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# ON THE EXISTENGE, UNIQUENESS AND APPROXIMATION OF SADDLE-POINT PROBLEMS ARISING FROM LAGRANGIAN MULTIPLIERS 

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#### Abstract

Summary. - We give necessary and sufficient conditions for existence and uniqueness of a class of problems of «saddle point》 type which are often encountered in applying the method of Lagrangian multipliers. A study of the approximation of such problems by means of «discrete problems» (with or without numerical integration) is also given, and sufficient conditions for the convergence and error bounds are obtained.


## INTRODUCTION

The present paper has been suggested by the recent development of the so called «dual analysis» and in particular of the method of Lagrangian multipliers in elasticity problems; we shall refer for now only to a few papers, and in particular to [12], [14], [24], [25], [28], [29], and to the references contained in such papers; many other references, however, will be given in the following. Although the equilibrium, hybrid and mixed methods contained in the mentioned works are often quite satisfactory from a numerical point of view, a complete study of the convergence of these methods and of the behaviour of the error has not been done until last years, and, however, only in some particular case (see e.g. [20] and especially [18], [19] for the «mixed methods» and [5] for the «assumed stresses hybrid method»; other references on this subject can be founded in [31]). The interest of these methods, and in particular of hybrid methods, has been increased by papers [15], [27], [32], in which the theory of «non conforming» (or «delinquent») elements (see e.g. [30], [21], etc.) is presented as a « particular case» (in some sense) of hybrid methods. On the other hand, a careful analysis, for instance, of the work [11] on the Stoke's equations shows that the greatest difficulties in proving convergence and error bounds are connected with the use of the method of Lagrangian multipliers itself, rather than with the physical meaning of the problem. In

[^0]this sense, the «general strategy » employed in [11] and in [5], in order to have convergence and error bounds for discretizations of different problems is, in fact, quite similar.

These considerations have suggested the author to develop the present «abstract theory» about saddle-point problems. More generally the problem treated here is the following.

$$
\left\{\begin{array}{l}
\text { Find }(u, \psi) \text { in } V \times W \text { such that : }  \tag{P}\\
a(u, v)+b(v, \psi)=\langle f, v\rangle \forall v \in V \\
b(u, \varphi)=\langle g, \varphi\rangle \forall \varphi \in W
\end{array}\right.
$$

where $V, W$ are real Hilbert spaces, $a(u, v)$ and $b(v, \varphi)$ are continuous bilinear forms on $V \times V$ and $V \times W$ respectivelly and $f, g$ are given functionals in $V^{\prime}$ and $W^{\prime}$ resp.

In paragraph 1 we give necessary and sufficient conditions on $a(u, v)$ and $b(v, \varphi)$ in order to have existence and uniqueness of the solution of problem ( $P$ ) for all given ( $f, g$ ) in $V^{\prime} \times W^{\prime}$. In paragraph 2 we introduce the «approximate problem»:

$$
\left\{\begin{array}{l}
\text { find }\left(u_{h}, \psi_{h}\right) \text { in } V_{h} \times W_{h} \text { such that : }  \tag{h}\\
a\left(u_{h}, v_{h}\right)+b\left(v_{h}, \psi_{h}\right)=\left\langle f, v_{h}\right\rangle \forall v_{h} \in V_{h}, \\
b\left(u_{h}, \varphi_{h}\right)=\left\langle g, \varphi_{h}\right\rangle \forall \varphi_{h} \in W_{h},
\end{array}\right.
$$

(where $V_{h}$ and $W_{h}$ are closed subspaces of $V$ and $W$ resp.), and we give, under suitable assumptions, an upper bound for the «error»:

$$
E_{h}=\left\|u-u_{h}\right\|+\left\|\psi-\psi_{h}\right\| .
$$

The third paragraph is dedicated to further considerations concerning «numerical integration» and «non conforming» approximation of $W$ (that is $W_{h} \nsubseteq W$ ); this latest topic has been suggested by the papers [27], [32] and can be applied for instance to the «strongly diffusive» elements (equilibrium models) by F. de Veubeke.

Of course, the theoretical results given here do not answer any question related to the mentioned methods and in general to the problems in which the method of Lagrangian multipliers is employed. In some particular cases the greatest difficulty will often be the verification of the abstract hypotheses proposed here. It is reasonable, however, to think that the knowledge of a «winning strategy» will be, in any case, useful.

[^1]
## 0. PRELIMINARIES

Let $X$ be a real Hilbert space; we denote by $X^{\prime}$ its dual space; if $x^{\prime} \in X^{\prime}$ and $x \in X$ the value of $x^{\prime}$ at the point $x$ will be indicated by $\left\langle x^{\prime}, x\right\rangle$. The scalar product and the norm in $X$ will be indicated by (,) and \|\| (resp.) or by $(,)_{X}$ and and $\left\|\|_{x}\right.$ whenever confusion may rise. We denote also by $J_{X}$ the Riesz's «representation operator» from $X^{\prime}$ onto $X$, defined by

$$
\left(J_{X} x^{\prime}, x\right)=\left\langle x^{\prime}, x\right\rangle \quad \forall x \in X, x^{\prime} \in X^{\prime} .
$$

It is well known that $J_{X}$ is a norm preserving isomorphism from $X^{\prime}$ onto $X$. Let now $Y$ be another real Hilbert space and let $T$ be a continuous linear operator from $D(T) \subseteq X$ into $Y$. The domain $D\left(T^{\prime}\right)$ of the dual operator is defined by :

$$
D\left(T^{\prime}\right)=\left\{y^{\prime} \mid y^{\prime} \in Y^{\prime}, x \rightarrow\left\langle y^{\prime}, T x\right\rangle \text { is continuous on } X\right\} .
$$

Then the dual operator $T^{\prime}$ from $D\left(T^{\prime}\right)$ into $X^{\prime}$ is defined by :

$$
\left\langle T^{\prime} y^{\prime}, x\right\rangle=\left\langle y^{\prime}, T x\right\rangle \quad \forall x \in X, y^{\prime} \in D\left(T^{\prime}\right)
$$

We want now to prove a theorem that will be useful in the following.
Theorem 0.1. - Let $X, Y$ be real Hilbert spaces; let $\mathcal{G}(x, y)$ be a continuous bilinear form on $X \times Y$ and let $T$ be the continuous linear operator from $X$ into $Y^{\prime}$ associated to $\mathcal{G}(x, y)$, defined by:

$$
\langle T x, y\rangle=\mathscr{G}(x, y) \quad \forall x \in X, y \in Y .
$$

For all $k>0$ the three following statements are equivalent :
i) $\operatorname{Sup}_{x \in X-\{0\}} \frac{\mathfrak{G}(x, y)}{\|x\|} \geqslant k\|y\| \quad \forall y \in Y$,
ii) $\left\|T^{\prime} y\right\| \geqslant k\|y\| \quad \forall y \in Y$,
iii) $\exists S \in \mathcal{L}\left(Y^{\prime}, X\right)\left({ }^{1}\right)$ such that $T S=I$ (identity) on $Y^{\prime}$ and $\|S\| \leqslant k^{-1}$.

Proof
i) $\Leftrightarrow$ ii) follows obviously from :

$$
\operatorname{Sup}_{x \in X-\{0\}} \frac{\mathscr{C}(x, y)}{\|x\|}=\operatorname{Sup}_{x \in X-\{0\}} \frac{\left\langle T^{\prime} y, x\right\rangle}{\|x\|}=\left\|T^{\prime} y\right\| \quad, \quad \forall y \in Y .
$$

[^2]iii) $\Rightarrow$ ii) follows obviously from the relations $(y \neq 0)$ :
\[

\left\{$$
\begin{array}{c}
\operatorname{Sup}_{x \in X-\{0\}} \frac{\mathcal{G}(x, y)}{\|x\|} \geqslant \frac{\mathcal{G}\left(S J_{Y}^{-1} y, y\right)}{\left\|S J_{Y}^{-1} y\right\|}=\frac{\|y\|^{2}}{\left\|S J_{Y}^{-1} y\right\|} \\
\left\|S J_{Y}^{-1} y\right\| \leqslant k^{-1}\left\|J_{Y}^{-1}\right\|=k^{-1}\|y\|
\end{array}
$$\right.
\]

ii) $\Rightarrow$ iii) Let $N=\operatorname{ker}(T)$ the kernel of $T$; setting

$$
\begin{aligned}
N^{\perp} & =\{x \mid x \in X, \quad(x, \xi)=0 \quad \text { if } T \xi=0\} \\
T_{1} & =\text { restriction of } T \text { to } N^{\perp}
\end{aligned}
$$

from ii) and the closed range theorem (cfr. e.g. Yosida [33], p. 205), we have that $T_{1}$ is an isomorphism from $N^{\perp}$ onto $Y^{\prime}$. From i) we easily get that, for all $y$ in $Y$,

$$
\operatorname{Sup}_{x \in N^{+}-\{0\}} \frac{\mathcal{G}(x, y)}{\|x\|} \geqslant k\|y\| .
$$

Then (see part i) $\Leftrightarrow$ ii) of this proof) $\left\|\left(T_{1}^{\prime}\right)^{-1}\right\| \leqslant k^{-1}$; hence $\left\|T_{1}^{-1}\right\| \leqslant k^{-1}$, and setting $S=T_{1}^{-1}$ the proof is completed.

Corollary 0.1. - Under the hypotheses of theorem 0.1 for all $\bar{k}$ and $k$ positive numbers the three following statements are equivalent :
I) $\operatorname{Sup}_{x \in X-\{0\}} \frac{\mathfrak{C}(x, y)}{\|x\|} \geqslant k\|y\| \forall y \in Y$ and $\operatorname{Sup}_{y \in Y-\{0\}} \frac{\mathfrak{G}(x, y)}{\|y\|} \geqslant \vec{k}\|x\| \forall x \in X$,
II) $\quad\|T x\| \geqslant \vec{k}\|x\| \forall x \in X$ and $\left\|T^{\prime} y\right\| \geqslant k\|y\| \forall y \in Y$,
III) $T$ is an isomorphism from $X$ onto $Y^{\prime}$,

$$
\text { with }\left\|T^{-1}\right\| \leqslant k^{-1} \text { and }\left\|\left(T^{\prime}\right)^{-1}\right\| \leqslant \bar{k}^{-1}
$$

Proof. - It is sufficient to apply theorem 0.1 to the form $\mathcal{G}(x, y)$ and to the form $\mathfrak{C}^{\prime}(y, x)=\mathfrak{G}(x, y)$ (defined on $\left.Y \times X\right)$.

REmark 0.1. - The results contained in theorem 0.1 and in corollary 0.1 are of classical type and might not be new. For instance part I) $\Rightarrow$ III) of corollary 0.1 was used by Babuska [3].

## 1. EXISTENCE AND UNIQUENESS

Let now $V$ and $W$ be real Hilbert spaces, and let $a(u, v)$ and $b(v, \varphi)$ be continuous bilinear forms on $V \times V$ and $V \times W$ respectively. For any given pair $(f, g)$ in $V^{\prime} \times W^{\prime}$ we consider the problem :

$$
\left\{\begin{array}{l}
\text { find }(u, \psi) \text { in } V \times W \text { such that : }  \tag{1.1}\\
a(u, v)+b(v, \psi)=\langle f, v\rangle \forall v \in V, \\
b(u, \varphi)=\langle g, \varphi\rangle \forall \varphi \in W
\end{array}\right.
$$

We remark that, if, for instance, $a(u, v)$ is symmetric and $V$-elliptic, in the sense that there exists a positive constant $\delta$ such that

$$
a(v, v) \geqslant \delta\|v\|^{2} \forall v \in V
$$

then problem 1.1 is equivalent to the research of the saddle point on $V \times W$ of the functional

$$
\mathcal{f}(v, \varphi)=\frac{1}{2} a(v, v)+b(v, \varphi)-\langle f, v\rangle-\langle g, \varphi\rangle .
$$

We look now for necessary and sufficient conditions in order that for each $(f, g)$ in $V^{\prime} \times W^{\prime}$ problem (1.1) has a unique solution. In other words, if $A \in \mathscr{L}\left(V, V^{\prime}\right)$ and $B \in \mathscr{L}\left(V, W^{\prime}\right)$ are the operators associated to $a(u, v)$ and $b(v, \varphi)$ resp., we search for (necessary and) sufficient conditions in order that the operator $\Lambda: V \times W \rightarrow V^{\prime} \times W^{\prime}$, defined by

$$
\begin{equation*}
\Lambda(v, \varphi)=\left(A v+B^{\prime} \varphi, B v\right) \tag{1.2}
\end{equation*}
$$

results an isomorphism.
For this, first of all we introduce the space :

$$
\begin{equation*}
Z=\operatorname{Ker}(B)=\{v \mid v \in V, \quad b(v, \varphi)=0 \quad \forall \varphi \in W\} \tag{1.3}
\end{equation*}
$$

which is a closed subspace of $V$. Let $Z^{\prime}$ be the dual space of $Z ; Z^{\prime}$ can be identified with a closed subspace of $V^{\prime}$, consisting of all $f \in V^{\prime}$ such that

$$
\begin{equation*}
\langle f, v\rangle=0 \quad \text { if }(v, w)=0 \quad \forall w \in Z \tag{1.4}
\end{equation*}
$$

Let us denote by $\pi: V^{\prime} \rightarrow Z^{\prime}$ the orthogonal projection from $V^{\prime}$ onto $Z^{\prime}$. The closed subspace of $V^{\prime}$ consisting of all $f \in V^{\prime}$ such that $\pi f=0$ (polar set of $Z$ ) will be indicated by $Z^{0}$.

We can now prove the following theorem.

Theorem 1.1. - The operator $\Lambda$ defined in (1.2) is an isomorphism from $V \times W$ onto $V^{\prime} \times W^{\prime}$ iff the two following conditions are satisfied:
$\pi A$ is an isomorphism from $Z$ onto $Z^{\prime}$,

$$
\begin{equation*}
\exists k>0 \text { such that }\left\|B^{\prime} \varphi\right\| \geqslant k\|\varphi\| \quad \forall \varphi \in W\left(^{( }\right) . \tag{1.5}
\end{equation*}
$$

Proof. - Suppose that $\Lambda$ is an isomorphism. Let us define, for all $g$ in $W^{\prime}$, $S g$ as the first element of the pair $\Lambda^{-1}(0, g)$, that is :

$$
\begin{equation*}
w=S g \Leftrightarrow \exists \chi \in W, \quad \Lambda(w, \chi)=(0, g) \tag{1.7}
\end{equation*}
$$

We have from (1.2) and (1.7) that $B S=I$; since $\Lambda$ is an isomorphism, $S \in \mathscr{L}\left(W^{\prime}, V\right)$ and therefore, by theorem $0.1,(1.6)$ holds. We define now, for all $f \in Z^{\prime}, Q f$ as the first element of the pair $\Lambda^{-1}(f, 0)$, that is :

$$
\begin{equation*}
w=Q f \Leftrightarrow \exists \chi \in W, \quad \Lambda(w, \chi)=(f, 0) \tag{1.8}
\end{equation*}
$$

Since, by the closed range theorem and (1.6), $\pi B^{\prime} \varphi=0 \forall \varphi \in W$, we get from (1.8) and (1.2) that $\pi A Q f=\pi f=f$. So $\pi A Q=I$ and then $\pi A$ is surjective. Suppose now that $z \in Z$ and $\pi A z=0$; then $A z \in Z^{0}$ and by (1.6) and by the closed range theorem there exists a $\chi$ in $W$ such that $B^{\prime} \chi=-A z$. So $\Lambda(\chi, z)=(0,0)$ and then $z=0$. Therefore $\pi A$ is also injective and, obviously, continuous; hence (1.5) holds. Suppose now, conversely, that (1.5) and (1.6) hold. From (1.6) and theorem 0.1 the problem

$$
\begin{equation*}
\Lambda(u, \psi)=(f, g) \tag{1.9}
\end{equation*}
$$

is equivalent the problem

$$
\begin{equation*}
\Lambda(w, \psi)=(f-A \bar{u}, 0) \tag{1.10}
\end{equation*}
$$

with $u=w+\bar{u}$ and $B \bar{u}=g$. Hence $\Lambda$ is an isomorphism from $V \times W$ onto $V^{\prime} \times W^{\prime}$ if $\Lambda_{0}$, restriction of $\Lambda$ to $Z \times W$, is an isomorphism from $Z \times W$ onto $V^{\prime} \times\{0\}$. Let now be $f \in V^{\prime}$, and let $w \in Z$ be the unique solution of $\pi A w=\pi f$, which existence follows from (1.5). Since $\pi(f-A w)=0$ we have $f-A w \in Z^{0}$ and then from (1.6) there exists a unique $\psi$ in $W$ such that $B^{\prime} \psi=-A w+f$; we have proved in this way that for each $f \in V^{\prime}$ there exists a unique $(w, \psi) \in Z \times W$ such that $\Lambda_{0}(w, \psi)=(f, 0)$. Then $\Lambda_{0}$ is a continuous one to one mapping and therefore an isomorphism.

The following proposition expresses the norm of $\Lambda^{-1}$ and ( $\left.\Lambda^{\prime}\right)^{-1}$ as function of the constants related to $A$ and $B$ in theorem 1.1.

[^3]Proposition 1.1. - Suppose that $A$ and $B$ are such that (1.5) and (1.6) are satisfied. Let us define :

$$
\begin{gather*}
\gamma=\operatorname{Inf}_{u \in Z-\{0\}} \frac{\|\pi A u\|}{\|u\|}, \quad \gamma^{\prime}=\operatorname{Inf}_{u \in Z-\{0\}} \frac{\left\|\pi A^{\prime} u\right\|}{\|u\|},  \tag{1.11}\\
\alpha=\|A\|=\left\|A^{\prime}\right\| \quad, \quad \beta=\|B\|=\left\|B^{\prime}\right\| .
\end{gather*}
$$

Then, setting

$$
\begin{equation*}
M(\alpha, \gamma, k)=\max \left\{\left(\gamma^{-1}+k^{-1}\left(1+\alpha \gamma^{-1}\right)\right)\right. \tag{1.12}
\end{equation*}
$$

$$
\left.\left(k^{-1}+\alpha k^{-2}\right)\left(1+\alpha \gamma^{-1}\right)\right\}
$$

we have :

$$
\begin{align*}
& \left\|\Lambda^{-1}\right\| \leqslant M(\alpha, \gamma, k)  \tag{1.13}\\
& \left\|\left(\Lambda^{\prime}\right)^{-1}\right\| \leqslant M\left(\alpha, \gamma^{\prime}, k\right) \tag{1.14}
\end{align*}
$$

Proof. - Let $(f, g) \in V^{\prime} \times W^{\prime}$ and let $(u, \psi)=\Lambda^{-1}(f, g)$, that is :

$$
\left\{\begin{array}{l}
A u+B^{\prime} \psi=f  \tag{1.15}\\
B u=g
\end{array}\right.
$$

From (1.6) and theorem 0.1 there exists a $w$ in $V$ such that $B w=g$ and

$$
\begin{equation*}
\|w\| \leqslant k^{-1}\|g\| \tag{1.16}
\end{equation*}
$$

Setting now $v=u-w$ we get, from (1.15),

$$
\begin{equation*}
\pi A v=\pi f-\pi A w \tag{1.17}
\end{equation*}
$$

and from (1.11),

$$
\begin{equation*}
\|v\| \leqslant \gamma^{-1}(\|f\|+\alpha\|w\|) \tag{1.18}
\end{equation*}
$$

so we have :

$$
\begin{equation*}
\|u\| \leqslant\|v\|+\|w\| \leqslant \gamma^{-1}\|f\|+k^{-1}\left(\gamma^{-1} \alpha+1\right)\|g\| . \tag{1.19}
\end{equation*}
$$

Since from (1.15) we get

$$
\begin{equation*}
\left\|B^{\prime} \psi\right\| \leqslant\|f\|+\|A u\| \leqslant\|f\|+\alpha\|u\|, \tag{1.20}
\end{equation*}
$$

from (1.6) we obtain

$$
\begin{equation*}
\|\psi\| \leqslant k^{-1}\|f\|+k^{-1} \alpha\|u\|, \tag{1.21}
\end{equation*}
$$

and from (1.19) and (1.21) we have (1.13); the proof of (1.14) can be performed in a similar manner.
n ${ }^{\circ}$ août 1974, R-2.

Remark 1.1. - It can be easily verified that $\Lambda$ is the operator associated to the form

$$
\begin{equation*}
\mathscr{G}((u, \psi),(v, \varphi))=a(u, v)+b(u, \varphi)+b(v, \psi) . \tag{1.22}
\end{equation*}
$$

So by Corollary 0.1 with $X=Y=V \times W, \Lambda$ is an isomorphism iff there exist $\tau, \frac{d}{2} \bar{\tau}_{4}^{i}>0$ such that

$$
\begin{equation*}
\operatorname{Sup}_{x \in X-\{0\}} \frac{\mathcal{G}(x, y)}{\|x\|} \geqslant \tau\|y\| \forall y \in Y \quad \text { and } \operatorname{Sup}_{y \in Y-\{0\}} \frac{\mathcal{C}(x, y)}{\|y\|} \geqslant \bar{\tau}\|x\| \forall x \in X . \tag{1.23}
\end{equation*}
$$

On the other hand it can be shown that condition (1.23) holds iff (1.5) and (1.6) hold. Then, this can be another way, which extends and generalizes the idea of Babuska [4], in order to prove theorem 1.1.

The following corollary will be useful in the applications.
Corollary 1.1. - If $a(u, v)$ is Z-elliptic and (1.6) holds, then $\Lambda$ is an isomorphism.

The proof is immediate.
Remark 1.2. - In many applications (see e.g. Raviart-Thomas [27] and Thomas [32]) we are led to the problem (1.1) by the following procedure. Let $V_{0}$ and $V$ be real Hilbert spaces, with $V_{0}$ closed subspace of $V$, and let $a(u, v)$ be a continuous bilinear form on $V \times V$ which is $V_{0}$-elliptic; we want to solve the problem :

$$
\left\{\begin{array}{l}
\text { find } u \text { in } V_{0} \text { such that }  \tag{1.24}\\
a(u, v)=\langle f, v\rangle \forall v \in V_{0}
\end{array}\right.
$$

where $f$ is a given element in $V^{\prime}$. For this we consider the space $W=V_{0}^{0}$ (polar space of $V_{0}$ ) which is a closed subspace of $V^{\prime}$; problem (1.24) is now equivalent to:

$$
\left\{\begin{array}{l}
\text { find }(u, \psi) \text { in } V \times W \text { such that : }  \tag{1.25}\\
a(u, v)+\langle\psi, v\rangle=\langle f, v\rangle \quad \forall v \in V \\
\langle\varphi, u\rangle=0 \quad \forall \varphi \in W
\end{array}\right.
$$

and setting

$$
\begin{equation*}
b(v, \varphi)=\langle\varphi, v\rangle, \quad v \in V, \quad \varphi \in W \subseteq V^{\prime}, \tag{1.26}
\end{equation*}
$$

problem (1.25) is of the form (1.1). We note also that from (1.26) we have, in this case, $B^{\prime}=I$ (identity), so (1.6) is automatically satisfied; moreover we have obviously

$$
\begin{equation*}
Z=\operatorname{ker}(B)=V_{0} \tag{1.27}
\end{equation*}
$$

and then, since $a(u, v)$ is $V_{0}$-elliptic, corollary 1.1 is immediatelly applicable.

Examples. - We shall report here only a few examples, related to the applications of the hybrid methods by Pian and Tong to plate bending problem (Dirichlet problem for the biharmonic operator $\Delta^{2}$ ). The field of application of the theory is, however, quite large; for further examples of applications and for all the details we shall refer to others papers (i.e. Pian-Tong [25], Brezzi [5], [6], F. de Veubeke [15], Raviart-Thomas [27], Thomas [32], BrezziMarini [8], etc.) which have suggested the abstract theory which is presented here.

## Example 1.1. - Let us consider the problem :

$$
\left\{\begin{array}{l}
\Delta^{2} w=p \text { in } \Omega  \tag{1.28}\\
w=\frac{\partial w}{\partial n}=0 \quad \text { on } \quad \Gamma=\partial \Omega
\end{array}\right.
$$

where $\Omega$ is a convex polygon, $p(x, y)$ an element of $L^{2}(\Omega)$ and $n$ is the outward normal direction to $\partial \Omega$. We apply to this problem the first hybrid method (" assumed stresses hybrid method») by Pian and Tong [25]. For this let us consider, for any given decomposition of $\Omega$ into polygonal subdomains $\Omega_{i}$ ( $i=1, \ldots, N$ ), the spaces

$$
\begin{align*}
& F=\left\{v \in\left(L^{2}(\Omega)\right)^{3} ; v_{1, x x}+2 v_{2, x y}+v_{3, y y} \in L^{2}\left(\Omega_{i}\right) \quad(i=1, \ldots, N)\right\}  \tag{1.29}\\
& V=\left\{v \in F ; v_{1, x x}+2 v_{2, x y}+v_{3, y y}=0 \text { in } \Omega_{i} \quad(i=1, \ldots, N)\right\}  \tag{1.30}\\
& W=\left\{\varphi \in H_{0}^{2}(\Omega) ; \Delta^{2} \varphi=0 \text { in } \Omega_{i} \quad(i=1, \ldots, N)\right\} \tag{1.31}
\end{align*}
$$

and let $f$ be an element of $F$ such that :

$$
\begin{equation*}
f_{1, x x}+2 f_{2, x y}+f_{3, y y}=p \text { in } \Omega_{i} \quad(i=1, \ldots, N) \tag{1.32}
\end{equation*}
$$

Finally we consider the bilinear form $b(v, \varphi)$ defined on $F \times W$ by :

$$
\begin{align*}
b(v, \varphi)= & \sum_{i=1}^{N}\{  \tag{1.33}\\
& \left\{\int_{\Omega_{i}}\left(v_{1} \varphi_{, x x}+2 v_{2} \varphi, x y+v_{3} \varphi_{, y y}\right) \mathrm{d} x \mathrm{~d} y\right. \\
& \left.-\int_{\Omega_{i}}\left(v_{1, x x}+2 v_{2, x y}+v_{3, y y}\right) \varphi \mathrm{d} x \mathrm{~d} y\right\}
\end{align*}
$$

Setting now, for every $u, v$ in $F$,

$$
\begin{equation*}
[u, v]=\int_{\Omega}\left(u_{1} v_{1}+2 u_{2} v_{2}+u_{3} v_{3}\right) \mathrm{d} x \mathrm{~d} y \tag{1.34}
\end{equation*}
$$

we define

$$
\left\{\begin{array}{lll}
a(u, v)=[u, v] & , & u, v \in V  \tag{1.35}\\
L(v)=-[f, v] & , & v \in V \\
T(\varphi)=-b(f, \varphi) & , & \varphi^{\infty} \in W
\end{array}\right.
$$

$n^{\circ}$ août 1974, R-2.
and we introduce the norms :

$$
\begin{equation*}
\|v\|_{V}^{2}=[v, v] \quad, \quad v \in V \tag{1.36}
\end{equation*}
$$

Then by corollary 1.1 the problem

$$
\left\{\begin{array}{l}
\text { find }(u, \psi) \text { in } V \times W \text { such that : }  \tag{1.38}\\
a(u, v)+b(v, \psi)=L(v) \quad \forall v \in V \\
b(u, \varphi)=T(\varphi) \quad \forall \varphi \in W
\end{array}\right.
$$

has a unique solution. It can be shown (see Brezzi-Marini [8]) that the solution $(u, \psi)$ of (1.38) is related to the solution $w$ of (1.28) by :

$$
\begin{equation*}
\left(w,{ }_{x x}, w,{ }_{x y}, w,_{y y}\right)=u+f \text { in } \Omega \tag{1.39}
\end{equation*}
$$

$$
\begin{equation*}
(w, w, x, w, y)=-(\psi, \psi, x, \psi, y) \quad \text { on } \quad \Sigma=\bigcup_{i=1}^{N} \partial \Omega_{i} . \tag{1.40}
\end{equation*}
$$

Example 1.2. - We want to apply now to problem (1.28) the second hybrid method (« assumed displacements hybrid method») by Pian and Tong [25]; for this we consider, for any given decomposition of $\Omega$ into polygonal subdomains $\Omega_{i}(i=1, \ldots, N)$, the spaces :

$$
\begin{gather*}
V=\left\{v \mid v \in \prod_{i=1}^{N} H^{2}\left(\Omega_{i}\right) \quad, \quad v=\frac{\partial v}{\partial n}=0 \text { on } \partial \Omega\right\},  \tag{1.41}\\
\tilde{W}=\left\{M \mid M \in\left(L^{2}(\Omega)\right)^{3}, M_{1, x x}+2 M_{2, x y}+M_{3, y y}=0 \text { in } \Omega_{i}\right.  \tag{1.42}\\
(i=1, \ldots, N)\},
\end{gather*}
$$

$$
\begin{array}{r}
\tilde{W}_{0}=\left\{M \mid M \in \tilde{W}, M_{1}=\varphi,{ }_{x x}, M_{2}=\varphi,{ }_{x y}, M_{3}=\varphi, y y\right.  \tag{1.43}\\
\text { in each } \left.\Omega_{i}, \varphi \in V\right\}
\end{array}
$$

We define the bilinear form $b(v, M)$ on $V \times \tilde{W}$ by

$$
\begin{equation*}
b(v, M)=\sum_{i=1}^{N} \int_{\Omega_{1}}\left(v,{ }_{x x} M_{1}+2 v,{ }_{x y} M_{2}+v,{ }_{y y} M_{3}\right) \mathrm{d} x \mathrm{~d} y \tag{1.44}
\end{equation*}
$$ and then we define :

$$
\begin{equation*}
W=\left\{M \mid M \in \tilde{W}_{0} \quad, \quad b(v, M)=0 \quad \forall v \in H_{0}^{2}(\Omega)\right\} \tag{1.45}
\end{equation*}
$$

Using Southwell stress functions $U, V$, defined by

$$
\begin{equation*}
M_{1}=V,_{y} \quad, \quad M_{2}=-\frac{1}{2}\left(V,_{x}+U,_{y}\right) \quad, \quad M_{3}=U,_{x} \tag{1.46}
\end{equation*}
$$

(cfr. e.g. [16]), $W$ can be characterized as the set of $M$ in $\tilde{W}_{0}$ such that $U_{n}=U \nu_{x}+V \nu_{y}$ and $U_{t}=-V \nu_{x}+U \nu_{y}\left(\nu_{x}=\cos n_{i} x, \nu_{y}=\cos n_{i} y\right)$ are «continuous» across the interelement boundaries $\partial \Omega_{i}$.

In fact setting (see e.g. [15]).

$$
\begin{gather*}
M_{n}=\frac{\partial U_{t}}{\partial s} \quad, \quad M_{n t}=-\omega-\frac{\partial U_{n}}{\partial s}  \tag{1.47}\\
Q_{n}=\frac{\partial \omega}{\partial s} \quad, \quad \omega=\frac{1}{2}\left(V,{ }_{x}-U,{ }_{y}\right)
\end{gather*}
$$

$b(v, M)$ can be written formally as :

$$
\begin{align*}
b(v, M) & =\sum_{i=1}^{N} \int_{\partial \Omega_{i}}\left(M_{n} \frac{\partial v}{\partial n}+M_{n t} \frac{\partial v}{\partial s}-Q_{n} v\right) \mathrm{d} \sigma_{i}  \tag{1.48}\\
& =\sum_{i=1}^{N} \int_{\partial \Omega_{i}}\left(M_{n} \frac{\partial v}{\partial n}-\frac{\partial U_{n} \frac{\partial v}{\partial s} \partial s}{\partial}\right) \mathrm{d} \sigma_{i}
\end{align*}
$$

and formula (1.48) can be justified from a mathematical point of view as a pairing between spaces of the type $H^{1 / 2}\left(\partial \Omega_{i}\right)\left({ }^{1}\right)\left(\right.$ for $\frac{\partial v}{\partial n}$ and $\left.\frac{\partial v}{\partial s}\right)$, and their duals.

Let finally $f \in\left(L^{2}(\Omega)\right)^{3}$ be such that

$$
\begin{equation*}
f_{1, x x}+2 f_{2, x y}+f_{3, y y}=p \text { in each } \Omega_{i} \tag{1.49}
\end{equation*}
$$

and let, for all $v$ in $V$,

$$
\begin{equation*}
F(v)=\sum_{i=1}^{N} \int_{\Omega_{i}}\left(v,_{x x} f_{1}+2 v,{ }_{x y} f_{2}+v,{ }_{y y} f_{3}\right) \mathrm{d} x \mathrm{~d} y \tag{1.50}
\end{equation*}
$$

we define

$$
\begin{equation*}
a(u, v)=\sum_{i=1}^{N} \int_{\Omega_{i}}\left(u,_{x x} v,_{x x}+2 u,{ }_{x y} v,_{x y}+u,{ }_{y y} v,_{y y}\right) \mathrm{d} x \mathrm{~d} y \tag{1.51}
\end{equation*}
$$

$$
u, v \in V
$$

If $V$ and $W$ are equipped with the norms

$$
\begin{equation*}
\|u\|_{V}^{2}=\sum_{i=1}^{N}\|v\|_{2, \Omega_{i}}^{2}\left(^{2}\right), \quad\|M\|_{W}^{2}=\sum_{i=1}^{N}\|M\|_{\left(L^{2}\left(\Omega_{i}\right)\right)}^{3} \tag{1.52}
\end{equation*}
$$

(1) For the definitions and the properties of Sobolew spaces $H^{s}(\Omega)$ and $H^{s}(\Gamma)$ we refer to Lions-Magenes [22].
(2) Such notations are classical; see e.g. Ciarlet-Raviart [9], [10], Strang-Fix [31]. n ${ }^{0}$ août 1974, R-2.
it is easily proved that the conditions of corollary 1.1 are satisfied. Then the problem

$$
\left\{\begin{array}{l}
\text { find }(u, \bar{M}) \in V \times W \text { such that }:  \tag{1.53}\\
a(u, v)+b(v, \bar{M})=F(v) \quad \forall v \in V \\
b(u, M)=0 \quad \forall M \in W
\end{array}\right.
$$

has a unique solution. It can also be verified that, if $w$ is the solution of (1.28) and $(u, \bar{M})$ is the solution of (1.53), then :

$$
\begin{gather*}
w=u  \tag{1.54}\\
\left(w_{x x}, w_{x y}, w_{y y}\right)=-\bar{M}+f \tag{1.55}
\end{gather*}
$$

## 2. APPROXIMATION

Let now $V_{h}$ and $W_{h}$ be closed subspaces of $V$ and $W$ respectively. We substitute to problem (1.1) the «approximated problem »:

$$
\left\{\begin{array}{l}
\text { find }\left(u_{h}, \psi_{h}\right) \text { in } V_{h} \times W_{h} \text { such that : }  \tag{2.1}\\
a\left(u_{h}, v_{h}\right)+b\left(v_{h}, \psi_{h}\right)=\left\langle f, v_{h}\right\rangle \forall v_{h} \in V_{h}, \\
b\left(u_{h}, \varphi_{h}\right)=\left\langle g, \varphi_{h}\right\rangle \forall \varphi_{h} \in W_{h} .
\end{array}\right.
$$

We want now, at first, to find sufficient conditions on $V_{h}$ and $W_{h}$ in order that (2.1) has a unique solution, and, after that, to evaluate the distance between the «approximate solution» $\left(u_{h}, \psi_{h}\right)$ of (2.1) and the «exact solution» ( $u, \psi$ ) of (1.1).

First of all we suppose that the following hypothesis is satisfied.
H1. There exists a positive constant $k_{h}$ such that :

$$
\begin{equation*}
\operatorname{Sup}_{v_{h} \in V_{h}-\{0\}} \frac{b\left(v_{h}, \varphi_{h}\right)}{\left\|v_{h}\right\|} \geqslant k_{h}\left\|\varphi_{h}\right\| \quad \forall \varphi_{h} \in W_{h} . \tag{2.2}
\end{equation*}
$$

We define now :

$$
\begin{equation*}
Z_{h}=\left\{v_{h} \mid v_{h} \in V_{h}, b\left(v_{h}, \varphi_{h}\right)=0 \quad \forall \varphi_{h} \in W_{h}\right\} \tag{2.3}
\end{equation*}
$$

and we remark that, in general, $Z_{h} \ddagger Z$. Therefore we need also the following hypothesis.

H2. There exist two positive constants $\gamma_{h}$ and $\gamma_{h}^{\prime}$ such that :

$$
\begin{align*}
& \operatorname{Sup}_{u_{h} \in Z_{h}-\{0\}} \frac{a\left(u_{h}, v_{h}\right)}{\left\|u_{h}\right\|} \geqslant \gamma_{h}^{\prime}\left\|v_{h}\right\| \quad \forall v_{h} \in Z_{h},  \tag{2.4}\\
& \operatorname{Sup}_{v_{h} \in Z_{h}-\{0\}} \frac{a\left(u_{h}, v_{h}\right)}{\left\|v_{h}\right\|} \geqslant \gamma_{h}\left\|u_{h}\right\| \quad \forall u_{h} \in Z_{h} . \tag{2.5}
\end{align*}
$$

Let $\rho_{h}$ be the projection operator from $V \times W$ onto $V_{h} \times W_{h}$; identifying $V_{h}^{\prime} \times W_{h}^{\prime}$ with a closed subspace of $V^{\prime} \times W^{\prime}$ we can define the projection operator $\rho_{h}^{\prime}$ from $V^{\prime} \times W^{\prime}$ onto $V_{h}^{\prime} \times W_{h}^{\prime}$. Let now $\Lambda_{h}: V_{h} \times W_{h} \rightarrow V_{h}^{\prime} \times W_{h}^{\prime}$ be defined by :

$$
\begin{equation*}
\Lambda_{h}\left(v_{h}, \varphi_{h}\right)=\rho_{h}^{\prime} \Lambda\left(v_{h}, \varphi_{h}\right) \quad \forall v_{h} \in V_{h}, \varphi_{h} \in W_{h} . \tag{2.6}
\end{equation*}
$$

It is clear that the solution $\left(u_{h}, \psi_{h}\right)$ of (2.1) (if it exists) is such that

$$
\begin{equation*}
\Lambda_{h}\left(u_{h}, \psi_{h}\right)=\rho_{h}^{\prime}(f, g) \tag{2.7}
\end{equation*}
$$

Therefore the following proposition gives an answer to our first question about existence and uniqueness of the solution of (2.1).

Proposition 2.1. - Under the hypotheses $H 1$ and $H 2$ the operator $\Lambda_{h}=\rho_{h}^{\prime} \Lambda$ is an isomorphism between $V_{h} \times W_{h}$ and $V_{h}^{\prime} \times W_{h}^{\prime}$; moreover we have :

$$
\begin{gather*}
\left\|\Lambda_{h}^{-1}\right\| \leqslant M\left(\alpha, \gamma_{h}, k_{h}\right)  \tag{2.8}\\
\left\|\left(\Lambda_{h}^{\prime}\right)^{-1}\right\| \leqslant M\left(\alpha, \gamma_{h}^{\prime}, k_{h}\right) \tag{2.9}
\end{gather*}
$$

where $M\left(\alpha, \gamma_{h}, k_{h}\right)$ is always expressed by (1.12).
The proof is immediate by theorem 1.1 and proposition 1.1.
We can now prove the following theorem.
Theorem 2.1. - Under the hypotheses $H 1$ and H2, for every pair $(f, g)$ in $V^{\prime} \times W^{\prime}$ let

$$
\begin{gather*}
(u, \psi)=\Lambda^{-1}(f, g)  \tag{2.10}\\
\left(u_{h}, \psi_{h}\right)=\Lambda_{h}^{-1} \rho_{h}^{\prime}(f, g)
\end{gather*}
$$

Then we have :

$$
\begin{equation*}
\left\|u-u_{h}\right\|+\left\|\psi-\psi_{h}\right\| \leqslant \sigma_{h}\left(\operatorname{Inf}_{v_{h} \in V_{h}}\left\|u-v_{h}\right\|+\operatorname{Inf}_{\varphi_{h} \in W_{h}}\left\|\psi-\varphi_{h}\right\|\right) \tag{2.12}
\end{equation*}
$$

where

$$
\begin{equation*}
\sigma_{h}=M\left(\alpha, \gamma_{h}^{\prime}, k_{h}\right)(\alpha+\beta)+1 \tag{2.13}
\end{equation*}
$$

Proof. - First of all, we remark that, from (2.6), (2.10), (2.11), we have for every ( $w_{h}, \chi_{h}$ ) in $V_{h} \times W_{h}$ :

$$
\begin{align*}
\left\langle\Lambda_{h}\left(u_{h}, \psi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle=\left\langle f, w_{h}\right\rangle+ & \left\langle g, \chi_{h}\right\rangle  \tag{2.14}\\
& =\left\langle\Lambda(u, \psi),\left(w_{h}, \psi_{h}\right)\right\rangle
\end{align*}
$$

So if ( $v_{h}, \varphi_{h}$ ) is any other pair in $V_{h} \times W_{h}$ we have :

$$
\begin{equation*}
\left\langle\Lambda_{h}\left(u_{h}-v_{h}, \psi_{h}-\varphi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle=\left\langle\Lambda\left(u-v_{h}, \psi-\varphi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle \tag{2.15}
\end{equation*}
$$

Then by (2.9) and corollary 0.1 (part III) $\Rightarrow$ I) ) we have

$$
\begin{equation*}
\left\|u_{h}-v_{h}\right\|+\left\|\psi_{h}-\varphi_{h}\right\| \leqslant c\|\Lambda\|\left(\left\|u-v_{h}\right\|+\left\|\psi-\varphi_{h}\right\|\right) \tag{2.16}
\end{equation*}
$$

with $c=\left\|\left(\Lambda_{h}^{\prime}\right)^{-1}\right\| \leqslant M\left(\alpha, \gamma_{h}^{\prime}, k_{h}\right)$. On the other hand it is immediate to verify that

$$
\begin{equation*}
\|\Lambda\| \leqslant \alpha+\beta ; \tag{2.17}
\end{equation*}
$$

hence from (2.16), (2.17) we get

$$
\begin{equation*}
\left\|u-u_{h}\right\|+\left\|\psi-\psi_{h}\right\| \leqslant[c(\alpha+\beta)+1]\left(\left\|u-v_{h}\right\|+\left\|\psi-\varphi_{h}\right\|\right) \tag{2.18}
\end{equation*}
$$

for every $\left(v_{h}, \varphi_{h}\right)$ in $V_{h} \times W_{h}$, and the result follows immediately.
Corollary 2.1. - Suppose that H1 holds and that there exists a constant $\delta_{h}>0$ such that

$$
\begin{equation*}
a\left(v_{h}, v_{h}\right) \geqslant \delta_{h}\left\|v_{h}\right\|^{2} \quad \forall v_{h} \in Z_{h} ; \tag{2.19}
\end{equation*}
$$

then $\Lambda_{h}$ is an isomorphism from $V_{h} \times W_{h}$ onto $V_{h}^{\prime} \times W_{h}^{\prime}$. Moreover, for every pair $(f, g)$ in $V^{\prime} \times W^{\prime}$, if $(u, \psi)=\Lambda^{-1}(f, g)$ and $\left(u_{h}, \psi_{h}\right)=\Lambda_{h}^{-1} \rho_{h}^{\prime}(f, g)$, then :

$$
\begin{equation*}
\left\|u-u_{h}\right\|+\left\|\psi-\psi_{h}\right\| \leqslant \bar{\sigma}_{h}\left(\operatorname{Inf}_{v_{h} \in V_{h}}\left\|u-v_{h}\right\|+\operatorname{Inf}_{\varphi_{h} \in W_{h}}\left\|\psi-\varphi_{h}\right\|\right) \tag{2.20}
\end{equation*}
$$

with $\bar{\sigma}_{h}=M\left(\alpha, \delta_{h}, k_{h}\right)(\alpha+\beta)+1$.
The proof is immediate.
Remark 2.1. - Suppose for instance that $a(u, v)$ is $Z$-elliptic and that, for simplicity, $g=0$.

Then the first element $u$ of the solution of (1.1) can be characterized as the solution of :

$$
\left\{\begin{array}{l}
a(u, v)=\langle f, v\rangle \quad \forall v \in Z  \tag{2.21}\\
u \in Z .
\end{array}\right.
$$

Suppose now that $V_{h}$ and $W_{h}$ are closed subspaces of $V$ and $W$, such that $H 1$ is verified, and let again $Z_{h}$ be the space :

$$
Z_{h}=\left\{v_{h} \mid v_{h} \in V_{h}, \quad b\left(v_{h}, \varphi_{h}\right)=0 \quad \forall \varphi_{h} \in W_{h}\right\}
$$

If $a(u, v)$ is $Z_{h}$ elliptic then the first element $u_{h}$ of the solution of (2.1) can be presented as the solution of :

$$
\left\{\begin{array}{l}
a\left(u_{h}, v_{h}\right)=\left\langle f, v_{h}\right\rangle \quad \forall v_{h} \in Z_{h},  \tag{2.22}\\
u_{h} \in Z_{h} .
\end{array}\right.
$$

Since $Z_{h} \nsubseteq Z$, (2.22) can be regarded as an approximation of (2.21) by «non-conforming elements» (see e.g. [17], [21], [30], [31]); therefore given $Z \subseteq V, a(u, v)$ and $f \in V^{\prime}$, and given a closed subspace $Z_{h} \subset V$, the existence of $W, W_{h}, b(v, \varphi)$ such that the hypotheses of corollary 1.1 are satisfied, constitutes some kind of «abstract patch-test» for the elements of $\boldsymbol{Z}_{h}$ (see also, in the case of the elasticity and plate bending problems, F. de Veubeke [15]; also important in this contest are the papers by Raviart-Thomas [27] and Thomas [32]).

Example 2.1. - We return to the situation of the example 1.1, and we suppose, for sake of simplicity, that $\Omega$ is the square $] 0, l[\times] 0, l\left[\right.$ and that $\Omega_{i}$ are also squares of lenght $h=l N^{-1 / 2}$. Let $\hat{K}$ be the unit square $] 0,1[\times] 0,1[$ and let $\hat{P}_{V}$ be a finite dimensional space of smooth vectors functions $\left(\hat{v}_{1}, \hat{v}_{2}, \hat{v}_{3}\right)$ defined on $\hat{K}$ and self-equilibrating, in the sense that

$$
\hat{v}_{1, x x}+2 \hat{v}_{2, x y}+\hat{v}_{3, y y}=0 \quad \text { on } \quad \hat{K} ;
$$

let $\hat{P}_{W}$ be a finite dimensional space of smooth functions $\hat{\varphi}$ defined on $\hat{K}$ and such that $\Delta^{2} \hat{\varphi}=0$ in $\hat{K}$. For each $\Omega_{i}$ let $F_{i}$ be the «affine» invertible transformation that maps $\hat{K}$ on $\Omega_{i}$ and let $P_{V, i}, P_{W, i}$ the images of $\hat{P}_{V}$ and $\hat{P}_{W}$ (resp.) through $F_{i}$. We consider now the spaces

$$
\begin{array}{llll}
V_{h}=\left\{v_{h} \mid v_{h} \in V\right. & , & v_{h \mid \Omega_{i}} \in P_{V, i} & (i=1, \ldots, N)\} \\
W_{h}=\left\{\varphi_{h} \mid \varphi_{h} \in W\right. & , & \varphi_{h \mid \Omega_{i}} \in P_{W, i} & (i=1, \ldots, N)\}
\end{array}
$$

It can be verified (cfr. Brezzi [5], Brezzi-Marini [8]) that if $\hat{P}_{V}$ and $\hat{P}_{W}$ verify the following hypothesis :
$\hat{H} 1 \quad\left\{\begin{array}{l}\operatorname{Sup}_{\hat{v} \in \hat{P}_{\boldsymbol{V}}-\{0\}}\left(\int_{\hat{K}} \hat{v}_{1} \hat{\varphi}_{, x x}+2 \hat{v}_{2} \hat{\varphi}_{, x y}+\hat{v}_{3} \hat{\varphi}_{, y y} \mathrm{~d} x \mathrm{~d} y\right)\|\hat{v}\|_{\left(L^{2}(\hat{K})\right)^{3}}^{-1} \geqslant \hat{\lambda}|\hat{\varphi}|_{2, \hat{K}} \\ \text { for all } \hat{\varphi} \text { in } \hat{P}_{W}, \text { with } \hat{\lambda}>0,\end{array}\right.$
then $V_{h}$ and $W_{h}$ satisfy hypothesis Hl with constant $k_{h}>\lambda>0, \lambda$ independent of $h$. Since, obviously, in this case

$$
\alpha=\gamma_{h}^{\prime}=1
$$

for every decomposition, then the constant $\sigma_{h}$ which appears in (2.12), is in fact independent of $h$. We remark that in practice, since the value of $\hat{\varphi}$ in $\hat{K}$ is depending only on the values of $\hat{\varphi}$ and $\frac{\partial \hat{\varphi}}{\partial n}$ on $\partial \hat{K}, \hat{P}_{W}$ will be chosen as a space of biharmonic functions such that $\hat{\varphi}$ and $\frac{\partial \hat{\varphi}}{\partial n}$ are polynominals of assigned degree on $\partial \hat{K}$. Of course we ignore the value of $\hat{\varphi}$ at the interior of $\hat{K}$, but no août 1974, R-2.
this is not a difficulty since we can use sistematically, for the computations, Green's formula

$$
\int_{\hat{K}}\left(\hat{v}_{1} \hat{\varphi}_{, x x}+2 \hat{v}_{2} \hat{\varphi}_{, x y}+\hat{v}_{3} \varphi_{, y y}\right) \mathrm{d} x \mathrm{~d} y=\int_{\partial \hat{K}}\left(\hat{M}_{n} \frac{\partial \hat{\varphi}}{\partial n}+\hat{M}_{n t} \frac{\partial \hat{\varphi}}{\partial s}-\hat{Q}_{n} \hat{\varphi}\right) \mathrm{d} \sigma
$$

where

$$
\left\{\begin{array}{l}
\hat{M}_{n}=\hat{v}_{1} v_{x}^{2}+2 \hat{v}_{2} v_{x} v_{y}+\hat{v}_{3} v_{y}^{2} \\
\hat{M}_{n t}=\hat{v}_{1} v_{x} v_{y}+\left(v_{y}^{2}-v_{x}^{2}\right) \hat{v}_{2}-\hat{v}_{3} v_{x} v_{y} \\
Q_{n}=\left(\hat{v}_{1, x}+\hat{v}_{2, y}\right) v_{x}+\left(\hat{v}_{2, x}+\hat{v}_{3, y}\right) v_{y} \\
v_{x}=\cos n x \quad, \quad v_{y}=\cos n y
\end{array}\right.
$$

valid whenevever $\hat{v}$ is sufficiently smooth and $\hat{v}_{1, x x}+2 \hat{v}_{2, x y}+\hat{v}_{3, y y}=0$ on $\hat{K}$. For further details we refer to Brezzi [5] and Brezzi-Marini [8].

EXAMPLE 2.2. - We return now to the situation of the example 1.2, and we suppose again that $\Omega$ and all the $\Omega_{i}$ are squares, as in example 2.1. Let $\hat{K}$ be the unit square and let $\hat{P}_{V}$ be a finite dimensional linear space of smooth functions and $\hat{P}_{W}$ a finite dimensional linear space of smooth self equilibrating vectors of the type $\hat{M}=\left(\hat{\varphi},{ }_{x x}, \hat{\varphi}, x_{x y}, \hat{\varphi}, y_{y}\right)$. We define, for each $i$ $(i=1, \ldots, N), P_{V, i}$ and $P_{W, i}$ as the images of $\hat{P}_{V}$ and $\hat{P}_{W}$ through the «affine» i nvertible transformation $F_{i}$ which maps $\hat{K}$ on $\Omega_{i}$. We consider the spaces:

$$
\left.\begin{array}{lll}
V_{h}=\{v \mid v \in V \\
W_{h}=\{M \mid M \in W & , & v_{i \Omega_{i}} \in P_{V, i}
\end{array} \quad(i=1, \ldots, N)\right\},
$$

Suppose that $P_{V}$ and $P_{W}$ verify hypothesis


Then we can prove that $H 1$ is satisfied with constant $k_{h}>\lambda>0, \lambda$ independent of $h$. The chiefest difficulty is now, in the particular cases, to prove that $a(u, v)$ defined by (1.51), is $Z_{h}$-elliptic (where $Z_{h}$ is always defined by (2.3)) with constant $\delta_{h}$ independent of $h$. If this is the case, then we get that the constant $\bar{\sigma}_{h}$ which appears in (2.20) is in fact independent of $h$. The verification of $\hat{H 1}$ can, also in this case, be easily performed using (1.44), (1.47), (1.48), if we know the value of $\hat{U}$ and $\hat{V}$ on $\partial \hat{K}$. F. de Veubeke has shown (cfr. [15]) that in this case $Z_{h}$ is in fact a space of non conforming approximations
of $H_{0}^{2}(\Omega)$ and that we can find in this way all the classical non conforming elements for the biharmonic problem (see [30], [31], [21]); for further details we refer to $F$. de Veubeke [15]; in a forthcoming paper we shall treat this case from a mathematical point of view.

## 3. FURTHER CONSIDERATIONS

In many applications, the exact computation of $a\left(u_{h}, v_{h}\right), b\left(v_{h}, \varphi_{h}\right),\left\langle f, v_{h}\right\rangle$, $\left\langle g, \varphi_{h}\right\rangle$ which appear in the approximated problem (2.1) is rather difficult or, in some case, impossible. Therefore some kind of numerical integration (see e.g. Strang-Fix [31], Ciarlet-Raviart [10]) is needed in order to solve numerically problem (2.1). We shall shown that the classical results about the use of numerical integration for variational problems and for veriational inequalities can be easily extended to our case. For this, let $a_{h}\left(u_{h}, v_{h}\right)$ and $b_{h}\left(v_{h}, \varphi_{h}\right)$ be (continuous) bilinear forms on $V_{h} \times V_{h}$ and on $V_{h} \times W_{h}$ respectively; suppose moreover that $f_{h}$ and $g_{h}$ are (continuous) linear functionals on $V_{h}$ and $W_{h}$ resp., and consider the problem :

$$
\left\{\begin{array}{l}
\text { find }\left(u_{h}^{*}, \psi_{h}^{*}\right) \text { in } V_{h} \times W_{h} \text { such that : }  \tag{3.1}\\
a_{h}\left(u_{h}^{*}, v_{h}\right)+b_{h}\left(v_{h}, \psi_{h}^{*}\right)=\left\langle f_{h}, v_{h}\right\rangle \quad \forall v_{h} \in V_{h}, \\
b_{h}\left(u_{h}^{*}, \varphi_{h}\right)=\left\langle g_{h}, \varphi_{h}\right\rangle \quad \forall \varphi_{h} \in W_{h} .
\end{array}\right.
$$

We suppose that the following hypotheses are satisfied:
$\mathrm{H} 1^{*}$ ) There exists a positive constant $k_{h}^{*}$ such that :

$$
\operatorname{Sup}_{v_{h} \in V_{h}-\{0\}}\left\|v_{h}\right\|^{-1} b_{h}\left(v_{h}, \varphi_{h}\right) \geqslant k_{h}^{*}\left\|\varphi_{h}\right\| \quad \forall \varphi_{h} \in W_{h} .
$$

$\mathrm{H} 2^{*}$ ) There exist two positive constants $\gamma_{h}^{*}$ and $\bar{\gamma}_{h}^{*}$ such that:

$$
\begin{array}{ll}
\operatorname{Sup}_{u_{h} \in Z_{h}-\{0\}}\left\|u_{h}\right\|^{-1} a_{h}\left(u_{h}, v_{h}\right) \geqslant \bar{\gamma}_{h}^{*}\left\|v_{h}\right\| & \forall v_{h} \in Z_{h}^{*} \\
\operatorname{Sup}_{v h \in Z_{h}-\{0\}}\left\|v_{h}\right\|^{-1} a_{h}\left(u_{h}, v_{h}\right) \geqslant \gamma_{h}^{*}\left\|u_{h}\right\| & \forall u_{h} \in Z_{h}^{*},
\end{array}
$$

where, of course, $Z_{h}^{*}$ is defined by :

$$
\begin{equation*}
Z_{h}^{*}=\left\{v_{h} \mid v_{h} \in V_{h}, b_{h}\left(v_{h}, \varphi_{h}\right)=0 \quad \forall \varphi_{h} \in W_{h}\right\} \tag{3.2}
\end{equation*}
$$

Then, always from theorem 1.1 we get
Proposition 3.1. - Under the hypotheses $H 1^{*}$ and $H 2^{*}$, for all $\left(f_{h}, g_{h}\right)$ in $V_{h}^{\prime} \times W_{h}^{\prime}$, problem (3.1) has a unique solution.
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We want now to evaluate the distance between ( $u_{h}^{*}, \psi_{h}^{*}$ ), solution of (3.1), and $(u, \psi)$, solution of (1.1). For this we define at first the operator $\Lambda_{h}^{*}: V_{h} \times W_{h} \rightarrow V_{h}^{\prime} \times W_{h}^{\prime}$ by :

$$
\left\{\begin{array}{l}
\left\langle\Lambda_{h}^{*}\left(v_{h}, \varphi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle=a_{h}\left(v_{h}, w_{h}\right)+b_{h}\left(w_{h}, \varphi_{h}\right)+b_{h}\left(v_{h}, \chi_{h}\right),  \tag{3.3}\\
\text { for all }\left(v_{h}, \varphi_{h}\right) \text { and }\left(w_{h}, \chi_{h}\right) \text { in } V_{h} \times W_{h} .
\end{array}\right.
$$

Let now $\left(u_{h}, \psi_{h}\right)$ be the solution of (2.1) and let

$$
\begin{equation*}
\alpha^{*}=\operatorname{Sup}_{u_{h}, v_{h} \in V_{h}-\{0\}}\left\|u_{h}\right\|^{-1}\left\|v_{h}\right\|^{-1} a_{h}\left(u_{h}, v_{h}\right) . \tag{3.4}
\end{equation*}
$$

From proposition 1.1 we get that there exists $\left(v_{h}, \varphi_{h}\right) \in V_{h} \times W_{h}$ such that :

$$
\begin{align*}
& \left\|u_{h}-u_{h}^{*}\right\|+\left\|\psi_{h}-\psi_{h}^{*}\right\|  \tag{3.5}\\
& \left.\leqslant M\left(\alpha^{*}, \bar{\gamma}_{h}^{*}, k_{h}^{*}\right)<\Lambda_{h}^{*}\left(u_{h}-u_{h}, \psi_{h}-\psi_{h}^{*}\right),\left(v_{h}, \varphi_{h}\right)\right\rangle\left(\left\|v_{h}\right\|+\left\|\varphi_{h}\right\|\right)^{-1} .
\end{align*}
$$

Moreover we have

$$
\begin{align*}
\left\langle\Lambda_{h}^{*}\left(u_{h}-u_{h}^{*}, \psi_{h}-\psi_{h}^{*}\right),\left(v_{h}, \varphi_{h}\right)\right\rangle= & \left\langle\left(\Lambda_{h}^{*}-\Lambda_{h}\right)\left(u_{h}, \psi_{h}\right),\left(v_{h}, \varphi_{h}\right)\right\rangle  \tag{3.6}\\
& +\left\langle f-f_{h}, v_{h}\right\rangle+\left\langle g-g_{h}, \varphi_{h}\right\rangle
\end{align*}
$$

and also :

$$
\begin{align*}
& \left|\left\langle\left(\Lambda_{h}^{*}-\Lambda_{h}\right)\left(u_{h}, \psi_{h}\right),\left(v_{h}, \varphi_{h}\right)\right\rangle\right| \leqslant\left|a_{h}\left(u_{h}, v_{h}\right)-a\left(u_{h}, v_{h}\right)\right|  \tag{3.7}\\
& \quad+\left|b_{h}\left(v_{h}, \psi_{h}\right)-b\left(v_{h}, \psi_{h}\right)\right|+\left|b_{h}\left(u_{h}, \varphi_{h}\right)-b\left(u_{h}, \varphi_{h}\right)\right| .
\end{align*}
$$

Setting now :

$$
\begin{aligned}
& \mathcal{Y}=\operatorname{Sup}_{v_{h} \in V_{h}-\{0\}}\left\|v_{h}\right\|^{-1}\left|\left\langle f-f_{h}, v_{h}\right\rangle\right|, \\
& \mathcal{G}=\operatorname{Sup}_{\varphi_{h} \in W_{h}-\{0\}}\left\|\varphi_{h}\right\|^{-1}\left|\left\langle g-g_{h}, \varphi_{h}\right\rangle\right|, \\
& \mathcal{A}\left(u_{h}\right)=\operatorname{Sup}_{v_{h} \in V_{h}-\{0\}}\left\|v_{h}\right\|^{-1}\left|a\left(u_{h}, v_{h}\right)-a_{h}\left(u_{h}, v_{h}\right)\right|, \\
& \mathcal{B}\left(u_{h}\right)=\operatorname{Sup}_{\varphi_{h} \in W_{h}-\{0\}}\left\|\varphi_{h}\right\|^{-1}\left|b\left(u_{h}, \varphi_{h}\right)-b_{h}\left(u_{h}, \varphi_{h}\right)\right|, \\
& \mathcal{B}^{\top}\left(\psi_{h}\right)=\operatorname{Sup}_{v_{h} \in V_{h}-\{0\}}\left\|v_{h}\right\|^{-1}\left|b\left(v_{h}, \psi_{h}\right)-b_{h}\left(v_{h}, \psi_{h}\right)\right|,
\end{aligned}
$$

we have from (3.5), (3.6), (3.7), that :

$$
\begin{align*}
& \left\|u_{h}-u_{h}^{*}\right\|+\left\|\psi_{h}-\psi_{h}^{*}\right\|  \tag{3.8}\\
& \quad \leqslant M\left(\alpha^{*}, \bar{\gamma}_{h}^{*}, k_{h}^{*}\right)\left(\mathcal{Y}+\mathcal{G}+\mathfrak{A}\left(u_{h}\right)+\mathfrak{B}\left(u_{h}\right)+\mathfrak{B}^{\top}\left(\psi_{h}\right)\right)
\end{align*}
$$

Therefore we can conclude with the following theorem.

Theorem 3.1. - If hypotheses $H 1^{*}, H 2^{*}$ are satisfied and if $\left(u_{h}^{*}, \psi_{h}^{*}\right)$ and $(u, \psi)$ are the solutions of (3.1) and (1.1) respectively, we have :

$$
\begin{aligned}
& \left\|u-u_{h}^{*}\right\|+\left\|\psi-\psi_{h}^{*}\right\| \leqslant\left\|u-u_{h}\right\|+\left\|\psi-\psi_{h}\right\| \\
& +M\left(\alpha^{*}, \bar{\gamma}_{h}^{*}, k_{h}\right)\left(\mathcal{F}+\mathcal{G}+\left(\mathscr{A}+\mathfrak{B}+\mathfrak{B}^{\top}\right)\left(\left\|u_{h}\right\|+\left\|\psi_{h}\right\|\right)\right),
\end{aligned}
$$

where $\left(u_{k}, \psi_{h}\right)$ is the solution of $(2.1)$ and where $\mathcal{A}, \mathfrak{B}, \mathscr{B}^{\top}$ are defined by :

$$
\begin{aligned}
\mathcal{A} & =\operatorname{Sup}_{w_{h} \in V_{h}-\{0\}} \mathcal{A}\left(w_{h}\right)\left\|w_{h}\right\|^{-1}, \\
\mathfrak{B} & =\operatorname{Sup}_{w_{h} \in V_{h}-\{0\}} \mathfrak{B}\left(w_{h}\right)\left\|w_{h}\right\|^{-1}, \\
\mathfrak{B}^{\top} & =\operatorname{Sup}_{\varphi_{h} \in W_{h}-\{0\}} \mathcal{B}^{\top}\left(\varphi_{h}\right)\left\|\varphi_{h}\right\|^{-1} .
\end{aligned}
$$

The proof follows immediatelly from (3.8) and the triangular inequality.
Remark 3.1. - As in corollary 2.1, hypothesis $H 2^{*}$ can be substituted, in the applications, by the $Z_{h}^{*}$-ellipticity, i.e. there exists a positive constant $\delta_{h}^{*}$ such that

$$
a_{h}\left(v_{h}, v_{h}\right) \geqslant \delta_{h}^{*}\left\|v_{h}\right\|^{2} \quad \forall v_{h} \in Z_{h}^{*} .
$$

Remark 3.2. - In the applications the fact that $Z_{h} \neq Z$ is sometimes a difficulty. Then, it can happens that a choice of a «greater» $W_{h}$ is needed, in order to have $Z_{h} \subseteq Z$. This cannot, in general, be obtained unless $W_{h} \nsubseteq W$; therefore it is of some interest to consider the case of an «external approximation » of $W$. We shall give, in the following, some idea of the general case, but we refer for more precise results, in a large class of examples, to the papers by Raviart-Thomas [27] and Thomas [32] which contain the best treatment of the question from a mathematical point of view. On the other hand, from a numerical point of view, it is recommended to refer to the works by F. de Veubeke and his associateds (cfr. e.g. [12], [13], [14], [28], [29]) who have developed the theory of «strongly diffusive» elements, which is the most important case of application of the abstract situation described above.

We suppose then that another real Hilbert space, $H$, is given, such that

$$
\begin{equation*}
W \subseteq H \tag{3.9}
\end{equation*}
$$

with continuous injection. We suppose that $W$ is dense in $H$ and so we can identify $H^{\prime}$ with a dense subspace of $W^{\prime}$. Let now $V_{h}$ be a closed subspace of $V$ and $W_{h}$ a closed subspace of $H$, such that

$$
\begin{equation*}
B\left(V_{h}\right) \subseteq H^{\prime} \tag{3.10}
\end{equation*}
$$

and that, for all $v_{h}$ in $V_{h}$, if

$$
H^{\prime}\left\langle B v_{h}, \varphi_{h}\right\rangle_{H}=0 \quad \forall \varphi_{h} \in W_{h},
$$

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then :

$$
H_{H^{\prime}}\left\langle B v_{h}, \varphi\right\rangle_{H}=0 \quad \forall \varphi \in W
$$

We consider now the following approximation of problem (1.1).

$$
\left\{\begin{array}{l}
\text { Find }\left(\bar{u}_{h}, \bar{\psi}_{h}\right) \text { in } V_{h} \times W_{h} \text { such that : }  \tag{3.11}\\
a\left(\bar{u}_{h}, v_{h}\right)+\left\langle B v_{h}, \bar{\psi}_{h}\right\rangle=\left\langle f, v_{h}\right\rangle \quad \forall v_{h} \in V_{h}, \\
\left\langle B \bar{u}_{h}, \varphi_{h}\right\rangle=\left\langle g, \varphi_{h}\right\rangle \quad \forall \varphi_{h} \in W_{h},
\end{array}\right.
$$

where, of course, $g$ is supposed to belong to $H^{\prime}$. We always suppose that hypothesis $H 2$ is satisfied ${ }^{1}$ ) and we substitute $H 1$ with the following condition.
$\overline{H 1})$ There exists a positive constant $\bar{k}_{h}$ such that :

$$
\begin{equation*}
\operatorname{Sup}_{v_{h} \in V_{h}-\{0\}}\left\|v_{h}\right\|^{-1}\left\langle B v_{h}, \varphi_{h}\right\rangle \geqslant \bar{k}_{h}\left\|\varphi_{h}\right\|_{H} \quad \forall \varphi_{h} \in W_{h} . \tag{3.12}
\end{equation*}
$$

Then by $\overline{H 1}, H 2$ and theorem 1.1 we get immediatelly that problem (3.11) has a unique solution. In order to evaluate the distance between $(u, \psi)$ and $\left(\bar{u}_{h}, \bar{\psi}_{h}\right)$ we define at first the space $\mathcal{V}$ in the following way:

$$
\begin{equation*}
\vartheta=\left\{v \mid v \in V, \quad B v \in H^{\prime}\right\} \tag{3.13}
\end{equation*}
$$

and we remark that $V_{h} \subseteq \vartheta$ from (3.10), and also $u \in \mathcal{Y}$, since $g$ is supposed in $H^{\prime}$ and $(u, \psi)$ is the solution of (1.1). We define then $\bar{\Lambda}_{h}: \vartheta \times W \rightarrow V_{h}^{\prime} \times W_{h}^{\prime}$ by :

$$
\left\{\begin{array}{l}
\left\langle\bar{\Lambda}_{h}(v, \varphi),\left(w_{h}, \chi_{h}\right)\right\rangle=a\left(v, w_{h}\right)+b\left(w_{h}, \varphi\right)+\left\langle B v, \chi_{h}\right\rangle  \tag{3.14}\\
\text { for all }(v, \varphi) \text { in } \vartheta \times W \text { and }\left(W_{h}, \chi_{h}\right) \text { in } V_{h} \times W_{h}
\end{array}\right.
$$

Let now $\left(v_{h}, \varphi_{h}\right)$ be a pair in $V_{h} \times W_{h}$; from $\overline{H 1}, H 2$ and the proposition 1.1 we get that there exists $\left(w_{h}, \chi_{h}\right)$ in $V_{h} \times W_{h}$ such that :

$$
\begin{align*}
& \left\langle\bar{\Lambda}_{h}\left(\bar{u}_{h}-v_{h}, \bar{\psi}_{h}-\varphi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle  \tag{3.15}\\
& \quad \geqslant M\left(\alpha, \gamma_{h}^{\prime}, k_{h}\right)^{-1} \cdot\left(\left\|w_{h}\right\|+\left\|\chi_{h}\right\|_{H}\right) \cdot\left(\left\|\bar{u}_{h}-v_{h}\right\|+\left\|\bar{\psi}_{h}-\varphi_{h}\right\|_{H}\right)
\end{align*}
$$

On the other hand we have :

$$
\begin{array}{r}
\left\langle\bar{\Lambda}_{h}\left(\bar{u}_{h}-v_{h}, \bar{\psi}_{h}-\varphi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle=\left\langle\bar{\Lambda}_{h}\left(u-v_{h}, \psi-\psi_{h}\right),\left(w_{h}, \chi_{h}\right)\right\rangle  \tag{3.16}\\
\forall\left(v_{h}, \varphi_{h}\right),\left(w_{h}, \chi_{h}\right) \in V_{h} \times W_{h} .
\end{array}
$$

[^4]Observing now that

$$
\begin{equation*}
\left|\left\langle\bar{\Lambda}_{h}(v, \varphi),\left(w_{h}, \chi_{h}\right)\right\rangle\right| \leqslant \alpha\|v\| \cdot\left\|w_{h}\right\|+\bar{\beta}\left\|w_{h}\right\| \cdot\|\varphi\|_{H}+\bar{\beta}\|v\| \cdot\left\|\chi_{h}\right\|_{H} \tag{3.17}
\end{equation*}
$$

where

$$
\begin{equation*}
\bar{\beta}=\operatorname{Sup}_{\substack{v \in \mathcal{Y}_{-\{0}-\{0\} \\ \varphi \in U_{W_{h}}-\{0\}}}\|v\|^{-1}\|\varphi\|_{H}^{-1}\langle B v, \varphi\rangle \tag{3.18}
\end{equation*}
$$

we get from (3.15), (3.16), (3.17), that :

$$
\begin{aligned}
\left\|u-\bar{u}_{h}\right\|+\left\|\psi-\bar{\psi}_{h}\right\|_{H} \leqslant\left((\alpha+\bar{\beta}) M\left(\alpha, \gamma_{h}^{\prime}, \bar{k}_{h}\right)\right. & +1)\left(\operatorname{Inf}_{v_{h} \in V_{h}}\left\|u-v_{h}\right\|\right. \\
& \left.+\operatorname{Inf}_{\varphi_{h} \in W_{h}}\left\|\psi-\varphi_{h}\right\|_{H}\right)
\end{aligned}
$$

We can conclude with the following theorem.
Theorem 3.2. - Under the hypotheses of corollary 1.1, if (3.9), (3.10) and $\overline{H 1}$ are satisfied, for every $(f, g)$ in $V^{\prime} \times W^{\prime}$ we have that, if $(u, \psi)$ and $\left(\bar{u}_{h}, \bar{\psi}_{k}\right)$ are the solutions of (1.1) and (3.11) respectivelly, then :

$$
\begin{aligned}
\left\|u-\bar{u}_{h}\right\|+\left\|\psi-\bar{\psi}_{h}\right\|_{H} \leqslant\left((\alpha+\bar{\beta}) M\left(\alpha, \gamma_{h}^{\prime}, \bar{k}_{h}\right)\right. & +1)\left(\operatorname{Inf}_{v_{h} \in V_{h}}\left\|u-v_{h}\right\|^{\prime}\right. \\
& \left.+\operatorname{Inf}_{\varphi_{h} \in W_{h}}\left\|\psi-\varphi_{h}\right\|_{H}\right)
\end{aligned}
$$

where $\bar{\beta}$ is given by (3.18).

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[^1]:    Note. - Some of the results of this paper were also reported in a previous note (see [7]) ; I wish to thank Prof. J. L. Lions for presenting it to the C.R. Acad. Sc. Thanks are also due to Prof. P. A. Raviart for his help in useful personel conversations.

[^2]:    (1) If $H_{1}$ and $H_{2}$ are Hilbert spaces, $\mathcal{L}\left(H_{1}, H_{2}\right)$ will be the space of all linear continuous operators from $H_{1}$ into $H_{2}$, with the norm :

    $$
    \|S\|=\|S\| \mathbb{E}\left(H_{1}, H_{2}\right)=\operatorname{Sup}_{x \in H_{1}-\{0\}} \frac{\|S x\|}{\|x\|}
    $$

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[^3]:    (1) For sufficient conditions in order that $\Lambda$ be an isomorphism, in more general cases, see [2].

[^4]:    (1) In this case, of course, we will use $\bar{Z}_{h}=\left\{v_{h} \mid v_{h} \in V_{h}, B v_{h}=0\right\} \subseteq Z$; we remark therefore that, if $a(u, v)$ is $Z$-elliptic, then $H 2$ is automatically satisfied.

