Appendix

A1 Fractional powers of nonnegative operators

Let A be a nonnegative operator in a Banach space E, and let $\alpha \in \mathbf{C}$ with $\text{Re}\alpha > 0$.

Definition A1.1. (i) If $A \in \mathbf{L}(E)$ and $0 \in \rho(A)$,

$$A^\alpha := \frac{1}{2\pi i}\int_C \lambda^\alpha R(\lambda;\ A)d\lambda,$$

where the contour C surrounds $\sigma(A)$, avoiding the negative real axis and the origin, and λ^α is taken to be positive for $\lambda > 0$.

(ii) If $A \in \mathbf{L}(E)$ and $0 \in \sigma(A)$,

$$A^\alpha := \lim_{\varepsilon \to 0+}(A+\varepsilon)^\alpha.$$

(iii) If $A \notin \mathbf{L}(E)$ and $0 \in \rho(A)$,

$$A^\alpha := \left[(A^{-1})^\alpha\right]^{-1}.$$

(iv) If $A \notin \mathbf{L}(E)$ and $0 \in \sigma(A)$, A^α is defined by

$$A^\alpha u := \lim_{\varepsilon \to 0+}(A+\varepsilon)^\alpha u, \qquad u \in \mathcal{D}(A^\alpha),$$

where $\mathcal{D}(A^\alpha)$ is the set of all $u \in E$ for which the above limit exists.

Theorem A1.2. *$\mathcal{D}[(A+\varepsilon)^\alpha] = \mathcal{D}(A^\alpha)$ for each $\varepsilon > 0$.*

Theorem A1.3. *A^α is a closed linear operator in E.*

Theorem A1.4. *If $\alpha \in N$, then A^α is the usual power of A.*

Theorem A1.5. (i) *For $0 < \text{Re}\alpha < 1$, $u \in \mathcal{D}(A)$,*

$$A^\alpha u = \frac{\sin \alpha\pi}{\pi}\int_0^\infty \lambda^{\alpha-1}(\lambda + A)^{-1}Au\,d\lambda.$$

(ii) *For* $0 < \mathrm{Re}\alpha < 2$, $u \in \mathcal{D}(A^2)$,

$$A^\alpha u = \frac{\sin \alpha\pi}{\pi} \int_0^\infty \lambda^{\alpha-1} \left[(\lambda + A)^{-1} - \lambda(1+\lambda^2)^{-1}\right] Au d\lambda + \sin\left(\frac{\alpha\pi}{2}\right) Au.$$

Theorem A1.6. *Let* $\mathrm{Re}\alpha$, $\mathrm{Re}\beta > 0$. *Then*

$$A^{\alpha+\beta} = A^\beta A^\alpha = A^\alpha A^\beta.$$

Theorem A1.7. *Let* $0 < \alpha < 1$. *Then* A^α *is a nonnegative operator and for* $\beta \in \mathbf{C}$ *with* $\mathrm{Re}\beta > 0$ *we have*

$$(A^\alpha)^\beta = A^{\alpha\beta}.$$

Theorem A1.8. $\sigma(A^\alpha) = \{|z|^\alpha e^{i\alpha \arg z};\ \ z \in \sigma(A),\ |\arg z| < \pi\}$.

Theorem A1.9. *Let* $0 < \alpha < 1$. *Then*

$$\|A^\alpha u\| \le \mathrm{const}\left(a^\alpha \|u\| + a^{\alpha-1}\|Au\|\right)$$

for all $u \in \mathcal{D}(A)$, $a > 0$.

Definition A1.10. If $0 \in \rho(A)$,

$$A^{-\alpha} := (A^\alpha)^{-1}.$$

For details on fractional powers of nonnegative operators, please see, e.g., Balakrishnan [1], Martínez-Sanz-Marco [1], Fattorini [6, 7] and Pazy [2].

A2 Strongly continuous semigroups and cosine functions

Definition A2.1. Let E be a SCLCS. A family $\{T(t)\}_{t\ge 0}$ of continuous linear operators on E is a (exponentially equicontinuous) strongly continuous (operator) semigroup if

(i) $T(0) = I$, $\ T(s+t) = T(t)T(s) \quad (t,\ s \ge 0)$,

(ii) $\lim_{t\to 0+} T(t)u = u \quad (u \in E)$,

(iii) there exists $\omega > 0$ such that $\{e^{-\omega t}T(t);\ t \ge 0\}$ is equicontinuous.

The generator A of a strongly continuous semigroup $\{T(t)\}_{t\ge 0}$ is defined by

$$Au = \lim_{h\to 0+} \frac{1}{h}[T(h)u - u], \quad u \in \mathcal{D}(A).$$

where $\mathcal{D}(A)$ is the set of all $u \in E$ for which the above limit exists.

A strongly continuous (operator) group (as well as its generator) is defined analogously, with the parameter t running over R instead of R^+ (with $h \to 0$ instead of $h \to 0^+$).

Condition (iii) is implicitly contained in conditions (i) and (ii) in the case when E is a Banach space.

Definition A2.2. Let E be a SCLCS. A family $\{C(t)\}_{t\geq 0}$ of continuous linear operators on E is a strongly continuous cosine (operator) function if

(i) $C(0) = I, \quad 2C(t)C(s) = C(s+t) + C(|s-t|) \quad (t,\ s \geq 0)$,

(ii) $\lim_{t\to 0^+} C(t)u = u \quad (u \in E)$,

(iii) there exists $\omega > 0$ such that $\{e^{-\omega t}C(t);\ t \geq 0\}$ is equicontinuous.

The generator A of a strongly continuous cosine function $\{C(t)\}_{t\geq 0}$ is defined by

$$Au = \lim_{t\to 0^+} \frac{2}{t^2}[C(t)u - u], \quad u \in \mathcal{D}(A),$$

where $\mathcal{D}(A)$ is the set of all $u \in E$ for which the above limit exists. Clearly, condition (iii) is implicitly contained in (i) and (ii) in the case when E is a Banach space; a strongly continuous cosine function $\{C(t)\}_{t\geq 0}$ can be extended to the real axis R by defining

$$C(t) = C(-t), \qquad t < 0$$

such that $\{C(t)\}_{t\in R}$ satisfies

$$2C(t)C(s) = C(s+t) + C(s-t), \qquad t,\ s \in R.$$

Theorem A2.3. *Let A be a closed linear operator in a SCLCS. Then the following statements are equivalent.*

(i) *A generates a strongly continuous semigroup $T(t)$.*

(ii) *The Cauchy problem for $u'(t) = Au(t)$ $(t \geq 0)$ is wellposed (with the propagator $T(t)$).*

(iii) *$\{\lambda \in \mathbf{C};\ \mathrm{Re}\lambda > \omega\} \subset \rho(A)$ for some $\omega > 0$ and*

$$\lambda \longmapsto R(\lambda;\ A) \in LT - \mathbf{L}(E)$$

(with the determining function $T(t)$).

Theorem A2.4. *Let A be a closed linear operator in a SCLCS. Then the following statements are equivalent.*

(i) *A generates a strongly continuous cosine function $C(t)$.*

(ii) *The Cauchy problem for $u''(t) = Au(t)$ $(t \geq 0)$ is wellposed (with the two propagators $C(t)$, $\int_0^t C(s)ds$).*

(iii) *$\{\lambda^2;\ \mathrm{Re}\lambda > \omega\} \subset \rho(A)$ for some $\omega > 0$ and*

$$\lambda \longmapsto \lambda R(\lambda^2;\ A) \in LT - \mathbf{L}(E)$$

(*with the determining function* $C(t)$).

In the sequel, we assume that E is a Banach space.

Definition A2.5. Let $\{T(t)\}_{t\geq 0}$ be a strongly continuous semigroup on E.

(i) $T(t)$ is a semigroup of contractions on E if

$$\|T(t)\| \leq 1, \qquad \text{for all } \ t \geq 0.$$

(ii) $T(t)$ is an analytic semigroup of angle θ $\left(\theta \in \left(0, \ \frac{\pi}{2}\right]\right)$ if it extends to a semigroup $\{T(z); \ z \in \Sigma_\theta\}$, analytic (in the norm of $\mathbf{L}(E)$) in Σ_θ and satisfying that

$$T(z)u \longrightarrow u, \quad \text{as } \ z \longrightarrow 0 \ \ (z \in \Sigma_{\theta'}),$$

for each $u \in E$ and each fixed $\theta' \in (0, \ \theta)$.

(iii) $T(t)$ is a differentiable semigroup (or differentiable for $t > 0$) if for every $u \in E$, $t \longmapsto T(t)u$ is differentiable for $t > 0$.

Theorem A2.6 (Phillips' perturbation theorem). *Let A be the generator of a strongly continuous semigroup on E. If $B \in \mathbf{L}(E)$, then $A + B$ is also the generator of a strongly continuous semigroup on E.*

Theorem A2.7 (Stone). *A is the generator of a strongly continuous group of unitary operators on a Hilbert space if and only if iA is self-adjoint.*

Theorem A2.8. *Let A generate a strongly continuous semigroup $T(t)$ on E. Then $T(t)$ is norm continuous at $t = 0$ if and only if $A \in \mathbf{L}(E)$.*

For the proofs, please see Davies [1, Section 1.3] and Pazy [2, Section 1.1].

Theorem A2.9. *Let A generate a strongly continuous semigroup on E. Then $-(-A)^{\frac{1}{2}}$ generates an analytic semigroup of angle $\frac{\pi}{2}$.*

Please see Fattorini [6, Section 6.4] for a proof.

Theorem A2.10. *Assume A is the generator of a strongly continuous cosine function $\{C(t)\}_{t\geq 0}$ on E. Then A generates an analytic semigroup $\{T(t)\}_{t\geq 0}$ of angle $\frac{\pi}{2}$, given by the abstract Weierstrass formula*

$$T(t)u = \frac{1}{(\pi t)^{\frac{1}{2}}} \int_0^\infty e^{-\frac{s^2}{4t}} C(s)u ds, \qquad t > 0, \ u \in E.$$

Please see Fattorini [7, §VI.2] for a proof.

Definition A2.11. A linear operator A in E is dissipative if for every $u \in \mathcal{D}(A)$ there is a $u^* \in E^*$ with $\langle u^*, \ u\rangle = \|u\|^2 = \|u^*\|^2$ such that $\operatorname{Re}\langle u^*, \ Au\rangle \leq 0$.

Theorem A2.12. *A linear operator A in E is dissipative if and only if*

$$\|(\lambda - A)u\| \geq \lambda\|u\|, \qquad u \in \mathcal{D}(A),\ \lambda > 0.$$

Theorem A2.13. *Let A be a dissipative operator in E.*

(i) *If A is closable, then $\overline{A}$ is also dissipative.*

(ii) *If $\overline{\mathcal{D}(A)} = E$, then A is closable.*

Please see Pazy [2, Section 1.4] for a proof.

Theorem A2.14 (Lumer-Phillips). *Let A be a densely defined linear operator in E. If A is dissipative and there exists a $\lambda_0 > 0$ such that $\mathcal{R}(\lambda_0 - A) = E$, then A is the generator of a strongly continuous semigroup of contractions on E.*

Theorem A2.15. *If A generates a strongly continuous semigroup of contractions on a Hilbert space H, then so does A^*.*

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