Jean Descloix
Jacques Rappaz

Approximation of solution branches of nonlinear equations

RAIRO. Analyse numérique, tome 16, n° 4 (1982), p. 319-349

<http://www.numdam.org/item?id=M2AN_1982__16_4_319_0>
We present a general theory for the approximation of regular and bifurcating branches of solutions of nonlinear equations. It can be applied to numerous problems, including differential equations on unbounded domains, in connection with various numerical algorithms, for example Galerkin methods with numerical integration.

Résumé — On présente une théorie générale de l'approximation de branches, régulières ou avec bifurcation, de solutions d'équations non linéaires. Cette théorie s'applique à de nombreux problèmes, y compris les équations différentielles sur des domaines non bornés, résolus par des méthodes numériques variées, par exemple des méthodes de Galerkin avec intégration numérique.

1. INTRODUCTION

In their three papers [1], [2], [3], Brezzi, Rappaz and Raviart consider the approximation of nonlinear equations of the type

\[ u + TG(\lambda, u) = 0 \] (1.1)

by a family of equations of the form

\[ u + T_h G(\lambda, u) = 0 \] (1.2)

here \( G : \mathbb{R} \times V^l \rightarrow W \) is a regular nonlinear mapping, \( T : W \rightarrow V \) and \( T_h : W \rightarrow V_h \) are bounded linear operators; \( V \) and \( W \) are real Banach spaces.

(*) Received in December 1981

(**) This work was supported by the Fonds National Suisse de la Recherche Scientifique

(1) Département de Mathématiques, École Polytechnique Fédérale, Lausanne, Suisse.
\( \{ V_h \}_h \) is a family of finite dimensional subspaces of \( V \). As a main hypothesis connecting (1 1) and (1 2), they suppose that

\[
\lim_{h \to 0} \| T - T_h \|_{\mathcal{L}(V)} = 0 ,
\]

which implies in particular that \( T \) is compact.

Brezzi, Rappaz and Raviart have limited their investigations to regular branches of solutions [1], limit points [2] and simple bifurcation points [3], whereas in [12], [13] Rappaz and Raugel have considered in the same context bifurcation at multiple eigenvalues.

The purpose of this paper is to generalize in an unified treatment some of the main results contained in the references mentioned above. In particular, our theory includes the possibility to analyze two new situations

a) in (1 1), \( T \) is non compact, b) the approximation is of Galerkin type with numerical integration.

Also most concrete problems can be written naturally in the form (1 1), we have found suitable to adopt the following framework. Let \( X \) and \( Y \) be real Banach spaces, \( F : X \to Y \) be a sufficiently regular nonlinear map, \( x_0 \in X \) be such that \( F(x_0) = 0 \). In a neighborhood of \( x_0 \), we consider the equation

\[
F(x) = 0 ,
\]

we shall suppose that \( F(x_0) : X \to Y \) is a Fredholm operator of index 1, however we shall assume no compactness hypothesis on \( F(x_0) \).

Several authors have considered bifurcation problems in the general form (1 4) (see for example Magnus [10]), since with it the parameter \( \lambda \in \mathbb{R} \) does not appear explicitly, a simple limit point cannot be distinguished from a regular point, in the same way, the “ double limit point ” introduced by Decker and Keller in [5], can be treated as an usual simple bifurcation point (see Descloux, Rappaz [8]).

For approximating the equation \( F(x) = 0 \) we consider two families of finite dimensional subspaces \( \{ X_h \}_h , \{ Y_h \}_h \) of \( X \) and \( Y \) respectively, nonlinear mappings \( F_h : X_h \to Y_h \) and the equations

\[
F_h(x) = 0 ,
\]

instead of (1 3), we impose on \( F \) and \( F_h \) a consistency condition and a stability condition which are given by relations (3 5) and (3 7) in Section 3, remark that they do not suppose that \( F(x_0) \) possesses any property of compactness.

As for the analysis of problems (1 1), (1 2) by Brezzi, Rappaz, Raviart and Raugel, our investigation will be based on the implicit function theorem.
Section 1, we recall a version of this theorem and prove a basic error estimate (Theorem 2.2).

Section 3 deals with "regular points", i.e. we require that $F'(x_0)$ is surjective. Theorem 3.1 contains the general results. In Theorem 3.2, we suppose that $X$ is of the form $\mathbb{R} \times V$, and that $x_0 = (\lambda_0, u_0) \in X$ is a turning point; for Galerkin methods, as in [2], we obtain an improved bound for the parameter $\lambda$ at the approximate turning point.

The main results of this paper are contained in Section 4 which is devoted to bifurcation points. Although not impossible, we have found it very complicated to work with the approximate problem (1.5) when $F_h$ operates on finite dimensional subspaces; for this reason we require that $F_h$ admits a suitable extension $\bar{F}_h : X \to Y$ such that, in particular, the equations $F_h(x) = 0$ and $\bar{F}_h(x) = 0$ possess the same solutions. As in Section 3, we impose to $F$ and $F_h$ (where now $F_h$ denotes the extended operator $X \to Y$) a consistency condition (4.4) and a stability condition (4.6). Supposing that the dimension of the kernel of $F'(x_0)$ is $n + 1$ with $n \geq 1$, we apply the Lyapunov-Schmidt procedure to $F$ and $F_h$ (Theorem 4.1) and reduce problems (1.4) and (1.5) to equations of the form $f(\sigma) = 0$ and $f_h(\sigma) = 0$, where $f$ and $f_h$ operate on the same finite dimensional subspaces. Theorems 4.2 and 4.3 are based on the following hypothesis:

$$f(0) = f'(0) = \cdots = f^{(q-1)}(0) = 0, \quad f_h(0) = f_h'(0) = \cdots = f_h^{(q-1)}(0) = 0$$

for some $q \geq 2$ and there exists a non degenerate characteristic ray (Hypotheses (4.16), (4.17)); they show the existence of a branch $\Gamma$ of solutions of the exact problem (1.4) passing through $x_0$ and tangent to the characteristic ray at $x_0$ and, on the other side, the existence of a branch $\Gamma_h$ of solutions of the approximate problem (1.5) converging to $\Gamma$. The particular case of a simple bifurcation point is treated in Theorems 4.4 and 4.5 which give error estimates similar to those obtained in [3].

The aim of Section 5 is to show how the results of Section 4 can be applied to the following classical problem

$$(\lambda, u) \in \mathbb{R} \times H^1_0(\Omega), \quad -\Delta u - \lambda u + u^3 = 0;$$

here $\Omega$ is the unit square $0 < x, y < 1$ and we are interested by solutions in the neighborhood of $(\lambda_0, 0)$ where $\lambda_0 = 5 \Pi^2$ is a double eigenvalue of the eigenvalue equation $\Delta u + \lambda u = 0$. The approximate problem is obtained by the Galerkin method with numerical integration. The exact problem can be written in the form (1.1) with $T$ compact; however, due to the presence of numerical integration and to the fact that $H^1_0(\Omega)$ is not imbedded in $C^0(\overline{\Omega})$, the approxi-
mate problem cannot be put in the form (1.2). Note that this difficulty can be overcome by replacing $H^1_0(\Omega)$ by $W^{p}_0(\Omega)$ for $p > 2$, but, then, the estimate $0(h)\text{ in (5.25)}$ should be replaced by $0(h^{1-\epsilon}), \epsilon > 0$ (see [11]).

Except for a part of Section 5, all the results of this paper are contained in our Report [8] in which however some further questions are discussed, for example bifurcation in presence of symmetry, the situation of imperfect numerical bifurcation (i.e. using the above notations, $f$ satisfies the relations $f(0) = f'(0) = f^{(q-1)}(0) = 0$, but $f_h$ does not satisfy the relations $f_h(0) = f_h'(0) = f^{(q-1)}(0) = 0$). Let us also mention the analysis of a nonlinear Sturm-Liouville eigenvalue problem on the infinite interval $(0, \infty)$, here, the exact problem can be written in the form (1.1), but with $T$ non compact (see also [9]).

2. NOTATIONS. PRELIMINARIES

We first introduce some notations. Let $X, Y, Z$ be real Banach spaces. For the sake of simplicity, we shall denote by $\| \cdot \|$ the various norms in $X, Y, Z$, $\mathcal{L}_m(X, Y), \mathcal{L}_m(X \times Y, Z)$, where $\mathcal{L}_m(X, Y)$ is the space of continuous $m$-linear mappings of $X^m$ into $Y$. In the same way, for any space, $B(a, p)$ denotes the open ball of center $a$ and radius $p$. The norm in $X \times Y$ is defined by the relation $\| (x, y) \| = \| x \| + \| y \|$. For a map $G : \Omega \subset X \to Y$, $D^m G$ or $G^{(m)} : \Omega \to \mathcal{L}_m(X, Y)$ represents the $m$-th Frechet derivative of $G$, for $x \in \Omega$, $\xi = (\xi_1, \ldots, \xi_m) \in X^m$, we use the notations $G^{(m)}(x)(\xi_1, \ldots, \xi_m) \in Y$, $G^{(m)}(x) \xi = G^{(m)}(x)(\xi_1, \ldots, \xi_m)$. If $\xi_1 = \xi_2 = \ldots = \xi_{m-1}$, or if $\xi_1 = \xi_2 = \ldots = \xi_m$, we may also write $G^{(m)}(x) \xi = G^{(m)}(x)(\xi_1) \xi_2^{m-1}$ or $G^{(m)}(x) \xi = G^{(m)}(x) \xi_1^{m-1}$, respectively.

For a map $G : \Omega \subset X \times Y \to Z, D_x G, D_y G, D_{xx} G, D_{xy} G, D_{yy} G$ will denote the partial derivatives.

As in [1], [2], [3], the essential tool of this work will be the implicit function theorem.

We quote here a particular version of it, for the proof, see, for example [8].

**Theorem 2.1** Let $X, Y$ and $Z$ be Banach spaces, $x_0 \in X, y_0 \in Y, \delta$ be a positive number, $\Omega = B(x_0, \delta) \times B(y_0, \delta) \subset X \times Y$, $G : \Omega \to Z$ be a $C^p$ mapping with $p \geq 2$. We suppose that $D_y G(x_0, y_0)$ is an isomorphism from $Y$ onto $Z$ and that there exist the numbers $c_0, c_1, \ldots, c_p$ such that

$$
\| D_y G(x_0, y_0)^{-1} \| \leq c_0,
$$
$$
\| G^{(k)}(x, y) \| \leq c_k \quad \forall (x, y) \in \Omega, \quad k = 1, 2, \ldots, p
$$

RAIRO Analyse numérique/Numerical Analysis
Then, there exist positive numbers $a$, $b$, $d$ depending only on $\delta$, $c_0$, $c_1$, $c_2$ and for $k = 1, 2, ..., p$, the numbers $M_k$ depending only on $c_0$, $c_1$, ..., $c_k$ such that:

1) for any $(x, y) \in B(x_0, a) \times B(y_0, b)$, $D_y G(x, y)$ is an isomorphism from $Y$ onto $Z$ such that $\| D_y G(x, y)^{-1} \| \leq 2 c_0$,

2) if $\| G(x_0, y_0) \| < d$, there exists a $C^p$ mapping $g : B(x_0, a) \to B(y_0, b)$ such that, for any $x \in B(x_0, a)$, $y = g(x)$ is the unique solution of the equation $G(x, y) = 0$, $y \in B(y_0, b)$, i.e.

$$G(x, g(x)) = 0, \quad g(x) \in B(y_0, b) \quad \forall x \in B(x_0, a);$$

furthermore

$$\| g^{(k)}(x) \| \leq M_k \quad \forall x \in B(x_0, a), 1 \leq k \leq p.$$

The next theorem provides a key result for error estimates.

**Theorem 2.2:** We consider the situation given by Theorem 2.1 with $\| G(x_0, y_0) \| < d$. Let $W$ be a real Banach space, $\Delta \subset W$ be open, $s : B(x_0, a) \to B(y_0, b)$ and $\alpha : \Delta \to B(x_0, a)$ be $C^{p-1}$ mappings, $\bar{g} = g \circ \alpha$ and $\bar{s} = s \circ \alpha : \Delta \to B(y_0, b)$. We suppose that there exist constants

$$e_1, e_2, ..., e_{p-1}, \quad \gamma_1, \gamma_2, ..., \gamma_{p-1}$$

such that

$$\| s^{(k)}(x) \| \leq e_k \quad \forall x \in B(x_0, a), \quad \| \alpha^{(k)}(t) \| \leq \gamma_k \quad \forall t \in \Delta, \quad k = 1, 2, ..., p - 1.$$

Then, for $k = 0, 1, ..., p - 1$, there exist constants $K_k$ depending only on $c_0$, $c_1$, ..., $c_{k+1}$, $e_1$, $e_2$, ..., $e_k$, $\gamma_1$, $\gamma_2$, ..., $\gamma_k$ such that

$$\| \bar{g}^{(k)}(t) - \bar{s}^{(k)}(t) \| \leq K_k \sum_{l=0}^{k} \| H^{(l)}(t) \| \quad \forall t \in \Delta, \quad 0 \leq k \leq p - 1, \quad (2.1)$$

where $H : \Delta \to Z$ is the $C^{p-1}$ mapping defined by $H(t) = G(\alpha(t), \bar{s}(t))$.

**Proof:** Since $G(\alpha(t), \bar{g}(t)) = 0$, we obtain by the fundamental theorem of calculus:

$$H(t) = G(\alpha(t), \bar{s}(t)) - G(\alpha(t), \bar{g}(t)) = E(t) (\bar{s}(t) - \bar{g}(t)),$$

where

$$E(t) = \int_0^1 D_x G(\alpha(t), \bar{g}(t)) + \tau (\bar{s}(t) - \bar{g}(t)) \, d\tau; \quad (2.3)$$

vol 16, no 4, 1982
by the same theorem again, we have that \( \| E(t) - D_y G(x_0, y_0) \| \leq c_2(a + b) \). Without restriction of generality we can assume in Theorem 2.1 that 
\[ 2c_0 c_2(a + b) \leq 1 \]; writing

\[
E(t) = D_y G(x_0, y_0) \left( I - D_y G(x_0, y_0)^{-1} (D_y G(x_0, y_0) - E(t)) \right),
\]

we see that for any \( t \in \Delta \), \( E(t) \) is an isomorphism from \( Y \) onto \( Z \) with inverse bounded by \( 2c_0 \). By differentiating (2.3) \( j \) times, \( 1 \leq j \leq p - 1 \), and by using the bound \( \| g^{(k)}(x) \| \leq M_k \) of Theorem 2.1, we see that \( \| E^{(j)}(t) \| \) is bounded, uniformly with respect to \( t \), by a constant depending only on \( c_0, c_1, ..., c_{j+1}, e_1, e_2, ..., e_p, \gamma_1, ..., \gamma_p \). We now prove Theorem 2.2 by induction; for \( k = 0 \), we have by (2.2):

\[
\| \tilde{s}(t) - \tilde{g}(t) \| \leq \| E(t)^{-1} \| \| H(t) \| \leq 2c_0 \| H(t) \|
\]

which proves (2.1) for \( k = 0 \) with \( K_0 = 2c_0 \). Now suppose (2.1) true for \( 1 \leq k \leq q - 1, 1 \leq q \leq p - 1 \); by differentiating (2.2) \( q \) times we obtain for any \( \xi = (\xi_1, ..., \xi_q) \in W^q \) and any \( t \in \Delta \):

\[
E(t) (\tilde{s}^{(q)}(t) - \tilde{g}^{(q)}(t)) \xi = H^{(q)}(t) \xi - \sum_{j=1}^{q} \sum_{\Pi} D^j E(t) (\eta(\Pi_j)) \cdot D^{q-j}(\tilde{s}(t) - \tilde{g}(t)) (\zeta(\Pi_j)),
\]

where \( \Pi \) is any partition of the set \( \{ \xi_1, ..., \xi_q \} \) in two subsets \( \eta(\Pi_j) \) and \( \zeta(\Pi_j) \) containing respectively \( j \) and \( (q - j) \) elements; by the hypothesis of induction, this proves (2.1) for \( k = q \).

We conclude this section by recalling a classical result we shall use frequently in the following.

**Theorem 2.3**: Let \( X \) and \( Y \) be Banach spaces, \( D \) be a relatively compact subset of \( X \), \( f \) and \( f_n \), \( n \in \mathbb{N} \), be maps from \( D \) into \( Y \). We suppose:

a) \( \lim_{n \to \infty} f_n(x) = f(x) \ \forall x \in D \), b) there exists a constant \( L \) such that

\[
\| f_n(x) - f_n(\xi) \| \leq L \| x - \xi \| \ \forall x, \ \xi \in D, \ \forall n \in \mathbb{N}.
\]

Then \( \lim_{n \to \infty} f_n = f \) uniformly.

3. **Regular Points**

Let \( X \) and \( Y \) be two real Banach spaces, \( F : X \to Y \) be a \( C^p \) mapping with \( p \geq 2 \) and \( x_0 \in X \) be such that \( F(x_0) = 0 \). We suppose that \( x_0 \) is a regular
point in the following sense

\[ F'(x_0) \colon X \to Y \] is a Fredholm operator of index 1, \hfill (3.1)
\[
\text{Range } F'(x_0) = Y \hfill (3.2)
\]

Hypotheses (3.1) and (3.2) imply that the kernel of \( F'(x_0) \) is one-dimensional and consequently is spanned by some vector \( \varphi_0 \in X, \varphi_0 \neq 0 \). Let \( \psi_0 \in X^* \) be such that \( \langle \varphi_0, \psi_0 \rangle \neq 0 \), where \( X^* \) denotes the dual space of \( X \) and \( \langle ., . \rangle \) the duality pairing between \( X \) and \( X^* \). As we shall see in Theorem 3.1, there is an unique branch of solutions of the equation \( F(x) = 0 \) passing through \( x_0 \) which can be parametrized by a function \( x(t) \) satisfying the relations

\[
F(x(t)) = 0, \quad \langle x(t) - x_0, \psi_0 \rangle - t = 0
\]

In order to approximate this branch of solutions let \( \{ X_h \}_h \) and \( \{ Y_h \}_h \) be two families of finite dimensional subspaces of \( X \) and \( Y \) respectively, \( \{ F_h \}_h \) be a family of \( C^p \) functions mapping \( X_h \) into \( Y_h \) and \( \{ \Pi_h \}_h \) be a family of projectors mapping \( X \) onto \( X_h \), here \( h \) is a parameter which tends to zero. We suppose

\begin{enumerate}[a)]
  \item \( \lim_{h \to 0} \Pi_h x = x \quad \forall x \in X \), \hfill (3.3)
  \item \text{dimension} \( X_h = \text{dimension} Y_h + 1 \), \hfill (3.4)
  \item for any \( 0 \leq k \leq p - 1 \) and for any fixed \( x, \xi_1, \ldots, \xi_k \in X \), we have
    \[ \lim_{h \to 0} \left\| F^{(k)}(x)(\xi_1, \ldots, \xi_k) - F^{(k)}(\Pi_h x)(\Pi_h \xi_1, \ldots, \Pi_h \xi_k) \right\| = 0 \}, \hfill (3.5)
  \item there exist the positive constants \( \delta \) and \( c \) such that
    \[ \| F^{(k)}(x) \| \leq c, \quad \forall x \in X_h \quad \text{with} \quad \| x - \Pi_h x_0 \| < \delta, \quad \forall h, \ 1 \leq k \leq p \], \hfill (3.6)
  \item there is a positive constant \( \mu \) such that
    \[ \| F^k(\Pi_h x_0) \xi \| \geq \mu \| \xi \| \quad \forall \xi \in W_h, \quad \forall h \], \hfill (3.7)
\end{enumerate}

where \( W_h = \{ x \in X_h \mid \langle x, \psi_0 \rangle = 0 \} \).

(3.3) implies that the projectors \( \Pi_h \) are uniformly bounded, (3.4) is the discrete analogous of (3.1), (3.5) is a relation of pointwise convergence which can be interpreted as a condition of consistency whereas (3.7) will appear as a condition of stability allowing the use of the implicit function theorem.

\textbf{Remark 3.1} Let \( W = \{ x \in X \mid \langle x, \psi_0 \rangle = 0 \} \), by Hypotheses (3.1), (3.2) and by Banach’s theorem, \( F'(x_0) \) defines an isomorphism from \( W \) onto \( Y \).
and consequently there exists a positive constant \( c \) such that
\[
\| F(\xi) \| \geq c \| \xi \| \quad \forall \xi \in W
\]

It follows that a \textit{sufficient} condition which ensures the stability hypothesis (3.7) is the following one
\[
\lim_{h \to 0} \sup_{\| \xi \| = 1} \| (F_h^n(\Pi_h x_0) \xi - F(x_0) \xi) \| = 0,
\]
(3.8)
such a condition has been used for example in [7] in connection with eigenvalue problems.

Let \( \mathcal{G} : \mathbb{R} \times X \rightarrow \mathbb{R} \times Y \) and \( \mathcal{G}_h : \mathbb{R} \times X_h \rightarrow \mathbb{R} \times Y_h \) be defined by the relations
\[
\mathcal{G}(t, x) = \langle x - x_0, \psi_0 \rangle - t, F(x), \quad \mathcal{G}_h(t, x) = \langle x - x_0, \psi_0 \rangle - t, F_h(x)
\]
(3.9)

\textbf{Lemma 3.1} Assume Hypotheses (3.1) to (3.7) Then a) \( D_x \mathcal{G}(0, x_0) \) is an isomorphism from \( X \) onto \( \mathbb{R} \times Y \) b) For \( h \) small enough, \( D_x \mathcal{G}_h(0, \Pi_h x_0) \) is an isomorphism from \( X_h \) onto \( \mathbb{R} \times Y_h \) with uniformly (with respect to \( h \)) bounded inverse.

\textit{Proof} By Hypotheses (3.1), (3.2) and the fact that \( \langle \omega_0, \psi_0 \rangle \neq 0 \), part a) of lemma 3.1 follows immediately from Banach’s theorem. In the following, \( c \) will denote a positive generic constant independent of \( h \), since \( X_h \) and \( \mathbb{R} \times Y_h \) have the same finite dimension, it suffices, for proving part b), to show, for \( h \) small enough, that
\[
\| D_x \mathcal{G}_h(0, \Pi_h x_0) \xi \| \geq c \| \xi \| \quad \forall \xi \in X_h
\]
Let \( \omega_{oh} = \Pi_h \omega_0 \), by Hypotheses (3.3) and (3.5) we have that \( \lim_{h \to 0} \omega_{oh} = \omega_0 \) and \( \lim_{h \to 0} F_h(\Pi_h x_0) \omega_{oh} = 0 \) Any \( \xi \in X_h \) can be decomposed as \( \xi = \alpha \omega_{oh} + w, \) \( \alpha \in \mathbb{R}, w \in W_h \) and we obtain by Hypothesis (3.7)
\[
\| D_x \mathcal{G}_h(0, \Pi_h x_0) \xi \| \geq \| \alpha \langle \omega_{oh}, \psi_0 \rangle + \| F_h(\Pi_h x_0) (\alpha \omega_{oh} + w) \| \geq c | \alpha | + c \| w \| - | \alpha | \| F_h(\Pi_h x_0) \omega_{oh} \|
\]
\[
\geq c \{ | \alpha | + | w | \} \geq c \| \xi \| \quad \Box
\]

\textbf{Theorem 3.1} Assume Hypotheses (3.1) to (3.7) Then there exist positive constants \( h_0, t_0, \alpha, K \) and two unique maps \( x(t) \in X \) and \( x_h(t) \in X_h \), \( |t| < t_0 \) satisfying respectively the conditions
\[
\mathcal{G}(t, x(t)) = 0, \quad \| x(t) - x_0 \| < \alpha, \quad \text{for} \ |t| < t_0, \quad (3.10)
\]
\[
\mathcal{G}_h(t, x_h(t)) = 0, \quad \| x_h(t) - \Pi_h x_0 \| < \alpha, \quad \text{for} \ |t| < t_0 \text{ and } h < h_0,
\]
(3.11)
moreover \( x(0) = x_0 \), \( x'(0) \neq 0 \), \( x(.) \) and \( x_h(.) \) are of class \( C^p \) with bounded derivatives of order \( 0, 1, \ldots, p \) where the bounds are uniform with respect to \( t \) and \( h < h_0 \), and we have

\[
\lim_{h \to 0} \sup_{|t| < t_0} \| x^{(k)}(t) - x^{(k)}_h(t) \| = 0, \quad k = 0, 1, \ldots, p - 1, \quad (3.12)
\]

\[
\| x^{(k)}(t) - x^{(k)}_h(t) \| \leq K \sum_{i=0}^{k} \left\{ \frac{d^i}{dt^i} F_h(\Pi_h x(t)) + \| (I - \Pi_h) x^{(i)}(t) \| \right\} , \quad |t| < t_0, \quad h < h_0, \quad 0 \leq k \leq p - 1 \quad (3.13)
\]

**Proof** By Hypotheses (3.1)-(3.7) and by Lemma 3.1, relations (3.10), (3.11) and the boundedness of the derivatives of \( x(t) \) and of \( x_h(t) \) follow easily from Theorem 2.1 applied to \( \mathcal{G} \) and \( \mathcal{G}_h \). By applying Theorem 2.2 to \( \mathcal{G}_h \), with \( W = \mathbb{R}, \alpha(t) = t, \mathcal{S}(t) = \Pi_h x(t) \), we obtain for \( 0 \leq k \leq p - 1, |t| < t_0 \) and some constant \( c \)

\[
\| x^{(k)}_h(t) - \Pi_h x^{(k)}(t) \| \leq c \sum_{i=0}^{k} \frac{d^i}{dt^i} \mathcal{G}_h(t, \Pi_h x(t)) ,
\]

from which, by using (3.10), (3.13) follows immediately. Hypotheses (3.3), (3.5) together with the fact that \( F(x(t)) = 0 \) imply that the right member of (3.13) converges, for each \( t \), to zero as \( h \) tends to zero, in fact, by Theorem 2.3, the convergence is uniform with respect to \( t \), this proves (3.12). \( \Box \)

Besides Hypotheses (3.1)-(3.7), we shall assume from now on that we have the following particular situation \( X = \mathbb{R} \times V \), where \( V \) is a real Banach space, \( X_h = \mathbb{R} \times V_h \), where \( V_h \) is a subspace of \( V \), an element of \( \mathbb{R} \times V \) will be denoted by \( (\lambda, u) \), \( \lambda \in \mathbb{R}, u \in V \) and we shall write \( F(\lambda, u) \) for \( F(x) \) and \( F_h(\lambda, u) \) for \( F_h(x) \). We set \( x_0 = (\lambda_0, u_0), x(t) = (\lambda(t), u(t)), x_h(t) = (\lambda_h(t), u_h(t)), |t| < t_0 \), where \( x(t) \) and \( x_h(t) \) are defined by Theorem 3.1, we suppose that

\[
\text{Range } D_u F(\lambda_0, u_0) \text{ is closed and of codimension 1 in } Y, \quad (3.14)
\]

\[
D_\lambda F(\lambda_0, u_0) \notin \text{Range } D_u F(\lambda_0, u_0), \quad (3.15)
\]

note that (3.14) and (3.15) are consistent with (3.2), in fact it is easy to prove (see Appendix I of [8]) that (3.1) implies that \( D_u F(\lambda_0, u_0) \) is a Fredholm operator of index 0 so that (3.14) is a consequence of (3.1), (3.2) and (3.15).

Let \( Y \times Y \to \mathbb{R} \) be a continuous and coercive bilinear form, we assume that \( F_h \) is the Galerkin approximation of \( F \) with respect to \( a \) if

\[
a(F_h(\lambda, u), y) = a(F(\lambda, u), y) \quad \forall v \in Y_h, \quad \forall (\lambda, u) \in X_h, \quad \forall h, \quad (3.16)
\]

\[
\lim_{h \to 0} \inf_{z \in Y_h} \| y - z \| = 0, \quad \forall v \in Y \quad (3.17)
\]
By differentiating the relation \( F(\lambda(t), u(t)) = 0 \) at \( t = 0 \), and by taking into account (3.15), we obtain that \( \lambda'(0) = 0 \), i.e., \((\lambda_0, u_0)\) is a limit point, we shall assume furthermore that it is a turning point i.e.

\[ \lambda''(0) \neq 0 \]  

Our purpose is to show that the approximate branch parametrized by \((\lambda_h(t), u_h(t))\) has also a turning point for some \( t = t_h \) near \( t = 0 \) and to give an « improved » estimate for the quantity \( \lambda_0 - \lambda_h(t_h) \).

Hypothesis (3.14) implies the existence of an element \( y_0 \in Y \) such that

\[ v_0 \neq 0, \quad a(D_u F(\lambda_0, u_0), v, y_0) = 0 \quad \forall v \in V \]  

**THEOREM 3.2** Assume Hypotheses (3.1)-(3.7), (3.14)-(3.18) and suppose that \( p \geq 3 \) Then there exist positive constants \( t_1 \) and \( h_1 \) such that for \( h < h_1 \) there exists an unique \( t_h \in (-t_1, t_1) \) with \( \lambda_h'(t_h) = 0 \), \( \lambda_h''(t_h) \neq 0 \), furthermore there exists a constant \( c \) such that, for \( h \) small enough, we have

\[ |\lambda_h(t_h) - \lambda_0| \leq c \left\{ \| x_h'(0) - x'(0) \|^2 + \| x_h(0) - x_0 \| \times \right. 
\]

\[ \times \left( \| x_h(0) - x_0 \| + \inf_{y \in Y_h} \| y_0 - y \| \right) \right\} \]  

**Proof** In the following, \( c \) will denote a generic positive constant independent of \( h \). We use estimate (3.12) of Theorem 3.1 for \( k = 1, 2 \). Since \( \lambda'(0) = 0 \), we obtain that \( \lim_{h \to 0} \lambda_h'(0) = 0 \), by (3.18), there exists \( t_1 > 0 \) such that, for \( h \) small enough, \( |\lambda_h''(t) - \lambda_0''| \geq c |t| < t_1 \) consequently there exists \( h_1 > 0 \) and for \( h < h_1 \) an unique \( t_h \in (-t_1, t_1) \) such that \( \lambda_h'(t_h) = 0 \), furthermore, we have the estimates

\[ |t_h| \leq c |\lambda_h'(0)| = c |\lambda_h'(0) - \lambda'(0)| \leq c \| x_h'(0) - x'(0) \|, \]  

\[ \lambda_h(0) = \lambda_h(t_h) - (\lambda_h'(t_h)) t_h + 0(t_h^2) = \lambda_0(t_h) + 0(t_h^2) \]  

In order to prove (3.20), let \( z_h \in Y_h \) such that \( \| y_0 - z_h \| = \inf_{z \in Y_h} \| y_0 - z \| \)

By (3.14), (3.15), (3.19), \( a(D_x F(\lambda_0, u_0), y_0) \neq 0 \) and consequently, by (3.17), we shall have that \( |a(D_x F(\lambda_0, u_0), z_h)| \geq c \) for \( h \) small enough by (3.16), \( a(F(\lambda_h(0), u_h(0)), z_h) = a(F_h(\lambda_h(0), u_h(0))), z_h) = 0 \) and by Taylor's expansion we have

\[ 0 = a(F(\lambda_h(0), u_h(0)), z_h) - a(F(\lambda_0, u_0), z_h) \]

\[ = (\lambda_h(0) - \lambda_0) a(D_1 F(\lambda_0, u_0), z_h) + a(D_u F(\lambda_0, u_0) (u_h(0) - u_0), z_h) + \]

\[ + 0(\| x_h(0) - x_0 \|^2) \]
by (3.19),
\[ a(D_u F(\lambda_0, u_0), (u_h(0) - u_0), z_h) = a(D_u F(\lambda_0, u_0), (u_h(0) - u_0), (z_h - y_0)) \]
and, for \( h \) small enough, we deduce the estimate
\[ |\lambda_h(0) - \lambda_0| \leq c \| x_h(0) - x_0 \| (\| x_h(0) - x_0 \| + \| z_h - y_0 \|), \quad (3.23) \]
combining (3.21), (3.22) and (3.23), we obtain (3.20) \( \blacksquare \)

Remark 3.2 (3.21) and (3.22) are independent of the fact that \( \tilde{F}_h \) is a Galerkin approximation of \( F \), whereas (3.23) is independent of the condition \( \lambda''(0) \neq 0 \)

4. BIFURCATION POINTS

Let \( X \) and \( Y \) be two real Banach spaces, \( F : X \rightarrow Y \) be a \( C^p \) mapping with \( p \geq 2 \) and \( x_0 \in X \) be such that \( F(x_0) = 0 \). We suppose that \( x_0 \) is a critical point of order \( n \) in the following sense
\[ a) \quad F'(x_0) : X \rightarrow Y \text{ is a Fredholm operator of index 1}, \quad (4.1) \]
\[ b) \quad \text{codimension } \text{Range } F'(x_0) = n \quad (4.2) \]

Hypotheses (4.1), (4.2) imply that \( X_1 = \text{Ker } F'(x_0) \) has dimension \( n + 1 \) and, if we set \( Y_2 = \text{Range } F'(x_0) \), there exist two closed subspaces \( X_2 \subset X \) and \( Y_1 \subset Y \) such that
\[ X = X_1 \oplus X_2, \quad Y = Y_1 \oplus Y_2, \quad (4.3) \]
clearly dimension \( Y_1 = n \) and the restriction of \( F'(x_0) \) to \( X_2 \) defines an isomorphism from \( X_2 \) onto \( Y_2 \).

Let \( Q : Y \rightarrow Y_2 \) and \( I - Q : Y \rightarrow Y_1 \) be the projectors associated with the decomposition \( Y = Y_1 \oplus Y_2 \).

In order to approximate the solutions of the equation \( F(x) = 0 \) in a neighborhood of \( x_0 \), we consider a family \( \{ F_h \}_h \) of \( C^p \) operators \( F_h : X \rightarrow Y \), where \( h \) is a positive parameter tending to zero. In applications, \( F_h \) will appear as a suitable extension of a function defined on a finite dimensional subspace \( X_h \) of \( X \) with values in a finite dimensional subspace \( Y_h \) of \( Y \). We suppose
\[ c) \quad \text{for any } 0 \leq k \leq p - 1 \text{ and for any fixed } x, \xi_1, \xi_2, \xi_k \in X, \text{we have} \]
\[ \lim_{h \to 0} \| F^{(k)}(x) (\xi_1, \xi_2, \xi_k) - F^{(k)}_h(x) (\xi_1, \xi_2, \xi_k) \| = 0, \quad (4.4) \]
\[ d) \quad \text{there exist the positive constants } \delta \text{ and } c \text{ such that} \]
\[ \| F^{(k)}_h(x) \| \leq c \quad \forall x \in X \quad \text{with} \quad \| x - x_0 \| < \delta, \quad \forall h, \quad 1 \leq k \leq p, \quad (4.5) \]
e) $QF'(x_0)$ is an isomorphism from $X_2$ onto $Y_2$ with uniformly bounded inverse with respect to $h$.  

(4.4) is a relation of pointwise convergence which can be interpreted as a condition of consistency whereas (4.6) will appear as a condition of stability which will allow, in Theorem 4.1, the Lyapunov-Schmidt procedure for $F_h$; clearly (4.4) and (4.6) are analogous to Hypotheses (3.5) and (3.7) introduced in the preceding section.

**Theorem 4.1**: We suppose that Hypotheses a) to e) are satisfied. Then there exist positive constants $h_0$, $\zeta$, $\alpha$, $K$ and two unique maps $v : B(0, \zeta) \subset X_1 \rightarrow X_2$, $v_h : B(0, \zeta) \subset X_1 \rightarrow X_2$ such that:

\begin{align*}
QF(x_0 + \sigma + v(\sigma)) = 0, \quad \| v(\sigma) \| < \alpha \quad \forall \sigma \in B(0, \zeta), \tag{4.7}
QF_h(x_0 + \sigma + v_h(\sigma)) = 0, \quad \| v_h(\sigma) \| < \alpha \quad \forall \sigma \in B(0, \zeta), \quad \forall h < h_0; \tag{4.8}
\end{align*}

$v$ and $v_h$ are $C^p$ mappings with bounded derivatives of order $0$, $1$, ..., $p$ where the bounds are uniform with respect to $\sigma \in B(0, \zeta)$ and $h < h_0$; furthermore, we have:

\begin{align*}
&\lim_{h \to 0} \sup_{\sigma \in B(0, \zeta)} \| v^{(k)}(\sigma) - v_h^{(k)}(\sigma) \| = 0, \quad k = 0, 1, ..., p - 1, \tag{4.9}
&\| v^{(k)}(\sigma) - v_h^{(k)}(\sigma) \| \leq K \sum_{j=0}^{k-1} \left\| \frac{d^j}{d\sigma^j} QF_h(x_0 + \sigma + v(\sigma)) \right\|, \tag{4.10}
&0 \leq k \leq p - 1, \quad \sigma \in B(0, \zeta), \quad h < h_0.
\end{align*}

**Proof**: We apply Theorems 2.1 and 2.2 to $G : X_1 \times X_2 \rightarrow Y_2$ and $G_h : X_1 \times X_2 \rightarrow Y_2$, where $G(\sigma, v) = QF(x_0 + \sigma + v)$, $G_h(\sigma, v) = QF_h(x_0 + \sigma + v)$ from which (4.7), (4.8) and (4.10) follow immediately; then (4.9) is a consequence of Theorem 2.3, of (4.10), of Hypotheses (4.4), (4.5) and from the fact that $X_1$ is finite dimensional.

By Theorem 4.1, the equations $F(x) = 0$ and $F_h(x) = 0$ are reduced, in a neighborhood of $x_0$, to the equation $f(\sigma) = 0$ and $f_h(\sigma) = 0$ in a neighborhood of 0, where $f$ and $f_h$ are the bifurcation functions defined by:

\begin{align*}
f : B(0, \zeta) \rightarrow Y_1, \quad f(\sigma) = (I-Q) F(x_0 + \sigma + v(\sigma)), \tag{4.11}
f_h : B(0, \zeta) \rightarrow Y_1, \quad f_h(\sigma) = (I-Q) F_h(x_0 + \sigma + v_h(\sigma)). \tag{4.12}
\end{align*}

The following relations are either obvious or easy to verify:

\begin{align*}
v(0) = 0, \quad v'(0) = 0, \quad f(0) = 0, \quad f'(0) = 0, \tag{4.13}
F'(x_0) \xi = 0 \quad \forall \xi \in X_1, \quad (I-Q) F'(x_0) = 0. \tag{4.14}
\end{align*}
We now introduce the following new hypotheses: $p \geq 4$, there exist $\sigma_0 \in X_1$ and the integer $q$ with $2 \leq q \leq p/2$ such that

\begin{align*}
&f) f^{(k)}(0) = 0 \quad 2 \leq k \leq q - 1, \\
g) f^{(q)}(0) \sigma_0^q = 0, \\
h) \text{the relations } \sigma \in X_1, f^{(q)}(0) \sigma_0^{q-1} \sigma = 0 \text{ imply the existence of } \tau \in \mathbb{R} \\
&i) f^{(h)}(0) = 0 \quad 0 \leq k \leq q - 1
\end{align*}

**Remark 4.1** Consider the conditions $\alpha) (I-Q) F^{(k)}(x_0) = 0$, $2 \leq k \leq q - 1$, $\beta)$ the restriction of $F^{(k)}(x_0)$ to $X^k_1$ vanishes for $2 \leq k \leq q - 1$, then it is easy to verify that $\alpha)$ or $\beta)$ is a sufficient condition for obtaining (4 15), furthermore, if $\alpha)$ or $\beta)$ is satisfied, then $f^{(q)}(0)$ is equal to the restriction of $(I-Q) F^{(q)}(x_0)$ to $X^q_1$, which allows to express (4 16) and (4 17) in terms of $F$ directly.

**Remark 4.2** We could replace (4 18) by the more general hypothesis $\gamma)$ there exists $\eta_h \in X_1$ such that $\lim_{h \to 0} \eta_h = 0$ and $f^{(h)}(\eta_h) = 0$ for $0 \leq k \leq q - 1$, in fact, with minor modifications, all the following results of this section would remain valid. However, it is possible to reduce $\gamma)$ to (4 18) in the following way, let $z_h = \eta_h + u_h(\eta_h)$ and $\tilde{F}_h(x) = F_h(x + z_h)$, then by applying Theorem 4 1 to $\tilde{F}_h$ we obtain a map $\tilde{v}_h : B(0, \zeta) \subset X_1 \to X_2$ such that

$$Q \tilde{F}_h(x_0 + \sigma + \tilde{v}_h(\sigma)) = 0$$

and a new bifurcation function $\tilde{f}_h(\sigma) = (I-Q) \tilde{F}_h(x_0 + \sigma + \tilde{v}_h(\sigma))$, it is possible to verify that $\tilde{f}_h(\sigma) = f_h(\sigma + \eta_h)$ and consequently, by $\gamma)$, $f^{(h)}(0) = 0$ for $0 \leq k \leq q - 1$, note also that $\tilde{F}_h(x_0) = 0$.

Under the above hypotheses, we shall show the existence of a $C^{p-q}$ branch of solutions of the equation $F(x) = 0$ passing through $x_0$ and of a corresponding approximate branch for the equation $F_h(x) = 0$, the « exact » branch will be parametrized by a function $x(t) \in X$ such that $x(0) = x_0$, $x'(0) = \sigma_0$. To this end, let $\psi_0 \in X^*$ be such that $\langle \sigma_0, \psi_0 \rangle \neq 0$, where $X^*$ denotes the dual of $X$ and $\langle \cdot, \cdot \rangle$ the duality pairing between $X$ and $X^*$, we introduce the following mappings

\begin{align*}
&\mathcal{B}(t, \sigma) = \left( \langle \sigma - \sigma_0, \psi_0 \rangle, \frac{1}{t^q} f(t \sigma) \right), \\
&\mathcal{B}_h(t, \sigma) = \left( \langle \sigma - \sigma_0, \psi_0 \rangle, \frac{1}{t^q} f_h(t \sigma) \right),
\end{align*}

vol 16 n° 4 1982
\( \mathcal{G} \) and \( \mathcal{G}_h \) (\( h \) small enough) are defined on some neighborhood \( \Omega = \mathbb{R} \times X_1 \) of \( (0, \sigma_0) \) with values in \( \mathbb{R} \times Y_1 ; \Omega \) is independent of \( h \); by (4.13) and Hypotheses (4.15) and (4.18), \( \mathcal{G} \) and \( \mathcal{G}_h \) are \( C^{p-q} \) mappings where we recall that \( p - q \geq 2 \).

**THEOREM 4.2 :** We assume that Hypotheses a) to i) are satisfied. Then there exist positive constants \( h_0, t_0, \beta, M \) and two unique maps \( \sigma(.) : (-t_0, t_0) \rightarrow X_1 \), \( \sigma_h(.) : (-t_0, t_0) \rightarrow X_1 \) such that

\[
\mathcal{G}(t, \sigma(t)) = 0, \quad \| \sigma(t) - \sigma_0 \| \leq \beta, \quad |t| < t_0, \quad (4.21)
\]

\[
\mathcal{G}_h(t, \sigma_h(t)) = 0, \quad \| \sigma_h(t) - \sigma_0 \| \leq \beta, \quad |t| < t_0, \quad h < h_0; \quad (4.22)
\]

\( \sigma(.) \) and \( \sigma_h(.) \) are \( C^{p-q} \) mappings with bounded derivatives of order \( 0, 1, ..., p - q \) where the bounds are uniform with respect to \( |t| < t_0 \) and \( h < h_0 \); furthermore \( \mathcal{G}(0, \sigma_0) = 0 \) and we have for \( 0 \leq k \leq p - 2q + 1 \):

\[
\lim_{h \to 0} \sup_{|t| < t_0} \left\| \frac{d^k}{dt^k} (t\sigma(t) - t\sigma_h(t)) \right\| = 0, \quad (4.23)
\]

\[
\sup_{|t| < t_0} \left\| \frac{d^k}{dt^k} (t\sigma(t) - t\sigma_h(t)) \right\| \leq M \sum_{j=0}^{k+q-1} \sup_{|t| < t_0} \left\| \frac{d^j}{dt^j} f_h(t\sigma(t)) \right\|, \quad h < h_0. \quad (4.24)
\]

**Proof :** By (4.13) and (4.15) we have for any \( \sigma \in X_1 \):

\[
D_\sigma \mathcal{G}(0, \sigma_0) \sigma = \left( \langle \sigma, \psi_0 \rangle, \frac{1}{(q-1)!} f^{(q)}(0) \sigma_0^{q-1} \sigma \right);
\]

by (4.17) and the fact that \( \langle \sigma_0, \psi_0 \rangle \neq 0 \), we see that \( D_\sigma \mathcal{G}(0, \sigma_0) \) is injective; since \( X_1 \) and \( \mathbb{R} \times Y_1 \) have the same finite dimension \( n + 1 \), we conclude that \( D_\sigma \mathcal{G}(0, \sigma_0) \) defines an isomorphism between these two spaces. Moreover, by (4.13), (4.15) and (4.16), we have \( \mathcal{G}(0, \sigma_0) = 0 \). By (4.4), (4.5), (4.9) and Theorem 2.3, we obtain

\[
\lim_{h \to 0} \sup_{\sigma \in B(0, \xi)} \| f_h^{(k)}(\sigma) - f_h^{(k)}(\sigma) \| = 0, \quad 0 \leq k \leq p - 1; \quad (4.25)
\]

furthermore \( f_h^{(p)} \) is bounded on \( B(0, \xi) \) uniformly with respect to \( h \); by (4.13), (4.15), (4.18) and Taylor’s formula, we obtain:

\[
\mathcal{G}(t, \sigma) - \mathcal{G}_h(t, \sigma) = \left( 0, \frac{1}{(q-1)!} \int_0^1 (1-s)^{q-1} (f^{(q)}(st\sigma) - f_h^{(q)}(st\sigma)) \sigma^q ds \right);
\]

\( (4.26) \)
together with (4.25), this proves
\[ \lim_{h \to 0} \sup_{t, \sigma} \| \mathcal{G}^{(k)}(t, \sigma) - \mathcal{G}_h^{(k)}(t, \sigma) \| = 0, \quad 0 \leq k \leq p - q - 1, \quad (4.27) \]

and that \( \mathcal{G}_h^{(p-q)} \) is bounded on \( \Omega \) uniformly with respect to \( h \). In particular we have:
\[ \lim_{h \to 0} \| D_\sigma \mathcal{G}(0, \sigma_0) - D_\sigma \mathcal{G}_h(0, \sigma_0) \| = 0, \]
which shows that, for \( h \) small enough, \( D_\sigma \mathcal{G}_h(0, \sigma_0) \) is an isomorphism from \( X_1 \) onto \( \mathbb{R} \times Y_1 \) with inverse uniformly bounded with respect to \( h \).

In the following, \( c \) will denote a generic constant independent of \( h \). By using the above preliminary results, in particular (4.25), we can apply the implicit function Theorem 2.1 to \( \mathcal{G} \) and \( \mathcal{G}_h \) from which we deduce (4.21), (4.22) and the boundedness of the first \((p-q)\) derivatives of \( \sigma(.) \) and of \( \sigma_h(.) \). Applying furthermore Theorem 2.2 to \( \mathcal{G}_h \), we obtain, for \( h \) small enough, \( 0 \leq k \leq p - q - 1 \) and \( |t| < t_0 \), the estimate
\[ \| \sigma^{(k)}(t) - \sigma_h^{(k)}(t) \| \leq c \sum_{j=0}^{k} \left\| \frac{d^j}{dt^j} \mathcal{G}_h(t, \sigma(t)) \right\|; \quad (4.28) \]

since \( \mathcal{G}(t, \sigma(t)) = 0 \), it follows that \( \langle \sigma(t) - \sigma_0, \psi_0 \rangle = 0 \) and consequently that \( \mathcal{G}_h(t, \sigma(t)) = (0, t^{-q} e_h(t)) \), where we set \( e_h(t) = f_h(t \sigma(t)) \); then, by (4.28), we have for \( h \) small enough, \( 0 \leq k \leq p - q - 1 \) and \( |t| < t_0 \):
\[ \left\| \frac{d^k}{dt^k} (t \sigma(t) - t \sigma_h(t)) \right\| \leq c \left\{ |t| \left\| \frac{d^k}{dt^k} (t^{-q} e_h(t)) \right\| + \sum_{j=0}^{k-1} \left\| \frac{d^j}{dt^j} (t^{-q} e_h(t)) \right\| \right\} \leq c \left\{ \left\| \frac{d^k}{dt^k} (t^{-q+1} e_h(t)) \right\| + \sum_{j=0}^{k-1} \left\| \frac{d^j}{dt^j} (t^{-q} e_h(t)) \right\| \right\}; \quad (4.29) \]

using once more Hypothesis (4.18) and Taylor's formula, we have for \( 0 \leq m \leq q \) and, in particular for \( m = q - 1, m = q \):
\[ \frac{1}{t^m} e_h(t) = \frac{1}{(m - 1)!} \int_0^1 (1 - s)^{m-1} e_h^{(m)}(st) \, ds, \]
by replacing this expression in (4.29), we obtain the desired estimate (4.24).

We now can define the parametrizations of the two above announced branches of solutions for the equations \( F(x) = 0 \) and \( F_h(x) = 0 \). We set:
\[ x(.) : (-t_0, t_0) \to X; \quad x(t) = x_0 + t \sigma(t) + v(t \sigma(t)); \quad (4.30) \]
\[ x_h(.) : (-t_0, t_0) \to X; \quad x_h(t) = x_0 + t \sigma_h(t) + v_h(t \sigma_h(t)), \quad (4.31) \]
where the mappings $u(\cdot), v_h(\cdot), \sigma(\cdot)$ and $\sigma_h(\cdot)$ are defined by Theorems 4.1 and 4.2.

**THEOREM 4.3:** We assume that Hypotheses a) to i) are satisfied; let $x(\cdot)$ and $x_h(\cdot)$ be given by (4.30) and (4.31). Then there exist positive constants $h_0$ and $L$ such that

i) $x(\cdot)$ and $x_h(\cdot)$ are $C^{p-q}$ mappings with uniformly bounded derivatives (with respect to $|t| < t_0$ and $h < h_0)$ of order $0, 1, \ldots, p - q \geq 2$;

ii) $F(x(t)) = 0, \ F_h(x_h(t)) = 0, \ |t| < t_0, \ h < h_0; \ x(0) = x_0; \ x'(0) = \sigma_0$;

$$
(4.32)
$$

iii) $\lim_{h \to 0} \sup_{|t| < t_0} \| x^{(k)}(t) - x_h^{(k)}(t) \| = 0, \ 0 \leq k \leq p - 2q + 1;

$$
(4.33)
$$

iv) for $0 \leq k \leq p - 2q + 1$ and $h < h_0$, we have the error estimate

$$
\sup_{|t| < t_0} \| x^{(k)}(t) - x_h^{(k)}(t) \| \leq L \sum_{j=0}^{k+q-1} \sup_{|t| < t_0} \left\| \frac{d^j}{dt^j} F_h(x(t)) \right\| .
$$

(4.34)

**Proof:** Clearly, by Theorems 4.1 and 4.2, we have to verify only (4.34). In the following, $c$ will denote a generic constant independent of $h$. By using the boundedness of the derivatives of $v_h$ of order $\leq p$ (Theorem 4.1), we can write for $0 \leq k \leq p - 2q + 1$:

$$
\| x^{(k)}(t) - x_h^{(k)}(t) \| \leq \left\{ \left\| \frac{d^k}{dt^k} (t\sigma(t) - t\sigma_h(t)) \right\| + \left\| \frac{d^k}{dt^k} (v(t\sigma(t)) - v_h(t\sigma(t))) \right\| + \left\| \frac{d^k}{dt^k} (v_h(t\sigma(t)) - v_h(t\sigma_h(t))) \right\| \right\} \leq c \left\{ \left\| \frac{d^k}{dt^k} (t\sigma(t) - t\sigma_h(t)) \right\| + \left\| \frac{d^k}{dt^k} (v(t\sigma(t)) - v_h(t\sigma(t))) \right\| \right\} .
$$

(4.35)

As for the proof of Theorem 4.1, we now apply Theorem 2.2 to $G : X_1 \times X_2 \to Y_2, \ G(\sigma, v) = QF_h(x_0 + \sigma + v)$; with $\tilde{g}(t) = v_h(t\sigma(t))$ and $\tilde{s}(t) = v(t\sigma(t))$, we obtain, for $0 \leq j \leq p - q$ and $|t| < t_0$, the estimate

$$
\left\| \frac{d^j}{dt^j} (v(t\sigma(t)) - v_h(t\sigma(t))) \right\| \leq c \sum_{l=0}^{l} \left\| \frac{d^l}{dt^l} QF_h(x(t)) \right\| \leq c \sum_{l=0}^{l} \left\| \frac{d^l}{dt^l} F_h(x(t)) \right\| .
$$

(4.36)

RAIRO Analyse numérique/Numerical Analysis
By (4.24), the definition (4.12) of $f_h$ and (4.5), we have:

\[ \left\| \frac{d^k}{dt^k}(t\sigma(t) - t\sigma_h(t)) \right\| \leq c \sum_{j=0}^{k+q-1} \sup_{|\tau| < t_0} \left\| \frac{d^j}{d\tau^j} F_h(x_0 + \tau\sigma(\tau) + v_h(\tau\sigma(\tau))) \right\| \leq \]

\[ \leq c \sum_{j=0}^{k+q-1} \left\{ \sup_{|\tau| < t_0} \left\| \frac{d^j}{d\tau^j} F_h(x(\tau)) \right\| + \sup_{|\tau| < t_0} \left\| \frac{d^j}{d\tau^j} (v(\tau\sigma(\tau)) - v_h(\tau\sigma(\tau))) \right\| \right\} : \]

\[ (4.37) \]

(4.34) is then a direct consequence of (4.35), (4.36) and (4.37).

Remark 4.3: If $\sigma_0 \neq 0$ satisfies condition (4.16), we shall say that $\sigma_0$ is a characteristic ray; if $\sigma_0$ satisfies conditions (4.16) and (4.17), we shall say that $\sigma_0$ is a non-degenerate characteristic ray. Let $\Sigma \subset X_1$ be the set of characteristic rays with norm 1; by using a compactness argument bounded to the fact that $X_1$ is finite dimensional, it is easy to establish the following result: if all characteristic rays are non-degenerate, then $\Sigma$ is a finite set.

Remark 4.4: Let us denote by $P_1$ and $P_2$ the projectors associated with the decomposition $X = X_1 \oplus X_2$; let

\[ \Gamma = \{ x(t) | |t| < t_0 \} , \quad \Gamma_h = \{ x_h(t) | |t| < t_0 \} \]

be the branches of solutions given by Theorem 4.3; for the constant $\beta$ introduced in Theorem 4.2, we consider the cone

\[ C = \{ \sigma \in X_1 | \| \langle \sigma_0, \psi_0 \rangle \sigma - \langle \sigma, \psi_0 \rangle \sigma_0 \| < \beta | \langle \sigma, \psi_0 \rangle | \} ; \]

by the uniqueness of the maps $\sigma(.)$ and $\sigma_h(.)$ in Theorem 4.2, it is fairly easy to establish the existence of positive constants $\gamma$ and $h_0$ such that

\[ \{ x \in X | F(x) = 0 , \quad \| x - x_0 \| < \gamma , \quad P_1(x - x_0) \in C \} \subset \Gamma , \]
\[ \{ x \in X | F_h(x) = 0 , \quad \| x - x_0 \| < \gamma , \quad P_1(x - x_0) \in C \} \subset \Gamma_h , \quad h < h_0 . \]

Furthermore, let $\Sigma$ be the set of characteristic rays with norm 1 and suppose that all characteristic rays are non-degenerate; by Remark 4.3, $\Sigma$ is a finite set with elements $\xi_1, \xi_2, \ldots, \xi_m$, say; by Theorem 4.3, to each $\xi_i$ corresponds a branch of solutions $\Gamma_i$ of the equation $F(x) = 0$ and a branch $\Gamma_{ih}$ of the equation $F_h(x) = 0$, for $h$ small enough; note that for each $i$ corresponds $j$ such that $\xi_i = - \xi_j$, so that $\Gamma_i = \Gamma_j$ and $\Gamma_{ih} = \Gamma_{jh}$; it is then possible to show by ele-
mentary means the existence of positive constants $\gamma$ and $h_0$ such that

$$\{ x \in X | F(x) = 0, \| x - x_0 \| < \gamma \} \subset \bigcup_{i=1}^{n} \Gamma_i,$$

$$\{ x \in X | F_h(x) = 0, \| x - x_0 \| < \gamma \} \subset \bigcup_{i=1}^{n} \Gamma_{ih}, \quad h < h_0$$

We shall conclude this section by discussing the particular case of simple bifurcation points, i.e., essentially the case $n = 1, q = 2$. Note that our analysis will include implicitly the treatment of the «double limit bifurcation point» [5].

Specifically, we shall suppose, from now on, that

$$j) \quad n = \text{codimension Range } F'(x_0) = 1, p \geq 4,$$  (4.38)

with $q = 2$, then Hypothesis (4.15) is void, furthermore, by Remark 4.1, $f^{"}(0) (\xi, \eta) = (I - Q) F^{"}(x_0) (\xi, \eta)$ for all $\xi, \eta \in X_1$, so that (4.16) and (4.17) are equivalent, in this case, to the existence of $\sigma_0 \in X_1$ such that

$$k) \quad (I - Q) F^{"}(x_0) (\sigma_0, \sigma_0) = 0,$$  (4.39)

$$l) \quad \text{the relations } \sigma \in X_1, (I - Q) F^{"}(x_0) (\sigma_0, \sigma) = 0 \text{ imply the existence of } \tau \in \mathbb{R} \text{ with } \sigma = \tau \sigma_0$$  (4.40)

$X_1 = \text{Ker } F'(x_0)$ has dimension 2 and $Y_1$ has dimension 1, let $e_1, e_2$ be a basis of $X_1$ and let $g \neq 0$ be an element of $Y_1$, for any $\sigma = e_1 e_1 + e_2 e_2 \in X_1$, $e_1$ and $e_2 \in \mathbb{R}$, we can write

$$f^{"}(0) (\sigma, \sigma) = (I - Q) F^{"}(x_0) (\sigma, \sigma) = R(e_1, e_2) g,$$  (4.41)

where $R : \mathbb{R}^2 \to \mathbb{R}$ is a quadratic form, as easily verified, (4.39) together with (4.40) are equivalent to the property that $R$ is indefinite and non-degenerate, i.e., that the determinant of the matrix associated with $R$ is negative, consequently, (4.39) and (4.40) imply the existence of a non-degenerate characteristic ray $\sigma_1$ linearly independent of $\sigma_0$ such that any characteristic ray is parallel to $\sigma_0$ or to $\sigma_1$.

In connection with Remark 4.2, we state the following result

**Theorem 4.4** Let Hypotheses a) to e) and j) to l) be satisfied, we suppose the existence of two $C^1$ mappings $x(.)$ and $x_h(.)$ ($-t_0, t_0) \subset \mathbb{R} \to X_1, t_0 > 0$, such that $F(x(t)) = F_h(x_h(t)) = 0$ for $|t| < t_0, x(0) = x_0, x'(0) = \sigma_0$,

$$\lim_{h \to 0} \sup_{|t| < t_0} \| x^{(k)}(t) - x_h^{(k)}(t) \| = 0 \quad \text{for} \quad k = 0, 1$$
Then there exist positive constants $h_0$ and $\theta$ and, for $h < h_0$, an unique point $\eta_h \in X_1$ such that

$$\| \eta_h \| < \theta, \quad f_h(\eta_h) = 0, \quad f_h'(\eta_h) = 0 \quad \text{for} \quad h < h_0 \quad \text{and} \quad \lim_{h \to 0} \eta_h = 0,$$

(4.42)

Furthermore, there exists a constant $c$ such that

$$\| \eta_h \| < c \| f_h'(0) \|$$

(4.43)

**Proof** Recalling the definitions (4.11) and (4.12) of $f$ and $f_h$, we set $\omega = f'$ and $\omega_h = f'_h \colon B(0, \zeta) \to \mathcal{L}(X_1, Y_1)$, the non-degeneracy of the quadratic form $R$ in (4.41) implies that $\omega'(0) \in \mathcal{L}(X_1, \mathcal{L}(X_1, Y_1))$ is an isomorphism, by using (4.25), which is valid under the sole Hypotheses $a)$ to $e)$, (4.13) and Theorems 2.1, 2.2, we obtain for $h$ small enough and in some neighborhood of $0$ the existence of an unique $\eta_h \in X_1$ satisfying the relation $\omega(\eta_h) = f'(\eta_h) = 0$ and the estimate (4.43). It remains to show that $f_h'(\eta_h) = 0$, to this end, we decompose $x(t)$ in the form $x(t) = x_0 + \theta(t) + w(t)$ where $\theta(t) \in X_1$, $w(t) \in X_2$, since $F'(x_0) x'(0) = 0$, we have $w'(0) = 0$ and $\theta'(0) = \sigma_0$, in the same way we write $x_h(t) = x_0 + \theta_h(t) + w_h(t)$, $\theta_h(t) \in X_1$, $w_h(t) \in X_2$ and we set $\omega_h(t) = f'_h(\theta_h(t)) \xi$ where $\xi \in X_1$ is a fixed element linearly independent of $\sigma_0$, by (4.13), (4.25) and (4.40) we have $\lim_{h \to 0} \omega_h(0) = 0$,

$$\lim_{h \to 0} \omega_h'(0) = f''(0) (\xi, \sigma_0) \neq 0,$$

since $\omega'_h$ and $\omega^*_h$ are bounded in a neighborhood of $0$, uniformly with respect to $h$, there exists, for $h$ small enough, $t_h$ such that $\omega_h(t_h) = 0$ with $\lim_{h \to 0} t_h = 0$,

clearly $f'_h(\theta_h(t)) = 0$ which implies that $f'_h(\theta_h(t)) \theta'_h(t) = 0$ and $f'_h(\theta_h(t)) = 0$,

since $\lim_{h \to 0} \theta'_h(t) = \sigma_0$, it follows that $f'_h(\theta_h(t)) = 0$ for $h$ small enough, by the uniqueness of $\eta_h$ we have $\eta_h = \theta_h(t_h)$ for $h$ small enough.

**Remark 4.5** In Theorem 4.4, the existence of the map $x(.)$ is clearly insured by Theorem 4.3, the existence of the map $x_h$ can be obtained, in « practical » situations, in two cases a) when $x(.)$ parametrizes a « trivial branch » and then $x_h(t) = x(t)$, b) in presence of symmetries (for more details see [3], [8]).

**Theorem 4.5** Let Hypotheses $a)$ to $e)$ and $j)$ to $l)$ be satisfied and let $f_h$ be defined by (4.12), we suppose the existence, for $h$ small enough, of $\eta_h \in X_1$ such that $f_h(\eta_h) = 0$, $f_h'(\eta_h) = 0$ and $\lim_{h \to 0} \eta_h = 0$ Then, for some $t_0 > 0$ and $h_0 > 0$ we have

vol 16, n° 4, 1982
(4.44) \[ F(x_i(t)) = 0, \quad |t| < t_0, \quad x_i(0) = x_{i0}, \quad x'_i(0) \neq 0, \quad i = 0, 1, \quad x'_0(0) \neq x'_1(0); \]

\[ \lim_{h \to 0} \sup_{|t| < t_0} \left\| x^{(k)}_i(t) - x^{(k)}_{ih}(t) \right\| = 0, \quad 0 \leq k \leq p - 3, \quad i = 0, 1; \]

(4.46) \[ \lim_{h \to 0} \sup_{|t| < t_0} \left\| F_{ih}(x(t)) \left| t_0 \right| \right\| = 0, \quad h < h_0; \]

\[ \sup_{|t| < t_0} \left\| x^{(k)}_i(t) - x^{(k)}_{ih}(t) \right\| \leq c \left\{ \left\| \eta_h \right\| + \sum_{j=0}^{k+1} \sup_{|t| < t_0} \left\| \frac{d^j}{dt^j} F_h(x(t)) \right\| \right\}, \quad h < h_0. \]
clearly (4.45) is then satisfied By (4.10),
\[ \| v_h(\eta_h) - v(\eta_h) \| \leq c \| F_h(x_0 + \eta_h + v(\eta_h)) \| , \]
since \( v(0) = 0 \) (4.13), with Hypothesis (4.5), we obtain the estimate
\[ \| v_h(\eta_h) \| \leq c \{ \| \eta_h \| + \| F_h(x_0) \| \} \]
and consequently \( \| z_h \| \leq c \{ \| \eta_h \| + \| F_h(x_0) \| \} \), in particular, by Hypothesis (4.4), we have \( \lim_{h \to 0} z_h = 0 \), then (4.46) and (4.48) follow immediately from (4.49) and (4.50). It remains to prove (4.47), clearly the hypotheses of Theorem 4.4 are satisfied and by (4.43), it suffices to estimate \( \| f_h'(0) \| \), since \( \sigma_0 \) and \( \sigma_1 \) form a fixed basis of \( X_1 \), the proof of Theorem 4.5 will be achieved, if we show, for \( h \) small enough, the estimate
\[ \| f_h'(0) \| \leq c \sum_{j=0}^{1} \left\| \frac{d}{dt} F_h(x_i(t)) \bigg|_{t=0} \right\| , \quad i = 0, 1 , \quad (4.52) \]
we prove (4.52) for \( i = 0 \), by (4.30) and (4.32), \( x_0(t) \) is of the form
\[ x_0(t) \equiv x(t) = x_0 + t\sigma(t) + v(t\sigma(t)) , \]
with \( \sigma(0) = \sigma_0 \), by definition (4.12) of \( f_h \) we have
\[ \| f_h'(0) \sigma_0 \| = \left\| \frac{d}{dt} f_h(t\sigma(t)) \bigg|_{t=0} \right\| \leq c \left\| \frac{d}{dt} F_h(x_0 + t\sigma(t) + v_h(t\sigma(t))) \bigg|_{t=0} \right\| , \quad (4.53) \]
by using the estimate (4.36) (which is valid without Hypothesis i)), we easily deduce (4.52) from (4.53) \( \blacksquare \)

5. AN EXAMPLE

Let \( \Omega = (0, 1) \times (0, 1) \) be the unit square in \( \mathbb{R}^2 \). \( H^1_0 = H^1_0(\Omega) \) will denote the set of square integrable functions on \( \Omega \), vanishing on \( \partial \Omega \) and possessing square integrable first partial derivatives.

We consider the classical nonlinear eigenvalue problem of finding \( (\lambda, u) \in \mathbb{R} \times H^1_0 \) such that
\[ -\Delta u - \lambda u + u^3 = 0 \text{ in } \Omega \quad (5.1) \]
Let us introduce the symmetric bilinear forms $a$ and $b$ by

$$a : H^1_0 \times H^1_0 \to \mathbb{R}, \quad a(u, v) = \int_{\Omega} (\partial_x u \partial_x v + \partial_y u \partial_y v), \quad (5.2)$$

$$b : L^2 \times L^2 \to \mathbb{R}, \quad b(u, v) = \int_{\Omega} u.v, \quad (5.3)$$

clearly (5.1) is equivalent to the problem of finding $(\lambda, u) \in \mathbb{R} \times H^1_0$ such that

$$a(u, v) - \lambda b(u, v) + b(u^3, v) = 0 \quad \forall u \in H^1_0 \quad (5.4)$$

For $n$, positive integer, we divide the closure $\overline{\Omega}$ of $\Omega$ in $n^2$ closed equal squares of side $h = 1/n$, let $\mathcal{S}_h$ be the set of these squares and

$$V_h = \{ f \in H^1_0, \ f|_{K} \in Q_1, \ \forall K \in \mathcal{S}_h \}, \quad (5.5)$$

where $Q_1$ is the set of polynomials of the form $axy + bx + cv + d$. We introduce the $a$-projector $\Pi_h$, the interpolatory projector $P_h$ and the symmetric bilinear form $b_h$ defined by

$$\Pi_h : H^1_0 \to V_h, \quad a(\Pi_h u - u, v) = 0 \quad \forall v \in V_h, \ u \in H^1_0, \quad (5.6)$$

$$P_h : C^0_0 \to V_h, \ (P_h u)(ih, jh) = u(ih, jh), \ 1 \leq i, j \leq n - 1, \ u \in C^0_0, \quad (5.7)$$

$$b_h : C^0_0 \times C^0_0 \to \mathbb{R}, \quad b_h(u, v) = \int_{\Omega} P_h(u, v), \quad (5.8)$$

here, $C^0_0 = C^0_0(\overline{\Omega})$ denotes the set of continuous functions on $\overline{\Omega}$, vanishing on $\partial \Omega$. As an approximation of (5.1) or (5.4), we consider the problem of finding $(\lambda, u) \in \mathbb{R} \times V_h$ such that

$$a(u, v) - \lambda b_h(u, v) + b_h(u^3, v) = 0 \quad \forall v \in V_h \quad (5.9)$$

Note that, if $f \in C^0_0$, we have

$$\int_{\Omega} P_h f = h^2 \sum_{i,j=1}^{n-1} f(ih, jh), \quad (5.10)$$

so that (5.9) is equivalent to an explicit system of $(n - 1)^2$ nonlinear equations for the $(n - 1)^2 + 1$ unknowns $\lambda, u(ih, jh), 1 \leq i, j \leq n - 1$. 

R A I R O Analyse numerique/Numerical Analysis
In the following, we shall be concerned with the approximation of solutions of Problem (5.1) in the neighborhood of \((\lambda_0, u_0) = (5\Pi^2, 0) \in \mathbb{R} \times H_0^1\); let \(Y_1 \subset H_0^1\) be the two-dimensional subspace spanned by

\[
\varphi_1(x, y) = \frac{2}{\sqrt{\lambda_0}} \sin \pi x \sin y, \quad \varphi_2(x, y) = \frac{2}{\sqrt{\lambda_0}} \sin 2\pi x \sin y : \quad (5.11)
\]

as easily verified, we have \(a(\varphi_i, \varphi_j) = \delta_{ij}, 1 \leq i, j \leq 2\); furthermore \(\lambda_0 = 5\Pi^2\) is a double eigenvalue of the problem of finding \((\lambda, u) \in \mathbb{R} \times H_0^1\) such that \(-\Delta u = \lambda u; Y_1\) is the corresponding eigenspace. Concerning the approximate problem of finding \((\lambda, u) \in \mathbb{R} \times V_h\) such that

\[
a(u, v) = \lambda b_h(u, v) \quad \forall v \in V_h, \quad (5.12)
\]

we have the following result:

**Theorem 5.1:** There exists \(\varepsilon > 0\) and, for \(h\) small enough, there exists an unique eigenvalue \(\lambda_h \in (\lambda_0 - \varepsilon, \lambda_0 + \varepsilon)\) of Problem (5.12); \(\lambda_h\) is a double eigenvalue with error estimate: \(|\lambda_0 - \lambda_h| = O(h^2)\).

For convenience, we shall first present all the results, and delay a sketch of their proofs to the end of the section.

We define by Lax-Milgram Theorem the operators \(T\) and \(T_h\) as

\[
T : L^2 \to H_0^1, \quad a(Tu, v) = b(u, v) \quad \forall v \in H_0^1, \quad \forall u \in L^2, \quad (5.13)
\]

\[
T_h : C_0^0 \to V_h, \quad a(T_h u, v) = b_h(u, v) \quad \forall v \in V_h, \quad \forall u \in C_0^0; \quad (5.14)
\]

then (5.4) is equivalent to the equation

\[
u + T(-\lambda u + u^3) = 0, \quad (\lambda, u) \in \mathbb{R} \times H_0^1,
\]

whereas (5.9) is equivalent to the equation \(u + T_h(-\lambda u + u^3) = 0, \quad (\lambda, u) \in \mathbb{R} \times V_h\); since the range of \(T_h\) is \(V_h\), (5.9) is also equivalent to the problem of finding \((\lambda, u) \in \mathbb{R} \times H_0^1\) such that

\[
u + T_h(-\lambda \Pi_h u + (\Pi_h u)^3) = 0;
\]

in this last expression, note that it is not possible to suppress the introduction of the projector \(\Pi_h\) defined in (5.6); indeed \(T_h\) is defined in \(C_0^0\) and \(H_0^1\) is not imbedded in \(C_0^0\).

In order to use the results of Section 4, we set \(X = \mathbb{R} \times H_0^1\) and \(Y = H_0^1\).
Following Sattinger [14], we introduce, for $\zeta = \pm 1$, the functions

$$F : X \to Y, \quad F(x) = u + T(- (\lambda_0 + \zeta s^2) u + u^3),$$

$$x = (s, u), \quad (5 \ 15)$$

$$F_h : X \to Y, \quad F_h(x) = u + T_h(- (\lambda_h + \zeta s^2) \Pi_h u + (\Pi_h u)^3),$$

$$x = (s, u), \quad (5 \ 16)$$

clearly, by the change of variable $\lambda = \lambda_0 + \zeta s^2$, solving (5 1) is equivalent to solve the equation $F(x) = 0$ for $\zeta = 1$ and $\zeta = -1$, in the same way, by the change of variable $\lambda = \lambda_h + \zeta s^2$, solving (5 9) is equivalent to solve the equation $F_h(x) = 0$ for $\zeta = 1$ and $\zeta = -1$, since, by Theorem 5 1,

$$\lambda - \lambda_h = 0(h^2),$$

it is reasonable to compare, separately for $\zeta = 1$ and $\zeta = -1$, the solutions of $F(x) = 0$ with the solutions of $F_h(x) = 0$ in the neighborhood of $x_0 = 0$

**Theorem 5 2** $F$ and $F_h$ are $C^\infty$ mappings from $X$ into $Y$. For any $k \geq 0$ and any bounded subset $B \subset X$, we have

$$\lim_{h \to 0} \sup_{x \in B} \| D^k F(x) - D^k F_h(x) \| = 0 \quad (5 \ 17)$$

We consider $Y = H^1_0$ as a Hilbert space equipped with the scalar product $a(\cdot, \cdot)$.

Let $Y_2$ be the orthogonal complement of $Y_1$ in $Y$ where $Y_1$ is defined in (5 11).

Let $\Phi_0 = (1, 0), \Phi_1 = (0, \phi_1), \Phi_2 = (0, \omega_2) \in \mathbb{R} \times H^1_0 = X$ and let $X_1 \subset X$ be the three-dimensional subspace spanned by $\Phi_0, \Phi_1, \Phi_2$. Setting

$$X_2 = \{0\} \times Y_2 \subset X,$$

we see that $X = X_1 \oplus X_2$. Finally let $Q : Y \to Y$ be the orthogonal projector from $Y$ onto $Y_2$. By (5 15) we have

$$F'(0)(s_1, u_1) = u_1 - \lambda_0 T u_1, \quad \forall (s_1, u_1) \in X,$$

since $T$, defined by (5 13), is selfadjoint in $H^1_0$ with respect to $a(\cdot, \cdot)$, we immediately obtain

$$X_1 = \ker F'(0), \quad Y_2 = \operatorname{Range} F'(0) \quad (5 \ 19)$$

Clearly, for $x_0 = 0$, $F$ satisfies Hypotheses (4 1) and (4 2) of Section 4 with $n = 2$, furthermore Theorem 5 2 insures that $F$ and $F_h$ verify Hypo-
theses (4.4), (4.5) and (4.6). Consequently, we can apply Theorem 4.1 and define maps \( v(.) \) and \( v_h(.) \) satisfying (4.7) and (4.8); we deduce the bifurcation functions \( f \) and \( f_h \) defined by (4.11) and (4.12).

**Theorem 5.3**: a) \( f^{(k)}(0) = 0, f_h^{(k)}(0) = 0, k = 0, 1, 2, h \) small enough; (5.20)

b) for \( \sigma = s\Phi_0 + \eta_1 \Phi_1 + \eta_2 \Phi_2 \in X_1 \), we have

\[
f'''(0) \sigma^3 = (A\zeta s^2 \eta_1 + B\eta_1^3 + C\eta_1 \eta_2^2) \phi_1 + \]
\[
+ (A\zeta s^2 \eta_2 + B\eta_2^3 + C\eta_1^2 \eta_2) \phi_2 \, ,
\]  
where

\[
A = -\frac{6}{\lambda_0} , \quad \beta = \frac{27}{2\lambda_0^2} , \quad C = \frac{18}{\lambda_0^2} .
\]

We remark that (5.20) implies that Hypotheses (4.15) and (4.18) are satisfied with \( q = 3 \). By using (5.21), it is now easy to solve the equation \( f'''(0) \sigma^3 = 0 \) and to determine a maximal set of linearly independent characteristic rays (see Remark 4.3); using the notation \( \sigma = (r_0, r_1, r_2) \) for

\[
\sigma = r_0 \Phi_0 + r_1 \Phi_1 + r_2 \Phi_2 ,
\]
we obtain:

\[
\zeta = -1 : \sigma_{00} = (1, 0, 0) ; \]
\[
\zeta = 1 : \sigma_{00} = (1, 0, 0) , \quad \sigma_{01} = (1, \alpha, 0) , \quad \sigma_{01} = (1, -\alpha, 0) , \]
\[
\sigma_{02} = (1, 0, \alpha) , \quad \sigma_{02} = (1, 0, -\alpha) , \quad \sigma_{03} = (1, \beta, \beta) , \]
\[
\sigma_{03} = (1, -\beta, -\beta) , \quad \sigma_{04} = (1, \beta, \beta) , \quad \sigma_{04} = (1, -\beta, -\beta) ,
\]  
where

\[
\alpha = \frac{2}{3}\sqrt{\lambda_0} , \quad \beta = \sqrt{\frac{4\lambda_0}{21}} ;
\]

it is also easy to check that all the rays given in (5.22) and (5.23) are not degenerated, i.e. they satisfy Hypothesis (4.17).

**Theorem 5.4**: Let \( \sigma_0 \in X_1 \) be one of the characteristic rays given in (5.22) and (5.23). Then there exist positive constants \( s_0, h_0 \) and the \( C^\infty \) mappings \( u(.) , u_h(.) : (-s_0, s_0) \to H^1_0 \) such that by setting

\[
x(s) = (s, u(s)) , \quad x_h(s) = (s, u_h(s)) \in X ,
\]

vol. 16, n° 4, 1982
we have

\[ a) \quad F(x(s)) = 0, \quad F_h(x_h(s)) = 0, \quad |s| < s_0, \quad h < h_0, \quad x(0) = x_h(0) = 0, \quad x'(0) = \sigma_0, \quad (5.24) \]

\[ b) \quad \text{for any } k = 0, 1, 2, \ldots, u^{(k)}(.) \text{ and } u_h^{(k)}(.) \text{ are uniformly bounded with respect to } s \text{ and } h, \]

\[ c) \quad \text{for any } k = 0, 1, 2, \ldots, \text{ we have} \]

\[ \sup_{|s| < s_0} \| u^{(k)}(s) - u_h^{(k)}(s) \|_{H^1(\Omega)} = O(h) \quad (5.25) \]

Consider \( u(s) \) and \( u_h(s) \) defined by Theorem 5.4 and set \( \lambda(s) = \lambda_0 + \zeta s^2, \lambda_h(s) = \lambda_h + \zeta s^2 \) where \( \lambda_h \) is given by Theorem 5.1, clearly, by definitions (5.15), (5.16) of \( F \) and \( F_h \), \( (\lambda(s), u(s)) \) and \( (\lambda_h(s), u_h(s)) \in \mathbb{R} \times H_0^1 \) will be respectively solutions of our original problems (5.1) and (5.9) If \( \sigma_0 = \sigma_{00} \) with \( \zeta = -1 \), we obtain the branch \( \{ (\lambda, 0) | \lambda \leq \lambda_0 \} \) and the approximate branch \( \{ (\lambda, 0) | \lambda \leq \lambda_h \} \), if \( \sigma_0 = \sigma_{00} \) with \( \zeta = 1 \), we obtain respectively the branches \( \{ (\lambda, 0) | \lambda \geq \lambda_0 \} \) and \( \{ (\lambda, 0) | \lambda \geq \lambda_h \} \), together, this gives the trivial branch, solution of both the exact and approximate problems Suppose now that \( u(s) \) and \( u_h(s) \) correspond to \( \sigma_{01} \) and let \( \bar{u}(s) \) and \( \bar{u}_h(s) \) correspond to \( \sigma_{01} \), from the relations

\[ f(s\Phi_0 + \eta_1 \Phi_1 \Phi_2) = f(-s\Phi_0 + \eta_1 \Phi_1 \Phi_2), \quad f_h(s\Phi_0 + \eta_1 \Phi_1 \Phi_2) = f_h(-s\Phi_0 + \eta_1 \Phi_1 \Phi_2) \text{ for all } s, \eta_1, \eta_2 \in \mathbb{R}, \]

we deduce that, for \( s \) small enough, \( u(s) = \bar{u}(-s) \) and \( u_h(s) = \bar{u}_h(-s) \), consequently the branches parametrized by \( (\lambda_0 + s^2, u(s)), (\lambda_h + s^2, u_h(s)) \), \( |s| < s_0 \), are respectively identical to the branches parametrized by

\[ (\lambda_0 + s^2, \bar{u}(s)), (\lambda_h + s^2, \bar{u}_h(s)), \quad |s| < s_0 \]

The same argument works for the pairs \( \sigma_{0i}, \tilde{\sigma}_{0i}, i = 2, 3, 4 \) so that each of the original exact and approximate problems possess in fact four non-trivial branches in the neighborhood of \( (\lambda_0, 0) \), it is easy to verify that these four branches are different and supercritical, that the problems possess no further solution is a consequence of Remark 4.4 By Theorem 5.4, we then deduce our final result

**Theorem 5.5** In a neighborhood of \( (\lambda_0, 0) \in \mathbb{R} \times H_0^1 \), the exact problem (5.1) and the approximate problem (5.9) possess each four non-trivial branches which can be parametrized respectively in the form \( (\lambda_0 + s^2, u_i(s)) \),

R A I R O Analyse numerique/Numerical Analysis
\[(\lambda_h + s^2, u_{ih}(s)), |s| < s_0, i = 1, 2, 3, 4,\] where \(u_i\) and \(i_{ih} : (-s_0, s_0) \rightarrow H^1_0\) are \(C^\infty\) mappings such that

\[\sup_{|s| < s_0} \left\| u_{ih}^{(k)}(s) - u_{ih}^{(k)}(s) \right\|_{H^1(\Omega)} = O(h), \quad i = 1, 2, 3, 4, \quad k = 0, 1, 2, \ldots\]

As announced, we shall only sketch the proofs of Theorems 5.1 to 5.5 which essentially rely on the results of Section 4. To this end, we need some preliminary lemmas.

We first introduce some further notations. For \(u \in H^1 = H^1(\Omega),\)

\[\|u\| = \left(\int_{\Omega} u^2 + (\partial_x u)^2 + (\partial_y u)^2\right)^{1/2}, \quad |u| = \left(\int_{\Omega} (\partial_x u)^2 + (\partial_y u)^2\right)^{1/2} .\]

For \(u \in L^p = L^p(\Omega)\) and \(1 \leq p < \infty,

\[\|u\|_p = \left(\int_{\Omega} |u|^p\right)^{1/p} .\]

As before \(Q_1\) is the set of polynomials of the form \(axy + bx + cy + d.\) \(P : C^0(\Omega) \rightarrow Q_1\) is the interpolatory operator at the four vertices of \(\Omega.\) Furthermore, \(c\) will denote a generic constant.

**Lemma 5.1**: Let \(u_i \in Q_1, 1 \leq i \leq 4;\) then

\[a) \left| \int_{\Omega} P\left(\prod_{i=1}^4 u_i\right) \right| \leq c \prod_{i=1}^4 \|u_i\|_{p_i}, \quad \text{where} \quad \sum_{i=1}^4 \frac{1}{p_i} = 1 \quad (c \text{ depends on } p_i); \quad (5.26)\]

\[b) \left| \int_{\Omega} \prod_{i=1}^4 u_i - \int_{\Omega} P\left(\prod_{i=1}^4 u_i\right) \right| \leq c \prod_{i=1}^4 \left| u_i \right| \prod_{i \neq j} \|u_i\|_{p_i}; \quad (5.27)\]

\[c) \left| \int_{\Omega} u_1 u_2 - \int_{\Omega} P(u_1 u_2) \right| \leq c \left| u_1 \right| \left| u_2 \right|. \quad (5.28)\]

**Proof**: (5.26) is a consequence of the equivalence of the norms in finite dimensional spaces and of Hölder’s inequality. Let \(\mu_i\) be the mean value of \(u_i, i.e. \mu_i = \int_{\Omega} u_i; \) we have \(\|u_i - \mu_i\|_2 \leq c \left| u_i \right| (\text{see for example Ciarlet [4], page 115});\) then we deduce (5.27) from (5.26) and from the relations

\[\int_{\Omega} \prod_{i=1}^4 u_i - \int_{\Omega} P\left(\prod_{i=1}^4 u_i\right) = \int (u_1 - \mu_1) u_2 u_3 u_4 + \int \mu_1 (u_2 - \mu_2) u_3 u_4 +\]

\[+ \cdots + \int \mu_1 \mu_2 \mu_3 (u_4 - \mu_4) - \int P((u_1 - \mu_1) u_2 u_3 u_4)\]
\[ - \cdots - \int P(\mu_1, \mu_2, \mu_3(u_4 - \mu_4)) + \left( \int \mu_1 \mu_2 \mu_3 \mu_4 - \int P(\mu_1, \mu_2, \mu_3, \mu_4) \right), \]

since the last parenthesis vanishes. In the same way, (5.28) follows from the identity
\[
\int u_1 u_2 - \int P(u_1 u_2) = \int (u_1 - \mu_1) (u_2 - \mu_2) - \int P((u_1 - \mu_1)(u_2 - \mu_2)) + \left( \int \mu_1 (u_2 - \mu_2) - \int P(\mu_1(u_2 - \mu_2)) \right) + \left( \int \mu_2 u_1 - \int P(\mu_2 u_1) \right),
\]

since the two last parentheses vanish.

By the standard argument of the « reference element » (see Ciarlet [4]) and the continuous injection of \( H^1 \) in \( L^p (1 \leq p < \infty) \), we deduce easily from Lemma 5.1:

**Lemma 5.2**: Let \( u_1, u_2, u_3, v \in V_h \); then
\[ a) \quad |b_h(u_1, u_2, u_3, v)| \leq c \| u_1 \| \| u_2 \| \| u_3 \| \| v \| , \]
\[ b) \quad |b(u_1, u_2, u_3, v) - b_h(u_1, u_2, u_3, v)| \leq \frac{ch^2}{n} \| u_1 \| \| u_2 \| \| u_3 \| \| v \| , \]
\[ c) \quad |b(u_1, v) - b_h(u_1, v)| \leq c h^2 \| u_1 \| \| v \| . \]

It is well-known that \( T \), defined in (5.13), maps continuously \( L^2 \) into \( H^2 = H^2(\Omega) \); by using the standard techniques of finite elements in connection with numerical integration, we obtain by (5.30) and (5.31).

**Lemma 5.3**:
\[
\| T(u_1 u_2 u_3) - T_h(u_1 u_2 u_3) \| \leq c h \| u_1 \| \| u_2 \| \| u_3 \| \quad \forall u_1, u_2, u_3 \in V_h ; \quad (5.32)
\]
\[
\| Tu - T_h u \| \leq c h \| u \| \quad \forall u \in V_h . \quad (5.33)
\]

**Proof of Theorem 5.1**: By Lemma 5.3 and classical results on spectral approximation (see for example [6], p. 140), there exist exactly two eigenvalues (repeated following their multiplicity) \( \lambda_{1h} \) and \( \lambda_{2h} \) of Problem (5.12) which converge to \( \lambda_0 \); from symmetry arguments, it is easy to show that, in fact,
\( \lambda_{1h} = \lambda_{2h} \) for \( h \) small enough and we set \( \lambda_h = \lambda_{1h} \). By [6], again, there exists an eigenfunction \( \omega_{1h} \in V_h \) corresponding to \( \lambda_h \) such that \( a(\omega_{1h}, \omega_{1h}) = 1 \) and \( \| \omega_1 - \omega_{1h} \| = 0(h) \), where \( \omega_1 \) is given in (5 11). Let \( \mu_0 = \lambda_0^{-1}, \mu_h = \lambda_h^{-1} \), we have \( \mu_0 a(\omega_1, v) = b(\omega_1, v) \) \( \forall v \in H_0^1 \) and \( \mu_h a(\omega_{1h}, v) = b_h(\omega_{1h}, v) \) \( \forall v \in V_h \) from which we deduce

\[
\mu_h - \mu_0 = b_h(\omega_{1h}, \omega_{1h}) - \mu_0 a(\omega_{1h}, \omega_{1h}) \\
= (b_h(\omega_{1h}, \omega_{1h}) - b(\omega_{1h}, \omega_{1h})) + (b(\omega_{1h} - \omega_1, \omega_{1h} - \omega_1) - \\
- \mu_0 a(\omega_{1h} - \omega_1, \omega_{1h} - \omega_1)),
\]

by (5 31), we obtain \( \mu_h - \mu_0 = 0(h^2) \) and consequently \( \lambda_h - \lambda_0 = 0(h^2) \). 

**Proof of Theorem 5 2** The fact that \( F \) is a \( C^\infty \) mapping is well-known, it is based on the continuous, in fact compact, injection of \( H_0^1 \) into \( L^p, 1 \leq p < \infty \). Since \( V_h \) is finite-dimensional, the restriction of \( F_h \) to \( V_h \), equipped with the norm \( \| \cdot \| \), is clearly a \( C^\infty \) mapping, since \( \Pi_h \) is a continuous linear operator in \( H_0^1, F_h \) is also a \( C^\infty \) mapping. Let \( J : H_0^1 \rightarrow L^6 \) denote the injection and \( J^* (L^6)^* \rightarrow H_0^1 \) be its dual operator, \( J \) and consequently \( J^* \) are compact, for any \( u \in H_0^1 \), \( \lim_{h \rightarrow 0} \Pi_h u = u \), in \( H_0^1 \) equipped with the scalar product \( a(\cdot, \cdot) \), \( \Pi_h \) is selfadjoint, by a classical result, it follows that \( (I - \Pi_h) J^* \) and consequently its dual operator \( J(I - \Pi_h) \) converge in norm to zero, i.e.

\[
\lim_{h \rightarrow 0} \| I - \Pi_h \|_{L^2(H_0^1, L^6)} = 0 \quad (5 34)
\]

Setting \( x = (s, u) \) as in (5 15), (5 16), we can write

\[
\| D^k F(s, u) - D^k F_h(s, u) \| \leq \| D^k F(s, u) - D^k F(s, \Pi_h u) \| + \\
+ \| D^k F(s, \Pi_h u) - D^k F_h(s, u) \|, \quad (5 35)
\]

with (5 35), (5 34) and Lemma 5 3, we can deduce (5 17) by elementary calculations. 

**Proof of Theorem 5 3** By (4 13), \( f(0) = 0, f'(0) = 0 \), since \( F''(0) = 0 \), we also have \( f''(0) = 0 \), by Remark 4 1, \( f'''(0) \) is equal to the restriction of \( (I - Q) F''(0) \) which allows to obtain (5 21) by elementary calculations. In the same way, we have \( F_h(0) = 0, F_h''(0) = 0 \) which imply that \( f_h''(0) = 0, f_h''(0) = 0 \), by Theorem 5 1, the kernel of \( F_h(0) \) is two-dimensional from which follows that \( f_h(0) = 0 \).

**Proof of Theorem 5 4** \( F, F_h \) and \( \sigma_0 \) satisfy Hypotheses a) to i) with \( q = 3 \) of Section 4 at \( x_0 = 0 \), we apply Theorem 4 3 and remark that the parameterization by \( t \) is determined by the choice of \( \psi_0 \in X^* \) in (4 19), (4 20), by
(5 22) and (5 23), we can choose $\psi_0$ such that $\langle \Phi_0, \psi_0 \rangle = 1$, $\langle \Phi_p, \psi_0 \rangle = 0$, $t = 1, 2$, then, for $x(t) = (s(t), u(t))$ and $x_h(t) = (s_h(t), u_h(t))$ given by Theorem 4 3, we obtain $s(t) = s_h(t) = t$. It remains to verify the estimate (5 25), by (4 34), it suffices to prove that for any $j = 0, 1, 2, \ldots$, we have
\[
\sup_{|s| < s_0} \left\| \frac{d^j}{ds^j} F_h(x(s)) \right\| = \sup_{|s| < s_0} \left\| \frac{d^j}{ds^j} (F_h(x(s)) - F(x(s))) \right\| = 0(h), \quad (5 36)
\]
since $T$ maps continuously $L^2$ into $H^2$, for any $k > 0$, $u^{(k)}(s)$ is uniformly bounded in $H^2$ with respect to $|s| < s_0$, by standard approximation results (see Ciarlet [4]), $\sup_{|s| < s_0} \| (I - \Pi_h) u^{(k)}(s) \| = 0(h)$, together with Lemma 5 3 and the arguments already used in the proof of Theorem 5 2, the estimate (5 36) follows easily.

REFERENCES


R A I R O Analyse numerique/Numerical Analysis
[11] J-C PAUMIER, Une méthode numérique pour le calcul des points de retournement
Application à un problème aux limites non-linéaire II Analyse numérique d'un
problème aux limites non-linéaire, Numer Math, 37, 1981, 445-454

[12] J RAPPAZ and G RAUGEL, Finite Dimensional Approximation of Bifurcation
Problems at a Multiple Eigenvalue, Rapport no 71, Centre de Mathématiques
appliquées, Ecole Polytechnique, Palaiseau, 1981

Nonlinear Eigenvalue Problems, MAFELAP 1981 (Ed J Whiteman), Academic
Press (to appear)

in Mathematics 762, Springer-Verlag, Berlin, 1979