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

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Abstract

In this paper we consider the problem of finding periodic solutions of certain Euler-Lagrange equations, which include, among others, equations involving the p-Laplace and, more generality, the (p, q)-Laplace operator. We employ the direct method of the calculus of variations in the framework of anisotropic Orlicz-Sobolev spaces. These spaces appear to be useful in formulating a unified theory of existence for the type of problem considered.

1 Introduction

Let $\Phi : \mathbb{R}^d \to [0, +\infty)$ be a differentiable and convex function satisfying that $\Phi(0) = 0$, $\Phi(y) > 0$ if $y \neq 0$, $\Phi(-y) = \Phi(y)$, and

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

where $|\cdot|$ denotes the euclidean norm on $\mathbb{R}^d$. From now on, we say that Φ is a N_∞ function if Φ verifies the previous properties.

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For $T > 0$, we assume that $F : [0,T] \times \mathbb{R}^d \to \mathbb{R}^d$ ($F = F(t,x)$) is a differentiable function with respect to x for a.e. $t \in [0,T]$ and $F(t,x)$ is measurable with respect to t for every $x \in \mathbb{R}$. Moreover, suppose that 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

$$|F(t,x)| + |\nabla_x F(t,x)| \leqslant a(x)b(t). \tag{2}$$

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

The goal of this paper is to obtain existence of solutions for the following problem:

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

Our approach involves the direct method of the calculus of variations in the framework of *anisotropic Orlicz-Sobolev spaces*. We suggest the article [17] for definitions and main results on anisotropic Orlicz spaces. These spaces allow us to unify and extend previous results on existence of solutions for systems like (P_Φ). We will find solutions of (P_Φ) for finding extreme points of the *action integral*

$$I(u) := \int_0^T \Phi(u'(t)) + F(t,u(t))\, dt. \tag{IA}$$

In what follows, we shall denote by $\mathcal{L} = \mathcal{L}_{\Phi,F}$ to the function $\Phi(y) + F(t,x)$, and we will call it *Lagrangian*.

Problem (P_Φ) contains, as a particular case, many problems that are usually considered in the literature. For example, the classic book [12] deals mainly with problem (P_Φ) with $\Phi_2(x) := |x|^2/2$, through various methods: direct, dual, saddle points, minimax, etc. The results in [12] were extended and improved in several articles, see [19, 20, 21, 25, 28] to cite some examples. The case $\Phi_p(y) := |y|^p/p$, for arbitrary $1 < p < \infty$ were considered in [22, 23], among other papers. In this case (P_Φ) is reduced to the *p-laplacian system.* If $\Phi_{p_1,p_2} : \mathbb{R}^d \times \mathbb{R}^d \to [0,+\infty)$ is defined 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 (P_Φ) becomes (p_1,p_2)-Laplacian system, see [11, 13, 14, 15, 16, 26, 27].

Hence (P_Φ) contains several problems that have been considered by many authors in the past. Our results still improve some results on (p_1,p_2)-Laplacian systems since we obtain existence of solutions for these systems under conditions less restrictive that the previously established. For all this, we believe that Sobolev-Orlicz's anisotropic spaces can provide a suitable framework for unifying many known results. On the other hand, we consider that one of the most important aspects in our work is considering functions Φ with faster growth than powers function. For example we obtain existence for

$$XXXXX.$$

As far as we know, this type of result are a novelty. In a previous paper (see [1]), we consider similar results in a isotropic framework.

The paper is organized as follows. In Section 2 we summarize some results, most known, about Orlicz and Orlicz-Sobolev spaces. In order to obtain existence of minimizers of action integrals it is necessary that the functional I be coercive. In the past, several conditions on F have been useful to obtain coercivity of I for the functions Φ_p and Φ_{p_1,p_2} . In this paper we investigate the condition that in the literature was called sublinearity (see [19, 25, 28] for the laplacian, [10, 22] for the p-laplacian and [11, 13, 14, 27] for (p_1, p_2)-laplacian). In Section 3, we contextualize the sublinearity within our framework (see (B) below) and we establish results of existence of minimizers of (IA) (Theorem 3.2). In Section 4 we establish conditions for that a minimum of (IA) be a solution of (P_Φ).

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 $\Phi : \mathbb{R}^d \to [0, +\infty)$. References for these topics are [4, 5, 6, 8, 9, 17, 18, 24]. For the theory of convex functions in general we suggest [7]. Note that, unlike in [9], we do not require that N_∞ functions be superlinear near from 0, i.e. $\Phi(x)/|x| \to 0$ when $|x| \to 0$. However, most of the results proved in [9] do not depend on this property.

If $\Phi(y)$ is a N_∞ function which depends to $|y|$ ($\Phi(y) = \overline{\Phi}(|y|)$) then we say that Φ is *radial*.

We can use the following example for obtain new N_∞ functions from N_∞ functions given.

Example 2.1. Let $(d_1, \dots, d_k) \in \mathbb{Z}^k_+$. Suppose that $\Phi_j : \mathbb{R}^{d_j} \to [0, +\infty)$, $j = 1, \dots k$, are N_∞ functions and that $O_j \in L(\mathbb{R}^d, \mathbb{R}^{d_j})$ are bounded linear functions satisfying $\bigcap_{j=1}^k \ker O_j = \{0\}$. Then

$$\Phi(y) := \sum_{j=1}^{k} \Phi_j(O_j y)$$

is a N_∞ function.

Let us briefly show that Φ satisfies (1). Suppose $|y_n| \to \infty$ and $\Phi(y_n)/|y_n|$ bounded. If for some $j = 1, \dots, k$ there exists $\epsilon > 0$ and a subsequence n_s such that $|O_j(y_{n_s})| \geqslant \epsilon |y_{n_s}|$, then $\Phi_j(O_j y_{n_s})/|y_{n_s}| \to \infty$, contrary our assumption.

Hence $O_j(y_n)/|y_n| \to 0$ when $n \to \infty$. Passing to a subsequence, we can assume that there exists $y \in \mathbb{R}^d$ with $y_n/|y_n| \to y$. Then $y \in \ker O_j$ and $y \neq 0$, which is a contradiction.

As a consequence the function $\Phi : \mathbb{R}^d \times \mathbb{R}^d \to [0, +\infty)$ defined by

$$\Phi(y_1, y_2) = e^{|y_1 - y_2|} - 1 + |y_2|^p,$$

with $1 < p < \infty$, is a N_∞ function.

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

$$\Phi^\star(\zeta) = \sup_{y \in \mathbb{R}^d} y \cdot \zeta - \Phi(y) \tag{3}$$

From the continuity of Φ and (1), we have that $\Phi^\star : \mathbb{R}^d \to [0, \infty)$. The complementary function $\Phi^\star$ is a N_∞ function (see [12, Chapter 2] and [17, Th. 2.2]). The Moreau Theorem (see [7, Th. 4.21]) implies that $\Phi^{\star\star} = \Phi$.

Some useful properties which are satisfied by N_∞ functions are:

(P1) $\Phi(\lambda x) \leqslant \lambda \Phi(x)$, for every $\lambda \in [0, 1], x \in \mathbb{R}^d$,

(P2) $0 < |\lambda_1| \leqslant |\lambda_2|, x \in \mathbb{R}^d \Rightarrow \Phi(\lambda_1 x) \leqslant \Phi(\lambda_2 x)$,

(P3) $x \cdot y \leqslant \Phi(x) + \Phi^\star(y)$,

(P4) $x \cdot \nabla\Phi(x) = \Phi(x) + \Phi^\star(\nabla\Phi(x))$.

The following inequality, which is valid for $\Lambda > 1$, will be useful, it is consequence of ((P4)) and of that $(d/dt)\Phi(tx) = \nabla\Phi(tx) \cdot x$ is an non decreasing function of t.

$$\Phi^\star(\nabla\Phi(x)) \leqslant x \cdot \nabla\Phi(x) \leqslant \frac{1}{\Lambda - 1} \int_1^\Lambda \frac{d}{dt}\Phi(tx)dt \leqslant \frac{1}{\Lambda - 1}\Phi(\Lambda x). \tag{4}$$

We say that $\Phi : \mathbb{R}^d \to [0, +\infty)$ satisfies the Δ_2-*condition*, it is denoted by $\Phi \in \Delta_2$, if there exists a constant $C > 0$ such that

$$\Phi(2x) \leqslant C\Phi(x) + 1, \quad x \in \mathbb{R}^d. \tag{5}$$

Throughout this article, we denote by $C = C(\lambda_1, \ldots, \lambda_n)$ a positive constant that may depend on T and Φ, or other N_∞ functions, and the parameters $\lambda_1, \ldots, \lambda_n$. We assume that the value that C represents may change in different occurrences in the same chain of inequalities.

If $\Phi \in \Delta_2$ then Φ satisfies the following properties:

(P5) There exists $C > 0$ such that for every $x, y \in \mathbb{R}^d$, $\Phi(x + y) \leqslant C(\Phi(x) + \Phi(y)) + 1$.

(P6) For any $\lambda > 1$ there exists $C(\lambda) > 0$ such that $\Phi(\lambda x) \leqslant C(\lambda)\Phi(x) + 1$.

(P7) There exists $1 < p < \infty$, $C > 0$ such that $\Phi(x) \leqslant C|x|^p + 1$.

Let Φ_1 and Φ_2 be N_∞ functions. Following to [24] we write $\Phi_1 \dashv \Phi_2$ if there exists $k, C > 0$ such that

$$\Phi_1(x) \leqslant C + \Phi_2(kx), \quad x \in \mathbb{R}^d. \tag{6}$$

For example, if Φ is Δ_2 then there exist $p = C(k) > 0$ such that (6) holds we write $\Phi_1 \ll \Phi_2$. We observe that $\Phi_1 \dashv \Phi_2$ implies that $\Phi_2^\star \dashv \Phi_1^\star$.

If $\Phi^\star \in \Delta_2$ then Φ satisfies the ∇_2-*condition*, i.e. for every $0 < r < 1$ there exists $l = l(r) > 0$ and $C' = C'(r) > 0$

$$\Phi(x) \leqslant \frac{r}{l}\Phi(lx) + C', \quad x \in \mathbb{R}^d. \tag{7}$$

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

$$C^\Phi := \{u \in \mathcal{M} | \rho_\Phi(u) < \infty\}. \tag{8}$$

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

$$L^\Phi := \{u \in \mathcal{M} | \exists \lambda > 0 : \rho_\Phi(\lambda u) < \infty\}. \tag{9}$$

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

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

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. The equality $L^\Phi = E^\Phi$ is true if and only if $\Phi \in \Delta_2$ (see [17, Cor. 5.1]).

A generalized version of *Hölder's inequality* holds in Orlicz spaces (see [17, Thm. 7.2]). Namely, if $u \in L^\Phi$ and $v \in L^{\Phi^\star}$ then $u \cdot v \in L^1$ and

$$\int_0^T v \cdot u\ dt \leqslant 2\|u\|_{L^\Phi}\|v\|_{L^{\Phi^\star}}. \tag{10}$$

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

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

This set is related to the Orlicz class C^Φ by the following inclusions

$$\Pi(E^\Phi, r) \subset rC^\Phi \subset \overline{\Pi(E^\Phi, r)} \tag{11}$$

for any positive r. This relation is a trivial generalization of [17, Thm. 5.6]. If $\Phi \in \Delta_2$, 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 $L^\Phi \hookrightarrow \left[L^{\Phi^\star}\right]^\star$, where a function $v \in L^\Phi$ is associated to $\xi_v \in \left[L^{\Phi^\star}\right]^\star$ given by

$$\langle \xi_v, u\rangle = \int_0^T v \cdot u \; dt, \tag{12}$$

It is easy to prove that $L^\infty \hookrightarrow L^\Phi \hookrightarrow L^1$ for any N_∞ function Φ.

Suppose $u \in L^\Phi([0,T], \mathbb{R}^d)$ and consider $K := \rho_\Phi(u) + 1 \geqslant 1$. Then from ((P1)) we have $\rho_\Phi(K^{-1}u) \leqslant K^{-1}\rho_\Phi(u) \leqslant 1$. Therefore we conclude the inequality

$$\|u\|_{L^\Phi} \leqslant \rho_\Phi(u) + 1. \tag{13}$$

We highlight the following result (see [9, Th. 3.3]).

Proposition 2.1. $L^\Phi\left([0,T], \mathbb{R}^d\right) = \left[E^{\Phi^\star}\left([0,T], \mathbb{R}^d\right)\right]^\star$.

As a consequence of previous proposition, $L^\Phi\left([0,T], \mathbb{R}^d\right)$ can be equipped with the weak$\star$ topology induced by $E^{\Phi^\star}\left([0,T], \mathbb{R}^d\right)$.

We define the *Sobolev-Orlicz space* $W^1L^\Phi\left([0,T], \mathbb{R}^d\right)$ by

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

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

$$\|u\|_{W^1L^\Phi} = \|u\|_{L^\Phi} + \|u'\|_{L^\Phi}. \tag{14}$$

We define the function $A_\Phi : \mathbb{R}^d \to [0, +\infty)$ as the greatest convex radial minorant of Φ, i.e.

$$A_\Phi(x) = \sup\left\{\Psi(x)\right\}, \tag{15}$$

where the supremum is taken over all the convex, non negative and radial functions Ψ with $\Psi(x) \leqslant \Phi(x)$.

Proposition 2.2. *A_Φ is a radial and N_∞ function.*

Proof. The convexity and radiality of A_Φ is a consequence of the fact that the supremum preserving these properties. It is only necessary to show that $A_\Phi(x) > 0$, when $x \neq 0$ and $A_\Phi(x)/|x| \to \infty$, when $|x| \to \infty$. We write, for $r \in \mathbb{R}$, $r^+ = \max\{r, 0\}$. Since Φ is N_∞ function, for every $k > 0$ there exists $r_0 > 0$

such that $\Phi(x) \geqslant k(|x| - r_0)^+$, for $|x| > r_0$. Since $k(|x| - r_0)^+$ is a non negative radial and convex function, it follows that $A_\Phi(x) \geqslant k(|x| - r_0)^+$. Therefore $\liminf_{|x|\to\infty} A_\Phi(s)/|x| \geqslant k$. This implies that $\lim_{|x|\to\infty} A_\Phi(x)/|x| = \infty$.

As Φ is a N_∞ and continuous function, for every $r > 0$ there exists $k(r) > 0$ such that $\Phi(x) \geqslant k(r)|x| \geqslant k(r)(|x| - r)^+$, when $|x| \geqslant r$. This fact implies that $A_\Phi(x) > 0$ for $x \neq 0$. □

By abuse of notation, we sometime identify A_Φ with a (invertible) function defined on $[0, +\infty)$.

Corollary 2.3. $L^\Phi([0,T], \mathbb{R}^d) \hookrightarrow L^{A_\Phi}([0,T], \mathbb{R}^d)$.

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 $\widetilde{u} = u - \overline{u}$.

Lemma 2.4. *Let $\Phi : \mathbb{R}^d \to [0, +\infty)$ be a N_∞ function and let $u \in W^1L^\Phi\left([0,T], \mathbb{R}^d\right)$. Let $A_\Phi : \mathbb{R}^d \to [0, +\infty)$ be the isotropic function defined by* (15)*. Then*

1. Morrey's inequality*. For every $s, t \in [0,T]$, $s \neq t$*

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

2. Sobolev's inequality*.*

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

3. Poincaré-Wirtinger's inequality*. We have $\widetilde{u} \in L^\infty\left([0,T], \mathbb{R}^d\right)$ and*

$$\|\widetilde{u}\|_{L^\infty} \leqslant T A_\Phi^{-1}\left(\frac{1}{T}\right) \|u'\|_{L^\Phi} \tag{P-W.I}$$

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

Proof. It is immediate consequence of Corollary 2.3 and [1, Lemma 2.1, Corollary 2.2]. □

Lemma 2.4 gives us estimates for isotropic norms of u. In these type of inequalities some information is lost. The following result gives us an estimate that takes into account the anisotropic nature of the space $W^1L^\Phi\left([0,T], \mathbb{R}^d\right)$. The proof is similar to the proof of [4, Th. 4.5].

Lemma 2.5 (Anisotropic Poincaré-Wirtinger's inequality)**.** *Let $\Phi : \mathbb{R}^d \to [0, +\infty)$ be a N_∞ function and let $u \in W^1L^\Phi\left([0,T], \mathbb{R}^d\right)$. Then*

$$\Phi\left(\tilde{u}(t)\right) \leqslant \frac{1}{T}\int_0^T \Phi\left(Tu'(r)\right) dr. \tag{A.P-W.I}$$

Proof. Applying Jensen's inequality two times, we get

$$\begin{aligned}
\Phi(\tilde{u}(t)) &= \Phi\left(\frac{1}{T}\int_0^T (u(t)-u(s))\,ds\right)\\
&\leqslant \frac{1}{T}\int_0^T \Phi(u(t)-u(s))ds\\
&\leqslant \frac{1}{T}\int_0^T \Phi\left(\int_s^t |t-s|u'(r)\frac{dr}{|t-s|}\right)ds\\
&\leqslant \frac{1}{T}\int_0^T \frac{1}{|t-s|}\int_s^t \Phi\left(|t-s|u'(r)\right)drds
\end{aligned}$$

From ((P1)) we have that $\Phi(rx)/r$ is increasing with respecto to $r>0$ for $x\in\mathbb{R}^d$ fix. Therefore, previous inequality implies (A.P-W.I). □

Remark 1. As consequence of Lemma 2.4 we obtain that

$$\|u\|'_{W^1L^\Phi} = |\overline{u}| + \|u'\|_{L^\Phi},$$

define an equivalent norm to $\|\cdot\|_{W^1L^\Phi}$ on $W^1L^\Phi([0,T],\mathbb{R}^d)$.

Another immediate consequence of Lemma 2.4 is the following result.

Corollary 2.6. *Every bounded sequence $\{u_n\}$ in $W^1L^\Phi([0,T],\mathbb{R}^d)$ has an uniformly convergent subsequence.*

3 Existence of minimizers

It is well known that an important ingredient in the direct method of calculus of variations is the coercivity of action integrals. To obtain coercivity for integral I, defined in (IA), it is necessary to impose more restrictions on the potential F.

There are several restrictions that were explored in the past. The one we will study in this article is based on what is known in the literature as sublinearity (see [19, 25, 28] for the laplacian, [22, 10] for the p-laplacian and [27, 11, 13, 14] for (p,q)-laplacian). In this article we will use another denomination for this property.

Definition 3.1. *Let $F:[0,T]\times\mathbb{R}^d\to\mathbb{R}$ be a functions satisfying (C) and (A). We say that F satisfies condition (B) if there exist an N_∞ function Φ_0, with $\Phi_0 \lll \Phi$, a function $d\in L^1([0,T],\mathbb{R})$, with $d\geqslant 1$, such that*

$$\Phi^\star(d^{-1}(t)\nabla_x F) \leqslant \Phi_0(x)+1 \tag{B}$$

The condition (B) encompasses the sublinearity condition as it was introduced in the context of p-laplacian or (p_1,p_2)-laplacian systems. For example, in [11, Th. 1.1.] Li, Ou and Tang considered a potential $F:[0,T]\times\mathbb{R}^d\times\mathbb{R}^d\to\mathbb{R}$ satisfying (C) and (A) and the following condition (we recall that $p'=p/(p-1)$).

(H) There exists $f_i, g_i, h_i \in L^1([0,T],\mathbb{R}_+)$, $\alpha_i \in [0, p_i/p_i')$, $i = 1,2$, $\beta_1 \in [0, p_2/p_1')$ and $\beta_2 \in [0, p_1/p_2')$ such that

$$|\nabla_{x_i} F(t,x_1,x_2)| \leqslant f_i(t)|x_1|^{\alpha_i} + g_i(t)|x_2|^{\beta_i} + h_i(t), \quad i = 1,2$$

It is easy to prove that (H)$\Rightarrow$$(B)$, with $\Phi = \Phi_{p_1,p_2}$, $\Phi_0 = \Phi_{\overline{p}_1,\overline{p}_2}$, where $\overline{p}_i$, $i = 1,2$, are taken so that $\max\{\alpha_1 p_1', \beta_2 p_2'\} \leqslant \overline{p}_1 < p_1$ and $\max\{\alpha_2 p_2', \beta_1 p_1'\} \leqslant \overline{p}_2 < p_2$ and $d = C(1 + \sum_i \{f_i + g_i + h_i\}) \in L^1$, with $C > 0$ chosen large enough.

Theorem 3.2. *Let Φ be an N_∞-function whose complementary function $\Phi^\star$ satisfies the Δ_2-condition. Let F be a potential that satisfies (C), (A),(B) and the following condition*

$$\lim_{|x|\to\infty} \frac{\int_0^T F(t,x)\, dt}{\Phi_0(2x)} = +\infty. \tag{16}$$

Let M be a weak$\star$ closed subspace of L^Φ and let $V \subset C([0,T],\mathbb{R}^d)$ be closed in the $C([0,T],\mathbb{R}^d)$-strong topology. Then I attains a minimum on $H = \{u \in W^1L^\Phi | u \in V$ and $u' \in M\}$.

Proof. Step 1. The action integral is coercive.

Let λ be any positive number with $\lambda > 2\max\{T,1\}$. Since $\Phi_0 \ll \Phi$ there exists $C(\lambda) > 0$ such that

$$\Phi_0(x) \leqslant \Phi\left(\frac{x}{2\lambda}\right) + C(\lambda), \quad x \in \mathbb{R}^d. \tag{17}$$

By the decomposition $u = \overline{u} + \tilde{u}$, the absolutely continuity of $F(t, x + sy)$ with respect to $s \in \mathbb{R}$, Young's inequality, (B), the convexity of Φ_0, ((P2)), (17) and (A.P-W.I) we obtain

$$\begin{aligned}
J &:= \left|\int_0^T F(t,u) - F(t,\overline{u})dt\right| \\
&\leqslant \int_0^T \int_0^1 |\nabla_x F(t,\overline{u} + s\tilde{u})\tilde{u}| ds dt \\
&\leqslant \lambda \int_0^T d(t) \int_0^1 \left[\Phi^\star\left(d^{-1}(t)\nabla_x F(t,\overline{u}+s\tilde{u})\right) + \Phi\left(\frac{\tilde{u}}{\lambda}\right)\right] dsdt \\
&\leqslant \lambda \int_0^T d(t) \int_0^1 \left[\frac{1}{2}\Phi_0(2\overline{u}) + \frac{1}{2}\Phi_0(2\tilde{u})ds + \Phi\left(\frac{\tilde{u}}{\lambda}\right) + 1\right] dsdt \\
&\leqslant \lambda \int_0^T d(t) \int_0^1 \left[\Phi_0(2\overline{u}) + 2\Phi\left(\frac{\tilde{u}}{\lambda}\right) + C(\lambda)\right] dsdt \\
&\leqslant C_1\Phi_0(2\overline{u}) + \lambda C_2 \int_0^T \Phi\left(\frac{Tu'(s)}{\lambda}\right) ds + C_1
\end{aligned}$$

where $C_2 = C_2(\|d\|_{L^1})$ and $C_1 = C_1(\|d\|_{L^1}, \lambda)$. Since $\Phi^\star$ is Δ_2 we can choose λ large enough so that $l = \lambda T^{-1}$ satisfies (7) for $r = \frac{1}{2}\min\{(C_2T)^{-1}, 1\}$. Thus we have

$$J \leqslant C_1 \Phi_0(2\overline{u}) + \frac{1}{2}\int_0^T \Phi\left(u'(s)\right) ds + C_1$$

Then

$$\begin{aligned} I(u) &= \int_0^T \Phi(u') + F(t,u)dt \\ &= \int_0^T \{\Phi(u') + [F(t,u) - F(t,\overline{u})] + F(t,\overline{u})\}dt \\ &\geqslant \frac{1}{2}\int_0^T \Phi(u')dt - C_1\Phi_0(2\overline{u}) + \int_0^T F(t,\overline{u})dt - C_1 \end{aligned} \tag{18}$$

We take $u_n \in W^1L^\Phi$ with $\|u_n\|_{W^1L^\Phi} \to \infty$. From Remark 1, we can suppose that $\|u_n'\|_{L^\Phi} \to \infty$ or $|\overline{u}_n| \to \infty$. In the first case, we have from (13) that $\rho_\Phi(u_n) \to \infty$ and hence $I(u_n) \to \infty$. In the second case, $I(u_n) \to \infty$ as consequence of (16).

Step 2. Suppose that $u_n \to u$ uniformly and $u_n' \xrightharpoonup{\star} u'$ in $L^\Phi([0,T],\mathbb{R}^d)$ then $I(u) \leqslant \liminf_{n\to\infty} I(u_n)$.

Without loss of generality, passing to subsequences, we may assume that the lim inf is really a lim. The embedding $L^\Phi([0,T],\mathbb{R}^d) \hookrightarrow L^1([0,T],\mathbb{R}^d)$ implies that $u_n' \rightharpoonup u'$ in $L^1([0,T],\mathbb{R}^d)$. Now, applying [3, Th. 3.6] we obtain $I(u) \leqslant \lim_{n\to\infty} I(u_n)$.

Step 3. Final step. The proof of the theorem is concluded with a usual argument. We take a minimizing sequence $u_n \in H$ of I. From the coercivity of I we have that u_n is bounded in $W^1L^\Phi([0,T],\mathbb{R}^d)$. By Corollary 2.6 (passing to subsequences) we can suppose that u_n converges uniformly to a function $u \in V$. On the other hand, u_n' is bounded in $L^\Phi = \left[E^{\Phi^\star}\right]^\star$. Thus, since $E^{\Phi^\star}$ is separable (see [17, Thm. 6.3]), it follows from [2, Cor. 3.30] there exist a subsequence of u_n' (we denote it u_n' again) and $v \in M$ such that $u_n' \xrightharpoonup{\star} v$. From this fact and the uniform convergence of u_n to u, we obtain that

$$\int_0^T \varphi' \cdot u \; dt = \lim_{n\to\infty}\int_0^T \varphi' \cdot u_n \; dt = -\lim_{n\to\infty}\int_0^T \varphi \cdot u_n' \; dt = -\int_0^T \varphi \cdot v \; dt,$$

for every function $\varphi \in C^\infty([0,T],\mathbb{R}^d) \subset E^{\Phi^\star}$ with $\varphi(0) = \varphi(T) = 0$. Thus u has a derivative in the weak sense in L^Φ. Taking account of $L^\Phi \hookrightarrow L^1$ and [3, Thms. 2.3 and 2.17], we obtain $u \in W^1L^\Phi$ and $v = u'$ a.e. $t \in [0,T]$. Hence, $u \in H$.

Finally, the semicontinuity of I, established in step 2, implies that u is a minimum of I. □

Remark 2. The results of this section extend without difficulty to any Lagrangian $\mathcal{L}$ with $\mathcal{L} \geqslant \mathcal{L}_{\Phi,F}$ (see [1]).

4 Differentiability of solutions and Euler-Lagrange equations

This section will address the question of when minimizers of I are solutions of (P_Φ). It is classical result that minimizers, on an appropriate set, of action integral satisfying an a priori smothness condition (e.g. Lipschitz continuity) are solutions of (P_Φ) (see [3]). In Theorem 4.1 we obtain a better a priori condition for the action integral under consideration.

We denote by $\mathrm{Lip}([0,T],\mathbb{R}^d)$ the set of $\mathbb{R}^d$-valued Lipschitz continuous functions defined on $[0,T]$. If $X \subset L^\Phi([0,T],\mathbb{R}^d)$ and $u \in L^\Phi([0,T],\mathbb{R}^d)$, we denote by $d(u,X)$ the distance of u to X computed with respect to the Luxemburg norm. We recall that $u \in \mathrm{Lip}([0,T],\mathbb{R}^d)$ implies $d(u', L^\infty([0,T],\mathbb{R}^d)) = 0$. The following is the main result of this section.

Theorem 4.1. *Assume Φ, Φ_0 and F as in Theorem 3.2 and Φ strictly convex. If u is a minimum of I on the set $H = \{u \in W^1L^\Phi([0,T],\mathbb{R}^d) | u(0) = u(T)\}$ and $d(u', L^\infty([0,T],\mathbb{R}^d)) < 1$ then u is solution of (P_Φ).*

The proof of the previous theorem depends on the Gâteaux differentiability of the action integral on the space $W^1L^\Phi([0,T],\mathbb{R}^d)$. We will consider a more general Lagrangian function $\mathcal{L} : [0,T] \times \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$, which is assumed measurable in t for each $(x,y) \in \mathbb{R}^d \times \mathbb{R}^d$ and continuously differentiable in (x,y) for almost every $t \in [0,T]$. We denote by $I = I_\mathcal{L}$ the action integral associated to $\mathcal{L}$. In order to obtain differentiability of I, it is necessary to assume some condictions on $\mathcal{L}$. In the paper [4], Chmara and Maksymiuk obtained differentiability assuming a conditions very similar to Definition 4.2 and that $\Phi \in \Delta_2 \cap \nabla_2$. This last condition allows to Chmara and Maksymiuk a less technical proof of the differentiability. However, for our purposes the condition $\Phi \in \Delta_2$ is a very serious limitation, since it leaves out of consideration functions that grow faster than powers. That is one of the greatest achievements of considering anisotropic Orlicz spaces according to our criterion. For this reason, we present a proof of the results obtained in [4] without the assumption $\Phi \in \Delta_2$.

Definition 4.2. *We say that a lagrangian $\mathcal{L}$ satisfies the condition (S) if*

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

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

Our condition (S) includes structure conditions that have previously been considered in the literature in the case of p-laplacian and p_1,p_2-laplacian systems. For example, it is easy to see that, when $\Phi(x)$ is as in Example **??**, then the condition (S) is equivalent to the structure condition in [12, Th. 1.4]. If Φ is a radial N_∞ function such that $\Phi^\star$ satisfies that Δ_2 function then (S) is related to conditions [1, Eq. (2)-(4)]. If Φ is as in Example **??** and $\mathcal{L} = \mathcal{L}(t, x_1, x_2, y_1, y_2)$

is a lagrangian with $\mathcal{L} : [0,T] \times \mathbb{R}^d \times \mathbb{R}^d \times \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$ then inequality (S) is related to estructure conditions like [23, Lemma 3.1, Eq. (3.1)]. As can be seen, condition (S) is a more compact expression than [23, Lemma 3.1, Eq. (3.1)] and moreover weaker, because (S) does not imply a control of $|D_{y_1}L|$ independent of y_2.

As a consequence of the previous result, we obtain that if a Lagrange function $\mathcal{L}$ satisfies structure condition (S) and $\Phi \dashv \Phi_0$ then $\mathcal{L}$ satisfies (S) with Φ_0 instead to Φ and possibly with other functions b, a and constants Λ and λ.

An important example of lagrangian is giving by:

$$\mathcal{L}_{\Phi,F}(t,x,y) := \Phi(y) + F(t,x). \tag{19}$$

Remark 3. The lagrangian $\mathcal{L}_{\Phi,F}$ satisfies condition (S), for every $\Lambda < 1$. In order to prove this, the only non trivial fact that we should to establishis is that $\Phi^\star(\nabla_y \mathcal{L}) \leqslant a(x)\{b(t) + \Phi(y/\Lambda)\}$. But, from inequality (4) below, $\Phi^\star(\nabla_y\mathcal{L}) = \Phi^\star(\nabla\Phi(y)) \leqslant \Lambda(1-\Lambda)^{-1}\Phi(y/\Lambda)$, for every $\Lambda < 1$.

The next step is to obtain variational solutions of (P_Φ). For this purpose we define the $C([0,T],\mathbb{R}^d)$-closed linear set $V := \{u \in C([0,T],\mathbb{R}^d) | u(0) = u(T)\}$, $M := L^\Phi([0,T],\mathbb{R}^d)$ and H as in Theorem 3.2.

According to Remark 3 and Theorem 4.5, I is Gâteaux differentiable on $W^1L^\Phi([0,T],\mathbb{R}^d) \cap \{u | d(u', E^\Phi) < 1\}$. Let u be a minimum and suppose that $d(u', E^\Phi) < 1$. By the Fermat's rule (see [7, Prop. 4.12]), $\langle I'(u), v\rangle = 0$, for every $v \in H$. Therefore

$$\int_0^T \nabla\Phi(u'(t)) \cdot v'(t)dt = -\int_0^T \nabla_x F(t,u(t)) \cdot v(t)dt. \tag{20}$$

From Theorem 4.5, $\nabla_x F(t,u(t)) \in L^1([0,T],\mathbb{R}^d)$ and $\nabla\Phi(u'(t)) \in L^{\Phi^\star}([0,T],\mathbb{R}) \hookrightarrow L^1([0,T],\mathbb{R})$. Identity (20) holds for every $v \in C^\infty([0,T],\mathbb{R}^d)$ with $v(0) = v(T)$. Using the [12, Fundamental Lemma, p. 6] we get that $\nabla\Phi(u'(t))$ is absolutely continuous and $(d/dt)(\nabla\Phi(u'(t))) = \nabla_x F(t,u(t))$, a.e. on $[0,T]$. Moreover, $\nabla\Phi(u'(0)) = \nabla\Phi(u'(T))$. We can not move forward without assuming that Φ is *strictly convex*, i.e. $\Phi(\lambda x + (1-\lambda)y) < \lambda\Phi(x) + (1-\lambda)\Phi(y)$, when $\lambda \in (0,1)$. It is well known that, in this case $\nabla\Phi : \mathbb{R}^d \to \mathbb{R}^d$ is a one-to-one map (see, e.g. [7, Ex. 4.17, p. 67]). Hence, we coclude that $u'(0) = u'(T)$. We have proved Theorem 4.1.

Remark 4. If u is a minimum of I on H then $d(u', E^\Phi) \leqslant 1$. This follows of that $\rho_\Phi(u') < \infty$ and (11). Then, the possible minima of I that do not satisfy the hypotheses of Theorem 4.1 lie in a nowhere dense set of the domain of I.

Remark 5. The condition $d(u', E^\Phi) < 1$ is trivially satisfied when Φ is a Δ_2 function, because, in this case, $E^\Phi([0,T],\mathbb{R}^d) = L^\Phi([0,T],\mathbb{R}^d)$. Therefore our Theorem 4.1 implies existence of solutions, among others, for the system (**??**) and more generally for the system (**??**).

Remark 6. It seems that it is not possible to choose M otherwise than as in the proof of Theorem 4.1. The set M must contain the space $C^\infty([0,T],\mathbb{R}^d)$ so that we are able to infer (20). Thus, M must contain $E^{\Phi}([0,T],\mathbb{R}^d)$. But, it can be proved that $E^{\Phi}([0,T],\mathbb{R}^d)$ is weak$\star$ dense in $L^{\Phi}([0,T],\mathbb{R}^d)$.

Given a function $a:\mathbb{R}^d\to\mathbb{R}$, we define the composition operator $\boldsymbol{a}:\mathcal{M}\to\mathcal{M}$ 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 4.3. *If $a\in C(\mathbb{R}^d,\mathbb{R}^+)$ then $\boldsymbol{a}:W^1L^{\Phi}\to L^{\infty}([0,T])$ is bounded. More concretely, there exists a non decreasing function $A:[0,+\infty)\to[0,+\infty)$ such that $\|\boldsymbol{a}(u)\|_{L^{\infty}([0,T])}\leqslant A(\|u\|_{W^1L^{\Phi}})$.*

The following theorem will be used repeatedly. We adapted the proof of [1, Lemma 2.5] to the anisotropic case. For an alternative approach see [4].

Lemma 4.4. *Let $\{u_n\}_{n\in\mathbb{N}}$ be a sequence of functions converging to $u\in\Pi(E^{\Phi},\lambda)$ 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 $\Phi(u_{n_k}/\lambda)\leqslant h$ a.e.*

Proof. Since $d(u,E^{\Phi})<\lambda$ and u_n converges to u, there exists a subsequence of u_n (again denoted u_n), $\overline{\lambda}\in(0,\lambda)$ and $u_0\in E^{\Phi}$ such that $d(u_n,u_0)<\overline{\lambda}$, $n=1,\ldots$. Since $L^{\Phi}\left([0,T],\mathbb{R}^d\right)\hookrightarrow L^1\left([0,T],\mathbb{R}^d\right)$, the sequence u_n converges in measure to u. Therefore, we can to extract a subsequence (denoted again u_n) such that $u_n\to u$ a.e. and

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

We can assume $\lambda_n>0$ for every $n=1,\ldots$. We write $\lambda_1:=\|u_1-u_0\|_{L^{\Phi}}$ and $\lambda_0:=\lambda-\sum_{n=1}^{\infty}\lambda_n$ and define $h:[0,T]\to\mathbb{R}$ by

$$h(t)=\frac{\lambda_0}{\lambda}\Phi\left(\frac{u_0}{\lambda_0}\right)+\sum_{j=0}^{\infty}\frac{\lambda_{j+1}}{\lambda}\Phi\left(\frac{u_{j+1}-u_j}{\lambda_{j+1}}\right). \tag{21}$$

Since $\Phi(0)=0$ and from the convexity of Φ we have for any $n=1,\ldots$

$$\begin{aligned}\Phi\left(\frac{u_n}{\lambda}\right)&=\Phi\left(\frac{u_0}{\lambda}+\sum_{j=0}^{n-1}\frac{u_{j+1}-u_j}{\lambda}\right)\\&\leqslant\frac{\lambda_0}{\lambda}\Phi\left(\frac{u_0}{\lambda_0}\right)+\sum_{j=0}^{n-1}\frac{\lambda_{j+1}}{\lambda}\Phi\left(\frac{u_{j+1}-u_j}{\lambda_{j+1}}\right)\leqslant h\end{aligned}$$

Since $u_0\in E^{\Phi}\subset C^{\Phi}$ and E^{Φ} is a subspace we have that $\Phi(u_0/\lambda_0)\in L^1([0,T],\mathbb{R})$. On the other hand $\|u_{j+1}-u_j\|_{L^{\Phi}}=\lambda_{j+1}$, therefore

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

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

□

The proof of the following theorem follows the same lines as [1, Th. 3.2] but with some modifications by the lack of monotony of Φ with respect to the euclidean norm and the fact that the notion of absolutely continuous norm (used intensely in [1, Th. 3.2]) does not work very well in the framework of anisotropic Orlicz spaces.

Theorem 4.5. *Let $\mathcal{L}$ be a differentiable Carathéodory function satisfying (S). Then the following statements hold:*

1. *The action integral given by (IA) is finitely defined on the set $\mathcal{E}^{\Phi}_{\Lambda} := W^1L^{\Phi} \cap \{u | u' \in \Pi(E^{\Phi}, \Lambda)\}$.*
2. *The function I is Gâteaux differentiable on $\mathcal{E}^{\Phi}_{\Lambda}$ and its derivative I' is demicontinuous from $\mathcal{E}^{\Phi}_{\Lambda}$ into $\left[W^1L^{\Phi}\right]^{\star}$, i.e. I' is continuous when $\mathcal{E}^{\Phi}_{\Lambda}$ is equipped with the strong topology and $\left[W^1L^{\Phi}\right]^{\star}$ with the weak$\star$ topology. Moreover, I' is given by the following expression*
$$\langle I'(u), v\rangle = \int_0^T \left[\nabla_x \mathcal{L}\big(t, u, u'\big) \cdot v + \nabla_y \mathcal{L}\big(t, u, u'\big) \cdot v'\right] \, dt. \tag{22}$$
3. *If $\Phi^{\star} \in \Delta_2$ then I' is continuous from $\mathcal{E}^{\Phi}_{\Lambda}$ into $\left[W^1L^{\Phi}\right]^{\star}$ when both spaces are equipped with the strong topology.*

Proof. Let $u \in \mathcal{E}^{\Phi}_{\Lambda}$. From (11) we obtain $\Phi(u'(t)/\Lambda) \in L^1$. Now, from (S) and Lemma 4.3 we have

$$\begin{aligned} |\mathcal{L}(t, u(t), u'(t))| + |\nabla_x \mathcal{L}(t, u(t), u'(t))| + \Phi^{\star}\left(\frac{\nabla_y \mathcal{L}(t, u, u')}{\lambda}\right) \\ \leqslant A(\|u\|_{W^1L^{\Phi}}) \left[b(t) + \Phi\left(\frac{u'(t)}{\Lambda}\right)\right] \in L^1, \end{aligned} \tag{23}$$

Thus item (1) is proved integrating this inequality.

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

Step 1. The non linear operator $u \mapsto \nabla_x \mathcal{L}(\cdot, u, u')$ is continuous from $\mathcal{E}^{\Phi}_{\Lambda}$ 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 $\mathcal{E}^{\Phi}_{\Lambda}$ and let $u \in \mathcal{E}^{\Phi}_{\Lambda}$ such that $u_n \to u$ in W^1L^{Φ}. By (S.I), $u_n \to u$ uniformly. As $u'_n \to u' \in \mathcal{E}^{\Phi}_{\Lambda}$, by Lemma 4.4, there exist a subsequence of u'_n (again denoted u'_n) and a function $h \in L^1([0, T], \mathbb{R})$ such that $u'_n \to u'$ a.e. and $\Phi(u'_n/\Lambda) \leqslant h$ a.e.

Since u_n, $n = 1, 2, \ldots$, is a bounded sequence in W^1L^{Φ}, according to Lemma (4.3), there exists $M > 0$ such that $\|\boldsymbol{a}(u_n)\|_{L^{\infty}} \leqslant M$, $n = 1, 2, \ldots$. From the previous facts and (23), we get

$$|\nabla_x \mathcal{L}(\cdot, u_n, u'_n)| \leqslant a(u_n) \left[b + \Phi\left(\frac{u'_n}{\Lambda}\right)\right] \leqslant M(b + h) \in L^1.$$

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

$$\nabla_x \mathcal{L}(t, u_{n_k}(t), u'_{n_k}(t)) \to \nabla_x \mathcal{L}(t, u(t), u'(t)) \quad \text{for a.e. } t \in [0, T].$$

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

Step 2. The non linear operator $u \mapsto \nabla_y \mathcal{L}(\cdot, u, u')$ *is continuous from* $\mathcal{E}^{\Phi}_{\Lambda}$ *with the strong topology into* $\left[L^{\Phi}\right]^{\star}$ *with the weak*$\star$ *topology.*

Let $u \in \mathcal{E}^{\Phi}_{\Lambda}$. From (23) it follows that

$$\nabla_y \mathcal{L}(\cdot, u, u') \in \lambda C^{\Phi^\star}\left([0,T], \mathbb{R}^d\right) \subset L^{\Phi^\star}\left([0,T], \mathbb{R}^d\right) \subset \left[L^{\Phi}\left([0,T], \mathbb{R}^d\right)\right]^{\star}. \quad (24)$$

Let $u_n, u \in \mathcal{E}^{\Phi}_{\Lambda}$ such that $u_n \to u$ in the norm of $W^1 L^{\Phi}$. We must prove that $\nabla_y \mathcal{L}(\cdot, u_n, u_n') \xrightarrow{w^\star} \nabla_y \mathcal{L}(\cdot, u, u')$. On the contrary, there exist $v \in L^{\Phi}$, $\epsilon > 0$ and a subsequence of $\{u_n\}$ (denoted $\{u_n\}$ for simplicity) such that

$$\left|\langle \nabla_y \mathcal{L}(\cdot, u_n, u_n'), v\rangle - \langle \nabla_y \mathcal{L}(\cdot, u, u'), v\rangle\right| \geqslant \epsilon. \quad (25)$$

We have $u_n \to u$ in L^{Φ} and $u_n' \to u' \in \Pi(E^{\Phi}, \Lambda)$. By Lemmas 2.6 and 4.4, 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 $u_n \to u$ uniformly, $u_n' \to u'$ a.e. and $\Phi(u_n'/\Lambda) \leqslant h$ a.e. As in the previous step, Lemma 4.3 implies that $a(u_n(t))$ is uniformly bounded by a certain constant $M > 0$. Therefore, from inequality (23) with u_n instead of u, we have

$$\Phi^\star\left(\frac{\nabla_y \mathcal{L}(\cdot, u_n, u_n')}{\lambda}\right) \leqslant M(b + h) =: h_1 \in L^1. \quad (26)$$

As $v \in L^{\Phi}$ there exists $\lambda_v > 0$ such that $\Phi(v/\lambda_v) \in L^1$. Now, by Young inequality and (26), we have

$$\begin{aligned} \nabla_y \mathcal{L}(\cdot, u_n, u_n') \cdot v(t) &\leqslant \lambda\lambda_v \left[\Phi^\star\left(\frac{\nabla_y \mathcal{L}(\cdot, u_n, u_n')}{\lambda}\right) + \Phi\left(\frac{v}{\lambda_v}\right)\right] \\ &\leqslant \lambda\lambda_v M(b+h) + \lambda\lambda_v \Phi\left(\frac{v}{\lambda_v}\right) \in L^1 \end{aligned} \quad (27)$$

Finally, from the Lebesgue Dominated Convergence Theorem, we deduce

$$\int_0^T \nabla_y \mathcal{L}(t, u_n, u_n') \cdot v dt \to \int_0^T \nabla_y \mathcal{L}(t, u, u') \cdot v \, dt \quad (28)$$

which contradicts the inequality (25). This completes the proof of step 2.

Step 3. We will prove (22). Note that (23), (24) and the imbeddings $W^1 L^{\Phi} \hookrightarrow L^{\infty}$ and $L^{\Phi^\star} \hookrightarrow \left[L^{\Phi}\right]^\star$ imply that the second member of (22) defines an element of $\left[W^1 L^{\Phi}\right]^\star$.

The proof follows similar lines as [12, Thm. 1.4]. For $u \in \mathcal{E}^{\Phi}_{\Lambda}$ and $0 \neq v \in W^1 L^{\Phi}$, we define the function

$$H(s,t) := \mathcal{L}(t, u(t) + sv(t), u'(t) + sv'(t)).$$

For $|s| \leqslant s_0 := \left(\Lambda - d(u', E^\Phi)\right)/\|v\|_{W^1L^\Phi}$ we have that $u' + sv' \in \Pi(E^\Phi, \Lambda)$. This fact implies, in virtue of Theorem 4.5 item 1, that $I(u+sv)$ is well defined and finite for $|s| \leqslant s_0$.

We write $s_1 := \min\{s_0, 1-d(u', E^\Phi)/\Lambda\}$. Let $\lambda_v > 0$ such that $\Phi(v'/\lambda_v) \in L^1$. As $u' \in \Pi(E^\Phi, \Lambda)$, then

$$d\left(\frac{u'}{(1-s_1)\Lambda}, E^\Phi\right) = \frac{1}{(1-s_1)\Lambda} d(u', E^\Phi) < 1$$

Consequently $(1-s_1)^{-1}\Lambda^{-1}u' \in C^\Phi$. Hence, if $v' \in L^\Phi$ and $|s| \leqslant s_1\Lambda\lambda_v^{-1}$, from the convexity of Φ and ((P2)), we get

$$\begin{aligned}
\Phi\left(\frac{u'+sv'}{\Lambda}\right) &\leqslant (1-s_1)\Phi\left(\frac{u'}{(1-s_1)\Lambda}\right) + s_1\Phi\left(\frac{s}{s_1\Lambda}v'\right) \\
&\leqslant (1-s_1)\Phi\left(\frac{u'}{(1-s_1)\Lambda}\right) + s_1\Phi\left(\frac{v'}{\lambda_v}\right) \\
&=: h(t) \in L^1
\end{aligned} \tag{29}$$

We also have $\|u+sv\|_{W^1L^\Phi} \leqslant \|u\|_{W^1L^\Phi} + s_0\|v\|_{W^1L^\Phi}$; then, by Lemma 4.3, there exists $M > 0$, independent of s, such that $\|a(u+sv)\|_{L^\infty} \leqslant M$. Now, applying Young's Inequality, (23), the fact that $v \in L^\infty$, (29) and $\Phi(v'/\lambda_v) \in L_1$, we get

$$\begin{aligned}
|D_sH(s,t)| &= \left|\nabla_x\mathcal{L}(t, u+sv, u'+sv')\cdot v + \nabla_y\mathcal{L}(t, u+sv, u'+sv')\cdot v'\right| \\
&\leqslant M\left[b(t) + \Phi\left(\frac{u'+sv'}{\Lambda}\right)\right]|v| \\
&\quad + \lambda\lambda_v\left[\Phi^\star\left(\frac{\nabla_y\mathcal{L}(t, u+sv, u'+sv')}{\lambda}\right) + \Phi\left(\frac{v'}{\lambda_v}\right)\right] \\
&\leqslant M\left[b(t) + \Phi\left(\frac{u'+sv'}{\Lambda}\right)\right](|v| + \lambda\lambda_v) + \lambda\lambda_v\Phi\left(\frac{v'}{\lambda_v}\right) \\
&\leqslant M\left(b(t) + h(t)\right)(|v| + \lambda\lambda_v) + \lambda\lambda_v\Phi\left(\frac{v'}{\lambda_v}\right) \in L^1.
\end{aligned} \tag{30}$$

Consequently, I has a directional derivative and

$$\langle I'(u), v\rangle = \frac{d}{ds}I(u+sv)\big|_{s=0} = \int_0^T \left[\nabla_x\mathcal{L}(t,u,u')\cdot v + \nabla_y\mathcal{L}(t,u,u')\cdot v'\right]\,dt.$$

Moreover, from the previous formula, (23), (24), and Lemma 2.4, we obtain

$$|\langle I'(u), v\rangle| \leqslant \|\nabla_x\mathcal{L}\|_{L^1}\|v\|_{L^\infty} + \|\nabla_y\mathcal{L}\|_{L^{\Phi^\star}}\|v'\|_{L^\Phi} \leqslant C\|v\|_{W^1L^\Phi}$$

with a appropriate constant C. This completes the proof of the Gâteaux differentiability of I. The previous steps imply the demicontinuity of the operator $I' : \mathcal{E}^\Phi_\Lambda \to \left[W^1L^\Phi_d\right]^\star$.

In order to prove item 3, it is necessary to see that the maps $u \mapsto \nabla_x\mathcal{L}(t,u,u')$ and $u \mapsto \nabla_y\mathcal{L}(t,u,u')$ are norm continuous from $\mathcal{E}^\Phi_\Lambda$ into

L^1 and $L^{\Phi^\star}$, respectively. It remains to the continuity of the second map. To this purpose, we take $u_n, u \in \mathcal{E}^{\Phi}_{\Lambda}$, $n = 1, 2, \dots$, with $\|u_n - u\|_{W^1 L^\Phi} \to 0$. As before, we can deduce there exist a subsequence (denoted u_n' for simplicity) and $h_1 \in L^1$ such that (26) holds and $u_n \to u$ a.e. Since $\Phi^\star \in \Delta_2$,

$$\Phi^\star(\nabla_y \mathcal{L}(\cdot, u_n, u_n')) \leqslant c(\lambda)\Phi^\star\left(\frac{\nabla_y \mathcal{L}(\cdot, u_n, u_n')}{\lambda}\right) + 1 \leqslant c(\lambda)h_1 + 1 =: h_2 \in L^1. \tag{31}$$

Then, from the quasi-subadditivity of $\Phi^\star$ we have

$$\Phi^\star\left(\nabla_y \mathcal{L}(\cdot, u_n, u_n') - \nabla_y \mathcal{L}(\cdot, u, u')\right) \leqslant K(h_2 + \Phi^\star(\nabla_y \mathcal{L}(\cdot, u, u'))) + 1.$$

Now, by Dominated Convergence Theorem, we obtain that $\nabla_y \mathcal{L}(\cdot, u_n, u_n')$ is $\rho_{\Phi^\star}$ modular convergent to $\nabla_y \mathcal{L}(\cdot, u, u'))$, i.e. $\rho_{\Phi^\star}(u_n - u) \to 0$. Since $\Phi^\star$ is Δ_2, modular convergence implies norm convergence (see [18]). $\square$

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