AN ABSTRACT EXISTENCE THEOREM AT RESONANCE¹

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Abstract. By Schauder's fixed point theorem and alternative method (bifurcation theory) an abstract existence theorem at resonance for operational equations is proved which contains as particular cases rather different existence theorems for ordinary and partial differential equations as those of Lazer and Leach and of Landesman and Lazer.

Landesman and Lazer [8] proved, by the use of the alternative method, an existence theorem for selfadjoint elliptic Dirichlet nonlinear problems. Their theorem has since been extended, by using the alternative method or other techniques, by various authors. Detailed references may be seen in Cesari [1]-[3].

In the present paper, again in terms of the alternative method, we prove an abstract theorem, from which one can derive most of the extensions referred to above. This abstract theorem is proved here by Schauder's fixed point theorem. We restrict ourselves to the selfadjoint case here.

For extensions and variants of the abstract theorem, including non-selfadjoint cases, we refer to Cesari [4]-[6].

Let $S$ be a real separable Hilbert space with inner product $(x, y)$ and norm $\|x\| = (x, x)^{1/2}$. Let $E: \mathcal{D}(E) \to S$ be a linear operator with domain $\mathcal{D}(E) \subset S$ and finite dimensional null space $S_0 = \ker E$. Let $P: S \to S$ denote the projection operator with range $S_0$ and null space $S_1 = (I - P)S$. Furthermore we assume that $S_1$ is also the range of $E$. Then $E: \mathcal{D}(E) \cap S_1 \to S_1$ is one-one and onto, and the partial inverse $H: S_1 \to \mathcal{D}(E) \cap S$ exists as a linear operator. We assume that $H$ is a linear bounded compact operator, and that $E, P, H$ satisfy the usual axioms $(h_1) E(I - P)E = I - P; (h_2) EP = PE; (h_3) EH(I - P) = I - P$.

We have depicted here in an abstract way a situation which is rather typical for the large class of differential operators $E$ which in [1] we denote as "the selfadjoint case", while we certainly have particularized the corresponding structure. We refer to [3], [4], [5] for much more general classes of operators and corresponding structures, in particular, the nonselfadjoint case, in the alternative method.

Let $N: S \to S$ be a continuous operator in $S$ not necessarily linear. The equation
(1) \( Ex = Nx, \quad x \in S, \)

is equivalent to the system of auxiliary and bifurcation equations

(2) \( x = Px + H(I - P)Nx, \)

(3) \( P(Ex - Nx) = 0. \)

We refer to [3] for details, and we note that here, having assumed \( \mathcal{R}(P) = S_0 = \ker E, \) the bifurcation equation reduces to \( PNx = 0. \) Also, for \( x^* = Px, \)

the auxiliary equation has the form \( x = x^* + H(I - P)Nx. \) Let \( L \) denote
the norm of the linear operator \( H(I - P): S \to S, \) or \( L = \|H(I - P)\|. \) We

denote by (B) and (N0) the following two assumptions:

(B) there is a constant \( J_0 \) such that \( \|Ax\| \leq J_0 \) for all \( x \in S; \)

(N0) there is a constant \( R_0 > 0 \) such that for all \( x \in S, \ x^* \in S_0, \) with
\( \|x^*\| \geq R_0, \ Px = x^*, \ \|x - x^*\| \leq LJ_0, \) we have \( (Nx, x^*) < 0 \) (or always
\( (Nx, x^*) > 0). \)

Condition (B) is the usual situation considered in the theorems of Lazer
and Leach [9], Landesman and Lazer [8], Williams [11], and in some work of
DeFigueiredo [7] and others. Condition (N0) can be shown to be implied (cf.
[3]) by the specific hypotheses of the aforementioned theorems. Variants of
conditions (N0) are implied by the hypotheses of other analogous theorems
(cf. [3]). Condition (N0) was encountered by Kannan in his previous work (see

In [4] Cesari has considered the condition (Ne) analogous to (N0) where
\( (Nx, x^*) < -\epsilon\|x^*\| \) is required (or \( (Nx, x^*) \geq \epsilon\|x^*\| \)) for some \( \epsilon > 0. \) This
condition is equally implied by the specific hypotheses of the same aforemen-
tioned theorems. Cesari has shown in [4] that condition (Ne) implies a
stronger conclusion.

**Theorem.** Under hypotheses (B) and (N0), the equation \( Ex = Nx \) has at least
one solution \( x \in S \) with \( \|x\| \leq (R_0^2 + L^2J_0^2)^{1/2}. \)

**Proof.** Let us assume we have \( (Nx, x^*) < 0 \) in (N0). Let \( w = (w_1, \ldots, \)
\( w_m) \) be an orthonormal base for the finite dimensional space \( S_0 = \ker E = \)
\( PS. \) Then, for \( x^* \in S_0, \) we have \( x^* = \sum c_i w_i, \) or briefly \( x^* = cw, \)
where \( c = (c_1, \ldots, c_m) \in \mathbb{R}^m, \ c_i = (x^*, w_i), \ i = 1, \ldots, m, \) and
\( \|x^*\| = |c| = (\sum c_i^2)^{1/2}. \) Then system (2.3) with \( Px = x^* \) can be written in the form
\( x = cw + H(I - P)Nx, \) \( (PNx, w) = 0, \) where in the last relation \( (PNx, w) \)
simply denotes the \( m \)-vector \( [(PNx, w_i), i = 1, \ldots, m]. \) Let

\[
L = \|H(I - P)\| = \|H\|, \quad J = LJ_0,
\]

and let \( R_1, R_2, R, \epsilon \) be constants so chosen that

\[
0 < R_0 < R_1 < R_2 < R, \quad R_2 + J_0 < R, \quad 0 < \epsilon < R_1/2.
\]

We shall consider the transformation \( T: (x, c) \to (\bar{x}, \bar{c}) \) defined by

\[
T: \bar{x} = cw + H(I - P)Nx, \quad \bar{c} = c + F(\bar{x}, c),
\]

\[
(x, c) \in \mathcal{C} = [(x, c) | x \in S, c \in \mathbb{R}^m, \|x\| \leq R + J, |c| \leq R].
\]
where \( x^* = cw = \sum^m_i c_i w_i, \bar{x}^* = \bar{c} w = \bar{c}_1 w_1 + \cdots + \bar{c}_m w_m, c, \bar{c} \in \mathbb{R}^m, \) and \( F(\bar{x}, c) = (F_1, \ldots, F_m) \) is explicitly given below. Note that
\[
\bar{x}^* = x^* + F(\bar{x}, c)w = x^* + \sum_i F_i w_i.
\]
Here, for \( 0 < |c| < R_1 \) we take \( F(\bar{x}, c) = (PN\bar{x}, w), \) or \( \bar{x}^* = x^* + PN\bar{x} \). For \( R_2 < |c| < R \), or \( R_2 \leq ||x^*|| = |c| < R \), we take
\[
F(\bar{x}, c) = \left[ (PN\bar{x}, x^*) - \varepsilon||PN\bar{x}|| \right] (2J_0||x^*||)^{-1}(x^*, w), \text{ or }
\bar{x}^* = x^* + \left[ (PN\bar{x}, x^*) - \varepsilon||PN\bar{x}|| \right] (2J_0||x^*||)^{-1}x^*.
\]
For \( R_1 \leq ||x^*|| = |c| < R_2 \) we take
\[
F(\bar{x}, c) = \lambda(PN\bar{x}, w) + (1 - \lambda)\left[ (PN\bar{x}, x^*) - \varepsilon||PN\bar{x}|| \right] (2J_0||x^*||)^{-1}(x^*, w), \text{ or }
\bar{x}^* = x^* + \lambda PN\bar{x} + (1 - \lambda)\left[ (PN\bar{x}, x^*) - \varepsilon||PN\bar{x}|| \right] (2J_0||x^*||)^{-1}x^*,
\]
\[
\lambda = \left( R_2 - R_1 \right)^{-1}(R_2 - |c|), \quad 0 < \lambda < 1.
\]
We have \( \bar{c} = c, \) or \( \bar{x}^* = x^* \), if and only if \( F(\bar{x}, c) = 0 \). For \( |c| < R_1 \) we have \( F = 0 \) if and only if \( PN\bar{x} = 0 \). For \( R_2 < |c| < R \) we have
\[
Fw = \left[ (PN\bar{x}, x^*) - \varepsilon||PN\bar{x}|| \right] (2J_0||x^*||)^{-1}x^*
\]
with \( x^* \neq 0 \) and \( (PN\bar{x}, x^*) - \varepsilon||PN\bar{x}|| < \varepsilon||PN\bar{x}|| \), and again \( F = 0 \) if and only if \( PN\bar{x} = 0 \). Thus, concerning the transformation \( T|_{\mathcal{C}} \), we have \((x, c) = T(x, c)\) if and only if \( x = x^* + H(I - P)Nx \) and \( PNx = 0 \), that is, the fixed points \((x, c)\) of \( T \) on \( \mathcal{C} \) correspond exactly to the solutions of system \((2, 3)\), that is, to the solutions of the original equation \( Ex = Nx \).

Let us prove that \( T \) maps \( \mathcal{C} \) into itself. First, for \((x, c) \in \mathcal{C} \) we have
\[
x^* = cw, ||x^*|| = ||cw|| = |c| \leq R, \text{ and }
\]
\[
||\bar{x}|| \leq ||cw|| + ||H(I - P)Nx|| < |c| + LJ_0 < R + J.
\]
Now we have \( P\bar{x} = cw = x^* \),
\[
||\bar{x} - P\bar{x}|| = ||\bar{x} - x^*|| = ||H(I - P)Nx|| < LJ_0 = J.
\]
Thus, \( (PN\bar{x}, x^*) = (N\bar{x}, x^*) < 0 \) for \( ||x^*|| > R_0 \), in particular, for \( R_1 < |c| = ||x^*|| < R \).

For \( |c| < R_1 \) we have \( \bar{c} = c + F(\bar{x}, c) = c + (PN\bar{x}, w) \), hence
\[
||\bar{c}|| \leq |c| + ||PN\bar{x}|| < R_1 + J_0 < R_2 + J_0 < R.
\]

For \( R_2 < |c| < R \) we have
\[ x^* = \left\{ 1 + \left[ (PNx, x^*) - \varepsilon \|PNx\| \right] \left(2J_0\|x^*\|\right)^{-1} \right\} x^* = \Lambda x^*, \]

where \( \Lambda \) is the number in braces, \((PNx, x^*) < 0\), \((|PNx, x^*|) < J_0\|x^*\|\), \(|PNx| < J_0\), \(|x^*| > R_2 > R_1\), \(\varepsilon < 1\), \(\frac{1}{2} < \frac{1}{2} < \frac{1}{2} < \Lambda < 1\). Thus, \(x^*\) is on the segment between \(x^*\) and \(x^*/4\), and \(|c| < |c| < R\).

For \(R_1 < c < R_2\) we have \(0 < \lambda < 1\),

\[ \bar{x}^* = \lambda(PNx) + \left[ 1 + (1 - \lambda)\left( (PNx, x^*) - \varepsilon \|PNx\| \right) \left(2J_0\|x^*\|\right)^{-1} \right] x^*, \]

and \(|x^*| < \|PNx\| + \|\cdots\|x^*\| < J_0 + R_2 < R\). We have proved that \(T : \mathcal{C} \rightarrow \mathcal{C}\).

Let us prove that \(T\) is compact. For this we consider any (bounded) sequence \((x_k, c_k)\), \(k = 1, 2, \ldots\), of points of \(\mathcal{C}\). Then the sequence \(Nx_k\) is bounded, actually, \(\|x_k\| < J_0\), \(\|y_k\| = \|I - PNx_k\| < U_0\), and since \(H\) is compact, there is a subsequence, say still \([k]\), so that \(y_k\) is convergent in \(S\). Certainly \(x_k^* = c_k w\), \(F(x_k, c_k) = d_k w\) are bounded sequences, actually \(|c_k| < R\), \(|d_k| < R\), both \(c_k\) and \(d_k\) in \(R^m\), a finite dimensional space. Thus, we can extract the subsequence, say still \([k]\), in such a way that \(c_k, d_k\) are convergent in \(R^m\), and then \(\bar{x}_k = x_k^* + y_k, \bar{c}_k = c_k + d_k\) are convergent in \(S\) and \(R^m\), respectively. We have proved that \(T\) is compact.

By Schauder’s fixed point theorem, \(T : \mathcal{C} \rightarrow \mathcal{C}\) has at least one fixed point \((x, c) = T(x, c)\). If \((Ax, x^*) > 0\), then the proof is the same provided we take \(-(PNx, x^*)\) instead of \((PNx, x^*)\) in the definition of \(F\).

REFERENCES


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