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A. Boulkhemair, A. Chakib, A. Nachaoui, A A Niftiyev, A Sadik. On a numerical shape optimization approach for a class of free boundary problems. 2019. hal-02073376v1

**HAL Id: hal-02073376**

**<https://hal.science/hal-02073376v1>**

Preprint submitted on 20 Mar 2019 (v1), last revised 8 Jul 2019 (v2)

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# On a numerical shape optimization approach for a class of free boundary problems

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*Dedicated to the memory of Professor Agaddin A. Niftiyev.*

March 19th, 2019

## Abstract

This paper is devoted to a numerical method for the approximation of a class of free boundary problems of Bernoulli's type, reformulated as optimal shape design problems with appropriate shape functionals. We show the existence of the shape derivative of the cost functional on a class of admissible domains and compute its shape derivative by using the formula proposed in [5, 6], that is, by means of support functions. On the numerical level, this allows us to avoid the tedious computations of the method based on vector fields. A gradient method combined with boundary element method are performed for the approximation of this problem, in order to overcome the re-meshing task required by the finite element method. Finally, we present some numerical results and simulations concerning practical applications, showing the effectiveness of the proposed approach.

**Keywords** shape optimization, free boundary problem, Bernoulli problem, optimal solution, shape derivative, convex domain, support function, cost functional.

## 1 Introduction

The main target of shape optimization is to provide a common and systematic framework for optimizing structures described by various practical physical or mechanical models; especially, hydrodynamics, elasticity, geophysics and aerodynamics models. Shape optimization problems consist in finding the optimal shape (or domain) which

minimizes a certain cost functional under given constraints such as a partial differential equation defined on the variable domain. Since the seventies of the last century, many authors investigated the shape optimization field and remarkable progress has been achieved in shape and topology optimization. In fact, the growing interest in this field reflects a growing sophistication in structural analysis and optimization which allow solving more and more difficult shape optimization problems. However, one may say that no uniform approach to shape optimization problems has yet emerged.

The numerical investigation of shape optimization problems is based on the study of the first variation of the cost functional, and in particular on the computation of its gradient. So, as the variation of the domain is characterized by the variation of its boundary, in this process arise both numerical and theoretical difficulties. The method of variation of domains using vector fields, introduced by C  a [11] and developed then, among others, by Murat, Simon, Sokolowski, Delfour and Zol  sio [12, 23], Allaire [2] and Henrot and Pierre [16], allowed to solve some of these issues. But these techniques themselves present some difficulties from both theoretical and numerical point of view. For example, when one wants to connect the set of admissible domains with vector fields, one has to suppose high smoothness conditions on the initial data in order to differentiate functions depending on the domain. Note also that to solve a conditional shape optimization problem by this method is yet more complicated and usually requires to reduce it to a non conditional problem (for example, by Lagrange’s multipliers method). Moreover, the numerical implementation of the shape optimization problem requires to extend the vector field (obtained only on the boundary) to all the domain or to re-mesh at each iteration of the process, and both approaches are expensive (see for example Allaire [2]). In this paper, in order to avoid part of the above issues, we define and use another way of variation of domains, a way that is linked to the convexity context and based on the Minkowski sum. Recall that for any convex bounded domain the support function of this domain is a continuous convex and positive homogeneous function. Conversely, it is known that each continuous convex and positive homogeneous function is the support function of a convex bounded set (sub-differential of this function at the origin). Using this, the variation of the domain is clearly characterized by the variation of the corresponding support function. Moreover, according to the works [5–7, 21], one can express the shape derivative of volume cost functionals by means of support functions, and when solving problems numerically one gets a support function at each step of the implementation, the domain being recovered as the subdifferential of the support function. This is why we think that, in the context of convexity and numerical approximation, the use of support functions is more advantageous than that of vectors fields.

More precisely, we are interested in this paper in a shape optimization problem for solving numerically the so-called Bernoulli’s free boundary problem or Bernoulli’s problem. Note that many applications to fluid dynamic and industrial application lead to such a free boundary problem. As an example, let us quote the problem where the design of an annular capacitor is required in which one of the plates is prescribed while the other must be determined, so that the intensity of the electrostatic field remains constant thereon. Depending on whether we describe the internal or external plate, we have an exterior or an interior Bernoulli problem. This class of problems has been extensively studied theoretically by several authors, see for example [1, 10, 13, 19] and references therein. In practice, a way to study this type of problem is to transform it into a shape optimization problem where one of the Dirichlet or Neumann boundary condition on the free boundary is included into a cost functional while the other boundary condition is considered as part of an appropriate state problem. The question of existence for such shape optimization formulations is studied for example in [14] or [8], using the  $C^2$  or  $C^1$  regularity of the free boundary. On the numerical level, approximations of such shape optimization formulations of this free boundary problem can be found in the literature, using techniques that are different from ours. For example, a variational approach to shape derivatives is introduced in [18], a fictitious domain approach for solving this free boundary problem is proposed in [15], a pseudo-solid approach for solving its discrete problem is introduced in [25], a shape optimization approach by tracking the Neumann data and using the lagrangian formulation is developed in [22] and an iterative method based on a level-set formulation and boundary element method is proposed in [4, 20]. In this

work, we propose a shape optimization formulation of this problem using a volume cost functional. We develop a method for the shape differentiability of this cost functional, and establish the expression for its shape derivative via support functions, using the formula of shape derivative with respect to convex domains proposed in [5, 6]. Then, we propose a gradient method for solving the shape optimization problem. Thereby, during the numerical solving of such problem, we get at each step support functions instead of domains. In this process, the discretization of the state problem is done using the boundary element method [9], while in most of shape optimization approaches, finite element method has been employed for sensitivity computation. However, the approaches generally suffer certain drawbacks; indeed, in shape optimization, cumbersome parameterization of design domain is required and time consuming re-meshing task is also necessary. Finally, we give some numerical results showing the effectiveness of the proposed approach.

The outline of the paper is as follows. In the second section, we present the shape optimization formulation for the approximation of Bernoulli's problem. In the third section, we give some preliminary results on the existence of the shape derivative of the cost functional on the considered family of admissible domains and establish the expression for its shape derivative by means of support functions. In the fourth section, we propose an algorithm for the approximation of the problem, based on a gradient method combined with the boundary element discretization. Finally, in order to illustrate the main result of this paper, the last section is focused on some numerical simulation applied to practical situations.

## 2 Shape optimization formulation of Bernoulli's problem

Let  $D$  be a fixed smooth convex bounded and open subset of  $\mathbb{R}^n$  ( $n \geq 2$ ). Let  $\Omega$  be a doubly connected open subset of  $D$ , that is,  $\Omega$  is of the form  $\Omega = \Omega_2 \setminus \Omega_1$ , where  $\Omega_2$  is a smooth convex bounded and open subset of  $D$  and  $\Omega_1$  is a smooth closed and bounded subset of  $\Omega_2$ . We denote by  $\Gamma_1$  the boundary of  $\Omega_1$  which is also the fixed inside part of the boundary of  $\Omega$  and by  $\Gamma_2$  the boundary of  $\Omega_2$  which is at the same time the outside free boundary of  $\Omega$  (see Figure 2).

Let us consider the external free boundary Bernoulli problem which consists in finding the free boundary  $\Gamma_2$  and  $u = u(x)$  solution of the problem

$$(P) \begin{cases} -\Delta u = f & \text{in } \Omega = \Omega_2 \setminus \Omega_1, \\ u = \varphi_1 & \text{on } \Gamma_1, \\ u = \varphi_2 & \text{on } \Gamma_2, \\ \partial_{\nu_2} u = \partial_{\nu_2} G & \text{on } \Gamma_2, \end{cases} \quad (1)$$

where  $f$ ,  $\varphi_1$ ,  $\varphi_2$  and  $G$  are given functions,  $\nu_2$  is the outward unit normal vector to  $\Gamma_2$  and  $\partial_{\nu_2} u = \langle \nabla u|_{\Gamma_2}, \nu_2 \rangle$ , where  $\langle \cdot, \cdot \rangle$  denotes the scalar product in  $\mathbb{R}^n$ .

Let us first remark that in the free boundary problem (1) two boundary conditions must be satisfied on  $\Gamma_2$ . This suggests to reformulate such a problem as an optimal shape design one to be able to solve it numerically. We refer for example to [8, 14, 18] where the idea of reformulating a free boundary problem into a shape optimization one is used. Here, it consists in finding  $\Gamma_2$  and  $u$  solution of the shape optimization problem

$$\left\{ \begin{array}{l} \text{Minimize } \mathcal{J}(\Omega, u_\Omega) \text{ for all } \Omega \in \mathcal{O} \\ \text{where } \mathcal{J}(\Omega, u_\Omega) = \int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 d\sigma \\ \text{and } u_\Omega \text{ is solution of} \\ (PE) \left\{ \begin{array}{ll} -\Delta v = f & \text{in } \Omega = \Omega_2 \setminus \Omega_1, \\ v = \varphi_1 & \text{on } \Gamma_1, \\ \partial_{\nu_2} v = \partial_{\nu_2} G & \text{on } \Gamma_2, \end{array} \right. \end{array} \right. \quad (2)$$

where  $\mathcal{O}$  is a set of admissible domains.

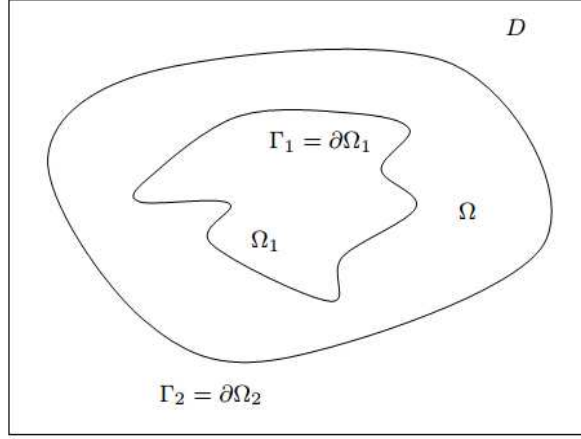


Figure 1: The considered domain  $\Omega$ .

In order to avoid the difficulties that arise because the cost functional introduced in the shape optimization problem (2) is defined by a surface integral, we propose in what follows a new formulation where the surface integral is replaced by a volume integral. This moreover will allow us to be able to use the shape derivative formulas developed in [5, 6].

## 2.1 New formulation of the problem

In order to propose a shape optimization formulation of the problem, we will first give some preliminary results on convex domains.

**Lemma 1.** *Let  $\Omega$  an open bounded convex subset of  $\mathbb{R}^n$  of class  $C^k$ , ( $k \geq 1$ ). Then, for all fixed  $y \in \Omega$ , we have*

$$\langle \nu(x), x - y \rangle > 0, \quad \text{for all } x \in \partial\Omega,$$

where  $\nu$  is the exterior unit normal vector to  $\partial\Omega$ .

In particular, if  $0 \in \Omega$ , we get

$$\langle \nu(x), x \rangle > 0, \quad \text{for all } x \in \partial\Omega.$$

**Proof.**

Let  $\Omega$  be an open convex domain. Assume first that  $0 \in \Omega$ , according to [12], there exists a convex function  $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}$  such that

$$\Omega = \{x \in \mathbb{R}^n / \varphi(x) < 0\} \text{ et } \partial\Omega = \{x \in \mathbb{R}^n / \varphi(x) = 0\}.$$

There exists also  $W$  a neighborhood of  $\Gamma$  such that

$$\varphi \in C^k(W), \quad \nabla\varphi \neq 0 \text{ on } W \text{ and } \nu = \frac{\nabla\varphi}{\|\nabla\varphi\|}.$$

Let  $x \in \partial\Omega$ , by the characterization of the convexity at the points 0 and  $x$  we have

$$\langle \nabla\varphi(x), 0 - x \rangle \leq \varphi(0) - \varphi(x).$$

Or since we have  $\varphi(0) < 0$  and  $\varphi(x) = 0$ , then

$$\langle \nabla\varphi(x), x \rangle \geq -\varphi(0) > 0.$$

Thus multiplying by  $\frac{1}{\|\nabla\varphi(x)\|}$ , we get

$$\langle \nu(x), x \rangle > 0.$$

If  $0 \notin \Omega$ , for a fixed  $y \in \Omega$ , we consider a translation of  $\Omega$  denoted by  $\Omega - y$  which is an open bounded convex subset of  $\mathbb{R}^n$  of class  $C^k$ , such that  $0 \in \Omega - y$ . Hence by application of the above result we obtain,

$$\langle \nu_{\Omega-y}(x), x \rangle > 0, \quad \text{for all } x \in \partial\Omega - y.$$

Since  $\nu_{\Omega-y}(x - y) = \nu(x)$  for all  $x \in \partial\Omega$ , we get

$$\langle \nu(x), x - y \rangle > 0, \quad \text{for all } x \in \partial\Omega.$$

■

Let now  $\Omega$  be a doubly connected domain such that  $\Omega = \Omega_2 \setminus \Omega_1$  where  $\Omega_2$  is a convex open subset of  $D$  of class  $C^2$  and  $\Omega_1$  is a closed smooth subset of  $\Omega_2$ . For the sake of simplicity, we suppose that  $0 \in \Omega_1$ . Then, according to Lemma 1, we have

$$(\nu_2(x), x) > 0, \quad \text{for all } x \in \Gamma_2.$$

So,

$$\int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_2(x), x \rangle d\sigma \geq 0.$$

As a result, we are able to propose as shape optimization formulation for the approximation of the free boundary problem (1) the following one

$$\left\{ \begin{array}{l} \text{Minimize } \mathcal{J}(\Omega, u_\Omega) \text{ for all } \Omega \in \mathcal{O} \\ \text{where } \mathcal{J}(\Omega, u_\Omega) = \int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_2(x), x \rangle d\sigma \\ \text{and } u_\Omega \text{ is solution of} \\ (PE) \left\{ \begin{array}{ll} -\Delta v = f & \text{in } \Omega = \Omega_2 \setminus \Omega_1, \\ v = \varphi_1 & \text{on } \Gamma_1, \\ \partial_{\nu_2} v = \partial_{\nu_2} G & \text{on } \Gamma_2, \end{array} \right. \end{array} \right. \quad (3)$$

where the set of admissible domains  $\mathcal{O}$  is defined by

$$\mathcal{O} = \{\Omega \subset \mathbb{R}^n / \Omega = \Omega_2 \setminus \Omega_1, \quad \Omega_2 \in \mathcal{O}(D)\},$$

and

$$\mathcal{O}(D) = \{\Omega \subset \mathbb{R}^n / \Omega \text{ is an open, } \Omega_1 \subset \Omega, \overline{\Omega} \subset D \text{ and } \Omega \in \mathcal{C}^2 \cap \mathcal{K}\},$$

here  $\mathcal{K}$  denotes the set of all convex domains,  $\mathcal{C}^2$  denotes the space of domains with boundaries of class  $C^2$ ,  $\Omega_1$  is a smooth closed bounded subset of  $\mathbb{R}^n$  and  $D$  is a smooth convex domain of  $\mathbb{R}^n$  chosen sufficiently large.

In what follows, we propose a shape optimization formulation using rather a volume cost functional defined on  $\Omega$ . Indeed, since the domain  $\Omega$  is doubly connected, the exterior unit normal vector to  $\Omega$  is given by

$$\begin{aligned} \nu : \partial\Omega &\longrightarrow S^{n-1} \\ x &\longmapsto \nu(x) = \begin{cases} \nu_2(x) & \text{si } x \in \Gamma_2 \\ -\nu_1(x) & \text{si } x \in \Gamma_1. \end{cases} \end{aligned}$$

where  $\nu_k$ , for  $k = 1, 2$  is the exterior unit normal vector to  $\Omega_k$  and  $S^{n-1}$  is the unit sphere in  $\mathbb{R}^n$ .

Let us consider  $u_\Omega$  the solution of  $(PE)$  associated to  $\Omega = \Omega_2 \setminus \Omega_1$ , and using the fact that  $u_\Omega = \varphi_1$  on  $\Gamma_1$ , we get

$$\begin{aligned} \int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_2(x), (x) \rangle d\sigma &= \int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu(x), (x) \rangle d\sigma \\ + \int_{\Gamma_1} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu(x), (x) \rangle d\sigma &= \int_{\Gamma_1} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu(x), (x) \rangle d\sigma. \end{aligned}$$

Hence

$$\int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_2(x), (x) \rangle d\sigma = \int_{\Gamma} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu(x), (x) \rangle d\sigma - \int_{\Gamma_1} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_1(x), (x) \rangle d\sigma.$$

From the Stokes formula we obtain

$$\int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_2(x), (x) \rangle d\sigma = \int_{\Omega} \operatorname{div}((u_\Omega(x) - \varphi_2(x))^2 x) dx - \int_{\Gamma_1} (\varphi_1(x) - \varphi_2(x))^2 \langle \nu_1(x), (x) \rangle d\sigma,$$

where  $\operatorname{div}(v)$  designates the divergence of the vector  $v$ .

According to the Lemma 1, we have

$$\langle \nu_2(x), (x) \rangle > 0, \quad \forall x \in \Gamma_2.$$

Moreover, since  $u_\Omega = \varphi_1$  on  $\Gamma_1$ , we deduce

$$0 \leq \int_{\Gamma_2} (u_\Omega(x) - \varphi_2(x))^2 \langle \nu_2(x), (x) \rangle d\sigma = \int_{\Omega} \operatorname{div}((u_\Omega(x) - \varphi_2(x))^2 x) dx - \int_{\Gamma_1} (\varphi_1(x) - \varphi_2(x))^2 \langle \nu_1(x), (x) \rangle d\sigma.$$

Since the term  $\int_{\Gamma_1} (\varphi_1(x) - \varphi_2(x))^2 \langle \nu_1(x), (x) \rangle d\sigma$  do not depend on the variation of  $\Omega_2$ , we can propose as shape optimization formulation for the approximation of the free boundary problem (1), the following one

$$(PO) \left\{ \begin{array}{l} \text{Minimize } \mathcal{J}(\Omega, u_\Omega) \text{ for all } \Omega \in \mathcal{O} \\ \text{where } \mathcal{J}(\Omega, u_\Omega) = \int_{\Omega} \operatorname{div}((u_\Omega(x) - \varphi_2(x))^2 x) dx \\ \text{and } u_\Omega \text{ is solution of} \\ (PE) \left\{ \begin{array}{ll} -\Delta v = f & \text{in } \Omega = \Omega_2 \setminus \Omega_1, \\ v = \varphi_1 & \text{on } \Gamma_1, \\ \partial_{\nu_2} v = \partial_{\nu_2} G & \text{on } \Gamma_2, \end{array} \right. \end{array} \right. \quad (4)$$

In the sequel, we will propose a numerical method of the approximation of this problem based on a gradient method. This requires to study the first variation or differentiability of the cost functional with respect to the family of domains  $\mathcal{O}$ . For this, we shall adapt the formulas proposed in [5, 6] to be able to express the shape derivative of the cost functional by means of support functions.

### 3 Shape derivative of the cost functional

In order to obtain an expression of shape derivative of the cost functional for the shape optimization problem (4), we begin first by recalling and adapting the result on the shape derivative formulas given in [5, 6] for the class of doubly connected domains  $\mathcal{O}$ .

#### 3.1 Preliminaries

We start this section by recalling some definitions on convex bounded domains and the associated support functions [24]. To any bounded convex domain  $\Omega$ , one can associate its support function defined by

$$P_\Omega : y \in \mathbb{R}^n \mapsto P_\Omega(y) = \max_{x \in \Omega} \langle y, x \rangle \in \mathbb{R}.$$

which is a continuous, convex and positively homogeneous function.

The opposite statement is also true, for any continuous, convex, positively homogeneous function  $P(x)$  there exists a unique convex bounded set  $\Omega$ , such that  $P(x)$  is its support function, i.e.  $P(x) = P_\Omega(x)$ , where  $\Omega$  is obtained as a sub-differential of its support function at the origin :

$$\overline{\Omega} = \partial P(0) := \{\xi \in \mathbb{R}^n \mid \langle \xi, y \rangle \leq P(y), \forall y \in \mathbb{R}^n\}.$$

In the sequel, in order to express the shape derivative formula of the cost functional, we propose a technique of deformation [17] which consists in defining the deformation of  $\Omega$  by  $\Omega' \in \mathcal{O}(D)$ , as follows  $\Omega_\varepsilon = \Omega + \varepsilon \Omega'$ , for  $\varepsilon \in [0, 1]$ . This in fact allow us to avoid the tedious use of the shape derivative method based on the vector fields and it permits, as we can see, to express the shape derivative of the cost functional with respect to support functions instead of vector fields.

For this, recall first the shape derivative formula for a volume integral shape functional  $J$  to type

$$\Omega \in \mathcal{O}(D) \mapsto J(\Omega) = \int_\Omega f(x) dx,$$

where  $f \in W^{1,1}(D)$ . According to [5, 6], we have

**Theorem 1.** *Let  $\Omega, \Omega' \in \mathcal{O}(D)$ , we have that the shape derivative of  $J$  at  $\Omega \in \mathcal{O}(D)$  is given by*

$$\lim_{\varepsilon \rightarrow 0^+} \frac{J(\Omega_\varepsilon) - J(\Omega)}{\varepsilon} = \int_{\partial\Omega} f(x) P_{\Omega'}(\nu(x)) d\sigma(x),$$

where  $\Omega_\varepsilon = \Omega + \varepsilon \Omega'$  and  $\nu$  denotes the exterior unit normal vector to  $\Omega$ .

**Remark 1.** *If we take as deformation of  $\Omega$  the domain  $\Omega_\varepsilon = (1 - \varepsilon)\Omega + \varepsilon \Omega'$ , according to [5, 6], we obtain similar shape derivative formula of  $J$ , that is*

$$\lim_{\varepsilon \rightarrow 0^+} \frac{J(\Omega_\varepsilon) - J(\Omega)}{\varepsilon} = \int_{\partial\Omega} f(x) (P_{\Omega'}(\nu(x)) - P_\Omega(\nu(x))) d\sigma(x),$$

thereby, in the following, depending on what it is needed, we use one of the two deformations and consequently investigate the associated shape derivative formula.

Now, let  $\varepsilon \in ]0, 1[$  and let  $\Omega$  be an element of  $\mathcal{O}$ , then there exists  $\Omega_2 \in \mathcal{O}(D)$  such that  $\Omega = \Omega_2 \setminus \Omega_1$  and let  $\Omega'_2$  be an element of  $\mathcal{O}(D)$ . We denote by  $\Lambda_\varepsilon$  and  $\Omega_\varepsilon$  the domains defined by  $\Lambda_\varepsilon = \Omega_2 + \varepsilon \Omega'_2$  and  $\Omega_\varepsilon = \Lambda_\varepsilon \setminus \Omega_1$ .

We have also that

$$J(\Omega_\varepsilon) = \int_D \chi_{\Omega_\varepsilon} f(x) dx = \int_D (\chi_{\Lambda_\varepsilon} - \chi_{\Omega_1}) f(x) dx.$$

Hence, according to the Theorem 1, we get



$$\frac{d}{d\varepsilon} (J(\Omega_\varepsilon))|_{\varepsilon=0^+} = \frac{d}{d\varepsilon} (J(\Lambda_\varepsilon))|_{\varepsilon=0^+} = \int_{\Gamma_2} f(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x). \quad (5)$$

Consequently, we have the corollary

**Corollary 1.** *Let  $\Omega_2, \Omega'_2 \in \mathcal{O}(D)$ , we have that the shape derivative of  $J$  at  $\Omega = \Omega_2 \setminus \Omega_1 \in \mathcal{O}$ , is given by*

$$\lim_{\varepsilon \rightarrow 0^+} \frac{J((\Omega_2 + \varepsilon \Omega'_2) \setminus \Omega_1) - J(\Omega_2 \setminus \Omega_1)}{\varepsilon} = \int_{\Gamma_2} f(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x),$$

where  $\nu_2$  denotes the exterior unit normal vector to  $\Omega_2$ .

In the situation where the function  $f$  depends on domains, one can show the following result.

**Proposition 1.** *Let  $(f_\varepsilon)_{\varepsilon \in ]0,1[} \subset L^1(D)$  be a family of functions and let  $f_0 \in W^{1,1}(D)$  and  $f$  be a function such that  $f = \lim_{\varepsilon \rightarrow 0^+} \frac{1}{\varepsilon} (f_\varepsilon - f_0)$  in  $L^1(D)$ . Consider the function*

$$\varepsilon \in ]0,1[ \mapsto I(\varepsilon) = \int_{\Omega_\varepsilon} f_\varepsilon(x) dx \in \mathbb{R}.$$

Then we have

$$\lim_{\varepsilon \rightarrow 0^+} \frac{I(\varepsilon) - I(0)}{\varepsilon} = \int_{\Omega_2 \setminus \Omega_1} f(x) dx + \int_{\Gamma_2} f_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x). \quad (6)$$

where  $\nu_2$  denotes the exterior unit normal vector to  $\Omega_2$ .

**Proof.**

Let  $\varepsilon \in ]0,1[$ , we have

$$\frac{I(\varepsilon) - I(0)}{\varepsilon} = \frac{1}{\varepsilon} \left( \int_{\Omega_\varepsilon} f_\varepsilon(x) dx - \int_{\Omega_\varepsilon} f_0(x) dx \right) + \frac{1}{\varepsilon} \left( \int_{\Omega_\varepsilon} f_0(x) dx - \int_{\Omega_0} f_0(x) dx \right).$$

Then

$$\frac{I(\varepsilon) - I(0)}{\varepsilon} = \int_D \chi_{\Omega_\varepsilon} \left( \frac{1}{\varepsilon} (f_\varepsilon - f_0)(x) - f(x) \right) dx + \int_D \chi_{\Omega_\varepsilon}(x) f(x) dx + \frac{1}{\varepsilon} \left( \int_{\Omega_\varepsilon} f_0(x) dx - \int_{\Omega_0} f_0(x) dx \right).$$

First, we get that

$$\left| \int_D \chi_{\Omega_\varepsilon} \left( \frac{1}{\varepsilon} (f_\varepsilon - f_0)(x) - f(x) \right) dx \right| \leq \int_D \left| \left( \frac{1}{\varepsilon} (f_\varepsilon - f_0)(x) - f(x) \right) \right| dx \xrightarrow{\varepsilon \rightarrow 0^+} 0.$$

On the other hand, since we have that  $\chi_{\Omega_\varepsilon} = \chi_{\Lambda_\varepsilon} - \chi_{\Omega_1}$  and that the characteristic functions  $\chi_{\Lambda_\varepsilon}$  converge almost everywhere to the characteristic function  $\chi_{\Omega_2}$ , then from the Lebesgue convergence theorem in  $L^1(D)$  and by the use of formula (5), it follows that

$$\lim_{\varepsilon \rightarrow 0^+} \frac{I(\varepsilon) - I(0)}{\varepsilon} = \int_D \chi_\Omega f dx + \int_{\Gamma_2} f_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x).$$

Consequently we get

$$\lim_{\varepsilon \rightarrow 0^+} \frac{I(\varepsilon) - I(0)}{\varepsilon} = \int_\Omega f(x) dx + \int_{\Gamma_2} f_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x)$$

■

We have also the following result, which concerns the situation where we use a translation of domains.

**Corollary 2.** Let  $(f_\varepsilon)_{\varepsilon \in ]0,1[} \subset L^1(D)$  be a family of functions and let  $f_0 \in W^{1,1}(D)$  and  $f$  be a function such that  $f = \lim_{\varepsilon \rightarrow 0^+} \frac{1}{\varepsilon}(f_\varepsilon - f_0)$  in  $L^1(D)$ . Let  $a$  and  $b$  elements of  $\mathbb{R}^n$ . Consider the function

$$\varepsilon \in ]0,1[ \mapsto I(\varepsilon) = \int_{((\Omega_2+a)+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} f_\varepsilon(x) dx \in \mathbb{R}.$$

Then we have

$$\lim_{\varepsilon \rightarrow 0^+} \frac{I(\varepsilon) - I(0)}{\varepsilon} = \int_{(\Omega_2+a) \setminus \Omega_1} f(x) dx + \int_{\partial(\Omega_2+b)} f_0(x) P_{\Omega'_2+b}(\nu_{\Omega_2+a}(x)) d\sigma(x). \quad (7)$$

where  $\nu_{\Omega_2+a}$  denotes the exterior unit normal vector to  $\Omega_2 + a$ .

**Proof.**

Let  $\varepsilon \in ]0,1[$ , we have that

$$\begin{aligned} \frac{1}{\varepsilon} \left( \int_{((\Omega_2+a)+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} f_\varepsilon - \int_{(\Omega_2+a) \setminus \Omega_1} f_0 \right) &= \int_D \chi_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} \left( \frac{1}{\varepsilon}(f_\varepsilon - f_0) - f \right) + \int_D \chi_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} f \\ &\quad + \frac{1}{\varepsilon} \left( \int_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} f_0 - \int_{(\Omega_2+a) \setminus \Omega_1} f_0 \right). \end{aligned}$$

Then

$$\left| \int_D \chi_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} \frac{1}{\varepsilon}(f_\varepsilon - f_0) - f dx \right| \leq \int_D \left| \frac{1}{\varepsilon}(f_\varepsilon - f_0)(x) - f(x) \right| dx \xrightarrow{\varepsilon \rightarrow 0^+} 0.$$

On the other hand, we know that  $\chi_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} = \chi_{\Omega_2+a+\varepsilon(\Omega'_2+b)} - \chi_{\Omega_1}$ , since the characteristic functions  $\chi_{\Omega_2+a+\varepsilon(\Omega'_2+b)}$  converges almost everywhere to the characteristic function  $\chi_{(\Omega_2+a)}$ . Thus it follows from the Lebesgue convergence theorem in  $L^1(D)$  that  $\chi_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} f$  converge to  $\chi_{(\Omega_2+a) \setminus \Omega_1} f$  in  $L^1(D)$ . Then according to [5], we have

$$\lim_{\varepsilon \rightarrow 0^+} \frac{1}{\varepsilon} \left( \int_{(\Omega_2+a+\varepsilon(\Omega'_2+b)) \setminus \Omega_1} f_0 - \int_{(\Omega_2+a) \setminus \Omega_1} f_0 \right) = \int_{\partial(\Omega_2+a)} f_0(x) P_{\Omega'_2+b}(\nu_{(\Omega_2+a)}(x)) d\sigma(x).$$

Hence, we get

$$\lim_{\varepsilon \rightarrow 0^+} \frac{I(\varepsilon) - I(0)}{\varepsilon} = \int_{(\Omega_2+a) \setminus \Omega_1} f(x) dx + \int_{\partial(\Omega_2+a)} f_0(x) P_{\Omega'_2+b}(\nu_{\Omega_2+a}(x)) d\sigma(x). \quad (8)$$

■

The following result concerns the situation where  $f$  is written as a product of two functions depending on the domains.

**Corollary 3.** Let  $(f_\varepsilon)_{\varepsilon \in ]0,1[}$  and  $(g_\varepsilon)_{\varepsilon \in ]0,1[}$  be two families of functions in  $L^2(D)$  and let  $f_0 \in H^1(D)$ ,  $g_0 \in H^1(D)$  and  $f, g$  be functions such that  $f = \lim_{\varepsilon \rightarrow 0^+} \frac{1}{\varepsilon}(f_\varepsilon - f_0)$  in  $L^2(D)$  and  $g = \lim_{\varepsilon \rightarrow 0^+} \frac{1}{\varepsilon}(g_\varepsilon - g_0)$  in  $L^2(D)$ . Consider the function

$$\varepsilon \in ]0,1[ \mapsto F(\varepsilon) = \int_{\Omega_\varepsilon} f_\varepsilon g_\varepsilon(x) dx \in \mathbb{R}$$

Then we have

$$\lim_{\varepsilon \rightarrow 0^+} \frac{F(\varepsilon) - F(0)}{\varepsilon} = \int_{\Omega_2 \setminus \Omega_1} (g f_0 + f g_0)(x) dx + \int_{\Gamma_2} f_0 g_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x), \quad (9)$$

where  $\nu_2$  denotes the exterior unit normal vector to  $\Omega_2$ .

**Proof.**

Let  $\varepsilon \in ]0, 1[$ , we have

$$\frac{1}{\varepsilon} (f_\varepsilon g_\varepsilon - f_0 g_0) - f_0 g - f g_0 = (f_\varepsilon - f_0) \frac{1}{\varepsilon} (g_\varepsilon - g_0) + g_0 \left( \frac{1}{\varepsilon} (f_\varepsilon - f_0) - f \right) + f_0 \left( \frac{1}{\varepsilon} (g_\varepsilon - g_0) - g \right).$$

Using the Hölder inequality we get

$$\begin{aligned} \left\| \frac{1}{\varepsilon} (f_\varepsilon g_\varepsilon - f_0 g_0) - f_0 g - f g_0 \right\|_{L^1(D)} &\leq \|f_\varepsilon - f_0\|_{L^2(D)} \left\| \frac{g_\varepsilon - g_0}{\varepsilon} \right\|_{L^2(D)} + \|g_0\|_{L^2(D)} \left\| \frac{f_\varepsilon - f_0}{\varepsilon} - f \right\|_{L^2(D)} \\ &\quad + \|f_0\|_{L^2(D)} \left\| \frac{g_\varepsilon - g_0}{\varepsilon} - g \right\|_{L^2(D)} \end{aligned}$$

Using the fact that there exists  $M > 0$  such that, for all  $\varepsilon \in [0, 1[$ ,  $\left\| \frac{g_\varepsilon - g_0}{\varepsilon} \right\|_{L^2(D)} \leq M$  and  $\|f_\varepsilon - f_0\|_{L^2(D)}$  converge to 0 as  $\varepsilon \rightarrow 0$ , we obtain

$$\begin{aligned} \left\| \frac{1}{\varepsilon} (f_\varepsilon g_\varepsilon - f_0 g_0) - f_0 g - f g_0 \right\|_{L^1(D)} &\leq M \|f_\varepsilon - f_0\|_{L^2(D)} + \|g_0\|_{L^2(D)} \left\| \frac{f_\varepsilon - f_0}{\varepsilon} - f \right\|_{L^2(D)} \\ &\quad + \|f_0\|_{L^2(D)} \left\| \frac{g_\varepsilon - g_0}{\varepsilon} - g \right\|_{L^2(D)}, \end{aligned}$$

consequently

$$\lim_{\varepsilon \rightarrow 0^+} \left\| \frac{1}{\varepsilon} (f_\varepsilon g_\varepsilon - f_0 g_0) - f_0 g - f g_0 \right\|_{L^1(D)} = 0.$$

So using the Proposition 1 to the functional

$$\varepsilon \in ]0, 1[ \mapsto F(\varepsilon) = \int_{\Omega_\varepsilon} f_\varepsilon(x) g_\varepsilon(x) dx \in \mathbb{R},$$

we deduce that

$$\lim_{\varepsilon \rightarrow 0^+} \frac{F(\varepsilon) - F(0)}{\varepsilon} = \int_{\Omega_2 \setminus \Omega_1} (f_0 g + f g_0)(x) dx + \int_{\Gamma_2} f_0(x) g_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x). \quad (10)$$

■

### 3.2 Shape derivative of the optimal shape design problem

In this section, we state the main theoretical result of this paper, which concerns the shape derivative of the shape functional

$$\mathcal{J}(\Omega, u_\Omega) = \int_{\Omega} \operatorname{div}((u_\Omega(x) - \varphi_2(x))^2 x) dx \quad (11)$$

where  $\Omega \in \mathcal{O}$  and  $u_\Omega$  is the solution of the state problem on  $\Omega$

$$\begin{cases} -\Delta v = f & \text{in } \Omega = \Omega_2 \setminus \Omega_1, \\ v = \varphi_1 & \text{on } \Gamma_1, \\ \partial_{\nu_2} v = \partial_{\nu_2} G & \text{on } \Gamma_2, \end{cases} \quad (12)$$

Let  $\varepsilon \in ]0, 1[$  and let  $\Omega'_2$  be an element of  $\mathcal{O}(D)$ . Denote by  $\Omega_\varepsilon = (\Omega_2 + \varepsilon \Omega'_2) \setminus \Omega_1$  and by  $\Gamma_{(\varepsilon)}$  the boundary of  $\Omega_2 + \varepsilon \Omega'_2$ . Let  $u_{\Omega_\varepsilon}$  be the solution of the state problem on  $\Omega_\varepsilon$

$$\begin{cases} -\Delta v = f & \text{in } \Omega_\varepsilon, \\ v = \varphi_1 & \text{on } \Gamma_1, \\ \partial_{\nu_2} v = \partial_{\nu_2} G & \text{on } \Gamma_{(\varepsilon)}, \end{cases} \quad (13)$$

Let us now note that

$$\operatorname{div}((u_\Omega - \varphi_2)^2 x) = 2(u_\Omega - \varphi_2) \langle \nabla(u_\Omega - \varphi_2), x \rangle + n(u_\Omega - \varphi_2)^2$$

so if we denote by  $F$  the following function

$$\begin{aligned} F : D \times \mathbb{R} \times \mathbb{R}^n &\longrightarrow \mathbb{R} \\ (x, y, z) &\longmapsto F(x, y, z) = 2(y - \varphi_2(x)) \langle z - \nabla \varphi_2(x), x \rangle + n(y - \varphi_2(x))^2, \end{aligned} \quad (14)$$

we can write

$$F(\cdot, u_\Omega, \nabla u_\Omega) = 2(u_\Omega - \varphi_2) \langle \nabla(u_\Omega - \varphi_2), I_d \rangle + n(u_\Omega - \varphi_2)^2 = \operatorname{div}((u_\Omega - \varphi_2)^2 I_d),$$

where  $I_d$  denotes the identity map in  $\mathbb{R}^n$ . Then  $\mathcal{J}$  can be written

$$\mathcal{J}(\Omega, u_\Omega) = \int_{\Omega} F(x, u_\Omega(x), \nabla u_\Omega(x)) dx. \quad (15)$$

**Remark 2.** We note that, when we assume that  $\Omega$  is a strongly convex domain,  $\Omega_\varepsilon$  can be considered as a deformation of the domain  $\Omega$  by the vector field  $V(x)$ , such that  $\langle V(x), \nu(x) \rangle = P_{\Omega'}(\nu(x))$  (see [5, 6]). Therefore, when  $f \in H^1(D)$ ,  $\varphi_1 \in H^{\frac{1}{2}}(\Gamma_1)$  and  $G \in H^3(D)$ , we can write

$$\tilde{u}_\varepsilon = \tilde{u} + \varepsilon u' + \varepsilon v_\varepsilon \text{ in } H^1(D),$$

where  $\tilde{u}$  and  $\tilde{u}_\varepsilon$  designate respectively extensions on  $D$  of  $u_\Omega$  and  $u_{\Omega_\varepsilon}$  and  $u'$  is the shape derivative of  $\tilde{u}$  with respect to the vector field  $V$  (see for example, [12, 23]). It follows from that result that there exists a function denoted  $F'_0$  in  $L^1(D)$ , such that

$$\frac{1}{\varepsilon} [F(\cdot, \tilde{u}_\varepsilon, \nabla \tilde{u}_\varepsilon) - F(\cdot, \tilde{u}, \nabla \tilde{u})] - F'_0 \longrightarrow 0 \text{ in } L^1(D), \quad \varepsilon \rightarrow 0,$$

which ensures the existence of the shape derivative of  $\mathcal{J}$  and allows to apply the proposition 1 in order to express its shape derivative.

Indeed, we have the following result

**Theorem 2.** Suppose that  $f \in H^1(D)$ ,  $\varphi_2 \in H^2(D)$ ,  $\varphi_1 \in H^{\frac{1}{2}}(\Gamma_1)$  and  $G \in H^3(D)$ . Let  $\Omega = \Omega_2 \setminus \Omega_1 \in \mathcal{O}$ ,  $\Omega'_2 \in \mathcal{O}(D)$  and  $\Omega_\varepsilon = (\Omega_2 + \varepsilon \Omega'_2) \setminus \Omega_1$ , then the shape derivative of  $\mathcal{J}(\Omega, u_\Omega)$  at  $\Omega$  is given by

$$\lim_{\varepsilon \rightarrow 0^+} \frac{\mathcal{J}(\Omega_\varepsilon, u_{\Omega_\varepsilon}) - \mathcal{J}(\Omega, u_\Omega)}{\varepsilon} = \int_{\Gamma_2} \mathcal{B}(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x). \quad (16)$$

where

$$\mathcal{B} = \operatorname{div}((u_\Omega - \varphi_2)^2 I_d) + \langle \nabla(u_\Omega - G), \nabla \psi \rangle - (f + \Delta G) \psi,$$

with  $\psi$  is the solution of the following problem (said the adjoint state problem):

$$\begin{cases} -\Delta \psi = 0 & \text{in } \Omega, \\ \psi = 0 & \text{on } \Gamma_1, \\ \partial_{\nu_2} \psi = -2(u_\Omega - \varphi_2) \langle \nu_2, I_d \rangle & \text{on } \Gamma_2, \end{cases} \quad (17)$$

and  $\nu_2$  denotes the exterior unit normal vector to  $\Gamma_2$ .

**Proof.**

Let  $\varepsilon \in ]0, 1[$  and let  $\Omega$  be an element of  $\mathcal{O}$ , then there exists  $\Omega_2 \in \mathcal{O}(D)$  such that  $\Omega = \Omega_2 \setminus \Omega_1$  and let  $\Omega'_2$  be an element of  $\mathcal{O}(D)$ . Let us suppose first that  $0 \in \Omega'_2$ . Denote by  $\Lambda_\varepsilon$  and  $\Omega_\varepsilon$  the domains defined respectively by  $\Lambda_\varepsilon = \Omega_2 + \varepsilon \Omega'_2$  and  $\Omega_\varepsilon = (\Omega_2 + \varepsilon \Omega'_2) \setminus \Omega_1$  having respectively as boundary  $\Gamma_{(\varepsilon)}$  and  $\Gamma_\varepsilon$ . It is clear that  $\Gamma_1$  is also inside boundary for  $\Omega_\varepsilon$ . Let  $u_\Omega$  and  $u_{\Omega_\varepsilon}$  be respectively the solution of the boundary value state problem (12) and

(13). Since  $f$ ,  $\varphi_1$  and  $G$  are smooth enough functions and the boundaries of  $\Omega$  and  $\Omega_\varepsilon$  are also smooth, we have that  $u_\Omega \in H^2(\Omega)$ ,  $u_{\Omega_\varepsilon} \in H^2(\Omega_\varepsilon)$ . On other hand, according to [24], for all  $\varepsilon \in ]0, 1[$  we have that

$$\Omega_\varepsilon \cap \Omega = (\Lambda_\varepsilon \cap \Omega_2) \setminus \Omega_1 = ((\Omega_2 + \varepsilon\Omega'_2) \cap \Omega_2) \setminus \Omega_1 = \Omega_2 \setminus \Omega_1. \quad (18)$$

Then  $\Omega = \Omega_2 \setminus \Omega_1 \subset \Omega_\varepsilon$ . Consequently, we obtain that  $u_\Omega$  and  $u_{\Omega_\varepsilon}$  are respectively solution of

$$\begin{cases} -\Delta u_\Omega = f & \text{in } \Omega, \\ u_\Omega = \varphi_1 & \text{on } \Gamma_1, \end{cases} \quad \begin{cases} -\Delta u_{\Omega_\varepsilon} = f & \text{in } \Omega, \\ u_{\Omega_\varepsilon} = \varphi_1 & \text{on } \Gamma_1. \end{cases}$$

Hence, if we denote by  $\delta u = u_{\Omega_\varepsilon} - u_\Omega$ , we have that  $\delta u$  is solution of

$$\begin{cases} -\Delta(\delta u) = 0 & \text{in } \Omega, \\ \delta u = 0 & \text{on } \Gamma_1 \subseteq \Gamma. \end{cases} \quad (19)$$

Now, Let us denote by  $\Delta\mathcal{J} := \mathcal{J}(\Omega_\varepsilon, u_{\Omega_\varepsilon}) - \mathcal{J}(\Omega, u_\Omega)$ , we have

$$\Delta\mathcal{J} = \int_{\Omega_\varepsilon} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x))dx - \int_{\Omega} F(x, u_\Omega(x), \nabla u_\Omega(x))dx.$$

Hence

$$\begin{aligned} \Delta\mathcal{J} &= \int_{\Omega_\varepsilon} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x))dx - \int_{\Omega} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x))dx \\ &\quad + \int_{\Omega} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x))dx - \int_{\Omega} F(x, u_\Omega(x), \nabla u_\Omega(x))dx \end{aligned}$$

Consider  $J_1$  the function defined by

$$\varepsilon \mapsto J_1(\varepsilon) = \int_{\Omega_\varepsilon} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x))dx - \int_{\Omega} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x))dx.$$

So, we get

$$\Delta\mathcal{J} = \int_{\Omega} (F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x)) - F(x, u_\Omega(x), \nabla u_\Omega(x)))dx + J_1(\varepsilon).$$

Let us denote by  $\delta F = F(., u_{\Omega_\varepsilon}, \nabla u_{\Omega_\varepsilon}) - F(., u_\Omega, \nabla u_\Omega)$ , we have

$$\begin{aligned} \delta F &= 2(u_{\Omega_\varepsilon} - \varphi_2)\langle \nabla(u_{\Omega_\varepsilon} - \varphi_2), I_d \rangle + n(u_{\Omega_\varepsilon} - \varphi_2)^2 - 2(u_\Omega - \varphi_2)\langle \nabla(u_\Omega - \varphi_2), I_d \rangle - n(u_\Omega - \varphi_2)^2 \\ &= F(., u_{\Omega_\varepsilon}, \nabla u_{\Omega_\varepsilon}) - 2(u_\Omega - \varphi_2)\langle \nabla(u_\Omega - u_{\Omega_\varepsilon}), I_d \rangle - 2(u_\Omega - \varphi_2)\langle \nabla(u_{\Omega_\varepsilon} - \varphi_2), I_d \rangle - n(u_\Omega - \varphi_2)^2 \\ &= 2(u_{\Omega_\varepsilon} - u_\Omega)\langle \nabla(u_{\Omega_\varepsilon} - \varphi_2), I_d \rangle - 2(u_\Omega - \varphi_2)\langle \nabla(u_\Omega - u_{\Omega_\varepsilon}), I_d \rangle + n(u_{\Omega_\varepsilon} - \varphi_2)^2 - n(u_\Omega - \varphi_2)^2 \\ &= 2\delta u\langle \nabla\delta u, I_d \rangle + 2\delta u\langle \nabla(u_\Omega - \varphi_2), I_d \rangle - 2(u_\Omega - \varphi_2)\langle \nabla(u_\Omega - u_{\Omega_\varepsilon}), I_d \rangle + n[(u_{\Omega_\varepsilon} - \varphi_2)^2 - (u_\Omega - \varphi_2)^2] \\ &= 2\delta u\langle \nabla(\delta u), I_d \rangle + 2\delta u\langle \nabla(u_\Omega - \varphi_2), I_d \rangle + 2(u_\Omega - \varphi_2)\langle \nabla(\delta u), I_d \rangle + n(u_{\Omega_\varepsilon} - \varphi_2)^2 - n(u_\Omega - \varphi_2)^2 \end{aligned}$$

since

$$\begin{aligned} (u_{\Omega_\varepsilon} - \varphi_2)^2 - (u_\Omega - \varphi_2)^2 &= u_{\Omega_\varepsilon}^2 - u_\Omega^2 + 2\varphi_2(u_\Omega - u_{\Omega_\varepsilon}) \\ &= (u_{\Omega_\varepsilon} - u_\Omega)^2 + 2u_\Omega(u_{\Omega_\varepsilon} - u_\Omega) - 2\varphi_2(u_{\Omega_\varepsilon} - u_\Omega) \\ &= (\delta u)^2 + 2\delta u(u_\Omega - \varphi_2), \end{aligned}$$

then

$$\delta F = 2\delta u \langle \nabla(\delta u), I_d \rangle + 2\delta u \langle \nabla(u_\Omega - \varphi_2), I_d \rangle + 2(u_\Omega - \varphi_2) \langle \nabla(\delta u), I_d \rangle + n(\delta u)^2 + 2n\delta u(u_\Omega - \varphi_2). \quad (20)$$

Thus the function  $\delta F$  depends only on  $\delta u$  and  $\nabla \delta u$ . On the other hand, let us consider the function  $H_{u_\Omega}$

$$\begin{aligned} H_{u_\Omega} : \Omega &\rightarrow \mathbb{R}^n \\ x &\mapsto H_{u_\Omega}(x) = 2(u_\Omega(x) - \varphi_2(x))x \end{aligned}$$

and denote by  $(H_{i,u_\Omega})_{i=1}^n$  the components of  $H_{u_\Omega}$ . Let us also consider the function

$$\begin{aligned} K_{u_\Omega} : \Omega &\rightarrow \mathbb{R} \\ x &\mapsto K_{u_\Omega}(x) = 2\langle \nabla(u_\Omega - \varphi_2)(x), x \rangle + 2n(u_\Omega(x) - \varphi_2(x)). \end{aligned}$$

We note that

$$\operatorname{div}(H_{u_\Omega}) = \sum_{i=1}^n \partial_i H_{i,u_\Omega} = K_{u_\Omega}. \quad (21)$$

It follows that

$$\delta F = \langle H_{u_\Omega}, \nabla(\delta u) \rangle + K_{u_\Omega} \delta u + n(\delta u)^2 + 2\delta u(x) \langle \nabla(\delta u)(x), x \rangle.$$

Denote by  $Err_{\delta u}$  the function

$$\varepsilon \mapsto Err_{\delta u}(\varepsilon) = n\|\delta u\|_{L^2(\Omega)}^2 + 2 \int_{\Omega} \delta u(x) \langle \nabla(\delta u)(x), x \rangle dx.$$

Then  $\triangle \mathcal{J}$  reads

$$\triangle \mathcal{J} = \int_{\Omega} (\langle H_{u_\Omega}, \nabla(\delta u) \rangle + K_{u_\Omega} \delta u)(x) dx + J_1(\varepsilon) + Err_{\delta u}(\varepsilon).$$

By using the relation (21), we get

$$\operatorname{div}(H_{u_\Omega} \delta u) = \sum_{i=1}^n \partial_i (H_{i,u_\Omega} \delta u) = \langle H_{u_\Omega}, \nabla(\delta u) \rangle + \operatorname{div}(H_{u_\Omega}) \delta u = \langle H_{u_\Omega}, \nabla(\delta u) \rangle + \delta u K_{u_\Omega}.$$

Then

$$\langle H_{u_\Omega}, \nabla(\delta u) \rangle = \operatorname{div}(H_{u_\Omega} \delta u) - \delta u K_{u_\Omega}.$$

Therefore

$$\int_{\Omega} (\langle H_{u_\Omega}, \nabla(\delta u) \rangle + K_{u_\Omega} \delta u)(x) dx = \int_{\Omega} \operatorname{div}(H_{u_\Omega} \delta u)(x) dx.$$

Consequently

$$\triangle \mathcal{J} = \int_{\Omega} \operatorname{div}(H_{u_\Omega} \delta u)(x) dx + J_1(\varepsilon) + Err_{\delta u}(\varepsilon). \quad (22)$$

From the Green formula, we get

$$\begin{aligned} \int_{\Omega} \operatorname{div}(H_{u_\Omega} \delta u)(x) dx &= \int_{\partial\Omega} \langle H_{u_\Omega}(x), \nu(x) \rangle \delta u(x) d\sigma(x) \\ &= \int_{\Gamma_2} \langle H_{u_\Omega}(x), \nu_2(x) \rangle \delta u(x) d\sigma(x) - \int_{\Gamma_1} \langle H_{u_\Omega}(x), \nu_1(x) \rangle \delta u(x) d\sigma(x) \\ &= 2 \int_{\Gamma_2} (u_\Omega - \varphi_2) \langle \nu_2(x), x \rangle \delta u(x) d\sigma - 2 \int_{\Gamma_1} (u_\Omega - \varphi_2) \langle \nu_1(x), x \rangle \delta u(x) d\sigma, \end{aligned}$$

On the other hand, let  $\psi$  be the unique solution of

$$\begin{cases} -\Delta\psi = 0 & \text{in } \Omega, \\ \psi = 0 & \text{on } \Gamma_1, \\ \partial_{\nu_2}\psi = -2(u_\Omega - \varphi_2)\langle \nu_2, I_d \rangle & \text{on } \Gamma_2. \end{cases}$$

We note that  $\psi \in \{v \in H^1(\Omega) / v_{\gamma_1} = 0\} \cap H^2(\Omega)$ . Then from the Stokes formula, we get

$$\int_{\Omega} \operatorname{div}(H_{u_\Omega} \delta u)(x) dx = - \int_{\Gamma_2} \partial_{\nu_2} \psi(x) \delta u(x) d\sigma - 2 \int_{\Gamma_1} (u_\Omega - \varphi_2) \langle \nu_1(x), x \rangle \delta u(x) d\sigma.$$

Since  $\delta u = 0$  on  $\Gamma_1$ , we have

$$\int_{\Omega} \operatorname{div}(H_{u_\Omega} \delta u)(x) dx = - \int_{\Gamma_2} \partial_{\nu_2} \psi(x) \delta u(x) d\sigma. \quad (23)$$

Now, using the fact that  $\Delta(\delta u) = \Delta\psi = 0$  on  $\Omega$  and  $\delta u = \psi = 0$  on  $\Gamma_1$ , by the Green formula we get

$$\begin{aligned} \int_{\Gamma_2} \partial_{\nu_2} \psi(x) \delta u(x) d\sigma &= \int_{\Gamma} \partial_{\nu} \psi(x) \delta u(x) d\sigma \\ &= \int_{\Omega} \nabla \psi \nabla \delta u dx \\ &= \int_{\Gamma} \psi(x) \partial_{\nu} \delta u(x) d\sigma \\ &= \int_{\Gamma_2} \psi(x) \partial_{\nu_2} \delta u(x) d\sigma = \int_{\Gamma} \psi(x) \partial_{\nu} \delta u(x) d\sigma. \end{aligned}$$

Thus

$$\int_{\Gamma_2} \partial_{\nu_2} \psi(x) \delta u(x) d\sigma = \int_{\Gamma} \psi(x) \partial_{\nu} \delta u(x) d\sigma.$$

Therefore

$$\int_{\Omega} \operatorname{div}(H_{u_\Omega} \delta u)(x) dx = - \int_{\Gamma} \psi(x) \partial_{\nu} \delta u(x) d\sigma.$$

Consequently

$$\Delta \mathcal{J} = J_1(\varepsilon) + J_2(\varepsilon) + \operatorname{Err}_{\delta u}(\varepsilon)$$

where

$$\begin{aligned} J_2(\varepsilon) &= - \int_{\Gamma} \partial_{\nu} \delta u(x) \psi(x) d\sigma, \\ \operatorname{Err}_{\delta u}(\varepsilon) &= n \|\delta u\|_{L^2(\Omega)}^2 + 2 \int_{\Omega} \delta u(x) \langle \nabla(\delta u)(x), x \rangle dx, \\ \text{and } J_1(\varepsilon) &= J_{1,1}(\varepsilon) - J_{1,2}(\varepsilon) \end{aligned}$$

with

$$J_{1,1}(\varepsilon) = \int_{\Omega_\varepsilon} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x)) dx, \quad J_{1,2}(\varepsilon) = \int_{\Omega} F(x, u_{\Omega_\varepsilon}(x), \nabla u_{\Omega_\varepsilon}(x)) dx,$$

According to the proposition 1 applied to the function  $F_\varepsilon = F(\cdot, u_{\Omega_\varepsilon}, \nabla u_{\Omega_\varepsilon})$ , we get

$$\frac{d}{d\varepsilon} (J_{1,1}(\varepsilon))|_{\varepsilon=0^+} = \int_{\Omega_2 \setminus \Omega_1} F'_0(x) dx + \int_{\Gamma_2} F_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma, \quad (24)$$

and

$$\frac{d}{d\varepsilon} (J_{1,2}(\varepsilon))|_{\varepsilon=0^+} = \int_{\Omega_2 \setminus \Omega_1} F'_0(x) dx. \quad (25)$$

So, by combining (24) and (25) we get

$$\frac{d}{d\varepsilon} (J_1(\varepsilon))|_{\varepsilon=0^+} = \int_{\Gamma_2} F_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma.$$

Consequently, since  $F_0 = F(\cdot, u_\Omega, \nabla u_\Omega)$ , one can deduce that

$$\frac{d}{d\varepsilon} J_1(\varepsilon)|_{\varepsilon=0^+} = \int_{\Gamma_2} F(\cdot, u_\Omega, \nabla u_\Omega)(x) P_{\Omega'_2}(\nu_2(x)) d\sigma. \quad (26)$$

Now let's calculate the derivative of  $J_2$ , we have

$$\begin{aligned} J_2(\varepsilon) &= - \int_{\Gamma} \partial_\nu \delta u(x) \psi(x) d\sigma = - \int_{\Gamma} \partial_\nu u_{\Omega_\varepsilon}(x) \psi(x) d\sigma + \int_{\Gamma} \partial_\nu u_\Omega(x) \psi(x) d\sigma \\ &= - \int_{\Gamma} (\partial_\nu u_{\Omega_\varepsilon}(x) - \partial_\nu G(x)) \psi(x) d\sigma + \int_{\Gamma} (\partial_\nu u_\Omega(x) - \partial_\nu G(x)) \psi(x) d\sigma \end{aligned}$$

which can be reads

$$J_2(\varepsilon) = J_{2,1}(\varepsilon) + J_{2,2}(\varepsilon),$$

where

$$J_{2,1}(\varepsilon) = - \int_{\Gamma} (\partial_\nu u_{\Omega_\varepsilon}(x) - \partial_\nu G(x)) \psi(x) d\sigma, \quad J_{2,2}(\varepsilon) = \int_{\Gamma} (\partial_\nu u_\Omega(x) - \partial_\nu G(x)) \psi(x) d\sigma.$$

Using the fact that  $u_\Omega$  satisfies the equation

$$\partial_{\nu_{(\varepsilon)}} u_{\Omega_\varepsilon} = \partial_{\nu_{(\varepsilon)}} G \quad \text{on} \quad \Gamma_{(\varepsilon)},$$

we get

$$J_{2,1}(\varepsilon) = - \int_{\Gamma} (\partial_\nu u_{\Omega_\varepsilon}(x) - \partial_\nu G(x)) \psi(x) d\sigma + \int_{\Gamma_{(\varepsilon)}} (\partial_{\nu_{(\varepsilon)}} u_{\Omega_\varepsilon}(x) - \partial_{\nu_{(\varepsilon)}} G(x)) \psi(x) d\sigma.$$

From the fact that  $\psi = 0$  on  $\Gamma_1$ , we obtain

$$\int_{\Gamma_1} (\partial_{\nu_1} u_{\Omega_\varepsilon}(x) - \partial_{\nu_1} G(x)) \psi(x) d\sigma = 0.$$

Or since  $\Gamma_\varepsilon = \Gamma_{(\varepsilon)} \cup \Gamma_1$  et  $\Gamma_{(\varepsilon)} \cap \Gamma_1 = \emptyset$ , then

$$\int_{\Gamma_\varepsilon} (\partial_{\nu_\varepsilon} u_{\Omega_\varepsilon}(x) - \partial_{\nu_\varepsilon} G(x)) \psi(x) d\sigma = \int_{\Gamma_{(\varepsilon)}} (\partial_{\nu_{(\varepsilon)}} u_{\Omega_\varepsilon}(x) - \partial_{\nu_{(\varepsilon)}} G(x)) \psi(x) d\sigma.$$

Therefore

$$J_{2,1}(\varepsilon) = - \int_{\Gamma} (\partial_\nu u_{\Omega_\varepsilon}(x) - \partial_\nu G(x)) \psi(x) d\sigma + \int_{\Gamma_\varepsilon} (\partial_{\nu_\varepsilon} u_{\Omega_\varepsilon}(x) - \partial_{\nu_\varepsilon} G(x)) \psi(x) d\sigma.$$

By the Green formula we get

$$J_{2,1}(\varepsilon) = - \int_{\Omega} \operatorname{div}(\nabla(u_{\Omega_\varepsilon} - G)\psi)(x) dx + \int_{\Omega_\varepsilon} \operatorname{div}(\nabla(u_{\Omega_\varepsilon} - G)\psi)(x) dx.$$



Using the fact that  $-\Delta u_{\Omega_\varepsilon} = f$  on  $\Omega_\varepsilon$  and  $\Omega \subset \Omega_\varepsilon$ , we have that  $-\Delta u_{\Omega_\varepsilon} = f$  on  $\Omega$ . Then

$$\operatorname{div}(\nabla(u_{\Omega_\varepsilon} - G)\psi) = \langle \nabla(u_{\Omega_\varepsilon} - G), \nabla\psi \rangle + \Delta(u_{\Omega_\varepsilon} - G)\psi = \langle \nabla(u_{\Omega_\varepsilon} - G), \nabla\psi \rangle + (-f - \Delta G)\psi.$$

Hence  $J_{2,1}(\varepsilon)$  can be written

$$J_{2,1}(\varepsilon) = J_{2,1}^{(1)}(\varepsilon) + J_{2,1}^{(2)}(\varepsilon) + J_{2,1}^{(3)}(\varepsilon) + J_{2,1}^{(4)}(\varepsilon),$$

where

$$\begin{aligned} J_{2,1}^{(1)}(\varepsilon) &= - \int_{\Omega} \langle \nabla(u_{\Omega_\varepsilon} - G), \nabla\psi \rangle(x) dx, & J_{2,1}^{(2)}(\varepsilon) &= - \int_{\Omega} (-f - \Delta G)\psi(x) dx, \\ J_{2,1}^{(3)}(\varepsilon) &= \int_{\Omega_\varepsilon} \langle \nabla(u_{\Omega_\varepsilon} - G), \nabla\psi \rangle(x) dx, & J_{2,1}^{(4)}(\varepsilon) &= \int_{\Omega_\varepsilon} (-f - \Delta G)\psi(x) dx. \end{aligned}$$

Denote by  $B_\varepsilon$  the function defined by  $B_\varepsilon = \langle \nabla(u_{\Omega_\varepsilon} - G), \nabla\psi \rangle$ , it is easy to see from the Remark 2, that there exists  $B'_0 \in L^1(\Omega)$ , such that

$$\frac{1}{\varepsilon}[B_\varepsilon - B_0] - B'_0 \longrightarrow 0 \quad \text{in } L^1(\Omega), \quad \varepsilon \rightarrow 0,$$

then using the proposition 1, we obtain the following shape derivative

$$\frac{d}{d\varepsilon} \left( J_{2,1}^{(1)}(\varepsilon) \right) \Big|_{\varepsilon=0^+} = - \int_{\Omega_2 \setminus \Omega_1} B'_0(x) dx, \quad (27)$$

$$\frac{d}{d\varepsilon} \left( J_{2,1}^{(2)}(\varepsilon) \right) \Big|_{\varepsilon=0^+} = 0, \quad (28)$$

$$\frac{d}{d\varepsilon} \left( J_{2,1}^{(3)}(\varepsilon) \right) \Big|_{\varepsilon=0^+} = \int_{\Omega_2 \setminus \Omega_1} B'_0(x) dx + \int_{\Gamma_2} B_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma, \quad (29)$$

and

$$\frac{d}{d\varepsilon} \left( J_{2,1}^{(4)}(\varepsilon) \right) \Big|_{\varepsilon=0^+} = \int_{\Gamma_2} (-f - \Delta G)\psi(x) P_{\Omega'_2}(\nu_2(x)) d\sigma. \quad (30)$$

So, using equations (27), (28), (29) and (30) we get

$$\frac{d}{d\varepsilon} (J_{2,1}(\varepsilon)) \Big|_{\varepsilon=0^+} = \int_{\Gamma_2} (B_0(x) + (-f - \Delta G)\psi(x)) P_{\Omega'_2}(\nu_2(x)) d\sigma. \quad (31)$$

Now for the function  $J_{2,2}$ , using the fact that  $u_\Omega$  satisfies

$$\partial_{\nu_2} u_\Omega = \partial_{\nu_2} G \quad \text{on } \Gamma_2.$$

and that  $\psi = 0$  on  $\Gamma_1$ , we have

$$\int_{\Gamma_1} (\partial_{\nu_1} u_\Omega(x) - \partial_{\nu_1} G(x)) \psi(x) d\sigma = 0.$$

Hence

$$\int_{\Gamma} (\partial_{\nu} u_\Omega(x) - \partial_{\nu} G(x)) \psi(x) d\sigma = \int_{\Gamma_1} (\partial_{\nu_1} u_\Omega - \partial_{\nu_1} G)(x) \psi(x) d\sigma + \int_{\Gamma_2} (\partial_{\nu_2} u_\Omega - \partial_{\nu_2} G)(x) \psi(x) d\sigma = 0$$

Then we get that,  $J_{2,2}(\varepsilon) = 0$ . Therefore

$$\begin{aligned}\frac{d}{d\varepsilon} (J_{2,1}(\varepsilon) + J_{2,2}(\varepsilon))|_{\varepsilon=0^+} &= \int_{\Gamma_2} B_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma + \int_{\Gamma_2} (-f - \Delta G)\psi(x) P_{\Omega'_2}(\nu_2(x)) d\sigma \\ &= \int_{\Gamma_2} (\langle \nabla(u_\Omega - G), \nabla\psi \rangle + (-f - \Delta G)\psi)(x) P_{\Omega'_2}(\nu_2(x)) d\sigma.\end{aligned}$$

Consequently

$$\frac{d}{d\varepsilon} (J_2(\varepsilon))|_{\varepsilon=0^+} = \int_{\Gamma_2} (\langle \nabla(u_\Omega - G), \nabla\psi \rangle + (-f - \Delta G)\psi)(x) P_{\Omega'_2}(\nu_2(x)) d\sigma. \quad (32)$$

Hence, from the formula (26) and (33) we obtain

$$\frac{d}{d\varepsilon} (J_1(\varepsilon) + J_2(\varepsilon))|_{\varepsilon=0^+} = \int_{\Gamma_2} \mathcal{B}(x) P_{\Omega'_2}(\nu_2(x)) d\sigma. \quad (33)$$

where

$$\mathcal{B}(x) = \operatorname{div}((u_\Omega(x) - \varphi_2(x))^2 x) + \langle \nabla(u_\Omega - G)(x), \nabla\psi(x) \rangle - (f + \Delta G)(x)\psi(x).$$

Since,  $(J_1 + J_2)(0) = 0$ , then we get

$$J_1(\varepsilon) + J_2(\varepsilon) = \varepsilon \int_{\Gamma_2} \mathcal{B}(x) P_{\Omega'_2}(\nu_2(x)) d\sigma + \operatorname{Err}_{\delta u}(\varepsilon).$$

We deduce that

$$\Delta \mathcal{J} = \varepsilon \int_{\Gamma_2} \mathcal{B}(x) P_{\Omega'_2}(\nu_2(x)) d\sigma + \operatorname{Err}_{\delta u}(\varepsilon).$$

To conclude, it suffices to show that

$$\operatorname{Err}_{\delta u}(\varepsilon) = o(\varepsilon) \quad \text{where} \quad \lim_{\varepsilon \rightarrow 0^+} \frac{o(\varepsilon)}{\varepsilon} = 0,$$

For this, let  $\varepsilon \in ]0, 1[$ , from equation (19), we have that  $\delta u$  is solution of this problem

$$\begin{cases} \Delta(\delta u) = 0 & \text{in } \Omega, \\ \delta u = 0 & \text{on } \Gamma_1 \subseteq \Gamma. \end{cases} \quad (34)$$

Then

$$\sum_{i=1}^n \partial_i(\delta u \partial_i(\delta u)) = \sum_{i=1}^n (\partial_i(\delta u))^2 + \sum_{i=1}^n \delta u \partial_i^2(\delta u).$$

Hence, we obtain

$$\delta u \Delta(\delta u) = \sum_{i=1}^n \partial_i^2 \delta u = - \sum_{i=1}^n (\partial_i(\delta u))^2 + \sum_{i=1}^n \partial_i(\delta u \partial_i(\delta u)).$$

From (34), we get  $\delta u \Delta(\delta u) = 0$  in  $\Omega$ , then we have

$$\sum_{i=1}^n (\partial_i(\delta u))^2 = \sum_{i=1}^n \partial_i(\delta u \partial_i(\delta u)) \text{ in } \Omega.$$

So, by using the Green formula we obtain

$$\|\nabla \delta u\|_{L^2(\Omega)}^2 = \sum_{i=1}^n \int_{\Omega} (\partial_i(\delta u))^2 = \sum_{i=1}^n \int_{\Omega} \partial_i(\delta u \partial_i(\delta u))(x) dx = \int_{\Gamma} \delta u \partial_\nu(\delta u)(x) d\sigma.$$

Therefore

$$\begin{aligned} \|\nabla \delta u\|_{L^2(\Omega)}^2 &= - \int_{\Gamma} \partial_{\nu} \delta u(x) \delta u(x) d\sigma = - \int_{\Gamma} \partial_{\nu} u_{\Omega_{\varepsilon}}(x) \delta u(x) d\sigma + \int_{\Gamma} \partial_{\nu} u_{\Omega}(x) \delta u(x) d\sigma \\ &= - \int_{\Gamma} (\partial_{\nu} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma + \int_{\Gamma} (\partial_{\nu} u_{\Omega}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma \end{aligned}$$

which can be written

$$\|\nabla \delta u\|_{L^2(\Omega)}^2 = \Xi_1(\varepsilon) + \Xi_2(\varepsilon),$$

where

$$\Xi_1(\varepsilon) = - \int_{\Gamma} (\partial_{\nu} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma, \quad \Xi_2(\varepsilon) = \int_{\Gamma} (\partial_{\nu} u_{\Omega}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma.$$

Using the fact that  $\delta u$  and  $u_{\Omega}$  satisfies respectively

$$\delta u = 0 \quad \text{on} \quad \Gamma_1, \quad \partial_{\nu_2} u_{\Omega} = \partial_{\nu_2} G \quad \text{on} \quad \Gamma_2.$$

Then

$$\Xi_2(\varepsilon) = \int_{\Gamma} (\partial_{\nu} u_{\Omega}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma = 0.$$

Also since  $\Gamma_{\varepsilon} = \Gamma_{(\varepsilon)} \cup \Gamma_1$  and  $\Gamma_{(\varepsilon)} \cap \Gamma_1 = \emptyset$ , using the fact that  $\partial_{\nu_{(\varepsilon)}} u_{\Omega_{\varepsilon}} = \partial_{\nu_{(\varepsilon)}} G$  on  $\Gamma_{(\varepsilon)}$ , we get

$$\begin{aligned} \int_{\Gamma_{\varepsilon}} (\partial_{\nu_{\varepsilon}} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu_{\varepsilon}} G(x)) \delta u(x) d\sigma &= \int_{\Gamma_{(\varepsilon)}} (\partial_{\nu_{(\varepsilon)}} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu_{(\varepsilon)}} G(x)) \delta u(x) d\sigma \\ &\quad + \int_{\Gamma_1} (\partial_{\nu_{(\varepsilon)}} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu_{(\varepsilon)}} G(x)) \delta u(x) d\sigma = 0. \end{aligned}$$

Thus

$$\Xi_1(\varepsilon) = - \int_{\Gamma} (\partial_{\nu} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma + \int_{\Gamma_{\varepsilon}} (\partial_{\nu_{\varepsilon}} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu_{\varepsilon}} G(x)) \delta u(x) d\sigma.$$

Hence

$$\Xi_1(\varepsilon) = - \int_{\Gamma} (\partial_{\nu} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu} G(x)) \delta u(x) d\sigma + \int_{\Gamma_{\varepsilon}} (\partial_{\nu_{\varepsilon}} u_{\Omega_{\varepsilon}}(x) - \partial_{\nu_{\varepsilon}} G(x)) \delta u(x) d\sigma.$$

So by using the Green formula, we get

$$\Xi_1(\varepsilon) = - \int_{\Omega} \operatorname{div}(\nabla(u_{\Omega_{\varepsilon}} - G)\delta u)(x) dx + \int_{\Omega_{\varepsilon}} \operatorname{div}(\nabla(u_{\Omega_{\varepsilon}} - G)\delta u)(x) dx.$$

Using the fact that  $-\Delta u_{\Omega_{\varepsilon}} = f$  in  $\Omega_{\varepsilon}$  and that  $\Omega \subset \Omega_{\varepsilon}$ , we have that  $-\Delta u_{\Omega_{\varepsilon}} = f$  in  $\Omega$ . Then

$$\operatorname{div}(\nabla(u_{\Omega_{\varepsilon}} - G)\delta u) = \langle \nabla(u_{\Omega_{\varepsilon}} - G), \nabla \delta u \rangle + \Delta(u_{\Omega_{\varepsilon}} - G)\delta u = \langle \nabla(u_{\Omega_{\varepsilon}} - G), \nabla \delta u \rangle + (-f - \Delta G)\delta u.$$

Hence  $\Xi_1(\varepsilon)$  can be written

$$\Xi_1(\varepsilon) = \Xi_{1,1}(\varepsilon) + \Xi_{1,2}(\varepsilon) + \Xi_{2,1}(\varepsilon) + \Xi_{2,2}(\varepsilon),$$

where

$$\begin{aligned} \Xi_{1,1}(\varepsilon) &= - \int_{\Omega} \langle \nabla(u_{\Omega_{\varepsilon}} - G), \nabla \delta u \rangle(x) dx, \quad \Xi_{1,2}(\varepsilon) = - \int_{\Omega} (-f - \Delta G)\delta u(x) dx, \\ \Xi_{2,1}(\varepsilon) &= \int_{\Omega_{\varepsilon}} \langle \nabla(u_{\Omega_{\varepsilon}} - G), \nabla \delta u \rangle(x) dx, \quad \Xi_{2,2}(\varepsilon) = \int_{\Omega_{\varepsilon}} (-f - \Delta G)\delta u(x) dx. \end{aligned}$$

Denote by  $W_{\varepsilon}$  the function defined by  $W_{\varepsilon} = \langle \nabla(u_{\Omega_{\varepsilon}} - G), \nabla \delta u \rangle$  and by  $D_{\varepsilon}$  the function defined by  $D_{\varepsilon} = (-f - \Delta G)\delta u$ , with  $W_0 = 0$  and  $D_0 = 0$ . It is easy to see from the Remark 2, that there exists  $D'_0 \in L^1(\Omega)$  and  $W'_0 \in L^1(\Omega)$ , such that

$$\frac{1}{\varepsilon}[D_{\varepsilon} - D_0] - D'_0 \longrightarrow 0 \quad \text{in} \quad L^1(\Omega), \quad \varepsilon \rightarrow 0$$

and

$$\frac{1}{\varepsilon}[W_\varepsilon - W_0] - W'_0 \longrightarrow 0 \quad \text{in } L^1(\Omega), \quad \varepsilon \rightarrow 0.$$

Then using the proposition 1, we get

$$\frac{d}{d\varepsilon} \Xi_{2,1}(\varepsilon)|_{\varepsilon=0^+} = \int_{\Omega_2 \setminus \Omega_1} W'_0(x) dx + \int_{\Gamma_2} W_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma = \int_{\Omega_2 \setminus \Omega_1} W'_0(x) dx \quad (35)$$

and

$$\frac{d}{d\varepsilon} \Xi_{2,2}(\varepsilon)|_{\varepsilon=0^+} = \int_{\Omega_2 \setminus \Omega_1} D'_0(x) dx + \int_{\Gamma_2} D_0(x) P_{\Omega'_2}(\nu_2(x)) d\sigma = \int_{\Omega_2 \setminus \Omega_1} D'_0(x) dx. \quad (36)$$

Hence, using (35) and (36) we obtain

$$\frac{d}{d\varepsilon} (\Xi_1(\varepsilon))|_{\varepsilon=0^+} = 0.$$

Consequently

$$\|\nabla \delta u\|_{L^2(\Omega)}^2 = o(\varepsilon) \quad \text{where,} \quad \lim_{\varepsilon \rightarrow 0^+} \frac{o(\varepsilon)}{\varepsilon} = 0. \quad (37)$$

On the other hand, from the Poincaré inequality, there exist a constant  $C_\Omega$  such that

$$\frac{1}{\varepsilon} \|\delta u\|_{L^2(\Omega)}^2 \leq C_\Omega \frac{1}{\varepsilon} \|\nabla \delta u\|_{L^2(\Omega)}^2 = \frac{o(\varepsilon)}{\varepsilon}.$$

Then

$$\|\delta u\|_{L^2(\Omega)}^2 = o(\varepsilon) \quad \text{where,} \quad \lim_{\varepsilon \rightarrow 0^+} \frac{o(\varepsilon)}{\varepsilon} = 0.$$

Thus by using once again the Poincaré and Hölder inequalities, there exists  $\alpha > 0$  independent of  $\varepsilon$  such that

$$0 \leq \left| 2 \int_{\Omega} \delta u \langle \nabla(\delta u), I_d \rangle \right| \leq \alpha \|\delta u\|_{L^2(\Omega)} \|\nabla \delta u\|_{L^2(\Omega)} \leq \alpha C_\Omega \|\nabla \delta u\|_{L^2(\Omega)}^2.$$

Hence from (37), we deduce that

$$2 \int_{\Omega} \delta u \langle \nabla(\delta u), I_d \rangle = o(\varepsilon) \quad \text{avec,} \quad \lim_{\varepsilon \rightarrow 0^+} \frac{o(\varepsilon)}{\varepsilon} = 0.$$

To conclude, we show that the above result remains true in the case where  $\Omega_2$  and  $\Omega'_2$  are not necessarily neighborhoods of 0. In fact, let  $c_0 \in \Omega_2$  and  $c \in \Omega'_2$ , then  $\Omega_2 - c_0$  and  $\Omega'_2 - c$  are neighborhoods of 0. Hence, applying the Corollary 2, for  $a = c_0$  and  $c = b$ , we get

$$\lim_{\varepsilon \rightarrow 0^+} \frac{1}{\varepsilon} \left( \int_{(\Omega_2 + \varepsilon \Omega'_2) \setminus \Omega_1} F_\varepsilon - \int_{\Omega_2 \setminus \Omega_1} F_0 \right) = \int_{\Gamma_2} \mathcal{B}(x) P_{\Omega'_2}(\nu_2(x)) d\sigma(x). \quad (38)$$

This achieves the proof of the theorem. ■

## 4 Identification process for optimal domain

The numerical optimization process used for the estimation of the unknown free boundary  $\Gamma_2$  of  $\Omega$  is based on the gradient method presented in the following.

## 4.1 Gradient Method

Using the gradient of  $\mathcal{J}$  determined by equation (4), the computation of the optimal shape is summarized in the following algorithm.

1. Choose  $\Omega_0 = \Omega_{0,2} \setminus \Omega_1 \in \mathcal{O}$ ,  $\rho \in ]0, 1[$  and a precision  $EP\mathcal{S}D$ .

2. Solve the state problem

$$\begin{cases} \Delta u = f & \text{in } \Omega_0, \\ u = \varphi_1 & \text{on } \Gamma_1, \\ \partial_{\nu_2} u = \partial_{\nu_2} G & \text{on } \Gamma_{0,2}. \end{cases} \quad (39)$$

3. Solve the adjoint state problem

$$\begin{cases} \Delta \psi = 0 & \text{in } \Omega_0, \\ \psi = 0 & \text{on } \Gamma_1, \\ \partial_{\nu_2} \psi = -2(u - \varphi_2) \langle \nu_2(x), x \rangle & \text{on } \Gamma_{0,2}. \end{cases} \quad (40)$$

4. Compute  $\mathcal{B}$  by the relation

$$\mathcal{B}(x) = \operatorname{div} \left( (u - \varphi_2)^2 x \right) + (\nabla(u - G), \nabla \psi) - (f + \Delta G) \psi.$$

5. Compute  $P_0 = P_{\Omega_{0,2}}$

6. Compute  $\widehat{P}$  the solution of

$$\arg \min_{P \in \mathcal{P}} j(P) \quad (41)$$

where

$$j(P) = \int_{\Gamma_{0,2}} B(x)(P - P_0)(\nu(x)) ds$$

and

$$\mathcal{P} = \{\Phi \in C(\mathbb{R}^2) / \Phi \text{ is convex and } P_{\Omega_1} \leq \Phi \leq P_D\}.$$

7. At step  $k$

$$\text{if } \|u^k - \varphi_2\|_{L^2(\Gamma_{k,2})} \leq EP\mathcal{S}D \quad \textbf{Go to 10.}$$

where  $u^k$  is the solution of the state equation in  $\Omega_k$  (the domain at step  $k$ ) and  $\Gamma_{k,2}$  is the outside boundary of  $\Omega_k$ .

8. Compute

$$P_{k+1} = (1 - \rho) P_k + \rho \widehat{P}_k$$

9. Compute the domain  $\overline{\Omega}_{k+1}$  associated to  $P_{k+1}$  by

$$\overline{\Omega}_{k+1} = \partial P_{k+1}(0) = \{l \in \mathbb{R}^2 / P_{k+1}(x) \geq (l, x), \forall x \in \mathbb{R}^2\} \quad \textbf{Go to 2.}$$

10. **End.**

## 4.2 Discretization of the problem

In this section, we approach the optimal shape design problem (4) using the boundary element method. For this, the state problem (39) and the adjoint state problem (40) can be written in terms of boundary integral equation [9] by the equation

$$c(\xi)u(\xi) = \int_{\partial\Omega} \{u(y)\partial_{\nu_y} \ln |\xi - y|\} ds_y - \partial_{\nu_y} u(y) \ln |\xi - y| ds_y \quad (42)$$

where  $c(\xi)$ , called the free term, is 0 if  $\xi \notin \Omega \cup \partial\Omega$ , 1 if  $\xi \in \Omega$  and  $\theta/2\pi$  if  $\xi \in \partial\Omega$ , where  $\theta$  is the interior angle between the left and right tangents to the boundary at the point  $\xi$ ;  $u^*(y; \xi) = (1/2\pi)\ln(1/r)$  is the fundamental solution for the Laplace equation;  $r = |y - \xi|$  is the distance between the collocation point  $\xi$  and the integration or observation point  $y$ ; and  $q^* = -(1/2\pi)\partial u^*/\partial\nu$  is the flux associated to the potential  $u^*(y; \xi)$ .

The subdivision of the boundary can be done using different types of elements. In the present investigation, constant elements are considered. Assuming that over each boundary element  $\partial\Omega_i$  of  $\partial\Omega$  the functions  $u$  and  $q = \frac{\partial u}{\partial\nu}$  are constant and take their values  $u_i$  and  $q_i$  at the centroid  $\xi_i$ , the resulted discretized boundary integral equation at node  $k$  has the following form

$$\sum_{l=1}^{NE} H_{kl} u_l = \sum_{l=1}^{NE} G_{kl} q_l, \quad (43)$$

where  $NE$  is the number of boundary elements  $\partial\Omega_i$  such that  $\partial\Omega = \cup_{i=1}^{NE} \partial\Omega_i$ . The components of the coefficient matrices  $H$  and  $G$  are given by

$$H_{kl} = \int_{\partial\Omega_l} q_k^* \text{ when } k \neq l, \quad (44)$$

$$H_{kl} = \int_{\partial\Omega_l} q_k^* + \frac{1}{2} \text{ when } k = l, \quad (45)$$

$$G_{kl} = \int_{\partial\Omega_l} u_k^*. \quad (46)$$

A four-point Gaussian quadrature rule is employed for numerical integration of the components of the coefficient matrices  $H$  and  $G$ . However, for calculating the diagonal components, special care must be taken. The diagonal terms  $H_{kk}$  vanish due to the orthogonality of the element coordinate and the normal. The terms  $G_{kk}$  can be calculated analytically and it is given by the following equation

$$G_{kk} = \frac{L_e}{2\pi} \left[ \ln\left(\frac{2}{L_e}\right) + 1 \right] \quad (47)$$

where  $L_e$  is the element length. The values of the off-diagonal coefficients of  $H$  and  $G$  can be written as [9]

$$H_{kl} = \sum_{i=1}^4 -\left(\frac{1}{d_s^2}\right) L w_s \frac{\sqrt{(R_1 - R_2)^2 + (S_1 - S_2)^2}}{2} \quad (48)$$

$$G_{kl} = \sum_{i=1}^4 \ln\left(\frac{1}{d_s}\right) w_s \frac{\sqrt{(R_1 - R_2)^2 + (S_1 - S_2)^2}}{2} \quad (49)$$

where  $R_1, R_2, S_1$  and  $S_2$  are the coordinates of the extreme mounts of each element,  $w_s$  are the weighting for each point,  $L$  is the distance from the collocation point to the line element tangent to the element and  $d$  is the distance from collocation point to the Gauss integration points on the boundary element. We note that the system (43) can easily be rearranged as a system of order  $n$  and written in a generic form

$$Ax = b \quad (50)$$

Its right-hand side is obtained by multiplication of the appropriate columns of the influence matrices  $H$  and  $G$  by values known from boundary conditions. Components of the vector of the unknowns  $x$  as well as components of the main matrix  $A$  depend on the boundary condition at the considered node. We obtain

$$A_{ij} = \begin{cases} -G_{ij} & \text{for Dirichlet's boundary condition} \\ H_{ij} & \text{for Neumann's boundary condition} \end{cases} \quad (51)$$

$$x^j = \begin{cases} q_j & \text{for Dirichlet's boundary condition} \\ u_j & \text{for Neumann's boundary condition} \end{cases} \quad (52)$$

Let now  $m$  be the number of the boundary elements located at the free boundary  $\Gamma_2$ , such that  $m < n$  and  $n - m$  is the number of boundary elements located at the inside fixed boundary  $\Gamma_1$  of  $\Omega$ . Let  $Y = (y_i)_{i=0}^m$  be a partition of  $\Gamma_2$ , where  $y_i = (y_i^{(1)}, y_i^{(2)})$ , we denote by  $\xi = (\xi_i)_{i=0}^m$  a partition of  $\Gamma_2$ , such that  $\xi_i = (\xi_i^{(1)}, \xi_i^{(2)})$  is the centroid of the boundary elements  $[y_i, y_{i+1}]$ .

The discrete gradient of the cost function can be read as follows

$$j(P) = \sum_{i=0}^m h_i B_i (P_i - P_\Omega(\nu(\xi_i)))$$

where  $h_i = \|y_{i+1} - y_i\|$ ;  $P = (P_i = P(\nu(\xi_i)))_{i=0}^m$ ;  $\nu(\xi_i)$  is the outward unit normal vector to the boundary elements  $y_i y_{i+1}$  and  $B_i = B(\xi_i^{(1)}, \xi_i^{(2)})$  is given by the relation

$$\begin{aligned} B_i &= 2(u_i - \varphi_2(\xi_i)) (\nabla u^h(\xi_i) - \nabla \varphi_2(\xi_i), \xi_i) + 2(u_i - \varphi_2(\xi_i))^2 \\ &+ (\nabla(u^h(\xi_i) - G^h(\xi_i)), \nabla \psi^h(\xi_i)) + (f(\xi_i) - \Delta G^h(\xi_i)) \psi_i \end{aligned}$$

where  $u^h$  is the approximate solution of the state equation, such that  $(u^h(\xi) = u_i)_{i=0}^n$  is the solution of a linear system of type (50),  $\psi^h$  is the approximate solution of the adjoint state equation, such that  $(\psi^h(\xi) = \psi_i)_{i=0}^n$  is the solution of a linear system of type (50) and  $G^h$  is a approximation of  $G$ . The discrete space of the admissible support function can be read

$$\begin{aligned} \mathcal{P} = \{ &P = (P_0, \dots, P_m) \in \mathbb{R}^{m+1} / P_{\Omega_1}(\nu(\xi_i)) \leq P_i \leq P_D(\nu(\xi_i)) \ i = 1, \dots, m-1, P_0 \leq \lambda_0 P_m + (1 - \lambda_0) P_1, \\ &P_i \leq \lambda_i P_{i-1} + (1 - \lambda_i) P_{i+1} \ i = 1, \dots, m-1 \text{ and } P_m \leq \lambda_m P_{m-1} + (1 - \lambda_m) P_0 \} \end{aligned}$$

where

$$\lambda_i = \frac{\|\nu(\xi_{i-1}) - \nu(\xi_i)\|}{\|\nu(\xi_i) - \nu(\xi_{i+1})\|} \quad \text{for } i = 1, \dots, m-1$$

and

$$\lambda_0 = \frac{\|\nu(\xi_m) - \nu(\xi_0)\|}{\|\nu(\xi_0) - \nu(\xi_1)\|} \quad \lambda_m = \frac{\|\nu(\xi_{m-1}) - \nu(\xi_m)\|}{\|\nu(\xi_m) - \nu(\xi_0)\|}.$$

The discrete domain associated to  $\bar{\Omega}_0 = \partial \bar{P}(0) = \{l \in \mathbb{R}^2 / \bar{P}(x) \geq (l, x), \forall x \in \mathbb{R}^2\}$  is given as solution of the following relations [21]

$$\nu^{(1)}(\xi_i) l_i^{(1)} + \nu^{(2)}(\xi_i) l_i^{(2)} = \bar{P}_i \quad \text{for } i = 0, \dots, m$$

To compute  $l_i = (l_i^{(1)}, l_i^{(2)})$ , we suppose that  $l_i - \xi_i$  is collinear to  $\nu(\xi_i)$  i.e.

$$\nu^{(1)}(\xi_i) l_i^{(2)} - \nu^{(2)}(\xi_i) l_i^{(1)} = \nu^{(1)}(\xi_i) \xi_i^{(2)} - \nu^{(2)}(\xi_i) \xi_i^{(1)} \quad \text{for } i = 0, \dots, m$$

## 5 Numerical results

To illustrate the ability of the present algorithm in estimating the optimal shape and location of the unknown boundary  $\Gamma_2$ , we consider in the following two the specific models: the analysis one and the design one.

In the analysis model, the exact boundary  $\Gamma_2$  and the exact solution  $u$  of the free boundary problem (4) are known. By using the exact value of  $u$  on  $\Gamma_1$  and  $\Gamma_2$ , and arbitrary initial guesses of the boundary, one is asked to reconstruct the exact boundary by the gradient method combined with our proposed method used for the computation of the gradient.

The design model is devoted to the investigation of some numerical experiment based on the approaches proposed in the previous works to explore free boundary problems of Bernoulli type.

## 5.1 Analysis model

The main objective of the analysis model is to show the validity of the present design algorithm in estimating the unknown boundary and to verify the accuracy of our method in the computation of the shape derivative of the cost function. For this reason the following numerical simulation is performed. For the first example, we consider the exact solution of (2) given by  $u(x, y) = x^2 - y^2$  and the exact domain given by considering  $\Omega = \Omega_2 \setminus \Omega_1$ , where

$$\Omega_2 = \{(x, y) / x^2 + y^2 < (1.5)^2\}$$

$$\Omega_1 = \{(x, y) / x^2 + y^2 \leq (0.75)^2\}$$

In all the test cases considered for this analysis model, the initial guesses of the domain  $\Omega_2$  is taken as a ellipse with axes of length 3 in  $x$  and 2 in  $y$  and of center  $(0, 0)$ . The number of boundary elements used for the discretization of the free boundary and the fixed boundary were taken to be respectively  $m = 40$  and  $n - m = 30$  ( $n = 70$ ). The coefficient of deformation and the precision are respectively taken  $\rho = 0.01$  and  $EP\!SD = 10^{-3}$ . The optimal boundary is reached after 181 iterations. In figure 5.1, we plot the fixed and initial domain, and the exact and the optimal solution. We note that our approach give a good solution. the variation of the cost function with respect to the number of iterations is presented in figure 5.1. In figure 5.1, we plot the initial boundary, the free boundaries at 10, 40, 80, 120 and 150 iterations.

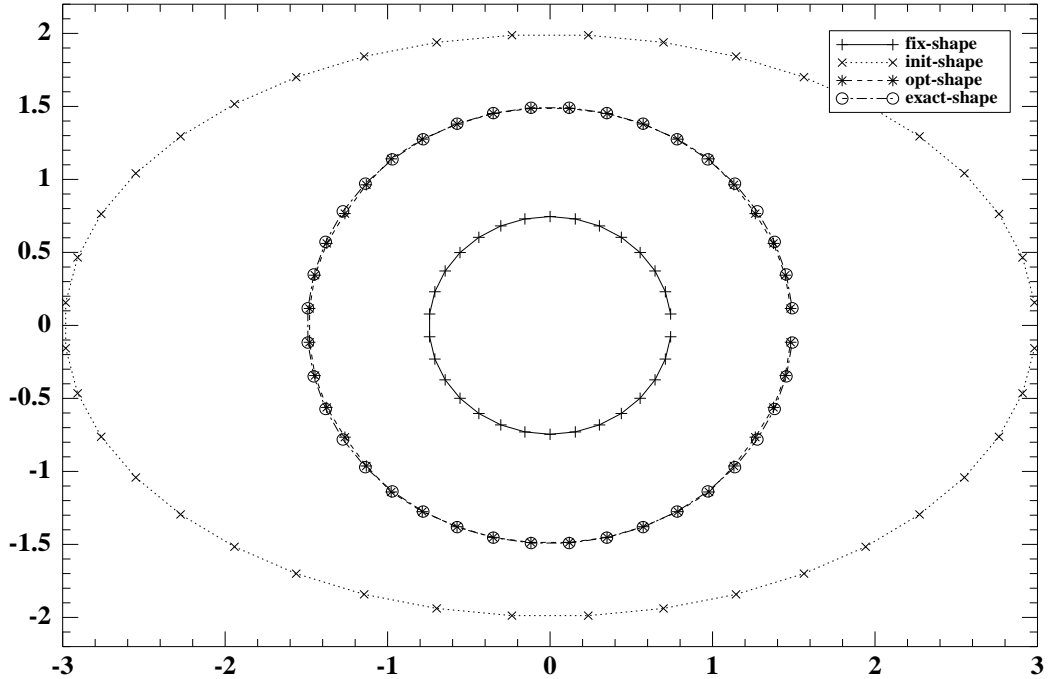


Figure 2: The optimal and the exact solutions



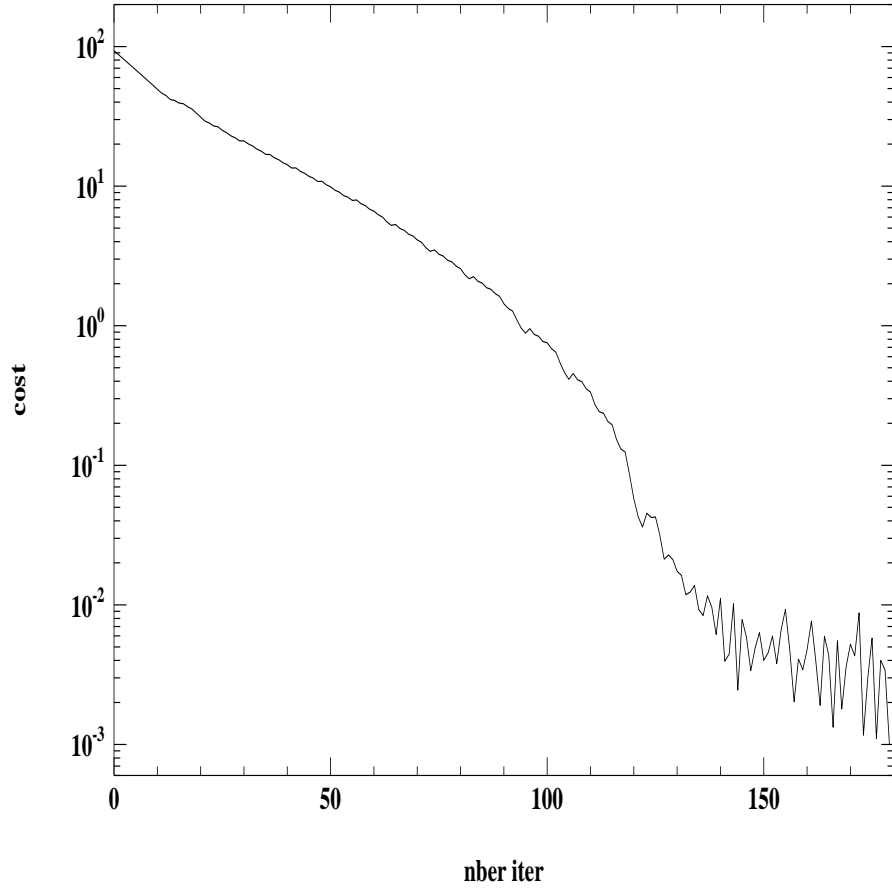


Figure 3: Variation of the cost with respect to the number of iterations

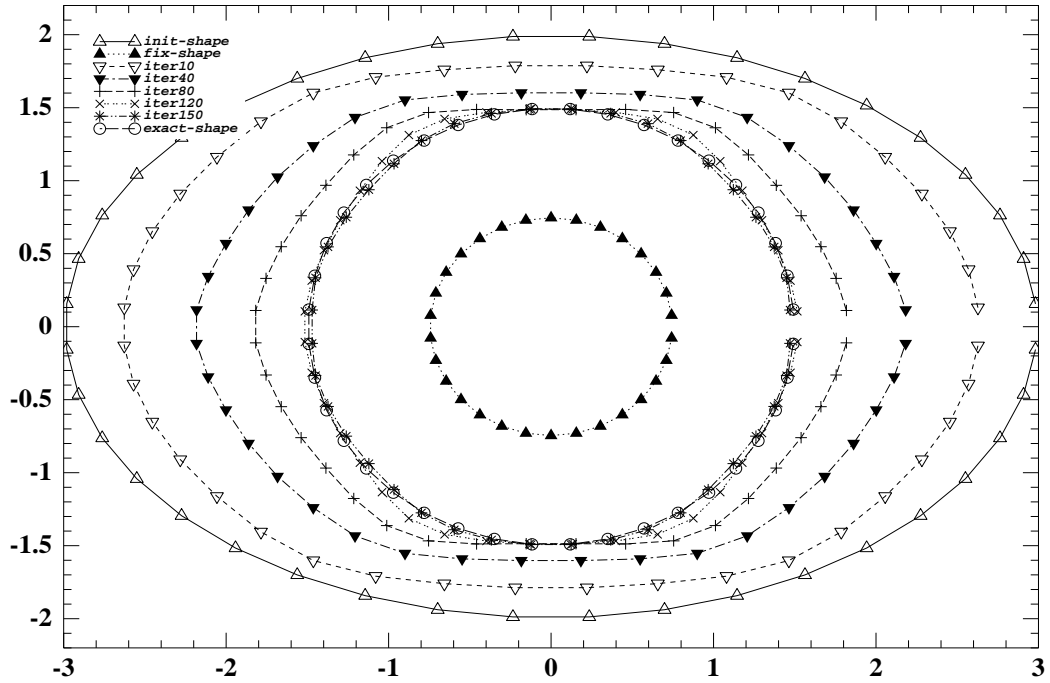


Figure 4: the free boundaries at different number of iterations.

Now we keep the same solution  $u = x^2 - y^2$ , but the exact domain is defined by the ellipse with axes of length 1.5 in  $x$  and 1 in  $y$  and of center  $(0,0)$ . For the same number of boundary elements and for the coefficient of deformation and the precision respectively taken  $\rho = 0.0001$  and  $EPSD = 10^{-3}$  the optimal boundary is reached after 111 iterations. The fixed and the initial domain, and the exact and the optimal solution are presented in figure 5.1. In figure 5.1, we plot the variation of the cost function with respect to the number of iterations.

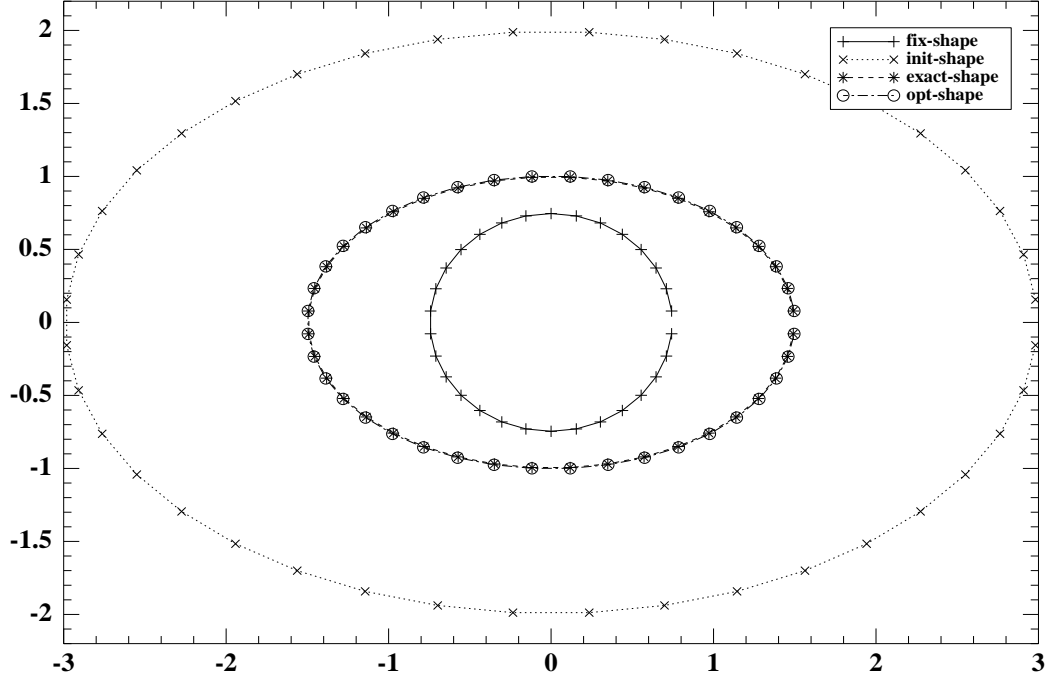


Figure 5: The optimal and the exact solutions.

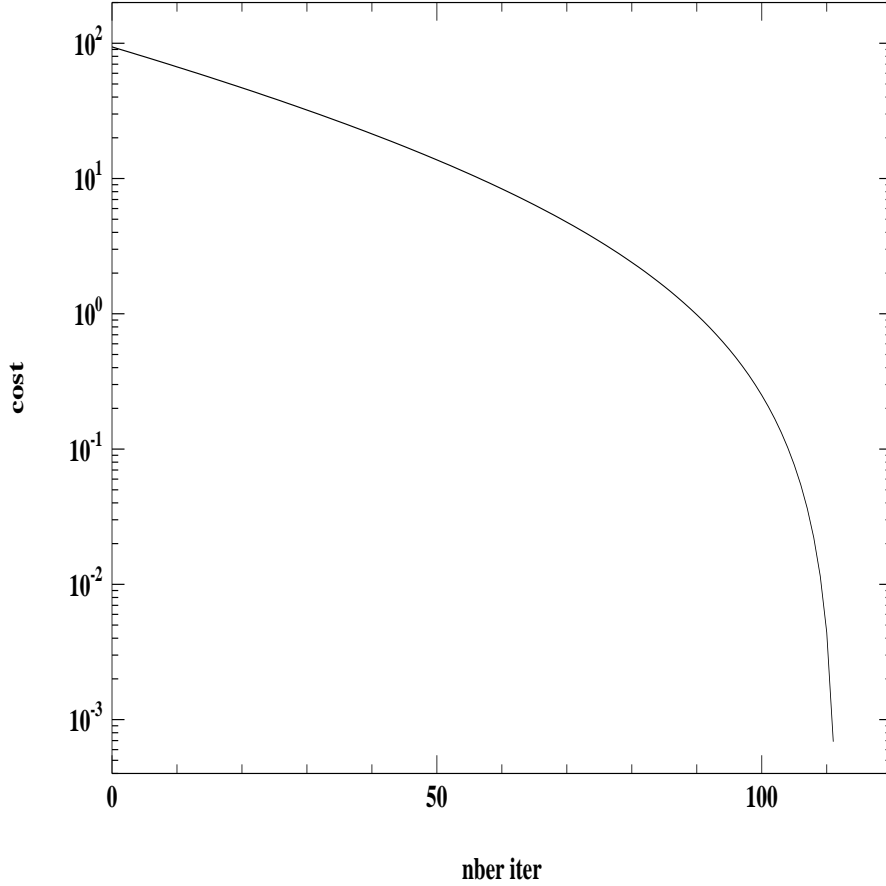


Figure 6: Variation of the cost with respect to the number of iterations.

## 5.2 Design model

In this section, we present some numerical results for the exterior free boundary problems using the approach presented in the previous section. The exterior Bernoulli free boundary reads as follows. Find outside boundary  $\Gamma_2$  and function  $u = u(x)$  solution of the problem

$$\begin{cases} -\Delta u = 0 & \text{in } \Omega, \\ u = 0 & \text{on } \Gamma_1, \\ u = 1 & \text{on } \Gamma_2, \\ \frac{\partial u}{\partial \nu} = C & \text{on } \Gamma_2, \end{cases} \quad (53)$$

where  $C$  is a negative constant.

The first numerical example is given in order to confirm the fundamental observation (see [13]), that is for a fixed domain  $\Omega_1$  which is the ball  $B_0^r$  of center  $(0, 0)$  and radius  $r$  a solution is a ball  $B_0^R$  of center  $(0, 0)$  and radius  $R$ , such that  $R > r$ ; and moreover  $R$  increases when  $C$  increases. In all the test cases considered for this design model, the initial guesses of the domain is taken as a circle of radius 3. and of center  $(0, 0)$ . In the first example, the fixed domain is chosen as circle of radius 0.75 and of center  $(0, 0)$ , and the number of boundary elements used for the discretization of the free and fixed boundaries are taken the same as in the above examples. The coefficient of deformation and the precision are respectively taken  $\rho = 0.01$  and  $EP\mathcal{S}D = 10^{-5}$ . The optimal domains for different values of  $C$  are presented in figure 5.2. The values of the cost functions for different values of  $C$  are given in table 5.2.

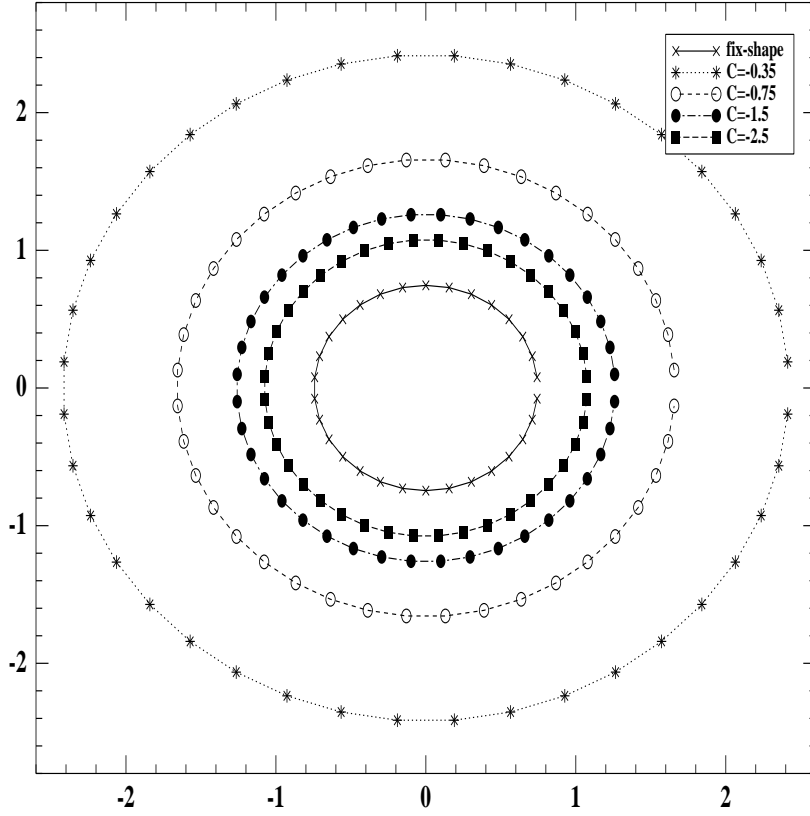


Figure 7: The optimal domains for different values of  $C$ .

$C$	-0.35	-0.75	-1.5	-2.5
$Cost$	$1.55 \cdot 10^{-6}$	$8.55 \cdot 10^{-8}$	$4.3 \cdot 10^{-8}$	$4.34 \cdot 10^{-6}$

Table 1: Cost functions for different values of  $C$ .

Now for the second example, we keep the same data, but the fixed domain  $\Omega_1$  is taken as a polygon. The number of boundary elements used for the discretization of the free boundary and the fixed boundary were taken to be respectively  $m = 40$  and  $n - m = 40$  ( $n = 80$ ). The fixed domain and the optimal domains for different values of  $C$  are presented in figure 5.2. We observe that the optimal shapes take the same profile to those obtained

in [15, 18].

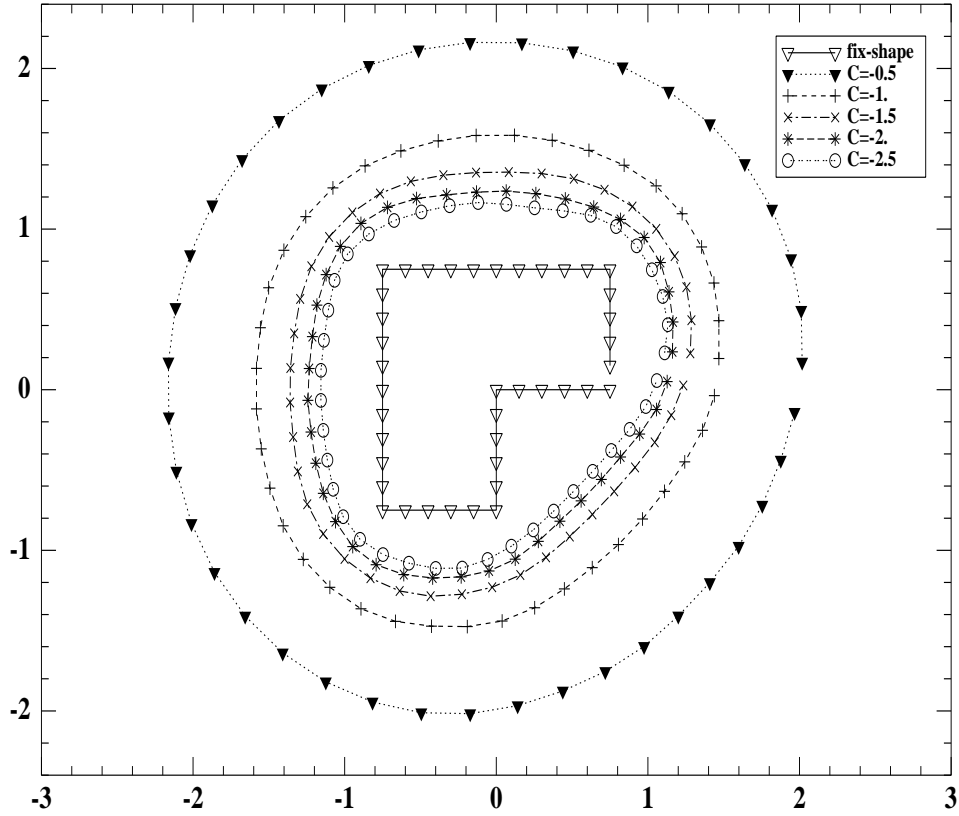


Figure 8: The optimal domains for different values of  $C$ .

## 6 Conclusion

In this work, a shape optimization formulation is considered for the approximation of the free boundary Bernoulli problem. We show the existence of the shape derivative of the cost functional and establish its expression via support functions, in order to avoid the tedious use of the shape derivative method based on the vector fields. Then the gradient method combined with the boundary element method are performed for the discretization of the problem. Finally we give some numerical results showing the ability and effectiveness of the proposed approach.

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