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EIGENVALUE CONDITION NUMBERS AND A FORMULA OF BURKE, LEWIS AND OVERTON*

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Abstract. In a paper by Burke, Lewis and Overton, a first order expansion has been given for the minimum singular value of $A-zI$, $z \in \mathbb{C}$, about a nonderogatory eigenvalue λ of $A \in \mathbb{C}^{n\times n}$. This note investigates the relationship of the expansion with the Jordan canonical form of A. Furthermore, formulas for the condition number of eigenvalues are derived from the expansion.

Key words. Eigenvalue condition numbers, Jordan canonical form, Singular values.

AMS subject classifications. 15A18, 65F35.

1. Introduction.

By $\pi_\Sigma(A)$ we denote the product of the nonzero singular values of the matrix $A \in \mathbb{C}^{n\times m}$, counting multiplicities. For the zero matrix $0 \in \mathbb{C}^{n\times m}$ we set $\pi_\Sigma(0) = 1$. If A is square then $\Lambda(A)$ denotes the spectrum and $\pi_\Lambda(A)$ stands for the product of the nonzero eigenvalues, counting multiplicities. If all eigenvalues of A are zero then we set $\pi_\Lambda(A) = 1$. The subject of this note is the ratio

$$q(A,\lambda) := \frac{\pi_\Sigma(A - \lambda I_n)}{|\pi_\Lambda(A - \lambda I_n)|}, \quad \lambda \in \Lambda(A).$$

In [1] the following first order expansion has been given for the function

$$z \mapsto \sigma_{\min}(A - zI_n),\ z \in \mathbb{C},$$

where $\sigma_{\min}(\cdot)$ denotes the minimum singular value and I_n is the $n\times n$ identity matrix.

THEOREM 1.1. *Let $\lambda \in \mathbb{C}$ be a nonderogatory eigenvalue of algebraic multiplicity m of the matrix $A \in \mathbb{C}^{n\times n}$. Then*

$$\sigma_{\min}(A - zI_n) = \frac{|z-\lambda|^m}{q(A,\lambda)} + \mathcal{O}(|z-\lambda|^{m+1}), \quad z \in \mathbb{C}.$$

The relevance of this result for the perturbation theory of eigenvalues is as follows. The closed $\epsilon-$ pseudospectrum of $A \in \mathbb{C}^{n\times n}$ with respect to the spectral norm, $\|\cdot\|$, is defined by

$$\Lambda_\epsilon(A) = \{\ z \in \mathbb{C} \mid\ z \in \Lambda(A+\Delta),\ \Delta \in \mathbb{C}^{n\times n},\ \|\Delta\| \le \epsilon\ \}.$$

In words, $\Lambda_\epsilon(A)$ is the set of all eigenvalues of all matrices of the form $A+\Delta$ where the spectral norm of the perturbation Δ is bounded by $\epsilon > 0$. It is well known [10] that

$$\Lambda_\epsilon(A) = \{\ z \in \mathbb{C} \mid\ \sigma_{\min}(A - zI) \le \epsilon\ \}.$$

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Theorem 1.1 yields an estimate for the size of pseudospectra for small ϵ: Roughly speaking if ϵ is small enough then the connected component of $\Lambda_\epsilon(A)$ that contains the eigenvalue λ is approximately a disk of radius $(\,q(A,\lambda)\,\epsilon\,)^{1/m}$ about λ. It follows that $q(A,\lambda)^{1/m}$ is the Hölder condition number of λ. We discuss this in detail in Section 4.

However, the main concern of this note is to establish the relationship of $q(A,\lambda)$ with the Jordan decomposition of A. For a simple eigenvalue the relationship is as follows. Let $x, y \in \mathbb{C}^n \setminus \{0\}$ be a right and a left eigenvector of A to the eigenvalue λ respectively, i.e. $Ax = \lambda\, x$, $y^*A = \lambda\, y^*$, where y^* denotes the conjugate transpose of y. Then

$$P = (y^*x)^{-1}xy^* \in \mathbb{C}^{n\times n}$$

is a projection onto the one dimensional eigenspace $\mathbb{C}\,x$. The kernel of P is the direct sum of all generalized eigenspaces belonging to the eigenvalues different from λ. As is well known [5, p.490],[3, p.202],[9, p.186], the condition number of λ equals the norm of P. Combined with the considerations above this yields that

$$q(A,\lambda) = \|P\|. \tag{1.1}$$

In Section 3 we give an elementary proof of the identity (1.1) without using Theorem 1.1. Furthermore, we show that for a nondegoratory eigenvalue of algebraic multiplicity $m \geq 2$,

$$q(A,\lambda) = \|N^{m-1}\|, \tag{1.2}$$

where N is the nilpotent operator associated with λ in the Jordan decomposition of A. The formulas (1.1) and (1.2) are the main results of this note. The proofs also show that the assumption that λ is nonderogatory is necessary.

The next section contains some preliminaries about the computation of the two products $\pi_\Sigma(A)$ and $\pi_\Lambda(A)$ and about the relationship of the Schur form of A with the Jordan decomposition.

Throughout this note, $\|\cdot\|$ stands for the spectral norm.

2. Preliminaries. Below we list some easily verified properties of $\pi_\Lambda(A)$, the product of the nonzero eigenvalues of A, and of $\pi_\Sigma(A)$, the product of the nonzero singular values of A. In the sequel A^T and A^* denote the transpose and the conjugate transpose of A respectively.

(*a*) If $A \in \mathbb{C}^{n\times n}$ is nonsingular then $\pi_\Lambda(A) = \det(A)$.
(*b*) For any $A \in \mathbb{C}^{n\times n}$: $\pi_\Lambda(A^T) = \pi_\Lambda(A)$ and $\pi_\Lambda(A^*) = \overline{\pi_\Lambda(A)}$.
(*c*) Let $S \in \mathbb{C}^{n\times n}$ be nonsingular. Then for any $A \in \mathbb{C}^{n\times n}$, $\pi_\Lambda(SAS^{-1}) = \pi_\Lambda(A)$.
(*d*) Let $A_{11} \in \mathbb{C}^{n\times n}$, $A_{22} \in \mathbb{C}^{m\times m}$ and $A_{12} \in \mathbb{C}^{n\times m}$. Then

$$\pi_\Lambda\left(\begin{bmatrix} A_{11} & A_{12} \\ 0 & A_{22}\end{bmatrix}\right) = \pi_\Lambda(A_{11})\,\pi_\Lambda(A_{22}).$$

(*e*) For any $A \in \mathbb{C}^{n\times m}$, $\pi_\Sigma(A)^2 = \pi_\Lambda(A^*A) = \pi_\Lambda(AA^*)$.

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(*f*) If $A \in \mathbb{C}^{n\times n}$ is nonsingular then $\pi_\Sigma(A) = |\det(A)| = |\pi_\Lambda(A)|$.
(*g*) Let $U \in \mathbb{C}^{n\times n}$ and $V \in \mathbb{C}^{m\times m}$ be unitary. Then for any $A \in \mathbb{C}^{n\times m}$, $\pi_\Sigma(UAV) = \pi_\Sigma(A)$.

In the next section we need the lemmas below.

LEMMA 2.1. *Let $M \in \mathbb{C}^{n\times n}$ be nonsingular, $X \in \mathbb{C}^{m\times n}$ and $Y = XM^{-1}$. Then*

$$\pi_\Sigma\left(\begin{bmatrix} M \\ X \end{bmatrix}\right) = \pi_\Sigma(M)\sqrt{\det(I_n + Y^*Y)}.$$

Proof. We have

$$\begin{aligned}\pi_\Sigma\left(\begin{bmatrix} M \\ X \end{bmatrix}\right)^2 &= \pi_\Lambda\left(\begin{bmatrix} M^* & X^* \end{bmatrix}\begin{bmatrix} M \\ X \end{bmatrix}\right)\\ &= \det(M^*M + X^*X)\\ &= \det(M^*(I_n + Y^*Y)M)\\ &= \det(M^*)\det(M)\det(I_n + Y^*Y)\\ &= \pi_\Sigma(M)^2\det(I_n + Y^*Y). \;\square\end{aligned}$$

LEMMA 2.2. *Let $Y \in \mathbb{C}^{m\times n}$. Then $\|I_n + Y^*Y\| = \|I_m + YY^*\|$ and $\det(I_n + Y^*Y) = \det(I_m + YY^*)$.*

Proof. The case $Y = 0$ is trivial. Let $Y \neq 0$. The matrices Y and Y^* have the same nonzero singular values $\sigma_1 \geq \sigma_2 \geq \ldots \geq \sigma_p > 0$ say. The eigenvalues different from 1 of both $I_n + Y^*Y$ and $I_m + YY^*$ are $1 + \sigma_1^2 \geq 1 + \sigma_2^2 \ldots \geq 1 + \sigma_p^2$. Thus $\|I_n + Y^*Y\| = \|I_m + YY^*\| = 1 + \sigma_1^2$ and $\det(I_n + Y^*Y) = \det(I_m + YY^*) = \prod_{k=1}^p(1 + \sigma_k^2)$. $\square$

We proceed with remarks on the Jordan decomposition. Let $\lambda_1, \ldots, \lambda_\kappa$ be the pairwise different eigenvalues of $A \in \mathbb{C}^{n\times n}$. Let $\mathcal{X}_j = \ker(A - \lambda_j I_n)^n$ be the generalized eigenspaces. By the Jordan decomposition theorem we have

$$A = \sum_{j=1}^{\kappa}(\,\lambda_j P_j + N_j\,), \tag{2.1}$$

where $P_1, \ldots, P_\kappa \in \mathbb{C}^{n\times n}$ are the projectors of direct decomposition $\mathbb{C}^n = \bigoplus_{j=1}^{\kappa}\mathcal{X}_j$, i.e.

$$P_j^2 = P_j, \quad \text{range}(P_j) = \mathcal{X}_j, \quad \ker(P_j) = \bigoplus_{k=1,k\neq j}^{\kappa}\mathcal{X}_k,$$

and $N_1, \ldots, N_\kappa \in \mathbb{C}^{n\times n}$ are the nilpotent matrices $N_j = (A - \lambda_j I_n)P_j$. The eigenvalue λ_j is said to be

- semisimple (nondefective) if $\mathcal{X}_j = \ker(A - \lambda_j I_n)$,
- simple if $\dim \mathcal{X}_j = 1$,
- nonderogatory if $\dim\ker(A - \lambda_j I_n) = 1$.

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In the following m denotes the algebraic multiplicity of λ_j. Note that if $m \geq 2$ then λ_j is nonderogatory if and only if $N_j^{m-1} \neq 0$. We now recall how to obtain the operators P_j and N_j from a Schur form of A. We only consider the nontrivial case that A has at least two different eigenvalues. By the Schur decomposition theorem there exists a unitary matrix $U \in \mathbb{C}^{n\times n}$ such that

$$U^*AU = \begin{bmatrix} \lambda_j I_m + T & A_{12} \\ 0 & A_{22} \end{bmatrix},$$

where $A_{12} \in \mathbb{C}^{m\times(n-m)}$, $A_{22} \in \mathbb{C}^{(n-m)\times(n-m)}$, $\Lambda(A_{22}) = \Lambda(A) \setminus \{\lambda_j\}$ and $T \in \mathbb{C}^{n\times n}$ is strictly upper triangular,

$$T = \begin{bmatrix} 0 & t_{12} & \dots & \dots & t_{1m} \\ & \ddots & t_{23} & & \vdots \\ & & \ddots & \ddots & \vdots \\ & & & \ddots & t_{m-1,m} \\ & & & & 0 \end{bmatrix}.$$

If $m = 1$ (i.e. λ_j is simple) then T is the 1×1 zero matrix. Since the spectra of T and $A_{22} - \lambda_j I_{n-m}$ are disjoint the Sylvester equation

$$R(A_{22} - \lambda_j I_{n-m}) - TR = A_{12}. \tag{2.2}$$

has a unique solution $R \in \mathbb{C}^{m\times(n-m)}$.

Proposition 2.3. *With the notation above the projector onto the generalized eigenspace and the nilpotent operator associated with λ_j are given by*

$$P_j = U \begin{bmatrix} I_m & -R \\ 0 & 0 \end{bmatrix} U^*, \quad \text{and} \quad N_j = U \begin{bmatrix} T & -TR \\ 0 & 0 \end{bmatrix} U^*.$$

For any integer $\ell \geq 1$ we have

$$N_j^\ell = U \begin{bmatrix} T^\ell & -T^\ell R \\ 0 & 0 \end{bmatrix} U^*. \tag{2.3}$$

The spectral norms of P_j and of N_j^ℓ satisfy

$$\|P_j\| = \|I_m + RR^*\|^{1/2} \tag{2.4}$$
$$\|N_j^\ell\| = \|T^\ell(I_m + RR^*)(T^*)^\ell\|^{1/2}. \tag{2.5}$$

Proof. Let $X_1 := U \begin{bmatrix} I_m \\ 0 \end{bmatrix} \in \mathbb{C}^{n\times m}$, $X_2 := U \begin{bmatrix} R \\ I_{n-m} \end{bmatrix} \in \mathbb{C}^{n\times(n-m)}$. Then obviously $\mathbb{C}^n = \text{range}(X_1) \oplus \text{range}(X_2)$ and

$$A\,X_1 = X_1\,(\lambda_j I_m + T). \tag{2.6}$$

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Furthermore, (2.2) yields that

$$A\,X_2 = X_2\,A_{22}. \tag{2.7}$$

Hence, range(X_1) and range(X_2) are complementary invariant subspaces of A. The relations (2.6) and (2.7) imply that for any $\lambda \in \mathbb{C}$ and any integer $\ell \geq 1$,

$$\begin{aligned} (A-\lambda I_n)^\ell X_1 &= X_1((\lambda_j-\lambda)I_m+T)^\ell, \\ (A-\lambda I_n)^\ell X_2 &= X_2(A_{22}-\lambda I_{n-m})^\ell. \end{aligned} \tag{2.8}$$

Using this and the fact that $\lambda_j \notin \Lambda(A_{22})$ it is easily verified that range$(X_1) = \ker(A-\lambda_j\,I_n)^n$ and range$(X_2) = \bigoplus_{k=1,k\neq j}^{\kappa} \ker(A-\lambda_k\,I_n)^n$. The matrix

$$P_j = U\begin{bmatrix} I_m & -R \\ 0 & 0 \end{bmatrix} U^*, \tag{2.9}$$

satisfies $P_j^2 = P_j$, $P_jX_1 = X_1$ and $P_jX_2 = 0$. Hence, P_j is the Jordan projector onto the generalized eigenspace $\ker(A-\lambda_j\,I_n)^n$. For the associated nilpotent matrix N_j one obtains

$$N_j = (A-\lambda_j\,I_n)P_j = U\begin{bmatrix} T & -T\,R \\ 0 & 0 \end{bmatrix} U^*. \tag{2.10}$$

The formulas (2.3), (2.4) and (2.5) are immediate from (2.9) and (2.10). ◻
We give an expression for $\|N_j^{m-1}\|$ which is a bit more explicit than formula (2.5). First note that if λ_j has algebraic multiplicity $m \geq 2$ then

$$T^{m-1} = \begin{bmatrix} 0 & \dots & 0 & \tau \\ \vdots & & \vdots & 0 \\ \vdots & & \vdots & \vdots \\ 0 & \dots & 0 & 0 \end{bmatrix}, \quad \text{where} \quad \tau = \prod_{k=1}^{m-1} t_{k,k+1}.$$

Let $e_m^T = [0\dots 0\ 1]^T \in \mathbb{C}^m$ and $r = e_m^T R$. Then r is the lower row of R. Since the lower row of TR is zero it follows from the Sylvester equation (2.2) that

$$r = e_m^T A_{12}(A_{22}-\lambda_j I_m)^{-1}. \tag{2.11}$$

From (2.3) or (2.5) we obtain

Proposition 2.4. *Suppose λ_j has algebraic multiplicity $m \in \{2,\dots,n-1\}$. Then*

$$\|N_j^{m-1}\| = |\tau|\,\sqrt{1+\|r\|^2}.$$

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3. Main result. We are now in a position to state and prove our main result on the ratio

$$q(A,\lambda_j) = \frac{\pi_\Sigma(A-\lambda_j I_n)}{|\pi_\Lambda(A-\lambda_j I_n)|}, \qquad \lambda_j \in \Lambda(A). \tag{3.1}$$

THEOREM 3.1. *Let $\lambda_j \in \mathbb{C}$ be an eigenvalue of $A \in \mathbb{C}^{n\times n}$. Let P_j and N_j be the eigenprojector and the nilpotent operator associated with λ_j. Then the following holds.*

(a) If λ_j is a semisimple eigenvalue then $q(A,\lambda_j) = \pi_\Sigma(P_j)$.

(b) If λ_j is a simple eigenvalue then $q(A,\lambda_j) = \|P_j\|$.

(c) If λ_j is a nonderogatory eigenvalue of algebraic multiplicity $m \geq 2$ then

$$q(A,\lambda_j) = \|N_j^{m-1}\|.$$

Proof. First, we treat the case that A has at least two different eigenvalues. In view of Proposition 2.3 and since the products $\pi_\Sigma(A-\lambda_j I_n)$, $\pi_\Lambda(A-\lambda_j I_n)$ are invariant under unitary similarity transformations we may assume that

$$A = \begin{bmatrix} \lambda_j I_m + T & A_{12} \\ 0 & A_{22} \end{bmatrix}, \quad P_j = \begin{bmatrix} I_m & -R \\ 0 & 0 \end{bmatrix},$$

where $\Lambda(A_{22}) = \Lambda(A)\backslash\{\lambda_j\}$, $T \in \mathbb{C}^{n\times n}$ is strictly upper triangular and $R \in \mathbb{C}^{m\times(n-m)}$ is the solution of the Sylvester equation $R(A_{22}-\lambda_j I_{n-m}) - TR = A_{12}$.
(a). Suppose λ_j is semisimple. Then $T = 0$ and $R(A_{22}-\lambda_j I_{n-m}) = A_{12}$. Thus,

$$\begin{aligned}(A-\lambda_j I_n)^*(A-\lambda_j I_n) &= \begin{bmatrix} 0 & 0 \\ 0 & (A_{22}-\lambda_j I_{n-m})^*(A_{22}-\lambda_j I_{n-m}) + A_{12}^* A_{12} \end{bmatrix} \\ &= \begin{bmatrix} 0 & 0 \\ 0 & (A_{22}-\lambda_j I_{n-m})^*(I_{n-m}+R^*R)(A_{22}-\lambda_j I_{n-m}) \end{bmatrix}.\end{aligned}$$

Thus

$$\begin{aligned}\pi_\Sigma(A-\lambda_j I_n)^2 &= \pi_\Lambda((A-\lambda_j I_n)^*(A-\lambda_j I_n)) \\ &= \det((A_{22}-\lambda_j I_{n-m})^*(I_{n-m}+R^*R)(A_{22}-\lambda_j I_{n-m})) \qquad (3.2) \\ &= |\det(A_{22}-\lambda_j I_{n-m})|^2 \det(I_{n-m}+R^*R) \\ &= |\pi_\Lambda(A-\lambda_j I_n)|^2 \det(I_{n-m}+R^*R). \qquad (3.3)\end{aligned}$$

Furthermore we have $P_j P_j^* = \begin{bmatrix} I_m + RR^* & 0 \\ 0 & 0 \end{bmatrix}$ and hence

$$\pi_\Sigma(P_j)^2 = \det(I_m + RR^*) = \det(I_{n-m} + R^*R). \tag{3.4}$$

The latter equation holds by Lemma 2.2. By combining (3.3) and (3.4) we obtain (a).
(b). If $m = 1$ then P_j has rank 1 and hence, $\pi_\Sigma(P_j) = \|P_j\|$. Thus (b) follows from (a).

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(c) Suppose $m \geq 2$ and λ_j is nonderogatory. Then $T = \begin{bmatrix} \begin{smallmatrix}0\\ \vdots \\ 0\end{smallmatrix} & D \\ & \begin{smallmatrix}\ldots & 0\end{smallmatrix} \end{bmatrix}$, where $D \in \mathbb{C}^{(m-1)\times(m-1)}$ is upper triangular and nonsingular. In the following we write $A_{12} = \begin{bmatrix} \tilde{A} \\ a \end{bmatrix}$, where a is the lower row of A_{12}. Let r denote the lower row of R. By Formula (2.11) we have

$$r = a(A_{22} - \lambda_j I)^{-1}. \tag{3.5}$$

Let us determine $\pi_\Sigma(A)$. Since removing of a column of zeros and a permutation of rows does not change the nonzero singular values of a matrix we have

$$\pi_\Sigma(A - \lambda_j I_n) = \pi_\Sigma\left(\begin{bmatrix} \begin{smallmatrix}0\\ \vdots\\ 0 \ldots 0\end{smallmatrix} & D & \tilde{A} \\ & & a \\ 0 & & A_{22} - \lambda_j I_{n-m} \end{bmatrix}\right) = \pi_\Sigma\left(\begin{bmatrix} D & \tilde{A} \\ 0 & A_{22} - \lambda_j I_{n-m} \\ 0 \ldots 0 & a \end{bmatrix}\right).$$

Lemma 2.1 yields

$$\begin{aligned} \pi_\Sigma\left(\begin{bmatrix} D & \tilde{A} \\ 0 & A_{22} - \lambda_j I_{n-m} \\ 0 \ldots 0 & a \end{bmatrix}\right) &= \pi_\Sigma\left(\begin{bmatrix} D & \tilde{A} \\ 0 & A_{22} - \lambda_j I \end{bmatrix}\right) \sqrt{\det(1 + yy^*)} \\ &= |\det(D)\det(A_{22} - \lambda_j I)| \sqrt{1 + \|y\|^2} \\ &= |\pi_\Lambda(A - \lambda_j I)|\, |\det(D)| \sqrt{1 + \|y\|^2}, \end{aligned}$$

where

$$y = \begin{bmatrix} 0 \ldots 0 & a \end{bmatrix} \begin{bmatrix} D & \tilde{A} \\ 0 & A_{22} - \lambda_j I \end{bmatrix}^{-1}.$$

From (3.5) it follows that $y = \begin{bmatrix} 0 \ldots 0 & r \end{bmatrix}$ and hence, $\|y\| = \|r\|$. In summary,

$$\pi_\Sigma(A - \lambda_j I_n) = |\pi_\Lambda(A - \lambda_j I_n)|\, |\det(D)| \sqrt{1 + \|r\|^2}.$$

But $|\det(D)|\sqrt{1 + \|r\|^2} = \|N_j^{m-1}\|$ by Proposition 2.4. Hence, (c) holds.

Finally, we treat the case that λ_1 is the only eigenvalue of A. Let $U^*AU = \lambda_1 I_n + T$ be a Schur decomposition. The eigenprojection is $P_1 = I_n$ and the nilpotent operator is $N_1 = A - \lambda_1 I_n = UTU^*$. Since all eigenvalues of $A - \lambda_1 I_n$ are zero we have $\pi_\Lambda(A - \lambda_1 I_n) = 1$ by definition. If λ_1 is semisimple then also $\pi_\Sigma(A - \lambda_1 I_n) = \pi_\Sigma(0) = 1$. Hence, $q(A, \lambda_1) = 1 = \pi_\Sigma(P_1)$. Suppose $n \geq 2$ and λ_1 is nonderogatory. Then

$$q(A, \lambda_1) = \pi_\Sigma(A - \lambda_1 I_n) = \pi_\Sigma(T) = |\det(D)| = \|T^{n-1}\| = \|N_1^{n-1}\|,$$

where $T = \begin{bmatrix} \begin{smallmatrix}0\\ \vdots \\ 0\end{smallmatrix} & D \\ & \begin{smallmatrix}\ldots & 0\end{smallmatrix} \end{bmatrix}$. □

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4. Condition numbers. In this section we show that $q(A,\lambda)^{1/m}$ equals the Hölder condition number of the nonderogatory eigenvalue λ of algebraic multiplicity m. To this end we introduce some additional notation. By $\mathcal{D}_\lambda(r)$ we denote the closed disk of radius $r > 0$ about $\lambda \in \mathbb{C}$. If $\lambda \in \Lambda(A)$, $A \in \mathbb{C}^{n\times n}$, then $\mathcal{C}_\lambda(\epsilon)$ denotes the connected component of the ϵ-pseudospectrum, $\Lambda_\epsilon(A)$, that contains λ. We define

$$R^+_\lambda(\epsilon) := \inf\{r > 0 \mid \ \mathcal{C}_\lambda(\epsilon) \subseteq \mathcal{D}_\lambda(r)\ \},$$
$$R^-_\lambda(\epsilon) := \sup\{r > 0 \mid \ \mathcal{D}_\lambda(r)\ \subseteq \mathcal{C}_\lambda(\epsilon)\}.$$

Then

$$\mathcal{D}_\lambda(R^-_\lambda(\epsilon)) \subseteq \mathcal{C}_\lambda(\epsilon) \subseteq \mathcal{D}_\lambda(R^+_\lambda(\epsilon)).$$

THEOREM 4.1. *Let $\lambda \in \Lambda(A)$ be a nonderogatory eigenvalue of algebraic multiplicity m. Then*

$$R^\pm_\lambda(\epsilon) = q(A,\lambda)^{1/m}\,\epsilon^{1/m} + o(\epsilon^{1/m}). \tag{4.1}$$

The proof uses Theorem 1.1 and the lemma below.

LEMMA 4.2. *Let $U \subseteq \mathbb{C}^n$ be an open neighborhood of $z_0 \in \mathbb{C}^n$. Let $f, g : U \to [0,\infty)$ be continuous functions. For $\epsilon \geq 0$ let $S_f(\epsilon)$ and $S_g(\epsilon)$ denote the connected component containing z_0 of the sublevel set $\{\, z \in U \mid \ f(z) \leq \epsilon \,\}$ and $\{\, z \in U \mid \ g(z) \leq \epsilon \,\}$ respectively. Assume that $0 = g(z_0)$ is an isolated zero of g, and*

$$\lim_{z\to z_0} \frac{f(z)}{g(z)} = 1. \tag{4.2}$$

Then there exists an $\epsilon_0 > 0$ and functions $h_\pm : [0,\epsilon_0] \to [0,\infty)$ with $\lim_{\epsilon\to 0} h_\pm(\epsilon) = 1$ such that for all $\epsilon \in [0,\epsilon_0]$,

$$S_g(\,h_-(\epsilon)\,\epsilon\,) \subseteq S_f(\epsilon) \subseteq S_g(\,h_+(\epsilon)\,\epsilon\,). \tag{4.3}$$

We postpone the proof of the lemma to the end of this section.

Proof of Theorem 4.1: Let in Lemma 4.2, $z_0 = \lambda$ and

$$f(z) = \sigma_{min}(A - zI_n), \qquad g(z) = \frac{|z-\lambda|^m}{q(A,\lambda)}, \qquad z \in \mathbb{C}.$$

Then $S_f(\epsilon) = \mathcal{C}_\lambda(\epsilon)$ and $S_g(\epsilon) = \mathcal{D}_\lambda((q(A,\lambda)\epsilon)^{1/m})$. Theorem 1.1 yields $\lim_{z\to\lambda} \frac{f(z)}{g(z)} = 1$. Hence, by the lemma there are functions $h_\pm$ with $\lim_{\epsilon\to 0} h_\pm(\epsilon) = 1$ and

$$\mathcal{D}_\lambda(\,(q(A,\lambda)\,h_-(\epsilon)\epsilon\,)^{1/m}\,) \subseteq \mathcal{C}_\lambda(\epsilon) \subseteq \mathcal{D}_\lambda(\,(q(A,\lambda)\,h_+(\epsilon)\epsilon\,)^{1/m}\,).$$

This shows (4.1). □

Now, we give the definition for the Hölder condition number of an eigenvalue of arbitrary multiplicity (see [2]). For $\lambda \in \mathbb{C}$, $m \in \mathbb{N}$ and $\widetilde{A} \in \mathbb{C}^{n\times n}$ we set

$$d_m(\widetilde{A},\lambda) := \min\{\ r \geq 0 \mid \ \mathcal{D}_\lambda(r) \text{ contains at least } m \text{ eigenvalues of } \widetilde{A}\ \}.$$

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If λ is an eigenvalue of $A \in \mathbb{C}^{n\times n}$ of algebraic multiplicity m then the Hölder condition number of λ to the order $\alpha > 0$ is defined by

$$\operatorname{cond}_\alpha(A,\lambda) = \lim_{\epsilon \searrow 0} \sup_{\|\Delta\|\le\epsilon} \frac{d_m(A+\Delta,\lambda)}{\|\Delta\|^\alpha}.$$

It is easily seen that $0 \neq \operatorname{cond}_\alpha(A,\lambda) \neq \infty$ for at most one order $\alpha > 0$.

THEOREM 4.3. *Let $\lambda \in \Lambda(A)$ be a nonderogatory eigenvalue of multiplicity m. Then*

$$\operatorname{cond}_{1/m}(A,\lambda) = q(A,\lambda)^{1/m} = \begin{cases} \|P\| & \text{if } m = 1, \\ \|N^{m-1}\|^{1/m} & \text{otherwise,} \end{cases} \tag{4.4}$$

where $P \in \mathbb{C}^{n\times n}$ is the eigenprojector onto the generalized eigenspace $\ker(A - \lambda I_n)^m$*, and $N = (A - \lambda I_m)P$.*

Proof. Let $\Delta \in \mathbb{C}^{n\times n}$ with $\|\Delta\| \le \epsilon$. Then the continuity of eigenvalues yields, that for any $t \in [0,1]$ at least m eigenvalues of $A + t\Delta$ are contained in $\mathcal{C}_\lambda(\epsilon)$ counting multiplicities. Hence

$$d_m(A+\Delta,\lambda) \le R_\lambda^+(\epsilon) = q(A,\lambda)^{1/m}\epsilon^{1/m} + o(\epsilon^{1/m}).$$

By letting $\epsilon = \|\Delta\|$ we obtain that for all $\Delta \in \mathbb{C}^{n\times n}$,

$$\frac{d_m(A+\Delta,\lambda)}{\|\Delta\|^{1/m}} \le q(A,\lambda)^{1/m} + o(\|\Delta\|^{1/m})\|\Delta\|^{-(1/m)}.$$

This yields

$$\operatorname{cond}_{1/m}(A,\lambda) \le q(A,\lambda)^{1/m}.$$

Let $r > 0$ be such that $\mathcal{D}_\lambda(r) \cap \Lambda(A) = \{\lambda\}$. Then by the continuity of eigenvalues there is an ϵ_0 such that the following holds for all $\epsilon < \epsilon_0$,

(*a*) $\mathcal{D}_\lambda(r) \cap \Lambda_\epsilon(A) = \mathcal{C}_\lambda(\epsilon)$.

(*b*) For any $\Delta \in \mathbb{C}^{n\times n}$ with $\|\Delta\| \le \epsilon$, the set $\mathcal{C}_\lambda(\epsilon)$ contains precisely m eigenvalues of $A + \Delta$ counting multiplicities.

Let $\epsilon < \epsilon_0$ and let $z_\epsilon \in \mathbb{C}$ be a boundary point of $\mathcal{C}_\lambda(\epsilon)$. Then $\sigma_{\min}(A - z_\epsilon I_n) = \epsilon$. Let $\Delta_\epsilon = -\epsilon\, u\, v^*$, where $u, v \in \mathbb{C}^n$ is a pair of normalized left and right singular vectors of $A - z_\epsilon I_n$ belonging to the minimum singular value, i.e.

$$(A - z_\epsilon I_n)\, v = \epsilon\, u, \quad u^*(A - z_\epsilon I_n) = \epsilon\, v^*, \quad \|u\| = \|v\| = 1.$$

Then $\|\Delta_\epsilon\| = \epsilon$ and $z_\epsilon \in \Lambda(A + \Delta_\epsilon)$ since $(A + \Delta_\epsilon)v = z_\epsilon\, v$. Thus, by (a) and (b),

$$\begin{aligned} d_m(A+\Delta_\epsilon,\lambda) &\ge |z_\epsilon - \lambda| \\ &\ge R_\lambda^-(\epsilon) \\ &= q(A,\lambda)^{1/m}\epsilon^{1/m} + o(\epsilon^{1/m}). \end{aligned}$$

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and therefore

$$\frac{d_m(A+\Delta_\epsilon,\lambda)}{\|\Delta_\epsilon\|^{1/m}} \geq q(A,\lambda)^{1/m} + o(\epsilon^{1/m})\epsilon^{-(1/m)}.$$

Hence, $\mathrm{cond}_{1/m}(A,\lambda) \geq q(A,\lambda)^{1/m}$. □

REMARK 4.4. In [7] (see also [2, 4]) the following generalization of Theorem 4.3 has been shown. Let λ be an *arbitrary* eigenvalue of A. If λ is semisimple then

$$\mathrm{cond}_1(A,\lambda) = \|P\|.$$

If λ is not semisimple then

$$\mathrm{cond}_{1/m}(A,\lambda) = \|N^{m-1}\|^{1/m},$$

where m denotes the index of nilpotency of N, i.e. $N^m = 0$, $N^{m-1} \neq 0$.

Proof of Lemma 4.2: By B_r we denote the closed ball of radius $r > 0$ about z_0. The condition that z_0 is an isolated zero of g combined with (4.2) yields that z_0 is also an isolated zero of f. Hence, there is an $r_0 > 0$ such that $f(z) > 0$ for all $z \in B_{r_0} \setminus \{z_0\}$. This implies that $\epsilon_r := \min_{z\in\partial B_r} f(z) > 0$ for any $r \in (0, r_0]$. If $\epsilon < \epsilon_r$ then ∂B_r does not intersect the sublevel sets $\{\, z \in U \mid \; f(z) \leq \epsilon \,\}$. Thus $S_f(\epsilon)$ is contained in the interior of B_r. Note that $S_f(\epsilon)$ being a connected component of a closed set is closed. It follows that $S_f(\epsilon)$ is compact if $\epsilon < \epsilon_{r_0}$. Now, let

$$\phi_\pm(z) := \begin{cases} (1 \pm \|z - z_0\|)\frac{g(z)}{f(z)} & z \in B_{r_0} \setminus \{z_0\}, \\ 1, & z = z_0. \end{cases}$$

Condition (4.2) yields that the functions $\phi_\pm : U \to \mathbb{R}$ are continuous. For $\epsilon < \epsilon_{r_0}$ let

$$h_-(\epsilon) := \min_{z\in S_f(\epsilon)} \phi_-(z), \quad h_+(\epsilon) := \max_{z\in S_f(\epsilon)} \phi_+(z).$$

Then we have for all $\epsilon < \epsilon_r$,

$$\min_{z\in B_r} \phi_\pm(z) \leq h_\pm(\epsilon) \leq \max_{z\in B_r} \phi_\pm(z).$$

As r tends to 0 the max and the min tend to $\phi_\pm(z_0) = 1$. This yields $\lim_{\epsilon\to 0} h_\pm(\epsilon) = 1$. If $z \in \partial S_f(\epsilon)$ then $f(z) = \epsilon$ and $g(z) > (1 - \|z - z_0\|)\frac{g(z)}{f(z)} f(z) \geq h_-(\epsilon)\epsilon$. Thus $\partial S_f(\epsilon)$ does not intersect $E := \{\, z \in U \mid \; g(z) \leq h_-(\epsilon)\epsilon \,\}$. Thus $S_g(h_-(\epsilon)\epsilon)$ being a connected component of E is either contained in the interior of $S_f(\epsilon)$ or in the complement of $S_f(\epsilon)$. The latter is impossible since $z_0 \in S_f(\epsilon) \cap S_g(h_-(\epsilon)\epsilon)$. Hence, $S_g(h_-(\epsilon)\epsilon) \subset S_f(\epsilon)$. This proves the first inclusion in (4.3). To prove the second suppose $z_0 \neq z \in \partial S_g(h_+(\epsilon)\epsilon) \cap S_f(\epsilon)$. Then $g(z) = h_+(\epsilon)\epsilon$ and $0 < f(z) \leq \epsilon$. Hence $g(z)/f(z) \geq h_+(\epsilon)$, a contradiction. Thus $S_f(\epsilon)$ is contained in the interior of $S_g(h_+(\epsilon)\epsilon)$. □

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