 doi:10.20944/preprints202210.0207.v11

On duality principles and related convex dual formulations suitable for local and global non-convex variational optimization

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Abstract

This article develops duality principles and related convex dual formulations suitable for the local and global optimization of non-convex primal formulations for a large class of models in physics and engineering. The results are based on standard tools of functional analysis, calculus of variations and duality theory. In particular, we develop applications to a Ginzburg-Landau type equation.

Key words: Convex dual variational formulation, duality principle for non-convex local primal optimization, Ginzburg-Landau type equation

MSC 49N15

1 Introduction

In this article we establish a duality principle and a related convex dual formulation suitable for the local optimization of the primal formulation for a large class of models in non-convex optimization.

The main duality principle is applied to the Ginzburg-Landau system in superconductivity in the absence of a magnetic field.

Such results are based on the works of J.J. Telega and W.R. Bielski [2, 3, 13, 14] and on a D.C. optimization approach developed in Toland [15].

About the other references, details on the Sobolev spaces involved are found in [1]. Related results on convex analysis and duality theory are addressed in [9, 5, 6, 7, 12]. Finally, similar models on the superconductivity physics may be found in [4, 11].

Remark 1.1. *It is worth highlighting, we may generically denote*

$$\int_\Omega [(-\gamma \nabla^2 + K I_d)^{-1} v^*] v^* \, dx$$

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simply by

$$\int_\Omega \frac{(v^*)^2}{-\gamma\nabla^2+K}\,dx,$$

where I_d denotes a concerning identity operator.

Other similar notations may be used along this text as their indicated meaning are sufficiently clear.

Finally, ∇^2 denotes the Laplace operator and for real constants $K_2>0$ and $K_1>0$, the notation $K_2 \gg K_1$ means that $K_2>0$ is much larger than $K_1>0$.

At this point we start to describe the primal and dual variational formulations.

Let $\Omega \subset \mathbb{R}^3$ be an open, bounded, connected set with a regular (Lipschitzian) boundary denoted by $\partial\Omega$.

For the primal formulation, consider a functional $J: V \to \mathbb{R}$ where

$$\begin{aligned} J(u) &= \frac{\gamma}{2}\int_\Omega \nabla u\cdot\nabla u\,dx \\ &+\frac{\alpha}{2}\int_\Omega (u^2-\beta)^2\,dx - \langle u,f\rangle_{L^2}. \end{aligned} \tag{1}$$

Here $\gamma>0$, $\alpha>0$, $\beta>0$ and $f \in L^2(\Omega)\cap L^\infty(\Omega)$.

Moreover, $V = W_0^{1,2}(\Omega)$ and we denote $Y=Y^*=L^2(\Omega)$.

Define the functionals $F_1: V\times Y \to \mathbb{R}$, $F_2: V\to\mathbb{R}$ and $G: V\times Y\to\mathbb{R}$ by

$$\begin{aligned} F_1(u,v_0^*) &= \frac{\gamma}{2}\int_\Omega \nabla u\cdot\nabla u\,dx - \frac{K}{2}\int_\Omega u^2\,dx \\ &+\frac{K_1}{2}\int_\Omega(-\gamma\nabla^2 u+2v_0^*u-f)^2\,dx+\frac{K_2}{2}\int_\Omega u^2\,dx, \end{aligned} \tag{2}$$

$$F_2(u)=\frac{K_2}{2}\int_\Omega u^2\,dx$$

and

$$G(u,v)=\frac{\alpha}{2}\int_\Omega (u^2-\beta+v)^2\,dx+\frac{K}{2}\int_\Omega u^2\,dx-\langle u,f\rangle_{L^2}.$$

We define also $F_1^*: [Y^*]^3\to\mathbb{R}$, $F_2^*: Y^*\to\mathbb{R}$, and $G^*: [Y^*]^2\to\mathbb{R}$, by

$$\begin{aligned} & F_1^*(v_2^*,v_1^*,v_0^*) \\ =& \sup_{u\in V}\{\langle u, v_1^*+v_2^*\rangle_{L^2}-F_1(u,v_0^*)\} \\ =& \int_\Omega \frac{(v_1^*+v_2^*+K_1(-\gamma\nabla^2+2v_0^*)f)^2}{2[K_2-K-\gamma\nabla^2+K_1(-\gamma\nabla^2+2v_0^*)^2]}\,dx \\ & -\frac{K_1}{2}\int_\Omega f^2\,dx, \end{aligned} \tag{3}$$

$$\begin{aligned} F_2^*(v_2^*) &= \sup_{u\in V}\{\langle u,v_2^*\rangle_{L^2}-F_2(u)\} \\ &= \frac{1}{2K_2}\int_\Omega (v_2^*)^2\,dx \end{aligned} \tag{4}$$

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and

$$\begin{aligned} G^*(v_1^*, v_0^*) &= \sup_{(u,v)\in V\times Y} \{-\langle u, v_1^*\rangle_{L^2} + \langle v, v_0^*\rangle_{L^2} - G(u,v)\} \\ &= \frac{1}{2}\int_\Omega \frac{(v_1^*-f)^2}{2v_0^*+K}\,dx + \frac{1}{2\alpha}\int_\Omega (v_0^*)^2\,dx \\ &\quad +\beta\int_\Omega v_0^*\,dx \end{aligned} \tag{5}$$

if $v_0^* \in B^*$ where

$$B^* = \left\{v_0^* \in Y^* \ : \ \|2v_0^*\|_\infty < K/8 \text{ and } -\gamma\nabla^2 + 2v_0^* > \varepsilon I_d\right\},$$

for a small parameter $0 < \varepsilon \ll 1$.

Furthermore, we define

$$D^* = \{v_1^* \in Y^* \ : \ \|v_1^*\|_\infty \leq (3/2)K\}$$

and $J_1^* : Y^* \times D^* \times B^* \to \mathbb{R}$, by

$$J_1^*(v_2^*, v_1^*, v_0^*) = -F_1^*(v_2^*, v_1^*, v_0^*) + F_2^*(v_2^*) - G^*(v_1^*, v_0^*).$$

Assuming

$$K_2 \gg K_1 \gg K \gg \max\{\|f\|_\infty, \alpha, \beta, \gamma, 1/\varepsilon^2\}$$

by directly computing $\delta^2 J_1^*(v_2^*, v_1^*, v_0^*)$ we may obtain that for such specified real constants, J_1^* in convex in v_2^* and it is concave in (v_1^*, v_0^*) on $Y^* \times D^* \times B^*$.

2 The main duality principle and a concerning convex dual formulation

Considering the statements and definitions presented in the previous section, we may prove the following theorem.

Theorem 2.1. *Let $(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) \in Y^* \times D^* \times B^*$ be such that*

$$\delta J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) = \mathbf{0}$$

and $u_0 \in V$ be such that

$$u_0 = \frac{\partial F_2^*(\hat{v}_2^*)}{\partial v_2^*}.$$

Under such hypotheses, we have

$$\delta J(u_0) = \mathbf{0},$$

and

$$\begin{aligned} J(u_0) &= \inf_{u\in V}\left\{J(u) + \frac{K_1}{2}\int_\Omega(-\gamma\nabla^2 u + 2\hat{v}_0^* u - f)^2\,dx\right\} \\ &= \inf_{v_2^*\in Y^*}\left\{\sup_{(v_1^*,v_0^*)\in D^*\times B^*} J_1^*(v_2^*, v_1^*, v_0^*)\right\} \\ &= J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*). \end{aligned} \tag{6}$$

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Proof. Observe that $\delta J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) = \mathbf{0}$ so that, since J_1^* is convex in v_2^* and concave in (v_1^*, v_0^*) on $Y^* \times D^* \times B^*$, from the Min-Max theorem, we obtain

$$J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) = \inf_{v_2^* \in Y^*} \left\{ \sup_{(v_1^*, v_0^*) \in D^* \times B^*} J_1^*(v_2^*, v_1^*, v_0^*) \right\}.$$

Now we are going to show that

$$\delta J(u_0) = \mathbf{0}.$$

From

$$\frac{\partial J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*)}{\partial v_2^*} = \mathbf{0},$$

and

$$\frac{\partial F_2^*(\hat{v}_2^*)}{\partial v_2^*} = u_0$$

we have

$$-\frac{\partial F_1^*(\hat{v}_2^*, \hat{v}_1^*, v_0^*)}{\partial v_2^*} + u_0 = \mathbf{0}$$

and

$$\hat{v}_2^* - K_2 u_0 = \mathbf{0}.$$

Observe now that denoting

$$H(v_2^*, v_1^*, v_0^*, u) = \langle u, v_1^* + v_2^* \rangle_{L^2} - F_1(u, v_0^*),$$

there exists $\hat{u} \in V$ such that

$$\frac{\partial H(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*, \hat{u})}{\partial u} = \mathbf{0},$$

and

$$F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) = H(\hat{v}_1^*, \hat{v}_2^*, \hat{v}_0^*, \hat{u}),$$

so that

$$\begin{aligned} \frac{\partial F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*)}{\partial v_2^*} &= \frac{\partial H(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*, \hat{u})}{\partial v_2^*} \\ &\quad + \frac{\partial H(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*, \hat{u})}{\partial u} \frac{\partial \hat{u}}{\partial v_2^*} \\ &= \hat{u}. \end{aligned} \tag{7}$$

Summarizing, we have got

$$u_0 = \frac{\partial F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*)}{\partial v_2^*} = \hat{u}.$$

Also, denoting

$$A(u_0, \hat{v}_0^*) = -\gamma \nabla^2 u_0 + 2\hat{v}_0^* u_0 - f,$$

from

$$\frac{\partial H(\hat{v}_1^*, \hat{v}_2{}^*, \hat{v}_0^*, u_0)}{\partial u} = \mathbf{0},$$

we have

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$$-\hat{v}_1^* + Ku_0 + \gamma\nabla^2 u_0 + K_1(-\gamma\nabla^2 + 2\hat{v}_0^*)A(u_0, \hat{v}_0^*) - \hat{v}_2^* + K_2 u_0 = \mathbf{0},$$

so that

$$-\hat{v}_1^* + Ku_0 + \gamma\nabla^2 u_0 + K_1(-\gamma\nabla^2 + 2\hat{v}_0^*)A(u_0, \hat{v}_0^*) = \mathbf{0}. \tag{8}$$

From such results, we may infer that

$$\begin{aligned} & \frac{\partial F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*)}{\partial v_1^*} \\ = & \frac{\partial H(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*, \hat{u})}{\partial v_1^*} \\ & + \frac{\partial H(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*, \hat{u})}{\partial u}\frac{\partial \hat{u}}{\partial v_1^*} \\ = & \hat{u} \\ = & u_0. \end{aligned} \tag{9}$$

Now observe that from the variation of J_1^* in v_1^*, we have

$$-\frac{\partial F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*)}{\partial v_1^*} - \frac{\partial G^*(\hat{v}_1^*, \hat{v}_0^*)}{\partial v_1^*} = \mathbf{0}$$

so that

$$-u_0 - \frac{\partial G^*(\hat{v}_1^*, \hat{v}_0^*)}{\partial v_1^*} = \mathbf{0}$$

that is

$$-u_0 - \frac{\hat{v}_1^* - f}{2\hat{v}_0^* + K} = \mathbf{0}.$$

From this and (8), we may infer that

$$\hat{v}_1^* = -\gamma\nabla^2 u_0 - Ku_0 - K_1(-\gamma\nabla^2 + 2\hat{v}_0^*)A(u_0, \hat{v}_0^*) = -(2\hat{v}_0^* + K)u_0 + f,$$

so that

$$-\gamma\nabla^2 u_0 + 2\hat{v}_0^* u_0 - f - K_1(-\gamma\nabla^2 + 2\hat{v}_0^*)A(u_0, \hat{v}_0^*) = 0.$$

From this and the concerning boundary conditions, since

$$A(u_0, v_0^*) = -\gamma\nabla^2 u_0 + 2\hat{v}_0^* u_0 - f,$$

we may obtain

$$-\gamma\nabla^2 u_0 + 2\hat{v}_0^* u_0 - f = A(u_0, \hat{v}_0^*) = 0.$$

Moreover, from

$$\frac{\partial J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*)}{\partial v_0^*} = \mathbf{0},$$

we have

$$A(u_0, \hat{v}_0^*)2u_0 - \frac{\hat{v}_0^*}{\alpha} + u_0^2 - \beta = \mathbf{0},$$

so that

$$v_0^* = \alpha(u_0^2 - \beta).$$

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From such last results we get

$$-\gamma\nabla^2 u_0 + 2\alpha(u_0^2 - \beta)u_0 - f = \mathbf{0},$$

and thus

$$\delta J(u_0) = \mathbf{0}.$$

Furthermore, also from such last results and the Legendre transform properties, we have

$$F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) = \langle u_0, \hat{v}_2^* + \hat{v}_1^* \rangle_{L^2} - F_1(u_0, \hat{v}_0^*),$$

$$F_2^*(\hat{v}_2^*) = \langle u_0, \hat{v}_2^* \rangle_{L^2} - F_2(u_0),$$

$$G^*(\hat{v}_1^*, \hat{v}_0^*) = -\langle u_0, \hat{v}_1^* \rangle_{L^2} + \langle 0, \hat{v}_0^* \rangle_{L^2} - G(u_0, \mathbf{0}),$$

so that

$$\begin{aligned} & J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) \\ = & -F_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) + F_2^*(\hat{v}_2^*) - G^*(\hat{v}_1^*, \hat{v}_0^*) \\ = & F_1(u_0, \hat{v}_0^*) - F_2(u_0) + G(u_0, \mathbf{0}) \\ = & J(u_0). \end{aligned} \tag{10}$$

Finally, observe that

$$J_1^*(v_2^*, v_1^*, v_0^*) \leq -\langle u, v_2^* \rangle_{L^2} + F_1(u, v_0^*) + F_2^*(v_2^*) + G(u, \mathbf{0}),$$

$\forall u \in V,\ v_2^* \in Y^*,\ v_1^* \in D^*, v_0^* \in B^*$.

Thus, we may obtain

$$\begin{aligned} & \inf_{v_2^* \in Y^*} J_1^*(v_2^*, \hat{v}_1^*, \hat{v}_0^*) \\ \leq & \inf_{v_2^* \in Y^*} \{-\langle u, v_2^* \rangle_{L^2} + F_1(u, \hat{v}_0^*) + F_2^*(v_2^*) + G(u, \mathbf{0})\} \\ = & F_1(u, \hat{v}_0^*) - F_2(u) + G(u, \mathbf{0}) \\ = & J(u) + \frac{K_1}{2} \int_\Omega (-\gamma\nabla^2 u + 2\hat{v}_0^* u - f)^2 \, dx, \ \forall u \in V. \end{aligned} \tag{11}$$

From this and (11), we obtain

$$\begin{aligned} & J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*) \\ = & \inf_{v_2^* \in Y^*} \left\{ \sup_{(v_1^*, v_0^*) \in D^* \times B^*} J_1^*(v_2^*, v_1^*, v_0^*) \right\} \\ \leq & \inf_{u \in V} \left\{ J(u) + \frac{K_1}{2} \int_\Omega (-\gamma\nabla^2 u + 2\hat{v}_0^* u - f)^2 \, dx \right\}. \end{aligned} \tag{12}$$

Joining the pieces, from a concerning convexity in u, we have got

$$\begin{aligned} J(u_0) &= \inf_{u \in V} \left\{ J(u) + \frac{K_1}{2} \int_\Omega (-\gamma\nabla^2 u + 2\hat{v}_0^* u - f)^2 \, dx \right\} \\ &= \inf_{v_2^* \in Y^*} \left\{ \sup_{(v_1^*, v_0^*) \in D^* \times B^*} J_1^*(v_2^*, v_1^*, v_0^*) \right\} \\ &= J_1^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_0^*). \end{aligned} \tag{13}$$

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The proof is complete.

□

Remark 2.2. *We could have also defined*

$$B^* = \left\{v_0^* \in Y^* \;:\; \|2v_0^*\|_\infty < K/8 \text{ and } -\gamma\nabla^2 + 2v_0^* < -\varepsilon I_d\right\},$$

for a small parameter $0 < \varepsilon \ll 1$. *This corresponds to* $-\gamma\nabla^2 + 2v_0^*$ *be negative definite, whereas the previous case corresponds to* $-\gamma\nabla^2 + 2v_0^*$ *be positive definite. It is worth recalling the inequality*

$$-\gamma\nabla^2 + 2v_0^* < -\varepsilon I_d$$

necessarily refers to a finite dimensional version for the model in question, in a finite elements or finite differences context.

3 One more duality principle suitable for the primal formulation global optimization

In this section we establish one more duality principle and related convex dual formulation. Let $\Omega \subset \mathbb{R}^3$ be an open, bounded, connected set with a regular (Lipschitzian) boundary denoted by $\partial\Omega$.

For the primal formulation, we define $V = W_0^{1,2}(\Omega)$ and consider a functional $J : V \to \mathbb{R}$ where we assume there exists $\alpha \in \mathbb{R}$ such that

$$\alpha = \inf_{u \in V} J(u).$$

We also suppose $K > 0$ is such that

$$\frac{\partial^2 J(u)}{\partial u^2} + K I_d > \mathbf{0},$$

$\forall u \in V$. We define,

$$V_1 = \{u \in V \;:\; \|u\|_\infty < K_8\},$$

for an appropriate constant $K_8 \approx 3$.

Define also the functionals $F_1 : V \to \mathbb{R}$, $F_2 : V \times Y \to \mathbb{R}$ by

$$F_1(u) = J(u) + \frac{K}{2}\int_\Omega u^2\,dx$$

and

$$F_2(u, v_3^*) = -\frac{K}{2}\int_\Omega u^2\,dx + \frac{K_1}{2}\int_\Omega (v_3^*(K_3 + K_5 u) - K_4)^2\,dx,$$

for appropriate positive constants K, K_1, K_3, K_4, K_5 to be specified.

Moreover, define $F_1^* : Y^* \to \mathbb{R}$, and $F_2^* : [Y^*]^2 \to \mathbb{R}$, by

$$F_1^*(v_2^*) = \sup_{u \in V}\{\langle u, v_2^*\rangle_{L^2} - F_1(u)\},$$

and

$$\begin{aligned} F_2^*(v_2^*, v_3^*) &= \sup_{u \in V}\{-\langle u, v_2^* \rangle_{L^2} - F_2(u, v_3^*)\} \\ &= \frac{1}{2}\int_\Omega \frac{(v_2^* + K_1K_5(K_3(v_3^*)^2 - K_4v_3^*))^2}{-K + K_1\ K_5^2(v_3^*)^2}\,dx - \frac{K_1}{2}\int_\Omega (K_3v_3^* - K_4)^2\,dx. \end{aligned}$$

Furthermore, we define

$$D^* = \{v_2^* \in Y^*\ :\ \|v_2^*\|_\infty \leq (3/2)K\}$$

$$B^* = \left\{v_3^* \in Y^*\ :\ \|v_3^*\|_\infty \leq \frac{8K_4}{K_3}\right\}.$$

and $J_1^* : D^* \times B^* \to \mathbb{R}$, by

$$J_1^*(v_2^*, v_3^*) = -F_1^*(v_2^*) - F_2^*(v_2^*, v_3^*).$$

Moreover, assuming $K_1 \gg 1$, $K_3 = \sqrt[4]{K_1}$, $K_4 = 1/K_3$ and $K_5 = \frac{K_3}{K_8+5}$, by directly computing $\delta^2 J_1^*(v_2^*, v_1^*, v_0^*, v_3^*)$ we may obtain that for such specified real constants, J_1^* in concave in v_2^* and it is convex in v_3^* on $D^* \times B^*$.

Indeed, denoting

$$\varphi_1 = v_2^* + K_1K_5(K_3(v_3^*)^2 - K_4v_3^*)$$

$$\varphi = -K + K_1K_5^2(v_3^*)^2,$$

$$u = -\frac{\varphi_1}{\varphi},$$

with may obtain

$$\begin{aligned} \frac{\partial^2 J_1^*(v_2^*, v_3^*)}{\partial(v_3^*)^2} &= K_1\ K_3^2 + u^2\ K_1\ K_5^2 \\ &\quad -(K_1\ K_5\ 2\ K_3\ v_3^* - K_1\ K_5\ K_4)^2/\varphi \\ &\quad +2\ u\ K_1\ K_5\ K_3 - u^2(2\ v_3^*\ K_1\ K_5^2)^2/\varphi \\ &\quad +2\ u\ (2\ v_3^*\ K_1\ K_5\ K_3 - K_1\ K_5\ K_4)\ 2\ v_3^*\ K_1\ K_5^2/\varphi \\ &\geq \mathcal{O}\left(\frac{3\ K_1\ 10^{10}}{8!\ 2500\ (15)}\right) \\ &> 0 \end{aligned} \tag{14}$$

and clearly

$$\frac{\partial^2 J_1^*(v_2^*, v_3^*)}{\partial(v_2^*)^2} < \mathbf{0}$$

From such results, as previously stated, we may easily obtain that J_1^* in concave in v_2^* and it is convex in v_3^* on $D^* \times B^*$.

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3.1 The main duality principle and a related convex dual formulation

Considering the statements and definitions presented in the previous section, we may prove the following theorem.

Theorem 3.1. *Let $(\hat{v}_2^*, \hat{v}_3^*) \in D^* \times B^*$ be such that*

$$\delta J_1^*(\hat{v}_2^*, \hat{v}_3^*) = \mathbf{0}$$

and $u_0 \in V_1$ be such that

$$u_0 = \frac{\partial F_1^*(\hat{v}_2^*)}{\partial v_2^*}.$$

Under such hypotheses, we have

$$\delta J(u_0) = \mathbf{0},$$

$$\hat{v}_3^*(K_3 + K_5\, u_0) - K_4 = \mathbf{0},$$

and

$$\begin{aligned} J(u_0) &= \inf_{u \in V_1} J(u) \\ &= \sup_{v_2^* \in D^*} \left\{ \inf_{v_3^* \in B^*} J_1^*(v_2^*, v_3^*) \right\} \\ &= J_1^*(\hat{v}_2^*, \hat{v}_3^*). \end{aligned} \tag{15}$$

Proof. Observe that $\delta J_1^*(\hat{v}_2^*, \hat{v}_3^*) = \mathbf{0}$ so that, since J_1^* is concave in v_2^* and convex in v_3^* on $D^* \times B^*$, from the Min-Max theorem, we obtain

$$J_1^*(\hat{v}_2^* \hat{v}_3^*) = \sup_{v_2^* \in D^*} \left\{ \inf_{v_3^* B^*} J_1^*(v_2^*, v_3^*) \right\}.$$

Now we are going to show that

$$\delta J(u_0) = \mathbf{0}.$$

From

$$\frac{\partial J_1^*(\hat{v}_2^*, \hat{v}_3^*)}{\partial v_2^*} = \mathbf{0},$$

and

$$\frac{\partial F_1^*(\hat{v}_2^*)}{\partial v_2^*} = u_0$$

we have

$$-\frac{\partial F_2^*(\hat{v}_2^*, \hat{v}_3^*)}{\partial v_2^*} - u_0 = \mathbf{0}$$

and

$$\hat{v}_2^* = K u_0.$$

Observe now that

$$F_2^*(\hat{v}_2^*, \hat{v}_3^*) = \sup_{u \in V} \{ -\langle u, v_2^* \rangle_{L^2} - F_2(u, v_3^*) \}.$$

 doi:10.20944/preprints202210.0207.v11

Denoting

$$H(v_2^*, v_3^*, u) = -\langle u, v_2^* \rangle_{L^2} - F_2(u, v_3^*),$$

there exists $\hat{u} \in V$ such that

$$\frac{\partial H(\hat{v}_2^*, \hat{v}_3^*, \hat{u})}{\partial u} = \mathbf{0},$$

and

$$F_2^*(\hat{v}_2^*, \hat{v}_3^*) = H(\hat{v}_2^*, \hat{v}_3^*, \hat{u}),$$

so that

$$\begin{aligned} \frac{\partial F_2^*(\hat{v}_2^*, \hat{v}_3^*)}{\partial v_2^*} &= \frac{\partial H(\hat{v}_2^*, \hat{v}_3^*, \hat{u})}{\partial v_2^*} \\ &\quad + \frac{\partial H(\hat{v}_2^*, \hat{v}_3^*, \hat{u})}{\partial u}\frac{\partial \hat{u}}{\partial v_2^*} \\ &= -\hat{u}. \end{aligned} \tag{16}$$

Summarizing, we have got

$$u_0 = -\frac{\partial F_2^*(\hat{v}_2^*, \hat{v}_3^*)}{\partial v_2^*} = \hat{u}.$$

From such results and the Legendre tranform proprieties we get

$$v_2^* = \frac{\partial F_1(u_0)}{\partial u}$$

and

$$v_2^* = -\frac{\partial F_2(u_0, \hat{v}_3^*)}{\partial u}.$$

On the other hand, from the variation of J_1^* in v_3^*, we have

$$\begin{aligned} & -\frac{\partial F_2^*(\hat{v}_2^*, \hat{v}_1^*, \hat{v}_3^*)}{\partial v_3^*} \\ &= K_1(\hat{v}_3^*(K_3 + K_5 u_0) - K_4)(K_3 + K_5\ u_0) - \frac{\partial H(\hat{v}_2^*, \hat{v}_3^*, \hat{u})}{\partial u}\frac{\partial \hat{u}}{\partial v_3^*} \\ &= K_1(\hat{v}_3^*(K_3 + K_5 u_0) - K_4)(K_3 + K_5\ u_0) \\ &= \mathbf{0}. \end{aligned} \tag{17}$$

Hence, since $|u_0| < \frac{K_3}{K_5}$ a.e. in Ω, we have got

$$\hat{v}_3^*(K_3 + K_5 u_0) - K_4 = \mathbf{0}.$$

Consequently, from such last results, we have

$$\begin{aligned} \mathbf{0} &= \hat{v}_2^* - \hat{v}_2^* \\ &= \frac{\partial F_1(u_0)}{\partial u} + \frac{\partial F_2(u_0, \hat{v}_3^*)}{\partial u} \\ &= \delta J(u_0). \end{aligned} \tag{18}$$

 doi:10.20944/preprints202210.0207.v11

Summarizing,

$$\delta J(u_0) = \mathbf{0}.$$

Furthermore, also from such last results and the Legendre transform properties, we have

$$F_1^*(\hat{v}_2^*) = \langle u_0, \hat{v}_2^* \rangle_{L^2} - F_1(u_0),$$

$$F_2^*(\hat{v}_2^*, \hat{v}_3^*) = -\langle u_0, \hat{v}_2^* \rangle_{L^2} - F_2(u_0, \hat{v}_3^*),$$

so that

$$\begin{aligned} & J_1^*(\hat{v}_2^*, \hat{v}_3^*) \\ = & -F_1^*(\hat{v}_2^*) - F_2^*(\hat{v}_2^*, \hat{v}_3^*) \\ = & F_1(u_0) + F_2(u_0, \hat{v}_3^*) \\ = & J(u_0). \end{aligned} \tag{19}$$

Finally, observe that

$$J_1^*(\hat{v}_2^*, v_3^*) \leq F_1(u) + F_2(u, v_3^*),$$

$\forall u \in V_1, \ v_3^* \in B^*$.

Thus, we may obtain

$$\begin{aligned} & \inf_{v_3^* \in B^*} J_1^*(\hat{v}_2^*, v_3^*) \\ \leq & \inf_{v_3^* \in B^*} \{F_1(u) + F_2(u, v_3^*)\} \\ \leq & F_1(u) - F_2(u, K_4/(K_3 + K_5 u)) \\ = & J(u), \ \forall u \in V_1. \end{aligned} \tag{20}$$

From this, we obtain

$$\begin{aligned} & J_1^*(\hat{v}_2^*, \hat{v}_3^*) \\ = & \sup_{v_2^* \in D^*} \left\{ \inf_{v_3^* \in B^*} J_1^*(v_2^*, v_3^*) \right\} \\ \leq & \inf_{u \in V_1} \{J(u)\}. \end{aligned} \tag{21}$$

Joining the pieces, we have got

$$\delta J(u_0) = \mathbf{0},$$

$$\hat{v}_3^*(K_3 + K_5 u_0) - K_4 = \mathbf{0},$$

and

$$\begin{aligned} J(u_0) &= \inf_{u \in V_1} J(u) \\ &= \sup_{v_2^* \in D^*} \left\{ \inf_{v_3^* \in B^*} J_1^*(v_2^*, v_3^*) \right\} \\ &= J_1^*(\hat{v}_2^*, \hat{v}_3^*). \end{aligned} \tag{22}$$

The proof is complete.

□

 doi:10.20944/preprints202210.0207.v11

4 Conclusion

In this article we have developed convex dual variational formulations suitable for the local optimization of non-convex primal formulations.

It is worth highlighting, the results may be applied to a large class of models in physics and engineering.

We also emphasize the duality principles here presented are applied to a Ginzburg-Landau type equation. In a future research, we intend to extend such results for some models of plates and shells and other models in the elasticity theory.

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