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# Deformations of constant mean curvature $1/2$ surfaces in $\mathbb{H}^2 \times \mathbb{R}$ with vertical ends at infinity

Sébastien Cartier and Laurent Hauswirth

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## Abstract

*We study constant mean curvature  $1/2$  surfaces in  $\mathbb{H}^2 \times \mathbb{R}$  that admit a compactification of the mean curvature operator. We show that a particular family of complete entire graphs over  $\mathbb{H}^2$  admits a structure of infinite dimensional manifold and deduce a result on the possible behaviors at infinity. Deforming non degenerate constant mean curvature  $1/2$  annuli, we provide a large class of (non rotational) examples and construct annuli (possibly embedded) without axis, namely with two vertical, asymptotically rotational, non aligned ends.*

*Mathematics Subject Classification: 53A10, 53C42.*

## 1 Introduction

This paper concerns the theory of constant mean curvature (*CMC* for short) surfaces  $H = 1/2$  in  $\mathbb{H}^2 \times \mathbb{R}$ . The value  $H = 1/2$  is critical in the sense that there is no compact CMC sphere for  $H \leq 1/2$  while for  $H > 1/2$  there are rotational compact examples. A half-space theorem in  $\mathbb{H}^2 \times \mathbb{R}$  (see [6]) proves that for CMC  $H = 1/2$ , complete multigraphs are entire graphs over  $\mathbb{H}^2$ . Entire graphs are classified by I. Fernández and P. Mira [4] and their moduli space is modeled on the set of quadratic holomorphic differential  $Q$  defined on the complex plane  $\mathbb{C}$  or the unit disk  $\mathbb{D}$ . The link between  $Q$  and the geometry of the graph is not very well understood.

We first deal with complete conformal immersions of the disk  $\mathbb{D}$ , properly immersed into the half-space  $\mathbb{H}^2 \times \mathbb{R}_+$  ( $x_3 \geq 0$ ), which are entire vertical graphs over  $\mathbb{H}^2$ . We assume that the third coordinate  $x_3 \rightarrow +\infty$  on any diverging sequence of points in  $\mathbb{D}$ , which means the height function is proper. Up to this date, the only simply connected example is a rotational example called the *hyperboloid*  $S_0$ . In the Poincaré disk model of  $\mathbb{H}^2 \times \mathbb{R}$  — see (2) below — with polar coordinates  $(r, \theta)$ , a parametrization of  $S_0$  as a graph over  $\mathbb{H}^2$  is:

$$(r, \theta) \in [0, 1) \times \mathbb{S}^1 \mapsto \left( re^{i\theta}, \frac{2}{\sqrt{1-r^2}} \right) \in \mathbb{H}^2 \times \mathbb{R}.$$

We describe a large family of examples endowed with a structure of infinite dimensional smooth manifold. The manifold structure arises from a suitable *compactification* of the mean curvature operator at infinity (Theorem 2.5) and is diffeomorphic to a codimension one submanifold of  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1) \times \mathbb{R}$  (Theorem 3.9). This construction comes with a control of the asymptotic behavior in terms of the horizontal (hyperbolic) distance from the hyperboloid  $S_0$ , namely:

**Theorem** (Theorem 3.10). *For any  $\gamma \in \mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  such that  $e^{-\gamma}$  has unit  $L^2(\mathbb{S}^1)$ -norm, there exists a CMC- $1/2$  complete entire graph at asymptotic horizontal signed distance  $2\gamma$  from  $S_0$ .*

These graphs are interesting, since any connected complete embedded CMC- $1/2$  surface in  $\mathbb{H}^2 \times \mathbb{R}$  which is contained in the half-space  $\mathbb{H}^2 \times \mathbb{R}_+$  and has a proper height function is a vertical entire graph. Indeed, apply Alexandrov reflection principle to such an immersion. There will be

no first point of tangent contact between the surface and the symmetry part of the constructed bigraph — i.e. the part of the bigraph which is not a part of the surface — since there is no compact CMC-1/2 sphere in  $\mathbb{H}^2 \times \mathbb{R}$ .

Then we study vertical annuli. In  $\mathbb{H}^2 \times \mathbb{R}$ , R. Sa Earp and E. Toubiana [2] construct a one-parameter family of CMC  $H = 1/2$  annuli which are rotationally invariant around a vertical geodesic. It is conjectured that for  $H > 1/2$ , CMC annuli which are cylindrically bounded around a vertical geodesic are rotational examples.

Though annuli are not cylindrically bounded for  $H = 1/2$ , we prove that in a bounded tubular neighborhood of a rotational example, there are annuli, eventually embedded, which are asymptotic to different rotational examples with different axis:

**Theorem** (Theorem 4.9). *There exist CMC-1/2 annuli in  $\mathbb{H}^2 \times \mathbb{R}$  with vertical ends, that are asymptotic — regarding the horizontal hyperbolic distance — to rotational examples with different vertical axis.*

It means that contrary to the case of embedded minimal surfaces in  $\mathbb{R}^3$  with finite total curvature and horizontal ends [7], the notion of *axis* is not relevant in general for CMC-1/2 annuli with vertical ends in  $\mathbb{H}^2 \times \mathbb{R}$ .

## Notations

Let  $\mathbb{D} = \{z \in \mathbb{C} \mid |z| < 1\}$  be the open unit disk,  $\overline{\mathbb{D}} = \{z \in \mathbb{C} \mid |z| \leq 1\}$  its closure and  $(r, \theta)$  the polar coordinates on  $\overline{\mathbb{D}}$ . We use two standard models of  $\mathbb{H}^2 \times \mathbb{R}$ , which are the Minkowski model:

$$\mathbb{H}^2 \times \mathbb{R} = \left( \left\{ (x_0, \dots, x_3) \in \mathbb{R}^4 \mid x_1^2 + x_2^2 - x_0^2 = -1 \right\}, ds_L^2 = dx_1^2 + dx_2^2 + dx_3^2 - dx_0^2 \right), \quad (1)$$

where  $\mathbb{H}^2 \times \mathbb{R}$  is seen as a subspace of the 4-dimensional Minkowski space  $\mathbb{L}^4$ , and the Poincaré disk model:

$$\mathbb{H}^2 \times \mathbb{R} = \left( \{(w, x_3) \in \mathbb{D} \times \mathbb{R}\}, ds_P^2 + dx_3^2 = \frac{4}{(1 - |w|^2)^2} |dw|^2 + dx_3^2 \right). \quad (2)$$

In the Poincaré disk model (2), the hyperbolic radius  $\rho_{\mathbb{H}}(w)$  of a point  $w$  is:

$$\rho_{\mathbb{H}}(w) = 2 \operatorname{argtanh} |w| = \log \left( \frac{1 + |w|}{1 - |w|} \right),$$

and we will need the following formula in the proof of Proposition 2.2:

$$\cosh \frac{\rho_{\mathbb{H}}(w)}{2} = \frac{1}{\sqrt{1 - |w|^2}}.$$

We call vertical graphs (resp. vertical annuli) in  $\mathbb{H}^2 \times \mathbb{R}$ , immersions which are complete graphs (resp. bi-graphs) over an open subset of the slice  $\mathbb{H}^2 \equiv \mathbb{H}^2 \times \{0\}$ .

For any  $R \in [0, 1)$ , we denote  $\Omega_R \subset \mathbb{D}$  the exterior domain  $\Omega_R = \{R \leq r < 1\}$ . We consider the set of *admissible domains*  $\mathcal{D} = \{\Omega_R \mid 0 \leq R < 1\}$ . The boundary at infinity  $\partial_{\infty} \mathbb{H}^2$  of  $\mathbb{H}^2$  is identified with  $\mathbb{S}^1$ .

Given  $\Omega \in \mathcal{D}$ , the spaces  $\mathcal{C}^{k, \alpha}(\overline{\Omega})$  and  $\mathcal{C}_0^{k, \alpha}(\overline{\Omega})$ , with  $k \geq 0$  and  $0 < \alpha < 1$ , are respectively the usual Hölder space and the subspace of functions that are zero on the exterior boundary  $\{r = 1\}$ . Finally, we consider the spaces  $L^2(\cdot)$  endowed with the natural scalar product denoted  $\langle \cdot, \cdot \rangle_{L^2(\cdot)}$  and Hilbert norm  $|\cdot|_{L^2(\cdot)}$ .

## 2 The mean curvature operator

Consider a surface  $S$  parametrized by an immersion  $X : \mathbb{D} \rightarrow \mathbb{H}^2 \times \mathbb{R}$  with complete induced metric  $g$ . By *compactification* of  $S$ , we mean a conformal change  $\bar{g}$  of metric such that  $\bar{g}$  extends to a metric on  $\overline{\mathbb{D}}$ .

The process is sensible to the parametrization. For instance, consider the hyperboloid  $S_0$ . It is a vertical graph over  $\mathbb{H}^2$  parametrized by:

$$(r, \theta) \in \mathbb{D} \mapsto \left( r e^{i\theta}, \frac{2}{\sqrt{1-r^2}} \right) \in \mathbb{H}^2 \times \mathbb{R},$$

in the Poincaré disk model (2), with induced metric:

$$g = \frac{4}{(1-r^2)^3} \begin{pmatrix} 2-r^2 & 0 \\ 0 & 1-r^2 \end{pmatrix}.$$

But  $g$  cannot be conformally extended to the boundary  $\{r=1\}$  of  $\mathbb{D}$ , since the terms of  $g$  have different rates of explosion when  $r \rightarrow 1$ . The resulting metric would degenerate for  $r=1$ .

To ensure the extension of the induced metric, we use a conformal parametrization  $S_0$ , namely the immersion:

$$X^0 : (r, \theta) \in \mathbb{D} \mapsto \left( F(r, \theta), \frac{2}{\sqrt{1-|F(r, \theta)|^2}} \right) = \left( F(r, \theta), 2 \frac{1+r^2}{1-r^2} \right) \in \mathbb{H}^2 \times \mathbb{R},$$

where  $F : \mathbb{D} \rightarrow \mathbb{H}^2$  is the  $\mathcal{C}^1$ -diffeomorphism defined in the Poincaré disk model (2) by:

$$F(r, \theta) = \frac{2r}{1+r^2} e^{i\theta}$$

and in the Minkowski model (1) by:

$$F(r, \theta) = (\cosh \chi(r, \theta), \sinh \chi(r, \theta) \cos \theta, \sinh \chi(r, \theta) \sin \theta) \quad \text{with} \quad \chi(r, \theta) = 2 \log \left( \frac{1+r}{1-r} \right).$$

**Definition 2.1.** A surface in  $\mathbb{H}^2 \times \mathbb{R}$  is said to *admit graph coordinates at infinity*, if there exist an admissible domain  $\Omega \subset \mathcal{D}$  and a function  $h : \Omega \rightarrow \mathbb{R}$  such that the surface can be parametrized as the immersion  $X : (r, \theta) \in \Omega \mapsto (F(r, \theta), h(r, \theta)) \in \mathbb{H}^2 \times \mathbb{R}$  on  $\Omega$ .

When defined, we call such a parametrization *graph coordinates at infinity*.

In the sequel, we use graph coordinates at infinity to compactify surfaces and quantify their asymptotic behaviour. Surfaces are thus considered as *compact surfaces* and we can apply the method first developed by B. White in [10].

### 2.1 The family $\mathcal{E}$

Let  $\mathcal{E}$  be the set of immersed surfaces in  $\mathbb{H}^2 \times \mathbb{R}$ , which admit — up to a symmetry with respect to the slice  $\mathbb{H}^2 \times \{0\}$  — graph coordinates at infinity written as:

$$X^\eta : (r, \theta) \in \Omega \mapsto \left( F(r, \theta), 2e^{\eta(r, \theta)} \frac{1+r^2}{1-r^2} \right) \in \mathbb{H}^2 \times \mathbb{R}, \quad (3)$$

for some admissible domain  $\Omega \in \mathcal{D}$  and  $\eta \in \mathcal{C}^{2, \alpha}(\overline{\Omega})$ . Elements of  $\mathcal{E}$  have *vertical ends* [3] i.e. topological annuli with no asymptotic point at finite height — in other words topological annuli properly embedded in  $(\mathbb{H}^2 \cup \partial_\infty \mathbb{H}^2) \times \mathbb{R}$ .

The hyperboloid  $S_0$  itself is in  $\mathcal{E}$  with  $\Omega = \mathbb{D}$  and  $\eta \equiv 0$ . And so are the rotational examples of E. Toubiana and R. Sa Earp studied in Section 4, owing the asymptotic development (9).

We highlight two properties of the family  $\mathcal{E}$ . The first is that it contains normal deformations of the hyperboloid  $S_0$ . Namely:

**Proposition 2.2.** *A normal graph  $S = \exp_{S_0}(\zeta N)$  over  $S_0$ , where  $N$  is the upward pointing normal to  $S_0$  and  $\zeta \in \mathcal{C}^{2,\alpha}(\mathbb{D})$ , is in  $\mathcal{E}$ . In other words, there exist  $\Omega \in \mathcal{D}$  and  $\eta \in \mathcal{C}^{2,\alpha}(\overline{\Omega})$  such that the end of  $S$  admits graph coordinates at infinity as in (3).*

*Furthermore, the asymptotic value of  $\eta$  is linked with the asymptotic horizontal (hyperbolic) distance between  $S$  and  $S_0$ :*

$$\eta|_{\partial\mathbb{D}} = \frac{1}{2}\zeta|_{\partial\mathbb{D}},$$

*Proof.* We use the Minkowski model (1) of  $\mathbb{H}^2 \times \mathbb{R}$ , where the map  $F$  reads:

$$F(r, \theta) = (\cosh \chi(r, \theta), \sinh \chi(r, \theta) \cos \theta, \sinh \chi(r, \theta) \sin \theta) \quad \text{with} \quad \chi(r, \theta) = 2 \log \left( \frac{1+r}{1-r} \right).$$

A computation shows the unit normal  $N$  to  $S_0$  is:

$$N = -\frac{2r}{1+r^2} \left( \sinh \chi \frac{\partial}{\partial x_0} + \cosh \chi \cos \theta \frac{\partial}{\partial x_1} + \cosh \chi \sin \theta \frac{\partial}{\partial x_2} \right) + \frac{1-r^2}{1+r^2} \frac{\partial}{\partial x_3},$$

in the canonical basis of  $\mathbb{L}^4$ . Hence,  $S$  is parametrized by the immersion:

$$\left( \cosh \left( \chi - \frac{2r\zeta}{1+r^2} \right), \sinh \left( \chi - \frac{2r\zeta}{1+r^2} \right) \cos \theta, \sinh \left( \chi - \frac{2r\zeta}{1+r^2} \right) \sin \theta, 2\frac{1+r^2}{1-r^2} + \frac{1-r^2}{1+r^2}\zeta \right).$$

We want to find new coordinates  $(\tilde{r}, \tilde{\theta})$  on an admissible domain verifying:

$$\chi(\tilde{r}, \tilde{\theta}) = \chi(r, \theta) - \frac{2r}{1+r^2}\zeta(r, \theta), \quad \cos \tilde{\theta} = \cos \theta \quad \text{and} \quad \sin \tilde{\theta} = \sin \theta,$$

to have graph coordinates at infinity on  $S$  as in (3). Taking  $\tilde{\theta} = \theta$ , compute:

$$\frac{\partial}{\partial r} \left( \chi(r, \theta) - \frac{2r}{1+r^2}\zeta(r, \theta) \right) = \frac{4}{1-r^2} - \frac{2}{1+r^2} \left( \frac{1-r^2}{1+r^2}\zeta + r\zeta_r \right) = \frac{4}{1-r^2} + O(1-r^2).$$

If  $r$  is sufficiently close to 1, the map  $r \mapsto \chi - 2r\zeta/(1+r^2)$  is strictly increasing (uniformly in  $\theta$ ), which ensures existence and uniqueness of  $\tilde{r}$ .

To compute the asymptotic horizontal distance, consider a horizontal slice  $\mathbb{H}^2 \times \{t\}$  intersecting  $S$  and  $S_0$ . The hyperbolic radii of  $S$  and  $S_0$  at height  $t$  and in the direction  $\theta$  respectively denoted  $\rho_{\mathbb{H}}(S)(t, \theta)$  and  $\rho_{\mathbb{H}}(S_0)(t, \theta)$  verify:

$$t = \frac{2e^\eta}{\sqrt{1-|F|^2}} = 2e^\eta \cosh \frac{\rho_{\mathbb{H}}(S)(t, \theta)}{2} \quad \text{and} \quad t = \frac{2}{\sqrt{1-|F|^2}} = 2 \cosh \frac{\rho_{\mathbb{H}}(S_0)(t, \theta)}{2},$$

and we deduce:

$$\begin{aligned} \rho_{\mathbb{H}}(S)(t, \theta) &= 2 \operatorname{argcosh} \frac{te^{-\eta}}{2} = 2 \log t - 2\eta + O\left(\frac{1}{t^2}\right) \\ \text{and} \quad \rho_{\mathbb{H}}(S_0)(t, \theta) &= 2 \operatorname{argcosh} \frac{t}{2} = 2 \log t + O\left(\frac{1}{t^2}\right). \end{aligned}$$

Therefore, the hyperbolic horizontal signed distance  $d_{\mathbb{H}}(S, S_0)(t, \theta)$  between  $S$  and  $S_0$  at height  $t$  and in the direction  $\theta$  is:

$$d_{\mathbb{H}}(S, S_0)(t, \theta) = \rho_{\mathbb{H}}(S_0)(t, \theta) - \rho_{\mathbb{H}}(S)(t, \theta) = 2\eta + O\left(\frac{1}{t^2}\right),$$

which establishes the equality  $\zeta|_{\partial\mathbb{D}} = 2\eta|_{\partial\mathbb{D}}$  at infinity. Indeed,  $\zeta|_{\partial\mathbb{D}}$  is the normal signed distance between  $S$  and  $S_0$  at infinity, and also the horizontal distance at infinity, since  $N$  is asymptotically horizontal.  $\square$

Proposition 2.2 emphasizes the fact that the relevant information at infinity is the asymptotic horizontal distance from the hyperboloid. And as suggested by (9) in Section 4, the asymptotic horizontal distance is also relevant for deformed annuli, since the rotational examples are at finite constant asymptotic horizontal distance from each other.

Therefore a general principle in our purpose is to fix a convenient surface, the *model surface*, and to construct deformations of the model surface prescribing the asymptotic horizontal distance from the model surface. It is also the supporting idea of the compactification of the mean curvature operator (Theorem 2.5).

A second interesting property of  $\mathcal{E}$  is the following:

**Proposition 2.3.** *The image of any element of  $\mathcal{E}$  under the action of any isometry of  $\mathbb{H}^2 \times \mathbb{R}$  is still an element of  $\mathcal{E}$ .*

*Proof.* Consider a surface  $S \in \mathcal{E}$  with graph coordinates at infinity  $(F, h)$  defined on  $\Omega \in \mathcal{D}$ , and denote by  $(F, h')$  the graph coordinates at infinity of its image  $S'$  under an isometry  $\psi$  of  $\mathbb{H}^2 \times \mathbb{R}$ . Using parametrization (3), we know that in the Poincaré disk model (2):

$$h = \frac{2e^\eta}{\sqrt{1-|F|^2}} \quad \text{with} \quad \eta \in \mathcal{C}^{2,\alpha}(\overline{\Omega}).$$

It is sufficient to examine the cases when  $\psi$  is either an isometry of  $\mathbb{H}^2$  fixing the coordinate  $x_3$  or a vertical translation. If  $\psi$  is a vertical translation of  $t_0 \in \mathbb{R}$ , we have:

$$h' = \frac{2e^\eta}{\sqrt{1-|F|^2}} + t_0 = 2 \exp \left( \eta + \log \left( 1 + t_0 \frac{e^{-\eta}}{2} \frac{1-r^2}{1+r^2} \right) \right) \frac{1}{\sqrt{1-|F|^2}},$$

eventually after a restriction to a domain  $\Omega' \in \mathcal{D}$  for which  $h|_{\Omega'} > -t_0$ .

If  $\psi$  reduces to an isometry of  $\mathbb{H}^2$  preserving the orientation of  $\mathbb{H}^2$ , there exist  $w_0 \in \mathbb{D}$  and  $\delta_0 \in \mathbb{R}$  such that:

$$\psi(w) = \frac{w + w_0}{1 + \overline{w_0}w} e^{i\delta_0}.$$

If  $\psi' = F^{-1} \circ \psi^{-1} \circ F$ , then:

$$\begin{aligned} h' &= h \circ \psi' = \frac{2e^{\eta \circ \psi'}}{\sqrt{1-|\psi'^{-1} \circ F|^2}} = \left( e^{\eta \circ \psi'} \frac{|1 - \overline{w_0}F|}{\sqrt{1-|w_0|^2}} \right) \frac{2}{\sqrt{1-|F|^2}} \\ &= \exp \left( \eta \circ \psi' + \log \left( \frac{|1 - \overline{w_0}F|}{\sqrt{1-|w_0|^2}} \right) \right) \frac{2}{\sqrt{1-|F|^2}}, \end{aligned}$$

and  $S' \in \mathcal{E}$ . Changing  $F$  in  $\overline{F}$ , gives the result when  $\psi$  reduces to an isometry of  $\mathbb{H}^2$  reversing the orientation.  $\square$

**Remark 2.4.** The value  $\eta|_{\partial\mathbb{D}}$  is invariant under vertical translations.

## 2.2 Compactification of the mean curvature

From now on, to ease the notations, we denote with indices 1, 2 quantities related to coordinates  $r, \theta$  respectively. Consider an admissible domain  $\Omega \in \mathcal{D}$  and a function  $a \in \mathcal{C}^{2,\alpha}(\overline{\Omega})$ . The model surface is the immersion  $X^a$ , written as in (3).

**Theorem 2.5.** *For any deformation  $X^{a+\xi}$  of the model surface  $X^a$ , with  $\xi \in \mathcal{C}^{2,\alpha}(\overline{\Omega})$ , the respective mean curvatures  $H(a+\xi)$  and  $H(a)$  verify the following:*

$$\sqrt{|g(a)|} (H(a+\xi) - H(a)) = \sum_{i,j} A_{ij}(r, \theta, a, D\xi) \xi_{ij} + B(r, \theta, a, \xi, D\xi), \quad (4)$$

where  $|g(a)|$  is the determinant of the metric induced by  $X^a$ ,  $A_{ij}$  and  $B$  are  $\mathcal{C}^{0,\alpha}$  functions on  $\overline{\Omega}$  which are real-analytic in their variables, and  $A = (A_{ij})$  is a coercive matrix on  $\overline{\Omega}$ .

*Proof* (See Appendix 5 for computation details). Denote  $\sigma$  the pullback metric  $F^*ds_P^2$ , i.e. in matrix terms:

$$\sigma = \frac{16}{(1-r^2)^4} \begin{pmatrix} (1-r^2)^2 & 0 \\ 0 & r^2(1+r^2) \end{pmatrix}.$$

Differential properties of a surface in  $\mathbb{H}^2 \times \mathbb{R}$  with graph coordinates at infinity  $(F, h)$  are the ones of the actual graph of  $h$  in  $\mathbb{D} \times \mathbb{R}$  endowed with the metric  $\sigma + dx_3^2$ . Following J. Spruck [8], the mean curvature  $H(a + \xi)$  is:

$$H(a + \xi) = \frac{1}{2} \operatorname{div}_\sigma \left( \frac{\nabla_\sigma h(a + \xi)}{W(a + \xi)} \right) \quad \text{with} \quad W(a + \xi) = \sqrt{1 + |\nabla_\sigma h(a + \xi)|_\sigma^2},$$

with quantities computed with respect to  $\sigma$ . If  $(\Gamma_{ij}^k)$  denote the Christoffel symbols associated to  $\sigma$ , we have:

$$H(a + \xi) = \frac{1}{2W(a + \xi)} \sum_{i,j} g^{ij}(a + \xi) \left( \partial_{ij} h(a + \xi) - \sum_k \Gamma_{ij}^k \partial_k h(a + \xi) \right),$$

where the non zero Christoffel symbols associated to the metric  $\sigma$  are:

$$\begin{aligned} \Gamma_{11}^1 &= \frac{2r}{1-r^2}, & \Gamma_{12}^2 &= \frac{4r}{1-r^2} \left( 1 + \frac{1+3r^2}{4r^2(1+r^2)}(1-r^2) \right) \\ \text{and} \quad \Gamma_{22}^1 &= -\frac{4r^3(1+r^2)^2}{(1-r^2)^3} \left( 1 + \frac{1+3r^2}{4r^2(1+r^2)}(1-r^2) \right). \end{aligned}$$

The induced metric  $g(a)$  reads:

$$\begin{aligned} g_{11}(a) &= \frac{64r^2 e^{2a}}{(1-r^2)^4} \left[ 1 + \frac{1+r^2}{2r} a_1(1-r^2) + \frac{(1+r^2)^2}{16r^2} \left( a_1^2 + \frac{4e^{-2a}}{(1+r^2)^2} \right) (1-r^2)^2 \right], \\ g_{12}(a) &= \frac{16r(1+r^2)e^{2a}}{(1-r^2)^3} a_2 \left[ 1 + \frac{1+r^2}{4r} a_1(1-r^2) \right] \\ \text{and} \quad g_{22}(a) &= \frac{16r^2(1+r^2)^2 e^{2a}}{(1-r^2)^4} \left[ e^{-2a} + \frac{a_2^2}{4r^2} (1-r^2)^2 \right], \end{aligned}$$

and the expression of  $W(a)$  is the following:

$$\begin{aligned} W(a) &= \frac{2re^a}{1-r^2} \left[ 1 + \frac{1+r^2}{2r} a_1(1-r^2) + \frac{(1+r^2)^2}{16r^2} \left( a_1^2 + \frac{4e^{-2a}}{(1+r^2)^2} \right) (1-r^2)^2 \right. \\ &\quad \left. + \frac{a_2^2}{16r^4} (1-r^2)^4 \right]^{1/2}. \quad (5) \end{aligned}$$

The computation detailed in Appendix 5 gives the expression (4) with the desired regularity and:

$$A_{11} = e^{-a} + O(1-r^2), \quad A_{12} = A_{21} = O(1-r^2) \quad \text{and} \quad A_{22} = e^a + O(1-r^2),$$

which shows that  $A$  is coercive.  $\square$

The quantity  $\sqrt{g(a)}(H(\eta) - H(a))$  with  $\eta \in \mathcal{C}^{2,\alpha}(\bar{\Omega})$  can be called a *compactification* of the mean curvature of  $X^\eta$  since it can be extended to the exterior boundary  $\{r=1\}$  of  $\Omega$ . It is strongly linked with the compactification of the induced metric  $g(a)$  by the following equality:

$$A^{-1} = \begin{pmatrix} e^a & 0 \\ 0 & e^{-a} \end{pmatrix} + O(1-r^2) = \frac{1}{\sqrt{|g(a)|}} g(a) + O(1-r^2).$$

### 3 Moduli space of CMC-1/2 entire graphs

In this section, we are interested in the subset  $\mathcal{G} \subset \mathcal{E}$  of CMC-1/2 complete entire graphs contained in the half-space  $\mathbb{H}^2 \times \mathbb{R}_+^*$ . Since elements of  $\mathcal{G}$  are simply connected, they can be *globally* parametrized in graph coordinates at infinity over the whole disk  $\mathbb{D}$  using (3):

$$X^\eta = \left( F, 2e^\eta \frac{1+r^2}{1-r^2} \right) \quad \text{with} \quad F(r, \theta) = \frac{2r}{1+r^2} e^{i\theta} \quad \text{and} \quad \eta \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}}),$$

and the geometrically defined function  $\eta|_{\partial\mathbb{D}} : \mathbb{S}^1 \rightarrow \mathbb{R}$  is the *value at infinity* of the surface.

Consider a CMC-1/2 entire graph  $S \in \mathcal{G}$ , with graph coordinates at infinity  $X^a$ , where  $a \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$ , and denote  $\gamma^a = a|_{\partial\mathbb{D}}$  the value at infinity. A simple computation shows that the vertical component  $\varphi^a$  of the upward pointing unit normal  $N^a$  to  $X^a$  can be expressed as:

$$\varphi^a = \frac{1}{W(a)} = \frac{e^{-a} (1-r^2)}{2c^a (1+r^2)} \quad \text{with} \quad c^a = \frac{e^{-a} (1-r^2)}{2(1+r^2)} W(a), \quad (6)$$

and  $W(a)$  given by (5). And  $c^a$  is a positive function on  $\overline{\mathbb{D}}$  such that  $c^a|_{\partial\mathbb{D}} = 1/2$ .

In the sequel, we make the following abuse of notation denoting  $H$  the operator:

$$H : \eta \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}}) \mapsto H(\eta) \in \mathcal{C}^{0,\alpha}(\overline{\mathbb{D}}),$$

where  $H(\eta)$  is the mean curvature of  $X^\eta$ , and calling it the *mean curvature operator*.

**Lemma 3.1.** *The differential of the operator  $H$  at point  $a$  is:*

$$\forall \eta \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}}), \quad DH(a) \cdot \eta = \frac{1}{2} L \left( \frac{\eta}{c^a} \right),$$

where  $L$  is the Jacobi operator of  $X^a$ .

*Proof.* If  $(X^{\eta_t})$  is a differentiable family in the parameter  $t$  such that  $\eta_0 = a$ , it is a standard fact that:

$$\left. \frac{d}{dt} \right|_{t=0} H(\eta_t) = \frac{1}{2} L \left\langle \left. \frac{d}{dt} \right|_{t=0} X^{\eta_t}, N^a \right\rangle = \frac{1}{2} L \left( 2e^a \varphi^a \frac{1+r^2}{1-r^2} \left. \frac{d\eta_t}{dt} \right|_{t=0} \right),$$

and the expression (6) of  $\varphi^a$  leads to the conclusion.  $\square$

Using Theorem 2.5, we define the *compactified mean curvature operator* to be:

$$\overline{H} : \xi \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}}) \mapsto \sqrt{|g(a)|} \left( H(a + 2c^a \xi) - \frac{1}{2} \right) \in \mathcal{C}^{0,\alpha}(\overline{\mathbb{D}}).$$

The *compactified Jacobi operator* is  $\overline{L} = D\overline{H}(0) : \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}}) \rightarrow \mathcal{C}^{0,\alpha}(\overline{\mathbb{D}})$  and using Lemma 3.1 we know that:

$$\overline{L} = \sqrt{|g(a)|} L.$$

**Lemma 3.2** (Green identity). *For any  $u, v \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$ ,  $\overline{L}$  satisfies the following identity:*

$$\int_{\overline{\mathbb{D}}} (u \overline{L}v - v \overline{L}u) d\overline{A} = \int_0^{2\pi} e^{-\gamma^a} \left( u \frac{\partial v}{\partial r} - v \frac{\partial u}{\partial r} \right) \Big|_{r=1} d\theta,$$

with  $d\overline{A}$  the Lebesgue measure on  $\overline{\mathbb{D}}$ .



*Proof.* Let  $u, v \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$ . For any  $R \in (0, 1)$ ,  $L$  satisfies a Green identity on  $\{r \leq R\}$ :

$$\int_{\{r \leq R\}} (uLv - vLu) dA = \int_{\{r=R\}} \left( u \frac{\partial v}{\partial \nu} - v \frac{\partial u}{\partial \nu} \right) ds,$$

where  $dA$  and  $ds$  are the measures corresponding to the metric induced by  $X^a$  on  $\{r \leq R\}$  and  $\{r = R\}$  respectively, and where  $\partial \cdot / \partial \nu$  denotes the co-normal derivative. Notice that:

$$dA = \sqrt{|g(a)|} d\overline{A}, \quad ds = \sqrt{g_{22}(a)} d\theta \quad \text{and} \quad \nu = \frac{1}{\sqrt{g_{22}(a)|g(a)|}} (g_{22}(a)X_1^a - g_{12}(a)X_2^a),$$

with  $d\overline{A}$  the Lebesgue measure on  $\mathbb{R}^2$ . Taking the limit when  $R \rightarrow 1$ , we obtain:

$$\lim_{R \rightarrow 1} \sqrt{g_{22}(a)} \nu = e^{-\gamma^a} \frac{\partial}{\partial r} \Big|_{r=1},$$

and the identity follows.  $\square$

Let  $\overline{L}_0$  be the restriction of  $\overline{L}$  to  $\mathcal{C}_0^{2,\alpha}(\overline{\mathbb{D}})$  and  $K = \ker \overline{L}_0$ . Using the standard inclusions  $\mathcal{C}_0^{2,\alpha}(\overline{\mathbb{D}}) \subset \mathcal{C}^{0,\alpha}(\overline{\mathbb{D}}) \subset L^2(\mathbb{D})$ , we denote by  $K^\perp$  the orthogonal to  $K$  in  $\mathcal{C}^{0,\alpha}(\overline{\mathbb{D}})$  for the natural scalar product of  $L^2(\mathbb{D})$  and  $K_0^\perp = K^\perp \cap \mathcal{C}_0^{2,\alpha}(\overline{\mathbb{D}})$ .

It is a standard fact that the restriction  $\overline{L}_0$  is a Fredholm operator with index zero (see for instance [5]). Namely  $K = \mathbb{R}\varphi^a$  and  $\overline{L}_0(\mathcal{C}_0^{2,\alpha}(\overline{\mathbb{D}})) = K^\perp$ . We deduce the following technical lemma:

**Lemma 3.3.** *There is no solution  $u \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$  to the equation:*

$$\begin{cases} \overline{L}u = 0 & \text{on } \overline{\mathbb{D}} \\ u|_{\partial\mathbb{D}} = 1 \end{cases}.$$

*Proof.* By contradiction, suppose such a  $u$  exist and apply Lemma 3.2 to  $\varphi^a$  and  $u$ :

$$0 = \int_{\overline{\mathbb{D}}} (\varphi^a \overline{L}u - u \overline{L}\varphi^a) d\overline{A} = \int_0^{2\pi} e^{-\gamma^a} \left( \varphi^a \frac{\partial u}{\partial r} - u \frac{\partial \varphi^a}{\partial r} \right) \Big|_{r=1} d\theta = \int_0^{2\pi} e^{-2\gamma^a} d\theta,$$

since  $\varphi^a|_{r=1} = 0$  and  $\frac{\partial \varphi^a}{\partial r} \Big|_{r=1} = -e^{-\gamma^a}$ ,

which is impossible.  $\square$

### 3.1 General deformations

Let  $\mu_a : \mathcal{C}^{2,\alpha}(\mathbb{S}^1) \rightarrow \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$  be the operator such that  $\mu_a(\gamma)$  is the harmonic function on  $\overline{\mathbb{D}}$  (for the flat laplacian) with value  $\gamma - \gamma^a$  on the boundary  $\partial\mathbb{D}$ . Denote  $\Pi_K$  and  $\Pi_{K^\perp}$  be the orthogonal projections on  $K$  and  $K^\perp$  respectively. Following B. White [10], we show:

**Lemma 3.4.** *Consider the map  $\Phi : \mathcal{C}^{2,\alpha}(\mathbb{S}^1) \times \mathbb{R} \times K_0^\perp \rightarrow K^\perp$  defined by:*

$$\Phi(\gamma, \lambda, \sigma) = \Pi_{K^\perp} \circ \overline{H}(\mu_a(\gamma) + \lambda\varphi^a + \sigma).$$

*Then  $D_3\Phi(\gamma^a, 0, 0) : K_0^\perp \rightarrow K^\perp$  is an isomorphism.*

*Proof.* A direct computation gives  $D_3\Phi(\gamma^a, 0, 0) = \Pi_{K^\perp} \circ \overline{L}_0|_{K_0^\perp}$  and we know  $K^\perp$  is the range of  $\overline{L}_0$ . Thus  $D_3\Phi(\gamma^a, 0, 0) = \overline{L}_0|_{K_0^\perp}$ , which is an isomorphism onto  $K^\perp$ .  $\square$

Therefore, we can apply the implicit function theorem to  $\Phi$ , which states that there exist a neighborhood  $U_a$  of  $(\gamma^a, 0)$  in  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1) \times \mathbb{R}$  and a unique smooth map  $\sigma : U_a \rightarrow K_0^\perp$  such that:

$$\forall (\gamma, \lambda) \in U_a, \Phi(\gamma, \lambda, \sigma(\gamma, \lambda)) = 0.$$

We define the maps  $\eta_a : U_a \rightarrow \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$  and  $\kappa_a : U_a \rightarrow K$  by:

$$\eta_a(\gamma, \lambda) = a + 2c^a(\mu_a(\gamma) + \lambda\varphi^a + \sigma(\gamma, \lambda)) \quad \text{and} \quad \kappa_a(\gamma, \lambda) = \Pi_K \circ \overline{H}(\mu_a(\gamma) + \lambda\varphi^a + \sigma(\gamma, \lambda)).$$

If a surface in  $\mathcal{E}$ , defined on  $\mathbb{D}$ , admits  $X^{\eta_a(\gamma, \lambda)}$  as graph coordinates at infinity, we say that  $\{\gamma, \lambda\}$  are the *data* of the surface with respect to  $S$  or to  $a$ .

**Lemma 3.5.** *The map  $\eta_a$  has the following properties:*

1.  $\eta_a(\gamma^a, 0) = a$ .
2.  $\forall (\gamma, \lambda) \in U_a, \eta_a(\gamma, \lambda)|_{\partial\mathbb{D}} = \gamma$ .
3.  $D_2\eta_a(\gamma^a, 0) : \lambda \in \mathbb{R} \mapsto 2\lambda c^a \varphi^a \in \mathcal{C}^{2,\alpha}(\overline{\mathbb{D}})$ .

*Proof.* Point 1 comes from the definition of  $\mu_a$  and from the uniqueness in the implicit function theorem. Point 2 is a direct computation:

$$\begin{aligned} \eta_a(\gamma, \lambda)|_{\partial\mathbb{D}} &= a|_{\partial\mathbb{D}} + 2c^a|_{\partial\mathbb{D}}(\mu_a(\gamma)|_{\partial\mathbb{D}} + \lambda\varphi^a|_{\partial\mathbb{D}} + \sigma(\gamma, \lambda)|_{\partial\mathbb{D}}) \\ &= \gamma^a + 2\frac{1}{2}((\gamma - \gamma^a) + \lambda 0 + 0) = \gamma. \end{aligned}$$

For Point 3, it is sufficient to show  $D_2\sigma(\gamma^a, 0) = 0$ . To do so we compute:

$$0 = \left. \frac{d}{dt} \right|_{t=0} \Phi(\gamma^a, t, \sigma(\gamma^a, t)) = \Pi_{K^\perp} \circ \overline{L}_0(\varphi^a + D_2\sigma(\gamma^a, 0) \cdot 1) = \overline{L}_0(D_2\sigma(\gamma^a, 0) \cdot 1).$$

Hence,  $D_2\sigma(\gamma^a, 0) \cdot 1 \in K \cap K^\perp = \{0\}$ , which means  $D_2\sigma(\gamma^a, 0) = 0$ .  $\square$

**Remark 3.6.** Let  $S' \in \mathcal{G}$  with graph coordinates at infinity  $X^{a'}$  and suppose there exist a surface in  $\mathcal{E}$  with data  $\{\gamma, \lambda\}$  and  $\{\gamma', \lambda'\}$  with respect to  $S$  and  $S'$  respectively. Therefore, this surface admits graph coordinates at infinity  $X^{\eta_a(\gamma, \lambda)}$  and  $X^{\eta_{a'}(\gamma', \lambda')}$  — i.e.  $\eta_a(\gamma, \lambda) = \eta_{a'}(\gamma', \lambda')$  — and we get:

$$\gamma' = \gamma \quad \text{and} \quad \lambda' = \frac{1}{|\varphi^{a'}|_{L^2(\mathbb{D})}^2} \left\langle \frac{\eta_a(\gamma, \lambda) - a'}{2c^{a'}} - \mu_{a'}(\gamma), \varphi^{a'} \right\rangle_{L^2(\mathbb{D})}. \quad (7)$$

The identity on values at infinity comes from Lemma 3.5 Point 2, and the expression of  $\lambda'$  is just the projection along  $\varphi^{a'}$ .

Lemma 3.5 Point 2 also shows that the value at infinity of a surface  $X^{\eta_a(\gamma, \lambda)}$  does not depend on  $\lambda$ , which means there exists a 1-parameter family of surfaces admitting the same value at infinity. This family is nothing but the vertical translations of  $X^{\eta_a(\gamma, \lambda)}$ :

**Proposition 3.7.** *Let  $(\gamma, \lambda) \in U_a$ . The surface  $X^{\eta_a(\gamma, \lambda')}$  exists for any  $\lambda' \in \mathbb{R}$  and coincides with  $X^{\eta_a(\gamma, \lambda)}$  up to a vertical translation.*

*Proof.* Changing  $a$  in  $\eta_a(\gamma, \lambda)$ , we can suppose — using (7) — that  $\gamma = \gamma^a$  and  $\lambda = 0$ . Denote  $h(a)$  the height function of  $X^a$  and  $m > 0$  the minimum of  $h(a)$  on  $\mathbb{D}$ . We know from Proposition 2.3 that the graph coordinates at infinity of the image of  $S$  under the vertical translation by some  $t \in \mathbb{R}$  can still be written  $X^{a'(t)}$  defined on  $\mathbb{D}$  if and only if  $t > -m$  and in that case:

$$a'(t) = a + \log \left( 1 + t \frac{e^{-a}}{2} \frac{1 - r^2}{1 + r^2} \right) = a + \log \left( 1 + \frac{t}{h(a)} \right).$$

We also know that  $a'(t)|_{\partial\mathbb{D}} = a|_{\partial\mathbb{D}}$ , which implies  $\mu_a(a'(t)) = 0$ . Writing:

$$a'(t) = a + 2c^a \left( \lambda'(t) \varphi^a + \sigma(\gamma^a, \lambda'(t)) \right),$$

we only have to show that  $\lambda'(t)$  is a bijection in the variable  $t$  from the interval  $(-m, +\infty)$  of possible translations onto  $\mathbb{R}$ . The expression of  $\lambda'(t)$  is:

$$\begin{aligned} \lambda'(t) &= \frac{1}{|\varphi^a|_{L^2(\mathbb{D})}^2} \left\langle \frac{a'(t) - a}{2c^a}, \varphi^a \right\rangle_{L^2(\mathbb{D})} = \frac{1}{2\pi|\varphi^a|_{L^2(\mathbb{D})}^2} \int_{\mathbb{D}} \frac{\varphi^a}{c^a} \log \left( 1 + \frac{t}{h(a)} \right) \\ &= \frac{1}{2\pi|\varphi^a|_{L^2(\mathbb{D})}^2} \int_{\mathbb{D}} (\varphi^a)^2 h(a) \log \left( 1 + \frac{t}{h(a)} \right) \quad \text{since} \quad \frac{1}{c^a} = \varphi^a h(a). \end{aligned}$$

Compute:

$$\frac{d\lambda'(t)}{dt} = \frac{1}{2\pi|\varphi^a|_{L^2(\mathbb{D})}^2} \int_{\mathbb{D}} \frac{(\varphi^a)^2 h(a)}{t + h(a)} > 0$$

i.e.  $\lambda'(t)$  is a strictly increasing bijection from  $(-m, +\infty)$  into  $\mathbb{R}$ . Also:

$$\lambda'(t) \leq \left[ \frac{1}{2\pi|\varphi^a|_{L^2(\mathbb{D})}^2} \int_{\mathbb{D}} (\varphi^a)^2 h(a) \right] \log \left( 1 + \frac{t}{m} \right) \xrightarrow{t \rightarrow -m} -\infty,$$

and if  $M > 0$  is the maximum of  $h(a)$  on the disk  $\{0 \leq r \leq 1/2\}$ , we get:

$$\begin{aligned} \lambda'(t) &\geq \frac{1}{2\pi|\varphi^a|_{L^2(\mathbb{D})}^2} \int_{\{0 \leq r \leq 1/2\}} (\varphi^a)^2 h(a) \log \left( 1 + \frac{t}{h(a)} \right) \\ &\geq \left[ \frac{m}{2\pi|\varphi^a|_{L^2(\mathbb{D})}^2} \int_{\{0 \leq r \leq 1/2\}} (\varphi^a)^2 \right] \log \left( 1 + \frac{t}{M} \right) \xrightarrow{t \rightarrow +\infty} +\infty, \end{aligned}$$

which ensures that  $\lambda'(t)$  is bijective from  $(-m, +\infty)$  onto  $\mathbb{R}$ . □

### 3.2 CMC-1/2 deformations

The values of the mean curvature of deformations  $X^{\eta_a(\gamma, \lambda)}$  of  $S$  are determined by  $\kappa_a$ . Indeed:

$$\overline{H}(\mu_a(\gamma) + \lambda\varphi^a + \sigma(\gamma, \lambda)) = \kappa_a(\gamma, \lambda) + \Phi(\gamma, \lambda, \sigma(\gamma, \lambda)) = \kappa_a(\gamma, \lambda),$$

since by construction  $\Phi(\gamma, \lambda, \sigma(\gamma, \lambda)) = 0$ . In particular:

$$\forall (\gamma, \lambda) \in U_a, \quad H(\eta_a(\gamma, \lambda)) = \frac{1}{2} \iff \kappa_a(\gamma, \lambda) = 0.$$

We consider  $\mathcal{U}_a = \kappa_a^{-1}(\{0\}) \cap U_a$  and  $\mathcal{V}_a \subset \mathcal{G}$  the set of surfaces admitting data in  $\mathcal{U}_a$ . Using Proposition 3.7, we know there exists a subset  $\Gamma_a \subset \mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  such that  $\mathcal{U}_a = \Gamma_a \times \mathbb{R}$ .

**Proposition 3.8.**  $\Gamma_a$  is a real-analytic codimension 1 submanifold of  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  such that the tangent space to  $\Gamma_a$  at  $\gamma^a$  is the orthogonal space  $\langle e^{-2\gamma^a} \rangle^\perp$  to  $e^{-2\gamma^a}$  in  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  for the scalar product of  $L^2(\mathbb{S}^1)$ .

Moreover,  $\Gamma_a$  is a closed subset of  $\left\{ \gamma \in \mathcal{C}^{2,\alpha}(\mathbb{S}^1) \mid |e^{-\gamma}|_{L^2(\mathbb{S}^1)} = |e^{-\gamma^a}|_{L^2(\mathbb{S}^1)} \right\}$ .

*Proof.* By construction,  $\Gamma_a$  is a smooth submanifold of  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  and its codimension is the rank of  $D\kappa_a(\gamma^a, 0)$ . We compute:

$$D_2\kappa_a(\gamma^a, 0) \cdot 1 = \frac{d}{dt} \Big|_{t=0} \kappa_a(\gamma^a, t) = \Pi_K \circ \bar{L} \left( \frac{1}{2c^a} D_2\eta_a(\gamma^a, 0) \cdot 1 \right) = \Pi_K \circ \bar{L}_0(\varphi^a) = 0,$$

since  $\varphi^a \in K$ . Thus the rank of  $D\kappa_a(\gamma^a, 0)$  is the rank of  $D_1\kappa_a(\gamma^a, 0)$ . We know that  $\text{rank } D_1\kappa_a(\gamma^a, 0) \leq \dim K = 1$ . Hence, we only need to find a curve  $\gamma \in \mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  such that  $D_1\kappa_a(\gamma^a, 0) \cdot \gamma$  is not identically zero. We can take  $\gamma = 1$ . Indeed:

$$D_1\kappa_a(\gamma^a, 0) \cdot 1 = \frac{d}{dt} \Big|_{t=0} \kappa_a(t, 0) = \Pi_K \circ \bar{L}u = \bar{L}u \quad \text{with} \quad u = \frac{1}{2c^a} D_1\eta_a(\gamma^a, 0) \cdot 1.$$

Lemma 3.5 Point 2 shows that  $u|_{\partial\mathbb{D}} = 1$ . And using Lemma 3.3, we know that  $D_1\kappa_a(\gamma^a, 0) \cdot 1$  is not identically zero.

Consider a smooth path  $\gamma_t$  in  $\Gamma_a$  with  $\gamma_0 = \gamma^a$  and tangent vectors  $\dot{\gamma}_t$ . Note that:

$$0 = D\kappa_a(\gamma^a, 0) \cdot (\dot{\gamma}_0, 0) = \frac{d}{dt} \Big|_{t=0} \kappa_a(\gamma_t, 0) = \Pi_K \circ \bar{L}v = \bar{L}v \quad \text{with} \quad v = \frac{1}{2c^a} D_1\eta_a(\gamma^a, 0) \cdot \dot{\gamma}_0.$$

Knowing that:

$$\varphi^a|_{r=1} = 0, \quad \frac{\partial\varphi^a}{\partial r} \Big|_{r=1} = -e^{-\gamma^a} \quad \text{and} \quad v|_{r=1} = \dot{\gamma}_0,$$

apply Lemma 3.2 to  $\varphi^a$  and  $v$ :

$$\begin{aligned} 0 &= \int_{\mathbb{D}} \left( \varphi^a \bar{L}v - v \bar{L}\varphi^a \right) d\bar{A} = \int_0^{2\pi} e^{-\gamma^a} \left( \varphi^a \frac{\partial v}{\partial r} - v \frac{\partial \varphi^a}{\partial r} \right) \Big|_{r=1} d\theta \\ &= \int_0^{2\pi} \dot{\gamma}_0 e^{-2\gamma^a} d\theta = 2\pi \langle \dot{\gamma}_0, e^{-2\gamma^a} \rangle_{L^2(\mathbb{S}^1)}. \end{aligned} \tag{8}$$

Therefore  $\langle e^{-2\gamma^a} \rangle^\perp$  is the tangent space to  $\Gamma_a$  at  $\gamma^a$ , since it is of codimension 1.

For a fixed  $t$ , consider the reparametrized path  $\gamma'_s = \gamma_{s+t}$  and denote  $a' = \eta_a(\gamma_t, 0)$ . There exists  $\varepsilon > 0$  such that  $\gamma'_s \in \Gamma_{a'}$  for any  $|s| < \varepsilon$ . Hence, the path of surfaces  $X^{\eta_a(\gamma'_s, 0)}$  can be described by a path of data  $\{\gamma'_s, \lambda'_s\}$  in  $\mathcal{U}_{a'}$ ,  $|s| < \varepsilon$ , with  $\lambda'_0 = 0$  and tangent vectors denoted  $\dot{\gamma}'_s$ . By construction, we know that  $\dot{\gamma}'_0 = \dot{\gamma}_t$ . The result (8) applies to  $\{\gamma'_s, \lambda'_s\}$ , thus:

$$\frac{d}{dt} |e^{-\gamma_t}|_{L^2(\mathbb{S}^1)}^2 = -2 \langle \dot{\gamma}_t, e^{-2\gamma_t} \rangle_{L^2(\mathbb{S}^1)} = 0,$$

for any  $t$ , i.e.  $|e^{-\gamma_t}|_{L^2(\mathbb{S}^1)}$  is constant.

To show that  $\Gamma_a$  is closed, consider  $\gamma$  in the closure  $\overline{\Gamma_a}$ , and a smooth path  $(\gamma_t)$  with  $\gamma_0 = \gamma^a$ ,  $\gamma_1 = \gamma$  and  $\gamma_t \in \Gamma_a$  for all  $0 \leq t < 1$ . For any  $t \in [0, 1)$ , there exists an immersion  $X_t$  with  $\gamma_t$  as value at infinity, and using Proposition 3.7, we can suppose the minimum height of  $X_t$  is exactly 1, to prevent the immersions from escaping to infinity. We only need to show that  $X_t$  converges as  $t \rightarrow 1$  to a vertical graph  $X_1$  with no asymptotic point at finite height. The fact that  $X_1$  admits  $\gamma$  as value at infinity is then straightforward, since surfaces are actually considered as surfaces with boundary, due to the compactification property.

Let  $d$  be the greatest distance of the family  $(X_t)$  from  $S_0$  at infinity:

$$d = 2 \max_{t \in [0, 1]} \left( \sup_{\mathbb{S}^1} |\gamma_t| \right),$$

and consider  $\beta = e^{d+1}$ . As discussed in the beginning of Section 4, there exists a rotational immersed annulus  $A_\beta$  which is at signed distance  $-\log \beta = -d - 1$  from  $S_0$  at infinity. It means that, at infinity, the hyperbolic distance between  $A_\beta$  and any  $X_t$  is greater than 1 and that the end of each  $X_t$  is contained in the mean-convex side of  $A_\beta$ . Up to a vertical translation (which preserves the behavior at infinity), we can suppose  $A_\beta \cap (\mathbb{H}^2 \times \mathbb{R}_+^*)$  is embedded and  $X_0$  is strictly contained in the mean-convex side of  $A_\beta$ . We use  $A_\beta$  as an exterior barrier and we only have to prove that  $X_t$  is completely included in the mean-convex side of  $A_\beta$  for all  $t \in [0, 1)$  to ensure the existence of  $X_1$ .

For small values of  $t$ ,  $X_t$  is strictly included in the mean-convex side of  $A_\beta$ , since the process is smooth. Acting by contradiction, suppose there exist a first value  $t_0 \in (0, 1)$  for which the hyperbolic distance between  $X_{t_0}$  and  $A_\beta$  is zero. By construction of  $A_\beta$ , the contact is not at infinity, so that we can apply the maximum principle to  $A_\beta$  and  $X_{t_0}$ , which is absurd.  $\square$

### 3.3 Applications

A direct consequence of Proposition 3.8 is the global structure of  $\mathcal{G}$ :

**Theorem 3.9.** *The family  $\mathcal{G}$  can be endowed with a structure of infinite dimensional smooth manifold modeled on the space  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1) \times \mathbb{R}$ .*

*Proof.* It is sufficient to show that for any surface  $S \in \mathcal{G}$  with graph coordinates at infinity  $X^a$ , a local chart around  $S$  is given by the map  $S' \in \mathcal{V}_a \mapsto (\gamma, \lambda) \in \mathcal{U}_a$  where  $\{\gamma, \lambda\}$  are the data of  $S'$  with respect to  $a$ . This fact is a direct consequence from identities (7).  $\square$

A. E. Treibergs showed (see [9]) that given a  $\mathcal{C}^2$  curve — generalized to continuous curves by H. I. Choi and A. E. Treibergs in [1] —  $\gamma : \mathbb{S}^1 \rightarrow \mathbb{R}$ , there exists a CMC-1/2 complete entire vertical graph in the 3-dimensional Minkowski space which is asymptotically at signed distance  $\gamma$  from the light cone. Namely, it is the graph of a smooth function  $f : \mathbb{R}^2 \rightarrow \mathbb{R}$  such that:

$$f(x) = |x| + \gamma \left( \frac{x}{|x|} \right) + \varepsilon(x) \quad \text{with} \quad \lim_{|x| \rightarrow +\infty} \varepsilon(x) = 0.$$

The local structure of  $\mathcal{G}$  allows us to prove a  $\mathcal{C}^{2,\alpha}$  version of this result in  $\mathbb{H}^2 \times \mathbb{R}$ :

**Theorem 3.10.** *Let  $S$  be a surface in  $\mathcal{G}$  with graph coordinates at infinity  $X^a$  and  $\gamma \in \mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  be such that  $|e^{-\gamma}|_{L^2(\mathbb{S}^1)} = |e^{-\gamma^a}|_{L^2(\mathbb{S}^1)}$ . There exists a surface in  $\mathcal{G}$  with  $\gamma$  as value at infinity. In particular, if  $S = S_0$  there exists a CMC-1/2 complete entire vertical graph at asymptotic horizontal signed distance  $\gamma$  from  $S_0$ , for any  $\gamma \in \mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  with unit  $L^2(\mathbb{S}^1)$ -norm.*

*Proof.* Consider the path  $\gamma_t$  in  $\mathcal{C}^{2,\alpha}(\mathbb{S}^1)$  defined for  $0 \leq t \leq 1$  by:

$$\gamma_t = -\frac{1}{2} \log \left( (1-t)e^{-2\gamma^a} + te^{-2\gamma} \right),$$

and denote by  $\mathcal{T}$  the set of  $t \in [0, 1]$  for which  $\gamma_t$  is the value at infinity of a surface in  $\mathcal{G}$ . We know that  $\mathcal{T}$  is not empty, since  $0 \in \mathcal{T}$ . Using Proposition 3.8 and that  $|e^{-\gamma_t}|_{L^2(\mathbb{S}^1)} = |e^{-\gamma^a}|_{L^2(\mathbb{S}^1)}$  for any  $t$ , we see that  $\mathcal{T}$  is open and closed in  $[0, 1]$ , which implies  $1 \in \mathcal{T}$ .  $\square$

**Corollary 3.11.** *For any surface in  $\mathcal{G}$  with graph coordinates at infinity  $X^a$ , we have:*

$$\Gamma_a = \left\{ \gamma \in \mathcal{C}^{2,\alpha}(\mathbb{S}^1) \mid |e^{-\gamma}|_{L^2(\mathbb{S}^1)} = |e^{-\gamma^a}|_{L^2(\mathbb{S}^1)} \right\}.$$

## 4 Deformations of CMC-1/2 annuli

R. Sa Earp and E. Toubiana showed in [2] that — up to a not necessarily orientation preserving isometry of  $\mathbb{H}^2 \times \mathbb{R}$  — a rotational CMC-1/2 vertical annulus is a bigraph, symmetrical with respect to the slice  $\mathbb{H}^2 \times \{0\}$ . The upper graph part of such an annulus admits graph coordinates at infinity  $(F, h_\beta)$ , with  $\beta$  a positive real number,  $\beta \neq 1$  and  $h_\beta$  defined by:

$$h_\beta(r) = \int_{|\log \beta|}^{2 \log \left( \frac{1+r}{1-r} \right)} \frac{\cosh t - \beta}{\sqrt{2\beta \cosh t - 1 - \beta^2}} dt \quad \text{where} \quad r \geq \left| \frac{\sqrt{\beta} - 1}{\sqrt{\beta} + 1} \right| = R_\beta.$$

We denote by  $A_\beta$  this annulus, which is embedded if  $0 < \beta < 1$  and only immersed when  $\beta > 1$ .

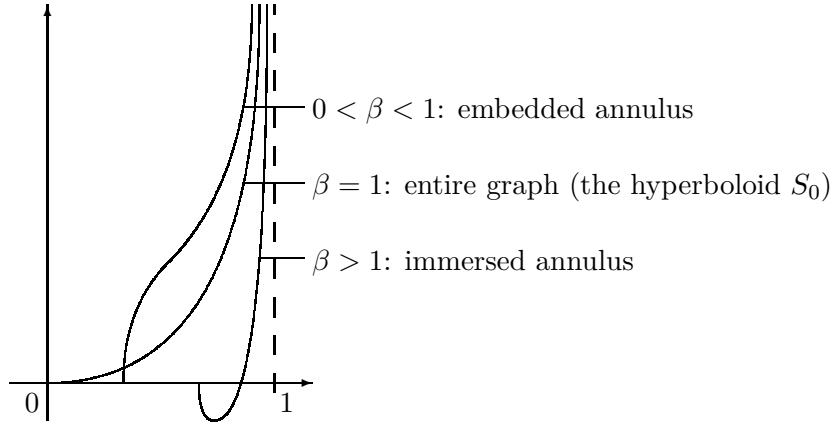


Figure 1: Profile curves of rotational CMC-1/2 examples in the Poincaré disk model (2)

We have the following asymptotic development as  $r \rightarrow 1$ :

$$h_\beta(r) = \frac{1}{\sqrt{\beta}} \frac{1+r}{1-r} + O(1), \quad (9)$$

which means that the restriction of  $(F, h_\beta)$  to the exterior domain  $\Omega_{R_\beta}$  is in  $\mathcal{E}$  with constant value  $-\log \beta$  at infinity. Therefore, the method developed in Section 3 should adapt to the study of deformations of these annuli.

For our purpose, we slightly change the notations. Fix  $\beta > 0$  with  $\beta \neq 1$ ; the annulus  $A_\beta$  is now the model surface. To deform rotational annuli, we need conformal coordinates to provide a compactification of the mean curvature. A conformal parametrization of the annulus  $A_\beta$ , written in cylindrical coordinates, is the following:

$$\begin{aligned} X^0 : (s, \theta) \in \Omega^\beta &\mapsto \left( F(r(s), \theta), \varepsilon(s) h_\beta(r(s)) \right) \quad \text{with} \quad \Omega^\beta = (-T, T) \times \mathbb{S}^1, \quad (10) \\ T &= \frac{4}{|\beta - 1|} \int_{R_\beta}^1 \frac{dt}{\sqrt{(t^2 - R_\beta^2)(R_\beta^{-2} - t^2)}}, \quad \varepsilon(s) = \text{sign}(s), \\ \frac{dr}{ds} &= \frac{|\beta - 1|}{4} \sqrt{(r^2(s) - R_\beta^2)(R_\beta^{-2} - r^2(s))} \quad \text{and} \quad r(0) = R_\beta. \end{aligned}$$

We also identify functions over  $A_\beta$  with functions over  $\Omega^\beta$ . The *cylindrical parametrization* of a deformed annulus is the following immersion:

$$X^\eta : (s, \theta) \in \Omega^\beta \mapsto \left( F(r(s), \theta), \varepsilon(s) e^{\eta(s, \theta)} h_\beta(r(s)) \right) \quad \text{with} \quad \eta \in \mathcal{C}^{2, \alpha}(\overline{\Omega^\beta}).$$

The determinant of the first fundamental form is  $|g(\eta)|$ , the mean curvature  $H(\eta)$  and the values at infinity are the couple  $(\eta(T, \cdot), \eta(-T, \cdot)) \in (\mathcal{C}^{2, \alpha}(\mathbb{S}^1))^2$ .

## 4.1 Non degeneracy of rotational annuli

As in Section 3, we need to understand the Jacobi functions in order to control the deformations. Thus, we focus the study on annuli in  $\mathcal{E}$  that are non degenerate in the following sense:

**Definition 4.1.** A surface in  $\mathcal{E}$  is said to be *non degenerate* if the only Jacobi functions that are zero at infinity on each end of the surface (i.e. when  $r = 1$  in the graph coordinates at infinity of the ends) come from isometries of  $\mathbb{H}^2 \times \mathbb{R}$ .

A direct consequence of the proof of Proposition 2.3 and the shape of the ends is that if an annulus in  $\mathcal{E}$  is non degenerate, then the space of Jacobi functions which are zero on the boundary is 1-dimensional, generated by the vertical component of the unit normal.

Another fact is that, since the rank of the Jacobi operator is locally constant, small deformations of a non degenerate annulus are still non degenerate.

Therefore, the method used in Section 3 can be strictly transposed to the study of deformations in a small neighborhood of a non degenerate example.

**Proposition 4.2.** *The annulus  $A_\beta$  is non degenerate for any value of  $\beta$  ( $\neq 1$ ).*

*Proof.* If  $L$  denotes the Jacobi operator of  $A_\beta$ , the compactified Jacobi operator  $\bar{L} = \sqrt{|g(0)|}L$  of  $A_\beta$  can be written  $\Delta + q(s)$  in the conformal parametrization (10), with  $\Delta$  the flat laplacian and  $q \in \mathcal{C}^0([-T, T])$ . Moreover,  $A_\beta$  being symmetric with respect to  $\mathbb{H}^2 \times \{0\}$ , the function  $q$  is even.

Since a Jacobi function is  $2\pi$ -periodic in  $\theta$ , using the Fourier decomposition, we reduce the problem to solving a family  $(D_n)$  of Dirichlet problems on  $\mathcal{C}^2([-T, T])$  for  $n \in \mathbb{N}$ :

$$\begin{cases} u'' + (q(s) - n^2)u = 0 \\ u(-T) = u(T) = 0 \end{cases} \quad (D_n)$$

We make two immediate observations:

- Considering a solution of  $(D_n)$  for any  $n \in \mathbb{N}$ , its odd and even parts are also solutions of  $(D_n)$ . Hence, we only have to consider odd and even solutions.
- The vertical component  $\varphi$  of the unit normal to  $A_\beta$  is an odd solution of  $(D_0)$  which does not vanish on  $(0, T)$ .

Let  $n \in \mathbb{N}$ . *An odd solution of  $(D_n)$  is proportional to  $\varphi$ .* Otherwise, using Sturm comparison theorem with  $q - n^2 \leq q$ ,  $\varphi$  should vanish once in  $(0, T)$ . *There is no even solution to  $(D_n)$ .* Suppose such a function exist. Using Sturm comparison theorem, this function vanishes nowhere in  $(-T, T)$ , which means  $n^2$  is the first eigenvalue of the elliptic operator:

$$\frac{d^2}{ds^2} + q(s),$$

which contradicts the existence of  $\varphi$ . □

## 4.2 Small deformations of annuli

Consider a  $\beta$ -deformable CMC-1/2 annulus  $A$  i.e. a surface such that:

- $A$  admits  $X^b$ , with  $b \in \mathcal{C}^{2,\alpha}(\bar{\Omega}^\beta)$ , as a cylindrical parametrization;
- $A$  is non degenerate;

- the values at infinity are the couple  $\gamma^b = (\gamma_+^b, \gamma_-^b) = b|_{\partial\Omega^\beta}$  satisfying the condition:

$$|e^{-\gamma_+^b}|_{L^2(\mathbb{S}^1)} = |e^{-\gamma_-^b}|_{L^2(\mathbb{S}^1)}.$$

Again, the vertical component  $\varphi^b$  of the unit normal to  $A$  reads:

$$\varphi^b = \varepsilon \frac{e^{-b}}{h_\beta(r)} \frac{1}{c^b} \quad \text{with} \quad c^b|_{\partial\Omega^\beta} = \frac{1}{2},$$

and we use a similar definition to Section 3 for the compactified mean curvature operator:

$$\overline{H} : \eta \in \mathcal{C}^{2,\alpha}(\overline{\Omega^\beta}) \mapsto \sqrt{|g(b)|} \left( H(b + 2c^b\eta) - \frac{1}{2} \right) \in \mathcal{C}^{0,\alpha}(\overline{\Omega^\beta}).$$

The compactified Jacobi operator is still  $\overline{L} = D\overline{H}(0)$ ,  $\overline{L}_0$  is its restriction to  $\mathcal{C}_0^{2,\alpha}(\overline{\Omega^\beta})$  and  $K, K^\perp, K_0^\perp$  are defined as before. The non degeneracy hypothesis on  $A$  means  $\overline{L}_0 = \mathbb{R}\varphi^b$ .

Again, define  $\mu_b : (\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2 \rightarrow \mathcal{C}^{2,\alpha}(\overline{\Omega^\beta})$  to be the harmonic function on  $\overline{\Omega^\beta}$  with values  $\gamma - \gamma^b$  on  $\partial\Omega^\beta$ .

The compactified Jacobi operator satisfies a Green identity similar to Lemma 3.2 for entire graphs:

**Lemma 4.3** (Green identity). *For any  $u, v \in \mathcal{C}^{2,\alpha}(\overline{\Omega^\beta})$ , the compactified Jacobi operator satisfies the following identity:*

$$\int_{\overline{\Omega^\beta}} (u\overline{L}v - v\overline{L}u) d\overline{A} = \sqrt{\beta} \int_0^{2\pi} e^{-\gamma_+^b} \left( u \frac{\partial v}{\partial s} - v \frac{\partial u}{\partial s} \right) \Big|_{s=T} d\theta - \sqrt{\beta} \int_0^{2\pi} e^{-\gamma_-^b} \left( u \frac{\partial v}{\partial s} - v \frac{\partial u}{\partial s} \right) \Big|_{s=-T} d\theta,$$

with  $d\overline{A}$  the Lebesgue measure on  $\overline{\Omega^\beta}$ .

And we also have the equivalent of Lemma 3.3:

**Lemma 4.4.** *There is no solution  $u \in \mathcal{C}^{2,\alpha}(\overline{\Omega^\beta})$  to the equation:*

$$\begin{cases} \overline{L}u = 0 & \text{on } \overline{\Omega^\beta} \\ u|_{\partial\Omega^\beta} = (1, -1) \end{cases}.$$

Let  $\Pi_K$  and  $\Pi_{K^\perp}$  be defined as in Section 3.1. Lemma 3.4) still holds:

**Lemma 4.5.** *Consider the map  $\Phi : (\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2 \times \mathbb{R} \times K_0^\perp \rightarrow K^\perp$  defined by:*

$$\Phi(\gamma, \lambda, \sigma) = \Pi_{K^\perp} \circ \overline{H}(\mu_b(\gamma) + \lambda\varphi^b + \sigma).$$

*Then  $D_3\Phi(\gamma^b, 0, 0) : K_0^\perp \rightarrow K^\perp$  is an isomorphism.*

We can apply again the implicit function theorem to  $\Phi$ , which states that there exist a neighborhood  $U_b$  of  $(\gamma^b, 0)$  in  $(\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2 \times \mathbb{R}$  and a unique smooth map  $\sigma : U_b \rightarrow K_0^\perp$  such that:

$$\forall (\gamma, \lambda) \in U_b, \quad \Phi(\gamma, \lambda, \sigma(\gamma, \lambda)) = 0.$$

We define similarly the maps  $\eta_b : U_b \rightarrow \mathcal{C}^{2,\alpha}(\overline{\Omega^\beta})$  and  $\kappa_b : U_b \rightarrow K$  by:

$$\eta_b(\gamma, \lambda) = b + 2c^b(\mu_b(\gamma) + \lambda\varphi^b + \sigma(\gamma, \lambda)) \quad \text{and} \quad \kappa_b(\gamma, \lambda) = \Pi_K \circ \overline{H}(\mu_b(\gamma) + \lambda\varphi^b + \sigma(\gamma, \lambda)).$$

Also, if an annulus, defined on  $\Omega^\beta$ , admits  $X^{\eta_b(\gamma, \lambda)}$  as a parametrization, we say that  $\{\gamma, \lambda\}$  are the *data* of the annulus with respect to  $A$  or to  $b$ .

Properties of  $\eta_b$  are similar to those of  $\eta_a$  in Section 3.1:



**Lemma 4.6.** *The map  $\eta_b$  has the following properties:*

1.  $\eta_b(\gamma^b, 0) = b$ .
2.  $\forall (\gamma, \lambda) \in U_b, \eta_b(\gamma, \lambda)|_{\partial\Omega^\beta} = \gamma$ .
3.  $D_2\eta_b(\gamma^b, 0) : \lambda \in \mathbb{R} \mapsto 2\lambda c^b \varphi^b \in \mathcal{C}^{2,\alpha}(\overline{\Omega^\beta})$ .

Let  $A'$  be a  $\beta$ -deformable annulus with cylindrical parametrization  $X^{b'}$ , and suppose there exist an annulus with data  $\{\gamma, \lambda\}$  and  $\{\gamma', \lambda'\}$  with respect to  $A$  and  $A'$  respectively. Therefore, this surface can be described as  $X^{\eta_b(\gamma, \lambda)}$  and  $X^{\eta_{b'}(\gamma', \lambda')}$  and we get:

$$\gamma' = \gamma \quad \text{and} \quad \lambda' = \frac{1}{|\varphi^{b'}|_{L^2(\Omega^\beta)}^2} \left\langle \frac{\eta_b(\gamma, \lambda) - b'}{2c^{b'}} - \mu_{b'}(\gamma), \varphi^{b'} \right\rangle_{L^2(\Omega^\beta)}.$$

Lemma 4.6 Point 2 shows that the values at infinity are still independent from the parameter  $\lambda$ . The reason is the same as before:

**Proposition 4.7.** *Let  $(\gamma, \lambda) \in U_b$ . The surface  $X^{\eta_b(\gamma, \lambda)}$  exists for any  $\lambda' \in \mathbb{R}$  and coincides with  $X^{\eta_b(\gamma, \lambda)}$  up to a vertical translation.*

We are now interested in deformations  $X^{\eta_b(\gamma, \lambda)}$  of  $A$  that are CMC-1/2, which means deformations such that  $\kappa_b(\gamma, \lambda) = 0$ . We consider  $\mathcal{U}_b = \kappa_b^{-1}(\{0\}) \cap U_b$  and  $\mathcal{V}_b \subset \mathcal{E}$  the set of annuli admitting data in  $\mathcal{U}_b$ . Using Proposition 4.7, we know there exists a subset  $\Gamma_b \subset (\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2$  such that  $\mathcal{U}_b = \Gamma_b \times \mathbb{R}$ .

**Proposition 4.8.**  $\Gamma_b$  is a real-analytic codimension 1 submanifold of  $(\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2$  which is a subset of:

$$\left\{ (\gamma_+, \gamma_-) \in (\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2 \mid |e^{-\gamma_+}|_{L^2(\mathbb{S}^1)} = |e^{-\gamma_-}|_{L^2(\mathbb{S}^1)} \right\}.$$

*Proof.* By construction,  $\Gamma_b$  is a smooth submanifold of  $(\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2$  and we know that its codimension is the rank of  $D\kappa_b(\gamma^b, 0)$ . Again  $D_2\kappa_b(\gamma^b, 0) = 0$  since:

$$D_2\kappa_b(\gamma^b, 0) \cdot 1 = \frac{d}{dt} \Big|_{t=0} \kappa_b(\gamma^b, t) = \Pi_K \circ \bar{L} \left( \frac{1}{2c^b} D_2\eta_b(\gamma^b, 0) \cdot 1 \right) = \Pi_K \circ \bar{L}_0(\varphi^b) = 0,$$

with  $\varphi^b \in K$ . Thus the rank of  $D\kappa_b(\gamma^b, 0)$  is the rank of  $D_1\kappa_b(\gamma^b, 0)$ . Consider a couple  $\gamma = (1, -1) \in (\mathcal{C}^{2,\alpha}(\mathbb{S}^1))^2$  and compute:

$$D_1\kappa_b(\gamma^b, 0) \cdot \gamma = \frac{d}{dt} \Big|_{t=0} \kappa_b((t, -t), 0) = \Pi_K \circ \bar{L}u = \bar{L}u \quad \text{with} \quad u = \frac{1}{2c^b} D_1\eta_b(\gamma^b, 0) \cdot (1, -1).$$

Lemma 4.6 Point 2 shows  $u|_{\partial\mathbb{D}} = (1, -1)$ . Using Lemma 4.4, we know that  $D_1\kappa_b(\gamma^b, 0) \cdot (1, -1)$  is not identically zero, and  $1 \leq \text{rank } D_1\kappa_b(\gamma^b, 0) \leq \dim K = 1$ .

Consider a smooth path  $\gamma_t = ((\gamma_+)_t, (\gamma_-)_t)$  in  $\Gamma_b$  with  $\gamma_0 = \gamma^b$  and tangent vector at  $t$   $\dot{\gamma}_t = ((\dot{\gamma}_+)_t, (\dot{\gamma}_-)_t)$ . Note that:

$$0 = D\kappa_b(\gamma^b, 0) \cdot (\dot{\gamma}_0, 0) = \frac{d}{dt} \Big|_{t=0} \kappa_b(\gamma_t, 0) = \Pi_K \circ \bar{L}v = \bar{L}v \quad \text{with} \quad v = \frac{1}{2c^b} D\eta_b(\gamma^b, 0) \cdot (\dot{\gamma}_0, 0).$$

Knowing that:

$$\begin{aligned} \varphi^b|_{s=T} = \varphi^b|_{s=-T} = 0, \quad \frac{\partial \varphi^b}{\partial s} \Big|_{s=T} &= -e^{-\gamma_+^b}, \quad \frac{\partial \varphi^b}{\partial s} \Big|_{s=-T} = -e^{-\gamma_-^b}, \\ v|_{s=T} = (\dot{\gamma}_+)_0 \quad \text{and} \quad v|_{s=-T} &= (\dot{\gamma}_-)_0, \end{aligned}$$

apply Lemma 4.3 to  $\varphi^b$  and  $v$ :

$$\begin{aligned} 0 &= \int_{\Omega^\beta} (\varphi^b \bar{L}v - v \bar{L}\varphi^b) d\bar{A} = \sqrt{\beta} \int_0^{2\pi} (\dot{\gamma}_+)_0 e^{-2\gamma_+^b} d\theta - \sqrt{\beta} \int_0^{2\pi} (\dot{\gamma}_-)_0 e^{-2\gamma_-^b} d\theta \\ &= 2\pi\sqrt{\beta} \left( \left\langle (\dot{\gamma}_+)_0, e^{-2\gamma_+^b} \right\rangle_{L^2(\mathbb{S}^1)} - \left\langle (\dot{\gamma}_-)_0, e^{-2\gamma_-^b} \right\rangle_{L^2(\mathbb{S}^1)} \right). \end{aligned} \quad (11)$$

For a fixed  $t$ , consider the reparametrized path  $\gamma'_s = \gamma_{s+t}$  and denote  $b' = \eta_b(\gamma_t, 0)$ . There exists  $\varepsilon > 0$  such that  $\gamma'_s \in \Gamma_{b'}$  for any  $|s| < \varepsilon$ . Hence, the path of surfaces  $X^{\eta_b(\gamma'_s, 0)}$  can be described by a path of data  $\{\gamma'_s, \lambda'_s\}$  in  $\mathcal{U}_{b'}$ ,  $|s| < \varepsilon$ , with  $\lambda'_0 = 0$  and tangent vector  $\dot{\gamma}'_0 = \dot{\gamma}_t$  at  $s = 0$ . The result (8) applies to  $(\gamma'_s, \lambda'_s)$  i.e.:

$$\frac{d}{dt} \left( |e^{-(\gamma_+)_t}|_{L^2(\mathbb{S}^1)}^2 - |e^{-(\gamma_-)_t}|_{L^2(\mathbb{S}^1)}^2 \right) = \left\langle (\dot{\gamma}_+)_t, e^{-2(\gamma_+)_t} \right\rangle_{L^2(\mathbb{S}^1)} - \left\langle (\dot{\gamma}_-)_t, e^{-2(\gamma_-)_t} \right\rangle_{L^2(\mathbb{S}^1)} = 0,$$

for any  $t$ , and thus:

$$|e^{-(\gamma_+)_t}|_{L^2(\mathbb{S}^1)}^2 - |e^{-(\gamma_-)_t}|_{L^2(\mathbb{S}^1)}^2 = |e^{-\gamma_+^b}|_{L^2(\mathbb{S}^1)}^2 - |e^{-\gamma_-^b}|_{L^2(\mathbb{S}^1)}^2 = 0,$$

since the annulus  $A$  is  $\beta$ -deformable.  $\square$

The condition on the values at infinity defining  $\Gamma_b$  is indeed the conservation of the vertical flux in the deformed annuli.

### 4.3 Annuli with non aligned ends

For minimal surfaces in  $\mathbb{R}^3$ , one can define two Noether vector-invariants associated to isometries, namely the flux — associated to translations — and the torque — associated to rotations. In the case of a minimal catenoidal end with growth  $\alpha > 0$  and vertical axis  $\{x_1 = u, x_2 = v\}$ , the flux and the torque are respectively  $(0, 0, 2\pi\alpha)$  and  $2\pi\alpha(v, -u, 0)$ . In other words, the growth and the position of the axis of the end are determined by the vertical component of the flux and horizontal components of the torque.

In  $\mathbb{H}^2 \times \mathbb{R}$ , Noether invariants are constructed similarly but the torque is not a vector anymore, since remain only rotations around vertical axis. In the case of a vertical rotational end with parameter  $\beta > 0$ , the flux is vertical with third component  $\beta$  and the torque is always zero, no matter where the rotation axis is situated. The fact the position of the axis is no longer caught by Noether invariants, indicates that the construction of CMC-1/2 annuli with vertical ends should be more flexible regarding the relative positions of the axis of the ends.

**Theorem 4.9.** *There exist CMC-1/2 annuli in  $\mathbb{H}^2 \times \mathbb{R}$  with vertical ends, that are asymptotic — regarding the horizontal hyperbolic distance — to rotational examples with different vertical axis.*

*Proof.* Fix  $\beta > 0$ ,  $\beta \neq 1$ . From Proposition 2.3, we know that, in the Poincaré disk model (2), a horizontal translation of  $w_0 = \varepsilon e^{i\theta_0} \in \mathbb{D}^*$  changes the top value at infinity of the rotational annulus  $A_\beta$  into:

$$\gamma(\theta) = \log \left( \frac{|1 - \varepsilon e^{i(\theta - \theta_0)}|}{\sqrt{1 - \varepsilon^2}} \right).$$

A direct computation shows that  $|e^{-\gamma}|_{L^2(\mathbb{S}^1)} = 1$ . Thus, for  $\varepsilon$  sufficiently small the CMC-1/2 annulus  $X^{\eta_0((\gamma, 0), 0)}$  exists.  $\square$

## 5 Appendix: Compactification of the mean curvature

Consider the product metric  $\sigma + dx_3^2$  on  $\mathbb{D} \times \mathbb{R}$  where:

$$\sigma = F^* ds_P^2 \quad \text{and} \quad F : (r, \theta) \in \mathbb{D} \mapsto \frac{2r}{1+r^2} e^{i\theta} \in \mathbb{H}^2,$$

in the Poincaré disk model (2). To ease the notations, we use indices 1, 2 for quantities respectively related to coordinates  $r, \theta$  on  $\mathbb{D}$ . In matrix terms, the metric is  $\sigma = (\sigma_{ij})$  with:

$$\sigma_{11} = \frac{16}{(1-r^2)^2}, \quad \sigma_{12} = \sigma_{21} = 0, \quad \sigma_{22} = \frac{16r^2(1+r^2)^2}{(1-r^2)^4} \quad \text{and} \quad |\sigma| = \left( \frac{16r(1+r^2)}{(1-r^2)^3} \right)^2.$$

The Christoffel symbols  $(\Gamma_{ij}^k)$  associated to  $\sigma$  for the Levi-Civita connection verify:

$$\Gamma_{ij}^k = \frac{1}{2} \sum_m \sigma^{kl} (\partial_i \sigma_{jm} + \partial_j \sigma_{im} - \partial_m \sigma_{ij}),$$

which means:

$$\begin{aligned} \Gamma_{11}^1 &= \frac{2r}{1-r^2}, & \Gamma_{12}^2 &= \frac{4r}{1-r^2} \left( 1 + \frac{1+3r^2}{4r^2(1+r^2)}(1-r^2) \right) \\ \text{and} \quad \Gamma_{22}^1 &= -\frac{4r^3(1+r^2)^2}{(1-r^2)^3} \left( 1 + \frac{1+3r^2}{4r^2(1+r^2)}(1-r^2) \right), \end{aligned}$$

the other terms being zero.

Fix  $\Omega \in \mathcal{D}$ . A surface in  $S \in \mathcal{E}$  defined on  $\Omega$  with graph coordinates at infinity:

$$(r, \theta) \in \Omega \mapsto (F(r, \theta), h(\eta)) \quad \text{with} \quad \eta \in \mathcal{C}^{2,\alpha}(\overline{\Omega}) \quad \text{and} \quad h(\eta) = 2e^\eta \frac{1+r^2}{1-r^2},$$

can be reparametrized as the actual graph of the function  $h(\eta) : \Omega \rightarrow \mathbb{R}$  in  $\mathbb{D} \times \mathbb{R}$  endowed with metric  $\sigma + dx_3^2$ . As shown by J. Spruck [8], the metric  $g(\eta) = (g_{ij}(\eta))$  induced by  $h(\eta)$  is given by:

$$g_{ij}(\eta) = \sigma_{ij} + \partial_i h(\eta) \partial_j h(\eta),$$

and denoting  $\eta_i = \partial_i \eta$ , for  $i = 1, 2$ , we obtain:

$$\begin{aligned} g_{11}(\eta) &= \frac{64r^2 e^{2\eta}}{(1-r^2)^4} \left[ 1 + \frac{1+r^2}{2r} \eta_1 (1-r^2) + \frac{(1+r^2)^2}{16r^2} \left( \eta_1^2 + \frac{4e^{-2\eta}}{(1+r^2)^2} \right) (1-r^2)^2 \right], \\ g_{12}(\eta) &= \frac{16r(1+r^2)e^{2\eta}}{(1-r^2)^3} \eta_2 \left[ 1 + \frac{1+r^2}{4r} \eta_1 (1-r^2) \right] \\ \text{and} \quad g_{22}(\eta) &= \frac{16r^2(1+r^2)^2 e^{2\eta}}{(1-r^2)^4} \left[ e^{-2\eta} + \frac{\eta_2^2}{4r^2} (1-r^2)^2 \right]. \end{aligned}$$

The determinant  $|g(\eta)|$  of the induced metric is:

$$|g(\eta)| = \left( \frac{32r^2(1+r^2)e^\eta}{(1-r^2)^4} \right)^2 w^2(\eta)$$

with  $w(\eta)$  denoting:

$$w(\eta) = \left[ 1 + \frac{1+r^2}{2r} \eta_1 (1-r^2) + \frac{(1+r^2)^2}{16r^2} \left( \eta_1^2 + \frac{4e^{-2\eta}}{(1+r^2)^2} \right) (1-r^2)^2 + \frac{\eta_2^2}{16r^4} (1-r^2)^4 \right]^{1/2}.$$

In the metric  $\sigma + dx_3^2$ , the mean curvature  $H(\eta)$  of  $S$  can be expressed as:

$$H(\eta) = \frac{1}{2} \operatorname{div}_\sigma \left( \frac{\nabla_\sigma h(\eta)}{W(\eta)} \right) = \frac{1}{2W(\eta)} \sum_{i,j} g^{ij}(\eta) \left( \partial_{ij} h(\eta) - \sum_k \Gamma_{ij}^k \partial_k h(\eta) \right)$$

with  $W(\eta) = \sqrt{1 + |\nabla_\sigma h(\eta)|_\sigma^2} = \frac{2re^\eta}{1-r^2} w(\eta)$ ,

where the quantities are computed with respect to the metric  $\sigma$  on  $\mathbb{D}$ , and  $g^{-1}(\eta) = (g^{ij}(\eta))$ .

In order to ease the notations, denote:

$$H_{ij}(\eta) = g^{ij}(\eta) \left( \partial_{ij} h(\eta) - \sum_k \Gamma_{ij}^k \partial_k h(\eta) \right).$$

Taking  $\eta = a + \xi$  with  $a, \xi \in \mathcal{C}^{2,\alpha}(\overline{\Omega})$ , we express the Taylor expansions of  $H_{ij}(a + \xi)$ . For  $H_{11}(a + \xi)$ , compute:

$$\begin{aligned} e^{-(a+\xi)} H_{11}(a + \xi) &= e^{-(a+\xi)} g^{11}(a + \xi) \left( \partial_{11} h(\eta) - \Gamma_{11}^1 \partial_1 h(\eta) \right) \\ &= \frac{e^{-a} w^2(a)}{w^2(a + \xi)} H_{11}(a) + \frac{(1+r^2)(1-r^2)}{8r^2 w^2(a + \xi)} \left( e^{-2a} (e^{-2\xi} - 1) + \frac{r}{1+r^2} \xi_1 (1-r^2) \right. \\ &\quad \left. + R_{11} (1-r^2)^2 \right) + \frac{2(1+r^2)}{1-r^2} g^{11}(a + \xi) \xi_{11}, \end{aligned}$$

with  $R_{11} = R_{11}(r, \theta, a, \xi, D\xi)$  defined on  $\Omega \cup \partial\mathbb{D}$ , identically zero if  $\xi = 0$  and real-analytic in its variables. For  $H_{12}(a + \xi)$ :

$$\begin{aligned} e^{-(a+\xi)} H_{12}(a + \xi) &= e^{-(a+\xi)} g^{12}(a + \xi) \left( \partial_{12} h(a + \xi) - \Gamma_{12}^2 \partial_2 h(a + \xi) \right) \\ &= \frac{e^{-a} w^2(a)}{w^2(a + \xi)} H_{12}(a) + R_{12} (1-r^2)^3 + \frac{2(1+r^2)}{1-r^2} g^{12}(a + \xi) \xi_{12}, \end{aligned}$$

again with  $R_{12} = R_{12}(r, \theta, a, \xi, D\xi)$  defined on  $\Omega \cup \partial\mathbb{D}$ , zero if  $\xi = 0$  and real-analytic in its variables. And for  $H_{22}(a + \xi)$ :

$$\begin{aligned} e^{-(a+\xi)} H_{22}(a + \xi) &= e^{-(a+\xi)} g^{22}(a + \xi) \left( \partial_{22} h(a + \xi) - \Gamma_{22}^1 \partial_1 h(a + \xi) \right) \\ &= \frac{e^{-a} w^2(a)}{w^2(a + \xi)} H_{22}(a) + \frac{1+r^2}{2rw^2(a + \xi)} \left\{ 2\xi_1 + \frac{1+r^2}{4r} \left[ 3\xi_1^2 + 3 \left( 2a_1 \right. \right. \right. \\ &\quad \left. \left. \left. + \frac{1+3r^2}{r(1+r^2)^2} \right) \xi_1 + \frac{4e^{-2a}}{(1+r^2)^2} (e^{-2\xi} - 1) \right] (1-r^2) + \frac{(1+r^2)^2}{16r^2} \left[ \xi_1^3 + 3 \left( a_1 \right. \right. \right. \\ &\quad \left. \left. \left. + \frac{1+3r^2}{r(1+r^2)^2} \right) \xi_1^2 + \left( 3a_1^2 + \frac{6(1+3r^2)}{r(1+r^2)^2} a_1 + \frac{4e^{-2a}}{(1+r^2)^2} e^{-2\xi} \right) \xi_1 \right. \right. \\ &\quad \left. \left. + \frac{4e^{-2a}}{(1+r^2)^2} \left( a_1 + \frac{1+3r^2}{r(1+r^2)^2} \right) (e^{-2\xi} - 1) \right] (1-r^2)^2 + R_{22} (1-r^2)^3 \right\} \\ &\quad + \frac{2(1+r^2)}{1-r^2} g^{22}(a + \xi) \xi_{22}, \end{aligned}$$

with  $R_{22} = R_{22}(r, \theta, a, \xi, D\xi)$  defined on  $\Omega \cup \partial\mathbb{D}$ , zero if  $\xi = 0$  and real-analytic in its variables.

Therefore, a Taylor expansion of the mean curvature  $H(a + \xi)$  is:

$$\begin{aligned}
H(a + \xi) &= \frac{w^3(a)}{w^3(a + \xi)} H(a) + \sum_{i,j} \frac{(1+r^2)g^{ij}(a + \xi)}{2rw(a + \xi)} \xi_{ij} + \frac{(1+r^2)(1-r^2)}{8r^2w^3(a + \xi)} \left\{ 2\xi_1 + \frac{1+r^2}{4r} \left[ 3\xi_1^2 \right. \right. \\
&+ 3 \left( 2a_1 + \frac{1+3r^2}{r(1+r^2)^2} \right) \xi_1 + \left. \left. \frac{(5+r^2)e^{-2a}}{(1+r^2)^2} (e^{-2\xi} - 1) \right] (1-r^2) + \frac{(1+r^2)^2}{16r^2} \left[ \xi_1^3 \right. \right. \\
&+ 3 \left( a_1 + \frac{1+3r^2}{r(1+r^2)^2} \right) \xi_1^2 + \left. \left. \left( 3a_1^2 + \frac{6(1+3r^2)}{r(1+r^2)^2} a_1 + \frac{4e^{-2a}}{(1+r^2)^2} e^{-2\xi} + \frac{4r^2}{(1+r^2)^3} \right) \xi_1 \right. \right. \\
&+ \left. \left. \frac{4e^{-2a}}{(1+r^2)^2} \left( a_1 + \frac{1+3r^2}{r(1+r^2)^2} \right) (e^{-2\xi} - 1) \right] (1-r^2)^2 \right\} + R_H(1-r^2)^4,
\end{aligned}$$

with as before  $R_H = R_H(r, \theta, a, \xi, D\xi)$  defined on  $\Omega \cup \partial\mathbb{D}$ , identically zero if  $\xi = 0$  and real-analytic in its variables.

The Taylor expansion of  $w^{-3}(a + \xi)$  is the following:

$$\begin{aligned}
\frac{1}{w^3(a + \xi)} &= \frac{1}{w^3(a)} \left\{ 1 - \frac{3(1+r^2)}{4rw^2(a)} \xi_1(1-r^2) + \frac{3(1+r^2)^2}{16r^2w^4(a)} \left[ 2\xi_1^2 - a_1\xi_1 \right. \right. \\
&- \left. \left. \frac{2e^{-2a}}{(1+r^2)^2} (e^{-2\xi} - 1) \right] (1-r^2)^2 - \frac{(1+r^2)^3}{32r^3w^6(a)} \left[ 5\xi_1^3 - 6a_1\xi_1^2 + 3 \left( a_1^2 \right. \right. \right. \\
&- \left. \left. \frac{5e^{-2a}}{(1+r^2)^2} (e^{-2\xi} - 1) \right) \xi_1 + \frac{6e^{-2a}}{(1+r^2)^2} a_1(e^{-2\xi} - 1) \right] (1-r^2)^3 \right\} + R_w(1-r^2)^4,
\end{aligned}$$

with  $R_w = R_w(r, \theta, a, \xi, D\xi)$  defined on  $\Omega \cup \partial\mathbb{D}$ , zero if  $\xi = 0$  and real-analytic in its variables. Finally, we obtain:

$$\begin{aligned}
H(a + \xi) &= H(a) + \frac{1}{\sqrt{|g(a)|}} \sum_{i,j} A_{ij} \xi_{ij} + \frac{1}{\sqrt{|g(a)|}} B, \\
\text{with } A_{11} &= \frac{(1+r^2)}{2rw(a + \xi)} \sqrt{|g(a)|} g^{11}(a + \xi) = \frac{(1+r^2)}{2rw(a + \xi)} \frac{g_{22}(a + \xi)}{\sqrt{|g(a)|}} = e^{-a} + O(1-r^2), \\
A_{12} &= \frac{(1+r^2)}{2rw(a + \xi)} \sqrt{|g(a)|} g^{12}(a + \xi) = -\frac{(1+r^2)}{2rw(a + \xi)} \frac{g_{12}(a + \xi)}{\sqrt{|g(a)|}} = O(1-r^2) \\
\text{and } A_{22} &= \frac{(1+r^2)}{2rw(a + \xi)} \sqrt{|g(a)|} g^{22}(a + \xi) = \frac{(1+r^2)}{2rw(a + \xi)} \frac{g_{11}(a + \xi)}{\sqrt{|g(a)|}} = e^a + O(1-r^2).
\end{aligned}$$

Moreover  $A_{ij} = A_{ij}(r, \theta, a, \xi, D\xi)$  and  $B = B(r, \theta, a, \xi, D\xi)$  are defined on  $\Omega \cup \partial\mathbb{D}$  and real-analytic in their variables, the matrix  $A = (A_{ij})$  is coercive on  $\Omega \cup \partial\mathbb{D}$ , and  $B$  is identically zero if  $\xi = 0$ .

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