

## A VARIATIONAL METHOD FOR SECOND ORDER SHAPE DERIVATIVES\*

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**Abstract.** We consider shape functionals obtained as minima on Sobolev spaces of classical integrals having smooth and convex densities, under mixed Dirichlet–Neumann boundary conditions. We propose a new approach for the computation of the second order shape derivative of such functionals, yielding a general existence and representation theorem. In particular, we consider the  $p$ -torsional rigidity functional for  $p \geq 2$ .

**Key words.** shape functionals, infimum problems, domain derivative, duality

**AMS subject classifications.** 49Q10, 49K10, 49M29, 49J45

**DOI.** 10.1137/15100494X

**1. Introduction.** The aim of this paper is to provide a new method for the computation of second order shape derivatives, which applies to a broad class of shape functionals associated with classical problems in the calculus of variations. Let us recall that if  $J(\cdot)$  is a functional depending on a subset  $\Omega$  of  $\mathbb{R}^n$  and  $V$  is a deformation field in  $C^1(\mathbb{R}^n; \mathbb{R}^n)$ , the first and second order shape derivatives of  $J$  at  $\Omega$  in direction  $V$ , if they exist, are given, respectively, by the limits

$$J'(\Omega, V) := \lim_{\varepsilon \rightarrow 0} \frac{J(\Omega_\varepsilon) - J(\Omega)}{\varepsilon}, \quad J''(\Omega, V) := \lim_{\varepsilon \rightarrow 0} 2 \frac{J(\Omega_\varepsilon) - J(\Omega) - \varepsilon J'(\Omega, V)}{\varepsilon^2},$$

where  $\Omega_\varepsilon$  are the perturbed domains  $\Omega_\varepsilon := \Psi_\varepsilon(\Omega)$ , with  $\Psi_\varepsilon(x) := x + \varepsilon V(x)$ .

The literature on shape derivatives is very extensive, and in recent years it has seen a rapid flourishing, also stimulated by advances in numerical methods for the determination of optimal shapes. We limit ourselves to quoting the monographs [18, 25, 27, 45], where a lot of bibliographical references in this field can be found. Concerning in particular second order shape derivatives, their computation is usually irksome, but often deserves some effort because the study of their sign allows one to detect whether a critical shape, namely, a domain with vanishing first order shape derivative, is actually an optimal one. For contributions in this direction, let us mention, without attempting to be comprehensive, the papers [1, 11, 17, 21, 24, 26, 32, 39, 28]. In particular, in [39] Novruzzi and Pierre proved a quite general and helpful structure result about second order shape derivatives, under the a priori assumption that they exist. Moreover, still in [39] the explicit expression of second order shape derivative is computed under the assumption that the boundary of the domain  $\Omega$  is sufficiently smooth (for the structure of shape derivatives around irregular domains, see [32]). Let us also mention that the linear and bilinear forms which appear in

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\*Received by the editors January 21, 2015; accepted for publication (in revised form) February 12, 2016; published electronically April 21, 2016. This work was supported by the University of Toulon and GNAMPA (INDAM).

<http://www.siam.org/journals/sicon/54-2/100494.html>

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the structure result have to be identified each time for the particular functional under study, and this turns out to be a delicate task (see the discussion in [27, section 5.9.4]).

In this work we propose a new approach to second order shape derivatives, which applies under rather mild regularity assumptions to shape functionals of the form

$$(1.1) \quad J(\Omega) := - \inf \left\{ \int_{\Omega} [f(\nabla u) + g(u)] dx : u \in H(\Omega) \right\}.$$

Here  $f$  and  $g$  are assumed to be convex and smooth functions satisfying suitable growth conditions, while  $H(\Omega)$  indicates the space of functions in  $H^1(\Omega)$  which satisfy the Dirichlet condition  $u = 0$  on a fixed, nonempty, measurable portion  $\Gamma_D \subset \partial\Omega$ ; the Neumann part of the boundary, i.e., the complement  $\partial\Omega \setminus \Gamma_D$ , will be denoted by  $\Gamma_N$ .

As a natural continuation of our previous paper [8], where we introduced a new approach to first order shape derivatives for functionals of type (1.1), here we tackle second order shape derivatives by the same method. The main results obtained in [8] are briefly recalled in section 2; see (2.8)–(2.9). The basic ingredients we employ are the analysis of the  $\Gamma$ -convergence of the differential quotients appearing in the definition of  $J''(\Omega, V)$ , and the duality principle

$$(1.2) \quad J(\Omega) = J^*(\Omega) := \inf \left\{ \int_{\Omega} [f^*(\sigma) + g^*(\operatorname{div} \sigma)] dx : \sigma \in X(\Omega; \mathbb{R}^n) \right\},$$

where  $X(\Omega; \mathbb{R}^n)$  is a suitable space of vector fields.

Our main results are as follows:

- an existence result for  $J''(\Omega, V)$  as a quadratic form in  $V$  (see Theorem 3.5 (i));
- a new necessary optimality condition, which involves the distributional divergence of a vector field  $B(\bar{u}, V)$  (see Proposition 3.4), along with a regularity result of type  $W_{\text{loc}}^{2,2}$  that we recover for the solution  $\bar{u}$  to  $J(\Omega)$  (see Proposition 3.2); notice that the latter issue is reminiscent of the celebrated Nirenberg translation method commonly used in regularity pde theory;
- a representation result for  $J''(\Omega, V)$  (see Theorem 3.5 (ii)), which holds provided the  $W_{\text{loc}}^{2,2}$  regularity of  $\bar{u}$  stated in Proposition 3.2 extends up to the boundary, and the latter is piecewise  $C^1$ ; it is obtained by exploiting the optimality condition given in Proposition 3.4 as a crucial tool and reads

$$(1.3) \quad J''(\Omega, V) = \int_{\partial\Omega} (\mathcal{C}(\bar{u}, V) \cdot n) d\mathcal{H}^{n-1} + q(\bar{u}, V);$$

here  $\mathcal{C}(\bar{u}, V) \cdot n$  is the normal trace of a suitable vector field (see (3.4)) depending on the solution  $\bar{u}$  to  $J(\Omega)$  and quadratically on the deformation  $V$ , whereas  $q(\bar{u}, V)$  is a non-local term which involves the above-mentioned vector field  $B(\bar{u}, V)$  and a quadratic form  $\mathcal{Q}(\bar{u}, \cdot)$  depending on the second derivatives of  $f$  and  $g$  (see Theorem 3.5); we stress that, as detailed in Remark 3.8 below, formula (1.3) fits the general representation result for second order shape derivatives given in [39, Corollary 2.4].

The paper is organized as follows. After providing some notation and preliminary background in section 2, we state in section 3 our main results, followed by some comments and examples. In fact, we show that we can recover straightforwardly the second order shape derivative of the torsional rigidity, as given, e.g., in [27, section 5.9.6], and we are able to extend the formula to the case of mixed Dirichlet–Neumann conditions.

Moreover, we consider the case of  $p$ -torsional rigidity for  $p > 2$ . In this case, to the best of our knowledge, only the first order shape derivative is available in the literature (see [15, 22]). We are able to compute the second order shape derivative under an additional assumption, which is quite technical and is related to a deep regularity issue for the  $p$ -Laplace operator; checking its validity seems to be a delicate problem of independent interest which goes beyond the scope of this paper.

The next three sections are devoted to the proofs: the existence of the second order shape derivative (Theorem 3.5 (i)) is achieved in section 4; the regularity result of Proposition 3.2 and the optimality conditions of Proposition 3.4 are proved in section 5; eventually, in section 6 we prove the representation formula for the second order shape derivative (Theorem 3.5 (ii)).

In section 7 we present some variants of our results, including in particular the case of the  $p$ -torsional rigidity for  $p \in [2, +\infty)$ , and then we conclude the paper by addressing some possible perspectives. Section 8 is an appendix where some auxiliary lemmas and technical facts are collected.

## 2. Preliminaries.

**Standing assumptions.** Unless otherwise stated, we work under the following hypotheses, which will be referred to as standing assumptions:

- $\Omega$  is an open bounded connected set, with a piecewise  $C^1$  boundary and unit outer normal  $n$ ;
- $f : \mathbb{R}^n \rightarrow \mathbb{R}$  and  $g : \mathbb{R} \rightarrow \mathbb{R}$  are of class  $C^2$  and are strongly convex; namely, there exist positive constants  $m$  and  $k$  such that

$$(2.1) \quad (\nabla^2 f - mI) \text{ is positively semidefinite,} \quad g'' - k \geq 0;$$

- $f$  and  $g$  satisfy the growth conditions

$$(2.2) \quad \begin{cases} C_1(|z|^2 - 1) \leq f(z) \leq C_2(|z|^2 + 1) & \forall z \in \mathbb{R}^n, \\ C_3(|v|^2 - 1) \leq g(v) \leq C_4(|v|^q + 1) & \forall v \in \mathbb{R}, \end{cases}$$

where  $C_i$  are positive constants, while the exponent  $q$  is assumed to satisfy  $q = 2^* := \frac{2n}{n-2}$  if  $n > 2$  and  $q \in (1, +\infty)$  if  $n \leq 2$ ;

- $g(0) = 0$  (which is not restrictive up to a translation);
- the solution  $\bar{u}$  to  $J(\Omega)$  is Lipschitz;
- the deformation field  $V$  belongs to  $C^1(\mathbb{R}^n; \mathbb{R}^n)$ .

*Remark 2.1.* Notice that, by strict convexity, the solution  $\bar{u}$  to  $J(\Omega)$  is unique. Its regularity is a delicate topic and exceeds the scope of this paper. The interested reader may refer to [35] for a detailed presentation of the Lipschitz regularity of  $\bar{u}$  in the interior of  $\Omega$ . As for the Lipschitz regularity up to the boundary, we mention the papers [10, 12, 23, 34, 46], in which such a property is guaranteed in the Dirichlet case, provided that  $\Omega$  is convex (namely, when the boundary datum zero satisfies the so-called bounded slope condition). We are not aware of any general result available in the literature for the case of mixed Dirichlet–Neumann boundary conditions.

**Some standard notation.** We adopt the convention of repeated indices. Given two vectors  $a, b$  in  $\mathbb{R}^n$ , we use the notation  $\langle a, b \rangle$  to denote their Euclidean scalar product; moreover we denote by  $a \otimes b$  the tensor product of  $a$  and  $b$ , namely, the matrix  $(a \otimes b)_{ij} = a_i b_j$ . Given two matrices  $A$  and  $B$  in  $\mathbb{R}^{n \times n}$ , we write  $A : B$  to denote their Euclidean scalar product, namely,  $A : B = A_{ij} B_{ij}$ . We denote by  $A^{-1}$

and  $A^T$  the inverse and the transpose matrices of  $A$ , by  $A^{-T}$  the transposition of the inverse of  $A$ , and by  $I$  the identity matrix. Moreover, we denote by  $a_k(A)$  the  $k$ th invariant of the matrix  $A$ , in particular

$$a_1(A) = \text{tr}(A), \quad a_2(A) = \frac{1}{2}(\text{tr}(A)I - A^T) : A, \quad a_n(A) = \det A.$$

For a tensor field  $A \in C^1(\mathbb{R}^n; \mathbb{R}^{n \times n})$ , by  $\text{div } A$  we mean its divergence with respect to lines, namely,  $(\text{div } A)_i := \partial_j A_{ij}$ .

Let  $\Omega$  be as in the standing assumptions. Given a vector field  $V$  on  $\partial\Omega$ , we decompose it into a *tangential and normal component* as  $V = V_\Gamma + V_n n$ , with  $V_n := \langle V, n \rangle$ .

We recall that for  $\varphi \in C^1(\partial\Omega)$  and  $V \in C^1(\partial\Omega; \mathbb{R}^n)$ , the *tangential gradient* of  $\varphi$  and the *tangential divergence* of  $V$  are given, respectively, by  $\nabla_\Gamma \varphi := \nabla \tilde{\varphi} - \langle \nabla \tilde{\varphi}, n \rangle n$  and  $\text{div}_\Gamma V := \text{div } \tilde{V} - \langle D\tilde{V}n, n \rangle$  on  $\partial\Omega$ , where  $\tilde{\varphi}$  and  $\tilde{V}$  are arbitrary  $C^1$  extensions to  $\mathbb{R}^n$  of  $\varphi$  and  $V$ . In particular, if  $\Omega$  is of class  $C^2$ , the tangential divergence of  $n$  gives the scalar mean curvature, that is,  $H_{\partial\Omega} = \text{div}_\Gamma n$ . The first and second order normal derivatives of  $\varphi$  will be denoted by  $\partial_n \varphi := \langle \nabla \varphi, n \rangle$  and  $\partial_{nn}^2 \varphi := \langle (\nabla^2 \varphi)n, n \rangle$ .

Given a vector field  $\Psi \in L^2(\Omega; \mathbb{R}^n)$  with distributional divergence in  $L^2(\Omega)$ , we denote by  $\Psi \cdot n$  its *normal trace* on  $\partial\Omega$ , meant as the unique element in  $H^{-1/2}(\partial\Omega)$  such that

$$(2.3) \quad \int_{\partial\Omega} (\Psi \cdot n) \varphi \, d\mathcal{H}^{n-1} = \int_{\Omega} (\langle \Psi, \nabla \varphi \rangle + \varphi \text{div } \Psi) \, dx \quad \forall \varphi \in H^1(\Omega),$$

where the boundary integral on the left-hand side (l.h.s.) is intended as the duality bracket between  $H^{-1/2}(\partial\Omega)$  and  $H^{1/2}(\partial\Omega)$ . For a detailed account on the theory of weak traces, we refer the reader to [3, 13] (see also [8, section 2.1]).

**Existence of solutions, dual formulation, and optimality conditions.**

Under the standing assumptions, the infimum problem  $J(\Omega)$  admits a unique solution (cf. [8, Lemma 2.1]), denoted by  $\bar{u}$ , in the space

$$H(\Omega) := \{u \in H^1(\Omega) : u = 0 \text{ on } \Gamma_D\}.$$

Moreover, by standard duality arguments (cf. [8, Lemma 2.2]), it holds that  $J(\Omega) = J^*(\Omega)$ , where  $J^*(\Omega)$  is the infimum problem introduced in (1.2), set over the space

$$(2.4) \quad X(\Omega; \mathbb{R}^n) := \{\sigma \in L^2(\Omega; \mathbb{R}^n) : \text{div } \sigma \in L^{q'}(\Omega), \sigma \cdot n = 0 \text{ on } \Gamma_N\},$$

being  $q' := q/(q - 1)$ . Also  $J^*(\Omega)$  admits a unique solution, denoted by  $\bar{\sigma}$ , which is related to  $\bar{u}$  by the following differential equalities:

$$(2.5) \quad \begin{cases} \bar{\sigma} = \nabla f(\nabla \bar{u}) & \text{a.e. in } \Omega, \\ \text{div } \bar{\sigma} = g'(\bar{u}) & \text{a.e. in } \Omega, \end{cases} \quad \text{or equivalently} \quad \begin{cases} \nabla \bar{u} = \nabla f^*(\bar{\sigma}) & \text{a.e. in } \Omega, \\ \bar{u} = (g^*)'(\text{div } \bar{\sigma}) & \text{a.e. in } \Omega. \end{cases}$$

Note that by (2.5) and in view of the regularity assumed on  $f$ ,  $g$ , and  $\bar{u}$ , we have  $\nabla \bar{u}, \bar{\sigma} \in L^\infty(\Omega; \mathbb{R}^n)$  and  $\bar{u}, \text{div } \bar{\sigma} \in L^\infty(\Omega)$ .

**First order shape derivative.** Let  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$  be a deformation field and set for every  $\varepsilon$

$$(2.6) \quad \Omega_\varepsilon := \Psi_\varepsilon(\Omega), \quad \text{being } \Psi_\varepsilon(x) := x + \varepsilon V(x).$$

Under the standing assumptions, the first order shape derivative of  $J$  at  $\Omega$  in direction  $V$ , defined by

$$(2.7) \quad J'(\Omega, V) := \lim_{\varepsilon \rightarrow 0} \frac{J(\Omega_\varepsilon) - J(\Omega)}{\varepsilon},$$

exists and is given by

$$(2.8) \quad J'(\Omega, V) = \int_{\Omega} A(\bar{u}) : DV \, dx = \int_{\partial\Omega} \langle A(\bar{u}) n, V \rangle \, d\mathcal{H}^{n-1},$$

where  $A(\bar{u})$  denotes the following tensor, which turns out to be divergence free on  $\Omega$  with a normal trace  $A(\bar{u}) n$  in  $L^\infty(\partial\Omega)$ :

$$(2.9) \quad A(\bar{u}) = \nabla \bar{u} \otimes \bar{\sigma} - (f(\nabla \bar{u}) + g(\bar{u})) I = \nabla \bar{u} \otimes \bar{\sigma} + (f^*(\bar{\sigma}) + g^*(\operatorname{div} \bar{\sigma}) - \langle \nabla \bar{u}, \bar{\sigma} \rangle - \bar{u} \operatorname{div} \bar{\sigma}) I$$

(with  $\bar{\sigma} = \nabla f(\nabla \bar{u})$ ). For the proof of (2.8), see Theorems 3.3 and 3.7 in [8]; actually, even though such results are not stated for the case of mixed Dirichlet–Neumann boundary conditions, it can be easily checked that their proofs continue to work unaltered in such a case. Moreover, if  $\bar{u}$  is Lipschitz and  $\nabla \bar{u}, \bar{\sigma}$  are in  $BV(\Omega; \mathbb{R}^n)$ , the boundary integral in (2.8) can be rewritten as a linear expression of  $V_n$ ; namely, it holds that  $J'(\Omega, V) = l_1(V_n)$  with

$$l_1(\varphi) := \int_{\Gamma_D} f^*(\bar{\sigma}) \varphi \, d\mathcal{H}^{n-1} - \int_{\Gamma_N} (f(\nabla \bar{u}) + g(\bar{u})) \varphi \, d\mathcal{H}^{n-1}.$$

**Reformulation from a variable domain to a fixed domain.** Following the same procedure adopted in [8, Lemma 4.1] in order to recast the first order shape derivative  $J'(\Omega, V)$ , we rewrite the variational problem  $J(\Omega_\varepsilon)$  over the fixed domain  $\Omega$ : by using a standard change of variables, we obtain

$$(2.10) \quad J(\Omega_\varepsilon) = - \inf_{u \in H(\Omega)} \int_{\Omega} [f_\varepsilon(\nabla u) + g_\varepsilon(u)] \, dx,$$

where  $f_\varepsilon$  and  $g_\varepsilon$  are given by

$$(2.11) \quad f_\varepsilon(x, z) := f(D\Psi_\varepsilon^{-T}(x)z)\beta_\varepsilon(x), \quad g_\varepsilon(x, v) := g(v)\beta_\varepsilon(x),$$

$\beta_\varepsilon$  being the Jacobian of the map  $\Psi_\varepsilon$ . Note that, in view of (2.6),  $\beta_\varepsilon$  can be written as a polynomial in  $\varepsilon$ , with the invariants of  $DV$  as coefficients:

$$(2.12) \quad \beta_\varepsilon := |\det D\Psi_\varepsilon| = 1 + a_1(DV)\varepsilon + a_2(DV)\varepsilon^2 + \dots + a_n(DV)\varepsilon^n.$$

In a similar way, the dual variational problems  $J^*(\Omega_\varepsilon)$  can be rewritten as

$$(2.13) \quad J^*(\Omega_\varepsilon) = \inf_{\sigma \in X(\Omega; \mathbb{R}^n)} \int_{\Omega} [f_\varepsilon^*(\sigma) + g_\varepsilon^*(\operatorname{div} \sigma)] \, dx,$$

where  $f_\varepsilon^*$  and  $g_\varepsilon^*$  are the Fenchel conjugates of  $f_\varepsilon$  and  $g_\varepsilon$  with respect to the second variable, which by direct computation satisfy

$$(2.14) \quad f_\varepsilon^*(x, z) = f^*(\beta_\varepsilon^{-1}(x)D\Psi_\varepsilon(x)z)\beta_\varepsilon(x), \quad g_\varepsilon^*(x, \xi) = g^*(\beta_\varepsilon^{-1}(x) \operatorname{div} \xi)\beta_\varepsilon(x).$$

In the subsequent asymptotic analysis as  $\varepsilon \rightarrow 0$ , we shall exploit the following developments holding for small  $\varepsilon$ , where  $\Psi_\varepsilon$  and  $\beta_\varepsilon$  are as defined, respectively, by (2.6) and (2.12):

$$(2.15) \quad D\Psi_\varepsilon^{-T} = I - \varepsilon DV^T + \varepsilon^2(DV^T)^2 + \varepsilon^3 M_\varepsilon, \quad \text{with } \sup_\varepsilon \|M_\varepsilon\| \leq C,$$

$$(2.16) \quad \beta_\varepsilon = 1 + \varepsilon \operatorname{div} V + \varepsilon^2 a_2(DV) + \varepsilon^3 m_\varepsilon, \quad \text{with } \sup_\varepsilon \|m_\varepsilon\| \leq C,$$

$$(2.17) \quad \beta_\varepsilon^{-1} = 1 - \varepsilon \operatorname{div} V + \varepsilon^2((\operatorname{div} V)^2 - a_2(DV)) + \varepsilon^3 \widetilde{m}_\varepsilon(V), \quad \text{with } \sup_\varepsilon \|\widetilde{m}_\varepsilon\| \leq C.$$

**3. Main results.** All the results in this section concern the shape functional  $J$  defined in (1.1) and are stated under the standing assumptions given in section 2. Our goal is to provide an existence and representation result for the second order shape derivative of  $J$ , defined as follows.

DEFINITION 3.1. *Given  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$ ,  $J$  is said to be second order differentiable at  $\Omega$  in the direction  $V$  if the following limit exists:*

$$(3.1) \quad J''(\Omega, V) := \lim_{\varepsilon \rightarrow 0} 2 \frac{J(\Omega_\varepsilon) - J(\Omega) - \varepsilon J'(\Omega, V)}{\varepsilon^2},$$

where  $J'$  is the first order shape derivative of  $J$  at  $\Omega$  in direction  $V$  (see (2.7) and (2.8) for its definition and representation formula).

To prepare our main result, some preliminaries are in order. The next two propositions will be necessary in order to prove the main theorem, but also seem to have an autonomous interest: as mentioned in the introduction, the former concerns the regularity of the unique solution  $\bar{u}$  to  $J(\Omega)$ ; the latter states a new necessary condition for optimality.

PROPOSITION 3.2 (regularity of the solution). *Under the standing assumptions,  $\bar{u}$  belongs to  $W_{\text{loc}}^{2,2}(\Omega)$ .*

Remark 3.3. We point out that the stronger condition  $\bar{u} \in W^{2,2}(\Omega)$  is satisfied, for instance, if  $\Omega$  is of class  $C^{1,1}$  (see [46, Theorem 3.1]). More generally, for  $W^{2,2}$ -type regularity results for solutions to quasilinear elliptic equations, we refer the reader, for instance, to [16, 44, 43] and references therein.

PROPOSITION 3.4 (necessary optimality condition). *Under the standing assumptions, the vector field defined by*

$$(3.2) \quad B(\bar{u}, V) := \nabla^2 f(\nabla \bar{u})(\nabla^2 \bar{u})V - (DV - \operatorname{div} V I)\bar{\sigma}$$

satisfies

$$(3.3) \quad \operatorname{div} [B(\bar{u}, V)] = g''(\bar{u})\langle V, \nabla \bar{u} \rangle + g'(\bar{u}) \operatorname{div} V \quad \text{in } \mathcal{D}'(\Omega).$$

The vector field  $B(\bar{u}, V)$  defined in (3.2) will appear in the representation formula for the second order shape derivative. Besides  $B(\bar{u}, V)$ , such formulas will involve another vector field depending on  $\bar{u}$  and  $V$  and a quadratic form on the space  $H(\Omega)$ , which are defined, respectively, as follows.

We let  $\mathcal{C}(\bar{u}, V)$  be the following vector field, which depends quadratically on  $V$ :

$$(3.4) \quad \begin{aligned} \mathcal{C}(\bar{u}, V) := & -\langle V, \nabla \bar{u} \rangle (\nabla^2 f(\nabla \bar{u})) (\nabla^2 \bar{u}) V - \langle V, \nabla \bar{u} \rangle (\operatorname{div} VI - DV) \nabla f(\nabla \bar{u}) \\ & + \langle DV \nabla f(\nabla \bar{u}), \nabla \bar{u} \rangle V - \langle DV V, \nabla \bar{u} \rangle \nabla f(\nabla \bar{u}) \\ & - (f(\nabla \bar{u}) + g(\bar{u})) (\operatorname{div} VI - DV) V. \end{aligned}$$

We emphasize that the distributional Hessian of  $\bar{u}$  appearing in (3.2) and (3.4) belongs to  $L^2_{\text{loc}}(\Omega)$  thanks to Proposition 3.2.

We let  $\mathcal{Q}(\bar{u}, \cdot)$  be the quadratic form given by

$$(3.5) \quad \mathcal{Q}(\bar{u}, w) := \int_{\Omega} 2 [Q_f(x, \nabla w) + Q_g(x, w)] dx \quad \forall w \in H(\Omega),$$

where  $Q_f(x, \cdot)$  and  $Q_g(x, \cdot)$  denote the quadratic integrands

$$Q_f(x, z) := \frac{1}{2} \langle \nabla^2 f(\nabla \bar{u}(x)) z, z \rangle \quad \forall z \in \mathbb{R}^n, \quad Q_g(x, v) := \frac{1}{2} g''(\bar{u}(x)) v^2 \quad \forall v \in \mathbb{R}.$$

For brevity, in what follows we shall omit denoting the dependence of  $Q_f$  and of  $Q_g$  on  $x$  and simply write  $Q_f(\cdot)$  and  $Q_g(\cdot)$  in place of  $Q_f(x, \cdot)$  and  $Q_g(x, \cdot)$ .

We are now in a position to state our main result.

**THEOREM 3.5** (existence and representation of the second order shape derivative). *Under the standing assumptions, the following hold:*

- (i) *the second order shape derivative  $J''(\Omega, V)$  defined in (3.1) exists for all  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$  and it is a quadratic form in  $V$ ;*
- (ii) *if  $\bar{u}$  is  $W^{2,2}(\Omega)$ , the vector fields  $\mathcal{C}(\bar{u}, V)$  and  $B(\bar{u}, V)$ , defined, respectively, in (3.4) and (3.2), admit a normal trace in  $H^{-1/2}(\partial\Omega)$ , and  $J''(\Omega, V)$  is given by*

$$(3.6) \quad J''(\Omega, V) = \int_{\partial\Omega} (\mathcal{C}(\bar{u}, V) \cdot n) d\mathcal{H}^{n-1} + q(\bar{u}, V),$$

where  $q(\bar{u}, V)$  is the following nonlocal term:

$$(3.7) \quad q(\bar{u}, V) := - \inf_{w \in H(\Omega)} \left\{ \mathcal{Q}(\bar{u}, w - \langle V, \nabla \bar{u} \rangle) + 2 \int_{\partial\Omega} (w - \langle V, \nabla \bar{u} \rangle) B(\bar{u}, V) \cdot n d\mathcal{H}^{n-1} \right\}.$$

*Remark 3.6.* Theorem 3.5 is still valid when  $g$  is linear and  $f$  is either as in the standing assumptions or the  $p$ -power function, with  $p > 2$ . In the latter case, we need to impose some additional technical assumption. For the benefit of the reader, we postpone to section 7 the discussion of these variants, in which the proof of Theorem 3.5 deserves ad hoc techniques.

*Remark 3.7.* Let us show how the representation formula for  $J''(\Omega, V)$  given by (3.6) can be rewritten if one prefers to separate the contributions coming from the Dirichlet and Neumann portions of the boundary. First observe that, since  $\bar{u}$  is assumed to be  $W^{2,2}$  up to the boundary, the product  $\langle V, \nabla \bar{u} \rangle$  belongs to  $H^1(\Omega)$ ; thus,

by considering the translation  $v := w - \langle V, \nabla \bar{u} \rangle$  in (3.7), the nonlocal term  $q(\bar{u}, V)$  can be recast as

$$(3.8) \quad q(\bar{u}, V) = - \inf_{\substack{v \in H^1(\Omega) \\ v = -V_n \partial_n \bar{u} \text{ on } \Gamma_D}} \left\{ \mathcal{Q}(\bar{u}, v) + 2 \int_{\Gamma_N} v B(\bar{u}, V) \cdot n \, d\mathcal{H}^{n-1} \right\} + 2 \int_{\Gamma_D} \langle V, \nabla \bar{u} \rangle B(\bar{u}, V) \cdot n \, d\mathcal{H}^{n-1}.$$

By combining (3.6) and (3.8), we obtain

$$(3.9) \quad J''(\Omega, V) = \int_{\Gamma_D} (\mathcal{C}(\bar{u}, V) + 2 \langle V, \nabla \bar{u} \rangle B(\bar{u}, V)) \cdot n \, d\mathcal{H}^{n-1} + \int_{\Gamma_N} (\mathcal{C}(\bar{u}, V) \cdot n) \, d\mathcal{H}^{n-1} - \inf_{\substack{v \in H^1(\Omega) \\ v = -V_n \partial_n \bar{u} \text{ on } \Gamma_D}} \left\{ \mathcal{Q}(\bar{u}, v) + 2 \int_{\Gamma_N} v B(\bar{u}, V) \cdot n \, d\mathcal{H}^{n-1} \right\};$$

in Remark 3.8 below we will see that, under suitable regularity assumptions, the infimum problem appearing in (3.9) is a quadratic form in  $V_n$ .

Next, in order to further simplify (3.9), we observe that the boundary integrals appearing therein depend only on the normal traces of  $\mathcal{C}(\bar{u}, V)$  and  $B(\bar{u}, V)$  on  $\partial\Omega$ . Therefore, such fields can be replaced by any simpler vector field with the same normal trace, which can be chosen in different ways on the Dirichlet and Neumann portions of the boundary. On  $\Gamma_D$ , since  $\nabla \bar{u}$  is parallel to  $n$  on  $\partial\Omega$ ,  $\mathcal{C}(\bar{u}, V) + 2 \langle V, \nabla \bar{u} \rangle B(\bar{u}, V)$  has the same normal trace as

$$(3.10) \quad \mathcal{C}_D(\bar{u}, V) := \langle V, \nabla \bar{u} \rangle (\nabla^2 f(\nabla \bar{u})) (\nabla^2 \bar{u}) V + (\langle \nabla f(\nabla \bar{u}), \nabla \bar{u} \rangle - f(\nabla \bar{u})) (\operatorname{div} VI - DV) V,$$

while on  $\Gamma_N$ , since  $\bar{\sigma} \cdot n = 0$  on such a portion of the boundary,  $\mathcal{C}(\bar{u}, V)$  has the same normal trace as

$$\mathcal{C}_N(\bar{u}, V) := -\langle V, \nabla \bar{u} \rangle (\nabla^2 f(\nabla \bar{u})) (\nabla^2 \bar{u}) V + \langle V, \nabla \bar{u} \rangle DV \nabla f(\nabla \bar{u}) + \langle DV \nabla f(\nabla \bar{u}), \nabla \bar{u} \rangle V - (f(\nabla \bar{u}) + g(\bar{u})) (\operatorname{div} VI - DV) V.$$

We end up with the following reformulation of (3.6):

$$(3.11) \quad J''(\Omega, V) = \int_{\Gamma_D} (\mathcal{C}_D(\bar{u}, V) \cdot n) \, d\mathcal{H}^{n-1} + \int_{\Gamma_N} (\mathcal{C}_N(\bar{u}, V) \cdot n) \, d\mathcal{H}^{n-1} - \inf_{\substack{v \in H^1(\Omega) \\ v = -V_n \partial_n \bar{u} \text{ on } \Gamma_D}} \left\{ \mathcal{Q}(\bar{u}, v) + 2 \int_{\Gamma_N} v B(\bar{u}, V) \cdot n \, d\mathcal{H}^{n-1} \right\};$$

note that we readily obtain the expression of the second order shape derivative in the pure Dirichlet case, i.e., when  $\Gamma_D = \partial\Omega$ , by dropping the integrals over  $\Gamma_N$  in the above equality.

*Remark 3.8.* It is interesting to compare our representation formula (3.6) with the structure result proved in [39], which allows us to illuminate the role played by the tangential and the normal components of the deformation field  $V$  on  $\partial\Omega$ . Notice that, in general, these components are not decoupled, i.e.,  $J''(\Omega, V) \neq J''(\Omega, V_\Gamma) + J''(\Omega, V_n n)$ .



In fact, according to the structure theorem given in [39, Corollary 2.4, Remark 2.10] (see also [27, Theorem 5.9.2]), under suitable regularity conditions  $J''(\Omega, V)$  can be decomposed as  $J''(\Omega, V) = l_1(z) + l_2(V_n)$ , where  $l_2$  is a quadratic form on  $C^1(\partial\Omega)$  and  $l_1$  is the linear form on  $C^0(\partial\Omega)$  associated with the first order shape derivative, evaluated in

$$(3.12) \quad z := \langle V_\Gamma, Dn V_\Gamma \rangle - 2\langle V_\Gamma, \nabla_\Gamma V_n \rangle;$$

in this way the scalar  $z$  encodes the coupling between the tangential and normal components of  $V$ .

In the case of our functional  $J$ , by Theorem 3.7 in [8], the linear form  $l_1$  is given by

$$(3.13) \quad l_1(\varphi) = \int_{\Gamma_D} f^*(\bar{\sigma}) \varphi \, d\mathcal{H}^{n-1} - \int_{\Gamma_N} (f(\nabla \bar{u}) + g(\bar{u})) \varphi \, d\mathcal{H}^{n-1},$$

and we claim that, as soon as  $\partial\Omega$  is  $C^2$ , by Theorem 3.5 the quadratic form  $l_2$  is given by

$$(3.14) \quad \begin{aligned} l_2(\varphi) := & \int_{\Gamma_D} \varphi^2 [\partial_n \bar{u} \langle D\bar{\sigma}n, n \rangle + f^*(\bar{\sigma})H_{\partial\Omega}] \, d\mathcal{H}^{n-1} \\ & + \int_{\Gamma_N} \left[ \langle \bar{\sigma}, \nabla_\Gamma(\varphi^2 \partial_n \bar{u}) \rangle - \varphi^2 [\langle (\nabla^2 \bar{u}) \bar{\sigma}, n \rangle + (f(\nabla \bar{u}) + g(\bar{u}))H_{\partial\Omega} + \partial_n \bar{u} \langle D\bar{\sigma}n, n \rangle] \right] \, d\mathcal{H}^{n-1} \\ & - \inf_{\substack{v \in H^1(\Omega) \\ v = -\varphi \partial_n \bar{u} \text{ on } \Gamma_D}} \left\{ \mathcal{Q}(\bar{u}, v) + 2 \int_{\Gamma_N} v [\varphi \langle D\bar{\sigma}n, n \rangle - \langle \bar{\sigma}, \nabla_\Gamma \varphi \rangle] \, d\mathcal{H}^{n-1} \right\}. \end{aligned}$$

This claim can be easily checked when  $V_\Gamma = 0$  and  $\partial\Omega = \Gamma_D$ . Indeed in this case we have  $z = 0$  and hence  $l_1(z) = 0$ ; moreover, starting from equality (3.6), if we replace  $\mathcal{C}(\bar{u}, V)$  by the simpler field  $\mathcal{C}_D(\bar{u}, V)$  given in (3.10) and use the identity  $\langle (\text{div } VI - DV)n, n \rangle = V_n H_{\partial\Omega}$  (holding thanks to the  $C^2$  regularity assumption on  $\partial\Omega$ ), we are led to the equality  $J''(\Omega, V) = l_2(V_n)$ , with  $l_2$  defined according to (3.14). The proof of the claim in the general case requires some tedious but straightforward computations, which we omit for the sake of conciseness.

*Remark 3.9.* We point out that the nonlocal part of the second variation, namely, the term  $q(\bar{u}, V)$  defined in (3.7), may also be reformulated in dual form. In analogy with (3.5), let us introduce the quadratic form  $\mathcal{Q}^*(\bar{\sigma}, \cdot)$  on the space  $X(\Omega; \mathbb{R}^n)$  defined in (2.4): we set

$$\mathcal{Q}^*(\bar{\sigma}, \eta) := \int_{\Omega} 2[Q_{f^*}(x, \eta) + Q_{g^*}(x, \text{div } \eta)] \, dx,$$

with  $Q_{f^*}(x, z) := \frac{1}{2} \langle \nabla^2 f^*(\bar{\sigma}(x))z, z \rangle$  and  $Q_{g^*}(x, v) := \frac{1}{2} (g^*)''(\text{div } \bar{\sigma}(x))v^2$ . (In what follows, for brevity we adopt the notation  $Q_{f^*}(\cdot)$  and  $Q_{g^*}(\cdot)$  in place of  $Q_{f^*}(x, \cdot)$  and  $Q_{g^*}(x, \cdot)$ .)

A standard duality argument (see Lemma 8.5) yields

$$q(\bar{u}, V) = \inf_{\eta \in X(\Omega; \mathbb{R}^n)} \left\{ \mathcal{Q}^*(\bar{\sigma}, \eta - B(\bar{u}, V)) + \int_{\Gamma_D} 2 \partial_n \bar{u} V_n (\eta \cdot n) \, d\mathcal{H}^{n-1} \right\},$$

or equivalently, via a translation,

$$q(\bar{u}, V) = \inf_{\eta \in X(\Omega; \mathbb{R}^n) - B(\bar{u}, V)} \left\{ \mathcal{Q}^*(\bar{\sigma}, \eta) + \int_{\Gamma_D} 2 \partial_n \bar{u} V_n (\eta \cdot n) d\mathcal{H}^{n-1} \right\} + \int_{\Gamma_D} 2 \partial_n \bar{u} V_n (B(\bar{u}, V) \cdot n) d\mathcal{H}^{n-1}.$$

*Example 3.10.* An example of a shape functional which is covered by Theorem 3.5 is the torsional rigidity under mixed Dirichlet–Neumann boundary conditions (see also Remark 3.6 and section 7.1):

$$J(\Omega) = - \inf \left\{ \int_{\Omega} \left( \frac{|\nabla u|^2}{2} - \lambda u \right) dx : u \in H(\Omega) \right\}.$$

In this case, assuming  $\partial\Omega$  of class  $C^2$  and taking deformations normal to the boundary, the second order shape derivative given in (3.11) reads

$$(3.15) \quad \begin{aligned} J''(\Omega, V) = & -\frac{1}{2} \int_{\Gamma_D} V_n^2 (2\lambda \partial_n \bar{u} + |\partial_n \bar{u}|^2 H_{\partial\Omega}) d\mathcal{H}^{n-1} \\ & -\frac{1}{2} \int_{\Gamma_N} V_n^2 [(-2\lambda \bar{u} + |\nabla \bar{u}|^2) H_{\partial\Omega} + 2\langle \nabla^2 \bar{u} \nabla \bar{u}, n \rangle] d\mathcal{H}^{n-1} \\ & - \inf_{\substack{v \in H^1(\Omega) \\ v = -V_n \frac{\partial_n \bar{u}}{\partial_n \bar{u}} \text{ on } \Gamma_D}} \left\{ \int_{\Omega} |\nabla v|^2 dx - 2 \int_{\Gamma_N} v \langle \nabla \bar{u}, \nabla_{\Gamma} V_n \rangle d\mathcal{H}^{n-1} \right\}. \end{aligned}$$

Here, as already pointed out in Remark 3.8, the second order shape derivative is given by  $l_2(V_n)$ , where  $l_2$  is the quadratic form defined in (3.14). The equality between  $l_2(V_n)$  and the right-hand side (r.h.s.) of (3.15) readily follows by using the identity  $\Delta \bar{u} = \partial_{nn}^2 \bar{u} + \partial_n \bar{u} H_{\partial\Omega}$  on  $\Gamma_D$ , the fact that  $\partial_n \bar{u} = 0$  on  $\Gamma_N$ , and by taking into account that  $Q_g \equiv 0$  and  $Q_f(z) = \frac{|z|^2}{2}$ .

We emphasize that in the pure Dirichlet case, i.e., when  $\Gamma_N = \emptyset$ , our formula (3.15) allows us to recover the known expression of the second order shape derivative of the torsional rigidity (see, for instance, [27, section 5.9.6]). Finally, let us point out that when the deformation field is not normal to the boundary, the expression of  $J''(\Omega, V)$  is slightly more complicated than (3.15). Precisely, it is given by  $l_1(z) + l_2(V_n)$ , with  $l_1$  and  $z$  defined, respectively, in (3.13) and (3.12); in other words, we have to add to the r.h.s. of formula (3.15) the following terms:

$$\int_{\Gamma_D} \frac{|\partial_n \bar{u}|^2}{2} (\langle V_{\Gamma}, Dn V_{\Gamma} \rangle - 2\langle V_{\Gamma}, \nabla_{\Gamma} V_n \rangle) d\mathcal{H}^{n-1} - \int_{\Gamma_N} \left( \frac{|\nabla \bar{u}|^2}{2} - \lambda \bar{u} \right) (\langle V_{\Gamma}, Dn V_{\Gamma} \rangle - 2\langle V_{\Gamma}, \nabla_{\Gamma} V_n \rangle) d\mathcal{H}^{n-1}.$$

*Example 3.11.* For a variant of the previous example, we can consider the  $p$ -torsion problem under Dirichlet boundary conditions (see also Remark 3.6):

$$(3.16) \quad J_p(\Omega) = - \inf \left\{ \int_{\Omega} \left( \frac{|\nabla u|^p}{p} - \lambda u \right) dx : u \in W_0^{1,p}(\Omega) \right\},$$

where  $p > 2$  and  $\lambda$  is a positive parameter. Note that in this case the integrands  $f$  and  $g$  do not satisfy the standing assumptions, in particular (2.1), so that we cannot

apply directly Theorem 3.5. In fact a major difficulty appears with the degeneracy at the origin of the Hessian of  $f$ . Nevertheless, by exploiting a suitable approximation argument, we are able to show that Theorem 3.5 is still valid, provided a suitable equality between weighted Sobolev spaces holds (cf. (7.8)). The resulting formula reads as follows. Let  $\partial\Omega$  be of class  $C^2$  and let the deformation field  $V$  be normal to the boundary. Observe that  $\bar{\sigma}$  is parallel to  $\nabla\bar{u}$  and satisfies  $\operatorname{div}\bar{\sigma} = -\lambda$ ; moreover, the equalities  $\langle (\operatorname{div}\bar{\sigma}I - D\bar{\sigma})n, n \rangle = \bar{\sigma}_n H_{\partial\Omega}$  and  $\Delta u = \partial_{nn}^2 \bar{u} + \partial_n \bar{u} H_{\partial\Omega}$  hold on  $\partial\Omega$ . Taking these facts into account, starting from (3.11) we obtain

$$(3.17) \quad J_p''(\Omega, V) = -\frac{1}{p} \int_{\partial\Omega} V_n^2 (p\lambda\partial_n \bar{u} + |\partial_n \bar{u}|^p H_{\partial\Omega}) d\mathcal{H}^{n-1} - \inf_{\substack{v \in H^1(\Omega) \\ v = -V_n \partial_n \bar{u} \text{ on } \partial\Omega}} \int_{\Omega} \langle P(\bar{u}) \nabla v, \nabla v \rangle dx,$$

with

$$P(\bar{u}) := |\nabla\bar{u}|^{p-2} \left( I + (p-2) \frac{\nabla\bar{u}}{|\nabla\bar{u}|} \otimes \frac{\nabla\bar{u}}{|\nabla\bar{u}|} \right).$$

The complete presentation of this variant is postponed to section 7.2; see Theorem 7.1.

**4. Existence of the second order shape derivative.** This section is devoted to the proof of Theorem 3.5 (i). We introduce for brevity the differential quotients

$$(4.1) \quad r_\varepsilon(V) := 2 \frac{J(\Omega_\varepsilon) - J(\Omega) - \varepsilon J'(\Omega, V)}{\varepsilon^2}.$$

By exploiting the formulation (2.10) of  $J(\Omega_\varepsilon)$  and taking therein as a test function  $\bar{u} + \varepsilon w$ , we infer

$$(4.2) \quad r_\varepsilon(V) \geq \frac{2}{\varepsilon^2} \left( - \int_{\Omega} [f_\varepsilon(\nabla\bar{u} + \varepsilon\nabla w) + g_\varepsilon(\bar{u} + \varepsilon w)] dx - J(\Omega, V) - \varepsilon J'(\Omega, V) \right).$$

We are thus led to introduce the sequence of functionals defined for  $w \in H(\Omega)$  and  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$  by

$$(4.3) \quad E_\varepsilon(w, V) := \frac{2}{\varepsilon^2} \left\{ \int_{\Omega} [f_\varepsilon(\nabla\bar{u} + \varepsilon\nabla w) + g_\varepsilon(\bar{u} + \varepsilon w)] dx + J(\Omega) + \varepsilon J'(\Omega, V) \right\}.$$

Moreover, still for  $w \in H(\Omega)$  and  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$ , let us define the functional  $E(w, V)$ , which will be seen to be the variational limit of  $E_\varepsilon(w, V)$ , and its “dual counterpart”  $E^*(\eta, V)$  (with  $\eta \in X(\Omega; \mathbb{R}^n)$  and  $V$  as above):

$$(4.4) \quad E(w, V) := 2 \int_{\Omega} [f(\nabla\bar{u}) + g(\bar{u})] a_2(DV) dx + 2 \left\{ \int_{\Omega} [Q_f(\nabla w - DV^T \nabla\bar{u}) + Q_g(w)] dx + \int_{\Omega} [-\langle (DV - \operatorname{div} V I) \nabla f(\nabla\bar{u}), \nabla w - DV^T \nabla\bar{u} \rangle dx + \operatorname{div} V g'(\bar{u}) w] dx \right\},$$

(4.5)

$$E^*(\eta, V) := 2 \int_{\Omega} [f^*(\bar{\sigma}) + g^*(\operatorname{div}\bar{\sigma}) - \langle \nabla f^*(\bar{\sigma}), \bar{\sigma} \rangle - \bar{u} \operatorname{div}\bar{\sigma}] a_2(DV) dx + 2 \left\{ \int_{\Omega} [Q_{f^*}((DV - \operatorname{div} V I)\bar{\sigma} + \eta) + Q_{g^*}(\operatorname{div}\eta - \operatorname{div} V \operatorname{div}\bar{\sigma}) + \langle \nabla f^*(\bar{\sigma}), DV \eta \rangle] dx \right\}.$$

Theorem 3.5 (i) holds in view of the following result.

PROPOSITION 4.1. *Under the standing assumptions, the second order shape derivative  $J''(\Omega, V)$  exists and is given by*

$$(4.6) \quad J''(\Omega, V) = \lim_{\varepsilon \rightarrow 0} \left( - \inf_{w \in H(\Omega)} E_\varepsilon(w, V) \right) = - \inf_{w \in H(\Omega)} E(w, V) = \inf_{\eta \in X(\Omega; \mathbb{R}^n)} E^*(\eta, V).$$

Moreover the map  $V \mapsto J''(\Omega, V)$  is a quadratic form in  $C^1(\mathbb{R}^n; \mathbb{R}^n)$ .

Proposition 4.1 will be obtained as a consequence of the two lemmas stated hereafter.

LEMMA 4.2 (upper and lower bounds). *Under the standing assumptions, the differential quotients defined in (4.1) satisfy*

$$(4.7) \quad \liminf_{\varepsilon \rightarrow 0} r_\varepsilon(V) \geq - \inf_{w \in H(\Omega)} E(w, V)$$

and

$$(4.8) \quad \limsup_{\varepsilon \rightarrow 0} r_\varepsilon(V) \leq \inf_{\eta \in X(\Omega; \mathbb{R}^n)} E^*(\eta, V).$$

LEMMA 4.3 ( $\Gamma$ -convergence). *Under the standing assumptions, for every  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$  the sequence  $\{E_\varepsilon(\cdot, V)\}$  is equicoercive and  $\Gamma$ -converges to  $E(\cdot, V)$ , with respect to the weak topology of  $H(\Omega)$ .*

Let us show how the proposition follows from these lemmas, and then turn back to their proofs.

*Proof of Proposition 4.1.* We begin by proving the last equality in (4.6). Let  $\Psi : L^2(\Omega; \mathbb{R}^n) \times L^q(\Omega) \rightarrow \mathbb{R}$  be the function

$$(4.9) \quad \Psi(z, v) := \int_{\Omega} [Q_f(z - a) + \langle z - a, b \rangle + Q_g(v) + v\alpha + \gamma] \, dx$$

with

$$a := DV^T \nabla \bar{u}, \quad b := -(DV - \text{div } V I) \bar{\sigma}, \quad \alpha := \text{div } V g'(\bar{u}), \quad \gamma := [f(\nabla \bar{u}) + g(\bar{u})] a_2(DV).$$

For every  $w \in H(\Omega)$ , it holds that  $E(w, V) = 2 \Psi(\nabla w, w)$ , in particular

$$(4.10) \quad - \inf_{w \in H(\Omega)} E(w, V) = -2 \inf_{w \in H(\Omega)} \{ \Psi(\nabla w, w) \}.$$

By applying Lemma 8.5 with  $Y = H(\Omega)$ ,  $Z = L^2(\Omega; \mathbb{R}^n) \times L^q(\Omega)$ ,  $A : Y \rightarrow Z$  the operator  $Av := (\nabla v, v)$ ,  $\Phi : Y \rightarrow \mathbb{R}$  the zero function, and  $\Psi$  defined as in (4.9), we can rewrite (4.10) as

$$(4.11) \quad -2 \inf_{w \in Y} \{ \Psi(Aw) + \Phi(w) \} = 2 \inf_{(\eta, \tau) \in Z^*} \{ \Psi^*(\eta, \tau) + \Phi^*(-A^*(\eta, \tau)) \}.$$

Let us compute the Fenchel conjugates appearing on the r.h.s. of (4.11). By exploiting Lemma 8.2, it is easy to see that

$$\Psi^*(\eta, \tau) = \int_{\Omega} [(Q_f)^*(\eta - b) + \langle \eta, a \rangle + (Q_g)^*(\tau - \alpha) + \gamma] \, dx.$$

Since  $\Phi \equiv 0$ , its Fenchel conjugate  $\Phi^*$  is 0 at 0 and  $+\infty$  otherwise. As an element of  $Y^*$ ,  $A^*(\eta, \tau)$  is characterized by its action on the elements of  $Y$ : since

$$\langle A^*(\eta, \tau), v \rangle_{Y^*, Y} = \langle (\eta, \tau), Av \rangle_{Z^*, Z} = \int_{\Omega} (\langle \eta, \nabla v \rangle + \tau v) \, dx,$$

we infer that  $\Phi^*(A^*(\eta, \tau)) = 0$  if and only if  $\tau = \operatorname{div} \eta$  (with the additional condition  $\eta \cdot n = 0$  on  $\Gamma_N$ ); note that, as a consequence, such vector fields  $\eta$  belong to  $X(\Omega; \mathbb{R}^n)$ .

Therefore we may rewrite the r.h.s. of (4.11) as

$$(4.12) \quad 2 \inf_{\eta \in X(\Omega; \mathbb{R}^n)} \left\{ \int_{\Omega} [(Q_f)^*(\eta - b) + \langle \eta, a \rangle + (Q_g)^*(\operatorname{div} \eta - \alpha) + \gamma] dx \right\}.$$

Since by Lemmas 8.3 and 8.4 we have  $(Q_f)^* = Q_{f^*}$  and  $(Q_g)^* = Q_{g^*}$ , and by the optimality conditions (2.5) there holds

$$\gamma = \int_{\Omega} [f^*(\bar{\sigma}) + g^*(\operatorname{div} \bar{\sigma}) - \langle \nabla f^*(\bar{\sigma}), \bar{\sigma} \rangle - \bar{u} \operatorname{div} \bar{\sigma}] a_2(DV) dx,$$

we conclude that the expression in (4.12) agrees with  $\inf_{\eta \in X(\Omega; \mathbb{R}^n)} E^*(\eta, V)$ , which achieves the proof of the last equality in (4.6). Combined with Lemma 4.2, such an equality implies the existence of the second order shape derivative and the fact that it agrees with any of the two infimum problems on the r.h.s. of (4.7) and (4.8). The second equality in (4.6) is a direct consequence of Lemma 4.3.

Finally, the fact that the map  $V \mapsto J''(\Omega, V)$  is a quadratic form is readily checked: one may start from the equality  $J''(\Omega, V) = -\inf_w E(w, V)$ , and look at the expression (4.4) of  $E(w, V)$ , by recalling in particular that  $Q_f$  is a quadratic form.  $\square$

*Proof of Lemma 4.2.* We first prove the lower bound in (4.7). We start from the inequality (4.2), where we choose  $w$  as an element of  $C^\infty(\bar{\Omega}) \cap H(\Omega)$ . Recalling the definitions (2.11) of  $f_\varepsilon$  and  $g_\varepsilon$ , the definition (1.1) of  $J(\Omega)$ , and the expression (2.8) of  $J'(\Omega; V)$ , we can rewrite the inequality (4.2) separating the terms of different orders in  $\varepsilon$ . Recalling that  $M_\varepsilon$  and  $m_\varepsilon$  are defined, respectively, according to (2.15) and (2.16), and setting for brevity

$$h_1 := \nabla w - DV^T \nabla \bar{u}, \quad h_2 := (DV^T)^2 \nabla \bar{u} - DV^T \nabla w, \quad h_\varepsilon := (DV^T)^2 \nabla w + M_\varepsilon (\nabla \bar{u} + \varepsilon \nabla w),$$

we get

$$(4.13) \quad r_\varepsilon(V) \geq \left( I_0(\varepsilon) + I_1(\varepsilon) + I_2(\varepsilon) \right),$$

where

$$\begin{aligned} I_0(\varepsilon) &:= -2 \int_{\Omega} [f(\nabla \bar{u} + \varepsilon h_1 + \varepsilon^2 h_2 + \varepsilon^3 h_\varepsilon) + g(\bar{u} + \varepsilon w)] (a_2(DV) + \varepsilon m_\varepsilon) dx, \\ I_1(\varepsilon) &:= -\frac{2}{\varepsilon} \int_{\Omega} [f(\nabla \bar{u} + \varepsilon h_1 + \varepsilon^2 h_2 + \varepsilon^3 h_\varepsilon) + g(\bar{u} + \varepsilon w) - f(\nabla \bar{u}) - g(\bar{u})] \operatorname{div} V dx, \\ I_2(\varepsilon) &:= -\frac{2}{\varepsilon^2} \int_{\Omega} [f(\nabla \bar{u} + \varepsilon h_1 + \varepsilon^2 h_2 + \varepsilon^3 h_\varepsilon) + g(\bar{u} + \varepsilon w) \\ &\quad - f(\nabla \bar{u}) - g(\bar{u}) + \varepsilon \langle \nabla f(\nabla \bar{u}), DV^T \nabla \bar{u} \rangle] dx. \end{aligned}$$

Let us study separately the asymptotic behavior of  $I_i(\varepsilon)$  as  $\varepsilon \rightarrow 0$ . By exploiting the growth assumptions on the integrands and the uniform  $L^\infty$  boundedness of  $m_\varepsilon$  and  $h_\varepsilon$ , we get

$$(4.14) \quad \lim_{\varepsilon \rightarrow 0} I_0(\varepsilon) = -2 \int_{\Omega} [f(\nabla \bar{u}) + g(\bar{u})] a_2(DV) dx.$$

By applying Lemma 8.1 (i) to the integral functionals  $I_f$  and  $I_g$  defined according to (8.1) (note that this can be done after possibly modifying  $g$  outside an interval, since  $\bar{u} + \varepsilon w$  remains uniformly bounded in  $L^\infty$ ), we get

$$(4.15) \quad \lim_{\varepsilon \rightarrow 0} I_1(\varepsilon) = -2 \int_{\Omega} [\langle \nabla f(\nabla \bar{u}), \nabla w - DV^T \nabla \bar{u} \rangle + g'(\bar{u})w] \operatorname{div} V \, dx .$$

Let us now consider  $I_2(\varepsilon)$ . We recall that, in view of the optimality conditions in (2.5), there holds  $\bar{\sigma} = \nabla f(\nabla \bar{u})$  and  $\operatorname{div} \bar{\sigma} = g'(\bar{u})$ , so that

$$(4.16) \quad \int_{\Omega} [\langle \nabla f(\nabla \bar{u}), \nabla w \rangle + g'(\bar{u})w] \, dx = \int_{\Omega} (\langle \bar{\sigma}, \nabla w \rangle + w \operatorname{div} \bar{\sigma}) \, dx = \int_{\partial \Omega} w \bar{\sigma} \cdot n \, d\mathcal{H}^{n-1} = 0 ,$$

where the last equality holds since  $w = 0$  on  $\Gamma_D$  and  $\bar{\sigma} \cdot n = 0$  on  $\Gamma_N$ . Thus,  $I_2(\varepsilon)$  remains unchanged if we add the zero term (4.16) (multiplied by  $2/\varepsilon$ ):

$$I_2(\varepsilon) = -\frac{2}{\varepsilon^2} \int_{\Omega} [f(\nabla \bar{u} + \varepsilon h_1 + \varepsilon^2 h_2 + \varepsilon^3 h_\varepsilon) - f(\nabla \bar{u}) - \varepsilon \langle \nabla f(\nabla \bar{u}), h_1 \rangle] \, dx \\ - \frac{2}{\varepsilon^2} \int_{\Omega} [g(\bar{u} + \varepsilon w) - g(\bar{u}) - \varepsilon g'(\bar{u})w] \, dx .$$

Hence, by applying Lemma 8.1, we obtain

$$(4.17) \quad \lim_{\varepsilon \rightarrow 0} I_2(\varepsilon) = -2 \int_{\Omega} [Q_f(h_1) + \langle \nabla f(\nabla \bar{u}), h_2 \rangle + Q_g(w)] \, dx .$$

By combining (4.13), (4.14), (4.15), and (4.17), by the arbitrariness of  $w \in C^\infty(\bar{\Omega}) \cap H(\Omega)$  we infer

$$(4.18) \quad \liminf_{\varepsilon \rightarrow 0} r_\varepsilon(V) \geq - \inf_{w \in C^\infty(\bar{\Omega}) \cap H(\Omega)} E(w, V) .$$

In order to conclude the proof of the inequality (4.7), it is enough to observe that the infimum on the r.h.s. of (4.18) coincides with the infimum on the r.h.s. of (4.7). Indeed, the integral functional  $E(\cdot, V)$  above is continuous on  $H(\Omega)$  (by the growth conditions (2.2) and the Sobolev embedding of  $W^{1,p}(\Omega)$  into  $L^p(\Omega)$ ), whereas  $C^\infty(\bar{\Omega}) \cap H(\Omega)$  is dense in  $H(\Omega)$ .

Let us now prove the upper bound in (4.8). Let  $\eta$  be an arbitrary element of the space  $C^\infty(\bar{\Omega}; \mathbb{R}^n) \cap X(\Omega; \mathbb{R}^n)$ . In view of (1.2), the differential quotients  $r_\varepsilon(V)$  introduced in (4.1) can be rewritten as

$$r_\varepsilon(V) = \frac{2}{\varepsilon^2} [J^*(\Omega_\varepsilon) - J^*(\Omega) - \varepsilon J'(\Omega, V)] .$$

Then, by exploiting the expression of  $J^*(\Omega_\varepsilon)$  in (2.13), we infer that

$$(4.19) \quad r_\varepsilon(V) \leq \frac{2}{\varepsilon^2} \left( \int_{\Omega} [f_\varepsilon^*(\bar{\sigma} + \varepsilon \eta) + g_\varepsilon^*(\operatorname{div} \bar{\sigma} + \varepsilon \operatorname{div} \eta)] \, dx - J^*(\Omega) - \varepsilon J'(\Omega, V) \right) .$$

Recalling the definitions (2.14) of  $f_\varepsilon^*$  and  $g_\varepsilon^*$ , the definition of  $J^*(\Omega)$  in (1.2), and the second expression for  $J'(\Omega; V)$  in (2.8), we can rewrite the inequality (4.19)

separating the terms of different orders in  $\varepsilon$ . Recalling the definition (2.17) of  $\widetilde{m}_\varepsilon$ , and setting for brevity

$$\begin{aligned} z_1 &:= (DV - \operatorname{div} VI)\bar{\sigma} + \eta, \\ z_2 &:= (DV - \operatorname{div} VI)\eta + ((\operatorname{div} V)^2 - \operatorname{div} V DV - a_2(DV))\bar{\sigma}, \\ z_\varepsilon &:= \widetilde{m}_\varepsilon(\bar{\sigma} + \varepsilon\eta) + ((\operatorname{div} V)^2 - a_2(DV))(DV\bar{\sigma} + \eta) - \operatorname{div} V DV\eta, \\ \tau_1 &:= \operatorname{div} \eta - \operatorname{div} V \operatorname{div} \bar{\sigma}, \\ \tau_2 &:= ((\operatorname{div} V)^2 - a_2(DV)) \operatorname{div} \bar{\sigma} - \operatorname{div} V \operatorname{div} \eta, \\ \tau_\varepsilon &:= ((\operatorname{div} V)^2 - a_2(DV)) \operatorname{div} \eta + \widetilde{m}_\varepsilon(\operatorname{div} \bar{\sigma} + \varepsilon \operatorname{div} \eta), \end{aligned}$$

we obtain

$$(4.20) \quad r_\varepsilon(V) \leq \left( I_0^*(\varepsilon) + I_1^*(\varepsilon) + I_2^*(\varepsilon) \right),$$

where

$$\begin{aligned} I_0^*(\varepsilon) &:= 2 \int_\Omega [f^*(\bar{\sigma} + \varepsilon z_1 + \varepsilon^2 z_2 + \varepsilon^3 z_\varepsilon) + g^*(\bar{\sigma} + \varepsilon \tau_1 + \varepsilon^2 \tau_2 + \varepsilon^3 \tau_\varepsilon)](a_2(DV) + \varepsilon m_\varepsilon) dx, \\ I_1^*(\varepsilon) &:= \frac{2}{\varepsilon} \int_\Omega [f^*(\bar{\sigma} + \varepsilon z_1 + \varepsilon^2 z_2 + \varepsilon^3 z_\varepsilon) + g^*(\bar{\sigma} + \varepsilon \tau_1 + \varepsilon^2 \tau_2 + \varepsilon^3 \tau_\varepsilon) \\ &\quad - f^*(\bar{\sigma}) - g^*(\operatorname{div} \bar{\sigma})] \operatorname{div} V dx, \\ I_2^*(\varepsilon) &:= \frac{2}{\varepsilon^2} \int_\Omega [f^*(\bar{\sigma} + \varepsilon z_1 + \varepsilon^2 z_2 + \varepsilon^3 z_\varepsilon) + g^*(\bar{\sigma} + \varepsilon \tau_1 + \varepsilon^2 \tau_2 + \varepsilon^3 \tau_\varepsilon) - f^*(\bar{\sigma}) \\ &\quad - g^*(\operatorname{div} \bar{\sigma}) - \varepsilon \langle \nabla f^*(\bar{\sigma}), (DV - \operatorname{div} V)\bar{\sigma} \rangle + \varepsilon \operatorname{div} V \operatorname{div} \bar{\sigma} (g^*)'(\operatorname{div} \bar{\sigma})] dx. \end{aligned}$$

Let us study separately the asymptotic behavior of  $I_i^*(\varepsilon)$  as  $\varepsilon \rightarrow 0$ . By exploiting the growth properties of the integrands (note that the growth assumptions on  $f$  and  $g$  made in (2.2) imply similar conditions on  $f^*$  and  $g^*$ ) and the uniform  $L^\infty$  boundedness of  $\widetilde{m}_\varepsilon$ , we get

$$(4.21) \quad \lim_{\varepsilon \rightarrow 0} I_0^*(\varepsilon) = 2 \int_\Omega [f^*(\bar{\sigma}) + g^*(\operatorname{div} \bar{\sigma})] a_2(DV) dx.$$

By applying Lemma 8.1 (i) to the integral functionals  $I_{f^*}$  and  $I_{g^*}$  defined according to (8.1) (note that this can be done after possibly modifying  $g^*$  outside an interval, since  $\operatorname{div} \bar{\sigma} + \varepsilon \operatorname{div} \eta$  remains uniformly bounded in  $L^\infty$ ), we get

$$(4.22) \quad \lim_{\varepsilon \rightarrow 0} I_1^*(\varepsilon) = 2 \int_\Omega [\langle \nabla f^*(\bar{\sigma}), z_1 \rangle + (g^*)'(\operatorname{div} \bar{\sigma}) \tau_1] \operatorname{div} V dx.$$

Let us now consider  $I_2^*(\varepsilon)$ . We recall that, in view of the optimality conditions (2.5), we have

$$(4.23) \quad \int_\Omega [\langle \nabla f^*(\bar{\sigma}), \eta \rangle + (g^*)'(\operatorname{div} \bar{\sigma}) \operatorname{div} \eta] dx = 0.$$

Thus,  $I_2^*(\varepsilon)$  remains unchanged by adding the zero term (4.23) (multiplied by  $-2/\varepsilon$ ):

$$\begin{aligned} I_2^*(\varepsilon) &= \frac{2}{\varepsilon^2} \int_\Omega [f^*(\bar{\sigma} + \varepsilon z_1 + \varepsilon^2 z_2 + \varepsilon^3 z_\varepsilon) - f^*(\bar{\sigma}) - \varepsilon \langle \nabla f^*(\bar{\sigma}), z_1 \rangle \\ &\quad + g^*(\bar{\sigma} + \varepsilon \tau_1 + \varepsilon^2 \tau_2 + \varepsilon^3 \tau_\varepsilon) - g^*(\operatorname{div} \bar{\sigma}) - \varepsilon (g^*)'(\operatorname{div} \bar{\sigma}) \tau_1] dx. \end{aligned}$$

Hence, by applying Lemma 8.1, we infer

$$(4.24) \quad \lim_{\varepsilon \rightarrow 0} I_2^*(\varepsilon) = 2 \int_{\Omega} [Q_{f^*}(z_1) + \langle \nabla f^*(\bar{\sigma}), z_2 \rangle + Q_{g^*}(\tau_1) + (g^*)'(\operatorname{div} \bar{\sigma})\tau_2] dx.$$

By combining (4.20) with (4.21), (4.22), and (4.24) and recalling the definition (4.5) of  $E^*$ , in view of the arbitrariness of  $\eta \in C^\infty(\bar{\Omega}; \mathbb{R}^n) \cap X(\Omega; \mathbb{R}^n)$ , we infer

$$(4.25) \quad \limsup_{\varepsilon \rightarrow 0} r_\varepsilon(V) \leq \inf_{\eta \in C^\infty(\bar{\Omega}; \mathbb{R}^n) \cap X(\Omega; \mathbb{R}^n)} E^*(\eta, V).$$

Finally we observe that, for every  $\eta \in X(\Omega; \mathbb{R}^n)$ , there exists a sequence  $\{\eta_h\} \subset C^\infty(\bar{\Omega}; \mathbb{R}^n) \cap X(\Omega; \mathbb{R}^n)$ , such that  $\eta_h \rightarrow \eta$  in  $L^2(\Omega; \mathbb{R}^n)$  and  $\operatorname{div} \eta_h \rightarrow \operatorname{div} \eta$  in  $L^q(\Omega)$ . Since  $E^*(\cdot, V)$  is continuous with respect to such convergence (thanks to the fact that the growth assumptions on  $f$  and  $g$  made in (2.2) imply similar conditions on  $f^*$  and  $g^*$ ), the infimum on the r.h.s. of (4.25) turns out to agree with the infimum on the r.h.s. of (4.8), and the proof is achieved.  $\square$

*Proof of Lemma 4.3.* For brevity, throughout the proof we fix the vector field  $V$  and omit it when writing the functionals  $E_\varepsilon$  and  $E$ . We begin by showing the equicoercivity of  $E_\varepsilon$ . In view of the convexity assumptions on  $f$  and  $g$ , we infer that the following bounds hold true, where  $m$  and  $k$  are the positive constants appearing in (2.1):

$$f(z_0 + z) \geq f(z_0) + \langle \nabla f(z_0), z \rangle + m|z|^2, \quad g(v_0 + v) \geq g(v_0) + g'(v_0)v + k|v|^2.$$

By exploiting such bounds for  $z_0 = \nabla \bar{u}$ ,  $z = -\nabla \bar{u} + D\Psi_\varepsilon^{-T}(\nabla \bar{u} + \nabla w)$ ,  $v_0 = \bar{u}$ , and  $v = \varepsilon w$ , we infer that for every  $\varepsilon$

$$E_\varepsilon(w) \geq c_1 \|\nabla w\|_{L^2}^2 + c_2 \|w\|_{L^2}^2 - c_3 \|\nabla w\|_{L^2} - c_4 \|w\|_{L^2} - c_5$$

for some positive constants  $c_i$ . Therefore the sequence  $E_\varepsilon$  is equicoercive in  $H(\Omega)$ .

Let us now show the  $\Gamma$ -convergence statement. By definition of  $\Gamma$ -convergence, we have to prove the so-called  $\Gamma$ -liminf and  $\Gamma$ -limsup inequalities:

$$(4.26) \quad \inf \left\{ \liminf E_\varepsilon(w_\varepsilon) : v_\varepsilon \xrightarrow{H(\Omega)} v \right\} \geq E(w),$$

$$(4.27) \quad \inf \left\{ \limsup E_\varepsilon(w_\varepsilon) : v_\varepsilon \xrightarrow{H(\Omega)} v \right\} \leq E(w).$$

Let us prove (4.26). For every  $w \in H(\Omega)$  and for every sequence  $w_\varepsilon$  which converges weakly to  $w$  in  $H(\Omega)$ , we have to prove that

$$(4.28) \quad E(w) \leq \liminf_{\varepsilon} E_\varepsilon(w_\varepsilon).$$

For a given  $w \in H(\Omega)$ , let us first consider a regular sequence  $\tilde{w}_\varepsilon \in C^\infty(\bar{\Omega}) \cap H(\Omega)$  weakly converging to  $w$ .

As already done in the proof of Lemma 4.2, by exploiting the  $C^1$  regularity of the integral functionals  $I_f$  and  $I_g$  and the  $L^2$ -Mosco convergence of the corresponding sequences  $\Delta_{\varepsilon, f}$  and  $\Delta_{\varepsilon, g}$  defined according to (8.2), we infer

$$(4.29) \quad E(w) \leq \liminf_{\varepsilon} E_\varepsilon(\tilde{w}_\varepsilon).$$



Let us now consider a generic sequence  $w_\varepsilon \in H(\Omega)$  weakly converging to  $w$ . By density, for every fixed  $\varepsilon$ , there exists  $\tilde{w}_{\varepsilon,k} \in C^\infty(\bar{\Omega}) \cap H(\Omega)$  such that  $\tilde{w}_{\varepsilon,k} \rightarrow w_\varepsilon$  strongly in  $H(\Omega)$  as  $k \rightarrow +\infty$ . With a diagonal argument, we may find a subsequence such that

$$(4.30) \quad \liminf_\varepsilon E_\varepsilon(w_\varepsilon) = \liminf_\varepsilon \lim_k E_\varepsilon(\tilde{w}_{\varepsilon,k}) = \lim_\varepsilon E_\varepsilon(\tilde{w}_{\varepsilon,k_\varepsilon}),$$

where the first equality follows by the strong continuity of  $E_\varepsilon$ . We remark that the subsequence  $\tilde{w}_{\varepsilon,k_\varepsilon}$  is regular and weakly converging to  $w$ ; hence it satisfies (4.29). Such a property, combined with the equality (4.30), concludes the proof of (4.28).

Let us now prove (4.27). For every fixed  $w \in H(\Omega)$  we have to find a recovery sequence, namely, a sequence  $w_\varepsilon$  which converges weakly to  $w$  in  $H(\Omega)$  and satisfies  $\limsup_{\varepsilon \rightarrow 0} E_\varepsilon(w_\varepsilon) \leq E(w)$ . If  $\tilde{w}$  is an element of the space  $C^\infty(\bar{\Omega}) \cap H(\Omega)$ , we are done simply by taking the constant sequence  $w_\varepsilon \equiv \tilde{w}$ . Indeed, by following the same procedure as that adopted in the proof of Lemma 4.2, we infer that  $\lim_{\varepsilon \rightarrow 0} E_\varepsilon(\tilde{w}) = E(\tilde{w})$ . If  $w$  is a generic element of  $H(\Omega)$ , we approximate it by a sequence  $\tilde{w}_k \in C^\infty(\bar{\Omega}) \cap H(\Omega)$ : by the lower semicontinuity on the l.h.s. of (4.27) (usually called  $\Gamma$ -lim sup  $E_\varepsilon$ ) and the continuity of  $E$ , we obtain

$$(\Gamma\text{-lim sup } E_\varepsilon)(w) \leq \liminf_k (\Gamma\text{-lim sup } E_\varepsilon)(\tilde{w}_k) \leq \liminf_k \limsup_\varepsilon E_\varepsilon(\tilde{w}_k) = E(w). \quad \square$$

### 5. Regularity of the solution and necessary optimality condition.

In this section we prove Propositions 3.2 and 3.4. Both are based on the crucial result given below, which in turn exploits the  $\Gamma$ -convergence statement given in the previous section (cf. Lemma 4.3).

**PROPOSITION 5.1.** *Under the standing assumptions, if  $V$  has compact support contained in  $\Omega$ , then the function  $\bar{\theta}_V := \langle V, \nabla \bar{u} \rangle$  solves the minimization problem  $\inf_{w \in H(\Omega)} E(\cdot, V)$ , where  $E(\cdot, V)$  is the functional defined by (4.4).*

*Proof.* We first prove the following claim: for every fixed  $\varepsilon > 0$ , the function

$$(5.1) \quad w_\varepsilon(x) := \frac{\bar{u}(x + \varepsilon V(x)) - \bar{u}(x)}{\varepsilon}$$

solves the minimization problem  $\inf_{w \in H(\Omega)} E_\varepsilon(\cdot, V)$ , where  $E_\varepsilon(\cdot, V)$  is the functional defined by (4.3).

Let  $u_\varepsilon \in H(\Omega)$  be optimal for problem  $J(\Omega_\varepsilon)$  in the formulation (2.10) set on the fixed domain  $\Omega$ . Via change of variables, we obtain

$$J(\Omega_\varepsilon) = - \int_\Omega [f_\varepsilon(\nabla u_\varepsilon) + g_\varepsilon(u_\varepsilon)] dx = - \int_{\Omega_\varepsilon} [f(\nabla(u_\varepsilon \circ \Psi_\varepsilon^{-1})) + g(u_\varepsilon \circ \Psi_\varepsilon^{-1})] dx.$$

We infer that the function  $u_\varepsilon \circ \Psi_\varepsilon^{-1} \in H(\Omega_\varepsilon)$  is optimal for problem  $J(\Omega_\varepsilon)$  in its original formulation as an infimum over  $H(\Omega_\varepsilon)$ . On the other hand, since  $V$  has compact support contained in  $\Omega$ , we know that  $J(\Omega_\varepsilon) = J(\Omega)$ , and hence (since  $\bar{u}$  is the unique solution to  $J(\Omega)$ ) we have  $u_\varepsilon \circ \Psi_\varepsilon^{-1} = \bar{u}$ , namely,  $u_\varepsilon(x) = \bar{u} \circ \Psi_\varepsilon(x) = \bar{u}(x + \varepsilon V(x))$ . It follows that the function  $w_\varepsilon$  defined in (5.1) minimizes  $E_\varepsilon(\cdot, V)$  over  $H(\Omega)$ , and our claim on the optimality of  $w_\varepsilon$  is proved.

In view of Lemma 4.3, the minimizing sequence  $\{w_\varepsilon\}$  is equibounded in  $H(\Omega)$  and, up to subsequences, it weakly converges to a minimizer of the  $\Gamma$ -limit, namely, to a minimizer of  $E(\cdot, V)$ . Clearly, the weak limit of  $w_\varepsilon$  necessarily agrees with the pointwise limit  $\langle V, \nabla \bar{u} \rangle$ , which allows us to conclude that  $\langle V, \nabla \bar{u} \rangle$  minimizes  $E(\cdot, V)$  over  $H(\Omega)$ .  $\square$

*Proof of Proposition 3.2.* In view of Proposition 5.1 we can assert that, for every vector field  $V$  compactly supported in  $\Omega$ , the function  $\langle V, \nabla \bar{u} \rangle$  belongs to  $H^1(\Omega)$ . By the arbitrariness of  $V \in C_0^1(\Omega; \mathbb{R}^n)$ , we infer that  $\bar{u}$  is an element of  $W_{loc}^{2,2}(\Omega)$ .  $\square$

*Proof of Proposition 3.4.* We consider the minimization of the functional  $E(\cdot, V)$  in (4.4) over  $H(\Omega)$ , written as done in the proof of Proposition 4.1; see (4.10). By duality, we have the equality (4.11). Then, by Lemma 8.5, a function  $w \in H(\Omega)$  and a pair  $(\eta, \tau) \in L^2(\Omega; \mathbb{R}^n) \times L^q(\Omega)$  are optimal, respectively, for the two problems in (4.11) if and only if  $(\eta, \tau) \in \partial\Psi(\nabla w, w)$  and  $(\operatorname{div} \eta, \tau) \in \partial\Phi(w)$ . Then, by computing explicitly the expressions of  $\partial\Phi$  and  $\partial\Psi$ , we get  $\tau = \operatorname{div} \eta$ , with the additional condition  $\eta \cdot n = 0$  on  $\Gamma_N$ , and

$$\begin{cases} \eta = \nabla^2 f(\nabla \bar{u})(\nabla w - DV^T \nabla \bar{u}) - (DV - \operatorname{div} V I) \bar{\sigma}, \\ \operatorname{div} \eta = g''(\bar{u})w + g'(\bar{u}) \operatorname{div} V. \end{cases}$$

Hence, for  $V \in C_0^1(\Omega; \mathbb{R}^n)$ , the distributional equality (3.3) follows by replacing  $w$  by  $\langle V, \nabla \bar{u} \rangle$  in the above optimality conditions (since we know by Proposition 5.1 that  $\bar{\theta}_V = \langle V, \nabla \bar{u} \rangle$  minimizes  $E(\cdot, V)$  over  $H(\Omega)$ ). For  $V \in C^1(\mathbb{R}^n; \mathbb{R}^n)$ , the equality (3.3) continues to hold by the following simple argument: in order to check (3.3) for a given test function  $\varphi \in \mathcal{D}(\Omega)$ , it is enough to use its validity when  $V$  is replaced by the product  $\mu V \in C_0^1(\Omega; \mathbb{R}^n)$ ,  $\mu$  being a cut-off function compactly supported in  $\Omega$  which equals 1 on the support of  $\varphi$ .  $\square$

**6. Representation formula for the second order shape derivative.** In this section we give the proof of Theorem 3.5 (ii).

*Proof of Theorem 3.5 (ii).* We start with the following equality, already proved in Proposition 4.1:

$$(6.1) \quad J''(\Omega, V) = - \inf_{w \in H(\Omega)} E(w, V).$$

Throughout the proof we set for brevity  $\bar{\theta}_V := \langle V, \nabla \bar{u} \rangle$ . By inserting into the definition (4.4) of  $E(w, V)$  the identities

$$\begin{aligned} Q_f(\nabla w - DV^T \nabla \bar{u}) &= Q_f(\nabla(w - \bar{\theta}_V)) + \langle \nabla^2 f(\nabla \bar{u})(\nabla^2 \bar{u})V, \nabla(w - \bar{\theta}_V) \rangle + Q_f((\nabla^2 \bar{u})V), \\ Q_g(w) &= Q_g(w - \bar{\theta}_V) + g''(\bar{u})\bar{\theta}_V(w - \bar{\theta}_V) + Q_g(\bar{\theta}_V), \end{aligned}$$

we obtain

$$\begin{aligned} E(w, V) &= \int_{\Omega} 2[Q_f(\nabla(w - \bar{\theta}_V)) + Q_g(w - \bar{\theta}_V)] dx \\ &\quad + \int_{\Omega} 2[\langle \nabla^2 f(\nabla \bar{u})(\nabla^2 \bar{u})V - (DV - \operatorname{div} V I) \bar{\sigma}, \nabla(w - \bar{\theta}_V) \rangle \\ &\quad \quad + (g''(\bar{u})\bar{\theta}_V + \operatorname{div} V g'(\bar{u}))(w - \bar{\theta}_V)] dx \\ &\quad + \int_{\Omega} [(f(\nabla \bar{u}) + g(\bar{u}))(\operatorname{div} V I - DV) : DV^T - 2\langle (DV - \operatorname{div} V I) \bar{\sigma}, (\nabla^2 \bar{u})V \rangle \\ &\quad \quad + 2 \operatorname{div} V g'(\bar{u})\bar{\theta}_V] dx \\ &\quad + \int_{\Omega} [2Q_f((\nabla^2 \bar{u})V) + 2Q_g(\bar{\theta}_V)] dx. \end{aligned}$$

Recalling the definition (3.5) of the quadratic form  $\mathcal{Q}(\bar{u}, \cdot)$  and the definition (3.2) of the vector field  $B(\bar{u}, V)$ , by also using Proposition 3.4 we can rewrite the above equality as  $E(w, V) = \text{(I)} + \text{(II)}$ , with

$$\text{(I)} = \mathcal{Q}(\bar{u}, w - \bar{\theta}_V) dx + \int_{\Omega} 2[\langle B(\bar{u}, V), \nabla(w - \bar{\theta}_V) \rangle + \operatorname{div} B(\bar{u}, V)(w - \bar{\theta}_V)] dx$$

and

$$\begin{aligned} \text{(II)} &= \int_{\Omega} [(f(\nabla \bar{u}) + g(\bar{u}))(\operatorname{div} VI - DV) : DV^T - 2\langle (DV - \operatorname{div} VI)\bar{\sigma}, (\nabla^2 \bar{u})V \rangle \\ &\quad + 2 \operatorname{div} V g'(\bar{u})\bar{\theta}_V] dx \\ &\quad + \int_{\Omega} [2Q_f((\nabla^2 \bar{u})V) + 2Q_g(\bar{\theta}_V)] dx. \end{aligned}$$

Note that, in view of the assumption  $\bar{u} \in W^{2,2}(\Omega)$ , the vector field  $B(\bar{u}, V)$  is in  $L^2$  and has bounded divergence; thus it admits a normal trace in  $H^{-1/2}(\partial\Omega)$ , and we are allowed to apply the integration-by-parts formula (2.3). Thus we get

$$(6.2) \quad \text{(I)} = \mathcal{Q}(\bar{u}, w - \bar{\theta}_V) dx + \int_{\partial\Omega} 2(w - \bar{\theta}_V) B(\bar{u}, V) \cdot n d\mathcal{H}^{n-1}.$$

We now want to rewrite (II) as a boundary integral. To this purpose we observe that, by (3.2) and (3.3), there hold

$$(6.3) \quad -\langle (DV - \operatorname{div} VI)\bar{\sigma} - \nabla^2 f(\nabla^2 \bar{u})V, (\nabla^2 \bar{u})V \rangle = \langle B(\bar{u}, V), (\nabla^2 \bar{u})V \rangle,$$

$$(6.4) \quad \operatorname{div} V g'(\bar{u})\bar{\theta}_V + g''(\bar{u})(\bar{\theta}_V)^2 = \operatorname{div} B(\bar{u}, V)\bar{\theta}_V.$$

Moreover, again thanks to the assumption  $\bar{u} \in W^{2,2}(\Omega)$ , the vector field

$$(6.5) \quad X_1 := (f(\nabla \bar{u}) + g(\bar{u}))(\operatorname{div} VI - DV)V$$

is bounded and has  $L^2$  divergence. Thus we are allowed to apply the integration-by-parts formula (2.3), and we get

$$\begin{aligned} &\int_{\Omega} (f(\nabla \bar{u}) + g(\bar{u}))(\operatorname{div} VI - DV) : DV^T dx \\ &= \int_{\partial\Omega} (f(\nabla \bar{u}) + g(\bar{u}))\langle (\operatorname{div} VI - DV)V, n \rangle d\mathcal{H}^{n-1} \\ (6.6) \quad &- \int_{\Omega} \langle (\operatorname{div} VI - DV)V, (\nabla^2 \bar{u})\bar{\sigma} + g'(\bar{u})\nabla \bar{u} \rangle dx. \end{aligned}$$

Using (6.3), (6.4), and (6.6), we infer that

$$\begin{aligned} \text{(II)} &= \int_{\partial\Omega} (X_1 \cdot n) d\mathcal{H}^{n-1} + \int_{\Omega} [\langle B(\bar{u}, V), (\nabla^2 \bar{u})V \rangle + \operatorname{div} B(\bar{u}, V)\bar{\theta}_V] dx \\ &\quad - \int_{\Omega} \langle (\nabla^2 \bar{u})DV\bar{\sigma} - DV^T(\nabla^2 \bar{u})\bar{\sigma} - g'(\bar{u})DV^T\nabla \bar{u}, V \rangle dx. \end{aligned}$$

Exploiting the equality  $(\nabla^2 \bar{u})V = \nabla \bar{\theta}_V - DV^T \nabla \bar{u}$ , we get

$$\begin{aligned} \text{(II)} &= \int_{\partial\Omega} (X_1 \cdot n) d\mathcal{H}^{n-1} + \int_{\Omega} [\langle B(\bar{u}, V), \nabla \bar{\theta}_V \rangle + \operatorname{div} B(\bar{u}, V) \bar{\theta}_V] dx \\ &\quad - \int_{\Omega} \left[ \langle \nabla^2 f(\nabla \bar{u})(\nabla^2 \bar{u})V, DV^T \nabla \bar{u} \rangle + \operatorname{div} V \langle \bar{\sigma}, DV^T \nabla \bar{u} \rangle + \langle (\nabla^2 \bar{u})DV \bar{\sigma}, V \rangle \right] dx \\ &\quad + \int_{\Omega} \left[ \langle DV \bar{\sigma}, DV^T \nabla \bar{u} \rangle + \langle DV^T (\nabla^2 \bar{u}) \bar{\sigma}, V \rangle + g'(\bar{u}) \langle DV^T \nabla \bar{u}, V \rangle \right] dx. \end{aligned}$$

Finally we remark that  $\langle B(\bar{u}, V), \nabla \bar{\theta}_V \rangle + \operatorname{div} B(\bar{u}, V) \bar{\theta}_V = \operatorname{div} (\bar{\theta}_V B(\bar{u}, V))$  and

$$\begin{aligned} & - \langle \nabla^2 f(\nabla \bar{u})(\nabla^2 \bar{u})V, DV^T \nabla \bar{u} \rangle - \operatorname{div} V \langle \bar{\sigma}, DV^T \nabla \bar{u} \rangle \\ & - \langle (\nabla^2 \bar{u})DV \bar{\sigma}, V \rangle + \langle DV \bar{\sigma}, DV^T \nabla \bar{u} \rangle \\ & + \langle DV^T (\nabla^2 \bar{u}) \bar{\sigma}, V \rangle + g'(\bar{u}) \langle DV^T \nabla \bar{u}, V \rangle = \operatorname{div} \left( - \langle DV \bar{\sigma}, \nabla \bar{u} \rangle V + \langle DV V, \nabla \bar{u} \rangle \bar{\sigma} \right). \end{aligned}$$

Hence

$$\text{(II)} = \int_{\partial\Omega} (X_1 \cdot n) d\mathcal{H}^{n-1} + \int_{\Omega} \operatorname{div} \left( \bar{\theta}_V B(\bar{u}, V) - \langle DV \bar{\sigma}, \nabla \bar{u} \rangle V + \langle DV V, \nabla \bar{u} \rangle \bar{\sigma} \right) dx;$$

moreover, thanks to the assumption  $\bar{u} \in W^{2,2}(\Omega)$ , the tensor field

$$X_2 := \bar{\theta}_V B(\bar{u}, V) - \langle DV \bar{\sigma}, \nabla \bar{u} \rangle V + \langle DV V, \nabla \bar{u} \rangle \bar{\sigma}$$

is in  $L^2$  and has  $L^2$  divergence. Then, by adding (6.2) and (6.7) and by applying the integration-by-parts formula (2.3), we obtain

$$\begin{aligned} \text{(6.9)} \quad E(w, V) &= \mathcal{Q}(\bar{u}, w - \bar{\theta}_V) dx + \int_{\partial\Omega} 2(w - \bar{\theta}_V) B(\bar{u}, V) \cdot n d\mathcal{H}^{n-1} \\ &\quad + \int_{\partial\Omega} (X_1 \cdot n) d\mathcal{H}^{n-1} + \int_{\Omega} (X_2 \cdot n) d\mathcal{H}^{n-1}. \end{aligned}$$

Now, the fact that the field  $\mathcal{C}(\bar{u}, V)$  defined in (3.4) admits a normal trace in  $H^{-1/2}(\partial\Omega)$  follows by observing that  $\mathcal{C}(\bar{u}, V) = -X_1 - X_2$ , with  $X_1$  and  $X_2$  defined, respectively, in (6.5) and (6.8). Finally the expression (3.6) of the second order shape derivative follows by combining (6.9) with (6.1) and using the equality  $\mathcal{C}(\bar{u}, V) = -X_1 - X_2$ .  $\square$

### 7. Variants and perspectives.

**7.1. The linear  $g$  case.** We claim that Theorem 3.5, Proposition 3.2, and Proposition 3.4 remain true in the case when  $g(v) = -\lambda v$  for some  $\lambda \in \mathbb{R}$ . Note just that in the definition (3.5) of the quadratic form  $\mathcal{Q}(\bar{u}, \cdot)$ , the term  $Q_g$  vanishes.

The proof of the lower bound inequality (4.7) works unaltered, whereas the proof of the upper bound inequality (4.8) must be modified as follows. Note first that since the Fenchel conjugate of  $g$  is the Dirac delta function  $g^*(\tau) = \delta_{-\lambda}$ , the dual energy  $E^*(\eta, V)$  introduced in (4.5) is finite only if  $\operatorname{div} \eta = -\lambda \operatorname{div} V$ , and in this case it reads

$$\begin{aligned} \text{(7.1)} \quad E^*(\eta, V) &= 2 \int_{\Omega} [f^*(\bar{\sigma}) - \langle \nabla f^*(\bar{\sigma}), \bar{\sigma} \rangle + \lambda \bar{u}] a_2(DV) dx \\ &\quad + 2 \int_{\Omega} [Q_{f^*}((DV - \operatorname{div} V I) \bar{\sigma} + \eta) + \langle \nabla f^*(\bar{\sigma}), DV \eta \rangle] dx. \end{aligned}$$

Next, we write the following inequality (which replaces (4.19)):

$$(7.2) \quad r_\varepsilon(V) \leq \frac{2}{\varepsilon^2} \left( \int_\Omega [f_\varepsilon^*(\sigma_\varepsilon) + g_\varepsilon^*(\operatorname{div} \sigma_\varepsilon)] dx - J^*(\Omega, V) - \varepsilon J'(\Omega, V) \right),$$

where  $\sigma_\varepsilon$  are the perturbations of  $\bar{\sigma}$  defined by

$$(7.3) \quad \sigma_\varepsilon := \bar{\sigma} + \sum_{k=1}^n \varepsilon^k \eta_k,$$

with, for  $k \in \{1, 2, \dots, n\}$ ,

$$(7.4) \quad \eta_k \in L^\infty(\Omega; \mathbb{R}^n), \quad \operatorname{div} \eta_k = -\lambda a_k(DV) \text{ in } \Omega, \quad \eta_k \cdot n = 0 \text{ on } \Gamma_N.$$

Notice that, for such a choice of  $\sigma_\varepsilon$ , the r.h.s. of the inequality (7.2) is finite. Namely, exploiting the expansion (2.12) and the fact that by (2.5) it holds that  $\operatorname{div} \bar{\sigma} = -\lambda$ , we obtain  $\operatorname{div} \sigma_\varepsilon = -\lambda \beta_\varepsilon$ , so that

$$(7.5) \quad g_\varepsilon^*(\operatorname{div} \sigma_\varepsilon) = \beta_\varepsilon g^*(\beta_\varepsilon^{-1} \operatorname{div} \sigma_\varepsilon) = \beta_\varepsilon g^*(-\lambda) = 0.$$

Notice also that the set of fields satisfying (7.4) is nonempty; indeed, every  $a_k(DV)$  can be expressed as the divergence of a suitable regular vector field  $\nu_k$  (see, for instance, [36, Lemma 4.6.4]); thus the conditions in (7.4) are verified by taking  $\eta_k := -\lambda \nu_k + \nabla w_k$ , with  $w_k$  being the solution of

$$\Delta w_k = 0 \text{ in } \Omega, \quad \partial_n w_k = h_k \text{ on } \partial\Omega,$$

where  $h_k = \lambda \nu_k \cdot n$  on  $\Gamma_N$ ,  $\int_{\partial\Omega} h_k = 0$ . By combining (7.2) and (7.5), we may write

$$(7.6) \quad r_\varepsilon(V) \leq \left( I_0^*(\varepsilon) + I_1^*(\varepsilon) + I_2^*(\varepsilon) \right),$$

with

$$I_0^*(\varepsilon) := 2 \int_\Omega f^*(\beta_\varepsilon^{-1} D\Psi_\varepsilon \sigma_\varepsilon) (a_2(DV) + \varepsilon m_\varepsilon) dx,$$

$$I_1^*(\varepsilon) := \frac{2}{\varepsilon} \int_\Omega [f^*(\beta_\varepsilon^{-1} D\Psi_\varepsilon \sigma_\varepsilon) - f^*(\bar{\sigma})] \operatorname{div} V dx,$$

$$I_2^*(\varepsilon) := \frac{2}{\varepsilon^2} \int_\Omega [f^*(\beta_\varepsilon^{-1} D\Psi_\varepsilon \sigma_\varepsilon) - f^*(\bar{\sigma}) - \varepsilon \langle \nabla f^*(\bar{\sigma}), (DV - \operatorname{div} V I) \bar{\sigma} \rangle - \varepsilon \lambda \operatorname{div} V \bar{u}] dx.$$

Now we argue in a way similar to that of the strictly convex case: we apply Lemma 8.1 to the integral functional  $I_{f^*}$  and, in order to deal with  $I_2^*(\varepsilon)$ , exploit the equality

$$\int_\Omega \lambda \operatorname{div} V \bar{u} dx = - \int_\Omega \bar{u} \operatorname{div} \eta_1 dx = \int_\Omega \langle \nabla f^*(\bar{\sigma}), \eta_1 \rangle dx;$$

thus we obtain

$$\lim_{\varepsilon \rightarrow 0} I_0^*(\varepsilon) = 2 \int_\Omega f^*(\bar{\sigma}) a_2(DV) dx,$$

$$\lim_{\varepsilon \rightarrow 0} I_1^*(\varepsilon) = 2 \int_\Omega \langle \nabla f^*(\bar{\sigma}), (DV - \operatorname{div} V I) \bar{\sigma} + \eta_1 \rangle \operatorname{div} V dx,$$

$$\begin{aligned} \lim_{\varepsilon \rightarrow 0} I_2^*(\varepsilon) &= 2 \int_\Omega Q_{f^*}((DV - \operatorname{div} V I) \bar{\sigma} + \eta_1) \\ &\quad + \langle \nabla f^*(\bar{\sigma}), ((\operatorname{div} V)^2 - \operatorname{div} V DV - a_2(DV)) \bar{\sigma} + (DV - \operatorname{div} V I) \eta_1 + \eta_2 \rangle dx. \end{aligned}$$

In view of (7.6), by adding up the three terms above and exploiting the equality  $\int_{\Omega} \langle \nabla f^*(\bar{\sigma}), \eta_2 \rangle dx = \int_{\Omega} \lambda \bar{u} a_2(DV) dx$ , we infer that  $\limsup_{\varepsilon \rightarrow 0} r_{\varepsilon}(V) \leq E^*(\eta_1, V)$ .

Now, since  $\eta_1$  is an arbitrary vector field in  $L^{\infty}(\Omega; \mathbb{R}^n)$  with  $\operatorname{div} \eta_1 = -\lambda$  and  $\eta_1 \cdot n = 0$  on  $\Gamma_N$ , in order to conclude the proof of the upper bound inequality (4.8) it is enough to show that every field  $\eta \in X(\Omega; \mathbb{R}^n)$  satisfying the two conditions  $\operatorname{div} \eta = -\lambda$  and  $\eta \cdot n = 0$  on  $\Gamma_N$  can be approximated strongly in  $L^2$  by a sequence of fields  $\eta^h$  belonging to  $L^{\infty}(\Omega; \mathbb{R}^n)$  and satisfying the same two conditions. To that aim we begin by noticing that, since by assumption  $\partial\Omega$  is piecewise  $C^1$ , there exists a sequence of smooth fields  $\tilde{\eta}^h$ , with  $\tilde{\eta}^h \cdot n = 0$  on  $\Gamma_N$ , such that  $\tilde{\eta}^h \rightarrow \eta$  in  $L^2(\Omega; \mathbb{R}^n)$  and  $\operatorname{div} \tilde{\eta}^h \rightarrow -\lambda$  in  $L^2(\Omega)$ . Then we let  $\phi^h$  be the unique solution to the Dirichlet-Neumann problem

$$-\Delta \phi^h = \rho^h := \lambda + \operatorname{div} \tilde{\eta}^h \quad \text{in } \Omega, \quad \phi^h = 0 \quad \text{on } \Gamma_D, \quad \partial_n \phi^h = 0 \quad \text{on } \Gamma_N.$$

Finally we define  $\eta^h := \tilde{\eta}^h + \nabla \phi^h$ , and we claim that such a sequence  $\eta^h$  has the required properties. Namely, since  $\rho^h$  is a sequence of smooth functions converging to 0 in  $L^2(\Omega)$ , the sequence  $\eta^h$  lies in  $L^{\infty}(\Omega; \mathbb{R}^n)$  and converges to  $\eta$  in  $L^2(\Omega; \mathbb{R}^n)$ ; moreover it holds that  $\operatorname{div} \eta^h = -\lambda$  and  $\eta^h \cdot n = 0$  on  $\Gamma_N$ .

Eventually, once (4.8) is established, the remaining parts of the proofs given in sections 4, 5, and 6 can be repeated, as done for  $g$  strictly convex.

**7.2. The  $p$ -torsion problem.** Here we prove formula (3.17) for the second order shape derivative of the  $p$ -torsional rigidity functional  $J_p(\Omega)$  introduced in (3.16), for  $p > 2$ . We recall that the first order derivative  $J'_p(\Omega, V)$  exists and is given by

$$J'_p(\Omega, V) = \int_{\partial\Omega} \frac{|\nabla \bar{u}|^p}{p'} V_n d\mathcal{H}^{n-1},$$

where  $\bar{u}$  is the unique solution in  $W_0^{1,p}(\Omega)$  to  $-\Delta_p \bar{u} = \lambda$  (see, for instance, [8, 15]). It is well known that  $\bar{u}$  is of class  $C^{1,\alpha}(\Omega)$  (see [19, 47]), and it is also in  $C^2(\Omega \setminus S)$ , where  $S$  is the critical set  $S := \{x \in \Omega : \nabla \bar{u} = 0\}$ . Let us also recall that  $S$  has vanishing Lebesgue measure (see [33]), and it is compactly contained in  $\Omega$  (thanks to the Hopf boundary lemma).

Let us introduce the weight function  $\rho := |\nabla \bar{u}|^{p-2}$ , which is continuous in  $\Omega$  and strictly positive outside  $S$ . Moreover,  $\rho^{-1}$  is in  $L^1(\Omega)$  (see [43]).

We denote by  $W_{\rho}^{1,2}(\Omega)$  the Hilbert space consisting of functions  $v \in W_{\text{loc}}^{1,1}(\Omega)$  such that

$$\|v\|_{W_{\rho}^{1,2}(\Omega)} = \|v\|_{L^2(\Omega)}^2 + \|\nabla v\|_{L^2(\Omega)}^2 < +\infty,$$

and by  $H_{\rho}^{1,2}(\Omega)$  the completion of  $C^1(\bar{\Omega})$  with respect to the above norm.

Let  $\mathcal{Q}(\bar{u}, \cdot)$  denote the quadratic functional defined on  $W_{\rho}^{1,2}(\Omega)$  by

$$(7.7) \quad \mathcal{Q}(\bar{u}, v) := \int_{\Omega} \langle P(\bar{u}) \nabla v, \nabla v \rangle dx, \quad \text{with } P(\bar{u}) := |\nabla \bar{u}|^{p-2} \left( I + (p-2) \frac{\nabla \bar{u}}{|\nabla \bar{u}|} \otimes \frac{\nabla \bar{u}}{|\nabla \bar{u}|} \right).$$

Notice that since the norm of the matrix  $P(\bar{u})$  is controlled by  $\rho$ , the functional  $\mathcal{Q}(\bar{u}, \cdot)$  is continuous on the Hilbert space  $W_{\rho}^{1,2}(\Omega)$ . By adapting the approach developed in section 4, we obtain the following second order differentiability result.

**THEOREM 7.1.** *Let  $\partial\Omega$  be of class  $C^2$ . Let  $p > 2$  and assume that the weight  $\rho := |\nabla \bar{u}|^{p-2}$  is such that*

$$(7.8) \quad H_{\rho}^{1,2}(\Omega) = W_{\rho}^{1,2}(\Omega).$$

Then the functional  $J_p(\Omega)$  is twice differentiable at  $\Omega$  in any direction  $V$ , and for  $V$  normal to the boundary it holds that

$$(7.9) \quad J_p''(\Omega, V) = -\frac{1}{p} \int_{\partial\Omega} V_n^2 (p\lambda\partial_n\bar{u} + |\partial_n\bar{u}|^p H_{\partial\Omega}) d\mathcal{H}^{n-1} - \inf_{\substack{v \in W_{\rho}^{1,2}(\Omega) \\ v = -V_n \partial_n \bar{u} \text{ on } \partial\Omega}} \mathcal{Q}(\bar{u}, v).$$

*Remark 7.2.* Notice that since  $\rho$  is strictly positive in a neighborhood of  $\partial\Omega$ , the space  $W_{\rho}^{1,2}(\Omega)$  is embedded into  $H_{\text{loc}}^1(\Omega \setminus S)$ , and hence the trace operator is well defined from  $W_{\rho}^{1,2}(\Omega)$  into  $H^{1/2}(\partial\Omega)$ . In particular, the infimum in (7.9) is well defined since, by the  $C^2$  regularity of  $\bar{u}$  in  $\Omega \setminus S$ , the function  $\langle V, \nabla\bar{u} \rangle$  belongs to  $H_{\text{loc}}^1(\Omega \setminus S)$ . Moreover, the infimum can be equivalently taken in  $H^1(\Omega)$  (as written in Example 3.11).

*Remark 7.3.* Let us add a few comments on assumption (7.8) and related bibliographical references. For general texts on weighted Sobolev spaces, see [31, 37]. Moreover, we refer to the paper [14] for a counterexample showing that the  $L^1$ -summability property of  $\rho^{-1}$  is not strong enough to ensure the validity of (7.8). A sufficient condition would be  $\rho \in \mathcal{A}_2$ , where  $\mathcal{A}_2$  is the Muckenhoupt class of functions satisfying  $\sup_B (\frac{1}{|B|} \int_B \rho) (\frac{1}{|B|} \int_B \rho^{-1}) < +\infty$ , where  $B$  varies among balls in  $\mathbb{R}^n$  (see, for instance, [29]), but this kind of regularity result seems hard to prove. On the other hand, equality (7.8) holds true if the set  $S$  has vanishing capacity in  $H_{\rho}^{1,2}(\Omega)$ , namely, if there exists a sequence of smooth functions  $\alpha_{\varepsilon} : \Omega \rightarrow [0, 1]$  which are equal to 1 in an  $\varepsilon$ -neighborhood of  $S$  and satisfy  $\lim_{\varepsilon} \int_{\Omega} |\nabla\alpha_{\varepsilon}|^2 \rho dx = 0$ . Indeed in this case, given  $w \in W_{\rho}^{1,2}(\Omega)$  with  $w = -\bar{\theta}_V$  on  $\partial\Omega$ , it is possible to construct an approximating sequence  $\{w_{\varepsilon}\} \in H_{\rho}^{1,2}(\Omega)$  with  $w_{\varepsilon} = -\bar{\theta}_V$  on  $\partial\Omega$ : it is enough to take  $w_{\varepsilon} := (1 - \alpha_{\varepsilon})w$  (which belong to  $H^1(\Omega)$ , and hence to  $H_{\rho}^{1,2}(\Omega)$ ). In particular, our assumption (7.8) turns out to be satisfied whenever  $S$  is a singleton. Concerning the geometry of  $S$ , recall that if  $\Omega$  is convex, the function  $\bar{u}$  is power concave [42], and hence  $S$  agrees with the set where  $\bar{u}$  assumes its maximum. If in addition  $\Omega$  is *strictly* convex, it is likely true that  $S$  is reduced to a singleton (cf. [5, 30]), or at least that it is of vanishing capacity, so that (7.8) holds true.

*Proof of Theorem 7.1.* Since shape derivatives only depend on the behavior of the deformation field on the boundary, with no loss of generality we may choose  $V$  vanishing in a neighborhood of  $S$  (recall that  $S \subset\subset \Omega$ ). Then, in order to show the equality (7.9), we proceed along the same scheme adopted in section 4; namely, we show that the lower and upper limits as  $\varepsilon \rightarrow 0$  of the differential quotients  $r_{\varepsilon}(V)$  defined in (4.1) are bounded, respectively, from below and from above by the same quantity, which is precisely the r.h.s. of formula (7.9). For convenience, we divide the remainder of the proof into three steps.

*Step 1 (lower bound).* Thanks to the assumption  $p \geq 2$ , the following lower bound can be achieved by arguing exactly as done in the proof the inequality (4.7) in Lemma 4.2,

$$\liminf_{\varepsilon \rightarrow 0} r_{\varepsilon}(V) \geq m_{\infty} := - \inf_{w \in C_0^{\infty}(\Omega)} E(w, V),$$

where  $E(w, V)$  is defined according to (4.4) by taking therein  $f(z) = |z|^p/p$  and  $g(v) = -\lambda v$ .

We claim that the field  $B(\bar{u}, V)$  introduced in (3.2) still satisfies Proposition 3.4, namely,

$$(7.10) \quad \operatorname{div} B(\bar{u}, V) = -\lambda \operatorname{div} V \quad \text{in } \mathcal{D}'(\Omega).$$

The proof of the above equality cannot be repeated as done in section 5, because the minimizer  $\bar{u}$  of the functional  $J_p(\Omega)$  satisfies the regularity condition  $\bar{u} \in W^{2,2}(\Omega)$  only for  $p \in (1, 3)$ ; nevertheless, for  $p \geq 3$ , one has that  $\bar{u} \in W^{2,q}(\Omega)$  for any  $q < (p - 1)/(p - 2)$  (see [16, Proposition 2.2]). Thus  $\nabla\bar{u}$  is always in  $W^{1,1}(\Omega)$ , and the distributional Hessian of  $\bar{u}$  appearing in the definition  $B(\bar{u}, V)$  is well defined as a function in  $L^1(\Omega)$ . Moreover, the function  $\bar{u}$  satisfies the crucial regularity condition  $|\nabla\bar{u}|^{p-2}\nabla\bar{u} \in W^{1,2}(\Omega)$  (see [44, Corollary 2.1]), which enables us to obtain the proof of (7.10) as follows. Recall that  $\bar{\sigma} = \nabla f(\nabla\bar{u}) = |\nabla\bar{u}|^{p-2}\nabla\bar{u}$ ; then, since  $\nabla f(\cdot)$  is a locally Lipschitz function and  $\nabla\bar{u} \in L^\infty(\Omega) \cap W^{1,1}(\Omega)$ , we can apply the chain rule and get  $D\bar{\sigma} = \nabla^2 f(\nabla\bar{u})\nabla^2\bar{u}$  a.e. in  $\Omega$ . Thus the field  $B(\bar{u}, V)$  may be rewritten in terms of  $\bar{\sigma}$  as  $B(\bar{u}, V) = D\bar{\sigma}V - (DV - \operatorname{div} VI)\bar{\sigma}$ , and in particular it belongs to  $L^2(\Omega; \mathbb{R}^n)$ . It is then straightforward to obtain (7.10). Namely, for any test function  $\varphi \in C_c^\infty(\Omega)$ , it holds that

$$\begin{aligned} \langle \operatorname{div}(D\bar{\sigma}V), \varphi \rangle &= -\langle D\bar{\sigma}V, \nabla\varphi \rangle = -\langle \partial_k \bar{\sigma}_i V_k, \partial_i \varphi \rangle = \langle \bar{\sigma}_i \partial_k V_k, \partial_i \varphi \rangle + \langle \bar{\sigma}_i V_k, \partial_{ik}^2 \varphi \rangle \\ &= \langle -\operatorname{div}(\bar{\sigma} \operatorname{div} V) + \operatorname{div}(V \operatorname{div} \bar{\sigma}) + \operatorname{div}(DV\bar{\sigma}), \varphi \rangle \\ &= \langle \operatorname{div}[(DV - \operatorname{div} VI)\bar{\sigma}], \varphi \rangle - \langle \lambda \operatorname{div} V, \varphi \rangle, \end{aligned}$$

where we have used the equality  $-\operatorname{div} \bar{\sigma} = \lambda$  (holding by (2.5) applied with  $g(t) = -\lambda t$ ).

Now, we are in a position to rewrite  $m_\infty$  similarly as in Theorem 3.5 (ii). Indeed, one can check that the proof of Theorem 3.5 (ii) given in section 6 continues to work, thanks in particular to the identity (7.10) and to the  $W^{2,q}$  regularity of  $\bar{u}$  for  $q < (p - 1)/(p - 2)$ . Thus, defining  $\mathcal{C}_D(\bar{u}, V)$  as in (3.10) (with  $f(z) = |z|^p/p$ ), letting  $\mathcal{Q}(\bar{u}, \cdot)$  be given by (7.7), and setting  $\bar{\theta}_V = \langle V, \nabla\bar{u} \rangle$ , we obtain

$$\begin{aligned} \liminf_{\varepsilon \rightarrow 0} r_\varepsilon(V) &\geq m_\infty = \int_{\partial\Omega} \mathcal{C}_D(\bar{u}, V) d\mathcal{H}^{n-1} - \inf_{w \in C_0^\infty(\Omega)} \mathcal{Q}(\bar{u}, w - \bar{\theta}_V) \\ (7.11) \qquad &= \int_{\partial\Omega} \mathcal{C}_D(\bar{u}, V) d\mathcal{H}^{n-1} - \inf_{w \in H_{\rho,0}^{1,2}(\Omega)} \mathcal{Q}(\bar{u}, w - \bar{\theta}_V); \end{aligned}$$

here  $H_{\rho,0}^{1,2}(\Omega)$  denotes the space of functions in  $H_\rho^{1,2}(\Omega)$  vanishing at  $\partial\Omega$ , and the last equality follows from the continuity of  $\mathcal{Q}(\bar{u}, \cdot)$  on  $W_\rho^{1,2}$ .

*Step 2 (upper bound).* Due to the growth of order  $p' \in (1, 2]$  of the Fenchel conjugate  $f^*(z^*) = |z^*|^{p'}/p'$ , in order bound from above  $r_\varepsilon(V)$ , we need to set up an approximation argument. Roughly speaking, we cover almost all  $\Omega$  with a suitable family of subdomains of  $\Omega$  in which the Hessian of  $f^*$  is bounded from above, and then we pass to the limit. More precisely, as  $\nabla\bar{u}$  is a continuous function which is strictly positive outside  $S$ , we can construct an increasing sequence of open sets  $\Omega_h \uparrow (\Omega \setminus S)$  such that, for every  $h \in \mathbb{N}$ ,  $|\nabla\bar{u}| > 1/h$  in  $\Omega_h$ , and the boundary  $\Gamma_h := \partial\Omega_h \setminus \partial\Omega$  is smooth and has a positive distance from  $\partial\Omega$ . For every fixed  $h$ , we follow the same procedure as that adopted for the proof of the inequality (4.8) in Lemma 4.2, in the variant when  $g$  is linear, described in section 7.1. We choose the fields  $\eta_k$  appearing in (7.3) as done in (7.4), with the additional condition that  $\eta_k = 0$  in  $\Omega \setminus \Omega_k$  (note that this is possible thanks to the assumption made on the support of the deformation field  $V$ ). We infer that, for every fixed  $h$ ,

$$(7.12) \qquad \limsup_{\varepsilon} r_\varepsilon(V) \leq m_h := \inf_{\substack{\eta \in X(\Omega; \mathbb{R}^n), \\ \operatorname{div} \eta = -\lambda \operatorname{div} V \text{ in } \Omega \\ \eta = 0 \text{ in } \Omega \setminus \Omega_h}} E^*(\eta, V),$$



where  $E^*(\eta, V)$  is defined according to (7.1) (with  $f^*(z^*) = |z^*|^{p'}/p'$ ).

By applying Lemma 8.5 and exploiting the regularity of  $\bar{u}$ , we may rewrite  $m_h$  in primal form as

$$(7.13) \quad m_h = \int_{\partial\Omega} \mathcal{C}_D(\bar{u}, V) d\mathcal{H}^{n-1} - \inf_{w \in V_h} \mathcal{Q}_h(\bar{u}, w - \bar{\theta}_V),$$

where  $V_h$  denotes the subspace of  $H^1(\Omega_h)$  of functions having zero trace on  $\partial\Omega$ , and

$$\mathcal{Q}_h(\bar{u}, v) := 2 \int_{\Omega_h} \langle P(\bar{u})\nabla v, \nabla v \rangle dx.$$

Now, in order to bound from above the upper limit of  $m_h$  as  $h \rightarrow +\infty$ , we are going to bound from below the infimum appearing on the r.h.s. of (7.13). We start by noticing that such an infimum can be equivalently taken in the space  $W_{\rho,0}^{1,2}(\Omega)$  of functions in  $W_\rho^{1,2}(\Omega)$  vanishing at  $\partial\Omega$ . Let  $\{w_h\} \subset W_{\rho,0}^{1,2}(\Omega)$  be a sequence of minimizers for  $\mathcal{Q}_h(\bar{u}, \cdot - \bar{\theta}_V)$ . For every fixed  $k \in \mathbb{N}$ , such a sequence is bounded in  $H^1(\Omega_k)$ , so that it admits a subsequence weakly converging in  $H^1(\Omega_k)$  to some element  $w^{(k)}$ . By a diagonalization argument, we can choose the same subsequence for every  $k$ , and hence the restriction of  $w^{(k)}$  to  $\Omega_l$  for  $l < k$  agrees with  $w^{(l)}$ . Hence we obtain a (not relabeled) subsequence of  $w_h$  and an element  $\hat{w} \in W_{\rho,0}^{1,2}(\Omega)$  such that  $w_h$  converges weakly to  $\hat{w}$  in  $H^1(\Omega_k)$  for every  $k$ . Then, by Fatou's lemma and monotone convergence, we get

$$(7.14) \quad \liminf_h \mathcal{Q}_h(\bar{u}, w_h - \bar{\theta}_V) \geq \mathcal{Q}(\bar{u}, \hat{w} - \bar{\theta}_V) \geq \inf_{w \in W_{\rho,0}^{1,2}(\Omega)} \mathcal{Q}(\bar{u}, w - \bar{\theta}_V).$$

By combining (7.12), (7.13), and (7.14), we obtain

$$(7.15) \quad \limsup_\varepsilon r_\varepsilon(V) \leq m_\infty^* := \int_{\partial\Omega} \mathcal{C}_D(\bar{u}, V) d\mathcal{H}^{n-1} - \inf_{w \in W_{\rho,0}^{1,2}(\Omega)} \mathcal{Q}(\bar{u}, w - \bar{\theta}_V).$$

*Step 3 (conclusion).* We finally need to show that the lower and upper bounds  $m_\infty$  and  $m_\infty^*$  in (7.11) and (7.15) agree, and that they are equal to the expression on the r.h.s. of (7.9). We first observe that, by arguing as in Remark 3.8, the integral over  $\partial\Omega$  of  $\mathcal{C}_D(\bar{u}, V)$  appearing in the expression (7.11) of  $m_\infty$  can be rewritten as in (7.9). Then it only remains to prove that no Lavrenteev phenomenon occurs for the infimum problems appearing in (7.11) and (7.15). In other words, after a translation, we are reduced to showing that

$$(7.16) \quad \inf_{w \in W_\rho^{1,2}(\Omega)} \{ \mathcal{Q}(\bar{u}, \cdot) : w = -\bar{\theta}_V \text{ on } \partial\Omega \} = \inf_{w \in H_\rho^{1,2}(\Omega)} \{ \mathcal{Q}(\bar{u}, \cdot) : w = -\bar{\theta}_V \text{ on } \partial\Omega \}.$$

The validity of (7.16) is an immediate consequence of our assumption (7.8) and of the continuity of  $\mathcal{Q}(\bar{u}, \cdot)$  in  $W_\rho^{1,2}(\Omega)$ .  $\square$

**7.3. Perspectives.** A natural perspective is the possible extension of our results to the case of convex *nonsmooth* integrands  $f$  and  $g$ . The main difficulty is that in this case one can no longer exploit the second order differentiability property for integral functionals stated in Lemma 8.1. However, we expect that in some cases the second order shape derivative still exists and admits a representation formula similar to (3.6), with the quadratic form  $\mathcal{Q}(\bar{u}, \cdot)$  (formerly associated with the second order differentials

of  $f$  and  $g$ ) replaced by a suitable convex, positively 2-homogeneous, nonquadratic function. This kind of generalization would be useful in applications: for instance, the shape functional obtained by taking the function  $f(z)$  equal to  $\frac{|z|^2}{2} + \frac{1}{2}$  if  $|z| \geq 1$  and  $|z|$  if  $|z| < 1$ , and the function  $g(v)$  equal to  $-\lambda v$  (for some  $\lambda \in \mathbb{R}$ ), is related to the optimization of thin rods in a torsion regime (see [2, 9]), and studying its second order shape derivative might be helpful in order to investigate the occurrence of homogenization regions in an optimal design. (For the computation of the first order shape derivative in this case, see Example 3.9 (ii) in [8].)

Another perspective is trying to understand whether the results obtained in section 7.2 may entail some useful information on the second order shape derivative of the shape functional  $J_\infty(\Omega)$  obtained as the limit as  $p \rightarrow +\infty$  of the  $p$ -torsional rigidity functionals  $J_p(\Omega)$  defined in (3.16). Actually, up to constant multiple, it is well known that here holds  $J_\infty(\Omega) = \int_\Omega d_{\partial\Omega}(x) dx$  and  $\lim_p u_p(x) = d_{\partial\Omega}(x)$ , where  $d_{\partial\Omega}$  is the distance function from  $\partial\Omega$ , and  $u_p$  is the unique solution to  $J_p(\Omega)$  (see [4, 7, 40]).

**8. Appendix.**

LEMMA 8.1. *Let  $\phi : \mathbb{R}^n \rightarrow \mathbb{R}$  be a strongly convex function of class  $C^2$  satisfying growth conditions of order 2 from above and below, and let  $I_\phi$  be the integral functional defined on  $L^2(\Omega; \mathbb{R}^n)$  by*

$$(8.1) \quad I_\phi(z) := \int_\Omega \phi(z(x)) dx.$$

*Let  $z_0$  be a fixed vector field in  $L^\infty(\Omega; \mathbb{R}^n)$  and, for  $h \in L^2(\Omega; \mathbb{R}^n)$ , set  $q_\phi(h) := \frac{1}{2} \int_\Omega \langle \nabla^2 \phi(z_0)h, h \rangle dx$  and*

$$(8.2) \quad \Delta_{\varepsilon,\phi}(h) := \frac{I_\phi(z_0 + \varepsilon h) - I_\phi(z_0) - \varepsilon \langle \nabla \phi(z_0), h \rangle_{L^2}}{\varepsilon^2}.$$

*Then*

- (i)  $I_\phi$  is of class  $C^1$  on the Hilbert space  $L^2(\Omega; \mathbb{R}^n)$ , and  $\nabla I_\phi(z) = \nabla \phi(z)$ ;
- (ii)  $\Delta_{\varepsilon,\phi}$  Mosco converges in  $L^2(\Omega; \mathbb{R}^n)$  to  $q_\phi$  as  $\varepsilon \rightarrow 0$ ;
- (iii)  $I_\phi$  is second order differentiable at  $z_0$  with respect to  $L^\infty$  variations; namely, for every  $h \in L^\infty(\Omega; \mathbb{R}^n)$ , it holds that  $\Delta_{\varepsilon,\phi}(h) \rightarrow q_\phi(h)$  as  $\varepsilon \rightarrow 0$ .

*Proof.* For statements (i) and (ii), see [38, Proposition 4.1 and Corollary 3.2]. Let us now prove (iii). For a fixed  $h \in L^\infty(\Omega; \mathbb{R}^n)$ , the Mosco convergence property stated in (ii) implies that

$$q_\phi(h) \leq \liminf_{\varepsilon \rightarrow 0} \Delta_{\varepsilon,\phi}(h).$$

In order to prove that  $\limsup_\varepsilon \Delta_{\varepsilon,\phi}(h) \leq q_\phi(h)$ , we exploit the second property given by the Mosco convergence: there exists a sequence  $h_\varepsilon \in L^2(\Omega; \mathbb{R}^n)$  such that  $h_\varepsilon \xrightarrow{L^2} h$  and  $q_\phi(h) = \lim_{\varepsilon \rightarrow 0} \Delta_{\varepsilon,\phi}(h_\varepsilon)$ . We note that the function  $\Delta_{\varepsilon,\phi}$  is convex, and therefore  $\Delta_{\varepsilon,\phi}(h) - \Delta_{\varepsilon,\phi}(h_\varepsilon) \leq \langle \nabla \Delta_{\varepsilon,\phi}(h), h - h_\varepsilon \rangle_{L^2}$ . If we prove that, for  $\varepsilon > 0$  small enough,

$$(8.3) \quad \|\nabla \Delta_{\varepsilon,\phi}(h)\|_{L^2} \leq C,$$

we are done, since we infer

$$\limsup_\varepsilon \Delta_{\varepsilon,\phi}(h) - q_\phi(h) = \limsup_\varepsilon \left( \Delta_{\varepsilon,\phi}(h) - \Delta_{\varepsilon,\phi}(h_\varepsilon) \right) \leq \lim_{\varepsilon \rightarrow 0} C \|h_\varepsilon - h\|_{L^2} = 0.$$

We conclude by proving the claim (8.3): we note that  $\nabla \Delta_\varepsilon(h) = [\nabla \phi(z_0 + \varepsilon h) - \nabla \phi(z_0)]/\varepsilon$ , and hence (8.3) follows from the local boundedness of the Hessian matrix

$\nabla^2\phi$  and by recalling that by assumption there exists  $R > 0$  such that  $\|z_0 + th\|_{L^\infty} \leq R$  for  $t$  small enough.  $\square$

LEMMA 8.2. *Let  $X$  be a normed vector space, and let  $X^*$  be its topological dual. We denote by  $\langle \cdot, \cdot \rangle$  the duality product. Let  $h : X \rightarrow \mathbb{R} \cup \{+\infty\}$  be a proper function. Then, for every  $a \in X$  and  $b \in X^*$ , there holds*

$$(h(\cdot - a))^*(z^*) = h^*(z^*) + \langle a, z^* \rangle, \quad (h(\cdot) + \langle b, \cdot \rangle)^*(z^*) = h^*(z^* - b).$$

*Proof.* The statement follows in a straightforward manner by using the definition of the Fenchel conjugate.  $\square$

LEMMA 8.3. *Let  $A$  be a positive definite  $n \times n$  matrix, and let  $Q_A$  denote the associated quadratic form, defined as  $Q_A(x) := \frac{1}{2}\langle Ax, x \rangle$ . Then  $(Q_A)^* = Q_{A^{-1}}$ .*

*Proof.* See [41, Chapter III].  $\square$

LEMMA 8.4. *Let  $X$  be a Banach space, and let  $h : X \rightarrow \mathbb{R}$  be a strongly convex function of class  $C^2$ . Then  $\text{dom}(h^*)$  has nonempty interior,  $h^*$  is  $C^2$  on the interior of  $\text{dom}(h^*)$ , and  $x^* = \nabla h(x)$  with  $x \in X$  implies  $x = \nabla h^*(x^*)$  and  $\nabla^2 h^*(x^*) = (\nabla^2 h(x))^{-1}$ .*

*Proof.* See [20, Proposition 10 in section 2 of Chapter II].  $\square$

LEMMA 8.5. *Let  $Y, Z$  be Banach spaces. Let  $A : Y \rightarrow Z$  be a linear operator with dense domain  $D(A)$ . Let  $\Phi : Y \rightarrow \mathbb{R} \cup \{+\infty\}$  be convex, and let  $\Psi : Z \rightarrow \mathbb{R} \cup \{+\infty\}$  be convex lower semicontinuous. Assume there exists  $u_0 \in D(A)$  such that  $\Phi(u_0) < +\infty$  and  $\Psi$  is continuous at  $Au_0$ . Let  $Z^*$  denote the dual space of  $Z$ ,  $A^*$  the adjoint operator of  $A$ , and  $\Phi^*, \Psi^*$  the Fenchel conjugates of  $\Phi, \Psi$ . Then*

$$(8.4) \quad - \inf_{u \in Y} \left\{ \Psi(Au) + \Phi(u) \right\} = \inf_{\sigma \in Z^*} \left\{ \Psi^*(\sigma) + \Phi^*(-A^* \sigma) \right\},$$

and the infimum on the r.h.s. is achieved.

Furthermore,  $\bar{u}$  and  $\bar{\sigma}$  are optimal for the l.h.s. and the r.h.s. of (8.4), respectively, if and only if there holds  $\bar{\sigma} \in \partial\Psi(A\bar{u})$  and  $-A^*\bar{\sigma} \in \partial\Phi(\bar{u})$ .

*Proof.* See [6, Proposition 14].  $\square$

**Acknowledgment.** We thank B. Sciunzi for pointing out some useful bibliographical references.

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