A

Appendices

Introduction

We conclude the book with three appendices. The first of these recalls a few basic facts about compactness, which is needed for our study of the layer potentials in Chapter 2. The second states for the sake of completeness the celebrated theorem of Coifman, McIntosh, and Meyer[98]. The third establishes the continuity method, which is useful for the proof of Theorem 2.21.

A.1 Compact Operators

Let X be a Banach space. A bounded linear operator T is compact, if whenever $\{x_j\}$ is a bounded sequence in X, the sequence $\{Tx_j\}$ has a convergent subsequence. The operator T is said to be of finite rank if Range(T) is finite-dimensional. Clearly every operator of finite rank is compact.

We now provide some basic results on compact operators.

Lemma A.1 *The set of compact operators on X is a closed two-sided ideal in the algebra of bounded operators on X with the norm topology.*

Lemma A.2 *If T is a bounded operator on the Banach space X and there is a sequence $\{T_N\}_{N\in\mathbb{N}}$ of operators of finite rank such that $||T_N - T|| \to 0$, then T is compact.*

Lemma A.3 *The operator T is compact on the Banach space X if and only if the dual operator T^* is compact on the dual space X^*.*

We also recall the main structure theorem for compact operators.

Theorem A.4 (Fredholm alternative) *Let T be a compact operator on the Hilbert space X (which we identify with its dual). For each $\lambda \in \mathbb{C}$, let $V_\lambda = \{x \in X : Tx = \lambda x\}$ and $V_{\overline{\lambda}} = \{x \in X : T^*x = \lambda x\}$.*

Then

(i) *The set of* $\lambda \in \mathbb{C}$ *for which* $V_\lambda \neq \{0\}$ *is finite or countable, and in the latter case, its only accumulation point is zero. Moreover,* $dim(V_\lambda) < +\infty$ *for all* $\lambda \neq 0$.
(ii) *If* $\lambda \neq 0$, $dim(V_\lambda) = dim(V_{\overline{\lambda}})$.
(iii) *If* $\lambda \neq 0$, *the range of* $\lambda I - T$ *is closed.*

Corollary A.5 *Suppose* $\lambda \neq 0$. *Then*

(i) *The equation* $(\lambda I - T)x = y$ *has a solution if and only if* $y \perp V_{\overline{\lambda}}$.
(ii) $(\lambda I - T)$ *is surjective if and only if it is injective.*

To conclude this appendix, we recall the concept of a Fredholm operator acting between Banach spaces X and Y. We say that a bounded linear operator $T : X \to Y$ is Fredholm if the subspace Range(T) is closed in Y and the subspaces Ker(T) and Y/Range(T) are finite-dimensional. In this case, the index of T is the integer defined by

$$\text{index } (T) = \dim \text{Ker}(T) - \dim(Y/\text{Range}(T)) \ .$$

The next theorem encapsulates the main conclusion of Fredholm's original theory.

Theorem A.6 *If* $T = I + K$, *where* $K : X \to X$ *is compact, then* $T : X \to X$ *is Fredholm with index zero.*

The last theorem shows that the index is stable under compact perturbations.

Theorem A.7 *If* $T : X \to Y$ *is Fredholm and* $K : X \to Y$ *is compact, then their sum* $T + K : X \to Y$ *is Fredholm, and* index $(T + K) =$ index (T).

A.2 Theorem of Coifman, McIntosh, and Meyer

The proof of Theorem 2.17 is based on the following celebrated theorem of Coifman, McIntosh, and Meyer [98].

Theorem A.8 *Let* A, φ *be Lipschitz functions on* $\mathbb{R}^{d-1}$. *The singular integral operator with the integral kernel*

$$\frac{A(x') - A(y')}{(|x' - y'|^2 + (\varphi(x') - \varphi(y'))^2)^{\frac{d}{2}}}$$

is bounded on $L^2(\mathbb{R}^{d-1})$.

Theorem A.8 was proved by reducing to one dimension using the method of rotation of Calderón[77], and then by using the following general theorem obtained in the same paper.

Theorem A.9 *Let K be a compact convex subset in the complex plane, U be an open set containing K, and $F : U \to \mathbb{C}$ be a holomorphic function. Let A and B be Lipschitz functions on $\mathbb{R}$ such that*

$$\frac{A(x) - A(y)}{x - y} \in K \; .$$

Then the principal value operator defined by the kernel

$$\frac{B(x) - B(y)}{(x - y)^2} F\left(\frac{A(x) - A(y)}{x - y}\right)$$

is bounded on $L^2(\mathbb{R})$.

The L^2-boundedness of the operators $\mathcal{K}_D$ and $\mathcal{K}_D^*$ in Theorem 2.17 follows immediately from Theorem A.8. In order to keep the technicalities to a minimum, we suppose that $d \geq 3$, and the domain D is given by a Lipschitz graph, namely, $D = \{(x', x_d) : x_d = \varphi(x')\}$, where $\varphi : \mathbb{R}^{d-1} \to \mathbb{R}$ is a Lipschitz function. If $x = (x', x_d), y = (y', y_d)$, then $\mathcal{K}_D$ is the principle value operator with the kernel

$$\frac{1}{\omega_d} \frac{\varphi(y') - \varphi(x') - \langle y' - x', \nabla\varphi(y')\rangle}{(|x' - y'|^2 + (\varphi(x') - \varphi(y'))^2)^{\frac{d}{2}}} \; ,$$

and $\mathcal{K}_D^*$ is the principle value operator with the kernel

$$\frac{1}{\omega_d} \frac{(\varphi(x') - \varphi(y') - \langle x' - y', \nabla\varphi(x')\rangle)\sqrt{1 + |\nabla\varphi(y')|^2}}{(|x' - y'|^2 + (\varphi(x') - \varphi(y'))^2)^{\frac{d}{2}}\sqrt{1 + |\nabla\varphi(x')|^2}} \; .$$

From Theorem A.8 [with first $A(x') = x'$, then $A(x') = \varphi(x')$] and the boundedness of $\nabla\varphi(x')$, we conclude that $\mathcal{K}_D$ is a bounded operator on $L^2(\partial D)$.

The integral kernel for the same operator $\mathcal{K}_D$ for the Lamé system involves terms defined by

$$\frac{(x_j' - y_j')^2 (x_k' - y_k')}{|x' - y'|^{d+2}} \; .$$

The L^2-boundedness of such operators can be proved in a similar way using the method of rotation and Theorem A.9.

A.3 Continuity Method

Theorem A.10 *For $0 \leq t \leq 1$, suppose that the family of operators $A_t : L^2(\mathbb{R}^{d-1}) \to L^2(\mathbb{R}^{d-1})$ satisfy*

(i) $||A_t\phi||_{L^2(\mathbb{R}^{d-1})} \geq C||\phi||_{L^2(\mathbb{R}^{d-1})}$, *where C is independent of t,*
(ii) $t \mapsto A_t$ *is continuous in norm,*
(iii) $A_0 : L^2(\mathbb{R}^{d-1}) \to L^2(\mathbb{R}^{d-1})$ *is invertible.*

Then, $A_1 : L^2(\mathbb{R}^{d-1}) \to L^2(\mathbb{R}^{d-1})$ *is invertible.*

We provide a brief proof for the sake of the reader. Let

$$T := \left\{ t \in [0,1] : A_t \text{ is invertible on } L^2(\mathbb{R}^{d-1}) \right\}.$$

Then T is non-empty by (iii). We can infer from (ii) that T is an open subset of $[0,1]$. To prove that T is closed, choose a sequence t_j, $j = 1, 2, \ldots$, from T and assume that t_j converges to t_0 as $j \to +\infty$. For a given $g \in L^2(\mathbb{R}^{d-1})$, let f_j be such that $A_{t_j} f_j = g$. Then by (i) there is a subsequence of f_j, which is still denoted by f_j, converging weakly to, say, f_0. We claim that $A_{t_0} f_0 = g$. In fact, if $h \in L^2(\mathbb{R}^{d-1})$, then

$$\begin{aligned} \langle A_{t_0} f_0 - g, h \rangle &= \langle A_{t_0}(f_0 - f_j) g, h \rangle + \langle (A_{t_0} - A_{t_j}) f_j, h \rangle \\ &= \langle (f_0 - f_j) g, A_{t_0}^* h \rangle + \langle (A_{t_0} - A_{t_j}) f_j, h \rangle \to 0 \quad \text{as } j \to +\infty \,. \end{aligned}$$

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