A NOTE ON THE SPECTRAL OPERATORS OF SCALAR TYPE AND SEMIGROUPS OF BOUNDED LINEAR OPERATORS

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It is shown that, for the spectral operators of scalar type, the well-known characterizations of the generation of $C_0$- and analytic semigroups of bounded linear operators can be reformulated exclusively in terms of the spectrum of such operators, the conditions on the resolvent of the generator being automatically met and the corresponding semigroup being that of the exponentials of the operator.

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1. Introduction. As known, the celebrated criteria of the generation of $C_0$- and analytic semigroups of bounded linear operators contain conditions on the geometry of the spectrum of the generator along with rather stringent restrictions on its resolvent behavior [6, 7, 12, 15].

For a normal operator in a complex Hilbert space, the restrictions on the resolvent can be dropped, being automatically satisfied when the conditions on the spectrum of the generator are met [6, 13].

If $A$ is such an operator and $E_A(\cdot)$ is its spectral measure (resolution of the identity), the generated semigroup consists of its exponentials in the sense of the corresponding operational calculus [4, 13]

$$e^{tA} = \int_{\sigma(A)} e^{t\lambda} dE_A(\lambda), \quad t \geq 0. \quad (1.1)$$

It is the purpose of the present note to highlight the fact that the criteria acquire purely geometrical form in the more general case of a spectral operator of scalar type (scalar operators) in a complex Banach space [2, 5].

Observe for that matter that, in a Hilbert space, the scalar operators are the operators similar to normal ones [14].

2. Preliminaries. Henceforth, unless specifically stated otherwise, $A$ is a scalar operator in a complex Banach space $X$ with a norm $\| \cdot \|$ and $E_A(\cdot)$ is its spectral measure.

For such operators, there is an operational calculus for Borel measurable functions on the spectrum [2, 5].

If $F(\cdot)$ is a Borel measurable function on the spectrum of $A$, $\sigma(A)$, a new scalar operator

$$F(A) = \int_{\sigma(A)} F(\lambda) dE_A(\lambda) \quad (2.1)$$
is defined as follows:

\[ F(A)f := \lim_{n \to \infty} F_n(A)f, \quad f \in D(F(A)), \]

\[ D(F(A)) := \left\{ f \in X \mid \lim_{n \to \infty} F_n(A)f \text{ exists} \right\}, \tag{2.2} \]

where

\[ F_n(\cdot) := F(\cdot) \chi_{\left\{ \lambda \in \sigma(A) \mid |F(\lambda)| \leq n \right\}}(\cdot), \quad n = 1, 2, \ldots, \tag{2.3} \]

\((\chi_\alpha(\cdot))\) is the characteristic function of a set \(\alpha\), and

\[ F_n(A) := \int_{\sigma(A)} F_n(\lambda) dE_A(\lambda), \quad n = 1, 2, \ldots, \tag{2.4} \]

being the integrals of bounded Borel measurable functions on \(\sigma(A)\), are bounded scalar operators on \(X\) defined in the same way as for normal operators (see, e.g., [4, 13]).

The properties of the spectral measure \(E_A(\cdot)\) and the operational calculus, which underlie the entire argument henceforth, are exhaustively delineated in [2, 5]. We just note here that, due to its strong countable additivity, the spectral measure \(E_A(\cdot)\) is bounded, that is, there is an \(M > 0\) such that

\[ \|E_A(\delta)\| \leq M, \quad \text{for any Borel set } \delta. \tag{2.5} \]

Observe that, in (2.5), the same notation as for the norm in \(X\), \(|\cdot|\), was used to designate the norm in the space of bounded linear operators on \(X\), \(\mathcal{L}(X)\). We will also adhere to this rather common economy of symbols in what follows for the norm in the dual space \(X^*\).

On account of compactness, the terms spectral measure and operational calculus for spectral operators, repeatedly referred to, will be abbreviated to s.m. and o.c., respectively.

3. \(C_0\)-semigroups

**Proposition 3.1.** A scalar operator \(A\) in a complex Banach space \(X\) generates a \(C_0\)-semigroup of bounded linear operators if and only if, for some real \(\omega\),

\[ \Re \lambda \leq \omega, \quad \lambda \in \sigma(A), \tag{3.1} \]

in which case the semigroup consists of the exponentials

\[ e^{tA} = \int_{\sigma(A)} e^{t\lambda} dE_A(\lambda), \quad t \geq 0. \tag{3.2} \]

**Proof.** Condition (3.1), being a constituent of the general \(C_0\)-semigroup generation criterion [6, 7, 15], obviously remains necessary. Thus, we are only to prove its sufficiency.

From (3.1), we immediately infer that \(\{\lambda \in \mathbb{C} \mid \Re \lambda > \omega\} \subseteq \rho(A)\), where \(\rho(A)\) is the resolvent set of \(A\).
Furthermore, for $z > \omega$, we have

$$
\|R(z, A)^n\| = \left\| \int_{\sigma(A)} (z - \lambda)^{-n} dE_A(\lambda) \right\| \text{ by the properties of the o.c.}
\leq 4M \sup_{\lambda \in \sigma(A)} |z - \lambda|^{-n} \text{ where } M \text{ is a constant from (2.5)}
= 4M \left[ \text{dist}(z, \sigma(A)) \right]^{-n} \text{ by (3.1)}
\leq \frac{4M}{(z - \omega)^n}.
$$

(3.3)

Whence, by the $C_0$-semigroup generation criterion (see, e.g., [6]), it follows that $A$ generates a certain $C_0$-semigroup of bounded linear operators $\{T(t) \mid t \geq 0\}$.

From condition (3.1), we also obtain the estimate

$$
|e^{t\lambda}| = e^{t \Re \lambda} \leq e^{t \omega}, \quad t \geq 0, \lambda \in \sigma(A),
$$

(3.4)

which, by the properties of the o.c., implies that exponentials (3.2) form a semigroup of bounded linear operators.

To prove that $\{e^{tA} \mid t \geq 0\}$ is a $C_0$-semigroup, it is enough to demonstrate its continuity at 0 in the weak sense [15].

For any $f \in X$ and an arbitrary $g^* \in X^*$,

$$
|\langle e^{tA}f - f, g^* \rangle| = \left| \int_{\sigma(A)} (e^{t\lambda} - 1) d\langle E_A(\lambda)f, g^* \rangle \right| \\
\leq \int_{\sigma(A)} |e^{t\lambda} - 1| d\nu(f, g^*, \lambda),
$$

(3.5)

by the properties of the o.c., $\langle \cdot, \cdot \rangle$ being the pairing between the space $X$ and its dual, $X^*$, where $\nu(f, g^*, \cdot)$, the total variation of the complex-valued Borel measure $\langle E_A(\cdot)f, g^* \rangle$, is a finite positive Borel measure.

By the Lebesgue Dominated Convergence theorem, whose conditions as easily seen are readily met, the latter integral approaches 0 as $t \to 0$.

Finally, we need to prove that $T(t) = e^{tA}, t \geq 0$.

We first show that, for arbitrary $f \in D(A)$ and $g^* \in X^*$,

$$
\frac{d}{dt} \langle e^{tA}f, g^* \rangle = \langle Ae^{tA}f, g^* \rangle, \quad t \geq 0.
$$

(3.6)

Note that, by the properties of the o.c., for all $f \in D(A)$,

$$
e^{At}f \in D(A), \quad Ae^{tA}f = e^{tA}Af, \quad t \geq 0.
$$

(3.7)

Fix a $t \geq 0$ and choose a small segment $[a,b] \subset [0, \infty)$ so that $t$ is its left endpoint if $t = 0$ and the midpoint otherwise. For all sufficiently small increments $\Delta t \neq 0$ such
that \( \Delta t \in [a,b] \), and arbitrary \( f \in D(A) \) and \( g^* \in X^* \), we have

\[
\left| \frac{e^{(t+\Delta t)A}f - e^{tA}f - Ae^{tA}f, g^*}{\Delta t} \right| \quad \text{by the properties of the o.c.}
\]

\[
= \int_{\sigma(A)} \left| \frac{e^{(t+\Delta t)\lambda} - e^{t\lambda}}{\Delta t} - \lambda e^{t\lambda} \right| d\langle E_A(\lambda) f, g^* \rangle
\]

\[
\leq \int_{\sigma(A)} \left| \frac{e^{(t+\Delta t)\lambda} - e^{t\lambda}}{\Delta t} - \lambda e^{t\lambda} \right| dv(f, g^*, \lambda) \to 0 \quad \text{as } \Delta t \to 0,
\] (3.8)

by the Lebesgue Dominated Convergence theorem,

\[
\left| \frac{e^{(t+\Delta t)\lambda} - e^{t\lambda}}{\Delta t} - \lambda e^{t\lambda} \right| \to 0 \quad \text{as } \Delta t \to 0, \quad \lambda \in \sigma(A).
\] (3.9)

For \( \lambda \in \sigma(A) \),

\[
\left| \frac{e^{(t+\Delta t)\lambda} - e^{t\lambda}}{\Delta t} - \lambda e^{t\lambda} \right| \quad \text{by the total change theorem}
\]

\[
\leq 2 \max_{\alpha \leq s \leq b} |\lambda e^{s\lambda}| = 2 \max_{\alpha \leq s \leq b} e^{sRe\lambda}|\lambda| \quad \text{by (3.1)}
\]

\[
\leq 2 \max_{\alpha \leq s \leq b} e^{s\omega}|\lambda| \quad \text{without restricting generality, } \omega \text{ can be regarded to be positive}
\]

\[
\leq 2e^{b\omega}|\lambda|.
\] (3.10)

Since \( f \in D(A), \int_{\sigma(A)} |\lambda| dv(f, g^*, \lambda) < \infty \) for any \( g^* \in X^* \) [3, 5]. Thus, for any \( f \in D(A) \) and \( g^* \in D(A^*) \), where \( A^* \) is the adjoint of \( A \) (\( D(A) \) is dense in \( X \)),

\[
\frac{d}{dt} \langle e^{tA}f, g^* \rangle = \langle Ae^{tA}f, g^* \rangle = \langle e^{tA}f, A^*g^* \rangle, \quad t \geq 0,
\] (3.11)

that is, \( e^{tA}f \) is a weak solution of the equation

\[
y'(t) = Ay(t)
\] (3.12)
on \([0, \infty)\) in the sense of [1].

Since \( A \) generates the \( C_0 \)-semigroup \( \{T(t) | t \geq 0\} \), such a solution is unique for any \( f \in X \) and is the orbit \( T(t)f, t \geq 0 \) [1].

Therefore, for any \( f \in D(A) \): \( e^{tA}f = T(t)f, t \geq 0 \). Whence, by the density of \( D(A) \) in \( X \), we conclude that

\[
e^{tA} = T(t), \quad t \geq 0.
\] (3.13)
4. Analytic semigroups

**Proposition 4.1.** A scalar operator $A$ in a complex Banach space $X$ generates an analytic semigroup of bounded linear operators if and only if, for some real $\omega$ and $0 < \theta < \pi/2$,

$$\sigma(A) \subseteq \{ z \in \mathbb{C} \mid | \arg(z - \omega) | \geq \pi/2 + \theta \}, \quad (4.1)$$

where $\arg \cdot$ is the principal value of the argument from the interval $(-\pi, \pi]$.

The semigroup is analytically continuable into the sector $\Sigma_\theta = \{ z \in \mathbb{C} \mid | \arg z | < \theta \}$ by the formula

$$e^{zA} = \int_{\sigma(A)} e^{z\lambda} dE_A(\lambda), \quad z \in \Sigma_\theta. \quad (4.2)$$

**Proof.** Condition (4.1) is necessary since it is a constituent of the general criterion of generation of analytic semigroup [6, 7, 15]. Thus, we need to validate its sufficiency only.

First, we infer that $\rho(A) \subseteq \{ z \in \mathbb{C} \mid | \arg(z - \omega) | < \pi/2 + \theta \}.

For an arbitrary $0 < \varepsilon < \theta$ and any $z$ such that $| \arg(z - \omega) | < \pi/2 + \theta - \varepsilon$, there are two possibilities:

(a) $\pi/2 - \theta < | \arg(z - \omega) | \leq \pi/2 + \theta - \varepsilon$,

(b) $| \arg(z - \omega) | \leq \pi/2 - \theta$.

In the first case,

$$||R(z,A)|| = \left| \left| \int_{\sigma(A)} (z - \lambda)^{-1} dE_A(\lambda) \right| \right| \leq 4M \sup_{\lambda \in \sigma(A)} |z - \lambda|^{-1} \quad \text{where } M \text{ is a constant from (2.5)} \quad (4.3)$$

$$= 4M \left( \text{dist} \left( z, \sigma(A) \right) \right)^{-1} \leq \frac{4M}{|z - \omega| \sin \varepsilon}.$$  

In the second case,

$$||R(z,A)|| = \left| \left| \int_{\sigma(A)} (z - \lambda)^{-1} dE_A(\lambda) \right| \right| \leq 4M \sup_{\lambda \in \sigma(A)} |z - \lambda|^{-1} \quad \text{by the properties of the o.c.} \quad (4.4)$$

$$\leq 4M \left( \text{dist} \left( z, \sigma(A) \right) \right)^{-1} \leq \frac{4M}{|z - \omega|}.$$  

Thus, for any $0 < \varepsilon < \theta$,

$$||R(z,A)|| \leq \frac{4M \csc \varepsilon}{|z - \omega|} \quad \text{whenever } | \arg(z - \omega) | < \frac{\pi}{2} + \theta - \varepsilon. \quad (4.5)$$

Condition (4.1) and the latter estimate imply that $A$ generates an analytic semigroup $\{ T(t) \mid t \geq 0 \}$ (see, e.g., [6]).

The fact that the exponentials

$$e^{zA} = \int_{\sigma(A)} e^{z\lambda} dE_A(\lambda), \quad | \arg z | < \theta, \quad (4.6)$$
are bounded linear operators with the semigroup property can be easily inferred from (4.1). And the fact that \( e^{tA} = T(t) \), \( t \geq 0 \), can be substantiated in the same way as in the case of \( C_0 \)-semigroups above.

5. Some final remarks. The author intentionally did not entertain the idea of developing here similar arguments for differentiable \( C_0 \)-semigroups \([6, 12]\) and, for that matter, the \( C_0 \)-semigroups with orbits belonging to the Gevrey or, more generally, Carleman classes of ultradifferentiable vector functions leaving that for a discussion in a more general context (for the case of the normal operators, see \([8, 9, 10, 11]\)).

References

The study of dynamic equations on a time scale goes back to its founder Stefan Hilger (1988), and is a new area of still fairly theoretical exploration in mathematics. Motivating the subject is the notion that dynamic equations on time scales can build bridges between continuous and discrete mathematics; moreover, it often reveals the reasons for the discrepancies between two theories.

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