

SPECTRAL APPROXIMATION BY FINITE RANK OPERATORS

In this section we focus on the approximation of compact operators. The framework here presented is due to BABUSKA-BRAMBLE-OSBORN. In [BRAMBLE-OSBORN 1973] a theory for the approximation of non self-adjoint compact operators, in Hilbert setting was presented under the hypothesis that the sequence of finite rank approximations converged uniformly. In [BRAMBLE 1975] the theory was extended to the Banach case and under the hypothesis that the finite-rank sequence of approximation was only point-wise convergent. In [BORG-BREZZI-GASTALDI 2000] a counter example to the fact that the sequence of finite-rank approximator is point-wise convergent suffices to guarantee the approximation of the SPECTRUM with no SPURIOUS MODES was found in the context of MIXED FEM. In [BABUSKA-OSBORN 1983] more refined estimates for the rate of convergence of the spectrum than the one presented in [OSBORN 1973] were in the Hilbert setting for SELF-ADJOINT operators.

Given $T \in K(X, X)$ we will here consider a sequence of $\{T_n\}_{n \in \mathbb{N}} \subseteq K(X, X)$ with $\dim R(T_n) < \infty$ for any $n \in \mathbb{N}$ and such that $\lim_{n \rightarrow \infty} \|T - T_n\|_{\mathcal{B}(X, X)} = 0$. Under this hypothesis the sequence $\{T_n\}_{n \in \mathbb{N}}$ is COLLECTIVELY COMPACT, i.e. the set $\{T_n z : \|z\| = 1, \text{ with } n \in \mathbb{N}\}$ is sequentially compact. In fact, let us consider a sequence $\{T_n z_{n_k}\}$ and prove that we can extract a Cauchy subsequence: $\|T_{n_k} z_{n_k} - T_{n_j} z_{n_j}\| \leq \|T_{n_k} z_{n_k} - T_{n_k} z_{n_j} + T_{n_k} z_{n_j} - T_{n_j} z_{n_j} + T_{n_j} z_{n_j}\|$

$$\leq \|T_{n_k} z_{n_k} - T_{n_k} z_{n_j}\| + \|T_{n_k} z_{n_j} - T_{n_j} z_{n_j}\| + \|T_{n_j} z_{n_j} - T_{n_j} z_{n_k}\|$$

We now extract a converging subsequence from $\{T_n z_n\}$ here by an abuse of notation also denoted $\{T_n z_n\}$, which can be done because T is compact. We can then conclude the proof observing that all the term on the right hand side vanish as $k \rightarrow \infty$.

Let us consider $\mu \in \sigma_T \setminus \{\mu\}$ and denote I' a loop wrapping once around μ , and not any other element of σ_T .

LEMMA (Approximability of the PSEUDO SPECTRA) Let T and $\{T_n\}_{n \in \mathbb{N}}$ be as in the above setting, for any fixed $\varepsilon > 0$ and $\delta < \varepsilon < \delta'$ it $\exists \ell \in \mathbb{N}$ such that $\sigma_{T_n, \delta} \subseteq \sigma_{T_\ell, \varepsilon} \forall n > \ell$.

PROOF We will first prove that $\exists n^* \in \mathbb{N}$ such that $\forall n > n^*$ we have $(\sigma_{T_\ell, \varepsilon})^c \subseteq (\sigma_{T_n, \delta})^c$. To prove this we observe that if $z \in \sigma_T$ belongs to then $\|R_T(z)\| \leq 1/\varepsilon$ which is equivalent to say that $\frac{1}{\|T - zI\|} \leq \frac{1}{\varepsilon}$. We aim to prove that it $\exists n^*$ such that $\forall n > n^* \quad \|T_n - zI\| \leq \frac{1}{\delta}$.

$$\|T_n - zI\| = \|T_n z + I - zI\| \geq \|\|T - T_n\| + \|T - zI\|\| \Rightarrow \frac{1}{\|T_n - zI\|} \leq \frac{1}{\|\|T - T_n\| + \|T - zI\|\|}$$

let $k \geq 2$, then if $|b| \leq \frac{a}{k}$ then $a-b \geq a-\frac{a}{k}$ thus $\frac{1}{a-b} \leq \left(\frac{k}{k-1}\right) \frac{1}{a}$ now since T_n uniformly converge to T it $\exists n^*$ such that $\forall n > n^* \quad \|T - T_n\| \leq \frac{1}{k} \|T - zI\|$ and thus we have,

$$\frac{1}{\|T_n - zI\|} \leq \left(\frac{k}{k-1}\right) \frac{1}{\|T - zI\|} \leq \left(\frac{k}{k-1}\right) \frac{1}{\varepsilon} \text{ picking } \left(\frac{k}{k-1}\right) \frac{1}{\varepsilon} = \frac{1}{\delta}, \text{ i.e. } k = \varepsilon / (\varepsilon - \delta),$$

concludes the first part of the proof.

We now pick $z \in \sigma_{T_\ell, \varepsilon}$ and observe that this implies $\|R_T(z)\| > 1/\varepsilon$, then we observe it exist an $n^{**} \in \mathbb{N}$ such that:

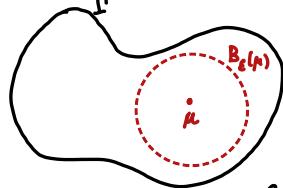
$$\|T_n - zI\| \leq \|T - T_n\| + \|T - zI\| \text{ hence } \forall n > n^{**} \frac{1}{\|R_{T_n}(z)\|} \leq \frac{1}{\|T - T_n\| + \|T - zI\|} \leq \frac{1}{\|T - zI\|} \left(\frac{k+1}{k}\right) \leq \left(\frac{k+1}{k}\right) \frac{1}{\varepsilon}$$

this because if $a, b > 0$ and $a \leq b/k$ then $a+b \geq b/k+b$ thus $\frac{1}{a+b} \leq \frac{1}{b} \left(\frac{k+1}{k}\right)$, and T_n converges uniformly to T .

Pick n such that $\frac{k+1}{k} \leq \frac{1}{\delta}$, i.e. $k\delta' + \delta' = \varepsilon k \Rightarrow k = \delta' / (\delta' - \varepsilon)$, to conclude the second bit of the proof. To conclude we set $\ell^* = \max\{n^{**}, n^*\}$.

COROLLARY In the setting described above fixed $\mu \in \sigma_T \setminus \{\mu\}$ we consider a loop $\Gamma \subseteq \mathbb{C}$ wrapping around μ and no other element of σ_T . Then it $\exists n \in \mathbb{N}$ such that $\forall n > n^* \quad \Gamma \subseteq g(T_n)$.

Proof Let us pick $\varepsilon > 0$ as in the figure below. From the bound $\|R_T(z)\| \geq \gamma(z, \sigma_T)^{-1}$ we then know that $I \subseteq (\overline{\sigma}_{T,\varepsilon})^c$ and from the previous result you see that it $\exists \ell^* \in \mathbb{N}$ such that $I \subseteq (\sigma_{T_n}, \delta)^c \subseteq \rho_{T_n}$.



This above result tells us that we can define the projector $\Delta_{T_n, I_\mu} : X \rightarrow X$ for all $n > \ell^*$. Furthermore notice that if T_n converges uniformly to T we have that $(T_n + I)$ converges uniformly to $T + I$, and thus $\lim \|R_T(z) - R_{T_n}(z)\| = 0 \quad \forall z \in \sigma_T \cap \rho_{T_n}$. Using the linearity of the integral (or if one prefers a more rigorous argument passing to the limit the Cauchy sequences discretising the integral) we get:

$$\begin{aligned} \#) \frac{1}{a-b} (a-c) \frac{1}{c-b} & \| \Delta_{T_n, I_\mu} z - \Delta_{T_n, I_\mu} x \| = \left\| \frac{1}{2\pi i} \int_{\Gamma} (R_T(z) - R_{T_n}(z)) z \right\| = \frac{1}{2\pi} \left\| \int_{\Gamma} R_{T_n}(z) (T - T_n) R_T(z) z dz \right\| \\ & = \frac{1}{2\pi} |\Gamma| \sup_{z \in \Gamma} \|R_{T_n}(z)\| \sup_{z \in \Gamma} \|R_T(z)\| \| (T - T_n) \| \end{aligned}$$

notice that since T_n is collectively compact we have that both maps are bounded in n , while $\lim \|T - T_n\| = 0$, hence $\lim_{n \rightarrow \infty} \|\Delta_{T_n, I_\mu} - \Delta_{T_n, I_\mu}\| = 0$, hence we know that Δ_{T_n, I_μ} converges uniformly to Δ_{T, I_μ} .

Proposition $\dim R(\Delta_{T_n, I_\mu}) = \dim R(\Delta_{T, I_\mu})$ for any $n > \ell^*$ starting from a certain ℓ^* .

Proof Since T and T_n are compact operators by FREDHOLM ALTERNATIVE THEOREM, we know that the eigen space are finite dimensional. Since T_n converges uniformly to T_n we know that $\dim R(\Delta_{T_n, I_\mu}) = m = \dim R(\Delta_{T, I_\mu})$. Notice that because the sequence converges to a constant number it $\exists \ell^*$ such that $\forall n > \ell^* \dim R(\Delta_{T_n, I_\mu}) = m$.

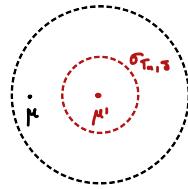
Corollary Let T and $\{\sigma_n\}_{n \in \mathbb{N}}$ be as in the setting of this section. Then fixed $\mu \in \sigma_T \setminus \{0\}$, with ASCENT $\alpha \in \mathbb{N}$, by the above proposition there $\exists \ell^*$ such that $\forall n > \ell^*$ there exist $m = \dim N((T - \mu I)^\alpha)$ eigenvalues of T_n , here denoted $\mu_n^{(j)}$ for $j = 1, \dots, m$, such that $\lim_{n \rightarrow \infty} \mu_n^{(j)} = \mu$.

Proof From the above discussion and proposition we know that fixed a curve I_μ as above it $\exists \ell^*$ s.t. Δ_{T_n, I_μ} is well-defined and $\dim R(\Delta_{T_n, I_\mu}) = \dim R(\Delta_{T, I_\mu})$. Thus since Δ_{T_n, I_μ} is the projection onto the eigen space of T_n we know that there are $m = \dim R(\Delta_{T, I_\mu})$ eigenvectors of T_n associated to the eigenvalues $\mu_n^{(j)}$ for $j = 1, \dots, m = \dim R(\Delta_{T, I_\mu})$. Since Δ_{T, I_μ} is the projection onto the eigenvectors and I only wraps around μ and no other element of σ_T we have that $m = \dim R(\Delta_{T, I_\mu})$. To conclude we consider a sequence of I shrinking to μ to prove that $\lim_{n \rightarrow \infty} \mu_n^{(j)} = \mu$ for any $j = 1, \dots, m$.

Notice that the "Approximability of the PSEUDO SPECTRA" guarantees the absence of SPURIOUS EIGENVALUES. In fact, let us consider a sequence of operator $\{T_n\}_{n \in \mathbb{N}}$ approximating the spectrum of a continuous operator T , i.e. we assume that fixed any $\mu \in \sigma_T \setminus \{0\}$, with ASCENT α it $\exists \ell^*$ such that $\forall n > \ell^*$ there exist $m = \dim N((T - \mu I)^\alpha)$ eigenvalues of T_n , here denoted $\mu_n^{(j)}$ for $j = 1, \dots, m$ and $\lim_{n \rightarrow \infty} \mu_n^{(j)} = \mu$. If this is the case a possible adverse event is that it in addition to the eigenvalues converging to μ the discrete sequence of operators T_n would present an extra sequence of eigenvalues converging to $\mu' \notin \sigma_T \setminus \{0\}$. For any $\varepsilon > 0$ and we notice that it $\exists \ell^*$ such that $\forall n > \ell^*$ we have $\mu' \in \sigma_{T_n, \delta} \subseteq \sigma_{T, \varepsilon}$. Letting $\varepsilon \downarrow 0$ we should find that we μ' is arbitrarily close to μ , which is a contradiction.

Thus we notice that if T_n converges uniformly to T , the spectrum of T_n converges to the spectrum of T with out any SPURIOUS eigenvalue and since there are a number of discrete eigenvalues approximating $\mu \in \sigma_T \setminus \{0\}$ equal to the algebraic multiplicity of μ , with no SPURIOUS GENERALISED EIGENFUNCTION EITHER.

As we previously remarked if $T \in \mathcal{L}(H, H)$ is SELF-ADJOINT the algebraic and geometric multiplicity



are the same which allow us to conclude that in this case if $\{\Pi_n\}_{n \in \mathbb{N}}$ is a sequence converging uniformly to T , then $\{\Pi_n\}_{n \in \mathbb{N}}$ approximates the spectrum of T with no SPURIOUS MODES. We now address the question of how fast does the discrete spectrum converge. We will do so in terms of gap between the discrete and continuous eigenspaces.

DEFINITION Given two closed subspaces A and B of the Banach space X we define the gap between A and B as $\delta(A, B) = \sup_{x \in A} \gamma(x, A)$. Notice that the notion of gap is not symmetric, i.e. in general $\delta(A, B) \neq \delta(B, A)$. We define the SYMMETRISED GAP as $\hat{\delta} = \max\{\delta(A, B), \delta(B, A)\}$. Many authors would refer to $\hat{\delta}(A, B)$ simply as the gap.

From the definition of gap we see that $\delta(A, B) \in [0, 1]$ as does $\hat{\delta}(A, B)$. Furthermore $\delta(A, B) = 0$ if and only if $A \subseteq B$, while $\hat{\delta}(A, B) = 0$ if and only if $A = B$.

LEMMA Let A and B be two close sub-spaces of X , such that $\dim A = \dim B < +\infty$, then we have:

$$\delta(B, A) \leq \delta(A, B) [1 - \delta(A, B)]^{-1}$$

PROOF Let us proceed by contradiction, if $\delta(B, A) \geq \delta(A, B) [1 - \delta(A, B)]^{-1}$ hence $\delta(A, B) \delta(B, A)^{-1} \leq 1 - \delta(A, B)$.

If $A = B$, then the results follows trivially, since if $\delta(A, B) = 1$, hence we can assume $\delta(A, B) \in (0, 1)$. Hence either $A \not\subseteq B$ or $B \not\subseteq A$, but this is a contradiction since $\dim(A) = \dim(B) < +\infty$.

LEMMA Let A, B_1, B_2 be two closed subspaces of X , such that $X = B_1 \oplus A = B_2 \oplus A$ and let Π_1 and Π_2 be the projections of X along A onto B_1 and B_2 respectively. If $\|I - \Pi_2\| \delta(B_1, B_2) < 1$, then we have:

$$\|\Pi_1 - \Pi_2\| \leq (\|I - \Pi_2\| \|I - \Pi_1\| \delta(B_1, B_2)) (1 - \|I - \Pi_2\| \delta(B_1, B_2))^{-1}$$

PROOF This proof comes from [OSBORN 1976], and is due to C. LAY. Let $d = \sup_{x \in B_1} \|x - Q_2 x\|$ and let $\delta > \delta(B_1, B_2)$. If we pick $x \in B_1$ such that $\|x\| = 1$, by the definition of $\delta(B_1, B_2)$ there exists $x' \in B_2$ such that $\|x - x'\| < \delta$. Since $(I - \Pi_2)x' = 0$, we have $\|x - \Pi_2 x\| = \|(I - \Pi_2)(x - x')\| \leq \|I - \Pi_2\| \delta$. Now notice that this implies $d \leq \|I - \Pi_2\| \delta$ for any $\delta > \delta(B_1, B_2)$, and therefore $d \leq \|I - \Pi_2\| \delta(B_1, B_2)$. We now observe that $R(I - \Pi_1) = N(\Pi_2)$, since $X = B_1 \oplus A = B_2 \oplus A$, implies $\Pi_2 = \Pi_2 \Pi_1$ and thus $\forall x \in X$ we have:

$$\|\Pi_1 x\| \leq \|\Pi_1 x - \Pi_2 \Pi_1 x\| + \|\Pi_2 \Pi_1 x\| \leq d \|\Pi_1 x\| + \|\Pi_2 x\| \Rightarrow \|\Pi_1 x\| \leq (1 - d)^{-1} \|\Pi_2 x\|. \text{ Using } \odot \text{ we get}$$

$$\|\Pi_1 x - \Pi_2 x\| \leq \|\Pi_1 x - \Pi_2 \Pi_1 x\| \leq d \|\Pi_1 x\| \leq (\|I - \Pi_2\| \delta(B_1, B_2) \|\Pi_1\|) (1 - \|I - \Pi_2\| \delta(B_1, B_2))^{-1}$$

THEOREM There $\exists c, r > 0$ and $\ell^* \in \mathbb{N}$ such that $\forall n > \ell^*$ we have $\delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu})) \leq c \|(T - T_n)\|$.

PROOF We begin observing that $\forall x \in R(\Delta_{T, \Gamma_\mu})$ with $\|x\| = 1$, then we have $\|x - \Delta_{T_n, \Gamma_\mu} x\|$ can be expressed as $\|(\Delta_{T, \Gamma_\mu} - \Delta_{T_n, \Gamma_\mu}) \Delta_{T_n, \Gamma_\mu} x\| \leq \|(\Delta_{T, \Gamma_\mu} - \Delta_{T_n, \Gamma_\mu}) \Delta_{T_n, \Gamma_\mu}\|$, this because $\Delta_{T, \Gamma_\mu} \Delta_{T_n, \Gamma_\mu} = \Delta_{T_n, \Gamma_\mu}$ and since $x \in R(\Delta_{T, \Gamma_\mu})$ then $x = \Delta_{T, \Gamma_\mu} x$. Thus we have $\delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu})) \leq \|(\Delta_{T_n, \Gamma_\mu} - \Delta_{T, \Gamma_\mu}) \Delta_{T_n, \Gamma_\mu}\|$. Since we have proven that Δ_{T_n, Γ_μ} converges uniformly to Δ_{T, Γ_μ} then $\lim_{n \rightarrow \infty} \delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu})) = 0$. We now apply one of the previous LEMMA to obtain that,

$$\delta(R(\Delta_{T_n, \Gamma_\mu}), R(\Delta_{T, \Gamma_\mu})) \leq \delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu})) [1 - \delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu}))]^{-1}$$

Since we know that $\delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu})) \downarrow$ this means

that it $\exists c, r > 0$ such that: $\delta(R(\Delta_{T_n, \Gamma_\mu}), R(\Delta_{T, \Gamma_\mu})) \leq c \delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu}))$.

We have thus obtained $\delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu})) \leq (1 + c) \delta(R(\Delta_{T, \Gamma_\mu}), R(\Delta_{T_n, \Gamma_\mu}))$, this estimate is more useful than the original one because we are only able to control the expression on the right hand side.

Now for $x \in R(\Delta_{T, \Gamma_\mu})$ we have,

$$\|x - \Delta_{T_n, \Gamma_\mu} x\| \leq \|\Delta_{T, \Gamma_\mu} x - \Delta_{T_n, \Gamma_\mu} x\| = \left\| \frac{1}{2\pi i} \int_{\Gamma} (R_T(z) - R_{T_n}(z)) x \right\| = \frac{1}{2\pi} \left\| \int_{\Gamma} R_{T_n}(z)(T - T_n) R_T(z) x dz \right\|$$

as previously discussed above the RHS can be simplified to be $c \|(T - T_n)\|_{R(\Delta_{T, \Gamma_\mu})}$, hence we obtained the desired result.