1 Hestenes Operator

1.1 Construction

We construct the Hestenes operator for domains $\Omega \subset \mathbb{R}^n$ with C^m boundary mainly following paragraphs 6.2,6.3 of [2]. First we consider a simple case where Ω is a C^m half strip.

Lemma 1. Let $l, n, m \in \mathbb{N}, m \geq l, 1 \leq p \leq \infty$ and $W = \prod_{i=1}^{n-1}]a_i, b_i[$ be an open cuboid of $\mathbb{R}^{n-1}$. Moreover define

$$S = W \times \mathbb{R}$$

$$\Omega = \{(\overline{x}, x_n) | \overline{x} \in W, x_n < \phi(\overline{x})\}$$

where $\phi \in C^m(\overline{W})$,$m \geq l$, and $\|D^\alpha \phi\| \leq M < \infty$ for every $1 \leq |\alpha| \leq l$. Then there exists a bounded extension operator T from $W^{l,p}(\Omega)$ to $W^{l,p}(S)$.

To prove Lemma 1 we prove first the case $\phi \equiv 0$ in the following result, that is a generalization of Lemma 9.2 in [1].

Lemma 2. Let $l, n \in \mathbb{N}, 1 \leq p \leq \infty$ and $W = \prod_{i=1}^{n-1}]a_i, b_i[$ be an open cuboid of $\mathbb{R}^{n-1}$. There exists a bounded extension operator

$$T : W^{l,p}(S^-) \to W^{l,p}(S)$$

where

$$S = W \times \mathbb{R}$$

$$S^- = W \times \mathbb{R}^-.$$

Proof. Let $f \in W^{l,p}(S^-)$. We define

$$Tf(\overline{x}, x_n) = \begin{cases} f(x), & \text{if } x_n < 0, \\ \sum_{k=1}^{l} \alpha_k f(\overline{x}, -\beta_k x_n), & \text{if } x_n > 0, \end{cases}$$

where α_k, β_k are real numbers that satisfy $\beta_k > 0$ and

$$\sum_{k=1}^{l} \alpha_k (-\beta_k)^s = 1 \tag{1}$$

for every $s = 0, ..., l-1$. Notice that given $\beta_1, ..., \beta_l > 0$ pairwise distinct, we can always find $\alpha_1, ..., \alpha_l$ that satisfy the condition by solving a Vandermonde square system of linear equations. First we prove that $Tf \in W^{l,p}(S)$. We take any $\phi \in C_c^\infty(S)$ and consider the integral

$$\int_S Tf(x)D^\alpha\phi(x)dx = \int_{S^+} Tf(x)D^\alpha\phi(x)dx + \int_{S^-} Tf(x)D^\alpha\phi(x)dx$$

where $S^+ = \{(\overline{x}, x_n) \mid \overline{x} \in W, x_n > 0\}$ and $\alpha \in \mathbb{N}_0^n, 1 \leq |\alpha| \leq l$. Let's write $\alpha = (\overline{\alpha}, \alpha_n)$, with $\overline{\alpha} \in \mathbb{N}_0^{n-1}$ and $\alpha_n \in \mathbb{N}_0$. By changing variables in the integrals we get

$$\begin{aligned}\int_S Tf(x)D^\alpha\phi(x)dx &= \int_{S^+} \sum_{k=1}^{l} \alpha_k f(\overline{x}, -\beta_k x_n)D^\alpha\phi(x)dx + \int_{S^-} f(x)D^\alpha\phi(x)dx \\ &= \int_{S^-} f(\overline{y}, y_n)D^\alpha\psi(\overline{y}, y_n)dy \qquad (*)\end{aligned}$$

where $\psi(\overline{x}, x_n) = \sum_{k=1}^{l} -\alpha_k(-\beta_k)^{\alpha_n - 1}\phi\left(\overline{x}, -x_n/\beta_k\right) + \phi(\overline{x}, x_n)$.Note that ψ belongs to $\in C^\infty(S^-)$ but does not have compact support in S^-. To bypass this problem we use an auxiliary function $\nu \in C^\infty(\mathbb{R})$ that satisfies

$$\begin{cases} \nu(x) = 0, & \text{if } x > -1/2, \\ \nu(x) = 1, & \text{if } x < -1, \end{cases}$$

and we define the functions $\nu_k(t) = \nu(kt)$ for $k \in \mathbb{N}$. It's clear that $\psi(x)\nu_k(x_n) \in C_c^\infty(S^-)$, hence we can integrate by parts

$$\int_{S^-} f(x)D^\alpha(\psi(x)\nu_k(x_n))dx = (-1)^{|\alpha|}\int_{S^-} D_w^\alpha f(x)\psi(x)\nu_k(x_n)dx \qquad (2)$$

By the Leibniz rule

$$\begin{aligned}D^\alpha(\psi(x)\nu_k(x_n)) &= \frac{\partial^{\alpha_n}}{\partial x_n^{\alpha_n}} D^{\overline{\alpha}}(\psi(x)\nu_k(x_n)) \\ &= \nu(kx_n)D^\alpha\psi(x) + \sum_{i=1}^{\alpha_n} \binom{\alpha_n}{i} k^i \nu^{(i)}(kx_n)\frac{\partial^{\alpha_n - i}}{\partial x_n^{\alpha_n - i}} D^{\overline{\alpha}}\psi(x).\end{aligned}$$

By the Dominated Convergence Theorem

$$\int_{S^-} f(x)\nu(kx_n)D^\alpha\psi(x)dx \to \int_{S^-} f(x)D^\alpha\psi(x)dx \text{ as } k \to \infty,$$

because $f \in L^1(S^- \cap \operatorname{supp}\psi)$ since $\operatorname{supp}\psi$ is bounded. Next, we claim that for every $i = 1, .., \alpha_n$

$$\int_{S^-} f(x) k^i \nu^{(i)}(kx_n) \frac{\partial^{\alpha_n - i}}{\partial x_n^{\alpha_n - i}} D^{\overline{\alpha}} \psi(x) dx \to 0 \tag{3}$$

as $k \to \infty$. To prove this first we notice that since α_k, β_k satisfies (1) we have that

$$\frac{\partial^j}{\partial x_n^j} D^{\overline{\alpha}} \psi(\overline{x}, 0) = 0 \ ; \ j = 0, ..., \alpha_n - 1,$$

hence by Taylor formula

$$\left| \frac{\partial^{\alpha_n - i}}{\partial x_n^{\alpha_n - i}} D^{\overline{\alpha}} \psi(\overline{x}, x_n) \right| \leq \frac{C |x_n|^i}{i!},$$

for all $i = 1, ..., \alpha_n$, where $C = \sup_{x \in S^-} |D^\alpha \psi(x)|$. Therefore we get the following estimate

$$\begin{aligned} \int_{S^-} \left| f(x) k^i \nu^{(i)}(kx_n) \frac{\partial^{\alpha_n - i}}{\partial x_n^{\alpha_n - i}} D^{\overline{\alpha}} \psi(x) \right| dx &\leq \frac{\widetilde{C} C}{i!} \int_{\{x \in S^- \cap \operatorname{supp} f \ , \ -1/k < x_n < 0\}} |f(x)| k^i |x_n|^i dx \\ &\leq \frac{\widetilde{C} C}{i!} \int_{\{x \in S^- \cap \operatorname{supp} f \ , \ -1 < x_n < 0\}} |f(x)| dx \end{aligned}$$

where $\widetilde{C} = \sup_{\mathbb{R}} |\nu^{(i)}|$. The second inequality comes from the fact that $\nu^{(i)}(x) = 0$ for $x < -1$ and $i \geq 1$. Hence we get (3) by Dominated Convergence Theorem. Passing to the limit in (2) we obtain

$$\int_{S^-} f(x) D^\alpha \psi(x) dx = (-1)^{|\alpha|} \int_{S^-} D_w^\alpha f(x) \psi(x) dx.$$

which, combined with (*), implies

$$\int_S Tf(x) D^\alpha \phi(x) dx = \int_{S^-} f(x) D^\alpha \psi(x) dx = (-1)^{|\alpha|} \int_{S^-} D_w^\alpha f(x) \psi(x) dx.$$

Finally going back to the original coordinates and using the definition of ψ we get

$$\int_S Tf(x) D^\alpha \phi(x) dx = (-1)^{|\alpha|} \int_{S^-} D_w^\alpha f(x) \left[\sum_{k=1}^{l} -\alpha_k (-\beta_k)^{\alpha_n - 1} \phi\left(\overline{x}, -\frac{x_n}{\beta_k} \right) + \phi(\overline{x}, x_n) \right] dx =$$

$$= (-1)^{|\alpha|} \int_{S^+} \sum_{k=1}^{l} \alpha_k (-\beta_k)^{\alpha_n} D_w^\alpha f(\overline{y}, -\beta_k y_n) \phi(y) dy + (-1)^{|\alpha|} \int_{S^-} D_w^\alpha f(y) \phi(y) dy$$

that implies that $D^\alpha_w Tf$ exists and

$$D^\alpha_w Tf(x) = \begin{cases} D^\alpha_w f(x), & \text{if } x \in S^-, \\ \sum_{k=1}^l \alpha_k(-\beta_k)^{\alpha_n} D^\alpha_w f(\overline{x}, -\beta_k x_n)\phi(x), & \text{if } x \in S^+. \end{cases}$$

It remains to prove the boundedness of T. It's immediate to verify that

$$\|Tf\|_{L^p(S^+)} \leq \sum_{i=1}^{l} |\alpha_k| \beta_k^{-1/p} \|f\|_{L^p(S^-)}$$

and that we have similar bounds for the norm of the weak derivatives of Tf. Hence there exists a constant C depending only on β_k, α_k, l such that $\|Tf\|_{W^{l,p}(S^+)} \leq C\|f\|_{W^{l,p}(S^-)}$. Observing that $\|Tf\|^p_{W^{l,p}(S)} = \|Tf\|^p_{W^{l,p}(S^+)} + \|f\|^p_{W^{l,p}(S^-)}$ the proof is concluded. □

Lemma 3. Let $l \in \mathbb{N}$ and Ω be a domain in $\mathbb{R}^n$. Suppose that $f \in L^1_{loc}(\Omega)$ admits all the weak derivatives up to order l and that $g : \Omega' \to \Omega$ is a diffeomorphism of class C^l with bounded derivatives $|D^\alpha g_k| \leq M$ for all $1 \leq |\alpha| \leq l$. Then $f \circ g$ admits weak derivative up to order l. Moreover for every $1 \leq |\alpha| \leq l$ we have to following bounds

$$|D^\alpha(f \circ g)(x)| \leq C \sum_{1 \leq |\beta| \leq |\alpha|} |D^\beta f(g(x))|$$

where C depends only on M and l.

Proof. We prove the statement by induction on l. For $l = 1$ we know that exists a sequence of functions $\{f_k\}_k \in C^\infty(\Omega)$ such that

$$f_k \to f \qquad \text{in } L^1_{loc}(\Omega)$$

$$\frac{\partial f_k}{\partial x_i} \to \frac{\partial f}{\partial x_i} \qquad \text{in } L^1_{loc}(\Omega).$$

Take $\phi \in C^\infty_c(\Omega')$ and integrate by parts

$$\int_{\Omega'} f_k(g(x)) \frac{\partial \phi}{\partial x_i}(x) dx = -\int_{\Omega'} \left(\sum_{j=1}^n \frac{\partial f_k}{\partial x_j}(g(x)) \frac{\partial g_j}{\partial x_i}(x) \right) \phi(x) dx.$$

Since $\phi(g^{-1}) \in C_c^l(\Omega)$ and the derivatives of g and g^{-1} are bounded, we can pass to the limit in the above equation

$$\int_{\Omega'} f(g(x))\frac{\partial \phi}{\partial x_i}(x)dx = -\int_{\Omega'} \left(\sum_{j=1}^{n} \frac{\partial f}{\partial x_j}(g(x))\frac{\partial g_j}{\partial x_i}(x)\right)\phi(x)dx.$$

Hence the case $l = 1$ is proved. Now suppose that the statement is true for l. We prove the case $l+1$, so we suppose that f admits weak derivatives up to order $l+1$ and that g is of class C^{l+1}. From the case $l = 1$ we know that $\frac{\partial (f\circ g)}{\partial x_i}$ exists and that

$$\frac{\partial (f\circ g)}{\partial x_i} = \sum_{j=1}^{n} (\frac{\partial f}{\partial x_j} \circ g)\frac{\partial g_j}{\partial x_i}$$

Since $\frac{\partial f}{\partial x_j}$ admits weak derivatives up to order l, by induction hypothesis the functions $\frac{\partial f}{\partial x_j} \circ g$ admit weak derivatives up to order l. Moreover $\frac{\partial g_j}{\partial x_i}$ is of class C^l, thus by the Leibniz rule the functions $(\frac{\partial f}{\partial x_j} \circ g)\frac{\partial g_j}{\partial x_i}$ admits weak derivatives of order l. In conclusion $\frac{\partial (f\circ g)}{\partial x_i}$ admits derivatives up to order l and this conclude the proof of the case $l+1$.

To prove the bounds we notice that the weak derivatives $D^\alpha(f\circ g)$ can be computed using the chain rule for usual derivatives. Such formula can be found in [3, formula B]:

$$D_w^\alpha(f(g))(x) = \sum_{1\le|\beta|\le|\alpha|} D_w^\beta(f(g(x))Q_{\alpha,\beta}(g,x)$$

In this formula $Q_{\alpha,\beta}(g,x)$ are homogeneous polynomials of degree $|\beta| \le l$ in the derivatives of order less than l of the components of g. Moreover the coefficients of these polynomials depend only on α, l, n. Hence there exists a constant C depending only on l, n, M such that $|Q_{\alpha,\beta}(g,x)| \le C$ uniformly on x. This concludes the proof. □

Proof of Lemma 1 . Let $f \in W^{l,p}(\Omega)$. Consider the function g from S^- onto Ω defined by

$$g(\overline{x}, x_n) = (\overline{x}, x_n + \phi(\overline{x}))$$

for all $(\overline{x}, x_n) \in S^-$ and its inverse g^{-1}

$$g^{-1}(\overline{x}, x_n) = (\overline{x}, x_n - \phi(\overline{x}))$$

where $S^- = W \times \mathbb{R}^-$. For all $f \in W^{l,p}(\Omega)$ we set

$$Gf = f \circ g$$

Since g is a diffeomorphism between S^- and Ω of class C^m, Lemma 3 guarantees that Gf admits weak derivatives up to order l. We claim that G defines a bounded operator from $W^{l,p}(\Omega)$ to $W^{l,p}(S^-)$, with bounded inverse. To prove this, first we compute the Jacobian matrix of g^{-1}

$$Jg^{-1}(x) = \begin{bmatrix} 1 & 0 & \dots & & 0 \\ 0 & 1 & \dots & & 0 \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \\ -\frac{\partial \phi(\overline{x})}{\partial x_1} & -\frac{\partial \phi(\overline{x})}{\partial x_2} & \dots & \dots & 1 \end{bmatrix}$$

from which $|\det(Jg^{-1}(x))| \equiv 1$. Moreover, again by Lemma 3, we have

$$|D_w^\alpha(f(g))| \leq C(l,M) \sum_{1\leq|\beta|\leq|\alpha|} |D_w^\beta f(g)|$$

where $C(l,M)$ depends only on l and M, with $M = \sup_{1\leq|\alpha|\leq l} \|D^\alpha \phi\|$. Next by the change of variable formula and Minkowski's inequality we get

$$\begin{aligned}
\left(\int_{S^-} |D_w^\alpha(f(g))(x)|^p dx\right)^{\frac{1}{p}} &\leq \sum_{1\leq|\beta|\leq|\alpha|} C(l,M) \left(\int_{S^-} |D_w^\beta f(g(x))|^p dx\right)^{\frac{1}{p}} \\
&= \sum_{1\leq|\beta|\leq|\alpha|} C(l,M) \left(\int_{\Omega} |D_w^\beta f(y)|^p |\det Jg^{-1}\big|_{g(y)}| dy\right)^{\frac{1}{p}} \\
&= \sum_{1\leq|\beta|\leq|\alpha|} C(l,M) \|D_w^\beta f\|_{L^p(\Omega)}
\end{aligned}$$

Thus, using the estimates for the intermediate derivatives, that

$$\|Gf\|_{W^{l,p}(S^-)} = \|f(g)\|_{W^{l,p}(S^-)} \leq C\|f\|_{W^{l,p}(\Omega)}$$

for a constant C independent of f. In a similar way we can also prove that

$$\|G^{-1}f\|_{W^{l,p}(\Omega)} = \|f(g^{-1})\|_{W^{l,p}(\Omega)} \leq D\|f\|_{W^{l,p}(S)}.$$

Now we can just define the operator T as

$$T = G^{-1} \circ \overline{T} \circ G$$

where $\overline{T}$ is the extension operator from $W^{l,p}(S^-)$ to $W^{l,p}(S)$ defined in Lemma 2. Therefore T is bounded as composition of bounded operators. An explicit for for T is

$$Tf(x) = \begin{cases} f(x), & \text{if } x \in \Omega, \\ \sum_{i=1}^{l} \alpha_k f(\overline{x}, \phi(\overline{x}) - \beta_k(x_n - \phi(\overline{x}))), & \text{if } x \in S \setminus \overline{\Omega}. \end{cases}$$

$\square$

We are now ready to define the Hestenes operator for a general domain Ω with C^m boundary. First we write the precise definition for this kind of domains.

Definition 1. Let $0 < d \leq D < \infty, M > 0, \varkappa > 0$ We say that an open set Ω in $\mathbb{R}^n$ has a resolved boundary with parameters $d, D, \varkappa$ if there exists a family of open cuboids $V_i, i = 1, ..., s$ (where $s \in \mathbb{N}$ if Ω is bounded and $s = \infty$ otherwise) such that

1. $(V_i)_d \cap \Omega \neq \emptyset$
2. $\Omega \subset \bigcup_{j=1}^{s} (V_i)_d$
3. The multiplicity of the cover $\{V_i\}_{i=1}^{s}$ is less than $\varkappa$.
4. There exist isometries λ_i of $\mathbb{R}^n$ such that

$$\lambda_j(V_j) = \prod_{i=1}^{n}]a_{ij}, b_{ij}[$$

and, if $\partial V_j \cap \Omega \neq \emptyset$,

$$\lambda_j(V_j \cap \Omega) = \{(\overline{x}, x_n) \in \mathbb{R}^n | \overline{x} \in W_j, a_{nj} + d < x_n < \phi_j(\overline{x})\}$$

where $W_j = \prod_{i=1}^{n-1}]a_{ij}, b_{ij}[$ and $\phi_j : W_j \to \mathbb{R}$.

Moreover

- if $\phi_j \in C^m(\overline{W}_i)$ with $\|D^\alpha \phi_j\| \leq M < \infty$, for every $1 \leq |\alpha| \leq m$, we say that Ω has a resolved C^m boundary with parameters $d, D, \varkappa, M$.
- if $\phi_j \in \mathrm{Lip}(\overline{W}_i)$ with $\mathrm{Lip}(\phi) = M$, we say that Ω has a resolved Lipschitz boundary with parameters $d, D, \varkappa, M$.

Finally we will say that a domain Ω has a resolved C^m (or Lipschitz) boundary if there exist parameters $d, D, \varkappa, M$ for which Ω has a C^m (or Lipschitz) boundary.

Remark 1. In the notation of Lemma 1, let $a, b \in \mathbb{R}$ such that $a < \phi(\overline{x}) < b$ for every $\overline{x} \in W$. We define $S^{a,b} = W \times (a, b)$, $\Omega_a = \Omega \cap (W \times (a, \infty))$ and $\widehat{W}^{l,p}(\Omega_a) = \{f \in W^{l,p}(\Omega_a) | \operatorname{supp} f \subset S\}$. Then exists a bounded extension operator

$$T : \widehat{W}^{l,p}(\Omega_a) \to W^{l,p}(S^{a,b}).$$

To see this we can just extend $f \in \widehat{W}^{l,p}(\Omega_a)$ naturally by 0 to $f_0 \in W^{l,p}(\Omega)$ and then define

$$Tf = (\widetilde{T} f_0)\big|_{S^{a,b}}$$

where $\widetilde{T}$ is the operator of the previous Lemmma .

Theorem 1. Let $m, l \in \mathbb{N}, l \leq m$ and $1 \leq p \leq \infty$. If Ω is a domain in $\mathbb{R}^n$ has a C^m resolved boundary then there exists a bounded extension operator

$$T : W^{l,p}(\Omega) \to W^{l,p}(\mathbb{R}^n).$$

Proof Sketch. Let $f \in W^{l,p}(\Omega)$. Let $\{V_i\}_{i=1}^s$ be the covering of cuboids for Ω as in Definition 1. It's possible to construct functions $\{\psi_i\}_{i=1}^s \subset C_c^\infty(\mathbb{R}^n)$ such that the functions $\{\psi_i^2\}_{i=1}^s$ form a partition of the unity corresponding to the covering $\{V_i\}_{i=1}^s$ and satisfying $\|D^\alpha \psi_i\|_{L^\infty} \leq M_1$ with M_1 depending only on n, l, d. If $\partial\Omega \cap V_i \neq \emptyset$ by Remark 1 there exists a bounded operator

$$T_i : \widehat{W}^{l,p}(\lambda_i(\Omega \cap V_i)) \to W^{l,p}(\lambda_i(V_i))$$

where $\widehat{W}^{l,p}(\lambda_i(V_i \cap \Omega) = \{f \in W^{l,p}(V_i \cap \Omega) | \operatorname{supp} f \subset \lambda_i(V_i)\}$. If $V_i \subset \Omega$ the operator T_i is defined to be just the identity. We set

$$Tf = \sum_{i=1}^{s} \psi_i T_i(\psi_i f(\lambda_i^{-1}))(\lambda_i).$$

assuming $(\psi_i T_i(\psi_i f(\lambda_i^{-1}))(\lambda_i)) = 0$ outside V_i. The functions $\psi_i f \in W^{l,p}(V_i \cap \Omega)$ are such that $\operatorname{supp} \psi_i f \subset \overline{\Omega} \cap V_i$, hence $\psi_i f(\lambda_i) \in \widehat{W}^{l,p}(\lambda_i(V_i \cap \Omega))$ and so T is well defined. To see that T is an extension operator, take $x \in \Omega$: if $x \in \operatorname{supp} \psi_i$ then $\psi_i(x) T_i(\psi_i f(\lambda_i^{-1}))(\lambda_i(x)) = \psi_i(x)^2 f(x)$; if $x \notin \operatorname{supp} \psi_i$ then $0 = \psi_i(x) T_i(\psi_i f(\lambda_i^{-1}))(\lambda_i(x)) = \psi_i(x)^2 f(x)$. So $Tf(x) = \sum_{i=1}^{s} \psi_i^2(x) f(x) = f(x)$.

We omit the proof of the boundedness of T, the details of which can be found in the proofs of Lemma 13-14 in [2]. $\square$

1.2 Hestenes operator on Morrey spaces

Definition 2. Let $1 \leq p < \infty$, ϕ a function from $\mathbb{R}^+$ to $\mathbb{R}^+$ and Ω be a domain in $\mathbb{R}^n$. For a function $f \in L^p_{loc}(\Omega)$ we define the Morrey space as

$$M_p^{\phi}(\Omega) = \{f \in L^p_{loc}(\Omega) \mid \|f\|_{M_p^{\phi}(\Omega)} < \infty\}$$

where

$$\|f\|_{M_p^{\phi}(\Omega)} := \sup_{B_r(x), x \in \Omega, r > 0} \left(\frac{1}{\phi(r)} \int_{B_r(x) \cap \Omega} |f(y)|^p dy \right)^{\frac{1}{p}}.$$

Lemma 4. Let $k \geq 1$ and Ω be set in $\mathbb{R}^n$ with diameter $D > 0$. Then there exists an integer $C_{n,k}$ depending only on k and n such that Ω can be covered by a collection of open balls $B_1, ..., B_h$ centered in Ω with radius D/k and $h \leq C_{k,n}$.

Proof. We start by claiming that if S is a set of points in $\mathbb{R}^n$ satisfying

i) $S \subset \Omega$,

ii) $\|z_1 - z_2\| \geq D/k$ for every $z_1, z_2 \in \Omega$ with $z_1 \neq z_2$,

then $|S| \leq C_{n,k}$ where $C_{k,n}$ is an integer depending only on k and n. To see this, first note that Ω is contained in some closed cube Q of side $2D$. Then we choose $m \in \mathbb{N}$ such that $2^{m-1} > \sqrt{n}k$. Next we cover Q with $(2^m)^n$ small closed cubes of side $2D/2^m$. The diagonal of a small cube measures $2D/2^m \cdot \sqrt{n} < D/k$. Thus each of these cubes can contain at most one point of S,so $|S| \leq (2^m)^n$. Therefore it's enough to choose $C_{n,k} = 2^{mn}$. Set $r := D/k$, we'll prove that we can cover Ω with a collection of balls $B_1, ..., B_h$ centered in Ω of radius r and such that $k \leq C_{n,k}$. Choose $x_1 \in \Omega$ and take

$B_1 = B_r(x_1)$, the ball centered in x_1 of radius r. If $\Omega \subset B_1$ we are done, if not there exists $x_2 \in \Omega \setminus B_1$ and we take $B_2 = B_r(x_2)$. Again, if $\Omega \subset (B_1 \cup B_2)$ we stop, else we can pick $x_3 \in \Omega \setminus (B_1 \cup B_2)$ and take $B_3 = B_r(x_3)$. We iterate this procedure : given $B_1, ..., B_i$ balls, if $\Omega \subset (B_1 \cup ... \cup B_i)$ we stop, else we can choose $x_{i+1} \in \Omega \setminus (B_1 \cup ... \cup B_i)$ and take $B_{i+1} = B_r(x_{i+1})$. We claim that this procedure stops with $i \leq C_{n,k}$. Suppose it doesn't, then we can find $B_1, ..., B_{C_{n,k}+1}$ balls centered respectively at $x_1, ..., x_{C_{n,k}+1}$. Setting $S = \{x_1, ..., x_{C_{n,k}+1}\}$, it's immediate to see that S satisfies i) and ii), but $|S| = C_{n,k} + 1$, that is a contradiction. $\square$

Lemma 5. Let $W \subset \mathbb{R}^{n-1}$ be open connected and define

$$\Omega = \{(\overline{x}, x_n) \mid \overline{x} \in W, x_n \leq \phi(\overline{x})\}$$

$$\Omega^+ = \{(\overline{x}, x_n) \mid \overline{x} \in W, x_n > \phi(\overline{x})\}$$

where $\phi \in \operatorname{Lip}(\overline{W})$. Let $\beta > 0$ and consider the function A_β from $W \times \mathbb{R}$ to Ω defined by

$$A_\beta(\overline{x}, x_n) = \begin{cases} (\overline{x}, \phi(\overline{x}) - \beta(x_n - \phi(\overline{x}))), & \text{if } (\overline{x}, x_n) \in \Omega^+, \\ (\overline{x}, x_n), & \text{if } (\overline{x}, x_n) \in \Omega. \end{cases}$$

Then for every $x_0 \in W \times \mathbb{R}$ and $r > 0$

$$A(B_r(x_0) \cap \Omega^+) \subset B_{cr}(A(x_0)) \cap \Omega$$

where $c \geq 1$ is a constant depending only on $\operatorname{Lip}\phi$ and β.

Proof. Notice that it is sufficient to prove that for every $x, y \in W \times \mathbb{R}$ we have

$$\|A(x) - A(y)\| \leq c\|x - y\|. \tag{4}$$

Set $M = \operatorname{Lip}\phi$. We distinguish three cases: 1. $x, y \in \Omega$: in this case $A(x) = x$ and $A(y) = y$, so $\|x - y\| = \|A(x) - A(y)\|$ and there is nothing to prove.

2. $x, y \in \Omega^+$: we have

$$\begin{aligned} |A(x)_n - A(y)_n| &= |\phi(\overline{x}) - \beta(x_n - \phi(\overline{x})) - \phi(\overline{y}) + \beta(y_n - \phi(\overline{y}))| \\ &\leq (1 + \beta)|\phi(\overline{x}) - \phi(\overline{y})| + \beta|x_n - y_n| \\ &\leq M(1 + \beta)\|\overline{x} - \overline{y}\| + \beta|x_n - y_n| \end{aligned}$$

Hence

$$\begin{aligned}\|A(x)-A(y)\|^2 &= \|\overline{A(x)}-\overline{A(y)}\|^2+|A(x)_n-A(y)_n|^2\\ &\le \|\overline{x}-\overline{y}\|^2+[M(1+\beta)\|\overline{x}-\overline{y}\|+\beta|x_n-y_n|]^2\\ &\le (1+2M^2(1+\beta)^2)\|\overline{x}-\overline{y}\|^2+2\beta^2|x_n-y_n|^2\\ &\le c_1^2(M,\beta)\|x-y\|^2\end{aligned}$$

for some constant $c_1(M,\beta)$.

3. $x\in\Omega^+, y\in\Omega$: first notice that, since $\phi(\overline{x})<x_n$, then $x_n-y_n>\phi(\overline{x})-y_n$. Moreover $\phi(\overline{y})>y_n$, hence $M\|\overline{x}-\overline{y}\|\ge\phi(\overline{y})-\phi(\overline{x})>y_n-\phi(\overline{x})$. This implies

$$|\phi(\overline{x})-y_n|<|x_n-y_n|+M\|\overline{x}-\overline{y}\|.$$

Now

$$\begin{aligned}|A(x)_n-A(y)_n| &= |\phi(\overline{x})-\beta(x_n-\phi(\overline{x}))-y_n|\\ &= |(1+\beta)(\phi(\overline{x})-y_n)+\beta(y_n-x_n)|\\ &\le M(1+\beta)\|\overline{x}-\overline{y}\|+(1+2\beta)|x_n-y_n|\end{aligned}$$

and

$$\begin{aligned}\|A(x)-A(y)\|^2 &= \|\overline{A(x)}-\overline{A(y)}\|^2+|A(x)_n-A(y)_n|^2\\ &\le \|\overline{x}-\overline{y}\|^2+[M(1+\beta)\|\overline{x}-\overline{y}\|+(1+2\beta)|x_n-y_n|]^2\\ &\le (1+2M^2(1+\beta)^2)\|\overline{x}-\overline{y}\|^2+2(1+2\beta)^2|x_n-y_n|^2\\ &\le c_2^2(M,\beta)\|x-y\|^2.\end{aligned}$$

for some constant $c_2(M,\beta)$. Then (4) by taking $c=max(\sqrt{c}_1,\sqrt{c}_2,1)$.

□

Lemma 6. Let $l,n,m\in\mathbb{N}, m\ge l, 1\le p\le\infty$, $W=\prod_{i=1}^{n-1}]a_i,b_i[$ be an open cuboid of $\mathbb{R}^{n-1}$ and ϕ a function from $\mathbb{R}^+$ to $\mathbb{R}^+$. Moreover define

$$S=W\times\mathbb{R}$$

$$\Omega=\{(\overline{x},x_n)|\overline{x}\in W, x_n<\phi(\overline{x})\}$$

where $\phi\in C^m(\overline{W})$ and $\|D^\alpha\phi\|\le M<\infty$ for every $1\le|\alpha|\le l$. Then for every $f\in W^{l,p}(\Omega)$

i) $\|Tf\|_{M_p^\phi(S)} \leq C\|f\|_{M_p^\phi(\Omega)}$

ii) $\|D_w^\alpha Tf\|_{M_p^\phi(S)} \leq C \sum_{1\leq|\beta|\leq|\alpha|} \|D_w^\beta f\|_{M_p^\phi(\Omega)}$, $1 \leq |\alpha| \leq l$

where T is the Hestenes operator defined in Lemma 1 and C is a constant independent of f.

Proof. Define $\Omega^+ = \{(\overline{x}, x_n) \mid \overline{x} \in W, x_n > \phi(\overline{x})\}$. We recall the definition of T

$$Tf(x) = \begin{cases} f(x) & x \in \Omega \\ \sum_{i=1}^l \alpha_k f(\overline{x}, \phi(\overline{x}) - \beta_k(x_n - \phi(\overline{x}))) & x \in \Omega^+ \end{cases}$$

and observe that we can rewrite it as

$$Tf(x) = \begin{cases} f(x), & \text{if } x \in \Omega, \\ \sum_{i=1}^l \alpha_k f(G_k(x)), & \text{if } x \in \Omega^+, \end{cases}$$

where $G_k(\overline{x}, x_n) = (\overline{x}, \phi(\overline{x}) - \beta_k(x_n - \phi(\overline{x})))$. Note that $G_k : \Omega^+ \to \Omega$ defines a diffeomorphism from Ω^+ to Ω of class C^m and satisfying $|\det JG_k^{-1}| \equiv 1/\beta_k$. First we prove ii). Let's fix $x_0 \in S$ and a radius $r > 0$. We want to estimate the quantity

$$I = \left(\frac{1}{\phi(r)} \int_{B_r(x_0)\cap S} |D_w^\alpha Tf(x)|^p dx\right)^{\frac{1}{p}}$$

for $1 \leq |\alpha| \leq l$. To do this we estimate the integral as follows

$$I \leq \underbrace{\left(\frac{1}{\phi(r)} \int_{B_r(x_0)\cap\Omega^+} |D_w^\alpha Tf(x)|^p dx\right)^{\frac{1}{p}}}_{I_1} + \underbrace{\left(\frac{1}{\phi(r)} \int_{B_r(x_0)\cap\Omega} |D_w^\alpha Tf(x)|^p dx\right)^{\frac{1}{p}}}_{I_2}.$$

Since $Tf(x) = f(x)$ when $x \in \Omega$, we have immediately

$$I_2 \leq \|D_w^\alpha f\|_{M_p^\phi(\Omega)}.$$

It remains to estimate I_1. We start by observing that from Lemma 3 there exists a constant C_k depending only on G_k and l such that

$$|D_w^\alpha(f \circ G_k)| \leq C_k \sum_{1\leq|\beta|\leq|\alpha|} |D_w^\beta f(G_k)|.$$

By the previous inequality and Lemma 5 we are able to produce the following bound

$$\begin{aligned}\frac{\|D_w^\alpha(f\circ G_k)\|_{L^p(B_r(x_0)\cap\Omega^+)}}{\phi(r)^{\frac{1}{p}}} &\le C_k \sum_{1\le|\beta|\le|\alpha|}\left(\phi(r)^{-1}\int_{G_k(B_r(x_0)\cap\Omega^+)}|D_w^\beta f(y)|^p|\det JG_k^{-1}|_{G_k(y)}|dy\right)^{\frac{1}{p}}\\ &\le C_k\beta_k^{-\frac{1}{p}}\sum_{1\le|\beta|\le|\alpha|}\left(\phi(r)^{-1}\int_{B_{c_k r}(A_{\beta_k}(x_0))\cap\Omega}|D_w^\beta f(y)|^p dy\right)^{\frac{1}{p}}\end{aligned}$$

where A_{α_k} is defined as in Lemma 5 and c_k depends only on β_k and M. By Lemma 4 the set $B_{c_k r}(A_{\beta_k}(x_0))\cap\Omega$ can be covered with a collection of open balls $B_1,...,B_h$ centered in Ω with radius r and $h\le m_k$, where m_k depends only on c_k. Hence we get

$$\frac{\|D_w^\alpha(f\circ G_k)\|_{L^p(B_r(x_0)\cap\Omega^+)}}{\phi(r)^{\frac{1}{p}}}\le C_k\beta_k^{-\frac{1}{p}}m_k\sum_{1\le|\beta|\le|\alpha|}\|D^\beta f\|_{M_p^\phi(\Omega)}$$

Next we estimate I_1:

$$\begin{aligned}I_1=\phi(r)^{-\frac{1}{p}}|D_w^\alpha Tf\|_{L^p(B_r(x_0)\cap\Omega^+)} &\le \phi(r)^{-\frac{1}{p}}\sum_{k=1}^{l}\alpha_k\|D_w^\alpha f(G_k)\|_{L^p(B_r(x_0)\cap\Omega^+)}\\ &\le\sum_{k=1}^{l}\alpha_k C_k\beta_k^{-\frac{1}{p}}m_k\left(\sum_{1\le|\beta|\le|\alpha|}\|D_w^\beta f\|_{M_p^\phi(\Omega)}\right).\end{aligned}$$

Finally putting the estimates of I_1, I_2 together

$$\begin{aligned}\|D_w^\alpha Tf\|_{M_p^\phi(S)} &=\sup_{x_0\in S,r>0}\left(\frac{1}{\phi(r)}\int_{B_r(x_0)\cap S}|D_w^\alpha Tf(x)|^p dx\right)^{\frac{1}{p}}\\ &\le\|D_w^\alpha f\|_{M_p^\phi(\Omega)}+\sum_{k=1}^{l}\alpha_k C_k\beta_k^{-\frac{1}{p}}m_k\left(\sum_{1\le|\beta|\le|\alpha|}\|D_w^\alpha f\|_{M_p^\phi(\Omega)}\right)\\ &\le\widetilde{C}\sum_{1\le|\beta|\le|\alpha|}\|D_w^\alpha f\|_{M_p^\phi(\Omega)}\end{aligned}$$

where $\widetilde{C}$ depends only on $\{b_k\}_k,\{\alpha_k\}_k,l,M,p$. This proves ii). The proof of i) is exactly analogous to the proof of ii). $\square$

Theorem 2. Let $m, l \in \mathbb{N}, l \leq m$, $1 \leq p \leq \infty$, ϕ a function from $\mathbb{R}^+$ to $\mathbb{R}^+$ and Ω a domain in $\mathbb{R}^n$ with C^m resolved boundary. Then for every $f \in W^{l,p}(\Omega)$

i) $\|Tf\|_{M_p^\phi(\mathbb{R}^n)} \leq C\|f\|_{M_p^\phi(\Omega)}$

ii) $\|D_w^\alpha Tf\|_{M_p^\phi(\mathbb{R}^n)} \leq C\sum_{1\leq|\beta|\leq|\alpha|}\|D_w^\beta f\|_{M_p^\phi(\Omega)}$, $1 \leq |\alpha| \leq l$

where T is the Hestenes operator defined in Theorem 1 and C doesn't depend on f.

Proof. Let $f \in W^{l,p}(\Omega)$ and $\{V_i\}_{i=1}^s$ be the covering of cuboids for Ω as in the definition of set with resolved boundary. We recall the definition of T :

$$Tf = \sum_{i=1}^s \psi_i T_i(\psi_i f(\lambda_i^{-1}))(\lambda_i)$$

where $\{\psi_i^2\}_{i=1}^s$ form a partition of the unity corresponding to the covering $\{V_i\}_{i=1}^s$ and satisfying $\|D^\alpha\psi_i\|_{L^\infty} \leq M_1$, with $|\alpha| \leq l$ and M_1 depending only on n, l, d. To make the notation simpler we will rewrite T as

$$Tf = \sum_{i=1}^s \psi_i \widetilde{T}_i(\psi_i f)$$

where the operator $\widetilde{T}_i$ is defined as $\widetilde{T}_i f = T_i(f(\lambda_i^{-1}))(\lambda_i)$. Before starting the proof we remark some facts that will be justified at the end of the proof:

a) Let C_i the constant such that

$$\|T_i g\|_{M_p^\phi(\lambda_i(V_i))} \leq C_i\|g\|_{M_p^\phi(\lambda_i(\Omega\cap V_i))}$$
$$\|D_w^\alpha T_i g\|_{M_p^\phi(\lambda_i(V_i)))} \leq C_i \sum_{1\leq|\beta|\leq|\alpha|}\|D_w^\alpha g\|_{M_p^\phi(\lambda_i(\Omega\cap V_i)))}$$

for $1 \leq |\alpha| \leq l$ and $g \in \widehat{W}^{l,p}(\lambda_i(\Omega \cap V_i))$. Then $\sup_{i=1,\dots,s} C_i \leq M_2$, where M_2 depends only on Ω, l, n.

b) We have

$$\|\widetilde{T}_i g\|_{M_p^\phi(V_i)} \leq C_i\|g\|_{M_p^\phi(\Omega\cap V_i)}$$
$$\|D_w^\alpha \widetilde{T}_i g\|_{M_p^\phi(V_i)} \leq M_3 C_i \sum_{1\leq|\beta|\leq|\alpha|}\|D_w^\alpha g\|_{M_p^\phi(\Omega\cap V_i)}$$

for $1 \leq |\alpha| \leq l$ and $g \in \widehat{W}^{l,p}(\Omega \cap V_i)$ and where M_3 doesn't depend on i.

$$\left(\frac{1}{\phi(r)}|Tf(x)|^p dx\right)^{\frac{1}{p}} \leq \left(\frac{1}{\phi(r)}\int_B |\sum_{i=1}^{s}\psi_i \widetilde{T}_i(f(\psi_i))(x)|^p dx\right)^{\frac{1}{p}}$$
$$\leq \sum_{i\in J}\left(\frac{1}{\phi(r)}\int_{B\cap V_i}|\widetilde{T}_i(f(\psi_i))(x)|^p|dx\right)^{\frac{1}{p}}$$

Let's now prove a),b),c),d),e).

a)Ω has a resolved C^m boundary with parameters $\varkappa, d, D, M$. Hence, if ϕ_i are the C^m functions of Definition 1, we have $\|D^\alpha\phi_i\| \leq M$ for every i and for every $1 \leq |\alpha| \leq l$. Therefore by the proof of Lemma 6 we deduce that C_i depends only on l, n, M and on the choice of the constants α_k, β_k, which can be chosen to be the same for every T_i. b) We notice that since λ_i are isometries, they are smooth and their derivatives are uniformly bounded with a bound depending only on n. Then the result follows from a straightforward computation using a change of variable and the Leibniz rule for derivatives. c) We have that

$$\sum_k |f|^p \mathbb{1}_{X_k} \leq \delta|f|^p.$$

Then it's enough to integrate on X and raise to the power $1/p$. d) A proof can be found in [2, Lemma 13]. e) For every $N \in \mathbb{N}$ and every $t \in T$ we have

$$\sum_{n=1}^{N} a_n(t) \leq \sum_{n=1}^{N} \sup_{t\in T} a_n(t),$$

which letting $N \to \infty$ gives

$$\sum_{n=1}^{\infty} a_n(t) \leq \sum_{n=1}^{\infty} \sup_{t\in T} a_n(t).$$

Applying the sup on the left-hand side we obtain the result.

□

1.3 Hestenes operator on Morrey spaces

Definition 3. Let $1 \leq p < \infty$, ϕ a function from $\mathbb{R}^+$ to $\mathbb{R}^+$ and Ω be a domain in $\mathbb{R}^n$. For a function $f \in L^p_{loc}(\Omega)$ we define the cubic-Morrey norm

$\|.\|_{M^\phi_{p,Q}(\Omega)}$ as

$$\|f\|_{M^\phi_{p,Q}(\Omega)} := \sup_{Q_r(x), x\in\Omega, r>0} \left(\frac{1}{\phi(r)}\int_{Q_r(x)\cap\Omega} |f(y)|^p dy\right)^{\frac{1}{p}}$$

where $Q_r(x)$ is the open cube centered in x of side $2r$.

Lemma 7. Let $1 \le p \le \infty$, ϕ a function from $\mathbb{R}^+$ to $\mathbb{R}^+$ and Ω be a domain in $\mathbb{R}^n$. Then then cubic-Morrey norm $\|.\|_{M^\phi_{p,Q}(\Omega)}$ is equivalent to the classical Morrey norm $\|.\|_{M^\phi_p(\Omega)}$. In particular

$$\|.\|_{M^\phi_p(\Omega)} \le \|.\|_{M^\phi_{p,Q}(\Omega)} \le 2^{n^2}\|.\|_{M^\phi_p(\Omega)}.$$

Lemma 8. Let $1 \le p < \infty, n \ge 2$ and ϕ a function from $\mathbb{R}^+$ to $\mathbb{R}^+$. Then T defines a bounded extension operator from $M^\phi_p(\mathbb{R}^n_+)$ to $M^\phi_p(\mathbb{R}^n)$.

Proof. We will prove that for an arbitrary open cube Q of side r contained in $\mathbb{R}^n$ we have

$$\left(\frac{1}{\phi(r/2)}\int_Q |Tf(x)|^p dx\right)^{\frac{1}{p}} \le C\|f\|_{M^\phi_{p,Q}(\mathbb{R}^n_+)} \tag{5}$$

for a constant C independent of f, then the main statement follows from Lemma 1. There are three cases: 1. $Q \subset \mathbb{R}^n_+$ 2. $Q \subset \mathbb{R}^n_-$ 3. $Q \cap \{x_n = 0\} \neq \emptyset$.

1. Since $Tf = f$ in $\mathbb{R}^n_+$

$$\left(\frac{1}{\phi(r/2)}\int_Q |Tf(x)|^p dx\right)^{\frac{1}{p}} = \left(\frac{1}{\phi(r/2)}\int_Q |f(x)|^p dx\right)^{\frac{1}{p}} \le \|f\|_{M^\phi_{p,Q}(\mathbb{R}^n_+)}$$

and we are done.

2. Let's write Q as $Q = \{(\overline{x}, y) \in \mathbb{R}^n \mid \overline{x} \in F, y \in (-a-r, -a)\}$ where $a > 0$ and F is an open cube of $\mathbb{R}^{n-1}$ of side r. Fix now $(\overline{x}, y) \in Q$, from the definition of Tf we have

$$|Tf(\overline{x}, y)| \le \int_1^\infty |f(\overline{x}, y+\lambda\delta^*(\overline{x}, y))||\psi(\lambda)|d\lambda \le A\int_1^\infty |f(\overline{x}, y+\lambda\delta^*(\overline{x}, y))|\frac{1}{\lambda^3}d\lambda$$

Let's apply the change of variable $s = y + \lambda\delta^*(\overline{x}, y)$

$$|Tf(\overline{x}, y)| \le \int_{y+\delta^*}^\infty |f(\overline{x}, s)|\frac{(\delta^*)^2}{(s-y)^3}ds \le c^2\int_{|y|}^\infty |f(\overline{x}, s)|\frac{|y|^2}{(s-y)^3}ds$$

because $c|y| \geq \delta^* \geq 2|y|$. Let's now decompose the last integral as follows

$$|Tf(\overline{x}, y)| \leq \sum_{k=0}^{\infty} c^2 \int_{|y|+kr}^{|y|+(k+1)r} |f(\overline{x}, s)| \frac{|y|^2}{(s-y)^3} ds.$$

Now by applying Minkowski's inequality for an infinite sum we get

$$\left(\int_{-a-r}^{-a} |Tf(\overline{x}, y)|^p dy \right)^{\frac{1}{p}} \leq c^2 \sum_{k=0}^{\infty} \left(\int_{-a-r}^{-a} \left(\int_{|y|+kr}^{|y|+(k+1)r} |f(\overline{x}, s)| \frac{|y|^2}{(s-y)^3} ds \right)^p dy \right)^{\frac{1}{p}}.$$

Next we plan to estimate each summand. First we apply to it the change of variable $'y = -y'$

$$\left(\int_{a}^{a+r} \left(\int_{y+kr}^{y+(k+1)r} |f(\overline{x}, s)| \frac{y^2}{(s+y)^3} ds \right)^p dy \right)^{\frac{1}{p}}$$

then we apply the change of variable $t = s/y$

$$\left(\int_{a}^{a+r} \left(\int_{1+kr/y}^{1+(k+1)r/y} |f(\overline{x}, ty)| \frac{1}{(t+1)^3} dt \right)^p dy \right)^{\frac{1}{p}}.$$

that can be rewritten as

$$\left(\int_{a}^{a+r} \left(\int_{1+kr/(a+r)}^{1+(k+1)r/a} |f(\overline{x}, ty)| \mathbb{1}_{(1+kr/y, 1+(k+1)r/y)}(t) \frac{1}{(t+1)^3} dt \right)^p dy \right)^{\frac{1}{p}}.$$

By Minkowsi's integral inequality

$$\left(\int_{a}^{a+r} \ldots \right)^{\frac{1}{p}} \leq \int_{1+kr/(a+r)}^{1+(k+1)r/a} \left(\int_{a}^{a+r} |f(\overline{x}, ty)|^p \mathbb{1}_{(1+kr/y, 1+(k+1)r/y)}(t) \frac{1}{(t+1)^{3p}} dy \right)^{\frac{1}{p}} dt.$$

We notice that for every $t, y \in \mathbb{R}$ with $a \leq y \leq a+r$

$$\mathbb{1}_{(1+kr/y, 1+(k+1)r/y)}(t) \leq \mathbb{1}_{(a+kr, a+(k+2)r)}(ty)$$

hence using the change of variable $z = ty$

$$
\begin{aligned}
\left(\int_a^{a+r} \dots\right)^{\frac{1}{p}} &\le \int_{1+kr/(a+r)}^{1+(k+1)r/a} \left(\int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p \frac{1}{t(t+1)^{3p}} dz\right)^{\frac{1}{p}} dt \\
&= \int_{1+kr/(a+r)}^{1+(k+1)r/a} \frac{1}{t^{\frac{1}{p}}(t+1)^3} dt \left(\int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}} \\
&\le \int_{1+kr/(a+r)}^{1+(k+1)r/a} \frac{1}{(t+1)^3} dt \left(\int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p dz\right) \\
&= \frac{1}{2}\left[\frac{1}{(1+(k+1)r/a)^2} - \frac{1}{1+kr/(a+r)^2}\right] \left(\int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}} \\
&= \frac{s_k(a,r)}{2} \left(\int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}}.
\end{aligned}
$$

Plugging in this estimate in the infinite sum we get

$$
\left(\int_{-a-r}^{-a} |Tf(\overline{x},y)|^p dy\right)^{\frac{1}{p}} \le \frac{c^2}{2} \sum_{k=0}^{\infty} s_k(a,r) \left(\int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}}.
$$

Integrating on F and applying again Minkowski inequality

$$
\begin{aligned}
\left(\int_F \int_{-a-r}^{-a} |Tf(\overline{x},y)|^p dy\right)^{\frac{1}{p}} &\le \frac{c^2}{2} \sum_{k=0}^{\infty} s_k(a,r) \left(\int_F \int_{a+kr}^{a+(k+2)r} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}} \\
&\le \frac{c^2}{2} \sum_{k=0}^{\infty} s_k(a,r) \left[\left(\int_{Q_k} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}} + \left(\int_{Q_{k+1}} |f(\overline{x},z)|^p dz\right)^{\frac{1}{p}}\right]
\end{aligned}
$$

where Q_i is the open cube $F \times (a+ir, a+(i+1)r)$. Dividing both sides by $\phi(r/2)^{\frac{1}{p}}$ we obtain

$$
\left(\frac{1}{\phi(r/2)} \int_Q |Tf(\overline{x},y)|^p dy\right)^{\frac{1}{p}} \le c^2 \sum_{k=0}^{\infty} s_k(a,r) \|f\|_{M_{p,Q}(\mathbb{R}^n_+)}
$$

We want now to estimate the series $\sum_{k=0}^{\infty} s_k(a,r)$, to do this we define $x = r/a$ that allows us to rewrite it as

$$
\sum_{k=0}^{\infty} s_k(a,r) = \sum_{k=1}^{\infty} \frac{x(x+2)}{(kx+1)^2}.
$$

To bound this series we distinguish two cases, when $x \leq 1$ and when $x > 1$. In the first case we can bound the series using a Riemann Sum

$$\sum_{k=1}^{\infty} \frac{x(x+2)}{(kx+1)^2} \leq 3 \sum_{k=1}^{\infty} \frac{x}{(kx+1)^2} \leq 3 \int_0^{\infty} \frac{1}{(t+1)^2} dt = 3.$$

In the second case

$$\sum_{k=1}^{\infty} \frac{x(x+2)}{(kx+1)^2} \leq \sum_{k=1}^{\infty} \frac{x(x+2)}{k^2 x^2} = \sum_{k=1}^{\infty} \frac{1+\frac{2}{x}}{k^2} \leq 3 \frac{\pi^2}{6} < 5.$$

Hence we get

$$\left(\frac{1}{\phi(r/2)} \int_Q |Tf(\overline{x}, y)|^p dy \right)^{\frac{1}{p}} \leq 5c^2 \|f\|_{M_{p,Q}(\mathbb{R}^n_+)}$$

that shows (1).

3. It's sufficient to notice that, up to a set of measure 0, we can cover Q with two open cubes Q_+, Q_- of side r with $Q_+ \subset \mathbb{R}^n_+$ and $Q_- \subset \mathbb{R}^n_-$. Hence

$$\left(\frac{1}{\phi(r/2)} \int_Q |Tf(x)|^p dx \right)^{\frac{1}{p}} \leq \left(\frac{1}{\phi(r/2)} \int_{Q_+} |f(x)|^p dx \right)^{\frac{1}{p}} + \left(\frac{1}{\phi(r/2)} \int_{Q_-} |Tf(x)|^p dx \right)^{\frac{1}{p}}$$

and we can conclude by part 1. and 2. □

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