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# Explicit expression of the microscopic renormalized energy for a pinned Ginzburg-Landau functional

Mickaël Dos Santos

**Abstract** We get a new expression of the microscopic renormalized energy for a pinned Ginzburg-Landau type energy modeling small impurities. This renormalized energy occurs in the simplified  $2D$  Ginzburg-Landau model ignoring the magnetic field as well as the full planar magnetic model.

As in the homogenous case, when dealing with heterogeneities, the notion of renormalized energies is crucial in the study of the variational Ginzburg-Landau type problems. The key point of this article is the location of singularities inside a small impurity.

The microscopic renormalized energy is defined *via* the minimization of a Dirichlet type functional with an  $L^\infty$ -weight. Namely, the main result of the present article is a sharp asymptotic estimate for the minimization of a weighted Dirichlet energy evaluated among  $\mathbb{S}^1$ -valued maps defined on a perforated domain with shrinking holes [in the spirit of the famous work of Bethuel-Brezis-Hélein]. The renormalized energy depends on the center of the holes and it is expressed in a computable way.

In particular we get an explicit expression of the microscopic renormalized energy when the weight in the Dirichlet energy models an impurity which is a disk. In this case we proceed also to the minimization of the renormalized energy.

**Keywords** Ginzburg-Landau type energy · pinning term · renormalized energy ·  $\mathbb{S}^1$ -valued function · weighted Dirichlet energy

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LAMA, Univ Paris Est Creteil, Univ Gustave Eiffel, UPEM, CNRS, F-94010 Créteil, France  
E-mail: mickael.dos-santos@u-pec.fr

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## 1 Introduction

The superconductivity phenomenon is an impressive property that appears on some materials called *superconductors*. When a superconductor is cooled below a critical temperature, it carries electric currents without dissipation [no electrical resistance] and expels magnetic fields from its body [Meissner effect].

But if the conditions imposed on the material are too strong [*e.g.* a strong magnetic field] then the superconductivity properties may be destroyed: the material has a classical behavior in some areas of the material. These areas are called *vorticity defects*.

The present work gives informations for type II superconductors which are characterized by the possible coexistence of vorticity defects with areas in a superconducting phase. This state is called the *mixed state*. Namely, for an increasing intensity of the magnetic field, the vorticity defects appear first with a small number and look like disks with small radii. [See [14] for a rigorous and quite complete presentation of these facts]

In an homogeneous superconductor, the vorticity defects arrange themselves into triangular Abrikosov lattice. In the presence of a current, vorticity defects may move, generating dissipation, and destroying zero-resistance state. A way to prevent this motion is to trap the vorticity defects in small areas called *pinning sites*. In practice, pinning sites are often impurities which are present in a non perfect sample or intentionally introduced by irradiation, doping of impurities.

In order to prevent displacements in the superconductor, the key idea is to consider very small impuri-

ties. The heart of this article is to answer the following question: *Once the vorticity defects are trapped by small impurities, what is their locations inside the impurities [microscopic location] ?*

Since the celebrated monograph of Bethuel, Brezis and Hélein [4], the mathematical study of the superconductivity phenomenon knew an increasing popularity. In their pioneering work, Bethuel, Brezis and Hélein studied the minimizers of the simplified Ginzburg-Landau energy

$$E_\varepsilon : H^1(\Omega, \mathbb{C}) \rightarrow \mathbb{R}^+ \\ u \mapsto \frac{1}{2} \int_\Omega |\nabla u|^2 + \frac{1}{2\varepsilon^2} (1 - |u|^2)^2$$

submitted to a Dirichlet boundary condition in the asymptotic  $\varepsilon \rightarrow 0$ . Here  $\Omega$  is a bounded simply connected domain which is a cross section of an homogenous superconducting cylinder  $\Omega \times \mathbb{R}$ .

In this simplified model, a map  $u$  which minimizes  $E_\varepsilon$  [under boundary conditions] models the state of the superconductor in the mixed state. The vorticity defects are the connected components of  $\{|u| \simeq 0\}$ . We mention that a quantization of the vorticity defects may be done by observing the *degree* of a minimizers around their boundaries. In this context we say that  $z$  is a *vortex* of  $u$  when it is an isolated zero of  $u$  with a non zero degree. With this model we recover the basic description of the vorticity defects as small discs with radii of order of  $\varepsilon$  centered at a vortex. In [4], a Dirichlet boundary condition [with a non zero degree] mimics the application of a magnetic field by forcing the presence of vorticity defects. More realistic models including the presence of a magnetic field were intensively studied. Despite the present work applies in these magnetic models [see [8]], in order to motivate our main results [see Theorem 1 and Proposition 1], for sake of simplicity of the presentation, we focus on the model ignoring the magnetic field.

A part of the main results of [4] concerns *quantization & location* of the vorticity defects and an asymptotic estimate of the energy of a minimizer. All these results are related with the crucial notion of *renormalized energy*. The renormalized energy may be seen as a  $\Gamma$ -limit [when  $\varepsilon \rightarrow 0$ ] of the energy  $E_\varepsilon$  [see [2]]. In particular it gives location informations on vorticity defects for minimizers. Despite the Dirichlet boundary condition used in [4] is not physical [non gauge invariant] <sup>(1)</sup>, the information on location of the vorticity defects

coincide with some observations done by physicists [repulsion between vorticity defects, confinement in  $\Omega$  and quantization of the defects].

As said above, our goal is to deal with superconductor containing small impurities. One may modify the above model in order to consider an heterogenous superconductor. This is done with the help of a *pinning term*  $a : \Omega \rightarrow \mathbb{R}^+$  by considering the functional

$$E_\varepsilon^{\text{pinned}} : H^1(\Omega, \mathbb{C}) \rightarrow \mathbb{R}^+ \\ u \mapsto \frac{1}{2} \int_\Omega |\nabla u|^2 + \frac{1}{2\varepsilon^2} (a^2 - |u|^2)^2.$$

There are a lot of works which deal with such an energy. Some variants are studied in the literature with the function  $a$  which is "smooth" or piecewise constant; independent of  $\varepsilon$  or depending on  $\varepsilon$ ... One may for example quote the work of Lassoued-Mironescu [12] for a model ignoring the magnetic field and [1], [3] or [10] for a magnetic model. All these studies obtain similar conclusions: vorticity defects are close to the minimum points of the pinning term [*pinning effect*].

In order to present an interpretation of the pinning term, we focus on the case of a pinning term  $a : \Omega \rightarrow \mathbb{R}$  piecewise constant. Say, for some  $b \in (0; 1)$  we have  $a(\Omega) = \{1; b\}$  and  $a^{-1}(\{b\})$  is a smooth compact subset of  $\Omega$  whose connected components represent the impurities. A possible interpretation of a such pinning term is an heterogeneity in temperature. Letting  $T_c$  be the critical temperature below which superconductivity appears, if  $T_1 < T_c$  is the temperature in  $a^{-1}(\{1\})$ , then  $T_b = (1 - b^2)T_c + b^2T_1$  is the temperature in  $a^{-1}(\{b\})$ . Here the impurities are "heat" areas [see Section 2.2 of the Introduction of [5]].

In order to consider "small" impurities we need to use an  $\varepsilon$ -dependent pinning term  $[a_\varepsilon : \Omega \rightarrow \{b; 1\}]$  with  $b$  independent of  $\varepsilon$ . Then we may model *shrinking impurities*: the diameter of the connected components of  $a_\varepsilon^{-1}(\{b\})$  tend to 0 when  $\varepsilon \rightarrow 0$ . A special case of small impurities are the case of *diluted impurities*. We say that the impurities are diluted when they have small diameter and when the inter-distance between two impurities is much larger than the diameter of the impurities. In [9] the case of *diluted impurities* without magnetic field is considered and, as in [4], vorticity defects are created by imposing a Dirichlet boundary condition  $g \in C^\infty(\partial\Omega, \mathbb{S}^1)$ . It is proved that, when vorticity defects are trapped by a diluted impurity, then their location inside the impurity [the microscopic location] is independent of the Dirichlet boundary condition  $g$ : the microscopic location of the defects tends to minimize a *microscopic renormalized energy* that is independent of  $g$ . This important fact hints that this microscopic renormalized energy should play a role in a more re-

<sup>1</sup> One may modify the renormalized energy by replacing the Dirichlet boundary condition with a degree condition, after this modification the renormalized energy plays a role in a more realistic model with no boundary condition and with a magnetic field [see e.g. [8] where this fact is highlighted or [13]]

alistic model with magnetic field. This is proved in [8] where the case of small impurities for a magnetic energy is treated.

The goal of this article is to give an explicit formula for the microscopic renormalized energy in the context of the study of a pinned Ginzburg-Landau type energy. As in the work of Bethuel, Brezis and Hélein, the microscopic renormalized energy is defined *via* an auxiliary minimization problem of a weighted Dirichlet functional involving unimodular maps defined in a perforated domain.

## 2 Main result

Before stating the main result of this article [Theorem 1] we may give few words on the auxiliary minimization problem treated in this theorem [see Section 2 of [7] for a more detailed presentation]. Note that a quite complete presentation of notation is done in Section 3. Consider the simplest diluted pinning term defined in a smooth bounded simply connected domain  $\Omega \subset \mathbb{R}^2$  [we assume  $0 \in \Omega$ ]:

$$a_\varepsilon(x) = \begin{cases} 1 & \text{in } \Omega \setminus (\delta \cdot \omega) \\ b & \text{in } \delta \cdot \omega \end{cases}$$

where  $\omega \subset \mathbb{R}^2$  is a smooth bounded simply connected open set s.t.  $0 \in \omega$ ,  $b \in (0; 1)$  and  $\delta \rightarrow 0$  &  $\delta^2 \gg \varepsilon$ . One may thus consider the pinned Ginzburg-Landau energy:

$$E_\varepsilon^{\text{pinned}}(u) = \frac{1}{2} \int_\Omega |\nabla u|^2 + \frac{1}{2\varepsilon^2} (a_\varepsilon^2 - |u|^2)^2, \quad u \in H^1(\Omega, \mathbb{C}).$$

Let  $U_\varepsilon$  be the unique minimizer of  $E_\varepsilon^{\text{pinned}}$  with the Dirichlet boundary condition  $U \equiv 1$  on  $\partial\Omega$  [see [12]]. Then  $U_\varepsilon \in H^2(\Omega, \mathbb{R})$  is a regularization of  $a_\varepsilon$  and, in  $\Omega$ ,  $U_\varepsilon \geq b$ .

For  $v \in H^1(\Omega, \mathbb{C})$  we have the *Lassoued-Mironescu decoupling*:

$$E_\varepsilon^{\text{pinned}}(U_\varepsilon v) = E_\varepsilon^{\text{pinned}}(U_\varepsilon) + F_\varepsilon(v)$$

$$\text{where } F_\varepsilon(v) = \frac{1}{2} \int_\Omega U_\varepsilon^2 |\nabla v|^2 + \frac{U_\varepsilon^4}{2\varepsilon^2} (1 - |v|^2)^2.$$

Let  $g \in C^\infty(\partial\Omega, \mathbb{S}^1)$  be s.t.  $\deg_{\partial\Omega}(g) = 1$ . It is clear that  $u_\varepsilon \in H^1(\Omega, \mathbb{C})$  minimizes  $E_\varepsilon^{\text{pinned}}$  w.r.t. the boundary condition  $g$  if and only if  $v_\varepsilon := u_\varepsilon / U_\varepsilon$  minimizes  $F_\varepsilon$  w.r.t the boundary condition  $g$ .

Note that a such minimizer  $v_\varepsilon$  always exists. Under some technical assumptions on  $\delta$  [see [9]], for small  $\varepsilon > 0$ ,  $v_\varepsilon$  admits a unique zero  $x_\varepsilon$ ,  $x_\varepsilon \in \delta \cdot \omega$  and  $|v_\varepsilon| = 1 + o(1)$  in  $\Omega \setminus B(x_\varepsilon, \delta^2)$ . One may prove:

$$F_\varepsilon(v_\varepsilon) = \frac{1}{2} \int_{\Omega \setminus \overline{B(0, \sqrt{\delta})}} \left| \nabla \frac{v_\varepsilon}{|v_\varepsilon|} \right|^2 + F_\varepsilon[v_\varepsilon, B(x_\varepsilon, \delta^2)] + \frac{1}{2} \int_{B(0, \sqrt{\delta}) \setminus \overline{B(x_\varepsilon, \delta^2)}} U_\varepsilon^2 \left| \nabla \frac{v_\varepsilon}{|v_\varepsilon|} \right|^2 + o(1).$$

It is standard to check that

$$\frac{1}{2} \int_{\Omega \setminus \overline{B(0, \sqrt{\delta})}} \left| \nabla \frac{v_\varepsilon}{|v_\varepsilon|} \right|^2 = \pi |\ln \sqrt{\delta}| + W_g^{BBH}(0) + o(1)$$

where  $W_g^{BBH}$  is the renormalized energy of Bethuel-Brezis-Hélein w.r.t the boundary condition  $g$ .

Moreover  $F_\varepsilon[v_\varepsilon, B(x_\varepsilon, \delta^2)] = b^2 \left[ \pi \ln \frac{b^2 \delta^2}{\varepsilon} + \gamma \right] + o(1)$  where  $\gamma$  is a universal constant.

Therefore the only contribution of the location of  $x_\varepsilon$  in  $\delta \cdot \omega$  appears in the term  $\frac{1}{2} \int_{B(0, \sqrt{\delta}) \setminus \overline{B(x_\varepsilon, \delta^2)}} U_\varepsilon^2 \left| \nabla \frac{v_\varepsilon}{|v_\varepsilon|} \right|^2$ .

Let  $\alpha = \begin{cases} 1 & \text{in } \mathbb{R}^2 \setminus \omega \\ b^2 & \text{in } \omega \end{cases}$ , since  $U_\varepsilon$  is a regularization of  $a_\varepsilon$ , letting  $z_\varepsilon = x_\varepsilon / \delta$ ,  $w_\varepsilon(\cdot / \delta) = v_\varepsilon(\cdot) / |v_\varepsilon(\cdot)|$  and, for  $z \in \omega$ ,  $\mathcal{D}_z = \mathcal{D}_{\delta^{-1/2}, \delta, z} = B(0, \delta^{-1/2}) \setminus \overline{B(z, \delta)}$  after scaling one may prove:

$$\begin{aligned} & \frac{1}{2} \int_{B(0, \sqrt{\delta}) \setminus \overline{B(x_\varepsilon, \delta^2)}} U_\varepsilon^2 \left| \nabla \frac{v_\varepsilon}{|v_\varepsilon|} \right|^2 \\ &= \frac{1}{2} \int_{\mathcal{D}_{z_\varepsilon}} \alpha |\nabla w_\varepsilon|^2 + o(1) \\ &= \inf_{\substack{w \in H^1(\mathcal{D}_{z_\varepsilon}, \mathbb{S}^1) \\ \deg(w) = 1}} \frac{1}{2} \int_{\mathcal{D}_{z_\varepsilon}} \alpha |\nabla w|^2 + o(1). \end{aligned}$$

Our main result gives the existence of a function  $W^{\text{micro}} : \omega \rightarrow \mathbb{R}$  s.t. for  $z \in \omega$  we have

$$\inf_{\substack{w \in H^1(\mathcal{D}_z, \mathbb{S}^1) \\ \deg(w) = 1}} \frac{1}{2} \int_{\mathcal{D}_z} \alpha |\nabla w|^2 \quad (1)$$

$$= f(\delta^{-1/2}) + b^2 \pi |\ln \delta| + W^{\text{micro}}(z) + o(1)$$

where  $f : (R_0; \infty) \rightarrow \mathbb{R}$  [ $R_0 > 1$  is sufficiently large] is a function independent of  $z \in \omega$ .

The previous calculations may be used to get upper and lower bounds for the minimization problem of  $E_\varepsilon^{\text{pinned}}$  in order to prove that  $z_\varepsilon$  tends to minimize  $W^{\text{micro}}$ .

Since the arguments used in this work apply in a more general framework than above, our main result gives an estimate of the minimal energy (1) in a more complete setting than above.

### Theorem 1 Let

- $\omega \subset \mathbb{R}^2 \simeq \mathbb{C}$  be a smooth bounded simply connected open set s.t.  $0 \in \omega$ ,
- $N \in \mathbb{N}^*$  and  $(\omega^N)^* := \{(z_1, \dots, z_N) \in \omega^N \mid z_i \neq z_j \text{ for } i \neq j\}$ ,
- $B \in (0; 1)$ ,  $b \in [B; B^{-1}]$  and  $\alpha \in L^\infty(\mathbb{R}^2, [B^2; B^{-2}])$  be s.t.  $\alpha \equiv b^2$  in  $\omega$ .

For  $\mathbf{d} \in \mathbb{Z}^N$  and  $\mathbf{z} \in (\omega^N)^*$ , we write for large  $R > 1$  and small  $\rho \in (0; 1)$ ,  $\mathcal{D}_{R, \rho, \mathbf{z}} := B(0, R) \setminus \cup_i B(z_i, \rho)$  and  $\mathcal{E}_{\mathbf{d}}(\mathcal{D}_{R, \rho, \mathbf{z}}) := \{u \in H^1(\mathcal{D}_{R, \rho, \mathbf{z}}, \mathbb{S}^1) \mid \deg(u) = \mathbf{d}\}$ .

Then there exist

- $f : (R_0, \infty) \rightarrow \mathbb{R}^+$  which satisfies  $B^2\pi \ln(R) - C_{\omega, B} \leq f(R) \leq B^{-2}\pi \ln(R) + C_{\omega, B}$  [where  $C_{\omega, B}$  is a constant depending only on  $\omega$  and  $B$  and  $R_0 > 1$  is sufficiently large],
- $W^{\text{micro}} : (\omega^N)^* \times \mathbb{Z}^N \rightarrow \mathbb{R}$   
 $(\mathbf{z}, \mathbf{d}) \mapsto W^{\text{micro}}(\mathbf{z}, \mathbf{d})$

s.t. for  $\mathbf{d} \in \mathbb{Z}^N$  and  $\mathbf{z} \in (\omega^N)^*$ , when  $R \rightarrow \infty$  and  $\rho \rightarrow 0^+$ , we have

$$\inf_{u \in \mathcal{E}_d(\mathcal{D}_{R, \rho, \mathbf{z}})} \frac{1}{2} \int_{\mathcal{D}_{R, \rho, \mathbf{z}}} \alpha |\nabla u|^2 = \left( \sum_{i=1}^N d_i \right)^2 f(R) + b^2 \pi \sum_{i=1}^N d_i^2 |\ln \rho| + W^{\text{micro}}(\mathbf{z}, \mathbf{d}) + o(1). \quad (2)$$

The function  $f(\cdot)$  is defined by

$$f(R) := \inf_{\substack{v \in H^1(B_R \setminus \overline{\omega}, S^1) \\ \deg(v)=1}} \frac{1}{2} \int_{B_R \setminus \overline{\omega}} \alpha |\nabla v|^2.$$

[Note that the *degree* of a function is defined in Section 3.2].

Even in a simpler framework than in Theorem 1 and despite the apparent basic form of the problem treated in Theorem 1, to the knowledge of the author, this theorem is a new result.

*Remark 1* 1. In Theorem 1,  $\omega$  is a small impurity rescaled

at scale 1, the  $N$ -tuple  $\mathbf{z}$  corresponds to the centers of  $N$  vorticity defects trapped by the impurity with degrees given by  $\mathbf{d}$ . The weight  $\alpha$  may be understood as  $a_\varepsilon^2$  after rescaling. Then the philosophy of (2) consists in decoupling asymptotically the energy around the vorticity defects as a divergent term that ignores the location of the vorticity defects pulse  $W^{\text{micro}}(\mathbf{z}, \mathbf{d})$ . In particular, for a minimal family  $(u_\varepsilon)_{0 < \varepsilon < 1}$  of  $E_\varepsilon^{\text{pinned}}$ , if  $(\mathbf{z}, \mathbf{d})$  is the asymptotic location of vorticity defects trapped by an impurities, then  $(\mathbf{z}, \mathbf{d})$  should minimize  $W^{\text{micro}}$ .

2. In [7]-[Section 2] it is explained in detailed the link between the minimization problem considered in Theorem 1 and the microscopic location of vortices in a diluted case.
3. The map  $W^{\text{micro}} : (\omega^N)^* \times \mathbb{Z}^N \rightarrow \mathbb{R}$  depends only on  $\alpha$ ,  $\omega$  and  $N$ . Namely we have [see (55)]:

$$W^{\text{micro}}(\mathbf{z}, \mathbf{d}) := b^2 W(\mathbf{z}, \mathbf{d}) + \min_{\substack{h \in H^{1/2}(\partial\omega, S^1) \\ \deg(h)=d}} \mathcal{K}(h)$$

where  $W(\cdot, \cdot)$  is the renormalized energy of Bethuel-Brezis-Hélein with degree boundary condition [see Theorem 3, page 9] and  $\mathcal{K}$  is defined in (36) [see also Sections 6.1&6.2 for notation].

4. Theorem 1 has a more general scope than needed to be used in Ginzburg-Landau models. Indeed:

- (a) In the diluted case we have to consider  $\alpha = \begin{cases} 1 & \text{outside } \omega \\ b^2 & \text{in } \omega \end{cases}$  where  $\omega$  is the form of the impurity.

- (b) With the help of the main result of [9], [6] and [8], in order to study  $W^{\text{micro}}$  in the context of a pinned Ginzburg-Landau type function [with or without magnetic field], we may focus on the case  $d_i = 1$  for  $i \in \{1, \dots, N\}$ . But, since the minimization problem considered in Theorem 1 is of its self-interest we treat the case of general degrees.

–  $\omega \subset Y := (-1/2; 1/2] \times (-1/2; 1/2]$  is as in Theorem 1,

$$\alpha = \begin{cases} 1 & \text{in } Y \setminus \omega \\ b^2 & \text{in } \omega \end{cases},$$

–  $\alpha$  is 1-periodic,

then  $W^{\text{micro}}$  [given in Theorem 1] should govern the limiting location of vortices inside an impurity for the periodic non diluted case. But, there is no result which asserts that in the non diluted case the microscopic location of the vortices may be studied with this minimization problem. [Despite we believe that in the non diluted periodic case the microscopic location of vortices should be given by minimal configurations of  $W^{\text{micro}}$  with degree 1]

In the diluted circular case, *i.e.*, the set  $\omega$  is the unit disk  $\mathbb{D}$  and  $\alpha \equiv 1$  outside  $\omega$ , we may obtain an explicit expression for  $W^{\text{micro}}$ .

**Proposition 1** *If  $\omega$  is the unit disk  $\mathbb{D}$  and*

$$\alpha = \begin{cases} b^2 & \text{if } x \in \omega \\ 1 & \text{if } x \notin \omega \end{cases},$$

*then the microscopic renormalized energy with  $N$  vortices  $(\mathbf{z}, \mathbf{d}) = \{(z_1, d_1), \dots, (z_N, d_N)\}$  is*

$$W^{\text{micro}}(\mathbf{z}, \mathbf{d}) = -b^2 \pi \left[ \sum_{i \neq j} d_i d_j \ln |z_i - z_j| + \frac{1-b^2}{1+b^2} \left( \sum_{j=1}^N d_j^2 \ln(1 - |z_j|^2) + \sum_{i \neq j} d_i d_j \ln |1 - z_i \overline{z_j}| \right) \right].$$

Section 8 is dedicated to the case of the weight considered in Proposition 1. Proposition 1 is proved in Section 8.4. The minimization of the renormalized energy  $W^{\text{micro}}$  in this situation is presented in some particular cases in Section 8.5.

*Remark 2* In [9], the existence and the role of  $W^{\text{micro}}$  was established. But its expression was not really usable.

In particular, in the case of an impurity which is a disk containing a unique vortex, it was expected that the limiting location is the center of the disc. The expression of  $W^{\text{micro}}$  obtained in [9] does not allow to get this result easily. This result was obtained from scratch in [7]. This result is now obvious with the explicit expression obtained in Proposition 1.

### 3 Notation and basic properties

#### 3.1 General notation

##### 3.1.1 Set and number

- For  $z \in \mathbb{C}$ ,  $|z|$  is the modulus of  $z$ ,  $\text{Re}(z) \in \mathbb{R}$  is the real part of  $z$ ,  $\text{Im}(z) \in \mathbb{R}$  is the imaginary part of  $z$  and  $\bar{z}$  is the conjugate of  $z$ .
- " $\wedge$ " stands for the vectorial product in  $\mathbb{C}$ , *i.e.*,  $z_1 \wedge z_2 = \text{Im}(\bar{z}_1 z_2)$ ,  $z_1, z_2 \in \mathbb{C}$ .
- For  $z \in \mathbb{C}$  and  $r > 0$ ,  $B(z, r) = \{\tilde{z} \in \mathbb{C} \mid |z - \tilde{z}| < r\}$ . When  $z = 0$  we simply write  $B_r := B(0, r)$  and, in the particular case  $z = 0$  &  $r = 1$ , we write  $\mathbb{D} = B(0, 1)$ .
- For a set  $A \subset \mathbb{R}^2 \simeq \mathbb{C}$ , we let  $\bar{A}$  be the closure of  $A$  and  $\partial A$  be the boundary of  $A$ ; in particular we write  $\mathbb{S}^1 = \partial \mathbb{D}$  for the unit circle.

##### 3.1.2 Asymptotic

- In this article  $R > 1$  is a large number and  $\rho \in (0; 1)$  is a small number. We are essentially interested in the asymptotic  $R \rightarrow \infty$  and  $\rho \rightarrow 0^+$ .
- The notation  $o_R(1)$  [resp.  $o_\rho(1)$ ] means a quantity depending on  $R$  [resp.  $\rho$ ] which tends to 0 when  $R \rightarrow +\infty$  [resp.  $\rho \rightarrow 0^+$ ]. When there is no ambiguity we write  $o(1)$ .
- The notation  $o[f(R)]$  [resp.  $o[f(\rho)]$ ] means a quantity  $g(R)$  [resp.  $g(\rho)$ ] s.t.  $\frac{g(R)}{f(R)} \rightarrow 0$  when  $R \rightarrow +\infty$  [resp.  $\frac{g(\rho)}{f(\rho)} \rightarrow 0$  when  $\rho \rightarrow 0$ ]. When there is no ambiguity we write  $o(f)$ .
- The notation  $\mathcal{O}[f(R)]$  [resp.  $\mathcal{O}[f(\rho)]$ ] means a quantity  $g(R)$  [resp.  $g(\rho)$ ] s.t.  $\frac{g(R)}{f(R)}$  [resp.  $\frac{g(\rho)}{f(\rho)}$ ] is bounded [independently of the variable] when  $R$  is large [resp.  $\rho > 0$  is small]. When there is no ambiguity we write  $\mathcal{O}(f)$ .

#### 3.2 Function and degree

The functions we consider are essentially defined on *perforated domains*:

**Definition 1** We say that  $\mathcal{D} \subset \mathbb{R}^2$  is a *perforated domain* when  $\mathcal{D} = \Omega \setminus \cup_{i=1}^P \bar{\omega}_i$  where  $P \in \mathbb{N}^*$  and  $\Omega, \omega_1, \dots, \omega_P$  are smooth simply connected bounded open sets s.t. for  $i \in \{1, \dots, P\}$  we have  $\bar{\omega}_i \subset \Omega$  and, for  $i \neq j$ ,  $\bar{\omega}_i \cap \bar{\omega}_j = \emptyset$ . If  $P = 1$  we say that  $\mathcal{D}$  is an annular type domain.

In this article the test functions stand in the standard Sobolev space of order 1 with complex values modeled on  $L^2$ , denoted by  $H^1(\Omega, \mathbb{C})$ , where  $\Omega$  is a smooth open set.

Our main interest is based on unimodular maps, *i.e.*, the test functions are  $\mathbb{S}^1$ -valued. Thus we focus on maps lying in  $H^1(\Omega, \mathbb{S}^1) := \{u \in H^1(\Omega, \mathbb{C}) \mid |u| = 1 \text{ a.e in } \Omega\}$

We let  $\text{tr}_{\partial\Omega} : H^1(\Omega, \mathbb{C}) \rightarrow H^{1/2}(\partial\Omega, \mathbb{C})$  be the surjective *trace operator*. Here  $H^{1/2}(\partial\Omega, \mathbb{C})$  is the *trace space*. For  $\Gamma$  a connected component of  $\partial\Omega$  and  $u \in H^1(\Omega, \mathbb{C})$ ,  $\text{tr}_\Gamma(u)$  is the restriction of  $\text{tr}_{\partial\Omega}(u)$  to  $\Gamma$ .

For  $\Gamma \subset \mathbb{R}^2$  a Jordan curve and  $g \in H^{1/2}(\Gamma, \mathbb{S}^1)$ , the degree (winding number) of  $g$  is defined as  $\text{deg}_\Gamma(g) := \frac{1}{2\pi} \int_\Gamma g \wedge \partial_\tau g \in \mathbb{Z}$  where:

- $\tau$  is the direct unit tangent vector of  $\Gamma$  ( $\tau = \nu^\perp$  where  $\nu$  is the outward normal unit vector of  $\text{int}(\Gamma)$ , the bounded open set whose boundary is  $\Gamma$ ),
- $\partial_\tau := \tau \cdot \nabla$  is the tangential derivative on  $\Gamma$ . For further use we denote  $\partial_\nu = \nu \cdot \nabla$  the normal derivative on  $\Gamma$ .

For simplicity of the presentation, when there is no ambiguity, we may omit the "trace" notation or the dependence on the Jordan curve in the notation of the degree. For example:

- if  $u \in H^1(\Omega, \mathbb{S}^1)$  and  $\Gamma \subset \Omega$  is a Jordan curve then we may write  $\text{deg}_\Gamma(u)$  instead of  $\text{deg}_\Gamma[\text{tr}_\Gamma(u)]$ .
- if  $\Gamma$  is a Jordan curve and if  $h \in H^{1/2}(\Gamma, \mathbb{S}^1)$ , then we may write  $\text{deg}(h)$  instead of  $\text{deg}_\Gamma(h)$ .
- If  $\mathcal{D} = \Omega \setminus \bar{\omega}$  is an annular type domain and  $u \in H^1(\mathcal{D}, \mathbb{S}^1)$ , then  $\text{deg}_{\partial\Omega}(u) = \text{deg}_{\partial\omega}(u)$ . Consequently, without ambiguity, we may write  $\text{deg}(u)$  instead of  $\text{deg}_{\partial\Omega}(u)$  or  $\text{deg}_{\partial\omega}(u)$ .

If  $\mathcal{D}$  is a perforated domain and if  $u \in H^1(\mathcal{D}, \mathbb{S}^1)$  then we write

$$\text{deg}(u) := (\text{deg}_{\partial\omega_1}(u), \dots, \text{deg}_{\partial\omega_P}(u)) \in \mathbb{Z}^P.$$

Note that for  $\mathbf{d} \in \mathbb{Z}^P$  we have

$$\mathcal{E}_{\mathbf{d}}(\mathcal{D}) := \{u \in H^1(\mathcal{D}, \mathbb{S}^1) \mid \text{deg}(u) = \mathbf{d}\} \neq \emptyset.$$

#### 3.3 Data of the problem

In this article we consider:

- $\omega \subset \mathbb{R}^2 \simeq \mathbb{C}$  be a smooth bounded simply connected open set s.t.  $0 \in \omega$ ,
- $N \in \mathbb{N}^*$ ,  $\mathbf{d} = (d_1, \dots, d_N) \in \mathbb{Z}^N$  and we let  $d := \sum_{i=1}^N d_i \in \mathbb{Z}$ ,
- $\mathbf{z} \in (\omega^N)^* := \{(z_1, \dots, z_N) \in \omega^N \mid z_i \neq z_j \text{ for } i \neq j\}$ ,
- $B \in (0; 1)$ ,  $b \in [B; B^{-1}]$  and  $\alpha \in L^\infty(\mathbb{R}^2, [B^2; B^{-2}])$  s.t.  $\alpha \equiv b^2$  in  $\omega$ .

We denote

$$R_0 := \max\{1; 10^2 \cdot \text{diameter}(\omega)\} \text{ and } \rho_0 := 10^{-2} \cdot \min \left\{ 1, \min_{i \neq j} |z_i - z_j|, \min_i \text{dist}(z_i, \partial\omega) \right\}.$$

For  $R > R_0$  and  $\rho_0 > \rho > 0$ , we denote

- $\mathcal{D}_{R,\rho,\mathbf{z}} := B_R \setminus \cup_{i=1}^N \overline{B}(z_i, \rho)$ ,
- $\Omega_R := B_R \setminus \overline{\omega}$ ,
- $\Omega_{\rho,\mathbf{z}} := \omega \setminus \cup_{i=1}^N \overline{B}(z_i, \rho)$ .

The main purpose of this article is the following minimization problem:

$$I(R, \rho, \mathbf{z}, \mathbf{d}) := \inf_{u \in \mathcal{E}_{\mathbf{d}}(\mathcal{D}_{R,\rho,\mathbf{z}})} \frac{1}{2} \int_{\mathcal{D}_{R,\rho,\mathbf{z}}} \alpha |\nabla u|^2. \quad (3)$$

Namely, we are interested in the asymptotic behavior of  $I(R, \rho, \mathbf{z}, \mathbf{d})$  when  $R \rightarrow \infty$  and  $\rho \rightarrow 0$ .

Without loss of generality and for simplicity of the presentation,  $R > R_0$  is considered as the major parameter writing  $\rho = \rho(R)$ .

In order to study the minimization problem (3) we will define other similar minimization problems. In particular we handle minimization problems of the following form:

$$\inf_{u \in \mathcal{E}_{\mathbf{d}'}(\mathcal{D})} \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla u|^2 \quad (4)$$

where

- $\mathcal{D} := \Omega \setminus \cup_{i=1}^P \overline{\omega}_i$  is a perforated domain as in Definition 1,
- $\mathbf{d}' \in \mathbb{Z}^P$ ,
- $\alpha' \in L^\infty(\mathcal{D}; [B^2; B^{-2}])$ ,  $B \in (0; 1)$ .

We have the following classical proposition [whose proof is left to the reader]:

**Proposition 2** *Minimization problem (4) admits solutions. Moreover if  $u$  is a solution of (4) then  $v$  is a solution of (4) if and only if there exists  $\lambda \in \mathbb{S}^1$  s.t.  $v = \lambda u$ .*

Moreover a minimizer  $u_{\mathbf{d}}$  solves

$$\begin{cases} -\text{div}(\alpha' \nabla u_{\mathbf{d}}) = \alpha' u_{\mathbf{d}} |\nabla u_{\mathbf{d}}|^2 & \text{in } \mathcal{D} \\ \partial_\nu u_{\mathbf{d}} = 0 & \text{on } \partial\mathcal{D} \end{cases}. \quad (5)$$

And there exists  $\psi_{\mathbf{d}}$  which is locally defined in  $\mathcal{D}$  and whose gradient is in  $L^2(\mathcal{D}, \mathbb{R}^2)$  s.t.  $u_{\mathbf{d}} = e^{i\psi_{\mathbf{d}}}$  and

$$\begin{cases} -\text{div}(\alpha' \nabla \psi_{\mathbf{d}}) = 0 & \text{in } \mathcal{D} \\ \partial_\nu \psi_{\mathbf{d}} = 0 & \text{on } \partial\mathcal{D} \end{cases}. \quad (6)$$

#### 4 First step in the proof of Theorem 1: splitting of the domain

The first step in the proof of Theorem 1 consists in a strategy which was already used in [7]. It is a splitting of the integral over  $\mathcal{D}_{R,\rho,\mathbf{z}}$  [in (3)] in two parts: the integral over  $\Omega_R$  and the one over  $\Omega_{\rho,\mathbf{z}}$ .

For each integral we consider a mixed minimization problem by adding an arbitrary Dirichlet boundary condition on  $\partial\omega$ :  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\text{deg}(h) = d = \sum d_i$ .

We then claim that these mixed minimization problems admit "unique" solutions.

In the next steps we will solve these problems, we will minimize among  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\text{deg}(h) = d$  and finally we will decouple the minimal energy according to the different data.

The splitting consists in the following obvious equality:

$$I(R, \rho, \mathbf{z}, \mathbf{d}) = \inf_{\substack{h \in H^{1/2}(\partial\omega, \mathbb{S}^1) \\ \text{s.t. } \text{deg}(h) = d}} \left\{ \inf_{\substack{v \in H^1(\Omega_R, \mathbb{S}^1) \\ \text{tr}_{\partial\omega}(v) = h}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2 + \inf_{\substack{w \in \mathcal{E}_{\mathbf{d}}(\Omega_{\rho,\mathbf{z}}) \\ \text{tr}_{\partial\omega}(w) = h}} \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w|^2 \right\}. \quad (7)$$

The three previous minimization problems admit "unique" solutions. Indeed we have the following proposition [whose proof is left to the reader].

**Proposition 3** *1. Both minimization problems in (7) having a [partial] Dirichlet boundary condition  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  in (7) admit each a unique solution.*  
*2. The minimization problem in (7) among  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\text{deg}(h) = d$  admits solutions. Moreover if  $h_0$  is a solution, then  $\tilde{h}_0$  is a minimizer if and only if there exists  $\lambda \in \mathbb{S}^1$  s.t.  $\tilde{h}_0 = \lambda h_0$ .*

#### 5 Second step in the proof of Theorem 1: the key ingredient

The key ingredient in this article is the use of *special solutions*. It is expressed in the following proposition.

**Proposition 4** *Let  $\mathcal{D} = \Omega \setminus \cup_{i=1}^P \overline{\omega}_i$  be a perforated domain,  $B \in (0; 1)$ ,  $\alpha' \in L^\infty(\mathcal{D}; [B^2; B^{-2}])$  and  $\mathbf{d}' \in$*

$\mathbb{Z}^P$ . We let  $u_{\mathbf{d}'}$  be a minimizer of (4). Then for  $\varphi \in H^1(\mathcal{D}, \mathbb{R})$  we have

$$\frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla(u_{\mathbf{d}'} e^{i\varphi})|^2 = \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla u_{\mathbf{d}'}|^2 + \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla \varphi|^2.$$

*Proof* We fix  $\mathcal{D}, B, \alpha', \mathbf{d}'$  be as in the proposition. First note that, from Proposition 2, we get the existence of  $u_{\mathbf{d}'}$ . Moreover  $u_{\mathbf{d}'}$  is a solution of (5). We may thus write  $u_{\mathbf{d}'} = e^{i\psi_{\mathbf{d}'}}$  where  $\psi_{\mathbf{d}'}$  is locally defined in  $\mathcal{D}$  and  $\nabla \psi_{\mathbf{d}'} \in L^2(\mathcal{D}, \mathbb{R}^2)$ . Thus  $\psi_{\mathbf{d}'}$  solves (6). Let  $\varphi \in H^1(\mathcal{D}, \mathbb{R})$ . We have

$$\begin{aligned} \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla(u_{\mathbf{d}'} e^{i\varphi})|^2 &= \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla(\psi_{\mathbf{d}'} + \varphi)|^2 \\ &= \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla \psi_{\mathbf{d}'}|^2 + \int_{\mathcal{D}} \alpha' \nabla \psi_{\mathbf{d}'} \cdot \nabla \varphi + \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla \varphi|^2. \end{aligned}$$

From (6) and an integration by parts we get  $\int_{\mathcal{D}} \alpha' \nabla \psi_{\mathbf{d}'} \cdot \nabla \varphi = 0$  and this equality ends the proof of the proposition since  $\frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla \psi_{\mathbf{d}'}|^2 = \frac{1}{2} \int_{\mathcal{D}} \alpha' |\nabla u_{\mathbf{d}'}|^2$ .

*Remark 3* It is easy to check that Proposition 4 allows to prove in a "different" way the uniqueness, up to a constant rotation, of a minimizer of (4).

Because minimizers of (4) are not unique, in order to fix such a minimizer we add an extra condition. This choice leads to the crucial notion of *special solution*.

In both next sections we define the special solutions in  $\Omega_R = B_R \setminus \bar{\omega}$  [Section 5.1] and in  $\Omega_{\rho, \mathbf{z}} = \omega \setminus \cup \bar{B}(z_i, \rho)$  [Section 5.2].

### 5.1 The special solution in $\Omega_R$

In this section we focus on the annular type domain  $\Omega_R$ . We first treat the case  $d = 1$  by considering:

$$\inf_{\substack{v \in H^1(\Omega_R, \mathbb{S}^1) \\ \deg(v)=1}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2. \quad (8)$$

With the help of Proposition 2, we may fix a map  $v_R \in H^1(\Omega_R, \mathbb{S}^1)$  s.t.  $\deg(v_R) = 1$  which is a solution of (8). We freeze the non-uniqueness of  $v_R$  by letting  $v_R$  be in the form

$$v_R = \frac{x}{|x|} e^{i\gamma_R} \text{ with } \gamma_R \in H^1(\Omega_R, \mathbb{R}), \int_{\partial\omega} \gamma_R = 0. \quad (9)$$

It is clear that such map  $v_R$  is unique and well defined. Moreover, for  $d \in \mathbb{Z}$ , we have  $v_R^d$  which is a solution of the minimization problem:

$$\inf_{\substack{v \in H^1(\Omega_R, \mathbb{S}^1) \\ \deg(v)=d}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2. \quad (10)$$

It is direct to check that  $v_R^d$  is the unique solution of the minimization problem (10) of the form  $\left(\frac{x}{|x|}\right)^d e^{i\tilde{\gamma}}$  with  $\tilde{\gamma} \in H^1(\Omega_R, \mathbb{R})$  s.t.  $\int_{\partial\omega} \tilde{\gamma} = 0$ .

The special solution  $v_R$  is fundamental in the analysis since it allows to get a decoupling of the weighted Dirichlet energy. Namely, from Proposition 4 we have:

**Lemma 1** For  $d \in \mathbb{Z}$  and  $\varphi \in H^1(\Omega_R, \mathbb{R})$  we have:

$$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla(v_R^d e^{i\varphi})|^2 = \frac{d^2}{2} \int_{\Omega_R} \alpha |\nabla v_R|^2 + \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi|^2.$$

The above lemma allows to get a crucial information on the asymptotic behavior of  $(\gamma_R)_R$ :

**Proposition 5** There exists  $\gamma_\infty \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega, \mathbb{R})$  s.t. when  $R \rightarrow \infty$  we have  $\gamma_R \rightarrow \gamma_\infty$  in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$ .

*Proof* Let  $R' > R > R_0$  and  $\varphi_R = \gamma_{R'} - \gamma_R$  in order to have  $v_{R'} = v_R e^{i\varphi_R}$  in  $\Omega_R$ .

From Lemma 1 we have

$$\begin{aligned} \int_{\Omega_R} \alpha |\nabla v_{R'}|^2 &= \int_{\Omega_R} \alpha |\nabla(v_R e^{i\varphi_R})|^2 \\ &= \int_{\Omega_R} \alpha |\nabla v_R|^2 + \int_{\Omega_R} \alpha |\nabla \varphi_R|^2. \end{aligned} \quad (11)$$

We need the following lemma:

**Lemma 2** There exists a constant  $C_{B, \omega} > 0$  depending only on  $B$  and  $\omega$  s.t.  $\frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R|^2 \leq C_{B, \omega}$ .

For the convenience of the reader the proof of this lemma is postponed to the Appendix A.

From Lemma 2 we get  $\int_{B_{\sqrt{R}} \setminus B_{R^{1/4}}} \alpha |\nabla \varphi_R|^2 \leq 2C_{B, \omega}$ .

*Notation.* In the rest of this proof,  $C_0$  stands for a constant depending only on  $\omega$  and  $B$  derived from  $C_{B, \omega}$  and with universal multiplicative constants. Its values may change from line to line.

Therefore, with the help of a mean value argument, we have the existence of  $r \in (R^{1/4}, \sqrt{R})$  and of a constant  $C_0$  depending only on  $B$  and  $\omega$  s.t.:

$$\int_0^{2\pi} |\partial_\theta \varphi_R(re^{i\theta})|^2 d\theta \leq \frac{C_0}{\ln R}.$$

We denote  $m_R := \int_0^{2\pi} \varphi_R(re^{i\theta}) d\theta$ . From the above estimate and with the help of a Poincaré-Wirtinger inequality, we have

$$\int_0^{2\pi} [\varphi_R(re^{i\theta}) - m_R]^2 d\theta \leq \frac{C_0}{\ln R}.$$

We now define  $\tilde{\varphi}_R \in H^1(B_R, \mathbb{R})$ :

$$\begin{aligned} \tilde{\varphi}_R(se^{i\theta}) &= \\ &= \begin{cases} m_R & \text{for } s \in [0, r/2] \\ \frac{s-r/2}{r/2} \varphi_R(re^{i\theta}) + \frac{r-s}{r/2} m_R & \text{for } s \in (r/2, r) \\ \varphi_R(se^{i\theta}) & \text{for } s \in [r, R] \end{cases}. \end{aligned}$$

It is easy to check that  $\tilde{\varphi}_R \in H^1(B_R, \mathbb{R})$  and with direct calculations we obtain:

$$\int_{B_r} |\nabla \tilde{\varphi}_R|^2 = \int_{B_r \setminus B_{r/2}} |\nabla \tilde{\varphi}_R|^2 \leq \frac{C_0}{\ln R}. \quad (12)$$

By noting that

$$\text{tr}_{\partial B_R}(v_R e^{i\tilde{\varphi}_R}) = \text{tr}_{\partial B_R}(v_R e^{i\varphi_R}) = \text{tr}_{\partial B_R}(v_{R'}),$$

with the help of  $\tilde{\varphi}_R$  we construct  $\tilde{v}_R \in H^1(\Omega_{R'}, \mathbb{S}^1)$ :

$$\tilde{v}_R = \begin{cases} v_{R'} & \text{in } B_{R'} \setminus \overline{B_R} \\ v_R e^{i\tilde{\varphi}_R} & \text{in } \Omega_R \end{cases}.$$

From the minimality of  $v_{R'}$  and Lemma 1 we get

$$\begin{aligned} \int_{\Omega_{R'}} \alpha |\nabla v_{R'}|^2 &\leq \int_{\Omega_{R'}} \alpha |\nabla \tilde{v}_R|^2 \\ &= \int_{\Omega_{R'} \setminus \overline{\Omega_R}} \alpha |\nabla v_{R'}|^2 + \\ &\quad + \int_{\Omega_R} \alpha |\nabla v_R|^2 + \int_{\Omega_R} \alpha |\nabla \tilde{\varphi}_R|^2. \end{aligned} \quad (13)$$

Estimate (13) implies:

$$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla v_{R'}|^2 \leq \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v_R|^2 + \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \tilde{\varphi}_R|^2.$$

This inequality coupled with (11) gives

$$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R|^2 \leq \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \tilde{\varphi}_R|^2.$$

On the other hand, from the definition of  $\tilde{\varphi}_R$  we have  $\tilde{\varphi}_R = \varphi_R$  in  $B_R \setminus \overline{B_r}$ . Consequently we deduce  $\frac{1}{2} \int_{\Omega_r} \alpha |\nabla \varphi_R|^2 \leq \frac{1}{2} \int_{\Omega_r} \alpha |\nabla \tilde{\varphi}_R|^2$ . With (12) and since  $r \in (R^{1/4}, \sqrt{R})$  we may conclude

$$\frac{1}{2} \int_{\Omega_{R^{1/4}}} \alpha |\nabla \varphi_R|^2 \leq \frac{C_0}{\ln R}.$$

In particular, for a compact set  $K \subset \mathbb{R}^2 \setminus \omega$  s.t.  $\partial\omega \subset \partial K$  we have for sufficiently large  $R$

$$\frac{1}{2} \int_K \alpha |\nabla \varphi_R|^2 \leq \frac{C_0}{\ln R}.$$

Since  $\int_{\partial\omega} \varphi_R = 0$ , we may use a Poincaré type inequality to get  $\|\varphi_R\|_{H^1(K)} \rightarrow 0$  when  $R \rightarrow \infty$  independently of  $R' > R$ .

It suffices to note that  $\varphi_R = \gamma_{R'} - \gamma_R$  in order to conclude that  $(\gamma_R)_R$  is a Cauchy family in  $H^1(K)$ . Then  $(\gamma_R)_R$  is a Cauchy family in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$ . The completeness of  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega, \mathbb{R})$  allows to get the existence of  $\gamma_\infty \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega, \mathbb{R})$  s.t.  $\gamma_R \rightarrow \gamma_\infty$  in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$ .

**Corollary 1** *We have two direct consequences of Proposition 5 :*

1.  $\text{tr}_{\partial\omega}(\gamma_R) \rightarrow \text{tr}_{\partial\omega}(\gamma_\infty)$  in  $H^{1/2}(\partial\omega)$ ,
2.  $v_R = \frac{x}{|x|} e^{i\gamma_R} \rightarrow v_\infty := \frac{x}{|x|} e^{i\gamma_\infty}$  in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$ .

## 5.2 The special solution in $\Omega_{\rho, \mathbf{z}}$

As for the special solution in  $\Omega_R$ , we first consider the minimization problem:

$$\inf_{w \in \mathcal{E}_d(\Omega_{\rho, \mathbf{z}})} \frac{1}{2} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla w|^2. \quad (14)$$

From Proposition 2, we may fix  $w_{\rho, \mathbf{z}, \mathbf{d}}$ , a unique solution of (14), by imposing

$$w_{\rho, \mathbf{z}, \mathbf{d}} = \prod_{i=1}^N \left( \frac{x - z_i}{|x - z_i|} \right)^{d_i} e^{i\gamma_{\rho, \mathbf{z}, \mathbf{d}}}, \quad \int_{\partial\omega} \gamma_{\rho, \mathbf{z}, \mathbf{d}} = 0. \quad (15)$$

For  $i \in \{1, \dots, N\}$ , we may locally define  $\theta_i$  in  $\mathbb{R}^2 \setminus \{z_i\}$  as a lifting of  $\frac{x - z_i}{|x - z_i|}$ , i.e.,  $e^{i\theta_i} = \frac{x - z_i}{|x - z_i|}$ . Moreover  $\nabla \theta_i$  is globally defined. We denote  $\Theta := d_1 \theta_1 + \dots + d_N \theta_N$  which is locally defined in  $\mathbb{R}^2 \setminus \{z_1, \dots, z_N\}$  and whose gradient is globally defined in  $\mathbb{R}^2 \setminus \{z_1, \dots, z_N\}$ . We then may write  $w_{\rho, \mathbf{z}, \mathbf{d}} = e^{i(\Theta + \gamma_{\rho, \mathbf{z}, \mathbf{d}})}$ .

In contrast with the previous section, the asymptotic behavior of  $w_{\rho, \mathbf{z}, \mathbf{d}}$  is well known when  $\rho \rightarrow 0$ . For example Lefter and Rădulescu proved the following theorem.

**Theorem 2** [Theorem 1 [13]] *For  $\rho_0 > \rho > 0$  we let  $w_\rho$  be a minimizer of (14) and we consider a sequence  $\rho_n \downarrow 0$ . Up to pass to a subsequence, there exists  $w_0 \in C^\infty(\overline{\omega} \setminus \{z_1, \dots, z_N\}, \mathbb{S}^1)$  s.t.  $w_{\rho_n} \rightarrow w_0$  in  $C_{\text{loc}}^k(\overline{\omega} \setminus \{z_1, \dots, z_N\})$  for all  $k \geq 0$ .*

*Moreover the limits  $w_0$  are unique up to the multiplication by a constant in  $\mathbb{S}^1$ .*

From Theorem 2, we get that the possible limits  $w_0$ 's are unique up to a constant rotation. Thus there exists a unique limit  $w_{0, \mathbf{z}, \mathbf{d}}$  [given by Theorem 2] which may be written:

$$w_{0, \mathbf{z}, \mathbf{d}} = \prod_{i=1}^N \left( \frac{x - z_i}{|x - z_i|} \right)^{d_i} e^{i\gamma_{0, \mathbf{z}, \mathbf{d}}}, \quad \int_{\partial\omega} \gamma_{0, \mathbf{z}, \mathbf{d}} = 0. \quad (16)$$

We thus have the following corollary:

**Corollary 2** *Let  $\gamma_{0,\mathbf{z},\mathbf{d}} \in H_{\text{loc}}^1(\bar{\omega} \setminus \{z_1, \dots, z_N\}, \mathbb{R})$  be defined by (16). When  $\rho \rightarrow 0$  we have  $\gamma_{\rho,\mathbf{z},\mathbf{d}} \rightarrow \gamma_{0,\mathbf{z},\mathbf{d}}$  in  $H_{\text{loc}}^1(\bar{\omega} \setminus \{z_1, \dots, z_N\})$ . Thus we also get  $\text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) \rightarrow \text{tr}_{\partial\omega}(\gamma_{0,\mathbf{z},\mathbf{d}})$  in  $H^{1/2}(\partial\omega)$ .*

*Proof* Let  $K \subset \bar{\omega} \setminus \{z_1, \dots, z_N\}$  be a connected compact set s.t.  $\partial\omega \subset \partial K$  and let  $\rho_n \downarrow 0$  be s.t.  $w_{\rho_n,\mathbf{z},\mathbf{d}} = e^{\vartheta + \gamma_{\rho_n,\mathbf{z},\mathbf{d}}} \rightarrow w_0 = e^{\vartheta + \gamma_0}$  in  $C^1(K)$  for some  $\gamma_0 \in C^1(K)$ . It suffices to prove that we may choose  $\gamma_0 = \gamma_{0,\mathbf{z},\mathbf{d}}$  defined by (16).

On the one hand, we have  $\nabla\gamma_{\rho_n,\mathbf{z},\mathbf{d}} = w_{\rho_n,\mathbf{z},\mathbf{d}} \wedge \nabla w_{\rho_n,\mathbf{z},\mathbf{d}} - \nabla\Theta \rightarrow w_0 \wedge \nabla w_0 - \nabla\Theta = \nabla\gamma_0$  in  $L^2(K)$ . Then  $\gamma_0 = \gamma_{0,\mathbf{z},\mathbf{d}} + \lambda$  for some  $\lambda \in \mathbb{R}$ .

On the other hand  $(\gamma_{\rho_n,\mathbf{z},\mathbf{d}})_n$  is bounded in  $H^1(K)$ , consequently, up to pass to a subsequence, we have  $\gamma_{\rho_n,\mathbf{z},\mathbf{d}} \rightharpoonup \gamma_0$  in  $H^1(K)$ . With the help of the previous paragraph, we get that the convergence is in fact strong. Thus  $\text{tr}_{\partial\omega}(\gamma_{\rho_n,\mathbf{z},\mathbf{d}}) \rightarrow \text{tr}_{\partial\omega}(\gamma_0)$  in  $L^2(\partial\omega)$ .

In conclusion

$$0 = \int_{\partial\omega} \gamma_{\rho_n,\mathbf{z},\mathbf{d}} \rightarrow \int_{\partial\omega} \gamma_0 = \lambda + \int_{\partial\omega} \gamma_{0,\mathbf{z},\mathbf{d}}.$$

This means  $\lambda = 0$  and thus  $\gamma_0 = \gamma_{0,\mathbf{z},\mathbf{d}}$ .

About the asymptotic energetic expanding, Lefter and Rădulescu proved the following result:

**Theorem 3** [Theorem 2 [13]] *For  $N \in \mathbb{N}^*$ , there exists a map  $W : (\omega^N)^* \times \mathbb{Z}^N \rightarrow \mathbb{R}$  s.t. for  $\mathbf{d} \in \mathbb{Z}^N$  and  $\mathbf{z} \in (\omega^N)^*$  when  $\rho \rightarrow 0$  we have:*

$$\inf_{w \in \mathcal{E}_{\mathbf{d}}(\Omega_{\rho,\mathbf{z}})} \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w|^2 = \pi \sum_{i=1}^N d_i^2 |\ln \rho| + W(\mathbf{z}, \mathbf{d}) + o_{\rho}(1).$$

## 6 Upper Bound

We are now in position to start the proof of Theorem 1. To this end, the goal of this section is to identify a map  $\mathcal{K} : \{h \in H^{1/2}(\partial\omega, \mathbb{S}^1) \mid \deg(h) = d\} \rightarrow \mathbb{R}$  s.t. for a fixed  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  with  $\deg(h) = d$ , when  $R \rightarrow \infty$  we have

$$\begin{aligned} & \inf_{\substack{v \in H^1(\Omega_R, \mathbb{S}^1) \\ \text{tr}_{\partial\omega}(v) = h}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2 + \inf_{\substack{w \in \mathcal{E}_{\mathbf{d}}(\Omega_{\rho,\mathbf{z}}) \\ \text{tr}_{\partial\omega}(w) = h}} \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w|^2 \\ &= \mathcal{K}(h) + d^2 f(R) + \\ & \quad + b^2 \left[ \pi \left( \sum_{i=1}^N d_i^2 \right) |\ln \rho| + W(\mathbf{z}, \mathbf{d}) \right] + o(1). \end{aligned} \quad (17)$$

In the above estimate we have:

- $\mathcal{K}$  is independent of  $R, \rho$  ;
- $f$  is defined in Theorem 1 and is independent of  $h, \rho, \mathbf{z}, \mathbf{d}$  and  $d = \sum d_i$ ;

- $W$  is defined in Theorem 3 and is independent of  $b, B, h, \rho$  and  $R$ .

Note that from Corollaries 1 and 2, we have the existence of

- $\gamma_{\infty} \in H^{1/2}(\partial\omega)$  s.t.  $\gamma_R \rightarrow \gamma_{\infty}$  in  $H^{1/2}(\partial\omega)$ ,
- $\gamma_{0,\mathbf{z},\mathbf{d}} \in H^{1/2}(\partial\omega)$  s.t.  $\gamma_{\rho,\mathbf{z},\mathbf{d}} \rightarrow \gamma_{0,\mathbf{z},\mathbf{d}}$  in  $H^{1/2}(\partial\omega)$ .

It is important to claim that since  $\int_{\partial\omega} \gamma_R = 0$  and  $\int_{\partial\omega} \gamma_{\rho,\mathbf{z},\mathbf{d}} = 0$ , we have  $\int_{\partial\omega} \gamma_{\infty} = 0$  and  $\int_{\partial\omega} \gamma_{0,\mathbf{z},\mathbf{d}} = 0$ .

### 6.1 Study in the domain $\Omega_R$

For  $R \in (R_0, \infty)$  and  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\deg(h) = d$  we consider

$$I_R(h) := \inf_{\substack{v \in H^1(\Omega_R, \mathbb{S}^1) \\ \text{tr}_{\partial\omega}(v) = h}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2. \quad (18)$$

Let  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\deg(h) = d$ . In this section we want to estimate  $I_R(h)$  when  $R \rightarrow \infty$ . We let  $g_h := h \left( \frac{|x|}{x} \right)^d \in H^{1/2}(\partial\omega)$ . It is clear that  $\deg(g_h) = 0$  and then we may fix a unique  $\phi_h \in H^{1/2}(\partial\omega, \mathbb{R})$  s.t.  $g_h = e^{i\phi_h}$  and  $\int_{\partial\omega} \phi_h \in (-\pi, \pi]$ .

*Remark 4* Since our goal is to estimate  $I_R(h)$  and since for  $\beta \in \mathbb{R}$  we have  $I_R(h) = I_R(e^{i\beta}h)$ , up to replacing  $h$  by  $e^{i\beta}h$  with  $\beta = -\int_{\partial\omega} \phi_h$ , we may assume that  $\int_{\partial\omega} \phi_h = 0$ .

Recall that for  $R \in (R_0, \infty]$  we have  $v_R = \frac{x}{|x|} e^{i\gamma_R}$  [see (9) and Corollary 1] and we let  $\phi_R^h := \phi_h - d \text{tr}_{\partial\omega}(\gamma_R) \in H^{1/2}(\partial\omega, \mathbb{R})$ . We then get  $h = \text{tr}_{\partial\omega}(v_R^d) e^{i\phi_R^h}$  and  $\int_{\partial\omega} \phi_R^h = 0$ .

From Corollary 1 we immediately obtain:

**Corollary 3**  $\phi_R^h \xrightarrow{R \rightarrow \infty} \phi_{\infty}^h$  in  $H^{1/2}(\partial\omega)$ .

For  $R \in (R_0, \infty)$  and  $v \in H^1(\Omega_R, \mathbb{S}^1)$  it is clear that

$$\text{tr}_{\partial\omega}(v) = h \iff v = v_R^d e^{i\varphi} \quad \text{with} \quad \begin{cases} \varphi \in H^1(\Omega_R, \mathbb{R}) \\ \text{tr}_{\partial\omega}(\varphi) = \phi_R^h \end{cases}.$$

On the other hand, for  $v = v_R^d e^{i\varphi} \in H^1(\Omega_R, \mathbb{S}^1)$ , from Lemma 1 we have

$$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2 = \frac{d^2}{2} \int_{\Omega_R} \alpha |\nabla v_R|^2 + \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi|^2. \quad (19)$$

Therefore, one may obtain that  $v = v_R^d e^{i\varphi}$  with  $\text{tr}_{\partial\omega}(\varphi) = \phi_R^h$  is a solution of the minimization problem (18) if and

only if  $\varphi \in H^1(\Omega_R, \mathbb{R})$  is a solution of the minimization problem

$$\inf_{\substack{\varphi \in H^1(\Omega_R, \mathbb{R}) \\ \text{tr}_{\partial\omega}(\varphi) = \phi_R^h}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi|^2. \quad (20)$$

It is standard to prove that Problem (20) admits a unique solution denoted by  $\varphi_R^h$ . Moreover this minimizer is the unique solution of

$$\begin{cases} -\text{div}(\alpha \nabla \varphi_R^h) = 0 & \text{in } \Omega_R \\ \text{tr}_{\partial\omega}(\varphi_R^h) = \phi_R^h \\ \partial_\nu \varphi_R^h = 0 & \text{on } \partial B_R \end{cases}.$$

We denote  $\Omega_\infty := \mathbb{R}^2 \setminus \bar{\omega}$  and for  $\phi \in H^{1/2}(\partial\omega, \mathbb{R})$  we let

$$\mathcal{H}_\phi := \left\{ \varphi \in H_{\text{loc}}^1(\bar{\Omega}_\infty, \mathbb{R}) \mid \begin{array}{l} \nabla \varphi \in L^2(\Omega_\infty) \\ \text{tr}_{\partial\omega}(\varphi) = \phi \end{array} \right\}. \quad (21)$$

We are now interested in the minimization problem:

$$\inf_{\varphi \in \mathcal{H}_{\phi_\infty^h}} \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi|^2. \quad (22)$$

By direct minimization, first order variations and from the strict convexity of the energy we get:

**Proposition 6** *Problem (22) admits a unique solution denoted by  $\varphi_\infty^h$ . Moreover  $\varphi_\infty^h$  is a solution of*

$$-\text{div}(\alpha \nabla \varphi_\infty^h) = 0 \text{ in } \Omega_\infty. \quad (23)$$

We are now able to prove the main result of this section:

**Proposition 7** *When  $R \rightarrow \infty$ , we have  $\varphi_R^h \rightarrow \varphi_\infty^h$  in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$  and  $\nabla \varphi_R^h \mathbb{I}_{\Omega_R} \rightarrow \nabla \varphi_\infty^h$  in  $L^2(\mathbb{R}^2 \setminus \bar{\omega})$ , with  $\mathbb{I}_{\Omega_R}(x) = \begin{cases} 1 & \text{if } x \in \Omega_R \\ 0 & \text{if } x \notin \Omega_R \end{cases}$ . And consequently:*

$$\int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 = \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2 + o_R(1).$$

*Proof* From Corollary 3 we have  $\varphi_R^h - \phi_\infty^h \rightarrow 0$  in  $H^{1/2}(\partial\omega)$ . Consequently, there exists  $\xi_R \in H^1(\Omega_\infty, \mathbb{R})$  s.t.  $\text{tr}_{\partial\omega}(\xi_R) = \phi_R^h - \phi_\infty^h$  and  $\|\xi_R\|_{H^1(\Omega_\infty)} \rightarrow 0$ .

The test function  $\varphi_\infty^h + \xi_R$  satisfies the boundary condition of Problem (20), therefore:

$$\begin{aligned} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 &\leq \frac{1}{2} \int_{\Omega_R} \alpha |\nabla(\varphi_\infty^h + \xi_R)|^2 \\ &= \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_\infty^h|^2 + o(1). \end{aligned} \quad (24)$$

We used  $\int_{\Omega_R} \alpha |\nabla \varphi_\infty^h|^2 \leq C_0 := \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2 < \infty$ .

From (24), we obtain

$$\limsup_{R \rightarrow \infty} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 \leq \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2. \quad (25)$$

We now prove *the* "lim inf"-lower bound:

$$\liminf_{R \rightarrow \infty} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 \geq \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2. \quad (26)$$

On the one hand, from (24), for  $R \in (R_0, \infty)$  sufficiently large, we have  $\int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 \leq C_0 + 1$  and thus, up to passing to a subsequence, we get that  $\nabla \varphi_R^h \mathbb{I}_{\Omega_R}$  weakly converges in  $L^2(\mathbb{R}^2 \setminus \bar{\omega}, \mathbb{R}^2)$ .

On the other hand, for a connected compact set  $K \subset \mathbb{R}^2 \setminus \omega$  s.t.  $\partial\omega \subset \partial K$ , the competitor  $\varphi_\infty^h + \xi_R$  is bounded in  $H^1(K)$ . We let  $\chi_R := \varphi_R^h - (\varphi_\infty^h + \xi_R) \in H^1(K)$  and then, for sufficiently large  $R$ , we have  $\|\nabla \chi_R\|_{L^2(\Omega_R)} \leq 2C_0 + 2$ . It is easy to check that  $\text{tr}_{\partial\omega}(\chi_R) = 0$ . Consequently, from a Poincaré type inequality, there exists a constant  $C_K > 1$  s.t.  $\|\chi_R\|_{L^2(K)} \leq C_K \|\nabla \chi_R\|_{L^2(K)} \leq C_K \times (2C_0 + 2)$ . Thus there exists a constant  $C'_K$  s.t., for sufficiently large  $R$ ,  $\|\varphi_R^h\|_{L^2(K)} \leq C'_K$ .

Consequently, with the help of an exhaustion by compact sets and a diagonal extraction process, we have the existence of a sequence  $R_k \uparrow \infty$  and  $\tilde{\varphi}_\infty \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega, \mathbb{R})$  s.t.

$$\begin{cases} \varphi_{R_k}^h \rightharpoonup \tilde{\varphi}_\infty & \text{in } H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega) \\ \nabla \varphi_{R_k}^h \mathbb{I}_{\Omega_{R_k}} \rightharpoonup \nabla \tilde{\varphi}_\infty & \text{in } L^2(\mathbb{R}^2 \setminus \bar{\omega}) \\ \liminf_{R \rightarrow \infty} \int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 = \lim_{R_k \rightarrow \infty} \int_{\Omega_{R_k}} \alpha |\nabla \varphi_{R_k}^h|^2 \end{cases}. \quad (27)$$

We thus get  $\nabla \tilde{\varphi}_\infty \in L^2(\mathbb{R}^2 \setminus \bar{\omega})$  and  $\text{tr}_{\partial\omega}(\tilde{\varphi}_\infty) = \phi_\infty^h$ , i.e.,  $\tilde{\varphi}_\infty \in \mathcal{H}_{\phi_\infty^h}$ .

From the definition of  $\varphi_\infty^h$  [Proposition 6] we have with (27)

$$\frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2 \leq \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \tilde{\varphi}_\infty|^2 \leq \liminf_{R \rightarrow \infty} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2.$$

We thus obtained (26). Therefore by combining (25) and (26) we get:

$$\int_{\Omega_R} \alpha |\nabla \varphi_R^h|^2 = \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2 + o_R(1). \quad (28)$$

The above estimate implies that a limiting map  $\tilde{\varphi}_\infty \in \mathcal{H}_{\phi_\infty^h}$  as previously obtained satisfies:

$$\frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \tilde{\varphi}_\infty|^2 \leq \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty^h|^2.$$

On the other hand  $\varphi_\infty^h$  is the unique solution of Problem (22). Therefore  $\tilde{\varphi}_\infty = \varphi_\infty^h$ . Consequently, the convergences in (27) hold for  $R \rightarrow \infty$  and from (28), these convergences are strong.

6.2 Study in the domain  $\Omega_{\rho,\mathbf{z}}$ 

Recall that we fixed a map  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\deg(h) = d$ . We are interested in getting an asymptotic estimate for the minimal energy

$$I_{\rho,\mathbf{z},\mathbf{d}}(h) = \inf_{\substack{w \in \mathcal{E}_{\mathbf{d}}(\Omega_{\rho,\mathbf{z}}) \\ \text{tr}_{\partial\omega}(w) = h}} \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w|^2. \quad (29)$$

First note that letting  $g_{\mathbf{z},\mathbf{d}}^h := h \prod_{i=1}^N \left( \frac{|x - z_i|}{x - z_i} \right)^{d_i} \in$

$H^{1/2}(\partial\omega, \mathbb{S}^1)$  we have  $\deg(g_{\mathbf{z},\mathbf{d}}^h) = 0$ . Thus, from a standard lifting result, we may fix  $\phi_{\mathbf{z},\mathbf{d}}^h \in H^{1/2}(\partial\omega, \mathbb{R})$  s.t.  $g_{\mathbf{z},\mathbf{d}}^h = e^{i\phi_{\mathbf{z},\mathbf{d}}^h}$  and  $\int_{\partial\omega} \phi_{\mathbf{z},\mathbf{d}}^h \in (-\pi, \pi]$ . It is clear that  $\phi_{\mathbf{z},\mathbf{d}}^h$  is uniquely defined.

*Remark 5* As in the previous section [see Remark 4], for  $\beta \in \mathbb{R}$  we have  $I_{\rho,\mathbf{z},\mathbf{d}}(h) = I_{\rho,\mathbf{z},\mathbf{d}}(he^{i\beta})$ . Thus up to replacing  $h$  by  $he^{i\beta}$ , with  $\beta = -\int_{\partial\omega} \phi_{\mathbf{z},\mathbf{d}}^h$ , in order to estimate  $I_{\rho,\mathbf{z},\mathbf{d}}(h)$ , we may assume that  $\int_{\partial\omega} \phi_{\mathbf{z},\mathbf{d}}^h = 0$ .

For  $\rho \in [0, \rho_0)$  we let  $\phi_{\rho,\mathbf{z},\mathbf{d}}^h := \phi_{\mathbf{z},\mathbf{d}}^h - \gamma_{\rho,\mathbf{z},\mathbf{d}} \in H^{1/2}(\partial\omega, \mathbb{R})$  [ $\gamma_{\rho,\mathbf{z},\mathbf{d}}$  is defined in (15) and (16)] in order to have  $h = \text{tr}_{\partial\omega}(w_{\rho,\mathbf{z},\mathbf{d}}) e^{i\phi_{\rho,\mathbf{z},\mathbf{d}}^h}$ . Moreover it is clear that  $\int_{\partial\omega} \phi_{\rho,\mathbf{z},\mathbf{d}}^h = 0$ .

*Notation.* For simplicity of the presentation, until the end of this section, we omit the subscripts  $\mathbf{z}, \mathbf{d}$  e.g. writing, for  $\rho \in [0, \rho_0)$ ,  $\phi_\rho^h$  instead of  $\phi_{\rho,\mathbf{z},\mathbf{d}}^h$ .

From Corollary 2 we get:

**Corollary 4**  $\phi_\rho^h \xrightarrow{\rho \rightarrow 0} \phi_0^h$  in  $H^{1/2}(\partial\omega)$ .

For  $\rho \in (0, \rho_0)$  and  $w \in H^1(\Omega_{\rho,\mathbf{z}}, \mathbb{S}^1)$ , we have

$$\text{tr}_{\partial\omega}(w) = h \iff w = w_\rho e^{i\varphi} \quad \text{with} \quad \begin{cases} \varphi \in H^1(\Omega_{\rho,\mathbf{z}}, \mathbb{R}) \\ \text{tr}_{\partial\omega}(\varphi) = \phi_\rho^h \end{cases}.$$

We follow the same strategy as in the previous section. For  $\varphi \in H^1(\Omega_{\rho,\mathbf{z}}, \mathbb{R})$ , from Proposition 4 we have for  $w = w_\rho e^{i\varphi}$

$$\frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w|^2 = \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w_\rho|^2 + \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi|^2. \quad (30)$$

Consequently a test function  $w = w_\rho e^{i\varphi}$  with  $\text{tr}_{\partial\omega}(\varphi) = \phi_\rho^h$  is a solution of the minimizing problem (29) if and only if  $\varphi \in H^1(\Omega_{\rho,\mathbf{z}}, \mathbb{R})$  is a solution of the minimizing problem

$$\inf_{\substack{\varphi \in H^1(\Omega_{\rho,\mathbf{z}}, \mathbb{R}) \\ \text{tr}_{\partial\omega}(\varphi) = \phi_\rho^h}} \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi|^2. \quad (31)$$

And then for  $\rho \in (0, \rho_0)$ , the minimizing Problem (31) admits a unique solution denoted by  $\varphi_\rho^h$ . About the asymptotic behavior of  $\varphi_\rho^h$  we have the following result:

**Proposition 8** When  $\rho \rightarrow 0$ , we have

$$\frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi_\rho^h|^2 = \frac{1}{2} \int_{\omega} |\nabla \tilde{\phi}_0^h|^2 + o_\rho(1)$$

where  $\tilde{\phi}_0^h$  is the harmonic extension of  $\phi_0^h$  in  $\omega$ .

*Proof* Let  $\xi_\rho$  be the harmonic extension of  $\phi_0^h - \phi_\rho^h$  in  $\omega$ . Since  $\|\phi_0^h - \phi_\rho^h\|_{H^{1/2}(\partial\omega)} \rightarrow 0$ , we have  $\xi_\rho \rightarrow 0$  in  $H^1(\omega)$ .

We now prove the proposition. On the one hand, by minimality of  $\varphi_\rho^h$  and since  $\text{tr}_{\partial\omega}(\tilde{\phi}_0^h - \xi_\rho) = \phi_\rho^h$  we get

$$\begin{aligned} \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi_\rho^h|^2 &\leq \frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla(\tilde{\phi}_0^h - \xi_\rho)|^2 \\ &\leq \frac{1}{2} \int_{\omega} |\nabla \tilde{\phi}_0^h|^2 + o_\rho(1). \end{aligned} \quad (32)$$

On the other hand, from the Estimate (32), denoting  $C_0 := \int_{\omega} |\nabla \tilde{\phi}_0^h|^2 + 1$ , for sufficiently small  $\rho$  we get

$$\sum_{i=1}^N \frac{1}{2} \int_{B(z_i, \sqrt{\rho}) \setminus \overline{B(z_i, \rho)}} |\nabla \varphi_\rho^h|^2 < C_0. \quad (33)$$

Thus for small  $\rho$ , we get the existence of  $\rho' \in (\rho, \sqrt{\rho})$  s.t.:

$$\sum_{i=1}^N \frac{1}{2} \int_0^{2\pi} |\partial_\theta \varphi_\rho^h(z_i + \rho' e^{i\theta})|^2 \leq \frac{2C_0}{|\ln \rho|}.$$

For  $i \in \{1, \dots, N\}$  we let  $m_{i,\rho} := \int_0^{2\pi} \varphi_\rho^h(z_i + \rho' e^{i\theta})$ . We now define  $\tilde{\varphi} \in H^1(\omega)$  by  $\tilde{\varphi} = \varphi_\rho^h$  in  $\omega \setminus \cup_i \overline{B(z_i, \rho')}$  and for  $x = z_i + s e^{i\theta} \in B(z_i, \rho')$  [with  $i \in \{1, \dots, N\}$ ]

$$\tilde{\varphi}(z_i + s e^{i\theta}) = \begin{cases} \frac{2s - \rho'}{\rho'} \varphi_\rho^h(z_i + \rho' e^{i\theta}) + \frac{2(\rho' - s)}{\rho'} m_{i,\rho} & \text{if } s \in (\frac{\rho'}{2}, \rho') \\ m_{i,\rho} & \text{if } s \leq \frac{\rho'}{2} \end{cases}.$$

A direct calculation gives for  $z \in \{z_1, \dots, z_N\}$

$$\int_{B(z, \rho')} |\nabla \tilde{\varphi}|^2 = \mathcal{O} \left[ \int_0^{2\pi} |\partial_\theta \varphi_\rho^h(z + \rho' e^{i\theta})|^2 \right] = o_\rho(1).$$

Therefore we obtain

$$\frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi_\rho^h|^2 \geq \frac{1}{2} \int_{\omega} |\nabla \tilde{\varphi}|^2 + o_\rho(1).$$

But  $\text{tr}_{\partial\omega}(\tilde{\varphi} + \xi_\rho) = \phi_0^h$  and consequently, from the Dirichlet principle, we have:

$$\frac{1}{2} \int_{\omega} |\nabla(\tilde{\varphi} + \xi_\rho)|^2 \geq \frac{1}{2} \int_{\omega} |\nabla\tilde{\phi}_0^h|^2$$

and thus with (32)

$$\frac{1}{2} \int_{\omega} |\nabla\tilde{\varphi}|^2 \geq \frac{1}{2} \int_{\omega} |\nabla\tilde{\phi}_0^h|^2 + o_\rho(1).$$

On the other hand, since  $\tilde{\varphi} = \varphi_\rho^h$  in  $\omega \setminus \cup_i \overline{B(z_i, \rho')}$   $\subset \Omega_{\rho, \mathbf{z}}$  and  $\frac{1}{2} \int_{\cup_i B(z_i, \rho')} |\nabla\tilde{\varphi}|^2 = o_\rho(1)$  we obtain:

$$\begin{aligned} \frac{1}{2} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla\varphi_\rho^h|^2 &\geq \frac{1}{2} \int_{\omega \setminus \cup_i \overline{B(z_i, \rho')}} |\nabla\varphi_\rho^h|^2 \\ &\geq \frac{1}{2} \int_{\omega} |\nabla\tilde{\phi}_0^h|^2 + o_\rho(1). \end{aligned}$$

Finally, using (32), by matching upper bound and lower bound we conclude:

$$\frac{1}{2} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla\varphi_\rho^h|^2 = \frac{1}{2} \int_{\omega} |\nabla\tilde{\phi}_0^h|^2 + o_\rho(1).$$

The last estimates ends the proof of the proposition.

### 6.3 Conclusion

For  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\deg(h) = d$  we have from (19) and Proposition 7:

$$\begin{aligned} \inf_{\substack{v \in H^1(\Omega_R, \mathbb{S}^1) \\ \text{tr}_{\partial\omega}(v) = h}} \frac{1}{2} \int_{\Omega_R} \alpha |\nabla v|^2 &= \\ \frac{d^2}{2} \int_{\Omega_R} \alpha |\nabla v_R|^2 + \inf_{\varphi \in \mathcal{H}_{\phi^h}} \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi|^2 + o_R(1). \end{aligned} \quad (34)$$

Using Theorem 3, (30) and Proposition 8 we have

$$\begin{aligned} \inf_{\substack{w \in H^1(\Omega_{\rho, \mathbf{z}}, \mathbb{S}^1) \\ \text{tr}_{\partial\omega}(w) = h}} \frac{1}{2} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla w|^2 &= \\ \pi |\ln \rho| \sum_i d_i^2 + W(\mathbf{z}, \mathbf{d}) + \frac{1}{2} \int_{\omega} |\nabla\tilde{\phi}_0^h|^2 + o_\rho(1). \end{aligned} \quad (35)$$

Letting  $\mathcal{K} : \{h \in H^{1/2}(\partial\omega, \mathbb{S}^1) \mid \deg(h) = d\} \rightarrow \mathbb{R}^+$  defined by

$$\mathcal{K}(h) := \inf_{\varphi \in \mathcal{H}_{\phi^h}} \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi|^2 + \frac{b^2}{2} \int_{\omega} |\nabla\tilde{\phi}_0^h|^2 \quad (36)$$

we get (17). Recall that, without loss of generality, the parameter "R" is considered as the major parameter writing  $\rho = \rho(R)$ . From (17), we get for  $h \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\deg(h) = d$ :

$$\begin{aligned} \limsup_{R \rightarrow \infty} \left\{ I(R, \rho, \mathbf{z}, \mathbf{d}) - \left[ d^2 f(R) + \right. \right. \\ \left. \left. + b^2 \left( \sum_i d_i^2 \pi |\ln \rho| + W(\mathbf{z}, \mathbf{d}) \right) \right] \right\} \leq \mathcal{K}(h). \end{aligned} \quad (37)$$

## 7 Lower bound

In this section we prove the existence of a map  $h_\infty \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  s.t.  $\deg(h_\infty) = d$  and

$$\liminf_{R \rightarrow \infty} \left\{ I(R, \rho, \mathbf{z}, \mathbf{d}) - \left[ d^2 f(R) + b^2 \left( \sum_i d_i^2 \pi |\ln \rho| + W(\mathbf{z}, \mathbf{d}) \right) \right] \right\} \geq \mathcal{K}(h_\infty). \quad (38)$$

Clearly a such map  $h_\infty$  should minimize

$$\mathcal{K} : \{h \in H^{1/2}(\partial\omega, \mathbb{S}^1) \mid \deg(h) = d\} \rightarrow \mathbb{R}^+.$$

But in order to get an explicit expression for  $h_\infty$  we do not define  $h_\infty$  in this way.

We let  $R_n \uparrow \infty$  be a sequence which realizes the "lim inf" in the left hand side of (38).

In order to keep notation simple, we drop the subscript  $n$  writing  $R = R_n$  when it will not be necessary to specify the dependance on  $n$ .

Let  $u_R$  be a minimizer of (3) [Proposition 2]. In  $\Omega_R$ , we may decompose  $u_R$  under the form  $u_R = v_R^d e^{i\varphi_R}$  where  $\varphi_R \in H^1(\Omega_R, \mathbb{R})$  and  $v_R$  is defined in (9).

Since  $u_R$  is unique up to a multiplicative constant [Proposition 2], we may freeze the non uniqueness by imposing  $\int_{\partial\omega} \varphi_R = 0$ .

*Notation.* For sake of simplicity of the presentation we use the shorthands:

- "  $R \in (R_0, \infty)$ " to consider an arbitrary term of the sequence  $(R_n)_n$ ;
- "  $R \in (R_0, \infty]$ " to consider either an arbitrary term of the sequence  $(R_n)_n$  or the limiting case  $R = \infty$ .

We denote:

- for  $R \in (R_0, \infty)$ ,  $h_R := \text{tr}_{\partial\omega} u_R$ , and thus we have 
$$h_R = \text{tr}_{\partial\omega} \left[ \left( \frac{x}{|x|} \right)^d e^{i(d\gamma_R + \varphi_R)} \right];$$
- $g_{\mathbf{z}, \mathbf{d}} := \text{tr}_{\partial\omega} \left[ \left( \frac{|x|}{x} \right)^d \prod_{i=1}^N \left( \frac{x - z_i}{|x - z_i|} \right)^{d_i} \right].$

Since  $g_{\mathbf{z}, \mathbf{d}} \in C^\infty(\partial\omega, \mathbb{S}^1)$  and  $\deg_{\partial\omega}(g_{\mathbf{z}, \mathbf{d}}) = 0$  we may fix  $\xi_{\mathbf{z}, \mathbf{d}} \in C^\infty(\partial\omega, \mathbb{R})$  s.t.  $e^{i\xi_{\mathbf{z}, \mathbf{d}}} = g_{\mathbf{z}, \mathbf{d}}$  and  $\int_{\partial\omega} \xi_{\mathbf{z}, \mathbf{d}} \in [-\pi, \pi)$ .

### 7.1 Compatibility conditions

From the minimality of  $u_R$ , it is obvious that the restriction of  $u_R$  to  $\Omega_R$  [resp.  $\Omega_{\rho, \mathbf{z}}$ ] is a solution of the problem (18) [resp. (29)] with  $h = h_R$ .

It is easy to check that we may write for  $R \in (R_0, \infty)$

$$h_R = \text{tr}_{\partial\omega}[v_R^d e^{i\varphi_R}] = \text{tr}_{\partial\omega}[w_{\rho,\mathbf{z},\mathbf{d}} e^{i\varphi_{\rho,\mathbf{z},\mathbf{d}}}]$$

where, omitting the superscript  $h_R$ , we have:

- $v_R$  is the special solution in  $\Omega_R$  defined in (9).
- $\varphi_R = \varphi_R^{h_R} \in H^1(\Omega_R, \mathbb{R})$  is the unique solution of Problem (20) [for the Dirichlet data  $h_R$  on  $\partial\omega$ ] s.t.  $u_R = v_R^d e^{i\varphi_R}$  in  $\Omega_R$  and  $\int_{\partial\omega} \varphi_R = 0$  [ $\varphi_R$  is defined above].
- $w_{\rho,\mathbf{z},\mathbf{d}} = \prod_{i=1}^N \left( \frac{x - z_i}{|x - z_i|} \right)^{d_i} e^{i\gamma_{\rho,\mathbf{z},\mathbf{d}}}$  is defined in (15);
- $\varphi_{\rho,\mathbf{z},\mathbf{d}} = \varphi_{\rho,\mathbf{z},\mathbf{d}}^{h_R} \in H^1(\Omega_{\rho,\mathbf{z}}, \mathbb{R})$  is the unique solution of (31) [for the Dirichlet data  $h_R$  on  $\partial\omega$ ] s.t.  $u_R = w_{\rho,\mathbf{z},\mathbf{d}} e^{i\varphi_{\rho,\mathbf{z},\mathbf{d}}}$  in  $\Omega_{\rho,\mathbf{z}}$  and  $\int_{\partial\omega} \varphi_{\rho,\mathbf{z},\mathbf{d}} \in (-\pi, \pi]$ .

By using Corollaries 1 and 2, we have the existence of  $\gamma_\infty, \gamma_{0,\mathbf{z},\mathbf{d}} \in H^{1/2}(\partial\omega, \mathbb{R})$  s.t.  $\gamma_R \rightarrow \gamma_\infty$  and  $\gamma_{\rho,\mathbf{z},\mathbf{d}} \rightarrow \gamma_{0,\mathbf{z},\mathbf{d}}$  in  $H^{1/2}(\partial\omega)$ . It is fundamental to note that

- $\gamma_\infty$  and  $\gamma_{0,\mathbf{z},\mathbf{d}}$  are independent of the sequence  $(R_n)_n$ ;
- $\int_{\partial\omega} \gamma_R = \int_{\partial\omega} \gamma_\infty = \int_{\partial\omega} \gamma_{0,\mathbf{z},\mathbf{d}} = \int_{\partial\omega} \gamma_{\rho,\mathbf{z},\mathbf{d}} = 0$ .

We have the following equivalences:

$$\begin{aligned} & e^{i[\text{tr}_{\partial\omega}(\varphi_R) - \text{tr}_{\partial\omega}(\varphi_{\rho,\mathbf{z},\mathbf{d}})]} = \text{tr}_{\partial\omega}(w_{\rho,\mathbf{z},\mathbf{d}}) \times \text{tr}_{\partial\omega}(\overline{v_R^d}) \\ \Leftrightarrow & e^{i[\text{tr}_{\partial\omega}(\varphi_R) - \text{tr}_{\partial\omega}(\varphi_{\rho,\mathbf{z},\mathbf{d}})]} = e^{i[\xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_R)]} \\ \Leftrightarrow & \exists k_0 \in \mathbb{Z} \text{ s.t. } \text{tr}_{\partial\omega}(\varphi_R) - \text{tr}_{\partial\omega}(\varphi_{\rho,\mathbf{z},\mathbf{d}}) = \\ & = \xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_R) + 2k_0\pi. \end{aligned} \quad (39)$$

We thus have

$$\begin{aligned} - \int_{\partial\omega} \varphi_{\rho,\mathbf{z},\mathbf{d}} &= \int_{\partial\omega} \varphi_R - \varphi_{\rho,\mathbf{z},\mathbf{d}} \\ &= \int_{\partial\omega} [\xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_R) + 2k_0\pi] \\ &= 2k_0\pi + \int_{\partial\omega} \xi_{\mathbf{z},\mathbf{d}}. \end{aligned}$$

Since  $\int_{\partial\omega} \varphi_{\rho,\mathbf{z},\mathbf{d}} \in (-\pi, \pi]$  and  $\int_{\partial\omega} \xi_{\mathbf{z},\mathbf{d}} \in [-\pi, \pi)$ , the above equalities imply that  $k_0 = 0$  in (39).

Consequently we get:

$$\text{tr}_{\partial\omega}(\varphi_R) - \text{tr}_{\partial\omega}(\varphi_{\rho,\mathbf{z},\mathbf{d}}) = \xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_R). \quad (40)$$

## 7.2 Asymptotic estimate of the energy

By using (19) and (30), we have the following decoupling:

$$\begin{aligned} I(R, \rho, \mathbf{z}, \mathbf{d}) &= \frac{1}{2} \int_{\mathcal{D}_{R,\rho,\mathbf{z}}} \alpha |\nabla u_R|^2 \\ &= \frac{1}{2} \int_{\Omega_R} \alpha |\nabla(v_R^d e^{i\varphi_R})|^2 + \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w_{\rho,\mathbf{z},\mathbf{d}} e^{i\varphi_{\rho,\mathbf{z},\mathbf{d}}}|^2 \\ &= d^2 f(R) + \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R|^2 + \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w_{\rho,\mathbf{z},\mathbf{d}}|^2 + \\ & \quad + \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi_{\rho,\mathbf{z},\mathbf{d}}|^2. \end{aligned} \quad (41)$$

From the minimality of  $u_R$  and by using (37), letting  $C_0 := \mathcal{K} \left( \frac{x^d}{|x|^d} \right) + 1$ , for sufficiently large  $R$ , we have:

$$\begin{aligned} I(R, \rho, \mathbf{z}, \mathbf{d}) &- \left[ d^2 f(R) + \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w_{\rho,\mathbf{z},\mathbf{d}}|^2 \right] \\ &= \frac{1}{2} \int_{\Omega_R} \alpha |\nabla \varphi_R|^2 + \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla \varphi_{\rho,\mathbf{z},\mathbf{d}}|^2 \leq C_0. \end{aligned} \quad (42)$$

Since  $\int_{\partial\omega} \varphi_R = 0$  [resp.  $\int_{\partial\omega} \varphi_{\rho,\mathbf{z},\mathbf{d}} \in (-\pi, \pi]$ ] for  $K_1$  a connected compact set of  $\mathbb{R}^2 \setminus \omega$  [resp.  $K_2$  a connected compact set of  $\overline{\omega} \setminus \{z_1, \dots, z_N\}$ ] s.t.  $\partial\omega \subset \partial K_1$  [resp.  $\partial\omega \subset \partial K_2$ ], there exists  $C_1 > 0$  [resp.  $C_2 > 0$ ] s.t. for large  $R$  we have  $\int_{K_1} |\varphi_R|^2 \leq C_1$  and  $\int_{K_2} |\varphi_{\rho,\mathbf{z},\mathbf{d}}|^2 \leq C_2$ .

Consequently :

- $(\varphi_R)_R$  is bounded in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$ . Thus there exists  $\varphi_\infty \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$  s.t., up to passing to a subsequence, we have  $\varphi_R \rightharpoonup \varphi_\infty$  in  $H_{\text{loc}}^1(\mathbb{R}^2 \setminus \omega)$ . (43)
- $(\varphi_{\rho,\mathbf{z},\mathbf{d}})_R$  is bounded in  $H_{\text{loc}}^1(\overline{\omega} \setminus \{z_1, \dots, z_N\})$ . Thus there exists  $\varphi_{0,\mathbf{z},\mathbf{d}} \in H_{\text{loc}}^1(\overline{\omega} \setminus \{z_1, \dots, z_N\})$  s.t., up to passing to a subsequence, we have  $\varphi_{\rho,\mathbf{z},\mathbf{d}} \rightharpoonup \varphi_{0,\mathbf{z},\mathbf{d}}$  in  $H_{\text{loc}}^1(\overline{\omega} \setminus \{z_1, \dots, z_N\})$ . (44)

From (40), we have  $\text{tr}_{\partial\omega}(\varphi_R) - \text{tr}_{\partial\omega}(\varphi_{\rho,\mathbf{z},\mathbf{d}}) = \xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_R)$ . On the other hand, with Corollaries 1&2, we get that  $\xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{\rho,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_R)$  strongly converges in  $H^{1/2}(\partial\omega)$  to  $\xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{0,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_\infty)$ . Consequently  $\text{tr}_{\partial\omega}(\varphi_R) - \text{tr}_{\partial\omega}(\varphi_{\rho,\mathbf{z},\mathbf{d}})$  strongly converges in  $H^{1/2}(\partial\omega)$  to  $\text{tr}_{\partial\omega}(\varphi_\infty) - \text{tr}_{\partial\omega}(\varphi_{0,\mathbf{z},\mathbf{d}}) = \xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{0,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_\infty)$ .

We thus may deduce

$$e^{i[\text{tr}_{\partial\omega}(\varphi_\infty) - \text{tr}_{\partial\omega}(\varphi_{0,\mathbf{z},\mathbf{d}})]} = e^{i[\xi_{\mathbf{z},\mathbf{d}} + \text{tr}_{\partial\omega}(\gamma_{0,\mathbf{z},\mathbf{d}}) - d\text{tr}_{\partial\omega}(\gamma_\infty)]},$$

i.e.:

$$\begin{aligned} & \left( \frac{x}{|x|} \right)^d e^{i\text{tr}_{\partial\omega}(d\gamma_\infty + \varphi_\infty)} \\ &= \prod_{i=1}^N \left( \frac{x - z_i}{|x - z_i|} \right)^{d_i} e^{i\text{tr}_{\partial\omega}(\gamma_{0,\mathbf{z},\mathbf{d}} + \varphi_{0,\mathbf{z},\mathbf{d}})}. \end{aligned} \quad (45)$$

We now define:

$$h_\infty := \text{tr}_{\partial\omega} \left[ \left( \frac{x}{|x|} \right)^d e^{i(d\gamma_\infty + \varphi_\infty)} \right] \in H^{1/2}(\partial\omega, \mathbb{S}^1). \quad (46)$$

It is clear that  $\deg(h_\infty) = d$ . We prove in the three next subsections [Sections 7.3&7.4&7.5] that  $h_\infty$  satisfies (38).

### 7.3 Calculations in $\mathbb{R}^2 \setminus \bar{\omega}$

From (42), we get that  $\nabla\varphi_R \mathbb{1}_{\Omega_R}$  is bounded in  $L^2(\mathbb{R}^2 \setminus \bar{\omega})$  and thus, up to passing to a subsequence,  $\nabla\varphi_R \mathbb{1}_{\Omega_R}$  weakly converges in  $L^2(\mathbb{R}^2 \setminus \bar{\omega})$ . Consequently, we may improve the convergence in (43), up to passing to a subsequence, we obtain that  $\nabla\varphi_R \mathbb{1}_{\Omega_R} \rightharpoonup \nabla\varphi_\infty$  in  $L^2(\mathbb{R}^2 \setminus \bar{\omega})$ . In particular we obtain  $\nabla\varphi_\infty \in L^2(\mathbb{R}^2 \setminus \bar{\omega})$ .

Consequently, denoting  $\phi_\infty := \text{tr}_{\partial\omega}(\varphi_\infty)$  we obtain  $\varphi_\infty \in \mathcal{H}_{\phi_\infty}$ . Therefore, with  $\Omega_\infty = \mathbb{R}^2 \setminus \bar{\omega}$ , we have:

$$\begin{aligned} & \liminf_{R_n \rightarrow \infty} \left\{ \frac{1}{2} \int_{\Omega_{R_n}} \alpha |\nabla u_{R_n}|^2 - \frac{d^2}{2} \int_{\Omega_{R_n}} \alpha |\nabla v_{R_n}|^2 \right\} \\ &= \liminf_{R_n \rightarrow \infty} \frac{1}{2} \int_{\Omega_{R_n}} \alpha |\nabla \varphi_{R_n}|^2 \\ &\geq \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi_\infty|^2 \geq \inf_{\varphi \in \mathcal{H}_{\phi_\infty}} \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi|^2. \end{aligned} \quad (47)$$

### 7.4 Calculations on $\omega$

We continue the calculations by proving:

$$\frac{1}{2} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla \varphi_{\rho, \mathbf{z}, \mathbf{d}}|^2 \geq \frac{1}{2} \int_{\omega} |\nabla \tilde{\phi}_{0, \mathbf{z}, \mathbf{d}}|^2 + o_\rho(1) \quad (48)$$

where  $\tilde{\phi}_{0, \mathbf{z}, \mathbf{d}}$  is the harmonic extension of  $\phi_{0, \mathbf{z}, \mathbf{d}} := \text{tr}_{\partial\omega} \varphi_{0, \mathbf{z}, \mathbf{d}}$  in  $\omega$ ,  $\varphi_{0, \mathbf{z}, \mathbf{d}}$  is defined in (44).

In order to get (48), we adapt the argument done to prove Proposition 8. From (42), we have

$$\sum_{i=1}^N \frac{1}{2} \int_{B(z_i, \sqrt{\rho}) \setminus \overline{B(z_i, \rho)}} |\nabla \varphi_{\rho, \mathbf{z}, \mathbf{d}}|^2 \leq C_0.$$

Thus, with a mean value argument, there exists  $\rho' \in (\rho, \sqrt{\rho})$  s.t.

$$\sum_{i=1}^N \frac{1}{2} \int_0^{2\pi} |\partial_\theta \varphi_{\rho, \mathbf{z}, \mathbf{d}}(z_i + \rho' e^{i\theta})|^2 d\theta \leq \frac{2C_0}{|\ln \rho|}.$$

Let  $\tilde{\varphi}_\rho \in H^1(\omega)$  be defined by  $\tilde{\varphi}_\rho = \varphi_{\rho, \mathbf{z}, \mathbf{d}}$  in  $\omega \setminus \cup_i \overline{B(z_i, \rho')}$ , for  $i \in \{1, \dots, N\}$  &  $x = z_i + s e^{i\theta} \in B(z_i, \rho')$

$$\tilde{\varphi}_\rho(z_i + s e^{i\theta}) = \begin{cases} 2 \frac{s - \rho'/2}{\rho'} \varphi_{\rho, \mathbf{z}, \mathbf{d}}(z_i + \rho' e^{i\theta}) + \frac{2(\rho' - s)}{\rho'} m_{i, \rho} & \text{if } s \geq \frac{\rho'}{2} \\ m_{i, \rho} & \text{if } s \leq \frac{\rho'}{2} \end{cases}$$

where  $m_{i, \rho} := \frac{1}{2\pi} \int_0^{2\pi} \varphi_{\rho, \mathbf{z}, \mathbf{d}}(z_i + \rho' e^{i\theta}) d\theta$ .

A direct calculation gives:

$$\begin{aligned} & \sum_{i=1}^N \int_{B(z_i, \rho')} |\nabla \tilde{\varphi}_\rho|^2 \\ &= \mathcal{O} \left[ \sum_{i=1}^N \int_0^{2\pi} |\partial_\theta \varphi_{\rho, \mathbf{z}, \mathbf{d}}(z_i + \rho' e^{i\theta})|^2 \right] = o_\rho(1). \end{aligned} \quad (49)$$

Letting  $\Omega_{\rho', \mathbf{z}} = \omega \setminus \cup_{i=1}^N \overline{B(z_i, \rho')}$  and  $\tilde{\mathcal{D}}_{\rho'} = \cup_{i=1}^N B(z_i, \rho') \setminus \overline{B(z_i, \rho)}$ , we obtain:

$$\begin{aligned} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla \varphi_{\rho, \mathbf{z}, \mathbf{d}}|^2 &= \int_{\Omega_{\rho', \mathbf{z}}} |\nabla \tilde{\varphi}_\rho|^2 + \int_{\tilde{\mathcal{D}}_{\rho'}} |\nabla \varphi_{\rho, \mathbf{z}, \mathbf{d}}|^2 \\ &\geq \int_{\Omega_{\rho', \mathbf{z}}} |\nabla \tilde{\varphi}_\rho|^2 \\ &\stackrel{(49)}{=} \int_{\omega} |\nabla \tilde{\varphi}_\rho|^2 + o_\rho(1). \end{aligned} \quad (50)$$

Since  $\tilde{\varphi}_\rho$  is bounded in  $H^1(\omega)$ , up to passing to a subsequence, we may assume the existence of  $\tilde{\varphi}_0 \in H^1(\omega)$  s.t.  $\tilde{\varphi}_\rho \rightharpoonup \tilde{\varphi}_0$  in  $H^1(\omega)$ .

On the other hand, it is clear that  $\text{tr}_{\partial\omega} \tilde{\varphi}_0 = \text{tr}_{\partial\omega} \varphi_{0, \mathbf{z}, \mathbf{d}} = \phi_{0, \mathbf{z}, \mathbf{d}}$ . Consequently from the Dirichlet principle we get [denoting  $\rho_n = \rho(R_n)$ ]

$$\liminf_{\rho_n \rightarrow 0} \int_{\omega} |\nabla \tilde{\varphi}_\rho|^2 \geq \int_{\omega} |\nabla \tilde{\varphi}_0|^2 \geq \int_{\omega} |\nabla \tilde{\phi}_{0, \mathbf{z}, \mathbf{d}}|^2. \quad (51)$$

By combining (50) and (51) we obtain (48). From (41) and (48) we may write

$$\begin{aligned} & \liminf_{\rho_n \rightarrow 0} \left\{ \frac{1}{2} \int_{\Omega_{\rho_n, \mathbf{z}}} |\nabla u_{R_n}|^2 - \frac{1}{2} \int_{\Omega_{\rho_n, \mathbf{z}}} |\nabla w_{\rho_n, \mathbf{z}, \mathbf{d}}|^2 \right\} \\ &= \liminf_{\rho_n \rightarrow 0} \frac{1}{2} \int_{\Omega_{\rho_n, \mathbf{z}}} |\nabla \varphi_{\rho_n, \mathbf{z}, \mathbf{d}}|^2 \geq \frac{1}{2} \int_{\omega} |\nabla \tilde{\phi}_{0, \mathbf{z}, \mathbf{d}}|^2. \end{aligned} \quad (52)$$

### 7.5 Conclusion

Using (47), (52) and the definition of the sequence  $(R_n)_n$  we get

$$\begin{aligned} & \liminf_{R \rightarrow \infty} \left\{ I(R, \rho, \mathbf{z}, \mathbf{d}) - \left( d^2 f(R) + \frac{b^2}{2} \int_{\Omega_{\rho, \mathbf{z}}} |\nabla w_{\rho, \mathbf{z}, \mathbf{d}}|^2 \right) \right\} \\ &= \lim_{R_n \rightarrow \infty} \left\{ \frac{1}{2} \int_{\mathcal{D}_{R_n, \rho_n, \mathbf{z}}} \alpha |\nabla u_{R_n}|^2 - \left( d^2 f(R_n) + \frac{b^2}{2} \int_{\Omega_{\rho_n, \mathbf{z}}} |\nabla w_{\rho_n, \mathbf{z}, \mathbf{d}}|^2 \right) \right\} \\ &\geq \liminf_{R_n \rightarrow \infty} \left\{ \frac{1}{2} \int_{\Omega_{R_n}} \alpha |\nabla u_{R_n}|^2 - d^2 f(R_n) \right\} + \\ &\quad + b^2 \liminf_{\rho_n \rightarrow 0} \left\{ \frac{1}{2} \int_{\Omega_{\rho_n, \mathbf{z}}} |\nabla u_{R_n}|^2 - \frac{1}{2} \int_{\Omega_{\rho_n, \mathbf{z}}} |\nabla w_{\rho_n, \mathbf{z}, \mathbf{d}}|^2 \right\} \\ &\geq \inf_{\varphi \in \mathcal{H}_{\phi_\infty}} \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi|^2 + \frac{b^2}{2} \int_{\omega} |\nabla \tilde{\phi}_{0, \mathbf{z}, \mathbf{d}}|^2. \end{aligned} \quad (53)$$

Recall that  $h_\infty = \left(\frac{x}{|x|}\right)^d e^{i(d\gamma_\infty + \phi_\infty)} \in H^{1/2}(\partial\omega, \mathbb{S}^1)$  [see (46)]. Therefore from (36) and (45) we may write

$$\mathcal{K}(h_\infty) = \inf_{\varphi \in \mathcal{H}_{\phi_\infty}^h} \frac{1}{2} \int_{\Omega_\infty} \alpha |\nabla \varphi|^2 + \frac{b^2}{2} \int_{\omega} |\nabla \tilde{\phi}_{0,\mathbf{z},\mathbf{d}}|^2.$$

Consequently (53) becomes

$$\liminf_{R \rightarrow \infty} \left\{ I(R, \rho, \mathbf{z}, \mathbf{d}) - \left( d^2 f(R) + \frac{b^2}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w_{\rho,\mathbf{z},\mathbf{d}}|^2 \right) \right\} \geq \mathcal{K}(h_\infty). \quad (54)$$

It suffices now to see that, from Theorem 3 we have

$$\frac{1}{2} \int_{\Omega_{\rho,\mathbf{z}}} |\nabla w_{\rho,\mathbf{z},\mathbf{d}}|^2 = \sum_i d_i^2 \pi |\ln \rho| + W(\mathbf{z}, \mathbf{d}) + o_\rho(1),$$

this combined with (37) gives

$$\lim_{R \rightarrow \infty} I(R, \rho, \mathbf{z}, \mathbf{d}) - f(R) - b^2 \left( \pi \sum_{i=1}^N d_i^2 |\ln \rho| + W(\mathbf{z}, \mathbf{d}) \right) \partial_\tau \psi_{0,\mathbf{z},\mathbf{d}} = \partial_\nu \left[ \sum_{j=1}^N d_j (\ln |x - z_j| - \ln |1 - \bar{z}_j x|) \right].$$

$$= \mathcal{K}(h_\infty).$$

We now define:

$$W^{\text{micro}}(\mathbf{z}, \mathbf{d}) := b^2 W(\mathbf{z}, \mathbf{d}) + \min_{\substack{h \in H^{1/2}(\partial\omega, \mathbb{S}^1) \\ \deg(h) = d}} \mathcal{K}(h) \quad (55)$$

in order to write

$$\begin{aligned} I(R, \rho, \mathbf{z}, \mathbf{d}) &= \\ &= d^2 f(R) + b^2 \pi \sum_{i=1}^N d_i^2 |\ln \rho| + W^{\text{micro}}(\mathbf{z}, \mathbf{d}) + o_\rho(1). \end{aligned}$$

The last equality ends the proof of Theorem 1.

## 8 The case of the radially symmetric diluted impurity: $\omega = \mathbb{D}$

In this section we focus on the circular case with  $\omega = \mathbb{D}$  is the unit disc and for  $b \in (0, \infty)$  we let

$$\alpha : \mathbb{R}^2 \rightarrow \begin{cases} \{b^2; 1\} \\ x \mapsto \begin{cases} b^2 & \text{if } x \in \mathbb{D} \\ 1 & \text{if } x \in \mathbb{R}^2 \setminus \mathbb{D} \end{cases} \end{cases}$$

We fix

- $N \in \mathbb{N}^*$ ,  $\mathbf{d} = (d_1, \dots, d_N) \in \mathbb{Z}^N$  and we let  $d := \sum_{i=1}^N d_i \in \mathbb{Z}$ ;
- $\mathbf{z} \in (\mathbb{D}^N)^* := \{(z_1, \dots, z_N) \in \mathbb{D}^N \mid z_i \neq z_j \text{ for } i \neq j\}$ .

### 8.1 Explicit expression of the special solutions

We use the same notation as in Section 5.

*Notation.* In this section and in the next sections, in order to keep notation simple, we use the shorthand " $x$ " to stand for the identity map. Namely we use the abuse of notation  $\text{Id} = x$  where  $\text{Id} : U \rightarrow U$ ,  $x \mapsto \text{Id}(x) = x$  and  $U \subset \mathbb{R}^2 \simeq \mathbb{C}$  is an arbitrary set .

We let  $v_\infty$  be the limiting function obtained in Corollary 1. It is easy to prove that  $v_\infty(x) = \frac{x}{|x|}$ , i.e.  $\gamma_\infty \equiv 0$ .

We let  $w_{0,\mathbf{z},\mathbf{d}} = \prod_{i=1}^N \left(\frac{x - z_i}{|x - z_i|}\right)^{d_i} e^{i\gamma_{0,\mathbf{z},\mathbf{d}}}$  be the function defined in (16). This function is the canonical harmonic map in  $\mathbb{D}$  associated to the singularities  $(\mathbf{z}, \mathbf{d})$ .

On the unit circle  $\mathbb{S}^1$  we have  $\text{tr}_{\mathbb{S}^1}(w_{0,\mathbf{z},\mathbf{d}}) = e^{i\psi_{0,\mathbf{z},\mathbf{d}}}$  with

$$\partial_\tau \psi_{0,\mathbf{z},\mathbf{d}} = \partial_\nu \left[ \sum_{j=1}^N d_j (\ln |x - z_j| - \ln |1 - \bar{z}_j x|) \right].$$

This result comes from [11] Eq. (2.25) and (4.1). From Identity (4.14) in [11] we get

$$\partial_\tau \psi_{0,\mathbf{z},\mathbf{d}} = \sum_{j=1}^N d_j [2\partial_\nu (\ln |x - z_j|) - 1].$$

Thus  $\partial_\tau \psi_{0,\mathbf{z},\mathbf{d}} = \sum_{j=1}^N d_j [2\partial_\tau (\arg(x - z_j)) - 1]$  with  $\frac{x - z_j}{|x - z_j|} = e^{i\arg(x - z_j)}$ .

Consequently we get

$$\begin{aligned} \text{tr}_{\mathbb{S}^1}(w_{0,\mathbf{z},\mathbf{d}}) &= e^{i\psi_{0,\mathbf{z},\mathbf{d}}} \\ &= \text{Cst} \times x^{-d} \prod_{j=1}^N \left(\frac{x - z_j}{|x - z_j|}\right)^{2d_j} \end{aligned} \quad (56)$$

where  $\text{Cst} \in \mathbb{S}^1$  is a constant.

### 8.2 Use of Fourier decompositions

In order to get an explicit expression of  $W^{\text{micro}}(\mathbf{z}, \mathbf{d})$  it seems natural to work on  $\mathcal{K}$ . For  $h \in H^{1/2}(\mathbb{S}^1, \mathbb{S}^1)$  we have [see (21) and (36)]

$$\mathcal{K}(h) = \inf_{\varphi \in \mathcal{H}_{\phi_\infty}^h} \frac{1}{2} \int_{\Omega_\infty} |\nabla \varphi|^2 + \frac{b^2}{2} \int_{\omega} |\nabla \tilde{\phi}_0^h|^2,$$

where:

- on the unit circle we have

$$\begin{cases} h = x^d e^{i\phi_\infty^h} = w_{0,\mathbf{z},\mathbf{d}} e^{i\phi_0^h} \\ \text{with } f_{\partial\omega} \phi_\infty^h, f_{\partial\omega} \phi_0^h \in (-\pi, \pi] \end{cases} ; \quad (57)$$

- $\tilde{\phi}_0^h$  is the harmonic extension of  $\phi_0^h$  in  $\mathbb{D}$ .

Condition (57) is a compatibility condition between the function  $\phi_\infty^h$  and  $\phi_0^h$ . Since our goal is to estimate  $\mathcal{K}(h)$ , it is clear that we may slightly modify Condition (57) by imposing

$$\left(\frac{x}{|x|}\right)^d e^{i\phi_\infty^h} = \text{Cst} \times w_{0,\mathbf{z},\mathbf{d}} e^{i\phi_0^h} \text{ with } \text{Cst} \in \mathbb{S}^1. \quad (58)$$

We may easily prove that

$$\inf_{\varphi \in \mathcal{H}_{\phi_\infty^h}} \frac{1}{2} \int_{\Omega_\infty} |\nabla \varphi|^2 = \frac{1}{2} \int_{\Omega_\infty} |\nabla \hat{\phi}_\infty^h|^2$$

where for  $\phi \in H^{1/2}(\mathbb{S}^1, \mathbb{R})$ ,  $\hat{\phi} \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \overline{\mathbb{D}})$  is the unique solution of

$$\begin{cases} -\Delta \varphi = 0 & \text{in } \mathbb{R}^2 \setminus \overline{\mathbb{D}} \\ \text{tr}_{\mathbb{S}^1}(\varphi) = \phi, \quad \nabla \varphi \in L^2(\mathbb{R}^2 \setminus \overline{\mathbb{D}}) \end{cases}$$

[See Proposition 9 for more details about  $\hat{\phi}$ ]

From (56), an equivalent reformulation of (58) is

$$\text{Cst} \prod_{j=1}^N \left( \frac{x - z_j}{|x - z_j| \times x} \right)^{2d_j} = e^{i(\phi_\infty^h - \phi_0^h)} \text{ with } \text{Cst} \in \mathbb{S}^1.$$

The above condition is equivalent to the compatibility condition:

$$\phi_\infty^h - \phi_0^h = \Psi_{\mathbf{z},\mathbf{d}} + \text{Cst} \text{ where } \text{Cst} \in \mathbb{R} \quad (59)$$

and  $\Psi_{\mathbf{z},\mathbf{d}} \in C^\infty(\mathbb{S}^1, \mathbb{R})$  is a lifting of  $\prod_{j=1}^N \left( \frac{x - z_j}{|x - z_j| \times x} \right)^{2d_j}$ .

With a direct calculation, for  $z_0 \in \mathbb{D}$  and  $x \in \mathbb{S}^1$ , we have

$$\begin{aligned} \left( \frac{x - z_0}{|x - z_0| \times x} \right)^2 &= \frac{x - z_0}{x - \overline{z_0} \times x^2} \\ &= \frac{x - z_0}{1 - \overline{z_0}x} \times \frac{1}{x} = M_{z_0}(x) \times \frac{1}{x} \end{aligned}$$

where  $M_{z_0} : \mathbb{D} \rightarrow \mathbb{D}$  is the Moebius function defined by  $M_{z_0}(x) = \frac{x - z_0}{1 - \overline{z_0}x}$ .

In [7], it is proved [Section 7] that if  $z_0 \in \mathbb{D} \cap \mathbb{R}^+$  then for  $e^{i\theta} \in \mathbb{S}^1$  we have  $M_{z_0}(e^{i\theta})e^{-i\theta} = e^{\Psi_{z_0,1}(e^{i\theta})}$

where  $\Psi_{z_0,1}(e^{i\theta}) = \sum_{n \in \mathbb{Z}^*} \frac{z_0^{|n|}}{in} e^{in\theta} + \text{Cst}$ ,  $\text{Cst} \in \mathbb{R}$ .

In the general case  $z_0 = te^{i\gamma} \in \mathbb{D}$  [with  $t \geq 0, \gamma \in \mathbb{R}$ ] we easily deduce from the previous equality:

$$M_{z_0}(e^{i\theta})e^{-i\theta} = M_t[e^{i(\theta-\gamma)}]e^{-i(\theta-\gamma)}.$$

Then there is  $\text{Cst} \in \mathbb{R}$  s.t.

$$\begin{aligned} \Psi_{z_0,1}(e^{i\theta}) &= \Psi_{t,1}(e^{i(\theta-\gamma)}) + \text{Cst} \\ &= \sum_{n \in \mathbb{Z}^*} \frac{t^{|n|}}{in} e^{in(\theta-\gamma)} + \text{Cst} \\ &= \sum_{n \in \mathbb{N}^*} \left[ \frac{\overline{z_0}^n}{in} e^{in\theta} - \frac{z_0^n}{in} e^{-in\theta} \right] + \text{Cst}. \end{aligned}$$

It is easy to prove that we have  $\Psi_{\mathbf{z},\mathbf{d}} = \sum_{j=1}^N d_j \Psi_{z_j,1} + \text{Cst}$  [ $\text{Cst} \in \mathbb{R}$ ] and then

$$\begin{aligned} \Psi_{\mathbf{z},\mathbf{d}}(e^{i\theta}) &= \text{Cst} + \sum_{n \in \mathbb{N}^*} \sum_{j=1}^N d_j \left[ \frac{\overline{z_j}^n}{in} e^{in\theta} - \frac{z_j^n}{in} e^{-in\theta} \right]. \quad (60) \end{aligned}$$

We now go back to the previously fixed function  $h \in H^{1/2}(\mathbb{S}^1, \mathbb{S}^1)$ . We are in position to reformulate the compatibility condition (59) in term of Fourier series.

Let  $\phi_0^h, \phi_\infty^h \in H^{1/2}(\mathbb{S}^1, \mathbb{R})$  [defined in (57)], consider their Fourier decompositions [we drop the superscript  $h$  for the coefficients]:

$$\begin{cases} \phi_0^h(e^{i\theta}) = \sum_{n \in \mathbb{Z}} c_{0,n} e^{in\theta} \\ \phi_\infty^h(e^{i\theta}) = \sum_{n \in \mathbb{Z}} c_{\infty,n} e^{in\theta} \end{cases} \quad (61)$$

The compatibility condition (58) is equivalent to (59). From (60), the condition (59) reads with Fourier decompositions:

$$\forall n \in \mathbb{Z}^*, c_{\infty,n} - c_{0,n} = \begin{cases} \sum_{j=1}^N d_j \frac{\overline{z_j}^n}{in} & \text{if } n > 0 \\ -\sum_{j=1}^N d_j \frac{z_j^n}{in} & \text{if } n < 0 \end{cases}.$$

### 8.3 Explicit expression of the minimal value of $\mathcal{K}$

Before going further we recall some basic facts.

**Proposition 9** *Let  $\phi \in H^{1/2}(\mathbb{S}^1, \mathbb{R})$  and consider  $\phi(e^{i\theta}) = \sum_{n \in \mathbb{Z}} c_n e^{in\theta}$  be its Fourier decomposition.*

*Then we have*

1. For all  $n \in \mathbb{N}$ ,  $c_n = \overline{c_{-n}}$ .
2.  $\sum_{n \in \mathbb{Z}} |n| |c_n|^2 < \infty$ .
3. The map  $\tilde{\phi} : \mathbb{D} \rightarrow \mathbb{R}$ ,  $re^{i\theta} \mapsto \sum_{n \in \mathbb{Z}} c_n r^{|n|} e^{in\theta}$  is the harmonic extension of  $\phi$ .  
Moreover  $\frac{1}{2} \int_{\mathbb{D}} |\nabla \tilde{\phi}|^2 = \pi \sum_{n \in \mathbb{Z}} |n| |c_n|^2$ .
4. The map  $\hat{\phi} : \mathbb{R}^2 \setminus \overline{\mathbb{D}} \rightarrow \mathbb{R}$ ,  $re^{i\theta} \mapsto \sum_{n \in \mathbb{Z}} c_n r^{-|n|} e^{in\theta}$  is an exterior harmonic extension of  $\phi$ . Moreover  $\frac{1}{2} \int_{\mathbb{R}^2 \setminus \overline{\mathbb{D}}} |\nabla \hat{\phi}|^2 = \pi \sum_{n \in \mathbb{Z}} |n| |c_n|^2$ .

5.  $\hat{\phi}$  is the unique solution of

$$\begin{cases} -\Delta\varphi = 0 \text{ in } \mathbb{R}^2 \setminus \overline{\mathbb{D}}, \\ \varphi \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \mathbb{D}, \mathbb{R}) \\ \text{tr}_{\mathbb{S}^1}(\varphi) = \phi, \nabla\varphi \in L^2(\mathbb{R}^2 \setminus \overline{\mathbb{D}}, \mathbb{R}^2) \end{cases}. \quad (62)$$

Therefore it is also the unique solution of the problem

$$\inf_{\varphi \in \mathcal{H}_\phi} \frac{1}{2} \int_{\mathbb{R}^2 \setminus \overline{\mathbb{D}}} |\nabla\varphi|^2. \quad (63)$$

*Proof* Assertions 1 and 2 are quite standard. Assertions 3 and 4 follow from standard calculations.

We now prove Assertion 5. Let  $\phi \in H^{1/2}(\mathbb{S}^1, \mathbb{R})$  and let  $\hat{\phi}$  be defined by Assertion 4. It is clear that  $\hat{\phi}$  solves (62). Assume that  $\varphi_0$  is a solution of (62) and let  $\eta := \hat{\phi} - \varphi_0$ . Then  $\eta$  satisfies:

$$\begin{cases} -\Delta\eta = 0 \text{ in } \mathbb{R}^2 \setminus \overline{\mathbb{D}}, \\ \eta \in H_{\text{loc}}^1(\mathbb{R}^2 \setminus \mathbb{D}, \mathbb{R}) \\ \text{tr}_{\mathbb{S}^1}(\eta) = 0, \nabla\eta \in L^2(\mathbb{R}^2 \setminus \overline{\mathbb{D}}, \mathbb{R}^2) \end{cases}.$$

From [16] [Theorem II.6.2.ii] we get  $\eta = 0$ . This clearly gives uniqueness of the solution of (62).

On the one hand, by direct minimization we know that Problem (63) admits solution(s). It is standard to check that a minimizer for (63) solves (62). Consequently  $\hat{\phi}$  is the unique solution of Problem (63).

*Notation.* From now on, for  $\phi \in H^{1/2}(\mathbb{S}^1, \mathbb{R})$  with Fourier decomposition  $\phi(e^{i\theta}) = \sum_{n \in \mathbb{Z}} c_n e^{in\theta}$ , we let the seminorm  $|\phi|_{H^{1/2}} := \sqrt{\pi \sum_{n \in \mathbb{Z}} |n| |c_n|^2}$ .

For  $n \in \mathbb{N}^*$ , letting  $\gamma_n = \sum_{j=1}^N d_j \frac{\overline{z_j^n}}{in}$ , i.e.  $\Psi_{\mathbf{z}, \mathbf{d}}(e^{i\theta}) = \text{Cst} + \sum_{n \in \mathbb{Z}^*} \gamma_n e^{in\theta}$  [see (60)], we get

$$\begin{aligned} & \inf_{\substack{h \in H^{1/2}(\mathbb{S}^1, \mathbb{S}^1) \\ \deg(h)=d}} \mathcal{K}(h) \\ &= \inf_{\substack{\phi_0, \phi_\infty \in H^{1/2}(\mathbb{S}^1, \mathbb{R}) \\ x^d e^{i\phi_\infty} = \text{Cst} \times w_{0, \mathbf{z}, \mathbf{d}} e^{i\phi_0}}} \left( \frac{1}{2} \int_{\Omega_\infty} |\nabla \hat{\phi}_\infty|^2 + \frac{b^2}{2} \int_\omega |\nabla \tilde{\phi}_0|^2 \right) \\ &= 2\pi \times \inf_{\substack{(c_0, n)_{n \in \mathbb{N}^*} \\ (c_\infty, n) \in \ell^2(\mathbb{N}^*) \\ c_{\infty, n} - c_{0, n} = \gamma_n \quad \forall n \in \mathbb{N}^*}} \left( \sum_{n \in \mathbb{N}} n |c_{0, n}|^2 + b^2 \sum_{n \in \mathbb{N}} n |c_{\infty, n}|^2 \right) \\ &= 2\pi \sum_{n \in \mathbb{N}^*} \left[ n \times \inf_{\substack{c_0, n, c_\infty, n \in \mathbb{C} \\ c_{\infty, n} - c_{0, n} = \gamma_n}} (|c_{0, n}|^2 + b^2 |c_{\infty, n}|^2) \right] \\ &= 2\pi \sum_{n \in \mathbb{N}^*} \left[ n \times \inf_{c_0, n \in \mathbb{C}} (|c_{0, n}|^2 + b^2 |c_{0, n} + \gamma_n|^2) \right] \\ &= 2\pi \sum_{n \in \mathbb{N}^*} \left[ n \times \left( \left| \frac{-b^2}{1+b^2} \gamma_n \right|^2 + b^2 \left| \frac{-b^2}{1+b^2} \gamma_n + \gamma_n \right|^2 \right) \right] \\ &= \frac{b^2}{1+b^2} 2\pi \sum_{n \in \mathbb{N}^*} n |\gamma_n|^2 = \frac{b^2}{1+b^2} |\Psi_{\mathbf{z}, \mathbf{d}}|_{H^{1/2}}^2. \quad (64) \end{aligned}$$

## 8.4 Explicit form of $W^{\text{micro}}$ : Proof of Proposition 1

We first recall the expression of  $W(\mathbf{z}, \mathbf{d})$  [see Proposition 1 in [13]]:

$$\begin{aligned} W(\mathbf{z}, \mathbf{d}) &= -\pi \sum_{i \neq j} d_i d_j \ln |z_i - z_j| + \pi \sum_{i=1}^N d_i^2 \ln(1 - |z_i|^2) + \\ &\quad + \pi \sum_{i \neq j} d_i d_j \ln |1 - z_i \overline{z_j}|. \end{aligned}$$

From (55) we have

$$W^{\text{micro}}(\mathbf{z}, \mathbf{d}) = b^2 W(\mathbf{z}, \mathbf{d}) + \min_{\substack{h \in H^{1/2}(\mathbb{S}^1, \mathbb{S}^1) \\ \deg(h)=d}} \mathcal{K}(h).$$

By combining (60) and (64) we may write

$$\begin{aligned} \min_{\substack{h \in H^{1/2}(\mathbb{S}^1, \mathbb{S}^1) \\ \deg(h)=d}} \mathcal{K}(h) &= \frac{2b^2}{1+b^2} \pi \sum_{n \in \mathbb{N}^*} n \left| \sum_{j=1}^N d_j \frac{\overline{z_j^n}}{in} \right|^2 \\ &= \frac{2b^2}{1+b^2} \pi \sum_{n \in \mathbb{N}^*} \frac{1}{n} \left| \sum_{j=1}^N d_j z_j^n \right|^2. \end{aligned}$$

For  $n \in \mathbb{N}^*$  we have the following expansion

$$\left| \sum_{j=1}^N d_j z_j^n \right|^2 = \sum_{j=1}^N d_j^2 |z_j|^{2n} + 2 \text{Re} \left[ \sum_{i < j} d_i d_j (z_i \overline{z_j})^n \right].$$

Therefore we obtain

$$\begin{aligned} & \sum_{n \in \mathbb{N}^*} \frac{1}{n} \left| \sum_{j=1}^N d_j z_j^n \right|^2 \\ &= \sum_{j=1}^N d_j^2 \left( \sum_{n \in \mathbb{N}^*} \frac{1}{n} |z_j|^{2n} \right) + 2 \sum_{i < j} d_i d_j \text{Re} \left[ \sum_{n \in \mathbb{N}^*} \frac{1}{n} (z_i \overline{z_j})^n \right] \\ &= - \sum_{j=1}^N d_j^2 \ln(1 - |z_j|^2) - 2 \sum_{i < j} d_i d_j \text{Re} [\ln(1 - z_i \overline{z_j})] \\ &= - \sum_{j=1}^N d_j^2 \ln(1 - |z_j|^2) - \sum_{i \neq j} d_i d_j \ln |1 - z_i \overline{z_j}|. \end{aligned}$$

We may thus conclude:

$$\begin{aligned}
& W^{\text{micro}}(\mathbf{z}, \mathbf{d}) \\
&= b^2 \pi \left[ - \sum_{i \neq j} d_i d_j \ln |z_i - z_j| + \sum_{i=1}^N d_i^2 \ln(1 - |z_i|^2) + \right. \\
&\quad \left. + \sum_{i \neq j} d_i d_j \ln |1 - z_i \bar{z}_j| - \right. \\
&\quad \left. - \frac{2}{1+b^2} \left( \sum_{j=1}^N d_j^2 \ln(1 - |z_j|^2) + \sum_{i \neq j} d_i d_j \ln |1 - z_i \bar{z}_j| \right) \right] \\
&= -b^2 \pi \left[ \sum_{i \neq j} d_i d_j \ln |z_i - z_j| + \right. \\
&\quad \left. + \frac{1-b^2}{1+b^2} \sum_{j=1}^N d_j^2 \ln(1 - |z_j|^2) + \right. \\
&\quad \left. + \frac{1-b^2}{1+b^2} \sum_{i \neq j} d_i d_j \ln |1 - z_i \bar{z}_j| \right].
\end{aligned}$$

These calculations end the proof of Proposition 1.

### 8.5 Minimization of $W^{\text{micro}}$ in some particular cases

We first claim that if  $\mathbf{d} = \mathbf{0}_{\mathbb{Z}^N}$  then  $W^{\text{micro}}(\cdot, \mathbf{d}) \equiv 0$ . In the following we consider  $\mathbf{d} \in \mathbb{Z}^N \setminus \{\mathbf{0}_{\mathbb{Z}^N}\}$ .

#### 8.5.1 The case $N = 1$ and the case $N \geq 2 \& \exists! k_0 \in \{1, \dots, N\}$ s.t. $d_{k_0} \neq 0$

We first treat the case  $N = 1$ . In this situation, we have for  $z \in \mathbb{D}$  and  $d \in \mathbb{Z}^*$  :

$$W^{\text{micro}}(z, d) = -\frac{b^2(1-b^2)}{1+b^2} \pi d^2 \ln(1 - |z|^2)$$

Therefore, if  $b < 1$  then  $z = 0$  is the unique minimizer of  $W^{\text{micro}}$ .

*Remark 6* This simple fact is the main result of [7] [where the explicit expression of  $W^{\text{micro}}$  was unknown].

If  $b = 1$  then  $W^{\text{micro}}(\cdot, d) \equiv 0$ .

If  $b > 1$  then  $W^{\text{micro}}(z, d) \rightarrow -\infty$  when  $|z| \rightarrow 1$ . This implies that  $W^{\text{micro}}(\cdot, d)$  does not admit minimizers.

*Remark 7* We may conclude that the condition  $b < 1$  creates a confinement effect for the points of minimum of  $W^{\text{micro}}(\cdot, d)$ . This confinement effect does not hold for  $b \geq 1$ .

We now consider the case  $N \geq 2$ . We assume that  $d_1 \neq 0$  and  $d_l = 0$  for  $l \neq 1$ .

This case is similar to the above one since for  $\mathbf{z} = (z_1, \dots, z_N) \in (\omega^N)^*$  we have  $W^{\text{micro}}(\mathbf{z}, \mathbf{d}) = W^{\text{micro}}(z_1, d_1)$ . Consequently as previously we have:

- If  $b < 1$  then the set of global minimizers of  $W^{\text{micro}}$  is  $\{\mathbf{z} \in (\omega^N)^* \mid z_1 = 0\}$ .
- If  $b = 1$  then  $W^{\text{micro}}(\cdot, \mathbf{d}) \equiv 0$ .
- If  $b > 1$  then  $W^{\text{micro}}(\mathbf{z}, \mathbf{d}) \rightarrow -\infty$  when  $|z_1| \rightarrow 1$ .

#### 8.5.2 The case $N \geq 2$ and there exist $k, l$ s.t. $d_k d_l < 0$

Let  $\mathbf{d} \in \mathbb{Z}^N$  s.t. there exist  $k \neq l$  satisfying  $d_k d_l < 0$ . In this situation we have

$$\inf_{\mathbf{z} \in (\omega^N)^*} W^{\text{micro}}(\mathbf{z}, \mathbf{d}) = -\infty.$$

Indeed, without loss of generality, we may assume that  $d_1 d_2 < 0$ . For  $n \in \mathbb{N}^*$ , we consider  $z_1^{(n)} := -1/n$ ,  $z_2^{(n)} := 1/n$  and for  $k \in \{1, \dots, N\} \setminus \{1, 2\}$ ,  $z_k := e^{i2k\pi/N}/2$ .

With direct calculations, we obtain  $\lim_n W(\mathbf{z}_n, \mathbf{d}) = -\infty$ .

*Remark 8* This fact underline that if we impose  $d_1 d_2 < 0$  then the main part of the *optimal* energy  $I(R, \rho, \mathbf{z}, \mathbf{d})$  is not

$$\left( \sum_{i=1}^N d_i \right)^2 f(R) + b^2 \pi \sum_{i=1}^N d_i^2 |\ln \rho|.$$

Indeed when we consider *very near* singularities  $z_1$  &  $z_2$  we may optimize the divergent term  $b^2 \left( \sum_{i=1}^N d_i^2 \right) |\ln \rho|$ . The key argument is that with degrees having different signs (e.g  $d_1 d_2 < 0$ ) we have

$$\sum_{i=1}^N d_i^2 > (d_1 + d_2)^2 + \sum_{i=3}^N d_i^2.$$

This is an example of the standard attractive effect of singularities having degrees with different signs.

#### 8.5.3 The case $b = 1$ , $N \geq 2$ , $d_k d_l \geq 0 \forall k, l$ and there exist $k_0, l_0$ s.t. $d_{k_0} d_{l_0} > 0$

When  $b = 1$ , for  $(\mathbf{z}, \mathbf{d}) \in (\omega^N)^* \times \mathbb{Z}^N$  we have  $W^{\text{micro}}(\mathbf{z}, \mathbf{d}) = -\pi \sum_{i \neq j} d_i d_j \ln |z_i - z_j|$ . Thus

$$\inf_{\mathbf{z} \in (\omega^N)^*} W^{\text{micro}}(\mathbf{z}, \mathbf{d}) > -\infty$$

but the lower bound is not attained. Indeed, it is easy to check that for  $\mathbf{z} \in (\omega^N)^*$

$$\inf_{\mathbf{z} \in (\omega^N)^*} W^{\text{micro}}(\mathbf{z}, \mathbf{d}) > -\pi \sum_{i \neq j} d_i d_j \ln 2.$$

Consequently  $W^{\text{micro}}(\cdot, \mathbf{d})$  is bounded from below. We now prove that the lower bound is not reached. Let  $\mathbf{z} \in (\omega^N)^*$ , and consider  $\tilde{\mathbf{z}} \in (\omega^N)^*$  be s.t.  $\tilde{z}_k = \lambda z_k$  with  $\lambda := \frac{2}{1 + \max_l |z_l|}$ . It is easy to check that  $\tilde{\mathbf{z}} \in (\omega^N)^*$ . Moreover we get  $W^{\text{micro}}(\tilde{\mathbf{z}}, \mathbf{d}) = W^{\text{micro}}(\mathbf{z}, \mathbf{d}) - \pi \ln \lambda \sum_{i \neq j} d_i d_j$ .

Since  $\lambda > 1$ , we have  $W^{\text{micro}}(\tilde{\mathbf{z}}, \mathbf{d}) < W^{\text{micro}}(\mathbf{z}, \mathbf{d})$ . This fact implies that the lower bound is not reached.

*Remark 9* When  $b = 1$ , the impurity  $\omega = \mathbb{D}$  does not play any role. Then, due to the standard repulsion effect between vortices, the more the vortices are distant the smaller the energy. Consequently, for fixed degrees having all the same sign, minimal sequences of singularities go to the boundary of the impurity which is not an admissible configuration in this framework.

#### 8.5.4 The case $b > 1$ and $N \geq 2$

If  $b > 1$  then taking, for  $n \in \mathbb{N}^*$  and  $k \in \{1, \dots, N\}$ ,  $z_k^{(n)} := (1 - 1/n)e^{i2\pi k/N}$  we have

$$\begin{aligned} & W^{\text{micro}}(\mathbf{z}_n, \mathbf{d}) \\ &= \mathcal{O}(1) + \frac{b^2 - 1}{1 + b^2} \sum_{j=1}^N d_j^2 \ln(1 - |z_j^{(n)}|^2) \xrightarrow{n \rightarrow \infty} -\infty. \end{aligned}$$

*Remark 10* The case  $b > 1$  corresponds to an impurity  $\omega = \mathbb{D}$  which have a repulsive effect on the singularities.

#### 8.5.5 The case $0 < b < 1$ , $N = 2$ and $\mathbf{d} \in (\mathbb{N}^*)^2$

This situation is the most challenging. Note that with the help of [9] we may obtain the existence of minimizers for  $W^{\text{micro}}(\cdot, \mathbf{d})$  with  $d_i = 1$  for  $i \in \{1, \dots, N\}$ ,  $N \in \mathbb{N}^*$ . But [9] does not give any information on the location of minimizers and for other configurations of degrees.

For simplicity, we restrict the study to  $N = 2$  and  $p = d_1, q = d_2 \in \mathbb{N}^*$ . Note that the case  $p, q < 0$  is obviously symmetric.

We are going to prove that there exist minimizers and they are unique up to a rotation [see (70)&(71)].

We may assume  $p \leq q$ . For  $z_1, z_2 \in \mathbb{D}$  we have, writing  $(\mathbf{z}, \mathbf{d}) = ((z_1, p), (z_2, q))$

$$\begin{aligned} & \frac{W^{\text{micro}}(\mathbf{z}, \mathbf{d})}{-b^2\pi} \\ &= 2pq \ln |z_1 - z_2| + \frac{1 - b^2}{1 + b^2} [p^2 \ln(1 - |z_1|^2) + \\ & \quad + q^2 \ln(1 - |z_2|^2) + 2pq \ln |1 - z_1 \bar{z}_2|]. \end{aligned}$$

We let:

- $\mathcal{B} := \frac{1 - b^2}{1 + b^2}$  and  $\mathcal{A} := \frac{p}{q} \leq 1$ ;
- The function defined by

$$\begin{aligned} f(z_1, z_2) &= 2 \ln |z_1 - z_2| + \mathcal{B} [\mathcal{A} \ln(1 - |z_1|^2) + \\ & \quad + \mathcal{A}^{-1} \ln(1 - |z_2|^2) + 2 \ln |1 - z_1 \bar{z}_2|]. \end{aligned}$$

Since  $W^{\text{micro}}[(z_1, z_2), (p, q)] = -b^2 pq \pi f(z_1, z_2)$ , in order to study minimizing points of  $W^{\text{micro}}[\cdot, (p, q)]$ , we have to maximize  $f(\cdot)$ .

We first claim that if either  $|z_1| \rightarrow 1$  or  $|z_2| \rightarrow 1$  or  $|z_1 - z_2| \rightarrow 0$ , then  $f(z_1, z_2) \rightarrow -\infty$ . Consequently, from the continuity of  $f$ ,  $f$  admits maximum points in  $(\mathbb{D}^2)^*$ .

Since  $z_1 \neq z_2$  and since for  $t \in \mathbb{R}$  we have  $f(z_1, z_2) = f(z_1 e^{it}, z_2 e^{it})$ , we may assume that  $z_1 = s \geq 0$ . We thus have for  $z_2 = \rho e^{i\theta}$  [ $0 \leq \rho < 1, \theta \in \mathbb{R}$ ]

$$\begin{aligned} & f(s, \rho e^{i\theta}) \\ &= \ln [s^2 + \rho^2 - 2s\rho \cos \theta] + \mathcal{B} [\mathcal{A} \ln(1 - s^2) + \\ & \quad + \mathcal{A}^{-1} \ln(1 - \rho^2) + \ln(1 + s^2 \rho^2 - 2s\rho \cos \theta)]. \end{aligned}$$

We first claim that if  $s = 0$  then  $\rho > 0$  and for  $\varepsilon > 0$  we have

$$f(\varepsilon, -\rho) = f(0, \rho e^{i\theta}) + \varepsilon(\rho^{-1} + 2\beta\rho) + \mathcal{O}(\varepsilon^2).$$

Consequently, for  $\varepsilon > 0$  sufficiently small we have  $f(\varepsilon, -\rho) > f(0, \rho e^{i\theta})$ . Therefore, if  $(s, \rho e^{i\theta})$  maximizes  $f$ , then  $s \in (0; 1)$ . Using a similar argument, we may prove that for  $s > 0$ , if  $(s, \rho e^{i\theta})$  maximizes  $f$ , then  $\rho \in (0; 1)$ .

On the other hand, from direct checking, for  $s, \rho > 0$ , the map  $\theta \in [0, 2\pi] \mapsto f(s, \rho e^{i\theta})$  is maximal if and only if  $\theta = \pi$ .

Consequently, we focus on the map

$$\begin{aligned} g : (0; 1)^2 &\rightarrow \mathbb{R} \\ (s, t) &\mapsto f(s, -t) \end{aligned}$$

We first look for critical points of  $g$ :

$$\begin{aligned} & \nabla g(s, t) = \mathbf{0} \\ & \Leftrightarrow \begin{cases} \frac{1}{s+t} + \mathcal{B} \left( \frac{-\mathcal{A}s}{1-s^2} + \frac{t}{1+st} \right) = 0 \\ \frac{1}{s+t} + \mathcal{B} \left( \frac{-\mathcal{A}^{-1}t}{1-t^2} + \frac{s}{1+st} \right) = 0 \end{cases} \\ & \Leftrightarrow \begin{cases} (1-s^2)(1+st) + \mathcal{B} [-\mathcal{A}s(1+st)(s+t) + \\ \quad + t(1-s^2)(s+t)] = 0 \\ (1-t^2)(1+st) + \mathcal{B} [-\mathcal{A}^{-1}t(1+st)(s+t) + \\ \quad + s(1-t^2)(s+t)] = 0 \end{cases} \quad (65) \end{aligned}$$

By considering the difference of both lines in (65) we get:

$$\begin{aligned}
& (t^2 - s^2)(1 + st) + \mathcal{B}[(\mathcal{A}^{-1}t - \mathcal{A}s)(1 + st)(s + t) + \\
& (t - s^2t - s + st^2)(s + t)] = 0 \\
& \iff (1 + st)(s + t)[t - s + \mathcal{B}((\mathcal{A}^{-1} + 1)t - (\mathcal{A} + 1)s)] \\
& = 0 \\
& \stackrel{[s, t > 0]}{\iff} [1 + \mathcal{B}(\mathcal{A}^{-1} + 1)]t - [1 + \mathcal{B}(\mathcal{A} + 1)]s = 0 \\
& \iff t = \lambda s \text{ with } \lambda := \frac{1 + \mathcal{B}(\mathcal{A} + 1)}{1 + \mathcal{B}(\mathcal{A}^{-1} + 1)}. \tag{66}
\end{aligned}$$

*Remark 11* It is important to note that  $0 < \lambda \leq 1$ . Moreover  $\lambda = 1$  if and only if  $p = q$ .

Using (66) in the first line of (65) we have

$$(1 - s^2)(1 + \lambda s^2) + \mathcal{B}[-\mathcal{A}s^2(1 + \lambda s^2)(1 + \lambda) + \lambda s^2(1 - s^2)(1 + \lambda)] = 0. \tag{67}$$

Thus, letting  $\sigma = s^2$ , we get the following equation:

$$\begin{aligned}
& [\lambda + (\mathcal{A} + 1)\mathcal{B}\lambda(1 + \lambda)]\sigma^2 + \\
& + [1 - \lambda + (\mathcal{A} - \lambda)\mathcal{B}(1 + \lambda)]\sigma - 1 = 0. \tag{68}
\end{aligned}$$

We let

$$\Delta := [1 - \lambda + (\mathcal{A} - \lambda)\mathcal{B}(1 + \lambda)]^2 + 4[\lambda + (\mathcal{A} + 1)\mathcal{B}\lambda(1 + \lambda)].$$

Note that  $\Delta > 0$  and  $\sqrt{\Delta} > 1 - \lambda + (\mathcal{A} - \lambda)\mathcal{B}(1 + \lambda)$ .

We obtain immediately that

$$\sigma_0 = \frac{-[1 - \lambda + (\mathcal{A} - \lambda)\mathcal{B}(1 + \lambda)] + \sqrt{\Delta}}{2[\lambda + (\mathcal{A} + 1)\mathcal{B}\lambda(1 + \lambda)]} \tag{69}$$

is the unique positive solution of (68).

Consequently

$$s_0 = \sqrt{\frac{-[1 - \lambda + (\mathcal{A} - \lambda)\mathcal{B}(1 + \lambda)] + \sqrt{\Delta}}{2[\lambda + (\mathcal{A} + 1)\mathcal{B}\lambda(1 + \lambda)]}} \tag{70}$$

is the unique positive solution of (67).

In conclusion, the set of minimizers of  $W^{\text{micro}}[\cdot, (p, q)]$  is

$$\{(s_0 e^{i\theta}, -\lambda s_0 e^{i\theta}) \in (\mathbb{D}^2)^* \mid \theta \in \mathbb{R}\} \tag{71}$$

where  $s_0$  is given by (70) and  $\lambda$  by (66).

*Remark 12* Note that if  $((z_1, z_2), (p, q)) \in (\mathbb{D}^2)^* \times (\mathbb{N}^*)^2$  is a minimizers for  $W^{\text{micro}}$  then we have:

$$|z_1| \leq |z_2| \iff p \geq q \text{ and } |z_1| = |z_2| \iff p = q.$$

## A Proof of Lemma 2

The key ingredient to get Lemma 2 is Proposition C.4 in [6] previously proved for  $W^{2, \infty}$  weights by Sauvageot in [15] [in fact Sauvageot's article treats the anisotropic case which is more general than Proposition 10 below].

For the convenience of the reader we state this proposition:

**Proposition 10** [Proposition C.4 in [6]]

Let  $\alpha \in L^\infty(\mathbb{R}^2, [B^2; B^{-2}])$  and  $R > r > 0$  we denote:

- $\mu^{\text{Dir}}(B_R \setminus \overline{B_r}) :=$
- $= \inf \left\{ \frac{1}{2} \int_{B_R \setminus \overline{B_r}} \alpha |\nabla w|^2 \left| \begin{array}{l} w \in H^1(B_R \setminus \overline{B_r}, \mathbb{S}^1) \\ \text{s.t. } w(re^{i\theta}) = e^{i\theta}, \\ w(Re^{i\theta}) = e^{i(\theta + \theta_0)}, \theta_0 \in \mathbb{R} \end{array} \right. \right\},$
- $\mu(B_R \setminus \overline{B_r}) := \inf \left\{ \frac{1}{2} \int_{B_R \setminus \overline{B_r}} \alpha |\nabla w|^2 \left| \begin{array}{l} w \in H^1(B_R \setminus \overline{B_r}, \mathbb{S}^1) \\ \text{s.t. } \deg(w) = 1 \end{array} \right. \right\}.$

There exists a constant  $C_B$  depending only on  $B$  s.t.

$$\mu(B_R \setminus \overline{B_r}) \leq \mu^{\text{Dir}}(B_R \setminus \overline{B_r}) \leq \mu(B_R \setminus \overline{B_r}) + C_B.$$

*Remark 13* In [6], Proposition C.4, was initially stated for  $\tilde{\alpha} \in L^\infty(\mathbb{R}^2, [b^2; 1])$  and  $b \in (0; 1)$ . Some obvious modifications allow to get the aforementioned formulation.

Lemma 2 is equivalent to

$$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla u_{R'}|^2 - \frac{1}{2} \int_{\Omega_R} \alpha |\nabla u_R|^2 \leq C_{B, \omega}. \tag{72}$$

Recall that  $R_0 := \max\{1; 10^2 \cdot \text{diam}(\omega)\}$ , thus  $\overline{\omega} \subset B_{R_0}$ .

We let

$$C_\omega := \frac{1}{2} \int_{B_{R_0} \setminus \overline{\omega}} \left| \nabla \left( \frac{x}{|x|} \right) \right|^2. \tag{73}$$

It is easy to check, e.g. using the direct method of minimization, that the minima  $\mu^{\text{Dir}}(B_{R'} \setminus \overline{B_R})$  and  $\mu^{\text{Dir}}(B_R \setminus \overline{B_{R_0}})$  are reached. Let  $u_1$  [resp.  $u_2$ ] be a minimizer of  $\mu^{\text{Dir}}(B_{R'} \setminus \overline{B_R})$  [resp.  $\mu^{\text{Dir}}(B_R \setminus \overline{B_{R_0}})$ ]. Up to multiply  $u_1$  by a constant rotation we may assume  $\text{tr}_{\partial B_R}(u_1) = \text{tr}_{\partial B_R}(u_2)$ . We are now in position to define

$$u = \begin{cases} u_1 & \text{in } B_{R'} \setminus \overline{B_R} \\ u_2 & \text{in } B_R \setminus \overline{B_{R_0}} \\ \frac{x}{|x|} & \text{in } B_{R_0} \setminus \overline{\omega} \end{cases}.$$

It is clear that  $u \in H^1(\Omega_{R'}, \mathbb{S}^1)$  and  $\deg(u) = 1$ . Consequently, with Proposition 10 and (73),

$$\begin{aligned}
\frac{1}{2} \int_{\Omega_{R'}} \alpha |\nabla u_{R'}|^2 & \leq \frac{1}{2} \int_{\Omega_{R'}} \alpha |\nabla u|^2 \\
& = \mu^{\text{Dir}}(B_{R'} \setminus \overline{B_R}) + \mu^{\text{Dir}}(B_R \setminus \overline{B_{R_0}}) + \\
& \quad + \frac{1}{2} \int_{B_{R_0} \setminus \overline{\omega}} \alpha \left| \nabla \left( \frac{x}{|x|} \right) \right|^2 \\
& \leq \mu(B_{R'} \setminus \overline{B_R}) + \mu(B_R \setminus \overline{B_{R_0}}) + 2C_B + B^{-2}C_\omega.
\end{aligned}$$

Since  $\mu(B_{R'} \setminus \overline{B_R}) \leq \frac{1}{2} \int_{B_{R'} \setminus \overline{B_R}} \alpha |\nabla u_{R'}|^2$  and  $\mu(B_R \setminus \overline{B_{R_0}}) \leq$

$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla u_R|^2$  we obtain:

$$\frac{1}{2} \int_{\Omega_R} \alpha |\nabla u_{R'}|^2 \leq \frac{1}{2} \int_{\Omega_R} \alpha |\nabla u_R|^2 + 2C_B + B^{-2}C_\omega.$$

Letting  $C_{B, \omega} := 2C_B + B^{-2}C_\omega$  the above inequality is exactly (72).

## Compliance with ethical standards

The author declares that there is no conflict of interest.

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