

The smoothness of solutions problems to nonlinear elliptic equations

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Abstract. *We obtained estimates in generalized Morrey spaces are used to study global regularity of the solution of the boundary problems of nonlinear elliptic equations in divergence form over a bounded non-smooth domain. For these is we used of Calderon-Zygmund theory. The main goal of the article is to obtain Hölder estimates for solutions to the boundary problems for nonlinear elliptic equations.*

Keywords. generalized Morrey spaces, nonlinear elliptic equation, Calderon-Zygmund theory, BMO space, Reifenberg flat domain, global regularity

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1 Introduction

The main goal of the article is to obtain Hölder estimates for solutions to the differently problems for nonlinear elliptic equations. In order to study the local behavior of solutions to elliptic and parabolic partial differential equations introduced in [32] the classical Morrey spaces $L_{p,\lambda}$. There are the inclusion between the Morrey and the Hölder spaces permits to obtain regularity of the solutions to elliptic and parabolic boundary problems. In paper [9], [25], [31], [33] authors the study generalized Morrey spaces.

Later this result is extended on spaces with weaker condition on the pair (φ_1, φ_2) (see [17]). For more recent results on boundedness and continuity of singular integral operators in generalized Morrey and fractional spaces and their application in the different order partial differential equations theory see [1, 3, 4, 13, 14, 19–21, 23, 24, 30, 34, 36, 38, 41, 42, 46].

In this paper we consider Neumann boundary problem for nonlinear elliptic equation in divergence form in a bounded non-smooth domain in generalized Morrey spaces. The problem for nondivergence second order linear elliptic equations with VMO coefficients in [23], for higher order linear elliptic equations in [24] considered.

We also recall papers [2, 5, 8, 11–13, 16, 18].

2 Preliminaries on generalized Morrey space

Let $\varphi : \Omega \times R_+ \rightarrow R_+$ be a measurable function. A function $f \in L_p(\Omega)$, $1 < p < \infty$, belongs to the generalized Morrey space $M_{p,\varphi}(\Omega)$ if the following norm is finite

$$\|f\|_{M_{p,\varphi}(\Omega)} = \sup_{x \in \Omega, r > 0} \frac{1}{\varphi(x, r)} \left(\frac{1}{r^n} \int_{\Omega_r} |f(y)|^p dy \right)^{1/p} < \infty.$$

The generalized Sobolev-Morrey space $W_{p,\varphi}^1(\Omega)$ consists of all functions $u \in W_p^1(\Omega)$ with distributional derivatives $D^s u \in M_{p,\varphi}(\Omega)$, endowed with the norm

$$\|u\|_{W_{p,\varphi}^1(\Omega)} = \sum_{0 \leq |s| \leq 1} \|D^s u\|_{M_{p,\varphi}(\Omega)}.$$

The space $W_{p,\varphi}^1(\Omega) \cap W_p^1(\Omega)$ consists of all functions $u \in W_p^1(\Omega)$ with $D^s u \in M_{p,\varphi}(\Omega)$, $0 \leq |s| \leq 1$ and is endowed by the same norm.

Let S^{n-1} is a unit sphere in R^n , $B_r(x) = B(x, r) = \{y \in R^n : |x - y| < r\}$, $B_r^c(x) = R^n \setminus B_r(x)$, $2B_r(x) = B(x, 2r)$, $\Omega_r(x) = \Omega \cap B_r(x)$, $x \in \Omega$, $B_r^+(x_0) \equiv B^+(x_0, r) = B(x_0, r) \cap \{x_n > 0\}$, $2B_r^+ = B^+(x_0, 2r)$, where $x_0 = (x', 0)$.

The investigation of nonlinear reaction, drift, diffusion processes has received many attention. This questions arise as mathematical models of different applied problems. For example, for instance diffusion processes of electrically charged species phase transition and transport in porons media.

Also we note for the semiconductor theory weight functions have derivative. Another example comes from phase separation problems. In this case usually used the Fermi integral and Fermi functions. This problems is connected with of nonlinear process which arise as mathematical models of different applied problems. The qualitative property of solution is investigated. The theorems obtained in this article have important applied significance in various issues of mechanics, physics, biology and other applied fields.

We give assumption about domain $\Omega \subset R^n$, $n \geq 2$. The measure the deviation of $\partial\Omega$ from being an $(n - 1)$ -dimensional affine space at each scale $\rho > 0$, use the following so-called "Reifenberg flatness".

Definition 2.1 A bounded domain Ω is said to be (δ, R) -Reifenberg flat if for every $x \in \partial\Omega$ and every $\rho \in (0, R]$, there exists a coordinate system $\{y_1, \dots, y_n\}$, which can depend on ρ and x such that $x = 0$ in this coordinate system and that

$$B_\rho(0) \cap \{y_n > \delta\rho\} \subset B_\rho(0) \cap \Omega \subset B_\rho(0) \cap \{y_n > -\delta\rho\}, \quad (2.1)$$

where $B_\rho(y) = \{x \in R^n : |x - y| < \rho\}$ denotes the open ball on R^n centered $y \in R^n$ and radius $\rho > 0$. Later $|E|$ denotes the n -dimensional Lebesgue measure of a set $E \subset R^n$.

The above definition warrants a few comments. Because our the main problem has a scaling invariance property, the constant R can be taken as 1 or any other constant greater than 1. However, the constant δ is a small positive constant still invariant under such scaling. In fact, the Reifenberg flatness (2.1) is meaningful when $0 < \delta < \frac{1}{8}$, see [43], and with such small δ , these flatness conditions mean that the deviation of $\partial\Omega$ from being an $(n - 1)$ -dimensional affine space is small enough at each scale $\rho > 0$. By (2.1), the following measure density condition is obtained for all $y \in \Omega$ and $\rho \in (0, R)$

$$|\Omega \cap B_\rho(y)| \geq \left(\frac{1 - \delta}{2} \right)^n |B_\rho(y)| \geq \left(\frac{3}{10} \right)^n |B_\rho(y)|.$$

We give the definitions of the functional spaces to which the coefficients and the data of the problem belong.

Let the nonlinearity $a = a(x, \xi) : R^n \rightarrow R^n \times R^n$ is measurable in x for all $\xi \in R^n$ and continuous in ξ for almost all $x \in R^n$. We give the regularity assumption on the nonlinearity $a(x, \xi)$. First set

$$\theta(a; B_\rho(y))(x) = \sup_{\xi \in R^n \setminus \{0\}} \frac{|a(x, \xi) - \bar{a}_{B_\rho(y)}(\xi)|}{|\xi|},$$

where

$$\bar{a}_{B_\rho(y)}(\xi) = \int_{B_\rho(y)} a(x, \xi) dx = \frac{1}{|B_\rho(y)|} \int_{B_\rho(y)} a(x, \xi) dx$$

is the integral average of $a(x, \xi)$ in the variable x over $B_\rho(y)$ for fixed $\xi \in R^n$. The function $\theta(a; B_\rho(y))$ provides the measurement of the oscillation of $\frac{a(x, \xi)}{|\xi|}$ in the variable x over $B_\rho(y)$, uniformly in ξ .

Definition 2.2 A vector field a is said to be (δ, R) -vanishing if

$$\sup_{0 < \rho \leq R} \sup_{y \in R^n} \int_{B_\rho(y)} \theta(a; B_\rho(y))(x) dx \leq \delta.$$

3 Statement of the problem

We the study Dirichlet problem, mixed problem and Neumann problem. Now we reduce Neumann problem.

Let Ω be a bounded domain in R^n , $n \geq 2$, with its non-smooth boundary $\partial\Omega$. We suppose domain Ω to be (δ, R) -Reifenberg flat. Let $f = f(x) : \Omega \rightarrow R^n$ be a given vector-valued function at least in $L^2(\Omega, R^n)$ and consider the following nonlinear elliptic equation

$$\begin{cases} \operatorname{div} a(x, Du) = \operatorname{div} f & \text{in } \Omega, \\ \frac{\partial u}{\partial n} = 0 & \text{on } \partial\Omega, \end{cases} \quad (3.1)$$

where the nonlinearity $a(x, \xi)$ as section 2. Here assume monotonicity and growth conditions on $a = a(x, \xi)$ as follows

$$\begin{cases} c_0 |\xi - \eta|^p \leq [a(x, \xi) - a(x, \eta)] \leq (\xi - \eta)^p \\ |a(x, \xi)| + |D_\xi a(x, \xi)| |\xi| \leq c_1 |\xi|^{p-2}, \end{cases} \quad (3.2)$$

for all $\xi, \eta \in R^n$ and for almost every $x \in R^n$ and c_0, c_1 some positive constants.

We consider a weak solution $W_p^1(\Omega)$, which means that the for any $\varphi \in W_p^1(\Omega)$ integral formula hold

$$\int_{\Omega} a(x, Du) D\varphi dx = \int_{\Omega} f D\varphi dx.$$

The existence and uniqueness of a weak solution to problem (3.1) can be obtained by the Minty-Browder method for monotone operators, see [26, 28], also [29], under the assumption $f \in L^2(\Omega, R^n)$, with the estimate

$$\| |Du|^2 \|_{L^1(\Omega, R^n)} \leq C \| |f|^2 \|_{L^1(\Omega, R^n)},$$

the constant C is independent of u and f .

We are now ready to state the main result.

Theorem 3.1 Let $p \in (1, \infty)$, $q_1 \in (p-1, n(p-1))$, $\frac{n}{q_1} - \frac{n}{q} = \frac{1}{p-1}$ and (φ_1, φ_2) satisfy the condition

$$\sup_{r < s < \infty} s^{-\frac{n}{q}} \operatorname{ess\,sup}_{s < \sigma < \infty} \varphi_1(\Omega_\sigma(y)) \sigma^{\frac{n}{q_1}} \leq C \varphi_2(\Omega_r(y)), \quad (3.3)$$

where C does not depend on y and r . Assume that (3.2) hold and u is a weak solution to problem (3.1). There is a small $\delta(n, \Lambda_1, \gamma) > 0$ such that if Ω is (δ, R_0) - Reifenberg flat and the nonlinearity $\mathbf{a}$ satisfies the small (δ, R_0) - BMO condition for some $R_0 > 0$ and $|f|^{\frac{1}{p-1}} \in M_{q_1, \varphi_1}(\Omega)$, then $Du \in M_{q, \varphi_2}(\Omega)$ with the estimate

$$\|Du\|_{M_{q, \varphi_2}(\Omega)} \leq C_1 \| |f|^{\frac{1}{p-1}} \|_{M_{q_1, \varphi_1}(\Omega)}, \quad (3.4)$$

the constant C_1 depending on $n, q, \Lambda_1, \gamma, R_0, |\Omega|$.

The boundedness results of maximal operators in generalized Morrey spaces is obtained in [1].

4 Auxiliary results

We give the following invariance property under normalization and scaling, later some result witch is needed from measure theory in the generalized Morrey space and one version of the Calderon-Zygmund type covering lemma. This results we is used to prove the main theorem.

Lemma 4.1 Let $u \in W_2^1(\Omega)$ be a weak solution to the problem (3.1) and nonlinearity $a(x, \xi)$ satisfies (3.2) and is (δ, R) -vanishing. For each $\lambda > 1$ and $0 < r < 1$, define the rescaled maps

$$\begin{aligned} \tilde{a}(x, \xi) &= \frac{a(rx, \lambda\xi)}{\lambda}, \\ \tilde{\Omega} &= \left\{ \frac{1}{r}x : x \in \Omega \right\}, \tilde{u}(x) = \frac{u(rx)}{\lambda r}, \\ \tilde{f}(x) &= \frac{f(rx)}{\lambda_0}. \end{aligned}$$

Then

1 $\tilde{u} \in W_2^1(\tilde{\Omega})$ is the weak solution of

$$\operatorname{div} \tilde{a}(x, D\tilde{u}) = \operatorname{div} \tilde{f} \quad \text{in } \tilde{\Omega},$$

2 $\tilde{a}(x, \xi)$ satisfies the conditions (3.2) with the same constants c_0 and c_1 ,

3 $\tilde{a}$ is $(\delta, \frac{R}{r})$ -vanishing and $\tilde{\Omega}$ is $(\delta, \frac{R}{r})$ - Reifenberg flat.

Proof. The proof follows by direct computations. Also for example see [7].

Now we give the Hardy-Littlewood maximal function and its basic properties. Let g be a locally integrable function on R^n . Then the Hardy-Littlewood maximal function is given by

$$(Mg)(x) = \sup_{\rho > 0} \int_{B_\rho(x)} |g(y)| dy = \sup_{\rho > 0} \frac{1}{|B_\rho(x)|} \int_{B_\rho(x)} |g(y)| dy.$$

If g is defined only on a bounded subset of R^n , then we define as $Mg = M\bar{g}$, where $\bar{g}$ is the zero extension of g in R^n . This maximal function holds the so-called weak inequality. More specifically, there exists a positive constant $c = c(n)$ such that, for any $\lambda > 0$

$$|\{x \in R^n : (Mg)(x) > \lambda\}| \leq \frac{C}{\lambda} \int_{R^n} |g(x)| dx. \quad (4.1)$$

We next state the Hardy-Littlewood maximal operators is bounded from generalized Morrey space $M_{p,\varphi}(R^n)$ to itself.

Lemma 4.2 (see [22]) Assume that there is a positive constant C such that for any fixed $x \in R^n$, $r > 0$ it holds

$$\sup_{r < s < \infty} \frac{\operatorname{ess\,inf}_{s < \sigma < \infty} \varphi(B_\sigma(x)) \sigma^{\frac{n}{p}}}{s^{\frac{n}{p}}} < C \varphi(B_r(x)). \quad (4.2)$$

Then there is a constant $C_p > 0$ such that

$$\|f\|_{M_{p,\varphi}(R^n)} \leq \|Mf\|_{M_{p,\varphi}(R^n)} \leq C_p \|f\|_{M_{p,\varphi}(R^n)},$$

$\forall f \in M_{p,\varphi}(R^n)$ with compact support in R^n .

We will use the following version of the Vitali covering Lemma.

Lemma 4.3 (see [15]) Assume that Ω is $(\delta, 1)$ -Reifenberg flat domain for some small $\delta > 0$. Let E and D be measurable sets with $E \subset D \subset \Omega$. Suppose that there exists small $\varepsilon > 0$ such that

- 1 for any $y \in \Omega$ $|E \cap B_1(y)| < \varepsilon |B_1(y)|$,
- 2 for each $y \in \Omega$ and $r \in (0, 1)$, if $|E \cap B_r(y)| \geq \varepsilon |B_r(y)|$, then $B_r(y) \cap \Omega \subset D$.

Then

$$|E| \leq C \cdot \varepsilon |D|,$$

the constant C depending only on n, Φ , and the constant $\frac{1}{1 - \delta}$.

Proof. The proof of this lemma also can be found in [6, Lemma 5.4] or [37, Lemma 3.4] with slight modification.

We also use the following standard arguments of measure theory

Lemma 4.4 (see [22]) Let f is a nonnegative an measurable function defined on a bounded domain $\Omega \subset R^n$ and φ be a weight satisfying (4.2) and in addition a kind of monotonicity condition

$$\varphi(B_r(y))r^n \leq \varphi(B_s(z))s^n \text{ for all } B_r(y) \subset B_s(z), \quad (4.3)$$

and let $\theta > 0$, $\lambda > 1$ be constants. Then $f \in M_{p,\varphi}(\Omega)$ if and only if

$$S = \sup_{y \in \Omega, r > 0} \sum_{k \geq 1} \frac{\lambda^k |\{x \in \Omega : f(x) > \theta \lambda^k\}|}{\varphi(B_r(y))r^n} < \infty,$$

and

$$\frac{1}{C} S \leq \|f\|_{M_{p,\varphi}(\Omega)} \leq C(1 + \delta),$$

where $C > 0$ is a constant depending only on θ, λ, φ .

Lemma 4.5 Assume $u \in W_2^1(\Omega)$ be the weak solution of (3.1). Then there exists a constant $N = N(c_0, c_1, n) > 1$ such that for each $\varepsilon \in (0, 1)$ fixed, one can select small $\delta = \delta(\varepsilon, c_0, c_1, n, \varphi) \in (0, \frac{1}{8})$ such that if $a(x, \xi)$ is $(\delta, 1)$ -vanishing, Ω is $(\delta, 1)$ -Reifenberg flat, and if for $0 < r < 1$ and $y \in \Omega$, $B_r(y)$ satisfies

$$|\{x \in \Omega : M(|Du|^2) > N^2\} \cap B_r(y)| \geq C |B_r(y)|.$$

Then we have

$$B_r(y) \cap \Omega \subset \{x \in \Omega : M(|Du|^2) > 1\} \cup \{x \in \Omega : M(|f|^2) > \delta^2\}.$$

Proof. Proof this lemma is based on the same method as in the proof in [29, Theorem 4.10].

5 Proof the main theorem

Now, we are ready to prove the main theorem.

Proof of Theorem 3.1. By to Lemma 4.1, it suffices to prove that

$$\| |Du|^2 \|_{M_{p,\varphi}(\Omega)} \leq C, \quad (5.1)$$

under the assumption $\| |f|^2 \|_{M_{p,\varphi}(\Omega)} \leq \delta^2$.

We take

$$u_1 = \frac{\delta u}{\sqrt{\| |f|^2 \|_{M_{p,\varphi}(\Omega)} + \sigma}}, f_1 = \frac{\delta f}{\sqrt{\| |f|^2 \|_{M_{p,\varphi}(\Omega)} + \sigma}};$$

in place of u and f , respectively, in the problem (3.1) estimate

$$\begin{aligned} & \frac{1}{c} \min \{ \|g\|_{M_{p,\varphi}(\Omega)}^{q_0}, \|g\|_{M_{p,\varphi}(\Omega)}^{q_1} \} \\ & \leq \int_{\Omega} |g(x)| dx \leq c \max \{ \|g\|_{M_{p,\varphi}(\Omega)}^{q_0}, \|g\|_{M_{p,\varphi}(\Omega)}^{q_1} \} \end{aligned} \quad (5.2)$$

This estimate follows from [7].

It follows from Lemma 4.5 and estimate (5.1) that

$$\| |f_1|^2 \|_{M_{p,\varphi}(\Omega)} \leq \delta^2, \quad \int_{\Omega} |f_1|^2 dx \leq C \delta^{2\tau_2}, \quad (5.3)$$

where $\tau_2 = \frac{q_0}{q_1}$. Therefore if (5.1) is obtained with Du_1 instead of Du , then the proof is completed after letting $\sigma \rightarrow 0$. However, in view of [7] and Lemma 4.2,

$$\begin{aligned} & \| |Du|^2 \|_{M_{p,\varphi}(\Omega)}^{\alpha} \leq \\ & \leq C \int_{\Omega} |Du|^2 dx \leq C \int_{\Omega} (M(|Du|^2)) dx \end{aligned}$$

for some $\alpha > 0$. Consequently, it suffices to show that, by Lemma 4.4,

$$S = \sup_{y \in \Omega, r > 0} \sum_{k \geq 1} \frac{(N^{2k}) |\{x \in \Omega : M(|Du|^2) > N^{2k}\}|}{\varphi(B_r(y)) r^n} < \infty.$$

Now we to derive the decay estimates of the measure of the upper-level set $\{x \in \Omega : M(|Du|^2) > N^{2k}\}$ for $k = 1, 2, \dots$. To apply Lemma 4.3, first fix ε and take δ and N as given in Lemma 4.5. Then define the sets

$$E = \{x \in \Omega : M(|Du|^2) > N^2\},$$

$$D = \{x \in \Omega : M(|Du|^2) > 1\} \cup \{x \in \Omega : M(|f|^2) > \delta^2\}.$$

Check its hypotheses. It is clearly, $E \subset D \subset \Omega$, and for each $y \in \Omega$

$$\frac{|E \cap B_1(y)|}{|B_1(y)|} \leq C \left(\frac{|E \cap B_1(y)|}{|B_1(y)|} \right)^{\tau_1} \stackrel{def}{=} A_1$$

for some constants $C > 1$ and $\tau_1 \in (0, 1)$ in case $E \subset B_1$. Here constants C and τ_1 depend only on n, p and thus not on E and B_1 . Then

$$\begin{aligned} A_1 &\leq C|E|^{\tau_1} \leq (\text{by estimate (4.1)}) \leq \\ &\leq C \left(\int_{\Omega} |Du|^2 dx \right)^{\tau_1} \leq C \left(\int_{\Omega} |f|^2 dx \right)^{\tau_1} \leq \\ &\leq (\text{by estimate(5.3)}) \leq C\delta^{2\tau_1\tau_2} < \varepsilon, \end{aligned}$$

for δ small enough. Because the second condition of Lemma 4.3 is already checked in Lemma 4.5,

$$\begin{aligned} &|\{x \in \Omega : M(|Du|^2) > N^{2k}\}| \leq \\ &\leq C\varepsilon|\{x \in \Omega : M(|Du|^2) > 1\}| + C\varepsilon|\{x \in \Omega : M(|f|^2) > \delta^2 N^{2(k-i)}\}|. \end{aligned} \quad (5.4)$$

On the other hand the main problem (3.1) has the invariance property from normalization Lemma 4.1 and therefore the same result(5) may be obtained for $\left(\frac{u}{N}, \frac{f}{N}\right), \left(\frac{u}{N^2}, \frac{f}{N^2}\right), \dots$, inductively.

After this iteration the following power decay estimates are obtained for $k = 1, 2, \dots$

$$\begin{aligned} &|\{x \in \Omega : M(|Du|^2) > N^{2k}\}| \leq \\ &\leq \varepsilon_1^k |\{x \in \Omega : M(|Du|^2) > 1\}| + \sum_{i=1}^k \varepsilon_1^i |\{x \in \Omega : M(|f|^2) > \delta^2 N^{2(k-i)}\}|, \end{aligned}$$

where $\varepsilon_1 = C\varepsilon$. Then a direct computation yields

$$S \leq C \sum_{k \geq 1} (\nu_1 \varepsilon_1)^k$$

where $\varepsilon_1 = C\varepsilon$ as in Lemma 4.3. First take sufficiently small $\varepsilon > 0$ to get

$$\nu_1 \varepsilon_1 < 1.$$

Then one can select correspondingly small $\delta = \delta(c_0, c_1, n, \varphi) > 0$ from Lemma 4.5. This completes the proof.

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