Periodic solutions of Euler-Lagrange equations in an anisotropic Orlicz-Sobolev space setting

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Abstract

1 Introduction

In this paper we obtain existence of solutions for systems of equations of the type:

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

where the function $\mathcal{L} : [0, T] \times \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$, $d \geqslant 1$ (called the *Lagrange function* or *lagrangian*) satisfying that it is measurable in t for each $(x, y) \in \mathbb{R}^d \times \mathbb{R}^d$ and continuously differentiable in (x, y) for almost every $t \in [0, T]$. The unknown function $u : [0, T] \to \mathbb{R}^d$ is assumed absolutely continuous.

Our approach involves the direct method of the calculus of variations in the framework of *anisotropic Orlicz-Sobolev spaces*. We suggest the articles [16] for definitions and main results on anisotropic Orlicz spaces, see also [2]. These spaces allow us to unify and extend previous results on existences of solutions for systems like ($\boldsymbol{P}$).

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2010 AMS Subject Classification. Primary: . Secondary: .

Keywords and phrases. .

Through this article we said that a function $\Phi : \mathbb{R}^d \to [0, +\infty)$ is of N_∞ class if Φ is convex, $\Phi(0) = 0$, $\Phi(x) > 0$ if $x \neq 0$ and $\Phi(-y) = \Phi(y)$, and

$$\lim_{|y| \to \infty} \frac{\Phi(y)}{|y|} = +\infty. \tag{1}$$

where $|\cdot|$ denotes the euclidean norm on $\mathbb{R}^d$. From [3, Cor. 2.35] a N_∞ function is continuous.

Associated to Φ we have the *complementary function* Ψ which is defined in $\xi \in \mathbb{R}^d$ as

$$\Psi(\xi) = \sup_{y \in \mathbb{R}^d} y \cdot \xi - \Phi(y) \tag{2}$$

then, from the continuity of Φ and (1), we have that $\Psi : \mathbb{R}^d \to [0, \infty)$. Moreover, it is easy to see that Ψ is a convex function such that $\Psi(0) = 0$, $\Psi(-\xi) = \Psi(\xi)$ and $\Psi(\xi) \to \infty$ when $|\xi| \to \infty$, see [3, Section 4.2], [8, Chapter 2]. Moreover Ψ satisfies (1) (see [16, Th. 2.2]). i.e. Ψ is N_∞ function.

Some examples of N_∞ functions are the following.

Example 1.1. $\Phi_p(y) := |y|^p/p$, for $1 < p < \infty$. In this case $\Psi(\xi) = |\xi|^q/q$, $q = p/(p-1)$.

Example 1.2. If $\Phi : \mathbb{R} \to [0, +\infty)$ is a N_∞ function on $\mathbb{R}$ then $\overline{\Phi}(y) = \Phi(|y|)$ is a N_∞ function on $\mathbb{R}^d$. In this example, as in the previous one, the function Φ is *radial*, i.e. the value of $\Phi(y)$ depends on the norm of y and not on its direction. These cases are not authentically anisotropic.

Example 1.3. An anisotropic function $\Phi(y)$ depends on the direction of y. For example, if $1 < p_1, p_2 < \infty$, we define $\Phi_{p_1, p_2} : \mathbb{R}^d \times \mathbb{R}^d \to [0, +\infty)$ by

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

Then Φ_{p_1, p_2} is a N_∞ function. In this case the complementary function is the function Φ_{q_1, q_2} with $q_i = p_i/(p_i - 1)$.

More generally, if $\Phi_k : \mathbb{R}^d \to [0, +\infty)$, $k = 1, \ldots, n$, are N_∞ functions, then $\Phi : \mathbb{R}^d \times \cdots \times \mathbb{R}^d \to [0, +\infty)$ defined by $\Phi(y_1, \ldots, y_n) = \Phi_1(y_1) + \cdots + \Phi_n(y_n)$ is a N_∞ function. These functions are truly anistropic, i.e. $|x| = |y|$ does not implies that $\Phi(x) = \Phi(y)$.

Example 1.4. If $\Phi : \mathbb{R} \to [0, +\infty)$ is a N_∞ function and $O \in GL(d, \mathbb{R})$, then $\Phi(y) = \Phi(Oy)$ is a N_∞ function.

Example 1.5. An anisotropic N_∞ function is not necessarily controlled by powers if it does not satisfy the Δ_2 condition (see xxxxx). For example $\Phi : \mathbb{R}^d :\to [0, +\infty)$ defined by $\Phi(y) = \exp(|y|) - 1$ is N_∞ function.

The occurrence of Orlicz Spaces in this paper obeys to we will consider the following structure condition on the lagrangian:

$$|\mathcal{L}| + |\nabla_x \mathcal{L}| + \Psi(\nabla_y \mathcal{L}) \leqslant a(x) \left\{ b(t) + \Phi\left(\frac{y}{\lambda}\right) \right\}, \tag{S}$$

for a.e. $t \in [0, T]$, where $a \in C\left(\mathbb{R}^d, [0, +\infty)\right)$, $b \in L^1\left([0, T], [0, +\infty)\right)$.

Our condition (S) includes structure conditions that have previously been considered in the literature. For example, it is easy to see that, when $\Phi(x)$ is as in Example

1.1, then the condition (S) is equivalent to the structure condition in [8, Th. 1.4]. If Φ is a radial N_∞ function such that Ψ satisfies tha Δ_2 function (see xxxxxx) then (S) is essentially equivalent to conditions [1, Eq. (2)-(4)]. If Φ is as in Example 1.3 and $\mathcal{L} = \mathcal{L}(t, x_1, x_2, y_1, y_2)$ then Inequality (S) is related to estructure conditions like [22, Lemma 3.1, Eq. (3.1)]. As can be seen, condition (S) is a more compact expression than [22, Lemma 3.1, Eq. (3.1)] and moreover is more weaker, because (S) does not imply a control of $|D_{y_1}L|$ independent of y_2. We will return to this point later.

An important example of lagrangian is giving by:

$$\mathcal{L}_{\Phi,F}(t, x, y) := \Phi(y) + F(t, x). \tag{3}$$

Here the function $F(t, x)$, which is often referred to potential, be differentiable with respect to x for a.e. $t \in [0, T]$. Moreover F satisfies the following conditions:

(C) F and its gradient $\nabla_x F$, 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

$$|F(t, x)| + |\nabla_x F(t, x)| \leqslant a(x)b(t). \tag{4}$$

where $a \in C\left(\mathbb{R}^d, [0, +\infty)\right)$ and $0 \leqslant b \in L^1([0, T], \mathbb{R})$.

The lagrangian $\mathcal{L}_{\Phi,F}$ satisfies condition (S). In order to prove this, the only non trivial fact that we should to establishis is that $\Psi(\nabla_y \mathcal{L}) \leqslant a(x)\{b(t) + \Phi(y/\lambda)\}$. But, from inequality xxxx below, $\Psi(\nabla_y \mathcal{L}) = \Psi(\nabla \Phi(y)) \leqslant \Phi(2y)$.

The laplacian $\mathcal{L}_{\Phi,F}$ leads to the system

$$\begin{cases} \frac{d}{dt}\nabla\Phi(u'(t)) = \nabla_x F(t, u(t)) & \text{a.e. } t \in (0, T), \\ u(0) - u(T) = u'(0) - u'(T) = 0, \end{cases} \tag{P_Φ}$$

Problem (P_Φ) contains, as a particular case, many problems that are usually considered in the literature. For example, the classic book [8] deals mainly with problem (P), for the lagrangian $\mathcal{L}_{\Phi,F}$, with $\Phi(x) = |x|^2/2$, through various methods: direct, dual action, minimax, etc. The results in [8] were extended and improved in several articles, see [20, 18, 23, 19, 26] to cite some examples. The case $\Phi(y) = |y|^p/p$, for arbitrary $1 < p < \infty$ were considered in [22, 21], among other papers, and in this case (P_Φ) is reduced to the p-laplacian system

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

If Φ is as in Example 1.3 and $F : [0, T] \times \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$ is a Carathéodory function, then the equations (P_Φ) become

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

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where $x = (x_1, x_2) \in \mathbb{R}^d \times \mathbb{R}^d$ and $u(t) = (u_1(t), u_2(t)) \in \mathbb{R}^d \times \mathbb{R}^d$. In the literature, these equations are known as (p_1, p_2)-Laplacian system, see [25, 12, 24, 9, 10, 11, 6].

In conclusion, the problem $(\boldsymbol{P})$ with conditions $(\boldsymbol{S})$ contains several problems that have been considered by many authors in the past.

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 N_∞ functions $\Phi : \mathbb{R}^n \to [0, +\infty)$. References for these topics are [4, 16, 17].

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

$$\Phi(2x) \leqslant K\Phi(x), \tag{5}$$

for every $|x| \geqslant M$.

We denote by $\mathcal{M} := \mathcal{M}\left([0, T], \mathbb{R}^d\right)$, with $d \geqslant 1$, 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 $u = (u_1, \ldots, u_d)$ for $u \in \mathcal{M}$.

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

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

Now, we introduce the *Orlicz class* $C^\Phi = C^\Phi\left([0, T], \mathbb{R}^d\right)$ by setting

$$C^\Phi := \left\{ u \in \mathcal{M} \,|\, \rho_\Phi(u) < \infty \right\}. \tag{6}$$

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

$$L^\Phi := \left\{ u \in \mathcal{M} \,|\, \exists \lambda > 0 : \rho_\Phi(\lambda u) < \infty \right\}. \tag{7}$$

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

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

is a Banach space.

The subspace $E^\Phi = E^\Phi\left([0, T], \mathbb{R}^d\right)$ is defined as the closure in L^Φ of the subspace $L^\infty\left([0, T], \mathbb{R}^d\right)$ of all $\mathbb{R}^d$-valued essentially bounded functions. It is shown that (see [16, 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 [16, Thm. 5.2]).

A generalized version of *Hölder's inequality* holds in Orlicz spaces (see [16, Thm. 7.2]). Namely, if $u \in L^\Phi$ and $v \in L^\Psi$ then $u \cdot v \in L^1$ and

$$\int_0^T v \cdot u \, dt \leqslant 2\|u\|_{L^\Phi}\|v\|_{L^\Psi}. \tag{8}$$

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

We consider the subset $\Pi(E^\Phi, r)$ of L^Φ given by

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

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

$$\Pi(E^\Phi, r) \subset rC^\Phi \subset \overline{\Pi(E^\Phi, r)} \tag{9}$$

for any positive r. This relation is a trivial generalization of [16, 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.

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 $\|y\|_X \leqslant C\|y\|_Y$ for any $y \in Y$. With this notation, Hölder's inequality states that $L^\Phi \hookrightarrow \left[L^\Psi\right]^*$, where a function $v \in L^\Phi$ is associated to $\xi_v \in \left[L^\Psi\right]^*$ being

$$\xi_v(u) = \langle \xi_v, u \rangle = \int_0^T v \cdot u \, dt, \tag{10}$$

We highlight the following result that is a consequence of Theorems 7.1 and 7.3 in [16].

Proposition 2.1. *If Ψ satisfies the Δ_2^∞-condition then $L^\Phi\left([0,T], \mathbb{R}^d\right) = \left[L^\Psi\left([0,T], \mathbb{R}^d\right)\right]^*$.*

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

$$W^1 L^\Phi\left([0,T], \mathbb{R}^d\right) \coloneqq \left\{u | u \in AC\left([0,T], \mathbb{R}^d\right) \text{ and } u' \in L^\Phi\left([0,T], \mathbb{R}^d\right)\right\},$$

where $AC\left([0,T], \mathbb{R}^d\right)$ denotes the space of all $\mathbb{R}^d$ valued absolutely continuous functions defined on $[0,T]$. The space $W^1 L^\Phi\left([0,T], \mathbb{R}^d\right)$ is a Banach space when equipped with the norm

$$\|u\|_{W^1 L^\Phi} = \|u\|_{L^\Phi} + \|u'\|_{L^\Phi}. \tag{11}$$

We introduce the following subspaces of $W^1 L^\Phi$

$$\begin{aligned}
W^1 E^\Phi &= \{u \in W^1 L^\Phi | u' \in E^\Phi\}, \\
W^1 E_T^\Phi &= \{u \in W^1 E^\Phi | u(0) = u(T)\}.
\end{aligned} \tag{12}$$

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

$$A_\Phi(s) = \min\left\{\Phi(x) \,\middle|\, |x| = s\right\}, \tag{13}$$

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

Proposition 2.2. *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* $\lim_{s\to+\infty} A_\Phi(s)/s = +\infty$.

Proof. It is well known that finite and convex functions defined on finite dimensional vector spaces are locally Lipschitz functions (see [3]). This fact implies 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,

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

Property in items 3 and 4 are obtained easily.

$\square$

Example 2.1. We compute A_Φ for the function $\Phi = \Phi_{p_1,p_2}$ given in Example (1.3). We apply the method of Lagrange multipliers (see [7, Ch. 11]) to solve the next minimization problem subject to constraints

$$\begin{cases} \text{minimize } \Phi_{p_1,p_2}(y_1,y_2) \\ \text{subject to } |y_1|^2 + |y_2|^2 = r^2 \end{cases}.$$

The first order conditions are

$$\begin{cases} |y_1|^{p_1-2}y_1 + \lambda y_1 &= 0 \\ |y_2|^{p_2-2}y_2 + \lambda y_2 &= 0 \\ |y_1|^2 + |y_2|^2 &= r^2 \end{cases} \tag{14}$$

These equations are solved, among others, by the following two sets of citical points: a) $|x| = r$, $y = 0$ and $\lambda = -r^{p_1-2}$ and b) $x = 0$, $|y| = r$ and $\lambda = -r^{p_2-2}$. These sets are infinite when $d > 1$. Associated with these critical points we have the following critical values: a) r^{p_1}/p_1 and b) r^{p_2}/p_2.

We deal with $p_1 \leqslant 2$ and $p_2 \leqslant 2$ being one of them (suppose p_2) different from 2. The remaining cases can be treated with similar techniques.

If (y_1, y_2) solve (14) with $y_1 \neq 0$ and $y_2 \neq 0$ then $|y_2| = |y_1|^{\frac{p_1-2}{p_2-2}}$ and $\lambda = -|y_1|^{p_1-2}$. We use second order conditions for constrained problems. We have to consider the tangent plane at the point $(y_1, y_2) \in \mathbb{R}^{2n}$, i.e. $M = \{(\xi, \eta) \in \mathbb{R}^{2n} : \xi y_1^t + \eta y_2^T = 0\}$. Let L be the Lagrangian associated to the constrained problem: $L(y_1, y_2, \lambda) = \Phi(y_1, y_2) + \lambda H(y_1, y_2)$ being $H = 0$ the constraint. We must analize the positivity of the quadratic form associated to the matrix of second partial derivatives $\mathcal{H} = D^2\Phi + \lambda D^2 H$ on the subspace M. By elementary computations we have for $(\xi, \eta) \in M$

$$(\xi, \eta)^t \mathcal{H}(\xi, \eta) = |\lambda|(\xi^t x)^2 [|y_1|^{-2}(p_1 - 2) + (p_2 - 2)|y_2|^{-2}],$$

on the subspace M. We note that $(-y_2, y_1) \in M$ and $(-y_2, y_1)^t \mathcal{H}(-y_2, y_1) < 0$. Then, by second order necessary conditions [7, p.333], at (y_1, y_2) there cannot be a minimum. Therefore, the only minima occur at $y_1 = 0$ or $y_2 = 0$, then

$$A_\Phi(x, y) = \min\{r^{p_1}/p_1, r^{p_2}/p_2\}.$$

More generally, it holds that

$$K_1 \min\{r^{p_1}, r^{p_2}\} \leqslant A_\Phi \leqslant K_2 \min\{r^{p_1}, r^{p_2}\}$$

with $K_1, K_2 > 0$, for every $1 < p_1, p_2 < \infty$.

As is customary, we will use the decomposition $u = \overline{u} + \widetilde{u}$ for a function $u \in L^1([0, T])$ where $\overline{u} = \frac{1}{T} \int_0^T u(t)\, dt$ and $\widetilde{u} = u - \overline{u}$.

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

Lemma 2.3. *Let $\Phi : \mathbb{R}^d \to [0, +\infty)$ be a Young's function and let $u \in W^1 L^\Phi([0, T], \mathbb{R}^d)$. Let $A_\Phi : \mathbb{R}^+ \to \mathbb{R}^+$ be the function defined by (13). Then*

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

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

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

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

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

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

$$\Phi\left(\frac{u(t) - u(s)}{\|u'\|_{L^\Phi} |s - t|}\right) \leqslant \Phi\left(\frac{1}{|s - t|} \int_s^t \frac{u'(r)}{\|u'\|_{L^\Phi}}\, dr\right)$$
$$\leqslant \frac{1}{|s - t|} \int_s^t \Phi\left(\frac{u'(r)}{\|u'\|_{L^\Phi}}\right) dr \leqslant \frac{1}{|s - t|}.$$

By Proposition 2.2(3) we have $A_\Phi^{-1}\Phi(x) \geqslant |x|$, therefore we get

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

then 1 holds.

Now, we use Morrey's inequality and Proposition 2.2 (2) and we have

$$|u(t) - \overline{u}| = \left| \frac{1}{T} \int_0^T u(t) - u(s) \, ds \right|$$

$$\leqslant \frac{1}{T} \int_0^T |u(t) - u(s)| \, ds$$

$$\leqslant \|u'\|_{L^\Phi} T A_\Phi^{-1} \left(\frac{1}{T} \right)$$

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

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

Then by By Proposition 2.2(3)

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

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

$$\|u\|_{L^\infty} \leqslant |\overline{u}| + \|\tilde{u}\|_{L^\infty}$$

$$\leqslant A_\Phi^{-1} \left(\frac{1}{T} \right) \|u\|_{L^\Phi} + T A_\Phi^{-1} \left(\frac{1}{T} \right) \|u'\|_{L^\Phi}$$

$$\leqslant A_\Phi^{-1} \left(\frac{1}{T} \right) \max\{1, T\} \|u\|_{W^1 L^\Phi}$$

In order to prove item 3, we take a bounded sequence u_n in $W^1 L^\Phi \left([0,T], \mathbb{R}^d \right)$. Since Φ is N_∞, from Proposition 2.2(4) we obtain $s A_\Phi^{-1}(1/s) \to 0$ when $s \to 0$. Therefore (Morrey's inequality) implies that u_n are equicontinuous. Furthermore (**??**) implies that u_n is bounded in $C \left([0,T], \mathbb{R}^d \right)$. Therefore by the Arzela-Ascoli Theorem we obtain a subsequence n_k and $u \in C \left([0,T], \mathbb{R}^d \right)$ with $u_{n_k} \to u$ in $C \left([0,T], \mathbb{R}^d \right)$. $\square$

Lemma 2.4. *Let $\{u_n\}_{n\in\mathbb{N}}$ be a sequence of functions in $\Pi(E^\Phi, 1)$ converging to $u \in \Pi(E^\Phi, 1)$ in the L^Φ-norm. Then, there exist a subsequence u_{n_k} and a real valued function $h \in L^1([0,T], \mathbb{R})$ such that $u_{n_k} \to u$ a.e. and $\Phi(u_{n_k}) \leqslant h$ a.e.*

Proof. Since $d(u, E^\Phi) < 1$ and u_n converges to u, there exists $u_0 \in E^\Phi$, a subsequence of u_n (again denoted u_n) and $0 < r < 1$ such that $d(u_n, u_0) < r$. Let $\lambda_0 \in (r, 1)$. By extracting more subsequences, if necessary, we can assume that $u_n \to u$ a.e. and

$$\lambda_n := \|u_{n+1} - u_n\|_{L^\Phi} < \frac{1 - \lambda_0}{2^n}, \quad \text{for } n \geqslant 1.$$

We can assume $\lambda_n > 0$ for every $n = 0, \ldots$.

Let $\lambda := 1 - \sum_{n=0}^{\infty} \lambda_n$ and define $h : [0, T] \to \mathbb{R}$ by

$$h(x) = \lambda \Phi \left(\frac{u_0}{\lambda} \right) + \sum_{n=0}^{\infty} \lambda_n \Phi \left(\frac{u_{n+1} - u_n}{\lambda_n} \right). \tag{15}$$

Note that $\sum_{n=0}^{\infty} \lambda_n + \lambda = 1$, therefore for any $n = 1, \dots$

$$\Phi(u_n) = \Phi \left(\lambda \frac{u_0}{\lambda} + \sum_{j=0}^{n-1} \lambda_j \frac{u_{j+1} - u_j}{\lambda_j} \right)$$
$$\leqslant \lambda \Phi \left(\frac{u_0}{\lambda} \right) + \sum_{j=0}^{n-1} \lambda_j \Phi \left(\frac{u_{j+1} - u_j}{\lambda_j} \right) \leqslant h$$

Since $u_0 \in E^\Phi \subset C^\Phi$ and E^Φ is a subspace we have that $\Phi(u_0/\lambda) \in L^1([0, T], \mathbb{R})$. On the other hand $\|u_{n+1} - u_n\|_{L^\Phi} \leqslant \lambda_n$, therefore

$$\int_0^T \Phi \left(\frac{u_{j+1} - u_j}{\lambda_j} \right) dt \leqslant 1.$$

Then $h \in L^1([0, T], \mathbb{R})$.

$\square$

3   Differentiability Gateâux of action integrals in anisotropic Orlicz spaces

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

Henceforth we assume that $f : [0, T] \times \mathbb{R}^d \to \mathbb{R}^d$ 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 $f : [0, T] \times \mathbb{R}^d \to \mathbb{R}^d$ we denote by $\boldsymbol{f}$ the Nemytskii (o superposition) operator defined for functions $u : [0, T] \to \mathbb{R}^d$ by*

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

In the following Theorem we enumerate some known properties for superposition operators defined on anisotropic Orlicz spaces of vector functions. For the proofs see [5] for scalar functions and [15, 14, 13] 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 $\Phi_1, \Phi_2 : \mathbb{R}^d \to [0, +\infty)$ are anisotropic Young functions. Then*

1. Measurability. *The operator $\boldsymbol{f}$ maps measurable function into measurable functions*

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

3. Continuity. *If the operator $\boldsymbol{f}$ acts from $\Pi(E^{\Phi_1}, r)$ into space E^{Φ_2}, then $\boldsymbol{f}$ is continuous.*

Given a continuous function $a \in C(\mathbb{R}^n, \mathbb{R}^+)$, we define the composition operator $a : \mathcal{M}_d \to \mathcal{M}_d$ by $\boldsymbol{a}(u)(x) = a(u(x))$.

We will often use the following result whose proof can be performed as that of Corollary 2.3 in [1].

Lemma 3.3. *If $a \in C(\mathbb{R}^d, \mathbb{R}^+)$ then $\boldsymbol{a} : W^1 L^{\Phi} \to L^{\infty}([0, T])$ is bounded. More concretely, there exists a non decreasing function $A : \mathbb{R}^+ \to \mathbb{R}^+$ such that $\|\boldsymbol{a}(u)\|_{L^{\infty}([0, T])} \leqslant A(\|u\|_{W^1 L^{\Phi}})$.*

Proof. Let $A \in C(\mathbb{R}^+, \mathbb{R}^+)$ be a non decreasing, continuous function defined by $\alpha(s) := \sup_{\|x\| \leqslant s, x \in \mathbb{R}^d} |a(x)|$. If $u \in W^1 L_d^{\Phi}$ then, by Sobolev's inequality, for a.e. $t \in [0, T]$

$$a(u(t)) \leqslant \alpha(\|u\|_{L^{\infty}}) \leqslant \alpha\left(A_{\Phi}^{-1}\left(\frac{1}{T}\right)\max\{1, T\}\|u\|_{W^1 L^{\Phi}}\right) =: A(\|u\|_{W^1 L^{\Phi}}).$$

$\square$

HABRÍA QUE VER DÓNDE SE UBICA LA CONDICIÓN DE ESTRUCTURA...QUIZÁS EN LA INTRODUCCIÓN?....

Next, we deal with the differentiability of the action integral

$$I(u) = \int_0^T \mathcal{L}(t, u(t), \dot{u}(t)) \, dt. \tag{16}$$

Theorem 3.4. *Let $\mathcal{L}$ be a differentiable Carathéodory function satisfying ($\boldsymbol{S}$). Then the following statements hold:*

1. *The action integral given by (16) is finitely defined on $\mathcal{E}^{\Phi} := W^1 L^{\Phi} \cap \{u|\dot{u} \in \Pi(E^{\Phi}, 1)\}$.*

2. *The function I is Gâteaux differentiable on $\mathcal{E}^{\Phi}$ and its derivative I' is demicontinuous from $\mathcal{E}^{\Phi}$ into $\left[W^1 L^{\Phi}\right]^*$. Moreover, I' is given by the following expression*

$$\langle I'(u), v \rangle = \int_0^T \left\{ D_x \mathcal{L}(t, u, \dot{u}) \cdot v + D_y \mathcal{L}(t, u, \dot{u}) \cdot \dot{v} \right\} dt. \tag{17}$$

3. *If $\Psi \in \Delta_2$ then I' is continuous from $\mathcal{E}^{\Phi}$ into $\left[W^1 L^{\Phi}\right]^*$ when both spaces are equipped with the strong topology.*

Proof. Let $u \in \mathcal{E}^{\Phi}$. As

$$\dot{u} \in \Pi(E^{\Phi}, 1) \subset C_1^{\Phi} \tag{18}$$

and (9), then $\Phi(\dot{u}(t)) \in L^1$. Now,

$$|\mathcal{L}(\cdot, u, \dot{u})| + |D_x\mathcal{L}(\cdot, u, \dot{u})| + \Psi(D_y\mathcal{L}(\cdot, u, \dot{u})) \leqslant A(\|u\|_{W^1L^{\Phi}})(b + \Phi(\dot{u})) \in L^1, \tag{19}$$

by ($\boldsymbol{S}$) and Lemma 3.3. Thus item (1) is proved.

We split up the proof of item 2 into four steps.

Step 1. The non linear operator $u \mapsto D_x\mathcal{L}(t, u, \dot{u})$ is continuous from $\mathcal{E}^{\Phi}$ into $L^1([0,T])$ with the strong topology on both sets.

Let $\{u_n\}_{n\in\mathbb{N}}$ be a sequence of functions in $\mathcal{E}^{\Phi}$ and let $u \in \mathcal{E}^{\Phi}$ such that $u_n \to u$ in W^1L^{Φ}. By (Sobolev's inequality), we have

$$|u_n(t) - u(t)| \leqslant T A_{\Phi}^{-1}\left(\frac{1}{T}\right)\|u_n - u\|_{L^{\Phi}}$$

then $u_n \to u$ uniformly. As $\dot{u}_n \to \dot{u} \in \mathcal{E}^{\Phi}$, by Lemma 2.4, there exist a subsequence of $\dot{u}_{n_k}$ (again denoted $\dot{u}_{n_k}$) and a function $h \in L^1([0,T], \mathbb{R})$ such that $\dot{u}_{n_k} \to \dot{u}$ a.e. and $\Phi(\dot{u}_{n_k}) \leqslant h$ a.e.

Since u_{n_k}, $k = 1, 2, \ldots$, is a strong convergent sequence in W^1L^{Φ}, it is a bounded sequence in W^1L^{Φ}. According to item (3) of Lemma 2.3, there exists $M > 0$ such that $\|\boldsymbol{a}(u_{n_k})\|_{L^\infty} \leqslant M$, $k = 1, 2, \ldots$. From the previous facts and (19), we get

$$|D_x\mathcal{L}(\cdot, u_{n_k}, \dot{u}_{n_k})| \leqslant a(|u_{n_k}|)(b + \Phi(\dot{u}_{n_k})) \leqslant M(b + h) \in L^1.$$

On the other hand, by the continuous differentiability of $\mathcal{L}$, we have

$$D_x\mathcal{L}(t, u_{n_k}(t), \dot{u}_{n_k}(t)) \to D_x\mathcal{L}(t, u(t), \dot{u}(t)) \quad \text{for a.e. } t \in [0,T].$$

Applying the Dominated Convergence Theorem we conclude the proof of step 1.

Step 2. The non linear operator $u \mapsto D_y\mathcal{L}(t, u, \dot{u})$ is continuous from $\mathcal{E}^{\Phi}$ with the strong topology into $\left[L^{\Phi}\right]^*$ with the weak topology.*

Let $u \in \mathcal{E}^{\Phi}$. From (19) it follows that

$$D_y\mathcal{L}(\cdot, u, \dot{u}) \in C^{\Psi}. \tag{20}$$

¿Así? o conviene poner la cota de $\Psi(D_y)$ explícitamente???

Note that (19), (20) and the imbeddings $W^1L^{\Phi} \hookrightarrow L^\infty$ and $L^{\Psi} \hookrightarrow \left[L^{\Phi}\right]^*$ imply that the second member of (17) defines an element of $\left[W^1L^{\Phi}\right]^*$.

Let $u_n, u \in \mathcal{E}^{\Phi}$ such that $u_n \to u$ in the norm of W^1L^{Φ}. We must prove that $D_y\mathcal{L}(\cdot, u_n, \dot{u}_n) \overset{w^*}{\rightharpoonup} D_y\mathcal{L}(\cdot, u, \dot{u})$. On the contrary, there exist $v \in L^{\Phi}$, $\epsilon > 0$ and a subsequence of $\{u_n\}$ (denoted $\{u_n\}$ for simplicity) such that

$$|\langle D_y\mathcal{L}(\cdot, u_n, \dot{u}_n), v\rangle - \langle D_y\mathcal{L}(\cdot, u, \dot{u}), v\rangle| \geqslant \epsilon. \tag{21}$$

We have $u_n \to u$ in L^{Φ} and $\dot{u}_n \to \dot{u}$ in L^{Φ}. By Lemma 2.4, there exist a subsequence of $\{u_n\}$ (again denoted $\{u_n\}$ for simplicity) and a function $h \in L^1([0,T], \mathbb{R})$ such that

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$u_n \to u$ uniformly, $\dot{u}_n \to \dot{u}$ a.e. and $\Phi(\dot{u}_n) \leqslant h$ a.e. As in the previous step, since u_n is a convergent sequence, Lemma 3.3 implies that $a(|u_n(t)|)$ is uniformly bounded by a certain constant $M > 0$. Therefore, from inequality (19) with u_n instead of u, we have

$$\Psi(D_y\mathcal{L}(\cdot, u_n, \dot{u}_n)) \leqslant M(b+h) \in L^1. \tag{22}$$

As $v \in L^\Phi$ there exists $\lambda > 0$ such that $\Phi(\frac{v}{\lambda}) \in L^1$. Now, by Young inequality and (22), we have

$$
\begin{aligned}
\lambda D_y&\mathcal{L}(\cdot, u_{n_k}, \dot{u}_{n_k}) \cdot \frac{v(t)}{\lambda} \\
&\leqslant \lambda\left[\Psi(D_y\mathcal{L}(\cdot, u_{n_k}, \dot{u}_{n_k})) + \Phi\left(\frac{v}{\lambda}\right)\right] \\
&\leqslant \lambda M(b+h) + \lambda\Phi\left(\frac{v}{\lambda}\right) \in L^1
\end{aligned}
\tag{23}
$$

Finally, from the Lebesgue Dominated Convergence Theorem, we deduce

$$\int_0^T D_y\mathcal{L}(t, u_{n_k}, \dot{u}_{n_k}) \cdot v \, dt \to \int_0^T D_y\mathcal{L}(t, u, \dot{u}) \cdot v \, dt \tag{24}$$

which contradicts the inequality (21). This completes the proof of step 2.

Step 3. We will prove (17). For $u \in \mathcal{E}^\Phi$ and $0 \neq v \in W^1L^\Phi$, we define the function

$$H(s,t) := \mathcal{L}(t, u(t) + sv(t), \dot{u}(t) + s\dot{v}(t)).$$

For $|s| \leqslant s_0 := \min\{\left(1 - d(\dot{u}, E^\Phi)\right)/\|v\|_{W^1L^\Phi}, 1 - d(\dot{u}, E^\Phi)\}$, using triangle inequality we get $d\left(\dot{u} + s\dot{v}, E^\Phi\right) < 1$ and thus $\dot{u} + s\dot{v} \in \Pi(E^\Phi, 1)$. These facts imply, in virtue of Theorem 3.4 item 1, that $I(u + sv)$ is well defined and finite for $|s| \leqslant s_0$.

We also have $\|u + sv\|_{W^1L^\Phi} \leqslant \|u\|_{W^1L^\Phi} + s_0\|v\|_{W^1L^\Phi}$; then, by Lemma 3.3, there exists $M > 0$ such that $\|a(u + sv)\|_{L^\infty} \leqslant M$.

Let $\lambda > 0$ such that $\Phi(\frac{\dot{v}}{\lambda}) \in L^1$. On the other hand, if $\dot{v} \in L^\Phi$ and $|s| \leqslant s_0\lambda^{-1}$, from the convexity and the parity of Φ, we get

$$
\begin{aligned}
\Phi(\dot{u} + s\dot{v}) &= \Phi\left((1-s_0)\frac{\dot{u}}{1-s_0} + s_0\frac{s}{s_0}\dot{v}\right) \leqslant (1-s_0)\Phi\left(\frac{\dot{u}}{1-s_0}\right) + s_0\Phi\left(\frac{s}{s_0}\dot{v}\right) \\
&\leqslant (1-s_0)\Phi\left(\frac{\dot{u}}{1-s_0}\right) + s_0\Phi\left(\frac{\dot{v}}{\lambda}\right) \in L^1
\end{aligned}
$$

As $\dot{u} \in \Pi(E^\Phi, 1)$ then

$$d\left(\frac{\dot{u}}{1-s_0}, E^\Phi\right) = \frac{1}{1-s_0}d(\dot{u}, E^\Phi) < 1$$

and therefore $\frac{\dot{u}}{1-s_0} \in C^\Phi$.

Now, applying (19), (23), the fact that $v \in L^\infty$ and $\dot{v} \in L^\Phi$, we get

$$
\begin{aligned}
|D_s H(s,t)| &= \left| D_x \mathcal{L}(t, u + sv, \dot{u} + s\dot{v}) \cdot v + \lambda D_y \mathcal{L}(t, u + sv, \dot{u} + s\dot{v}) \cdot \frac{\dot{v}}{\lambda} \right| \\
&\leqslant M \left[b(t) + \Phi(\dot{u} + s\dot{v}) \right] |v| \\
&\quad + \lambda \left[\Psi(D_y \mathcal{L}(t, u + sv, \dot{u} + s\dot{v})) + \Phi\left(\frac{\dot{v}}{\lambda} \right) \right] \\
&\leqslant M \left\{ \left[b(t) + \Phi(\dot{u} + s\dot{v}) \right] |v| \right\} + \lambda M \left[b(t) + \Phi(\dot{u} + s\dot{v}) \right] + \lambda \Phi\left(\frac{\dot{v}}{\lambda} \right) \\
&= M \left[b(t) + \Phi(\dot{u} + s\dot{v}) \right] (|v| + \lambda) + \lambda \Phi\left(\frac{\dot{v}}{\lambda} \right) \in L^1.
\end{aligned}
\tag{25}
$$

Consequently, I has a directional derivative and

$$
\langle I'(u), v \rangle = \frac{d}{ds} I(u + sv) \Big|_{s=0} = \int_0^T \left\{ D_x \mathcal{L}(t, u, \dot{u}) \cdot v + D_y \mathcal{L}(t, u, \dot{u}) \cdot \dot{v} \right\} \, dt.
$$

Moreover, from the previous formula, (19), (20), and Lemma 2.3, we obtain

$$
|\langle I'(u), v \rangle| \leqslant \|D_x \mathcal{L}\|_{L^1} \|v\|_{L^\infty} + \|D_y \mathcal{L}\|_{L^\Psi} \|\dot{v}\|_{L^\Phi} \leqslant C \|v\|_{W^1 L^\Phi}
$$

with a appropriate constant C.

This completes the proof of the Gâteaux differentiability of I.

Step 4. The operator $I' : \mathcal{E}^\Phi \to \left[W^1 L_d^\Phi \right]^*$ is demicontinuous. This is a consequence of the continuity of the mappings $u \mapsto D_x \mathcal{L}(t, u, \dot{u})$ and $u \mapsto D_y \mathcal{L}(t, u, \dot{u})$. Indeed, if $u_n, u \in \mathcal{E}^\Phi$ with $u_n \to u$ in the norm of $W^1 L^\Phi$ and $v \in W^1 L^\Phi$, then

$$
\begin{aligned}
\langle I'(u_n), v \rangle &= \int_0^T \left\{ D_x \mathcal{L}(t, u_n, \dot{u}_n) \cdot v + D_y \mathcal{L}(t, u_n, \dot{u}_n) \cdot \dot{v} \right\} \, dt \\
&\to \int_0^T \left\{ D_x \mathcal{L}(t, u, \dot{u}) \cdot v + D_y \mathcal{L}(t, u, \dot{u}) \cdot \dot{v} \right\} \, dt \\
&= \langle I'(u), v \rangle.
\end{aligned}
$$

In order to prove item 3, it is necessary to see that the maps $u \mapsto D_x \mathcal{L}(t, u, \dot{u})$ and $u \mapsto D_y \mathcal{L}(t, u, \dot{u})$ are norm continuous from $\mathcal{E}^\Phi$ into L^1 and L^Ψ, respectively.

The continuity of the first map has already been proved in step 1.

Si eliminamos la demicontinuidad del segundo item, hay que copiar la continuidad de D_x aquí!!!

Let $u_n, u \in \mathcal{E}^\Phi$ with $\|u_n - u\|_{W^1 L^\Phi} \to 0$.

Applying Lemma 2.4 to $\dot{u}_n$, there exists a subsequence (denoted $\dot{u}_n$ for simplicity) such that $\dot{u}_n \in L^\Phi$ and a function $h \in L^1$ such that $\Psi(\dot{u}_n) \leqslant h$ and $\dot{u}_n \to \dot{u}$ a.e.

Then, by (23) we have $\Psi(v_n) \leqslant m(t) \in L^1$ being $v_n := D_y \mathcal{L}(\cdot, u_n, \dot{u}_n)$ and $m(t) := M(b + h)$. In addition, from the continuous differentiability of $\mathcal{L}$, we have that $v_n \to v$ a.e. where $D_y \mathcal{L}(\cdot, u, \dot{u})$.

As $\Psi \in \Delta_2$, there exists $c : \mathbb{R}^+ \to ???$ such that $\Psi(\lambda x) \leqslant c(|\lambda|) \Psi(x)$. Then, $\Psi(\frac{v_n - v}{\lambda}) \leqslant c(|\lambda|^{-1}) \Psi(v_n - v)$ for every $\lambda \in \mathbb{R}$.

Therefore, $\Psi(\frac{v_n - v}{\lambda}) \to 0$ a.e. as $n \to \infty$ and $\Psi(\frac{v_n - v}{\lambda}) \leqslant c(|\lambda|^{-1}) K \Psi(v_n) + \Psi(v)) \leqslant c(|\lambda|^{-1}) K [m(t) + \Psi(v)]) \in L^1$.

Now, by Dominated Convergence Theorem, we get $\int \Psi\left(\frac{v_n - v}{\lambda}\right) dt \to 0$ for every $\lambda > 0$. Thus, $v_n \to v$ in L^Ψ.

The continuity of I' follows from the continuity of $D_x \mathcal{L}$ and $D_y \mathcal{L}$ using the formula (17). □

Acknowledgments

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