

Embeddings of a Multi-Weighted Anisotropic Sobolev Type Space

G.Sh. Iskakova^{1,*}, M.S. Aitenova^{2,3}, A.K. Sexenbayeva⁴

¹Karaganda Buketov University, Karaganda, Kazakhstan;

²Karaganda University of Kazpotrebsoyuz, Karaganda, Kazakhstan;

³Kazakhstan Branch of Lomonosov Moscow State University, Astana, Kazakhstan;

⁴L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
(E-mail: iskakova.1975@mail.ru, abibekove@mail.ru, aiisha08@mail.ru)

Parameters such as various integral and differential characteristics of functions, smoothness properties of regions and their boundaries, as well as many classes of weight functions cause complex relationships and embedding conditions for multi-weighted anisotropic Sobolev type spaces. The desire not to restrict these parameters leads to the development of new approaches based on the introduction of alternative definitions of spaces and norms in them or on special localization methods. This article examines the embeddings of multi-weighted anisotropic Sobolev type spaces with anisotropy in all the defining characteristics of the norm of space, including differential indices, summability indices, as well as weight coefficients. The applied localization method made it possible to obtain an embedding for the case of an arbitrary domain and weights of a general type, which is important in applications in differential operators' theory, numerical analysis.

Keywords: Anisotropic Sobolev Spaces, Multi-Weighted Spaces, Embedding Theorems, Localization Methods, Weighted Functions.

2020 Mathematics Subject Classification: 46E35.

Introduction

In the article embeddings of multi-weighted anisotropic Sobolev type spaces $W_{\bar{\rho}, p}^{\bar{l}}(G, \bar{\rho}, \nu)$ described by a finite norm

$$|u; W_{\bar{\rho}, p}^{\bar{l}}(G, \bar{\rho}, \nu)| = \sum_{i=1}^n \left(\int_G |D_i^{l_i} u|_i^p \rho_i dx \right)^{1/p_i} + \left(\int_G |u|^p \nu dx \right)^{1/p}$$

are investigated in the case when ρ_1, \dots, ρ_n and ν are connected by certain relations on average on parallelepipeds in G with an adjustable edge length.

The article extensively utilizes approaches developed in the works [1–5]. Nonetheless, they have enabled a slight expansion of the class of weights for which the considered embedding is valid. As before [5], the spaces are anisotropic in terms of derivative orders, integrability indices, and weight factors for these derivatives. Also, for the introduced class of weights, the localization method [1–4] allows not imposing conditions on the domains, in which the spaces are considered and embeddings are set. So, the conditions under which the embeddings (1) occur for a sufficiently broad class of weights, restricted by a special condition $\Pi_{(\delta, \varepsilon)}$ introduced in Definition 1 are studied. The localization method (Lemma 3) with the introduction of so-called “characteristic parallelepipeds” (3) allows considering the domain G , with no additional conditions imposed.

*Corresponding author. E-mail: iskakova.1975@mail.ru

This work is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. AP15473253).

Received: 21 September 2023; Accepted: 11 December 2023.

© 2024 The Authors. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

For domains with conditions, fundamental embedding results have been obtained for anisotropic Sobolev spaces [6, 7]; as for weighted cases, in [8–10] the weights are functions of the distance to the boundary, and inequalities in [8] are considered in cylindrical domains, in [9] — on a domain with cusp, and in [10] an open connected domain is considered with various conditions. In [11], along with other findings, an anisotropic Sobolev inequality is obtained for smooth bounded domains and the class of p -admissible weights. In the work [12], Sobolev spaces are considered in open domains with certain conditions of smoothness imposed on the functions introduced in them, anisotropy in terms of derivative orders, and integrable classes of weights; alternative descriptions of these spaces are presented, including norms and properties of the density of smooth functions within them, and the relationships between the weights and anisotropic properties of Sobolev spaces are described. In [13], alternative definitions of spaces are introduced, through which embeddings of weighted spaces are obtained. Here, we also present studies of anisotropic Sobolev type spaces [14, 15], and their embeddings [16–18].

1 Set up

Let us introduce the notation. Let R^n be an n -dimensional arithmetic space with a norm

$$\|x\| = \left(\sum_{i=1}^n x_i^2 \right)^{1/2}, \quad x = (x_1, \dots, x_n).$$

Denote by

$$\bar{l} = (l_1, \dots, l_n), \quad \bar{a} = (a_1, \dots, a_n), \quad \text{and} \quad \bar{b} = (b_1, \dots, b_n)$$

fixed vectors with coordinates $l_i, a_i > 0, b_i \geq 0, i = 1, \dots, n$. Set for $\lambda > 0$:

$$\bar{a} \pm \lambda = (a_1 \pm \lambda, \dots, a_n \pm \lambda), \quad \lambda \bar{a} = (\lambda a_1, \dots, \lambda a_n),$$

$$\bar{b} : \bar{a} = (b_1/a_1, \dots, b_n/a_n), \quad \bar{b}\bar{a} = (b_1 a_1, \dots, b_n a_n),$$

$$\lambda^{\bar{b}} = (\lambda^{b_1}, \dots, \lambda^{b_n}), \quad \bar{a}^\lambda = (a_1^\lambda, \dots, a_n^\lambda), \quad \bar{a}^{\bar{b}} = (a_1^{b_1}, \dots, a_n^{b_n}),$$

$$|\bar{b}| = \sum_{i=1}^n b_i, \quad \prod \bar{b} = \prod_{i=1}^n b_i, \quad \sum \bar{b} = \sum_{i=1}^n b_i.$$

For a multi-index $\alpha = (\alpha_1, \dots, \alpha_n)$ $D^\alpha = \frac{\partial^{\alpha_1 + \dots + \alpha_n}}{\partial x_1^{\alpha_1} \dots \partial x_n^{\alpha_n}}$, for integers l_i $D_i^{l_i} u = \frac{\partial^{l_i}}{\partial x_i^{l_i}} u$.

Let $L(G; loc)$ be the space of locally-summable functions, $L_q^\alpha(G; \omega)$ is the Lebesgue weighted space of functions $u(\cdot)$, with a finite semi-norm

$$|u; L_q^\alpha(G; \omega)| = |D^\alpha u; L_q(G; \omega)| = \left(\int_G |D^\alpha u|^q \omega(x) dx \right)^{1/q},$$

where $1 \leq q < \infty$,

$$D^\alpha u = \frac{\partial^\alpha u}{\partial x^\alpha} = \frac{\partial^{\alpha_1 + \dots + \alpha_n} u}{\partial x_1^{\alpha_1} \dots \partial x_n^{\alpha_n}}$$

are mixed derivatives corresponding to the multi-index $\alpha = \alpha_1, \dots, \alpha_n$. We denote the class

$$C^\infty W = \{u \in C^\infty : |u; W_{\bar{p}, p}^{\bar{l}}(G; \bar{\rho}, v)| < \infty\}$$

by $C^\infty W$.

We consider issues related to the description of the conditions under which the embedding takes place:

$$W_{\bar{\rho}, p}^{\bar{l}}(G; \bar{\rho}, \nu) \rightarrow L_q^\alpha(G; \omega). \tag{1}$$

The embedding (1) is revealed through the embedding inequality as follows:

$$\left(\int_G |D^\alpha u|^q \omega(x) dx \right)^{1/q} \leq C |u; W_{\bar{\rho}, p}^{\bar{l}}(G; \bar{\rho}, \nu)|, u \in C^\infty W.$$

This article discusses the embeddings of spaces $W_{\bar{\rho}, p}^{\bar{l}}(G; \bar{\rho}, \nu)$ in the case when $\kappa_\alpha = |(1 + \alpha) : \bar{l}| > 1$.

Further, by introducing weights satisfying multiplicative boundedness conditions on average on parallelepipeds (Definition 1), we obtain embeddings of multiweighted anisotropic Sobolev type spaces $W_{\bar{\rho}, p}^{\bar{l}}(G, \bar{\rho}, \nu)$ into the weighted space $L_q^\alpha(G; \omega)$ on a domain G with irregular geometry, and anisotropy is present in the orders of derivatives, in terms of summability and in weight multipliers for these derivatives.

2 Preliminaries

Let $a = (a_1, \dots, a_n)$, $a_i > 0$. We denote the parallelepiped

$$Q_a = Q_a(x) \{y \in R^n : |y_i - x_i| < \frac{a_i}{2}, i = 1, 2, \dots, n\},$$

by $Q_a = Q_a(x)$. For $\lambda > 0$ let $\lambda Q = \lambda Q_a = Q_{\lambda a}$.

We will consider a positive vector function $\bar{d}(x) = (d_1(x), \dots, d_n(x))$, satisfying the conditions:

- 1) $Q(x) = Q_{\bar{d}(x)}(x) \subset G$;
- 2) $\sup_G d_i(x) < \infty, i = 1, \dots, n$;
- 3) There exist the constants $0 < \varepsilon < 1$ and $b_0 > 1$:

$$\forall i = 1, \dots, n \quad b_0^{-1} \leq \frac{d_i(y)}{d_i(x)} \leq b_0$$

as soon as

$$Q_{(\varepsilon)}(y) \cap Q_{(\varepsilon)}(x) \neq \emptyset,$$

where $Q_{(\varepsilon)}(x) = (1 - \varepsilon)Q(x)$. We call the function $\bar{d}(x)$ by the edge length function. Let $\{Q(x), x \in G\}$ be the parallelepiped family

$$Q(x) = \{y \in R^n : |y_i - x_i| < \frac{d_i(x)}{2}, i = 1, 2, \dots, n\},$$

satisfying the conditions 1)–3). Let $\rho_i(x), \omega(x), \nu(x)$ be the weights in G , and

$$\sigma_i(x) = \tilde{\rho}_i(x) d_i^{l_i p_i'}(x) \in L(G; loc),$$

$$\tilde{\rho}_i = \rho_i^{1-p_i'}(p_i' = \frac{p_i}{p_i - 1}), 1 < p_i < \infty (i = 1, \dots, n).$$

Suppose

$$B(x) = \left[\prod_{i=1}^n \left(\int_{Q_{(\varepsilon)}(x)} \sigma_i \right)^{1/p_i'} \right]^{1/n} |Q_{\varepsilon}(x)|^{-1},$$

$$N_{(\delta)}(Q)\{e \subset Q : |e| \leq \delta|Q|\}, 0 \leq \delta < 1.$$

Let

$$M_{(\varepsilon, \delta)}(x) = B(x) \inf_{e \in N_{(\delta)}(Q_{(\varepsilon)}(x))} \left(\int_{Q_{(\varepsilon)}(x) \setminus e} v \right)^{1/p}, \varepsilon \in [0, 1).$$

Definition 1. [5] We say that the weight pair $(\bar{\rho}, v)$ satisfies the condition $\Pi_{(\delta, \varepsilon)}$ with respect to $\bar{d}(x) = (d_1(x), \dots, d_n(x))$, if there are numbers $\delta \in [0, 1)$ and $\varepsilon \in [0, 1)$ such that

$$M_{(\varepsilon, \delta)}(x) \geq 1 \text{ for a.a. } x \in G.$$

Short notation:

$$(\bar{\rho}, v) \in \Pi_{(\delta, \varepsilon)}.$$

At the same time $0 < \varepsilon < 1$, if $G \subset R^n, G \neq R^n$.

Lemma 1. [3] Let $1 < p_i, p < q < \infty, (i = 1, \dots, n), r = \min\{p_1, \dots, p_n, p\}, \omega \in L_1(\nabla)$, where $\xi \in \nabla = (-\frac{1}{2}, \frac{1}{2})^n, \omega \geq 0$ and

$$M^{1/q} = \sup_{\substack{t > 0 \\ Q_{(t, \bar{l})} \subset \nabla}} t^{1-\kappa} |Q_{(t, \bar{l})}|_{\omega}^{1/q} < \infty.$$

Then

$$\left(\int_{\nabla} |D^\alpha f|^q \omega(\xi) d\xi \right)^{1/q} \leq c M^{1/q} \|f\|_{W_r^{\bar{l}}(\nabla)},$$

where c does not depend on $f \in C^\infty(\bar{\nabla})$.

Let $\{\bar{P}(x), x \in E\}$ be the closed parallelepiped family

$$\bar{P}(x) = \{y \in R^n : |y_i - x_i| \leq a_i(x)/2, i = 1, \dots, n\}, \tag{2}$$

where $a(x) = (a_1(x), \dots, a_n(x))$ is a positive vector function defined on a bounded set E in R^n .

Theorem 1. Let E be a bounded set in $R^n, \{\bar{P}(x), x \in E\}$ is the closed parallelepiped family (2), satisfying the conditions:

- 1) $\sup_{x \in E} a_i(x) < \infty, (i = 1, \dots, n)$;
- 2) there is a number $c > 0$ such that

$$c^{-1} \leq a_i(y)/a_i(x) \leq c (i = 1, \dots, n),$$

as soon as

$$\bar{Q}(x) \cap \bar{P}(y) \neq \emptyset.$$

Then it is possible to distinguish from $\{\bar{P}(x), x \in E\}$ no more than a countable subfamily $\{\bar{P}^j\}_{j \in J}, \bar{P}^j = \bar{P}(x^j)$, such that:

- a) $E \subset \bigcup_{j \in J} \bar{P}^j$;
- b) $\sum_{j \in J} X_{\bar{P}^j}(x) \leq \kappa_1 = \kappa_1(c, n) < \infty$ for any x in R^n ;
- c) $\{\bar{P}^j\}_{j \in J}$ is represented as a union of no more than $\kappa_2 = \kappa_1 + 1$ subfamilies $\{\bar{P}^j\}_{j \in J_v}$ of pairwise disjoint parallelepipeds.

The cover $\{\bar{P}^j\}$ of the set E , which has the properties of finite multiplicity and finite separability (respectively, properties b) and c), in Theorem 1, we will call B -covering.

Let $X_i = X_i(G)$ ($i = 1, 2$) be spaces of functions defined in G , with the seminorms $\|\cdot\|_{X_i(G)}$, $X_i(G)$ is the space of functions $X_i(G)/G$ with an induced seminorm $\|\cdot\|_{X_i(G)}$.

Lemma 2. [5] Let the spaces X_i ($i = 1, 2$) meet the following conditions:

- i1) $C^\infty(\bar{Q}) \subset X_i$, $Q \in I^n$ such that $\bar{Q} \subset G$;
- i2) $\|f\|_{X_i(G_1)} \leq \|f\|_{X_i(G_2)}$, if $G_1 \subset G_2 \subset G$;

$$\|f\|_{X_i(G_k)} = \lim_{k \rightarrow \infty} \|f\|_{X_i(G_k)},$$

if

$$G_k \subset G_{k+1} \ (k \geq 1), \ G = \bigcup_1^\infty G_k \subset G;$$

- i3) $\|f\|_{X_i(G \setminus e)} = \|f\|_{X_i(G)}$, if $|e| = 0$;
- i4) There are numbers $s_i \geq 1$, $c_i \geq 1$ ($i = 1, 2$) such that for any family

$$G = \bigcup_j G_j \subset G$$

$\{G_i\}$ of open sets such that

$$\|f\|_{X_1(G)}^{s_1} \leq c_1^{s_1} \sum_j \|f\|_{X_1(G_j)}^{s_1}, \quad f \in X_1(G) \quad \|f\|_{X_2(G)}^{s_2} \leq c_2^{s_2} \|f\|_{X_2(G)},$$

if G_j do not intersect in pairs with $f \in X_2(G)$;

- i5) There are such a parallelepiped family $\{P(x), x \in G\}$ and a positive function $K(x)$ on G , that

$$\|f\|_{X_1(Q(x))} \leq cK(x) \|f\|_{X(Q(x))} \quad \forall f \in C^\infty(\bar{Q}(x));$$

i6) From the family $\{P(x), x \in G\}$, we can distinguish B -covers $E = G \cap B(x, r)$, multiplicity κ_1 and coefficients of finite separability κ_2 , which do not depend on r . Then we have a true inequality

$$\|f\|_{X_1} \leq cK \|f\|_{X_2}, \quad f \in C^\infty(G) \cap X_2,$$

where

$$K = K_{s_1 s_2} = \begin{cases} \sup_{x \in G} K(x), & \text{where } s_2 \leq s_1 \\ \sup \left(\sum_{j \in J} (K(x^j))^{s_1 s_2 / (s_2 - s_1)} \right)^{(s_2 - s_1) / (s_1 s_2)}, & \text{where } s_2 > s_1 \end{cases}$$

and sup is taken over all at most countable families of $\{Q^j\}_{j \in J}$ pairwise non-intersecting parallelepipeds $Q^j = Q(x^j)$.

3 Localization and embedding theorems

Below we will consider “characteristic parallelepipeds” of the form

$$Q(x) = Q_\rho^\tau(x) = \left\{ y \in R^n : |y_i - x_i| < \frac{(\tau(x) \rho_i(x))^{1/l_i}}{2}, \ i = 1, 2, \dots, n \right\}, \quad (3)$$

where $\tau(x)$ such a positive function in G that the functions

$$d_i(x) = (\tau(x) \rho_i(x))^{1/l_i} \leq 1$$

and satisfy the conditions 1)–3). With respect to the functions ρ_i ($i = 1, 2, \dots, n$) we will assume that

$$c_1 \leq \frac{\rho_i(y)}{\rho_i(x)} \leq c_2, \quad \text{if } y \in Q_{(\varepsilon)}^\tau(x) \quad (i = 1, \dots, n)$$

and we introduce the following values connecting to the “characteristic parallelepipeds” $Q(x) = Q_{\bar{\rho}}^\tau(x)$ of the weight of ρ_i , ω and numeric parameters $p_i, p, q, \alpha = (\alpha_1, \dots, \alpha_n)$ and $\bar{l} = (l_1, \dots, l_n)$; namely, let us put

$$A_{\bar{p}, p, q}^\tau(x|\bar{\rho}, \omega) = \sup_{t>0} \left\{ t^{1-\kappa} \left(\int_{\bar{p}} \omega \right)^{1/q}, p_t = ((1-\varepsilon)t)^{1/\bar{l}} Q_{\bar{p}^{1/\bar{l}}} \subset (1-\varepsilon)^{1/\bar{l}} Q(x) \right\},$$

$$K_{\bar{p}, p, q}^\tau(x|\bar{\rho}, \omega) = \left[\prod_{i=1}^n \left(\tau(x)^{1-\frac{1}{p}-\alpha_i-\frac{1}{r}} \right)^{1/l_i} \right] A_{\bar{p}, p, q}^\tau(x|\bar{\rho}, \omega).$$

Lemma 3. [3–5] Let $1 < p_i, p < q < \infty$ ($i = 1, \dots, n$), $r = \min_{1 \leq i \leq n} (p_i, p)$, and the conditions are met:

$$M_{(\delta, \varepsilon)}^\tau(x|\bar{\rho}, \tau(\cdot)) \geq 1$$

and

$$\mathbf{K}_{\bar{p}, p, q}(x|\bar{\rho}, \omega) < \infty.$$

Then

$$\left(\int_Q |D^\alpha u|^q \omega \right)^{1/q} \leq c \mathbf{K}_{(\varepsilon), \bar{p}, q}^\alpha(x|\bar{\rho}, \omega) \left[\sum_{i=1}^n \left(\int_Q |\rho_i D^{l_i} u|^{p_i} \right)^{\frac{1}{p_i}} + \left(\int_Q |vu|^p \right)^{\frac{1}{p}} \right],$$

where $Q = Q_{(\varepsilon)}(x) = (1-\varepsilon)^{1/\bar{l}} Q_{\bar{\rho}}^\tau(x)$.

Proof. Suppose $f(\zeta) = u(x + (1-\varepsilon)^{1/\bar{l}} d(x) \cdot \zeta)$, where

$$\bar{d}(x) = (d_1(x), \dots, d_n(x)) \subset d_i(x) = (\tau(x) \rho_i(x))^{1/l_i}, d_i = (1-\varepsilon)^{1/l_i} d_i(x).$$

Let

$$\hat{\omega}(\zeta) = \omega(x + \bar{d} \cdot \zeta), \bar{d} = (d_1, \dots, d_n), Q = Q_{(\varepsilon)}(x).$$

Then by virtue of Lemma 1

$$\begin{aligned} \left(\int_{Q_{(\varepsilon)}(x)} |D^\alpha u|^q \omega \right)^{1/q} &= |Q|^{1/q} \left(\prod_{i=1}^n d_i^{-\alpha_i} \right) \left(\int_{\nabla} |D^\alpha f|^q \hat{\omega}(\xi) d\xi \right)^{1/q} \leq \\ &\leq \left(M \frac{|\alpha|}{\prod_{i=1}^n d_i^{q\alpha_i}} \right)^{\frac{1}{q}} \left[\sum_{i=1}^n \left(\int_{\nabla} |D^{l_i} f|^r d\xi \right)^{1/r} + \left(\int_{\nabla} |f|^r d\xi \right)^{1/r} \right] \leq \\ &\leq \left(\frac{M}{\prod_{i=1}^n d_i^{q\alpha_i}} \right)^{\frac{1}{q}} |Q|^{\frac{1}{q}-\frac{1}{r}} \left\{ \sum_{i=1}^n |Q|^{\frac{1}{r}} \left(\int_Q |D^{l_i} f|^{p_i} \right)^{\frac{1}{p_i}} + \left(\int_Q |\omega|^r dy \right)^{1/r} \right\} \leq \\ &\leq \left(\frac{M}{\prod_{i=1}^n d_i^{q\alpha_i}} \right)^{\frac{1}{q}} |Q|^{\frac{1}{q}-\frac{1}{r}} \tau(x) \left[\sum_{i=1}^n |Q|^{\frac{1}{r}-\frac{1}{p_i}} \zeta_i(x) \|D^{l_i} u\|_{p_i Q} + \tau(x)^{-1} \left(\int_Q |u|^r \right)^{1/r} \right] \leq \end{aligned}$$

$$\leq \left(\frac{M}{\prod_{i=1}^n d_i^{q\alpha_i}} \right)^{\frac{1}{q}} |Q|^{\frac{1}{q}-\frac{1}{r}} \|u; W_{\bar{\rho}, p}^l(Q; \bar{\rho}, v)\|, \text{ where } \bar{\rho} = (\rho_1^{p_1}, \dots, \rho_n^{p_n}).$$

It remains to note that

$$\begin{aligned} & \left(\frac{M}{\prod_{i=1}^n d_i^{q\alpha_i}} \right)^{\frac{1}{q}} |Q|^{\frac{1}{q}-\frac{1}{r}} \tau(x) = \tau(x) \prod_{i=1}^n d_i^{-\alpha_i} |Q|^{\frac{1}{q}-\frac{1}{r}} \sup_{Q(t, \bar{l}) \subset Q} t^{1-\kappa} |Q(t, \bar{l})|_{\hat{\omega}}^{1/q} = \\ & = \tau(x) \prod_{i=1}^n d_i^{-\alpha_i} |Q|^{-\frac{1}{r}} \left(\tau(x)^{x-1} \sup_{t>0} \left\{ t^{1-\kappa} \left(\int_{\bar{p}} \omega \right)^{1/q}, p_t = ((1-\varepsilon)t)^{1/\bar{l}} Q_{\bar{p}^{1/\bar{l}}} \subset Q \right\} \right) = \\ & = \prod_{i=1}^n \left(\tau(x)^{1-\frac{1}{r}} \rho_i(x)^{-\alpha_i-\frac{1}{r}} \right)^{1/l_i} A_{\bar{p}, p, q}^\tau(x|\bar{\rho}, v) = \mathbf{K}_{\bar{p}, p, q, \alpha}^\tau(x|\bar{\rho}, \omega). \end{aligned}$$

Theorem 2. Let $1 < p_i, p < q < \infty (i = 1, \dots, n)$, $\alpha \in Z_+^n$, $\bar{\rho} = (\rho_1^{\bar{p}_1}, \dots, \rho_n^{\bar{p}_n})$. Let $(\bar{\rho}, v) \in \Pi_{(\delta, \varepsilon)}^r$ and

$$K = \sup_{x \in G} K_{\bar{p}, p, q, \alpha}^\tau(x|\bar{\rho}, r) < \infty.$$

Then on the class $C^\infty W$ the inequality

$$\left(\int_G |D^\alpha u|^q \omega(x) dx \right)^{1/q} \leq C \|u; W_{\bar{p}, p}^l(G; \bar{\rho}, v)\|, u \in C^\infty W$$

is valid with an exact constant $C \leq cK$.

Proof. It follows from Lemma 2 and Theorem 1 that a pair of spaces $X_1 = L_q^\alpha(G; \omega)$, $X_2 = (W_{\bar{p}, p}^l(G; \bar{\rho}v))$ satisfies all the requirements of Lemma 2, from which the statement of the theorem follows.

Corollary 1. Let $1 < p_i, p < q < \infty (i = 1, \dots, n)$, $\kappa = |1 : \bar{l}| \leq 1$, ω is the weight on R^n , which satisfies the conditions of uniform boundedness on unit cubes $Q = Q_1(x) = x + \nabla$:

$$K = \sup_x \left(\int_{Q_1(x)} \omega \right)^{1/q} < \infty.$$

Then

$$\left(\int_G |u|^q \omega(x) dx \right)^{1/q} \leq cK \|u; W_{\bar{p}, p}^{\bar{l}}(R^n)\|, u \in C^\infty W.$$

Let $\bar{\mu} = (m_1, \dots, m_n) - \infty < m_i, v < \infty (i = 1, \dots, n)$,

$$W_{\bar{p}, p}^{\bar{l}}(\bar{\mu}, v) = W_{\bar{p}, p}^{\bar{l}}(R^n; \bar{\rho}, v)$$

with

$$\rho_i(x) = (1 + |x|)^\mu, v(x) = (1 + |x|)^v.$$

Corollary 2. Let $1 < p_i, p < q < \infty (i = 1, \dots, n), \kappa = |1 : \bar{l}| \leq 1, -\infty < \mu_i, v, \gamma < \infty (i = 1, \dots, n)$, and let the conditions be met:

$$\frac{v}{p} - \frac{1}{n} \sum_{i=1}^n \frac{\mu_i}{p_i} \leq 0, \frac{\gamma}{q} \leq \min_{i < i < n} \frac{\mu_i}{p_i}.$$

Then the inequality is true

$$\left(\int_G |u|^q (1 + |x|)^\gamma dx \right)^{1/q} \leq C \|u; W_{\bar{p}, p}^{\bar{\gamma}}(\bar{\mu}, v)\|, \quad u \in C^\infty W.$$

Embeddings of weighted anisotropic Sobolev type spaces are relevant in applications where it is necessary to consider the heterogeneity of the medium or the complex geometry of the domain, such as in numerical methods for solving differential equations and in the theory of differential operators. Localization methods, in particular, the norms of embeddings on cubes with variable edge length considered in the work, can be applied for embeddings of more complex spaces, including fractional ones. Considering weights that satisfy multiplicative conditions of boundedness on average in parallelepipeds is particularly important for analyzing functions in multidimensional spaces with irregular geometries.

Acknowledgments

This work is funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. AP15473253).

Author Contributions

G.Sh. Iskakova collected and analyzed data, led manuscript preparation, conducted the main research process. M.S. Aitenova and A.K. Sexenbayeva assisted in data collection and analysis. All authors participated in the revision of the manuscript and approved the final submission.

Conflict of Interest

The authors declare no conflict of interest.

References

- 1 Отелбаев М. Теоремы вложения пространств с весом и их применения к изучению спектра оператора Шредингера / М. Отелбаев // Тр. МИАН СССР. — 1979. — 150. — С. 265–305.
- 2 Лизоркин П.И. Теоремы вложения и компактности для пространств соболевского типа с весами / П.И. Лизоркин, М. Отелбаев // Мат. сб. — 1979. — 108. — № 3. — С. 358–377.
- 3 Кусаинова Л.К. Теоремы вложения анизотропных весовых пространств типа Соболева. I / Л.К. Кусаинова // Изв. вузов. Математика. — 1987. — № 11. — С. 20–31.
- 4 Кусаинова Л.К. Теоремы вложения анизотропных весовых пространств типа Соболева. II / Л.К. Кусаинова // Изв. вузов. Математика. — 1988. — № 2. — С. 36–45.
- 5 Исакова Г.Ш. Теоремы вложения анизотропных многовесовых пространств Соболева: канд. дис. ... физ.-мат. наук / Г.Ш. Исакова. — Астана, 2010.
- 6 Besov O.V. Integral representations of functions, and imbedding theorems for a region with flexible horn condition / O.V. Besov // Proc. Steklov Inst. Math. — 1987. — 170. — P. 11–31.
- 7 Besov O.V. Sobolev's embedding theorem for anisotropically irregular domains / O.V. Besov // Eurasian mathematical journal. — 2011. — 2. — No. 1. — P. 32–51.

- 8 Filippas S. On a class of weighted anisotropic Sobolev inequalities / S. Filippas, L. Moschini, A. Tertikas // Journal of Functional Analysis. — 2008. — 255. — No. 1. — P. 90–119. <https://doi.org/10.1016/j.jfa.2008.03.014>
- 9 Vasil'eva A.A. Estimates for the Kolmogorov widths of weighted Sobolev classes on a domain with cusp: case of weights that are functions of the distance from the boundary / A.A. Vasil'eva // Eurasian mathematical journal. — 2017. — 8. — No. 4. — P. 102–106.
- 10 di Blasio G. A weighted anisotropic Sobolev type inequality and its applications to Hardy inequalities / G. di Blasio, G. Pisante, G. Psaradakis // Math. Ann. — 2021. — 379. — P. 1343–1362. <https://doi.org/10.1007/s00208-019-01930-4>
- 11 Bal K. Weighted anisotropic Sobolev inequality with extremal and associated singular problems / K. Bal, G. Prashanta // Differential Integral Equations. — 2023. — 36. — No. 1-2. — P. 59–92.
- 12 Metafune G. Anisotropic Sobolev Spaces with Weights / G. Metafune, L. Negro, Ch. Spina // Tokyo J. Math. Advance Publication. — 2023. — 25 p. <https://doi.org/10.3836/tjm/1502179386>
- 13 Li H. Embedding theorem of the weighted Sobolev–Lorentz spaces / H. Li, J. Ruan, Q. Sun // Glasgow Mathematical Journal. — 2022. — 64. — No. 2. — P. 358–375. <https://doi.org/10.1017/S0017089521000161>
- 14 Mukherjee S. On a scale of anisotropic Sobolev spaces / S. Mukherjee, I. Tice // arXiv:2312.06044. — 2023. <https://arxiv.org/abs/2312.06044>
- 15 Hoai-Minh N. On anisotropic Sobolev spaces / N. Hoai-Minh, S. Marco // Communications in Contemporary Mathematics. — 2019. — 21. — No. 01. — P. 1850017. <https://doi.org/10.1142/S0219199718500177>
- 16 Xu Ch. An embedding theorem for anisotropic fractional Sobolev spaces / Ch. Xu, W. Sun // Banach Journal of Mathematical Analysis. — 2021. — 15. — Article number 63. <https://doi.org/10.1007/s43037-021-00146-6>
- 17 Bartusel D. Embeddings of anisotropic Besov spaces into Sobolev spaces / D. Bartusel, H. Fuehr // Mathematische Nachrichten. — 2023. — 296. — No. 4. — P. 1380–1393. <https://doi.org/10.1002/mana.202100512>
- 18 Bekmaganbetov K.A. The embedding theorems for anisotropic Nikol'skii-Besov spaces with generalized mixed smoothness / K.A. Bekmaganbetov, K.Ye. Kervenev, Ye. Toleugazy // Bulletin of the Karaganda University. Mathematics series. — 2021. — No. 4(104). — P. 28–34. <https://doi.org/10.31489/2021m4/28-34>

Соболев типті көпсалмақты анизотроптық кеңістіктің енгізулері

Г.Ш. Искакова¹, М.С. Айтенова^{2,3}, А.К. Сексенбаева⁴

¹Академик Е.А. Бөкетов атындағы Қарағанды университеті, Қарағанды, Қазақстан;

²Қарағанды Қазтұтынуодағы университеті, Қарағанды, Қазақстан;

³М.В.Ломоносов атындағы Мәскеу мемлекеттік университетінің Қазақстан филиалы, Астана, Қазақстан;

⁴Л.Н. Гумилев атындағы Еуразия ұлттық университеті, Астана, Қазақстан

Функциялардың әртүрлі интегралды-дифференциалдық сипаттамалары, облыстар мен олардың шекараларының тегістігінің қасиеттері, сондай-ақ салмақтық функцияларының көптеген кластары сияқты параметрлер Соболев типіндегі көп салмақтық анизотропты кеңістіктердің күрделі өзара байланыстары мен енгізу шарттарын анықтайды. Бұл параметрлерді шектемеуге деген ұмтылыс жаңа тәсілдердің дамуына әкеледі, олардағы кеңістіктер мен нормаларды анықтаудың балама нұсқаларын енгізуге немесе оқшаулаудың арнайы әдістеріне негізделген. Мақалада көп салмақтық дифференциалдық индекстерді, қосындылану индекстерін қоса алғанда, кеңістік нормасының барлық айқындаушы сипаттамаларында анизотропиясы бар, сондай-ақ салмақ коэффициенттері бар Соболев типті

анизотропты кеңістіктердің енгізілуі зерттелген. Қолданылған локализация әдісі дифференциалдық операторлар теориясында және сандық талдаудың қосымшаларында маңызды болып табылатын кез келген облыс пен жалпы типтегі салмақ үшін енгізгенді алуға мүмкіндік береді.

Клт сөздер: анизотроптық Соболев кеңістіктері, көп салмақтық кеңістіктер, енгізу теоремалары, локализация әдістері, салмақтық функциялар.

Вложения многовесового анизотропного пространства типа Соболева

Г.Ш. Искакова¹, М.С. Айтенова^{2,3}, А.К. Сексенбаева⁴

¹ *Қарағандын университеті атындағы академик Е.А. Букетованың атындағы университеті, Қарағанды, Қазақстан;*

² *Қарағандын университеті Қазпотребсоюздың атындағы университеті, Қарағанды, Қазақстан;*

³ *Қазақстанның филиалы Мәскеоның мемлекеттік университеті атындағы М.В. Ломоносовтың атындағы университеті, Астана, Қазақстан;*

⁴ *Евразиялық ұлттық университеті атындағы Л.Н. Гумилевтің атындағы университеті, Астана, Қазақстан*

Такие параметры, как различные интегро-дифференциальные характеристики функций, свойства гладкости областей и их границ, а также множества классов весовых функций, обуславливают сложные взаимосвязи и условия вложений многовесовых анизотропных пространств типа Соболева. Стремление не ограничивать эти параметры приводит к развитию новых подходов, основанных на введении альтернативных вариантов определений пространств и норм в них либо на специальных методах локализации. В этой статье исследованы вложения многовесовых анизотропных пространств типа Соболева с анизотропией во всех определяющих характеристиках нормы пространства, включая дифференциальные индексы, индексы суммируемости, а также весовые коэффициенты. Примененный метод локализации позволил получить вложение для случая произвольной области и весов общего типа, что важно в приложениях в теории дифференциальных операторов и численном анализе.

Ключевые слова: анизотропные пространства Соболева, многовесовые пространства, теоремы вложения, методы локализации, весовые функции.

References

- Otelbaev, M. (1979). Teoremy vlozheniia prostranstv s vesom i ikh primeneniia k izucheniiu spektra operatora Shredingera [Embedding theorems for spaces with weight and their application to the study of the spectrum of the Schredinger operator]. *Trudy MIAN SSSR — Proceedings of the Steklov Mathematical Institute of the USSR*, 150, 265–305 [in Russian].
- Lizorkin, P.I., & Otelbaev, M. (1979). Teoremy vlozheniia i kompaktnosti dlia prostranstv sobolevskogo tipa s vesami [Embedding theorems and compactness for spaces of Sobolev type with weights]. *Matematicheskii sbornik — Mathematical Collection*, 108(3), 358–377 [in Russian].
- Kussainova, L.K. (1987). Teoremy vlozheniia anizotropnykh vesovykh prostranstv tipa Soboleva. I [Embedding theorems of anisotropic weighted Sobolev type spaces. I]. *Izvestiia vuzov. Matematika — News of universities. Mathematics*, 11, 20–31 [in Russian].
- Kussainova, L.K. (1988). Teoremy vlozheniia anizotropnykh vesovykh prostranstv tipa Soboleva. II [Embedding theorems of anisotropic weighted Sobolev type spaces. II]. *Izvestiia vuzov. Matematika — News of universities. Mathematics*, 2, 36–45 [in Russian].
- Iskakova, G.Sh. (2010). *Teoremy vlozheniia anizotropnykh mnogovesovykh prostranstv Soboleva [Embedding theorems of anisotropic multi-weighted Sobolev spaces]. Candidate's thesis.* Astana [in Russian].

- 6 Besov, O.V. (1987). Integral representations of functions, and imbedding theorems for a region with flexible horn condition. *Proc. Steklov Inst. Math.*, 170, 11–31.
- 7 Besov, O.V. (2011). Sobolev’s embedding theorem for anisotropically irregular domains. *Eurasian mathematical journal*, 2(1), 32–51.
- 8 Filippas, S., Moschini, L., & Tertikas, A. (2008). On a class of weighted anisotropic Sobolev inequalities. *Journal of Functional Analysis*, 255(1), 90–119. <https://doi.org/10.1016/j.jfa.2008.03.014>
- 9 Vasil’eva, A.A. (2017). Estimates for the Kolmogorov widths of weighted Sobolev classes on a domain with cusp: case of weights that are functions of the distance from the boundary. *Eurasian mathematical journal*, 8(4), 102–106.
- 10 di Blasio, G., Pisante, G., & Psaradakis, G. (2021). A weighted anisotropic Sobolev type inequality and its applications to Hardy inequalities. *Math. Ann.*, 379, 1343–1362. <https://doi.org/10.1007/s00208-019-01930-4>
- 11 Bal, K., & Prashanta, G. (2023). Weighted anisotropic Sobolev inequality with extremal and associated singular problems. *Differential Integral Equations*, 36(1-2), 59–92.
- 12 Metafune, G., Negro L., & Spina, Ch. (2023). Anisotropic Sobolev Spaces with Weights. *Tokyo J. Math. Advance Publication*. <https://doi.org/10.3836/tjm/1502179386>
- 13 Li, H., Ruan, J., & Sun, Q. (2022). Embedding theorem of the weighted Sobolev–Lorentz spaces. *Glasgow Mathematical Journal*, 64(2), 358–375. <https://doi.org/10.1017/S0017089521000161>
- 14 Mukherjee, S., & Tice, I. (2023). *On a scale of anisotropic Sobolev spaces*. arXiv:2312.06044. <https://arxiv.org/abs/2312.06044>
- 15 Hoai-Minh, N., & Marco, S. (2019). On anisotropic Sobolev spaces. *Communications in Contemporary Mathematics*, 21(01), 1850017. <https://doi.org/10.1142/S0219199718500177>
- 16 Xu, Ch., & Sun, W. (2021). An embedding theorem for anisotropic fractional Sobolev spaces. *Banach Journal of Mathematical Analysis*, 15, 63. <https://doi.org/10.1007/s43037-021-00146-6>
- 17 Bartusel, D., & Fuehr, H. (2023). Embeddings of anisotropic Besov spaces into Sobolev spaces. *Mathematische Nachrichten*, 296(4), 1380–1393. <https://doi.org/10.1002/mana.202100512>
- 18 Bekmaganbetov, K.A., Kervenev, K.Ye., & Toleugazy, Ye. (2021). The embedding theorems for anisotropic Nikol’skii-Besov spaces with generalized mixed smoothness. *Bulletin of the Karaganda University. Mathematics series*, 4(104), 28–34. <https://doi.org/10.31489/2021m4/28-34>

*Author Information**

Gaukhar Shamugutovna Iskakova (*corresponding author*) — Candidate of physical and mathematical sciences, Associate Professor of the Department of Mathematical Analysis and Differential Equations, Karaganda Buketov University, 28 Universitetskaya street, Karaganda, 100028, Kazakhstan; Kazakhstan Branch of Lomonosov Moscow State University, Astana, Kazakhstan; e-mail: iskakova.1975@mail.ru; <https://orcid.org/0000-0003-4953-6853>

Mansia Saparovna Aitenova — Candidate of physical and mathematical sciences, Associate Professor of the Department of Higher Mathematics, Karaganda University of Kazpotrebsoyuz, 9 Akademicheskaya street, Karaganda, 100009, Kazakhstan; e-mail: abibekove@mail.ru; <https://orcid.org/0009-0007-0884-3327>

Aisha Kurmanbekovna Sexenbayeva — Candidate of physical and mathematical sciences, Professor of the Department of Applied Mathematics, L.N.Gumilyov Eurasian National University, 2 Mirzoyan street, Astana, 010000, Kazakhstan; e-mail: aiisha08@mail.ru; <https://orcid.org/0009-0001-5646-4328>

*The author’s name is presented in the order: First, Middle and Last Names.