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NEW STABILITY RESULTS FOR SPHERES AND THE WULFF SHAPES

JULIEN ROTH

ABSTRACT. We prove that a closed convex hypersurface of a Euclidean space with almost constant anisotropic first and second mean curvatures in the L^p -sense is $W^{2,p}$ -close (up to rescaling and translations) to the Wulff shape. We also obtain characterizations of geodesic hypersphere of space forms improving those of [7] and [8].

1. INTRODUCTION

Let $F : \mathbb{S}^n \rightarrow \mathbb{R}^{n+1}$ be a smooth function satisfying the following convexity assumption

$$(1) \quad A_F = (\nabla dF + F \text{Id}_{|T_x \mathbb{S}^n})_x > 0,$$

for all $x \in \mathbb{S}^n$, where ∇dF is the Hessian of F . Here, > 0 mean positive definite in the sense of quadratic forms. Now, we consider the following map

$$\begin{aligned} \phi : \mathbb{S}^n &\longrightarrow \mathbb{R}^{n+1} \\ x &\longmapsto F(x)x + (\text{grad}_{|\mathbb{S}^n} F)_x \end{aligned}$$

The image $\mathcal{W}_F = \phi(\mathbb{S}^n)$ is called the Wulff shape of F and is a smooth hypersurface of \mathbb{R}^{n+1} . Moreover, by the condition (8), \mathcal{W}_F is convex. Note that if $F = 1$, the the Wulff shape is the sphere \mathbb{S}^n . Now, let (M^n, g) be a n -dimensional compact, connected, oriented manifold without boundary, isometrically immersed into by X into \mathbb{R}^{n+1} . We denote by ν a normal unit vector field globally defined on M , that is, we have $\nu : M \rightarrow \mathbb{S}^n$. We set $S_F = A_F \circ d\nu$, where A_F is defined in (1). S_F is called the F -Weingarten operator or anisotropic shape operator, and we can defined in this anisotropic setting all the corresponding extrinsic quantities like anisotropic principal curvatures and anisotropic mean curvature and higher order mean curvature (see the preliminaries section for the precise definitions).

In the isotropic context, geodesic hyperspheres in Euclidean spaces can be characterized among closed hypersurfaces by various properties. In particular, it is well known that geodesic hyperspheres are the only totally umbilical closed connected hypersurfaces in Euclidean spaces. The question of the stability of this characterization has been intensively studied in the last years by many authors (see [1, 3, 6, 7, 8, 9, 10] and references therein for instance). In the anisotropic setting, the so-called Wulff shape plays the role of geodesic spheres and can be characterized by similar results (see [4, 5] for instance). Analogously to spheres, the Wulff shape is, up to homotheties, the only closed convex hypersurfaces with vanishing traceless anisotropic second fundamental form. Very recently, De Rosa and Giofrè

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[2] studied the stability of this characterization. Namely, they proved that if the traceless part of the anisotropic second fundamental form is sufficiently small, then the hypersurface is closed to the Wulff shape. The aim of the present note is first to obtain a new stability result concerning the Wulff shape. Namely, we prove the following stability result.

Theorem 1.1. *Let $n \geq 2$ an integer, $F : \mathbb{S}^n \rightarrow \mathbb{R}$ be a smooth function satisfying the convexity assumption (8), $h > 0$, $p > 1$ and $R > 0$. Let M a closed and oriented hypersurface pf \mathbb{R}^{n+1} bounding a convex domain. Assume that $\text{Vol}(M) = \text{Vol}(\mathcal{W}_F)$ and that the extrinsic radius of M is smaller than R . Then, there exists $\varepsilon_0(n, p, h, R, F) > 0$ such that if for $\varepsilon \leq \varepsilon_0$, we have*

- $\|H^F - h\|_p < \varepsilon h$ and
- $\|H_2^F - h_2\|_p < \varepsilon h^2$ for a constant h_2 ,

then M is closed to the Wulff shape in the following sense : there exists a smooth parametrisation $\psi : \mathcal{W}_F \rightarrow M$, a vector $c_0 \in \mathbb{R}^{n+1}$ and a constant K depending on n, p, h, R and F so that

$$\|\psi - \text{Id} - c_0\|_{W^{2,p}(\mathcal{W})} \leq K\varepsilon^{\frac{p}{2}}.$$

Remark 1.2. • Here $\text{Vol}(M)$ is the volume of M for the induced metric g .

- We recall that the extrinsic radius of M is the radius of the smallest closed ball in \mathbb{R}^{n+1} containing M .
- Note that the right-hand sides in both pinching conditions of the theorem are respectively $h\varepsilon$ and $h^2\varepsilon$ for some homogeneity reasons, since for the Wulff shape, we have $H_2^F = (H^F)^2$. Equivalently, they can be replaced by $\frac{\varepsilon}{R}$ and $\frac{\varepsilon}{R^2}$.

This result is a generalization in the anisotropic context of the main result of [7], but not only since the hypothesis are that both first and second anisotropic mean curvatures are close to constants for the L^p -norm. We can also improve the results of [7] for space forms in the same way and obtain new characterizations of geodesic hyperspheres under weaker assumptions. Namely we prove the following result.

Theorem 1.3. *Let $n \geq 2$ an integer, $h > 0$, $p > n$ and $R > 0$. Assume that $\text{Vol}(M) = \text{Vol}(\mathbb{S}^2)$ and that the extrinsic radius of M is smaller than R . If $\delta > 0$, assume moreover that M is contained in an open hemisphere. Then, there exist $\varepsilon_0(n, p, h, R) > 0$, $C(n, p, h, R)$ and $\beta(n, p) \leq 1$ such that if for $\varepsilon \leq \varepsilon_0$, we have*

- $\|H - h\|_p < \varepsilon h$ and
- $\|H_2 - h_2\|_p < \varepsilon h^2$ for a constant h_2 ,

then M is diffeomorphic and $K\varepsilon^\beta$ -close to a geodesic hypersphere of radius $\frac{1}{\|H\|_2}$.

Remark 1.4. • For more convenience, we wrote the above theorem with H_2 , but due to the twice traced Gauss, formula, we have $n(n-1)H_2 + \delta = \text{Scal}$, we can reformulate equivalently the theorem with almost constant scalar curvature.

- Note that considering L^p -norms instead of pointwise almost proximity to constant is not the only improvement. Indeed, in the case where $\delta > 0$, we need that M is contained in an open hemisphere that is a geodesic ball of radius $\frac{\pi}{2\sqrt{\delta}}$ whereas in [7], the assumption was that M is contained in a geodesic ball of radius $\frac{\pi}{4\sqrt{\delta}}$.

From the following theorem, we can obtain new characterizations of geodesic hypersphere.

Corollary 1.5. *Let (M^n, g) be a closed and oriented Riemannian manifold, isometrically immersed into \mathbb{M}_δ^{n+1} and $p > n$. If $\delta > 0$, we assume that M is contained in a ball of radius $\frac{\pi}{2\sqrt{\delta}}$. Let $h > 0$. Then, there exists $\varepsilon(n, h, \delta) > 0$ such that if M has constant mean curvature $H = h$, and $\|\text{Scal} - s\|_p < \varepsilon$ for a constant s , then M is a geodesic sphere.*

Corollary 1.6. *Let (M^n, g) be a closed and oriented Riemannian manifold, isometrically immersed into \mathbb{M}_δ^{n+1} and $p > n$. If $\delta > 0$, we assume that M is contained in a ball of radius $\frac{\pi}{2\sqrt{\delta}}$. Let $s > 0$. Then, there exists $\varepsilon(n, \delta) > 0$ such that if M has constant scalar curvature $\text{Scal} = s$, and $\|H - h\|_p < \varepsilon$ for a constant h , then M is a geodesic sphere.*

When $p \in (1, n]$, one can not obtain similar result, since we use a pinching result for almost umbilical hypersurfaces for the L^p -norm with $p > n$. Nevertheless, we can obtain for the Euclidean space a stability result comparable to Theorem 1.1, with the assumption that the hypersurface is convex using a result by Giofrè [3]. Namely, we have the following for $p > 1$ which can also be deduced from Theorem 1.1 for $F = 1$.

Corollary 1.7. *Let $n \geq 2$ an integer, $h > 0$, $p > 1$ and $R > 0$. Let M a closed and oriented hypersurface of \mathbb{R}^{n+1} bounding a convex domain. Assume that $\text{Vol}(M) = V(\mathbb{S}^n)$ and that the extrinsic radius of M is smaller than R . Then, there exists $\varepsilon_0(n, p, h, R) > 0$ such that if for $\varepsilon \leq \varepsilon_0$, we have*

- $\|H - h\|_p < \varepsilon h$ and
- $\|H_2 - h_2\|_p < \varepsilon h^2$ for a constant h_2 ,

then M is closed to the unit sphere in the following sense : there exists a smooth parametrisation $\psi : \mathbb{S}^n \rightarrow M$, a vector $c_0 \in \mathbb{R}^{n+1}$ and a constant K depending on n, p, h and R so that

$$\|\psi - \text{Id} - c_0\|_{W^{2,p}(\mathcal{W})} \leq K\varepsilon^{\frac{p}{2}}.$$

Remark 1.8. *Note that there is no interest here to obtain corollaries comparable to Corollaries 1.5 and 1.6. Indeed, if the hypersurface (which is supposed to bound a domain) has constant mean curvature, the Alexandrov theorem gives that M is a sphere without need of the almost constancy of the scalar curvature.*

Remark 1.9. *In all the statements, we assume a normalization of the volume for a sake of simplicity, but by scaling, we can obtain statements with constants depending also on the volume.*

2. PRELIMINARIES

Let (M^n, g) be a n -dimensional compact, connected, oriented Riemannian manifold without boundary, isometrically immersed into the $(n+1)$ -dimensional simply connected real space form \mathbb{M}_δ^{n+1} of constant curvature δ . The (real-valued) second fundamental form B of the immersion is the bilinear symmetric form on $\Gamma(TM)$ defined for two vector fields X, Y by

$$B(X, Y) = -g(\bar{\nabla}_X \nu, Y),$$

where $\bar{\nabla}$ is the Riemannian connection on \mathbb{M}_δ^{n+1} and ν a normal unit vector field on M . When M is embedded, we choose ν as the inner normal field.

From B , we can define the mean curvature,

$$H = \frac{1}{n} \text{tr}(B).$$

Now, we recall the Gauss formula. For $X, Y, Z, W \in \Gamma(TM)$,

$$(2) \quad R(X, Y, Z, W) = \bar{R}(X, Y, Z, W) + \langle AX, Z \rangle \langle AY, W \rangle - \langle AY, Z \rangle \langle AX, W \rangle$$

where R and \bar{R} are respectively the curvature tensor of M and \mathbb{M}_δ^{n+1} , and A is the Weingarten operator defined by $AX = -\bar{\nabla}_X \nu$.

By taking the trace and for $W = Y$, we get

$$(3) \quad \text{Ric}(Y) = \bar{\text{Ric}}(Y) - \bar{R}(\nu, Y, \nu, Y) + nH \langle AY, Y \rangle - \langle A^2 Y, Y \rangle$$

Since, the ambient space is of constant sectional curvature δ , by taking the trace a seconde time, we have

$$(4) \quad \text{Scal} = n(n-1)\delta + n^2 H^2 - |A|^2,$$

or equivalently

$$(5) \quad \text{Scal} = n(n-1)(H^2 + \delta) - |\tau|^2,$$

where $\tau = A - H\text{Id}$ is the umbilicity tensor.

Now, we define the higher order mean curvatures, for $k \in \{1, \dots, n\}$, by

$$H_k = \frac{1}{\binom{n}{k}} \sigma_k(\kappa_1, \dots, \kappa_n),$$

where σ_k is the k -th elementary symmetric polynomial and $\kappa_1, \dots, \kappa_n$ are the principal curvatures of the immersion.

From the definition, it is obvious that H_1 is the mean curvature H . We also remark from the Gauss formula (2) that

$$(6) \quad H_2 = \frac{1}{n(n-1)} \text{Scal} - \delta.$$

On the other hand, we have the well-known Hsiung-Minkowski formula

$$(7) \quad \int_M \left(H_{k+1} \langle Z, \nu \rangle + c_\delta(r) H_k \right) = 0,$$

where $r(x) = d(p_0, x)$ is the distance function to a base point p_0 , Z is the position vector defined by $Z = s_\delta(r) \bar{\nabla} r$, and the functions c_δ and s_δ are defined by

$$c_\delta(t) = \begin{cases} \cos(\sqrt{\delta}t) & \text{if } \delta > 0 \\ 1 & \text{if } \delta = 0 \\ \cosh(\sqrt{-\delta}t) & \text{if } \delta < 0 \end{cases} \quad \text{and} \quad s_\delta(t) = \begin{cases} \frac{1}{\sqrt{\delta}} \sin(\sqrt{\delta}t) & \text{if } \delta > 0 \\ t & \text{if } \delta = 0 \\ \frac{1}{\sqrt{-\delta}} \sinh(\sqrt{-\delta}t) & \text{if } \delta < 0 \end{cases}$$

Finally, we define the function $t_\delta = \frac{s_\delta}{c_\delta}$.

On the other hand, let $F : \mathbb{S}^n \rightarrow \mathbb{R}^{n+1}$ be a smooth function satisfying the following convexity assumption

$$(8) \quad A_F = (\nabla dF + F\text{Id}|_{T_x \mathbb{S}^n})_x > 0,$$

for all $x \in \mathbb{S}^n$, where ∇dF is the Hessian of F . Here, > 0 mean positive definite in the sense of quadratic forms. Now, we consider the following map

$$\begin{aligned} \phi : \mathbb{S}^n &\longrightarrow \mathbb{R}^{n+1} \\ x &\longmapsto F(x)x + (\text{grad}_{|\mathbb{S}^n} F)_x \end{aligned}$$

The image $\mathcal{W}_F = \phi(\mathbb{S}^n)$ is called the Wulff shape of F and is a smooth hypersurface of \mathbb{R}^{n+1} . Moreover, by the condition (8), \mathcal{W}_F is convex. Note that if $F = 1$, the the Wulff shape is the sphere \mathbb{S}^n .

Now, let (M^n, g) be a n -dimensional compact, connected, oriented manifold without boundary, isometrically immersed into by X into \mathbb{R}^{n+1} . We denote by ν a normal unit vector field globally defined on M , that is, we have $\nu : M \rightarrow \mathbb{S}^n$. We set $S_F = A_F \circ d\nu$, where A_F is defined in (8). S_F is called the F -Weingarten operator or anisotropic shape operator, and it eigenvalues are the anisotropic principal curvatures that we will denote $\kappa_1, \kappa_2, \dots, \kappa_n$. Finally, for $r \in \{1, \dots, n\}$, the r -th anisotropic mean curvature is defined by

$$H_r^F = \frac{1}{\binom{n}{r}} \sum_{i_1 < \dots < i_r} \kappa_{i_1} \cdots \kappa_{i_r}.$$

We also set $H_0^F = 1$ for convenience. Note that if $F = 1$ then this is the definition of the classical r -th mean curvatures and the Wulff shape is just the unit sphere.

We finally recall these integral formulas proved by He and Li in [4] and which generalize the classical Hsiung-Minkowski formulas (7) in the anisotropic setting.

$$(9) \quad \int_M (F(\nu)H_{r-1}^F + H_r^F \langle X, \nu \rangle) dv_g = 0.$$

Now, we have the ingredient to prove the results.

3. KEY LEMMAS

Using the integral formula (9), we are able to prove the following technical lemma.

Lemma 3.1. *Let (M^n, g) be a closed Riemannian manifold, isometrically immersed into \mathbb{R}^{n+1} and assume that the extrinsic radius of M is smaller than R . Let h and h_2 be two positive constants and $\varepsilon \in (0, 1)$. If the first and second anisotropic mean curvatures satisfy*

- $\|H^F - h\|_p < \varepsilon h$ and
- $\|H_2^F - h_2\|_p < \varepsilon h^2$,

for some positive ε , then

$$\left| h^2 - h_2 \right| \leq A\varepsilon,$$

where A is an explicit positive constant depending on h , R and F .

Proof. The proof of this lemma is based on the Hsiung-Minkowski formulas (9) for $r = 1$ and $k = 2$. Indeed, the Hsiung-Minkowski formula for $r = 2$ is the following

$$(10) \quad \int_M \left(H_2^F \langle X, \nu \rangle + F(\nu)H^F \right) dv_g = 0.$$

Then, we get

$$\begin{aligned}
0 &= \int_M \left(H_2^F \langle X, \nu \rangle + F(\nu)H \right) dv_g \\
&= \int_M \left(h_2 \langle X, \nu \rangle + F(\nu)H \right) dv_g + \int_M (H_2^F - h_2) \langle X, \nu \rangle dv_g \\
&= \frac{h_2}{h} \int_M h \langle X, \nu \rangle + \int_M F(\nu)H^F dv_g + \int_M (H_2 - h_2) \langle X, \nu \rangle dv_g \\
&= \frac{h_2}{h} \int_M H^F \langle X, \nu \rangle dv_g + \frac{h_2}{h} \int_M (h - H^F) \langle X, \nu \rangle dv_g + \int_M F(\nu)h dv_g + \int_M F(\nu)(H^F - h) dv_g \\
&\quad + \int_M (H_2^F - h_2) \langle X, \nu \rangle dv_g
\end{aligned}$$

Now, we use the Hsiung-Minkowski formula for $r = 1$, that is

$$(11) \quad \int_M \left(H^F \langle X, \nu \rangle + F(\nu) \right) dv_g = 0,$$

to get

$$\begin{aligned}
0 &= -\frac{h_2}{h} \int_M F(\nu) dv_g + \frac{h_2}{h} \int_M (h - H^F) \langle X, \nu \rangle dv_g + \int_M F(\nu)h dv_g + \int_M F(\nu)(H^F - h) dv_g \\
&\quad + \int_M (H_2^F - h_2) \langle X, \nu \rangle dv_g \\
&= \left(h - \frac{h_2}{h} \right) \int_M F(\nu) dv_g + \frac{h_2}{h} \int_M (h - H^F) \langle X, \nu \rangle dv_g + \int_M F(\nu)(H^F - h) dv_g \\
&\quad + \int_M (H_2^F - h_2) \langle X, \nu \rangle dv_g
\end{aligned}$$

Then, since $|\langle X, \nu \rangle| \leq R$, using the Hölder inequality and both conditions $\|H^F - h\|_p < \varepsilon h$ and $\|H_2^F - h_2\|_p < \varepsilon h^2$, we get

$$\left| h - \frac{h_2}{h} \right| \int_M F(\nu) dv_g \leq h_2 \varepsilon R \text{Vol}(M) + \varepsilon h \sup(F) \text{Vol}(M) + \varepsilon h^2 R \text{Vol}(M).$$

Using the fact that $|H_2^F| \leq (H^F)^2$, we deduce

$$|h_2| \leq h^2 + (H^F - h)^2 + 2h(H^F - h) + (h_2 - H_2^F)$$

and so with the assumptions $\|H^F - h\|_p < \varepsilon h$ and $\|H_2^F - h_2\|_p < \varepsilon h^2$, we get

$$|h_2| \leq 5h^2.$$

Thus, we have

$$\begin{aligned}
|h^2 - h_2| \int_M F(\nu) dv_g &\leq \varepsilon h^2 \sup(F) \text{Vol}(M) + (h^3 + h h_2) R \text{Vol}(M) \varepsilon \\
&\leq \varepsilon h^2 \sup(F) \text{Vol}(M) + 6h^3 R \text{Vol}(M) \varepsilon
\end{aligned}$$

and we obtain

$$\begin{aligned}
|h^2 - h_2| &\leq \left(h^2 \frac{\sup(F)}{\inf(F)} + \frac{6h^3 R}{\inf(F)} \right) \varepsilon \\
&\leq A(h, R, F) \varepsilon,
\end{aligned}$$

which gives the wanted assertion. \square

Now, we give this second lemma for hypersurfaces of spheres and hyperbolic spaces.

Lemma 3.2. *Let (M^n, g) be a closed Riemannian manifold, isometrically immersed into \mathbb{M}_δ^{n+1} and assume that the extrinsic radius of M is smaller than R . Let $p > 1$, h and h_2 be two positive constants and $\varepsilon \in (0, 1)$. If the first and second mean curvatures satisfy*

- $\|H - h\|_p < \varepsilon h$ and
- $\|H_2 - h_2\|_p < \varepsilon h^2$,

for some positive ε , then

$$|h^2 - h_2| \leq B\varepsilon,$$

where B is an explicit positive constant depending on n , δ , h and R .

Proof: The proof is close to the proof of Lemma 3.1 with some slight differences. Proceeding as in the proof of Lemma 3.1 with the Hsiung-Minkowski (7) instead of the anisotropic one (9), we get

$$\begin{aligned} 0 &= \left(h - \frac{h_2}{h}\right) \int_M c_\delta(r) dv_g + \frac{h_2}{h} \int_M (h - H) \langle Z, \nu \rangle dv_g + \int_M c_\delta(r) (H - h) dv_g \\ &\quad + \int_M (H_2 - h_2) \langle Z, \nu \rangle dv_g. \end{aligned}$$

Then, since $|\langle Z, \nu \rangle| \leq s_\delta(R)$, using the Hölder inequality and both conditions $\|H - h\|_p < \varepsilon h$ and $\|H_2 - h_2\|_p < \varepsilon h^2$, we get

$$\left|h - \frac{h_2}{h}\right| \inf(c_\delta(r)) Vol(M) \leq h_2 \varepsilon s_\delta(R) Vol(M) + \varepsilon h \sup(c_\delta(r)) Vol(M) + \varepsilon h^2 s_\delta(R) Vol(M).$$

Using the fact that $|H_2| \leq (H)^2$, we deduce

$$|h_2| \leq h^2 + (H - h)^2 + 2h(H - h) + (h_2 - H_2)$$

and so with the assumptions $\|H - h\|_p < \varepsilon h$ and $\|H_2 - h_2\|_p < \varepsilon h^2$, we get

$$|h_2| \leq 5h^2.$$

Thus, we have

$$\begin{aligned} \left|h^2 - h_2\right| \inf(c_\delta(r)) Vol(M) &\leq \varepsilon h^2 \sup(c_\delta(r)) Vol(M) + (h^3 + hh_2) s_\delta(R) Vol(M) \varepsilon \\ &\leq \varepsilon h^2 \sup(c_\delta(r)) Vol(M) + 6h^3 s_\delta(R) Vol(M) \varepsilon \end{aligned}$$

and we obtain

$$|h^2 - h_2| \leq \left(h^2 \frac{\sup(c_\delta(r))}{\inf(c_\delta(r))} + \frac{6h^3 s_\delta(R)}{\inf(c_\delta(r))} \right) \varepsilon.$$

If $\delta = 0$, then $c_\delta = 1$ and so

$$\left(h^2 \frac{\sup(c_\delta(r))}{\inf(c_\delta(r))} + \frac{6h^3 s_\delta(R)}{\inf(c_\delta(r))} \right) = h^2 + 6h^3 R.$$

If $\delta > 0$, then $c_\delta(t) = \cos(\sqrt{\delta}t)$, so we deduce immediately that $c_\delta(R) \leq c_\delta(r) \leq 1$ and then

$$h^2 \frac{\sup(c_\delta(r))}{\inf(c_\delta(r))} + \frac{6h^3 s_\delta(R)}{\inf(c_\delta(r))} \leq \frac{h^2}{c_\delta(R)} + \frac{6h^3 s_\delta(R)}{c_\delta(R)}.$$

If $\delta < 0$, then $c_\delta(t) = \cosh(\sqrt{-\delta}t)$ and thus $c_\delta(R) \geq c_\delta(r) \geq 1$ and then

$$h^2 \frac{\sup(c_\delta(r))}{\inf(c_\delta(r))} + \frac{6h^3 s_\delta(R)}{\inf(c_\delta(r))} \leq h^2 c_\delta(R) + 6h^3 s_\delta(R).$$

Then, in the three cases, we have $|h^2 - h_2| \leq B\varepsilon$, with B a positive constant depending only on δ, h and R . This concludes the proof of the lemma. \square

4. PROOFS OF THE THEOREMS

Now, using this lemma together with appropriate result for almost umbilical hypersurfaces, we can prove the different theorems of this note.

Proof of Theorem 1.1. We begin with the proof of Theorem 1.1. For this, we first recall the main result of [2]. We will use this result together with Lemma 3.1 to conclude.

Theorem (De Rosa-Giofrè [2]). *Let $n > 2$, $p \in (1, p)$ and $F : \mathbb{S}^n \rightarrow \mathbb{R}^+$ satisfying the convexity assumption (8). There exists a constant $\delta_0 = \delta_0(n, p, F) > 0$ such that if Σ is closed convex hypersurface into \mathbb{R}^{n+1} satisfying*

$$\text{Vol}(M) = V(\mathcal{W}_F) \quad \text{and} \quad \int_M \|S_F - H^F \text{Id}\|^p dv_g \leq \delta$$

with $\delta \leq \delta_0$ then there exists a smooth parametrisation $\psi : \mathcal{W}_F \rightarrow M$, a vector $c_0 \in \mathbb{R}^{n+1}$ and a constant C depending on n, p and F so that

$$\|\psi - \text{Id} - c_0\|_{W^{2,p}(\mathcal{W})} \leq C\delta.$$

Now, if $\|H^F - h\| < \varepsilon h$ and $\|H_2^F - h_2\| < \varepsilon h^2$, then from Lemma 3.1

$$|h^2 - h_2| \leq A\varepsilon,$$

with A a positive constant depending on h, R and F . Thus, we deduce that

$$(H^F)^2 - H_2^F \leq (H^F - h)^2 + 2h(H^F - h) + |h^2 - h_2| + |h_2 - H_2^F|$$

and so

$$\|(H^F)^2 - H_2^F\|_p \leq (4h + A)\varepsilon = A'\varepsilon$$

where A' is a positive constant depending only on h, R and F . On the other hand, we have

$$(H^F)^2 - H_2^F = \frac{1}{n^2(n-1)} \sum_{i,j=1}^n (\kappa_i - \kappa_j)^2,$$

so we get

$$\left\| \sum_{i,j=1}^n (\kappa_i - \kappa_j)^2 \right\|_p \leq A''\varepsilon.$$

where $A'' = n^2(n-1)A'$ is also a positive constant depending only on h, n, R and F . Hence, M has almost vanishing anisotropic second fundamental form. Indeed,

we have at a point $x \in M$,

$$\begin{aligned} \|S_F - H^F \text{Id}\|^2 &= \sum_{i=1}^n (k_i - H^F)^2 \\ &= \sum_{i=1}^n \left(\kappa_i - \frac{1}{n} \sum_{j=1}^n \kappa_j \right)^2 \\ &= \frac{1}{n} \sum_{i,j=1}^n (\kappa_i - \kappa_j)^2 \end{aligned}$$

which give after integration

$$\|S_F - H^F \text{Id}\|_p^2 \leq \frac{1}{n} A'' \varepsilon.$$

Finally, we fix $p > 1$ and set $\varepsilon_0 = \inf \left\{ 1, \frac{n(\delta_0 \text{Vol}(\mathcal{W}_F))^{\frac{2}{p}}}{A''} \right\}$ where A'' is the constant defined above and δ_0 comes from Theorem 1.3. Note that ε_0 depends on n, p, h, R and F . Now, let $\varepsilon \leq \varepsilon_0$. We set $\delta = \frac{(A'' \varepsilon)^{\frac{p}{2}}}{n^{\frac{p}{2}} V(\mathcal{W}_F)}$. Since $\varepsilon \leq \varepsilon_0$ and from the definition of δ , we have $\delta \leq \delta_0$ and

$$\int_M \|S_F - H^F \text{Id}\|^p dv_g \leq \delta.$$

Thus, since by assumption, we also have $\text{Vol}(M) = \text{Vol}(\mathcal{W}_F)$, we can apply Theorem 1.3 to obtain that there exists a smooth parametrisation $\psi : \mathcal{W}_F \rightarrow M$ a vector $c_0 \in \mathbb{R}^{n+1}$ and a constant C depending on n, p, h, R and F so that

$$\|\psi - \text{Id} - c_0\|_{W^{2,p}(\mathcal{W})} \leq C\delta = K\varepsilon^{\frac{p}{2}},$$

where $K = \frac{(nA'')^{\frac{p}{2}} C}{\text{Vol}(\mathcal{W}_F)}$ is a positive constant depending only on n, p, h, R and F since A'' depends on n, h, R and F , $\text{Vol}(\mathcal{W}_F)$ depends on n and F and C depends on n, p and F . This concludes the proof of Theorem 1.1. \square

Proof of Theorem 1.3. The proof of Theorem 1.3 is a combination of Lemma 3.2 and the main Theorem of [10]. We recall this result

Theorem (Roth-Scheuer [10]). *Let $M \rightarrow \mathbb{R}^{n+1}$ be a closed, connected, oriented and isometrically immersed hypersurface with $\text{Vol}(M) = 1$. Let $p > n \geq 2$. Then, there exist $\eta_0(n, p, \|A\|_p) > 0$, $C(n, p, \|A\|_p) > 0$ and $\alpha(n, p) \leq 1$ such that if for $\eta \leq \eta_0$,*

$$\|A - H \text{Id}\|_p \leq \|H\|_p \eta$$

holds, then M is diffeomorphic and $C\eta^\alpha$ -close to a geodesic hypersphere (of radius $\frac{1}{\|H\|_2}$).

First, if $\|H - h\| < \varepsilon h$ and $\|H_2 - h_2\| < \varepsilon h^2$, then from Lemma 3.1

$$|h^2 - h_2| \leq B\varepsilon,$$

with B a positive constant depending on h, R and δ . Thus, we deduce that

$$H^2 - H_2 \leq (H - h)^2 + 2h(H - h) + |h^2 - h_2| + |h_2 - H_2|$$

and so after integration, we get immediately

$$\|H^2 - H_2\|_p \leq (4h + B)\varepsilon = B'\varepsilon$$

with B' a positive constant depending only on h , R and δ . But, since

$$\|H^2 - H_2\|_p = n(n-1)\|A - H\text{Id}\|_p^2,$$

we deduce that

$$\|A - H\text{Id}\|_p \leq \left(\frac{B'\varepsilon}{n(n-1)}\right)^{\frac{1}{2}} = B''\varepsilon^{\frac{1}{2}},$$

with B depending on n , h , R and δ . Second, from the assumption $\|H - h\|_p < \varepsilon h$, we get immediately

$$\frac{h}{2} \leq (1 - \varepsilon)h \leq \|H\|_p \leq (1 + \varepsilon)h \leq 2h,$$

if we assume that $\varepsilon < \frac{1}{2}$. Hence, we deduce that

$$\|A\|_p \leq B'' + 2h\sqrt{n}.$$

So $\|A\|_p$ is bounded from above by a constant depending only on n , h , R and δ .

Now, we set $\varepsilon_1 = \inf \left\{ \frac{1}{2}, \left(\frac{2\eta_1}{B''h} \right)^2 \right\}$. With this choice, if $\varepsilon < \varepsilon_1$, we get that

$$\eta = \frac{B''}{\|H\|_p} \varepsilon^{\frac{1}{2}} \leq \eta_1 \text{ and}$$

$$\|A - H\text{Id}\|_p^p \leq \|H\|_p \eta,$$

and we conclude that M is diffeomorphic and $C\eta^\alpha$ -close to a geodesic sphere of radius $\frac{1}{\|H\|_2}$. But, $C\eta^\alpha = C \left(\frac{B''}{\|H\|_p} \right)^\alpha \varepsilon^{\frac{\alpha}{2}} \leq C\eta^\alpha = C \left(\frac{2B''}{h} \right)^\alpha \varepsilon^{\frac{\alpha}{2}} = K\varepsilon^\beta$, where K is a constant depending only on n , p , h and R and $\beta = \frac{\alpha}{2}$ depends only on n and p . In the case where the ambient space is the space form of constant curvature δ , the proof is analogue using Theorem 3.1 of [10] for sphere and hyperbolic spaces obtain the Euclidean theorem with a conformal change of metric. In this case, the constants C , and so K too, depend also on δ . This concludes the proof. \square .

4.1. Proof of Corollaries 1.5 and 1.6. Assume that M has constant mean curvature $H = h$, and $\|\text{Scal} - s\|_p < \varepsilon$ for a constant s . First, by the Gauss formula, we have clearly $\text{Scal} = n(n-1)(H_2 + \delta)$ and so $\|\text{Scal} - s\|_p < \varepsilon$ gives $\|H_2 - h_2\|_p \varepsilon$ with $h_2 = \frac{1}{n(n-1)}\text{Scal} - \delta$ and we can apply Theorem 1.3 to conclude that M is diffeomorphic to a geodesic hypersphere of radius ρ . But this diffeomorphism is explicitly given (see [7, 8]) by $F = \rho \frac{X}{|X|}$ where X is the immersion of M into $\mathbb{M}^{n+1}(\delta)$. Hence, F is of the form $G \circ X$. Necessarily, X is injective and so the immersion of M is an embedding. By the Alexandrov theorem, we conclude that M is a geodesic hypersphere.

If Scal is constant and $\|H - h\|_p \leq \varepsilon$, the proof is the same and we conclude by the Alexandrov theorem for H_2 .

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