{on } \Gamma_3 \times (0, T). \hspace{1cm} (2.11)$$

Here $g : \Gamma_3 \to \mathbb{R}_+$ is a given function, the friction bound, and $\dot{u}_\tau$ represents the tangential velocity on the contact boundary. The strict inequality holds in the stick zone and the equality in the slip zone. Using now (2.10) it is straight or ward to see that the conditions (2.11) imply

$$\begin{cases}
|\mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta M_e.\nu| \leq g \\
|\mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta M_e.\nu| < g \Rightarrow \dot{u} = 0 \\
|\mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta M_e.\nu| = g \Rightarrow \exists \beta \geq 0, \\
\text{such that } \mu \partial_\nu u + \int_0^t G(t-s)\partial_\nu u(s)ds - \theta M_e.\nu = -\beta \dot{u}
\end{cases} \hspace{1cm} \text{on } \Gamma_3 \times (0, T)$$

Finally, we prescribe the initial displacement,

$$u(0) = u_0 \quad \text{in } \Omega,$$

where $u_0$ is the given function on $\Omega$.

We collect the above equations and conditions to obtain the classical formulation of the antiplane problem for thermo-viscoelastic materials with longterm memory, in frictional contact with a foundation.
Problem **P**: Find the displacement field \( u : \Omega \times (0, T) \rightarrow S^d \) and a temperature field \( \theta : \Omega \times (0, T) \rightarrow \mathbb{R}_+ \), such that
\[
\|u\|_{H^1(\Omega)} \leq C_P \|\nabla u\|_{L^2(\Omega)} \quad \forall u \in V.
\]
We consider on \( V \) the inner product given by
\[
(u, v)_V = \int_{\Omega} \nabla u \cdot \nabla v dx \quad \forall u, v \in V,
\]
where \( K \) is the thermal conductivity tensor, \( q(t) \) the density of volume heat sources. The associated temperature boundary condition is given by (2.18), where \( \theta_R \) is the temperature of the foundation, and \( k \) is the heat exchange coefficient between the body and the obstacle. Finally, \( u_0, \theta_0 \) represent the initial displacement and temperature, respectively.

We derive now the variational formulation of \( P \). To this end, we introduce the functional space
\[
V = \{ v \in H^1(\Omega) \mid v = 0 \text{ on } \Gamma_2 \},
\]
and we assume that
\[
E = \{ \eta \in H^1(\Omega) \mid \eta = 0 \text{ on } \Gamma_1 \cup \Gamma_2 \}.
\]
Since \( \text{meas} \Gamma_1 > 0 \), the Friedrichs - Poincare inequality holds, i.e. there exists a positive constant \( C_P \) depends only on \( \Omega \) and \( \Gamma_1 \), such that
\[
\| u \|_{H^1(\Omega)} \leq C_P \|\nabla u\|_{L^2(\Omega)} \quad \forall u \in V.
\]
We consider on \( V \) the inner product given by
\[
(u, v)_V = \int_{\Omega} \nabla u \cdot \nabla v dx \quad \forall u, v \in V,
\]
and let \( \| \cdot \|_V \) be the associated norm, i.e.

\[
\| v \|_V = \| \nabla v \|_{L^2(\Omega)} \quad \forall v \in V.
\]

It follows that \( \| \cdot \|_{H^1(\Omega)} \) and \( \| \cdot \|_V \) are equivalent norms on \( V \) and therefore \( (V, \| \cdot \|) \) is a real Hilbert space. By Sobolev’s trace theorem we deduce that there exists \( C_0 > 0 \) (depending only on \( \Omega, \Gamma_1 \) and \( \Gamma_3 \)) such that

\[
\| v \|_{H^1(\Omega)} \leq C_0 \| v \|_V \quad \forall v \in V.
\] (2.20)

If \( (X, \| \cdot \|_X) \) represents a real Banach space, we denote by \( C([0, T]; X) \), the space of continuous functions from \([0, T] \) to \( X \), with the norm

\[
\| v \|_{C([0; T]; X)} = \max_{t \in [0, T]} \| x(t) \|_X
\]

and we use standard notations for the Lebesgue space \( L^2(0, T; X) \) as well as for the Sobolev space \( W^{1,2}(0, T; X) \). In particular, recall that the norm on the space \( L^2(0, T; X) \) is given by

\[
\| u \|_{L^2(0,T;X)} = \left( \int_0^T \| u(t) \|_X^2 \, dt \right)^{\frac{1}{2}}
\]

and the norm on the space \( W^{1,2}(0, T; X) \) is given by

\[
\| u \|_{W^{1,2}(0,T;X)} = \left( \int_0^T \| u(t) \|_X^2 \, dt + \int_0^T \| \dot{u}(t) \|_X^2 \, dt \right)^{\frac{1}{2}}
\]

Finally, we suppress the argument \( X \) when \( X = \mathbb{R} \) thus, for example, we use the notation \( W^{1,2}(0, T) \) for the space \( W^{1,2}(0, T; \mathbb{R}) \) and the notation \( \| \cdot \|_{W^{1,2}(0, T)} \) for the norm \( \| \cdot \|_{W^{1,2}(0, T; \mathbb{R})} \). In the study \( P \), we assume that the friction bound function \( g \) satisfies

\[
g \in L^\infty(\Gamma_3) \quad \text{and} \quad g(x) \geq 0 \quad \text{a.e.} \quad x \in \Gamma_3.
\] (2.21)

The forces and tractions are assumed to have the regularity

\[
f_0 \in W^{1,2}(0, T; L^2(\Omega)), \quad f_2 \in W^{1,2}(0, T; L^2(\Gamma_2)).
\] (2.22)

and, for the relaxation function, we assume

\[
\mathcal{G} \in W^{1,2}(0, T)
\] (2.23)

We consider the functional \( j : V \to \mathbb{R}_+ \) given by

\[
j(v) = \int_{\Gamma_3} g|v| \, da \quad \forall v \in V
\] (2.24)
and let \( f : [0, T] \to V \) be defined by

\[
(f(t), v)_V = \int_{\Omega} f_0(t)v\,dx + \int_{\Gamma_2} f_2(t)v\,da \quad \forall v \in V, \forall t \in [0, T] \tag{2.25}
\]

The definition of \( f \) is based on Riesz’s representation theorem and by (2.22) and (2.25), we infer that

\[
f \in L^2(0, T; V). \tag{2.26}
\]

For the thermal tensors and the heat sources density, we suppose that

\[
M_e = (m_{ij}), \quad m_{ij} = m_{ji} \in L^\infty(\Omega). \tag{2.27}
\]

The boundary thermal data satisfy

\[
q \in W^{1,2}(0, T; L^2(\Omega)), \quad \theta_B \in W^{1,2}(0, T; L^2(\Gamma_3)), \quad k_e \in L^\infty(\Omega, \mathbb{R}^+). \tag{2.28}
\]

The thermal conductivity tensor verifies the usual symmetry and ellipticity: for some \( c_k > 0 \) and for all \( \xi_i \in \mathbb{R}^d \)

\[
K = (k_{ij}), \quad k_{ij} = k_{ji} \in L^2(\Omega), \quad \forall c_k > 0, \quad \forall \xi_i \in \mathbb{R}^d; \quad k_{ij}\xi_i\xi_j \leq c_k\xi_i\cdot\xi_j. \tag{2.29}
\]

Finally, we assume that the initial data verifies

\[
u_0 \in V, \quad \theta_0 \in L^2(\Omega), \tag{2.30}
\]

and moreover,

\[
\mu(u_0, v)_V + j(v) \geq (f(0), v)_V. \tag{2.31}
\]

Using Green’s formula it is straightforward to derive the following variational formulation of \( P \). We denote by \( (\cdot, \cdot)_{V' \times V} \) the duality pairing between \( V' \) and \( V \).

**Problem** \( P_V \): Find a displacement field \( u : [0; T] \to V \) and a temperature field \( \theta : (0; T) \to E \) such that

\[
\mu(u(t), v - \dot{u}(t))_V + \left( \int_0^t G(t - s)u(s)ds, v - \dot{u}(t) \right)_V + (M\theta(t), \varepsilon(v - \dot{u}(t)))_H
\]

\[
+ j(v) - j(\dot{u}(t)) \geq (f(t), v - \dot{u}(t))_V \quad \forall v \in V, \ t \in (0, T),
\]

\[
\dot{\theta}(t) + K\theta(t) = R\dot{u}(t) + Q(t) \quad \text{in } E',
\]

\[
u(0) = u_0, \quad \theta(0) = \theta_0 \quad \text{in } \Omega.
\]
Here, the function $Q : [0,T] \to E'$ and the operators $K : E \to E'$, $R : V \to E'$, $M : E \to V'$ are defined by $\forall v \in V, \forall \tau \in E, \forall \mu \in E$:

$$\langle Q(t), \mu \rangle_{E' \times E} = \int_{\Gamma_3} k_e \theta R \mu ds + \int_{\Omega} q \mu dx,$$

$$\langle K \tau, \mu \rangle_{E' \times E} = \sum_{i,j=1}^{d} \int_{\Omega} k_{ij} \frac{\partial \mu}{\partial x_j} \frac{\partial \mu}{\partial x_i} dx + \int_{\Gamma_3} k_e \tau \mu ds,$$

$$\langle R v, \mu \rangle_{E' \times E} = \int_{\Gamma_3} h_\tau (|v_\tau|) \mu ds - \int_{\Omega} (M_e \nabla v) \mu dx,$$

$$\langle M \tau, v \rangle_{V' \times V} = (-\tau M_e, \varepsilon(v))_{\mathcal{H}}.$$

Our main existence and uniqueness result is stated as follows.

**Theorem 2.1** Assume that (2.21)-(2.23), (2.26) and (2.27) hold. Then there exists a unique solution $u, \theta$ of problem $P_V$. Moreover, the solution satisfies

$$u \in W^{1,2}(0,T; V); \theta \in W^{1,2}(0,T; E') \cap L^2(0,T; E) \cap C(0,T; L^2(\Omega)).$$

An element $(u, \theta)$ which solves $P_V$ is called a weak solution of the mechanical problem $P$. We conclude by Theorem 2.1. that the antiplane contact problem $P$ has a unique weak solution, provided that (2.21)-(2.23), (2.26) and (2.27) hold.

### 3 An abstract existence and uniqueness result

The proof of Theorem 2.1, is carried out in several steps that we prove in what follows, everywhere in this section we suppose that assumptions of Theorem 2.1 hold and we denote by $c > 0$ a generic constant, which value may change from lines to lines.

In the first step of the proof, we introduce the set

$$\mathcal{W} = \{ \eta \in W^{1,2}(0,T; X) | \eta(0) = 0_X \},$$

and we prove the following existence and uniqueness result.

**Lemma 3.1** For all $\eta \in \mathcal{W}$, there exists a unique element $u \in W^{1,2}(0,T; X)$ such that

$$a(u_\eta(t), v - \dot{u}_\eta(t))_X + (\eta(t), v - \dot{u}_\eta(t))_X + j(v) - j(\dot{u}(t)) \geq (f(t), v - \dot{u}_\eta(t))_X \quad \forall v \in X, \ a.e. \ t \in (0,T),$$

$$u_\eta(0) = u_0.$$
Here $X$ is a real Hilbert space endowed with the inner product $(.,.)_X$ and the data $a$ is a bilinear continuous coercive and symmetric form.

**Proof.** We use an abstract existence and uniqueness result which may be found in [16].

In the second step, we use the displacement field $u_\eta$ obtained in Lemma 3.1 and we consider the following Lemma.

**Lemma 3.2** For all $\eta \in \mathcal{W}$, there exists a unique $\theta_\eta \in \mathcal{W}_{1,2}(0,T;V')$ satisfying

$$
\begin{aligned}
\dot{\theta}_\eta(t)K &= Ru_\eta(t) + Q(t) \quad \text{in } E' \quad \text{a.e. } t \in (0,T) \\
\theta_\eta(0) &= \theta_0,
\end{aligned}
$$

(3.4)

$$
|\theta_\eta - \theta_\eta_2|_{L^2(\Omega)}^2 \leq c \int_0^T |\dot{u}_1(s) - \dot{u}_2(s)|_V^2 ds \quad \forall t \in (0,T),
$$

(3.5)

and

$$
|\dot{\theta}_\eta - \dot{\theta}_\eta_2|_{L^2(\Omega)}^2 \leq c \int_0^T |u_1(s) - u_2(s)|_V^2 ds \quad \forall t \in (0,T).
$$

(3.6)

**Proof.** The existence and uniqueness result verifying (3.4) follows from classical result on first order evolution equation, applied to the Gelfand evolution triple $E \subset F \equiv F' \subset E'$.

We verify that the operator $K$ is linear continuous and strongly monotone. Now from the expression of the operator $R$, $v_\eta \in W^{1,2}(0,T;V) \Rightarrow Rv_\eta \in W^{1,2}(0,T;F)$, as $Q \in W^{1,2}(0,T;E)$ then $Rv_\eta + Q \in W^{1,2}(0,T;E)$, we deduce (3.5) and (3.6), (see [1], [10] and [11]).

In the next step, we consider the operator $\Lambda : \mathcal{W} \rightarrow \mathcal{W}$ defined by

$$
\langle \Lambda \eta(t), u \rangle_{V' \times V} = \int_0^t \mathcal{G}(t-s)u_\eta(s)ds - M\epsilon(t, \eta), \forall \eta \in \mathcal{W}, t \in (0,T).
$$

(3.7)

It follows from (3.4) that the operator $\Lambda$ is well defined. Since $u \in \mathcal{W}$, implies $\Lambda \eta \in \mathcal{W}$. We also note that

$$
\frac{d}{dt} \Lambda \eta(t) = \mathcal{G}(0)u_\eta(t) + \int_0^t \mathcal{G}(t-s)u_\eta(s)ds - M\epsilon(t), \forall \eta \in \mathcal{W}, t \in [0,T]
$$

We have the following result.
Lemma 3.3 The operator $\Lambda$ has a unique fixed point $\eta^* \in \mathcal{W}$.

Proof. Let $\eta_1, \eta_2 \in \mathcal{W}$ and, for the sake of simplicity, denote $u_1 = u_{\eta_1}$ and $u_2 = u_{\eta_2}$. Using (3.7) and (2.27), it follows that

$$
\|\Lambda \eta_1(s) - \Lambda \eta_2(s)\|_X^2 \leq c \int_0^t \|u_1(s) - u_2(s)\|_X^2 ds + \|u_1(s) - u_2(s)\|_X^2, \forall t \in [0, T]
$$

Here and in what follows $c$ represents a generic positive constant which may depend on $\|G\|_{W^{1,2}(0,T)}$, $a$ and $T$, whose value may change from line to line.

Moreover, from (3.8) we infer that for all $t$ in $(0; T)$

$$
\left\| \left( \frac{d}{dt} \Lambda \eta_1 \right)(t) - \left( \frac{d}{dt} \Lambda \eta_2 \right)(t) \right\|_X \leq |G(0)| \|u_1(t) - u_2(t)\|_X + \int_0^t \left| \frac{d}{dt} G(t - s) \right| \|u_1(s) - u_2(s)\|_X ds + \|\theta_1(s) - \theta_2(s)\| \leq c(\|u_1(t) - u_2(t)\|_X + \int_0^t \|u_1(s) - u_2(s)\| ds + \|\theta_1(s) - \theta_2(s)\|)
$$

which yields

$$
\left\| \left( \frac{d}{dt} \Lambda \eta_1 \right)(t) - \left( \frac{d}{dt} \Lambda \eta_2 \right)(t) \right\|_X^2 \leq c(\|u_1(t) - u_2(t)\|_X^2 + \int_0^t \|u_1(s) - u_2(s)\|_X^2 ds,
$$

using (3.6) we have the inequation

$$
\left\| \left( \frac{d}{dt} \Lambda \eta_1 \right)(t) - \left( \frac{d}{dt} \Lambda \eta_2 \right)(t) \right\|_X^2 \leq c \left( \int_0^t \|u_1(s) - u_2(s)\|_X^2 ds \right).
$$

On the other hand, taking into account (3.2), we have the inequalities

$$
a(u_1(s), v - \dot{u}_1(s)) + (\eta_1(s), v - \dot{u}_1(s))_X + j(v) - j(\dot{u}_1(s)) \geq (f(s), v - \dot{u}_1(s))_X
$$

$$
a(u_2(s), v - \dot{u}_2(s)) + (\eta_2(s), v - \dot{u}_2(s))_X + j(v) - j(\dot{u}_2(s)) \geq (f(s), v - \dot{u}_2(s))_X
$$

for all $v \in X$, a.e. $t \in (0, T)$.

The data $a$ is a bilinear, continuous, coercive and symmetric form.

We choose in the first inequality, $v = \dot{u}_1(s)$ in the second inequality, add the results to obtain

$$
\frac{1}{2} \frac{\partial}{\partial s} \|u_1(t) - u_2(t)\|_a^2 \leq ((\eta_1(t) - \eta_2(t), \dot{u}_1(t) - \dot{u}_2(t))_X, \ a.e. \ t \in (0, T).
$$
Integrating the previous inequality from 0 to $T$ and using (3.3), we get

$$\frac{1}{2}\|u_1(t) - u_2(t)\|_X^2 \leq (\eta_1(t) - \eta_2(t), u_1(t) - u_2(t))_X + \int_0^T (\dot{\eta}_1(s) - \dot{\eta}_2(s), u_1(s) - u_2(s))_X \, ds.$$ 

It follows that

$$c \|u_1(t) - u_2(t)\|_X^2 \leq \|\eta_1(t) - \eta_2(t)\|_X \|u_1(t) - u_2(t)\|_X + \int_0^T \|\dot{\eta}_1(s) - \dot{\eta}_2(s)\|_X \|u_1(s) - u_2(s)\|_X \, ds,$$

and, using the inequality $ab \leq \frac{a^2}{2\alpha} + 2\alpha b^2$ for $a, \alpha, b > 0$, we find

$$\|u_1(t) - u_2(t)\|_X^2 \leq c(\|\eta_1(t) - \eta_2(t)\|_X^2 + \int_0^T \|\dot{\eta}_1(s) - \dot{\eta}_2(s)\|_X^2 \, ds + \int_0^T \|u_1(s) - u_2(s)\|_X^2 \, ds).$$

(3.9)

As

$$\eta_1(t) - \eta_2(t) = \int_0^t (\dot{\eta}_1(s) - \dot{\eta}_2(s)) \, ds,$$

we deduce that

$$\|\eta_1(t) - \eta_2(t)\|_X \leq \int_0^t \|\dot{\eta}_1(s) - \dot{\eta}_2(s)\|_X \, ds.$$

Using this inequality in (3.11), we obtain

$$\|u_1(t) - u_2(t)\|_X^2 \leq c \left( \int_0^T \|\dot{\eta}_1(s) - \dot{\eta}_2(s)\|_X^2 \, ds + \int_0^T \|u_1(s) - u_2(s)\|_X^2 \, ds \right).$$

Applying now Gronwall’s inequality we deduce

$$\|u_1(t) - u_2(t)\|_X^2 \leq c \left( \int_0^t \|\dot{\eta}_1(s) - \dot{\eta}_2(s)\|_X^2 \, ds \right),$$

(3.10)

which yields

$$\int_0^t \|u_1(s) - u_2(s)\|_X^2 \leq c \left( \int_0^t \|\dot{\eta}_1(s) - \dot{\eta}_2(s)\|_X^2 \, ds \right).$$

(3.11)
Combining now (3.8), (3.9), (3.10) and (3.11), we obtain
\[ \| \Lambda \eta_1(t) - \Lambda \eta_2(t) \|^2_X + \left( \left\| \frac{d}{dt} \Lambda \eta_1 \right\|_X \right) (t) - \left( \left\| \frac{d}{dt} \Lambda \eta_2 \right\|_X \right) (t) \]
\[ \leq c \left( \int_0^t \| \dot{\eta}_2(s) - \dot{\eta}_2(s) \|^2_X \, ds \right). \]

Iterating the last inequality \( p \)-times we infer
\[ \| \Lambda \eta_1(t) - \Lambda \eta_2(t) \|^2_X + \left( \left\| \frac{d}{dt} \Lambda \eta_1 \right\|_X \right) (t) - \left( \left\| \frac{d}{dt} \Lambda \eta_2 \right\|_X \right) (t) \]
\[ \leq c^p \left( \int_0^{s_1} \int_0^{s_2} \int_0^{s_3} \ldots \int_0^{s_p-1} \| \dot{\eta}_2(s_p) - \dot{\eta}_2(s_p) \|^2_X \, ds_p \ldots ds_1 \right), \]

where \( A^p \) denotes the power of the operator \( A \). The last inequality implies
\[ \| \Lambda \eta_1(t) - \Lambda \eta_2(t) \|_{W^{1,2}(0,T;X)} \leq \| \eta_1(t) - \eta_2(t) \|_{W^{1,2}(0,T;X)}. \]

Since \( \lim_{p \to +\infty} \frac{c^p T^p}{p!} = 0 \), the previous inequality implies that a power \( A^p \) of \( A \), is a contraction in \( W \) for \( p \) large enough. It follows now from Banach’s fixed point theorem that, there exists a unique element \( \eta^* \in W \) such that \( A^p \eta^* = \eta^* \). Moreover, since \( A^p(A \eta^*) = A(A^p \eta^*) = A \eta^* \), we deduce that \( A \eta^* \) is also a fixed point of the operator \( A^p \). By the uniqueness of the fixed point, we conclude that \( A \eta^* = \eta^* \), which shows that \( \eta^* \) is a fixed point of \( A \). The uniqueness of the fixed point of the operator \( A \) follows from the uniqueness of the fixed point of the operator \( A^p \).

\[ \square \]

We have now all the ingredients to prove the theorem.

**Proof of Theorem 2.1**

**Existence.** Let \( \eta^* \in W \) be the fixed point of \( A \) and let \( u_{\eta^*} \) be the function defined by Lemma 1, for \( \eta = \eta^* \). Since, it follows from (3.7) that \( u_{\eta^*} \) is a solution to the problem (3.2)-(3.3). Moreover, the regularity \( u_{\eta^*} \in W^{1,2}(0,T;X) \) is obtained from Lemma 1, \( \theta_{\eta^*} \) be the solution to problems (3.4).

Consider the form \( a : V \times V \to \mathbb{R} \), defined by
\[ a(u,v) = \mu \int_{\Omega} \nabla u \cdot \nabla v \quad \forall u, v \in V. \]

Clearly this form is bilinear, continuous, coercive and symmetric; moreover, using (2.19) and (2.20) it follows that the functional \( j \) defined by (2.24) is convex, lower semicontinuous and proper. Taking into account (2.22) and (2.25)-(2.30) then, the \( u_{\eta^*} \) is also solution of (3.2)-(3.3); \( \theta_{\eta^*} \) be the solution to problems (3.4).
Then \((u_{\eta^*}, \theta_{\eta^*})\) be the solution to Problems \(P_V\).

**Uniqueness.** The uniqueness of the solution is a consequence of the uniqueness of the fixed point of operator defined by (3.7) and from uniqueness in Lemmas (3.1), (3.2) and (3.3).

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