

THE SPECTRA OF BOUNDED LINEAR OPERATORS ON THE SEQUENCE SPACES¹

CHARLES J. A. HALBERG, JR.

These remarks are the result of an investigation into the connections among the spectra of the various operators defined on the sequence spaces l_p by the same infinite matrix.

We will have need of the following notation. Let $[l_p]$ denote the algebra of bounded linear operators mapping the sequence space l_p into itself. If A is an infinite matrix which defines an element of $[l_p]$ (we shall sometimes use the statement $A \in [l_p]$ to express this state of affairs), we shall denote that operator by A_p . We shall denote the transpose of the matrix A by A^t . Let $\|A_p\|$ denote the norm of the operator A_p on the sequence space l_p , and let $\sigma(A_p)$, $|\sigma(A_p)|$ and $\rho(A_p)$ denote its spectrum, spectral radius and resolvent set respectively. If T is the operator defined by the infinite matrix (t_{ij}) we shall denote by \bar{T} the operator defined by the infinite matrix (\bar{t}_{ij}) , where \bar{z} denotes the complex conjugate of the complex number z . Similarly, if we have a vector $x = (\xi_1, \xi_2, \dots)$, then \bar{x} will denote the vector $(\bar{\xi}_1, \bar{\xi}_2, \dots)$. The symbol $l_p(n)$ will denote the vector space of n -tuples of complex numbers, such that if $x = (\xi_1, \xi_2, \dots, \xi_n) \in l_p(n)$, then $\|x\|_p = (\sum_{i=1}^n |\xi_i|^p)^{1/p}$. Given a number p , p' will denote the number $p/(p-1)$ if $1 < p < \infty$, and will denote ∞ or 1 respectively, according as $p=1$ or $p=\infty$. The statement " q lies between p and p' " will mean $p \leq q \leq p'$ or $p' \leq q \leq p$ respectively, according as $1 \leq p \leq 2$ or $2 < p \leq \infty$.

M. Riesz has proved that if A is a matrix transformation of $l_{1/\alpha}(n)$ into $l_{1/\beta}(m)$ and $M_{\alpha\beta}$ is its norm, then $M_{\alpha\beta}$ as a function of the point (α, β) has the property that $\log(M_{\alpha\beta})$ is a convex function in the triangle $0 \leq \alpha \leq 1$, $0 \leq \beta \leq 1$, $\alpha + \beta \leq 1$, [2, pp. 466-471]. G. O. Thorin has shown that the theorem actually holds for the entire first quadrant of the $\alpha\beta$ -plane, [4, pp. 5-6].

This result, with the use of a limiting process, implies the following inequality

$$(1) \quad \|A_{1/b}\|^{c-a} \leq \|A_{1/a}\|^{c-b} \|A_{1/c}\|^{b-a}$$

Presented to the Society, November 12, 1955; received by the editors August 20, 1956.

¹ The results of this paper are based in part on a University of California (at Los Angeles) thesis prepared under the direction of Professor Angus E. Taylor.

where $0 \leq a \leq b \leq c$. (It is understood that if $a = 0$, $1/a$ is replaced by ∞ .) For the case where $1 \leq p \leq q \leq r \leq \infty$, this gives

$$(2) \quad \|A_q\| \leq \|A_p\|^{(r-q)p/(r-p)q} \|A_r\|^{(q-p)r/(r-p)q},$$

it being understood that if $r = \infty$, then $(r-q)/(r-p) = r/(r-p) = 1$. (For the case where $p = 1$, $q = 2$, and $r = \infty$, this is simply a reformulation of a theorem due to J. Schur [3, p. 6].) Or, since it can easily be shown that $\|A_{p'}\| = \|(A^t)_p\|$, if we let $1 \leq p \leq \infty$ and let q lie between p and p' we can restate (2) as

$$(3) \quad \|A_q\| \leq \|A_p\|^{(p+q(1-p))/(2-p)q} \|(A^t)_p\|^{(q-p)/(2-p)q}.$$

We note that (2) implies that if $1 \leq p \leq q \leq r \leq \infty$ and A belongs to both $[l_p]$ and $[l_r]$, then $A \in [l_q]$ and that (3) implies that if $1 \leq p \leq \infty$, q lies between p and p' , and both A and A^t belong to $[l_p]$, then $A \in [l_q]$.

Borrowing from the phraseology of M. Riesz, we state the following theorem.

THEOREM 1. *If $A \in [l_{1/\alpha}]$ for each α , $0 \leq \alpha \leq 1$, then $|\sigma(A_{1/\alpha})|$ as a function of the number α has the property that $\log |\sigma(A_{1/\alpha})|$ is a convex function for $0 \leq \alpha \leq 1$.*

PROOF. We know that $\lim_{n \rightarrow \infty} \|(A_{1/\alpha})^n\|^{1/n} = |\sigma(A_{1/\alpha})|$ provided $0 \leq \alpha \leq 1$, and (1) implies that

$$\|(A_{1/b})^n\|^{(c-a)/n} \leq \|(A_{1/a})^n\|^{(c-b)/n} \|(A_{1/c})^n\|^{(b-a)/n},$$

for $0 \leq a \leq b \leq c \leq 1$. If we let n approach infinity, we obtain

$$(4) \quad |\sigma(A_{1/b})|^{c-a} \leq |\sigma(A_{1/a})|^{c-b} |\sigma(A_{1/c})|^{b-a},$$

which is the desired result.

When $1 \leq p \leq q \leq r$ we can restate the inequality (4) as

$$(5) \quad |\sigma(A_q)| \leq |\sigma(A_p)|^{(r-q)p/(r-p)q} |\sigma(A_r)|^{(q-p)r/(r-p)q}$$

provided A belongs to both $[l_p]$ and $[l_r]$.

In the special case where $1 \leq p \leq \infty$ and q lies between p and p' , we can use the well known fact that $\sigma(A_{p'}) = \sigma((A^t)_p)$ together with the inequality (5) to derive the following inequality, provided both A and A^t belong to $[l_p]$.

$$(6) \quad |\sigma(A_q)| \leq |\sigma(A_p)|^{(p+q(1-p))/(2-p)q} |\sigma((A^t)_p)|^{(q-p)/(2-p)q}.$$

Using the inequality (5) we can immediately state the following theorem.

THEOREM 2. *Suppose that T belongs to both $[l_p]$ and $[l_r]$, that*

$1 \leq p \leq q \leq r \leq \infty$ and that $|\sigma(T_p)| \neq |\sigma(T_r)|$. Then either

$$|\sigma(T_p)| > |\sigma(T_q)| \quad \text{or} \quad |\sigma(T_r)| > |\sigma(T_q)|$$

according as

$$|\sigma(T_p)| > |\sigma(T_r)| \quad \text{or} \quad |\sigma(T_r)| > |\sigma(T_p)|,$$

respectively.

The inequality (6) together with fact that if q lies between p and p' , then so does q' , and the fact that $|\sigma(A_{q'})| = |\sigma((A^t)_q)|$ imply the following theorem.

THEOREM 3. *Let both T and T^t belong to $[l_p]$, $1 \leq p \leq \infty$, let q lie between p and p' and let $|\sigma(T_p)| \neq |\sigma((T^t)_p)|$. Then either*

$$|\sigma(T_p)| > |\sigma(T_q)| \quad \text{or} \quad |\sigma((T^t)_p)| > |\sigma((T^t)_q)|$$

according as

$$|\sigma(T_p)| > |\sigma((T^t)_p)| \quad \text{or} \quad |\sigma((T^t)_p)| > |\sigma(T_p)|,$$

respectively.

We shall now use the inequalities (2) and (3) to derive some set relationships among the spectra of the operators defined on the sequence spaces l_p by the same infinite matrix.

THEOREM 4. *Let T belong to both $[l_p]$ and $[l_r]$ and let $1 \leq p \leq q \leq r \leq \infty$. Then*

$$(a) \quad \sigma(T_q) \subset \sigma(T_p) \cup \sigma(T_r),$$

and

(b) *if C is any component of $\sigma(T_q)$, then the set $C \cap (\sigma(T_p) \cap \sigma(T_r))$ is nonvoid.*

PROOF. (a) Assume that $\lambda \in \rho(T_p) \cap \rho(T_r)$. This implies that $(\lambda I - T)^{-1}$ belongs to both $[l_p]$ and $[l_r]$. From (2) we infer that $(\lambda I - T)^{-1} \in [l_q]$, whence $\lambda \in \rho(T_q)$. We have thus proved that

$$\rho(T_p) \cap \rho(T_r) \subset \rho(T_q),$$

whence, by complementation, we have

$$\sigma(T_p) \cup \sigma(T_r) \supset \sigma(T_q).$$

(b) Let us assume that $C \cap (\sigma(T_p) \cap \sigma(T_r))$ is void. It is clear that $C \cap \sigma(T_p)$ and $C \cap \sigma(T_r)$ are both closed, and by our assumption they have no point in common; moreover, it can be shown that they are both nonvoid [1, p. 288]. But

$$C = (C \cap \sigma(T_p)) \cup (C \cap \sigma(T_r))$$

since, by (a), $\sigma(T_q) \subset \sigma(T_p) \cup \sigma(T_r)$. We are therefore forced to conclude that C is not connected, which is in contradiction to our assumption that C is a component.

We note that (b) implies, among other things, that $\sigma(T_p)$ and $\sigma(T_r)$ always have points in common.

THEOREM 5. *Suppose that both T and T^t belong to $[l_p]$, $1 \leq p \leq \infty$, and q lies between p and p' . Then*

- (a) $\sigma(T_q) \subset \sigma(T_p) \cup \sigma((T^t)_p)$,
- (b) $\sigma(T_2) \subset \sigma(T_q) \cup \sigma((T^t)_q) \subset \sigma(T_p) \cup \sigma((T^t)_p)$,

and

- (c) *if C is any component of $\sigma(T_q)$, then the set*

$$C \cap (\sigma(T_p) \cap \sigma((T^t)_p))$$

is nonvoid.

PROOF. The statements (a) and (c) are proved in the same manner as statements (a) and (b) of Theorem 4 except that the inequality (3) is used instead of the inequality (2). The first containment of the statement (b) results from letting $q=2$ in (a), and the second containment results from (a) combined with the application of (a) to T^t .

Combining the result (b) of Theorem 5 with the classical result that the spectrum of a bounded operator defined on l_2 by a hermitian symmetric matrix is real, we obtain the following theorem.

THEOREM 6. *If $T \in [l_p]$, $T = \bar{T}^t$ and $1 \leq p \leq \infty$ then*

$$\sigma(T_2) \subset \sigma(T_p).$$

PROOF. Since if $x \in l_p$, $x \rightarrow \bar{x}$ gives an isometric isomorphic mapping of l_p onto itself we see that if $T \in [l_p]$, then $\sigma(T_p) = \text{Conj} [\sigma(\bar{T}_p)]$. Thus, since by hypothesis, $(T^t)_p = \bar{T}_p$, we have $\sigma((T^t)_p) = \text{Conj} [\sigma(T_p)]$; whence result (b) of Theorem 5 implies that

$$\sigma(T_2) \subset \sigma(T_p) \cup \text{Conj} [\sigma(T_p)].$$

Knowing from a classical result that $T_2 = (\bar{T}^t)_2$ implies that $\sigma(T_2)$ is real, we are led to the desired conclusion.

Our final theorem was suggested by Professor Angus E. Taylor.

THEOREM 7. *If $1 \leq p \leq q$, T belongs to both l_p and l_q , and $\lambda \in \rho(T_q)$, then a necessary and sufficient condition that $\lambda \in \rho(T_p)$ is that*

$$(\lambda I - T)(l_q - l_p) \subset l_q - l_p.$$

PROOF. Suppose that $\lambda \in \rho(T_p)$. Then $\lambda I - T$ maps l_p onto l_p in a 1-1 manner; and since by hypothesis $\lambda \in \rho(T_q)$, $\lambda I - T$ maps l_q onto l_q in a 1-1 manner. Hence

$$(\lambda I - T)(l_q - l_p) = l_q - l_p.$$

Now suppose that $(\lambda I - T)(l_q - l_p) \subset l_q - l_p$. It follows that $(\lambda I - T)^{-1}l_p \supset l_p$, for if $x \in l_p$ and $(\lambda I - T)x = y$, then $y \in l_p$ and $(\lambda I - T)^{-1}y = x$, whence $x \in (\lambda I - T)^{-1}l_p$. If we now assume that $x \in ((\lambda I - T)^{-1}(l_p) - l_p)$, then $x = (\lambda I - T)^{-1}y$, where $y \in l_p$ and $x \notin l_p$. But $(\lambda I - T)x = y$, which implies that $y \in l_q - l_p$ by our assumption that $(\lambda I - T)(l_q - l_p) \subset l_q - l_p$. This is a contradiction and we are thus led to the conclusion that $(\lambda I - T)^{-1}(l_p) - l_p$ is void, and this with our earlier conclusion implies that $l_p = (\lambda I - T)^{-1}l_p$. Thus we see that $(\lambda I - T)^{-1}$ (and hence also $\lambda I - T$) sets up a 1-1 map of l_p onto l_p . From this it follows that $(\lambda I - T)^{-1}$ is bounded, for it is known that the inverse of a linear 1-1 map of a Banach space onto itself is bounded. The desired conclusion follows immediately.

BIBLIOGRAPHY

1. Charles J. A. Halberg, Jr. and Angus E. Taylor, *On the spectra of linked operators*, Pacific J. Math. vol. 6 (1956) pp. 283-290.
2. M. Riesz, *Sur les maxima des formes bilinéaires et sur les fonctionnelles linéaires*, Acta Math. vol. 49 (1926) pp. 465-497.
3. J. Schur, *Bemerkungen zur Theorie der beschränkten Bilinearformen mit unendlich vielen Veränderlichen*, J. Reine Angew. Math. vol. 140 (1911) pp. 1-28.
4. G. O. Thorin, *Convexity theorems generalizing those of M. Riesz and Hadamard, with some applications*, University of Lund thesis, Uppsala, 1948.

UNIVERSITY OF CALIFORNIA, LOS ANGELES, AND
UNIVERSITY OF CALIFORNIA, RIVERSIDE