

Periodic solutions of Euler-Lagrange equations in an Orlicz-Sobolev space setting by the dual least action principle

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Abstract

1 Introduction

This paper deals with system of equations of the type:

$$\begin{cases} \frac{d}{dt} D_y \mathcal{L}(t, u(t), u'(t)) = D_x \mathcal{L}(t, u(t), u'(t)) & \text{a.e. } t \in (0, T) \\ u(0) - u(T) = u'(0) - u'(T) = 0, \end{cases} \quad (P_1)$$

where $\mathcal{L} : [0, T] \times \mathbb{R}^d \times \mathbb{R}^d \rightarrow \mathbb{R}$, $d \geq 1$, is called the *Lagrange function* or *lagrangian* and the unknown function $u : [0, T] \rightarrow \mathbb{R}^d$ is absolutely continuous. In other words, we are interested in finding *periodic weak solutions* of *Euler-Lagrange system*. This topic was deeply addressed for the *Lagrange function*

$$\mathcal{L}_{p,F}(t, x, y) := \frac{|y|^p}{p} + F(t, x), \quad (1)$$

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for $1 < p < \infty$. For example, the classic book [Mawhin and Willem, 1989] deals mainly with problem (P_1) , for the lagrangian $\mathcal{L}_{2,F}$, through various methods: direct, dual action, minimax, etc. The results in [Mawhin and Willem, 1989] were extended and improved in several articles, see [Tang, 1995, Tang, 1998, Wu and Tang, 1999, Tang and Wu, 2001, Zhao and Wu, 2004] to cite some examples. Lagrange functions (1) for arbitrary $1 < p < \infty$ were considered in [Tian and Ge, 2007, Tang and Zhang, 2010] and in this case (P_1) is reduced to the p -laplacian system

$$\begin{cases} \frac{d}{dt}(u'(t)|u'|^{p-2}) = \nabla F(t, u(t)) & \text{a.e. } t \in (0, T) \\ u(0) - u(T) = u'(0) - u'(T) = 0. \end{cases} \quad (P_2)$$

In this context, it is customary to call F a *potential function*, and it is assumed that $F(t, x)$ is differentiable with respect to x for a.e. $t \in [0, T]$ and the following conditions are verified:

(C) F and its gradient ∇F , with respect to $x \in \mathbb{R}^d$, are Carathéodory functions, i.e. they are measurable functions with respect to $t \in [0, T]$, for every $x \in \mathbb{R}^d$, and they are continuous functions with respect to $x \in \mathbb{R}^d$ for a.e. $t \in [0, T]$.

(A) For a.e. $t \in [0, T]$, it holds that

$$|F(t, x)| + |\nabla F(t, x)| \leq a(|x|)b(t). \quad (2)$$

In this inequality we assume that the function $a : [0, +\infty) \rightarrow [0, +\infty)$ is continuous and non decreasing and $0 \leq b \in L^1([0, T], \mathbb{R})$.

In [Acinas et al., 2015] it was treated the case of a lagrangian \mathcal{L} which is lower bounded by a Lagrange function

$$\mathcal{L}_{\Phi, F}(t, x, y) = \Phi(|y|) + F(t, x), \quad (3)$$

where Φ is an N -function (see section 2 for the definition of this concept). In the paper [Acinas et al., 2015] it was assumed a condition of *bounded oscillation* on F (see xxxxx below). In this paper we apply the dual method ([Mawhin and Willem, 1989, Ch. 3]) to obtain solutions of (P_1) .

2 Anisotropic Orlicz and Orlicz-Sobolev spaces

In this section, we give a short introduction to Orlicz and Orlicz-Sobolev spaces of vector valued functions associated to anisotropic Young functions $\Phi : \mathbb{R}^n \rightarrow \mathbb{R}_+$, i.e. functions such that $\Phi(x)$ depends on the direction of x , unlike the radial case where $\Phi(x) = \Phi(|x|)$. References for these topics are [Schappacher, 2005, Skaff, 1969, Desch and Grimmer, 2001].

In the framework of anisotropic Sobolev-Orlicz spaces, we can study system of p -laplacian equations as the following example shows.

Example 1. Let $1 < p_1, p_2 < \infty$. We define $\Phi_{p_1, p_2} : \mathbb{R}^2 \rightarrow \mathbb{R}_+$ by

$$\Phi_{p_1, p_2}(y_1, y_2) := \frac{|y_1|}{p_1} + \frac{|y_2|}{p_2}.$$

Suppose the following Lagrange function

$$\mathcal{L}(t, x, y) = \Phi_{p_1, p_2}(y) + F(t, x).$$

Then the equations (P_1) becomes

$$\begin{cases} \frac{d}{dt}(|u_1'|^{p_1-2}u_1') = F_{x_1}(t, u) & \text{a.e. } t \in (0, T) \\ \frac{d}{dt}(|u_2'|^{p_2-2}u_2') = F_{x_2}(t, u) & \text{a.e. } t \in (0, T) \\ u(0) - u(T) = u'(0) - u'(T) = 0, \end{cases} \quad (P_3)$$

These equations are known in the literature as (p_1, p_2) -Laplacian system, see [Yang and Chen, 2013, Pasca and Wang, 2016, Yang and Chen, 2012, Pasca, 2010, Paşca and Tang, 2010, Pasca and Tang, 2011].

On the other hand, anisotropic Orlicz-Sobolev spaces allow to simplify the writing, and they provide the natural frame of statements of the type [Tian and Ge, 2007, Lemma 3.1]. This type of question was what motivated us to use these spaces.

Hereafter we denote by \mathbb{R}^+ the set of all non negative real numbers. A function $\Phi : \mathbb{R}^d \rightarrow \mathbb{R}_+$ is called an *Young's function* if Φ is convex, $\Phi(0) = 0$, $\Phi(-x) = \Phi(x)$ and $\Phi(x) \rightarrow +\infty$, when $|x| \rightarrow +\infty$. Additionally, we assume that the Young's functions which we deal with, satisfy that $\Phi(x) > 0$ when $x \neq 0$. Following [Schappacher, 2005] we say that Φ is an N_∞ -function if

$$\lim_{|x| \rightarrow \infty} \frac{\Phi(x)}{|x|} = +\infty.$$

Given a Young's function Φ , we define function $A_\Phi : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ by

$$A_\Phi(s) = \min \{ \Phi(x) \mid \|x\| = s \}, \quad (4)$$

Let us establish some elementary properties of A_Φ that we will use in this article.

Proposition 2.1. *The function A_Φ has the following properties:*

1. A_Φ is continuous,
2. $A_\Phi(s)/s$ is increasing,
3. $A_\Phi(|x|)$ is the greatest radial minorant of $\Phi(x)$,
4. Φ is N_∞ if and only if A_Φ is.

Proof. It is well known that finite and convex functions defined in finite dimensional vectorial spaces are locally Lipschitz functions (see [Clarke, 2013]). This fact imply item 1 immediately.

In order to prove item 2, suppose $0 < r < s$ and $x \in \mathbb{R}^d$ with $A_\Phi(s) = \Phi(x)$. Then, from the definition of A_Φ and the convexity of Φ ,

$$\frac{A_\Phi(r)}{r} \leq \frac{\Phi\left(\frac{r}{s}x\right)}{r} \leq \frac{\Phi(x)}{s} = \frac{A_\Phi(s)}{s}.$$

Property in items 3 and 4 are obtained easily. □

We also say that $\Phi : \mathbb{R}^d \rightarrow \mathbb{R}^+$ satisfies the Δ_2^∞ -condition, denoted by $\Phi \in \Delta_2^\infty$, if there exist constants $K > 0$ and $M \geq 0$ such that

$$\Phi(2x) \leq KH(x), \quad (5)$$

for every $|x| \geq M$.

If Φ is a Young's function we define its *Fenchel conjugate* $\Phi^* : \mathbb{R}^d \rightarrow \mathbb{R}^+$ by:

$$\Phi^*(y) = \sup_{x \in \mathbb{R}^d} x \cdot y - \Phi(x) \quad (6)$$

We denote by $\mathcal{M} := \mathcal{M}([0, T], \mathbb{R}^d)$, with $d \geq 1$, the set of all measurable functions (i.e. functions which are limits of simple functions) defined on $[0, T]$ with values on \mathbb{R}^d and we write $u = (u_1, \dots, u_d)$ for $u \in \mathcal{M}$. For the set of functions \mathcal{M} , as for other similar sets, we will omit the reference to codomain \mathbb{R}^d when $d = 1$.

Given an N -function Φ we define the *modular function* $\rho_\Phi : \mathcal{M} \rightarrow \mathbb{R}^+ \cup \{+\infty\}$ by

$$\rho_\Phi(u) := \int_0^T \Phi(u) dt.$$

Here $|\cdot|$ is the euclidean norm of \mathbb{R}^d . Now, we introduce the *Orlicz class* $C^\Phi = C^\Phi([0, T], \mathbb{R}^d)$ by setting

$$C^\Phi := \{u \in \mathcal{M} | \rho_\Phi(u) < \infty\}. \quad (7)$$

The *Orlicz space* $L^\Phi = L^\Phi([0, T], \mathbb{R}^d)$ is the linear hull of C^Φ ; equivalently,

$$L^\Phi := \{u \in \mathcal{M} | \exists \lambda > 0 : \rho_\Phi(\lambda u) < \infty\}. \quad (8)$$

The Orlicz space L^Φ equipped with the *Luxemburg norm*

$$\|u\|_{L^\Phi} := \inf \left\{ \lambda \left| \rho_\Phi \left(\frac{v}{\lambda} \right) dt \leq 1 \right. \right\},$$

is a Banach space. By $u \cdot v$ we denote the usual dot product in \mathbb{R}^d between u and v .

The subspace $E^\Phi = E^\Phi([0, T], \mathbb{R}^d)$ is defined as the closure in L^Φ of the subspace $L^\infty([0, T], \mathbb{R}^d)$ of all \mathbb{R}^d -valued essentially bounded functions. It is shown that (see [Schappacher, 2005, Thm. 5.1]) $u \in E^\Phi$ if and only if $\rho_\Phi(\lambda u) < \infty$ for any $\lambda > 0$. The equality $L^\Phi = E^\Phi$ is true if and only if $\Phi \in \Delta_2^\infty$ (see [Schappacher, 2005, Thm. 5.2]). Another alternative characterization of E^Φ , which is particularly useful for us, is that $u \in E^\Phi$ if and only if u has *absolutely continuous norm*, i.e. if $E_n \subset [0, T]$, $n = 1, 2, \dots$ then $\|\chi_{E_n} u\| \rightarrow 0$ when $|E_n| \rightarrow 0$.

A generalized version of *Hölder's inequality* holds in Orlicz spaces (see [Skaff, 1969, Thm. 4.1]). Namely, if $u \in L^\Phi$ and $v \in L^{\Phi^*}$ then $u \cdot v \in L^1$ and

$$\int_0^T v \cdot u dt \leq 2 \|u\|_{L^\Phi} \|v\|_{L^{\Phi^*}}. \quad (9)$$

Like in [Krasnosel'skiĭ and Rutickiĭ, 1961] we will consider the subset $\Pi(E^\Phi, r)$ of L^Φ given by

$$\Pi(E^\Phi, r) := \{u \in L^\Phi | d(u, E^\Phi) < r\}.$$

This set is related to the Orlicz class C^Φ by means of inclusions, namely,

$$\Pi(E^\Phi, r) \subset rC^\Phi \subset \overline{\Pi(E^\Phi, r)} \quad (10)$$

for any positive r (see [Schappacher, 2005, Thm. 5.6]). If $\Phi \in \Delta_2^\infty$, then the sets L^Φ , E^Φ , $\Pi(E^\Phi, r)$ and C^Φ are equal.

Following to [Desch and Grimmer, 2001] we introduce the next definition.

Definition 2.2. Let $u_n, u \in L^\Phi([0, T], \mathbb{R}^d)$. We say that u_n converges monotonically to u if there exists $\alpha_n \in L^\infty([0, T], \mathbb{R})$, $n = 1, 2, \dots$, such that $0 \leq \alpha_n(t) \leq \alpha_{n+1}(t)$, $\alpha_n(t) \rightarrow 1$ a.e., when $n \rightarrow \infty$ and $u_n(t) = \alpha_n(t)u(t)$.

As usual, if $(X, \|\cdot\|_X)$ is a normed space and $(Y, \|\cdot\|_Y)$ is a linear subspace of X , we write $Y \hookrightarrow X$ and we say that Y is *embedded* in X when there exists $C > 0$ such that $\|y\|_X \leq C\|y\|_Y$ for any $y \in Y$. With this notation, Hölder's inequality states that $L^{\Phi^*} \hookrightarrow [L^\Phi]^*$, where a function $v \in L^{\Phi^*}$ is associated to $\xi_v \in [L^\Phi]^*$ being

$$\xi_v(u) = \langle \xi_v, u \rangle = \int_0^T v \cdot u \, dt, \quad (11)$$

In [Desch and Grimmer, 2001, Thm 2.9] it was characterized a subspace of $[L^\Phi]^*$ which can be identified with L^{Φ^*} .

Proposition 2.3. Let $F \in [L^\Phi([0, T], \mathbb{R}^d)]^*$. Then the following statements are equivalent

1. $\xi \in L^{\Phi^*}([0, T], \mathbb{R}^d)$
2. ξ satisfies the monotone convergence property, which is if u_n converges monotonically to u then $\langle \xi, u_n \rangle \rightarrow \langle \xi, u \rangle$.

If $\Phi \in \Delta_2^\infty$ and Φ is N_∞ then $L^{\Phi^*}([0, T], \mathbb{R}^d) = [L^\Phi([0, T], \mathbb{R}^d)]^*$ (see [Desch and Grimmer, 2001, Thm. 2.9, Thm. 2.10]).

We define the *Sobolev-Orlicz space* $W^1 L^\Phi$ by

$$W^1 L^\Phi([0, T], \mathbb{R}^d) := \{u | u \text{ is absolutely continuous on } [0, T] \text{ and } u' \in L^\Phi([0, T], \mathbb{R}^d)\}.$$

$W^1 L^\Phi([0, T], \mathbb{R}^d)$ is a Banach space when equipped with the norm

$$\|u\|_{W^1 L^\Phi} = \|u\|_{L^\Phi} + \|u'\|_{L^\Phi}. \quad (12)$$

And, we introduce the following subspaces of $W^1 L^\Phi$

$$\begin{aligned} W^1 E^\Phi &= \{u \in W^1 L^\Phi | u' \in E^\Phi\}, \\ W^1 E_T^\Phi &= \{u \in W^1 E^\Phi | u(0) = u(T)\}. \end{aligned} \quad (13)$$

We will use repeatedly the decomposition $u = \bar{u} + \tilde{u}$ for a function $u \in L^1([0, T])$ where $\bar{u} = \frac{1}{T} \int_0^T u(t) \, dt$ and $\tilde{u} = u - \bar{u}$.

The following lemma is an elementary generalization to anisotropic Sobolev-Orlicz spaces of known results of Sobolev spaces.

Lemma 2.4. *Let $\Phi : \mathbb{R}^d \rightarrow [0, +\infty)$ be a Young's function and let $u \in W^1 L^\Phi([0, T], \mathbb{R}^d)$. Let $A_\Phi : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ be the function defined by (4). Then*

1. *For every $s, t \in [0, T]$, $s \neq t$,*

$$|u(t) - u(s)| \leq \|u'\|_{L^\Phi} |s - t| A_\Phi^{-1} \left(\frac{1}{|s - t|} \right) \quad (\text{Morrey's inequality})$$

$$\|u\|_{L^\infty} \leq A_\Phi^{-1} \left(\frac{1}{T} \right) \max\{1, T\} \|u\|_{W^1 L^\Phi} \quad (\text{Sobolev's inequality})$$

2. *We have $\tilde{u} \in L^\infty([0, T], \mathbb{R}^d)$ and*

$$\|\tilde{u}\|_{L^\infty} \leq T A_\Phi^{-1} \left(\frac{1}{T} \right) \|u'\|_{L^\Phi} \quad (\text{Sobolev-Wirtinger's inequality})$$

3. *If Φ is N_∞ then the space $W^1 L^\Phi([0, T], \mathbb{R}^d)$ is compactly embedded in the space of continuous functions $C([0, T], \mathbb{R}^d)$.*

Proof. By the absolutely continuity of u , Jensen's inequality and the definition of the Luxemburg norm, we have

$$\begin{aligned} \Phi \left(\frac{u(t) - u(s)}{\|u'\|_{L^\Phi} |s - t|} \right) &\leq \Phi \left(\frac{1}{|s - t|} \int_s^t \frac{u'(r)}{\|u'\|_{L^\Phi}} dr \right) \\ &\leq \frac{1}{|s - t|} \int_s^t \Phi \left(\frac{u'(r)}{\|u'\|_{L^\Phi}} \right) dr \leq \frac{1}{|s - t|}. \end{aligned}$$

By Proposition 2.1(3) we have $A_\Phi^{-1} \Phi(x) \geq |x|$, therefore we get

$$\frac{|u(t) - u(s)|}{\|u'\|_{L^\Phi} |s - t|} \leq A_\Phi^{-1} \left(\frac{1}{|s - t|} \right),$$

then 1 holds.

Now, we use Morrey's inequality and Proposition 2.1 (2) and we have

$$\begin{aligned} |u(t) - \bar{u}| &= \left| \frac{1}{T} \int_0^T u(t) - u(s) ds \right| \\ &\leq \frac{1}{T} \int_0^T |u(t) - u(s)| ds \\ &\leq \|u'\|_{L^\Phi} T A_\Phi^{-1} \left(\frac{1}{T} \right) \end{aligned}$$

In order to prove the Sobolev's inequality, we note that, using Jensen's inequality and the definition of $\|u\|_{L^\Phi}$, we obtain

$$\Phi \left(\frac{\bar{u}}{\|u\|_{L^\Phi}} \right) \leq \frac{1}{T} \int_0^T \Phi \left(\frac{u(s)}{\|u\|_{L^\Phi}} \right) ds \leq \frac{1}{T}$$

Then by Proposition 2.1(3)

$$|\bar{u}| \leq A_{\Phi}^{-1} \left(\frac{1}{T} \right) \|u\|_{L^{\Phi}}.$$

Therefore, from this and (Sobolev-Wirtinger's inequality) we get

$$\begin{aligned} \|u\|_{L^{\infty}} &\leq |\bar{u}| + \|\tilde{u}\|_{L^{\infty}} \\ &\leq A_{\Phi}^{-1} \left(\frac{1}{T} \right) \|u\|_{L^{\Phi}} + T A_{\Phi}^{-1} \left(\frac{1}{T} \right) \|u'\|_{L^{\Phi}} \\ &\leq A_{\Phi}^{-1} \left(\frac{1}{T} \right) \max\{1, T\} \|u\|_{W^1 L^{\Phi}} \end{aligned}$$

In order to prove item 3, we take a bounded sequence u_n in $W^1 L^{\Phi}([0, T], \mathbb{R}^d)$. Since Φ is N_{∞} , from Proposition 2.1(4) we obtain $s A_{\Phi}^{-1}(1/s) \rightarrow 0$ when $s \rightarrow 0$. Therefore (Morrey's inequality) implies that u_n are equicontinuous. Furthermore (Sobolev's inequality) implies that u_n is bounded in $C([0, T], \mathbb{R}^d)$. Therefore by the Arzela-Ascoli Theorem we obtain a subsequence n_k and $u \in C([0, T], \mathbb{R}^d)$ with $u_{n_k} \rightarrow u$ in $C([0, T], \mathbb{R}^d)$. \square

3 Differentiability Gateaux of action integrals

In this section we give a brief introduction to superposition operators between anisotropic Orlicz Spaces. We apply these results to obtain Gateaux differentiability of action integrals associated to lagrangian functions defined in Sobolev-Orlicz spaces.

Henceforth we assume that $f : [0, T] \times \mathbb{R}^d \rightarrow \mathbb{R}^d$ is a *Carathéodory function*, i.e.

- (C) f is measurable with respect to $t \in [0, T]$ for every $x \in \mathbb{R}^d$, and f is a continuous function with respect to $x \in \mathbb{R}^d$ for a.e. $t \in [0, T]$.

Definition 3.1. For $f : [0, T] \times \mathbb{R}^d \rightarrow \mathbb{R}^d$ we denote by \mathbf{f} the Nemytskii (or superposition) operator defined for functions $u : [0, T] \rightarrow \mathbb{R}^d$ by

$$\mathbf{f}u(t) = f(t, u(t))$$

In the following Theorem we enumerate some known properties for superposition operators defined in anisotropic Orlicz spaces of vectorial functions. For the proofs see [Krasnosel'skii et al., 2011] for scalar functions and [Pluciennik, 1987, Pluciennik, 1985b, Pluciennik, 1985a] for the generalization to \mathbb{R}^d -valued (moreover Banach spaces valued) functions in a anisotropic Orlicz Spaces (moreover modular anisotropic spaces).

Theorem 3.2. We assume that f satisfies condition ((C)) and that $\Phi_1, \Phi_2 : \mathbb{R}^d \rightarrow [0, +\infty)$ are anisotropic Young functions. Then

1. Measurability. The operator \mathbf{f} maps measurable function into measurable functions

2. Extensibility. *If the operator f acts from the ball $B_{L^{\Phi_1}}(r) := \{u \in L^{\Phi_1} \mid \|u\|_{L^{\Phi_1}} < r\}$ into the space L^{Φ_2} or the space E^{Φ_2} then f can be extended to $\Pi(E^{\Phi_1}, r)$ into space L^{Φ_2} or E^{Φ_2} respectively.*
3. Continuity. *If the operator f acts from $\Pi(E^{\Phi_1}, r)$ into space E^{Φ_2} , then f is continuous.*

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