REMARKS ON NUMERICAL RANGES OF OPERATORS IN SPACES WITH AN INDEFINITE METRIC

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Abstract. The numerical range of an operator on an indefinite inner product space (possibly infinite dimensional) is studied. In particular, operators having bounded numerical ranges are characterized, and the angle points of the numerical range and their connections with eigenvalues are described.

1. Introduction

Let $H$ be a (complex) Hilbert space, with the scalar product $(\cdot, \cdot)$, and let $S$ be a bounded self-adjoint operator on $H$. For a linear bounded operator $A : H \to H$ we define

$$W_{\pm}^S(A) = \left\{ \frac{(SAx, x)}{(Sx, x)} : x \in H, (Sx, x) = \pm 1 \right\}.$$ 

For future reference define also $W_0^S(A) = \{(SAx, x) : x \in H, (Sx, x) = 0\}$. The sets $W_{\pm}^S(A)$ generalize the well-known and widely used notion of numerical range $W(A) = \{(Ax, x) : x \in H, (x, x) = 1\}$ of $A$. In fact, if $S$ is positive definite and invertible, then $W_+^S(A) = W(XAX^{-1})$, where $X$ is any operator on $H$ such that $S = X^*X$. If $S$ is invertible but indefinite, then the sets $W_+^S(A)$ can be understood as natural generalizations of the numerical range with respect to the Krein space structure defined by the indefinite scalar product $[x, y] = (Sx, y), \ x, y \in H$.

The sets $W_+^S(A)$, as well as other related sets, have been studied in [B, GP] (with the emphasis on the convexity properties) and in [LTU], where a more detailed description of the geometric shapes of $W_+^S(A)$ is given. In this paper we characterize operators $A$ whose numerical range is bounded, and investigate the geometric properties of $W_+^S(A)$ in relation to the spectrum of $A$. Some of our results are given for the finite-dimensional spaces $H$, in which case we identify $H$ with $\mathbb{C}^n$. Because $W_+^S(A) = W_-^S(A)$, we will state and prove our results for $W_+^S(A)$ only, with the understanding that analogous results are valid for $W_-^S(A)$ as well.

We denote by $L(H)$ the algebra of all bounded linear operators on $H$. For selfadjoint operators $X, Y \in L(H)$ the notation $X \geq Y$ means that the difference

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\[ X - Y \text{ is positive semidefinite. Throughout the paper it will be assumed that } H \text{ is separable.} \]

2. Basic properties

We start by recalling some basic and known results.

The joint numerical range \( W(G_1, \ldots, G_k) \) of \( k \) self-adjoint operators \( G_1, \ldots, G_k \in L(H) \) on \( H \) is defined by

\[ W(G_1, \ldots, G_k) = \{ (G_1x, x), \ldots, (G_kx, x) \} \in \mathbb{R}^k : x \in H, (x, x) = 1 \} \).

This notion is a useful generalization of the classical numerical range, and is well studied (see, e.g., [AT, BL]). Let Proposition 2.1. Let \( S = S^* \), \( A \in L(H) \). If \( G_1, G_2 \) are self-adjoint operators such that \( SA = G_1 + iG_2 \), then \( K(G_1, G_2, S) \) is convex. Consequently,

\[ W_S^+(A) = \{ x + iy \in C : (x, y, 1) \in K(G_1, G_2, S) \}, \]

is also convex.

The next proposition is very useful in studying the geometric properties of \( W_S^+(A) \).

Proposition 2.2. Let \( S = S^* \), \( A \in L(H) \).

(a) For every \( \alpha, \lambda \in C \), we have

\[ W_S^+(A + \lambda I) = W_S^+(A) + \lambda; \quad W_S^+(\alpha A) = \alpha W_S^+(A). \]

(b) Let \( H_0 \subseteq H \) be a (closed) subspace in \( H \), \( P_0 \) be the orthogonal projection on \( H_0 \), and let \( P_1 = 1 - P_0 \). Then \( W_{P_0 S}^+(L_0) \) \((P_0 A|H_0) \subseteq W_S^+(A) \).

Proof. Part (a) is clear. To prove (b), let \( x_0 \in H_0 \) be such that \( (P_0 Sx_0, x_0) = 1 \). Then it is easy to see that \( (Sx_0, x_0) = (P_0 Sx_0, x_0) = 1 \). The condition \( P_0 SP_1 \cdot P_1 AP_0 = 0 \) guarantees that

\[ (P_0 SP_0 \cdot P_0 Ax_0, x_0) = (SAx_0, x_0). \]

So the typical element \( (P_0 SP_0 \cdot P_0 Ax_0, x_0) \) of \( W_{P_0 S}^+(L_0)(P_0 A|H_0) \) also belongs to \( W_S^+(A) \). \qed

Besides convexity, another basic property for the classical numerical range is the boundedness. Actually, \( W(A) \) is always a compact convex set in the finite dimensional case. However, as shown in [LTU, Section 2], \( W_S^+(A) \) may be neither closed nor bounded in \( C \), even in the finite dimensional case. In fact, it was pointed out in Proposition 4.1 of [LTU] that if \( S \) is indefinite and \( SA \neq \lambda S \) for any \( \lambda \in C \), then \( W_S(A) \) is unbounded. In the following, we give complete characterization for \( S \) and \( A \) such that \( W_S(A) \) is nonempty and bounded.

Theorem 2.3. Let \( S = S^* \), \( A \in L(H) \). Then \( W_S^+(A) \) is nonempty and bounded if and only if EITHER
Therefore, \(W^+_S(A)\) is indefinite and \(SA = \lambda S\), for some \(\lambda \in \mathbb{C}\), OR

(b) the properties (i)-(ii) below are satisfied:

(i) \(S \geq 0\) and \(S \notin \mathbb{C}\);

(ii) the linear set \(\text{Ran } S^{\frac{1}{2}}\) is \(A^*-\)invariant, where \(S^{\frac{1}{2}}\) is the positive semidefinite square root of \(S\).

**Proof.** Clearly, if (a) holds, then \(W^+_S(A) = \{\lambda\}\). Assume (i) and (ii) hold. By Douglas’ lemma (see [D]), there exists \(\lambda \geq 0\) such that \(A^*SA \leq \lambda S\). Then for every \(x \in H\):

\[
|(SAx, x)|^2 = \left| \left(S^{\frac{1}{2}}Ax, S^{\frac{1}{2}}x\right) \right|^2 \leq \left( S^{\frac{1}{2}}Ax, S^{\frac{1}{2}}Ax \right) \cdot \left( S^{\frac{1}{2}}x, S^{\frac{1}{2}}x \right) = (A^*SAx, x)(Sx, x) \leq \lambda(Sx, x)^2.
\]

Thus, \(|z| \leq \lambda^{\frac{1}{2}}\) for every \(z \in W^+_S(A)\), and hence \(W^+_S(A)\) is bounded.

Conversely, assume that \(W^+_S(A)\) is nonempty and bounded. Assume first that \(S\) is indefinite. Let \(H_1 \subset H_2 \subset \cdots\) be a sequence of finite-dimensional subspaces such that

\[
\bigcup_m H_m = H,
\]

and \(P_mSP_m \in L(H_m)\) is indefinite (here \(P_m\) is the orthogonal projection on \(H_m\)). Using Proposition 2.2(b) and applying the finite dimensional result (Theorem 2.4 of [LTU]) to \(P_mSP_m\) and \(P_mAP_m\), we obtain that

\[
(SAx, y) = (\lambda Sx, y), \quad x, y \in H_m,
\]

where the constant \(\lambda\) is independent of \(m\). Now the condition (2.1) guarantees that \(SA = \lambda S\).

Next, assume that \(W^+_S(A)\) is non-empty and bounded, but \(S\) is positive semi-definite and nonzero. We will prove that (ii) holds. Suppose \(y = Ax \notin \text{Ker } S\) for some \(x \in \text{Ker } S\). Let \(z = Sy \neq 0\). Clearly, \(z \perp \text{Ker } S\). For a positive number \(\delta\) we have

\[
(S(x + \delta z), x + \delta z) = \delta^2 (Sz, z),
\]

\[
(SA(x + \delta z), x + \delta z) = \delta (SA(x + \delta z), z) = \delta [(z, z) + \delta(SAz, z)].
\]

Therefore, \(W^+_S(A)\) contains

\[
\frac{(SA(x + \delta z), x + \delta z)}{(S(x + \delta z), x + \delta z)} = \delta^{-1} \frac{(Sz, z)}{(S, z)} + \text{const.,}
\]

which tends to infinity as \(\delta \) tends to 0, a contradiction with the boundedness of \(W^+_S(A)\). Thus, \(\text{Ker } S\) is \(A\)-invariant, or, equivalently, \(\text{Ran } S = \text{Ran } S^{\frac{1}{2}}\) is \(A^*-\)invariant.

Let \(S_0 = PSP\), \(A_0 = PAP \in L(\text{Ran } S)\), where \(P\) is the orthogonal projection on \(\text{Ran } S\). For \(x \in H\), write \(x = x_1 + x_0\), where \(x_1 \in \text{Ker } S\), \(x_2 \in \text{Ran } S\). Because \(\text{Ker } S\) is \(A\)-invariant, it is easy to see that \((SAx, x) = (S_0A_0x_0, x_0); (Sx, x) = (S_0x_0, x_0)\). So \(W^+_S(A) = W^+_S(A_0)\). In other words, we can (and do) assume that \(\text{Ker } S = \{0\}\).

Define the linear operator \(C : \text{Ran } S^{\frac{1}{2}} \rightarrow \text{Ran } S^{\frac{1}{2}}\) by \(CS^{\frac{1}{2}}x = S^{\frac{1}{2}}Ax, \quad x \in H\). We
then have, for \(x \in H\), \(x \neq 0\),
\[
\frac{(S Ax, x)}{(S x, x)} = \frac{(S_\frac{1}{2} Ax, S_\frac{1}{2} x)}{(S_\frac{1}{2} x, S_\frac{1}{2} x)} = \frac{(Cy, y)}{(y, y)} = W^+_S(A),
\]
where \(y = S_\frac{1}{2} x\). Since \(W^+_S(A)\) is bounded, we have \(|(Cy, y)| \leq M\) for all \(y \in \text{Ran}S_\frac{1}{2}\), \(|y| = 1\), where \(M > 0\) is independent of \(y\). Using the polarization identity, we see that \(|(Cx, y)| \leq 4M\) for all normalized vectors \(x, y \in \text{Ran}S_\frac{1}{2}\). Thus, \(C\) is a bounded operator, and therefore can be extended to a bounded linear operator (also denoted by \(C\)) on \(H\). Now we have \(A^* S_\frac{1}{2} = S_\frac{1}{2} C^*\), and (ii) is obvious. \(\square\)

Note that (ii) can be stated in an equivalent form (see [D]):  
(iii) there exists \(\lambda \geq 0\) such that \(A^* S A \leq \lambda S\).

We also note that if \(W^+_S(A) \neq \emptyset\) is bounded, then either \(W^+_S(A) = \{\lambda\}\) (if \(S\) is indefinite), or \(S \geq 0\), \(S \neq 0\) and
\[
W^+_S(A) = \left\{ (Cy, y) : y \in \text{Ran}S_\frac{1}{2}, (y, y) = 1 \right\},
\]
for some \(C \in L(\text{Ran}S)\); in fact, \(C\) is explicitly given by \(CS_\frac{1}{2} = S_\frac{1}{2} A\).

It is well-known that if \(H\) is an orthogonal sum of two \(A\)-invariant subspaces \(H_1 \oplus H_2\), and if \(A\) is written in the form \(A = A_1 \oplus A_2\) with \(A_j \in \text{L}(H_j)\) for \(j = 1, 2\), then \(W(A) = \text{conv}\{W(A_1) \cup W(A_2)\}\) (we denote by \(\text{conv}\{X\}\) the convex hull of the set \(X\)). An extension of this result to \(W_S(A)\) is desirable. We will say that \(H\) has a direct sum decomposition compatible with \(S\) and \(A\) if \(H\) is a direct sum of two \(A\)-invariant (closed) subspaces: \(H = H_1 \oplus H_2\) such that \((Sx, y) = 0\) for all \(x \in H_1, y \in H_2\). We shall write \(A = A_1 \oplus A_2\) and \(S = S_1 \oplus S_2\), with \(A_j, S_j\) acting on \(H_j\) for \(j = 1, 2\), if such a decomposition exists. Of course, for each \(j = 1, 2\), one may consider \(W^+_S(A_j), W^-_S(A_j), W^0_S(A_j)\). By Proposition 2.2(b), we see that \(W^+_S(A_j) \subseteq W_S(A)\). To give a complete description of \(W_S(A)\) in terms of sets associated with \(S_j\) and \(A_j\) for \(j = 1, 2\), we need to consider complex numbers of the forms:

1. \(z = \alpha z_1 - (1 - \alpha) z_2\) for some \(\alpha > 1\), \(z_1 \in W^+_S(A_1), z_2 \in W^-_S(A_2)\);
2. \(z = z_1 + z_2\) for some \(z_1 \in W^+_S(A_1), z_2 \in W^-_S(A_2)\);
3. \(z = \alpha z_1 + (1 - \alpha) z_2\) for some \(\alpha > 0\), \(\alpha \in W^+_S(A_1), z_2 \in W^+_S(A_2)\);
4. \(z = z_1 + z_2\) for some \(z_1 \in W^+_S(A_1), z_2 \in W^+_S(A_2)\);
5. \(z = -\alpha z_1 + (1 - \alpha) z_2\) for some \(0 > \alpha > 0\), \(z_1 \in W^-_S(A_1), z_2 \in W^-_S(A_2)\).

We are now ready to state our result.

**Proposition 2.4.** Suppose \(H = H_1 \oplus H_2\) is a direct sum decomposition compatible with \(S\) and \(A\) so that \(A = A_1 \oplus A_2\) and \(S = S_1 \oplus S_2\), with \(A_j, S_j\) acting on \(H_j\) for \(j = 1, 2\). Then
\[
W^+_S(A) = T_1 \cup T_2 \cup T_3 \cup T_4 \cup T_5,
\]
where \(T_j\) is the set of \(z\) satisfying condition (j) above for \(j = 1, \ldots, 5\).

**Proof.** Let \(x = x_1 + x_2, x_1 \in H_1, x_2 \in H_2\) be such that \((Sx, x) = (S_1 x_1, x_1) + (S_2 x_2, x_2) = 1\). Then \((S Ax, x) = (S_1 A_1 x_1, x_1) + (S_2 A_2 x_2, x_2)\). If \((S_1 x_1, x_1) = 0\), we have \(z_1 = (S_1 A_1 x_1, x_1) \in W^0_{S_1}(A_1)\) and \((S_2 A_2 x_2, x_2) \in W^0_{S_2}(A_2)\), and hence \((S Ax, x) \in T_4\). Similarly, if \((S_2 x_2, x_2) = 0\), then one can show that \((S Ax, x) \in T_2\).
For all other cases, one can let $\alpha = (S_1 x_1, x_1)$ and $(1 - \alpha) = (S_2 x_2, x_2)$ and show that $(S A x, x)$ is in one of the forms (1), (3) or (5).

It is easy to show that complex numbers of the form (1) - (5) lie in $W_S(A)$. The result follows.

We have the following corollary that covers the classical result.

**Corollary 2.5.** Suppose $H = H_1 \oplus H_2$ is a direct sum decomposition compatible with $S$ and $A$ so that $A = A_1 \oplus A_2$ and $S = S_1 \oplus S_2$, with $A_j, S_j$ acting on $H_j$ for $j = 1, 2$.

(a) If $S_1$ is positive definite, then

$$W^+_S(A) = T_1 \cup T_2 \cup T_3.$$

(b) If both $S_1$ and $S_2$ are positive definite, then

$$W^+_S(A) = \text{conv}\{W^+_{S_1}(A_1) \cup W^+_{S_2}(A_2)\}.$$

3. Special boundary points and eigenvalues

As before, let $S = S^*$, $A \in L(H)$. It is well-known (e.g., see [HH, Section 1.6]) that if $W(A)$ has some special boundary points, then $H$ is an orthogonal sum of two $A$-invariant subspaces. We obtain similar results for $W^+_S(A)$ in this section.

**Theorem 3.1.** Assume that $z_0 \in W^+_S(A)$ is an angle point of $W^+_S(A)$, i.e., there exist $\theta \in \mathbb{R}$ and $\epsilon > 0$ such that for every $z \in W^+_S(A)$ the inequality

$$\text{Re}(z - z_0) \cos \theta + \text{Im}(z - z_0) \sin \theta \geq \epsilon \|z - z_0\|$$

holds. Then for every $x_0 \in H$ such that $(S A x_0, x_0) = 1$ and $z_0 = (S A x_0, x_0)$ we have

$$S A x_0 = (S_0 x_0);$$

in particular, if $\text{Ker} S = \{0\}$, then $x_0$ is an eigenvector of $A$ corresponding to the eigenvalue $z_0$. If, in addition, $S$ is invertible, then $x_0$ is also an eigenvector of $A^* S$ corresponding to $z_0$.

Here $A^* S = S^{-1} A^* S$ is the adjoint of $A$ in the indefinite scalar product induced by $S$.

**Proof.** Using Proposition 2.2(a), we can assume without loss of generality that $z_0 = 0$ and $\theta = 0$. The inequality (3.1) takes the form

$$\text{Re} z \geq \epsilon \|z\|$$

for every $z \in W^+_S(A)$. Let $x_0 \in H$ be such that

$$(S A x_0, x_0) = 0; \quad (S x_0, x_0) = 1.$$ Fix $w \in H$, and consider the vector $y = x_0 + t w$ for $t \in \mathbb{R}$ close to zero. Let

$$F(t) = \frac{(S A y, y)}{(S y, y)} \in W^+_S(A).$$

We have

$$F(t) = \frac{(S A(x_0 + t w), x_0 + t w)}{(S (x_0 + t w), x_0 + t w)} = \frac{t((S A x_0, w) + (S w, x_0)) + t^2(S w, w)}{1 + \alpha},$$

where

$$\alpha = t((S x_0, w) + (S w, x_0)) + t^2(S w, w).$$
So
\[
F(t) = \left[ t((SAx_0, w) + (SAw, x_0)) + t^2(SAw, w) \right] \cdot \frac{1}{1 + \alpha}
\]
\[
= \left[ t((SAx_0, w) + (SAw, x_0)) + t^2(SAw, w) \right] \cdot (1 - \alpha + \alpha^2 - \alpha^3 + \cdots)
\]
(3.3)
\[
= \left[ t((SAx_0, w) + (SAw, x_0)) + t^2((SAw, w)
- (SAx_0, w) + (SAw, x_0))((Sx_0, w) + (Sw, x_0))) + O(t^3) \right].
\]
If for some \( w \in H \) we had \( \text{Re}((SAx_0, w) + (SAw, x_0)) \neq 0 \), then taking \( t \) close to zero but of opposite signs, we would obtain a contradiction with (3.2). Thus,
(3.4) \[ \text{Re}((SAx_0, w) + (SAw, x_0)) = 0 \]
for all \( w \in H \).
If for some \( w \in H \) we had
\[ \text{Im}((SAx_0, w) + (SAw, x_0)) \neq 0, \]
then the formula (3.3) gives
\[ \frac{\text{Re}F(t)}{\text{Im}F(t)} \to 0 \quad \text{as } t \to 0, \]
a contradiction with (3.2). Thus,
\[ \text{Im}((SAx_0, w) + (SAw, x_0)) = 0, \]
for all \( w \in H \). So
(3.5) \[ (SAx_0, w) + (SAw, x_0) = 0 \]
for all \( w \in \mathbb{C}^n \). Replacing in (3.5) \( w \) by \( iw \), and comparing with (3.5), we obtain \( (SAx_0, w) = 0 \) and \( (SAw, x_0) = 0 \) for all \( w \in H \), which implies
(3.6) \[ SAx_0 = 0; \quad A^*Sx_0 = 0. \]
If, in addition, \( S \) is invertible, then the second equality in (3.6) implies \( A[^*]x_0 = 0. \)

**Proposition 3.2.** Let \( \mathcal{M} \) be an \( S \)-regular subspace. Then the \( S \)-orthogonal companion
\[ \mathcal{M}^\perp = \{ y \in H : (Sy, x) = 0 \text{ for all } x \in \mathcal{M} \} \]
is a direct complement of \( \mathcal{M} \), and \( \mathcal{M}^\perp \) is \( S \)-regular as well. If, in addition, \( \mathcal{M} \) is \( A \)-reducing, then \( \mathcal{M}^\perp \) is in turn \( A \)-reducing.

For the proof, see [GLR] (in the finite-dimensional case) or [AI] (Theorem 7.16).
Theorem 3.3. If \( z_0 \) is an eigenvalue of \( A \) having a positive eigenvector \( x_0 \), and if \( z_0 \) is a boundary point of \( W^+_S(A) \), then \( \text{Span}\{x_0\} \) is an \( A \)-reducing subspace.

Proof. We may assume \( (Sx_0,x_0) = 1 \). Also, without loss of generality we may assume that \( z_0 = 0 \) and that Re \( u \geq 0 \) for all \( u \in W^+_S(A) \). Now we repeat the construction of the proof of Theorem 3.1. Take \( w \in H \), let \( y = x_0 + tw \), and let

\[
F(t) = \frac{(S Ay, y)}{(Sy, y)} = \frac{t(S Aw, x_0) + t^2(S Aw, w)}{1 + \alpha},
\]

where \( \alpha = t((S x_0, x) + (Sw, x_0)) + t^2(Sw, w) \). As in the proof of Theorem 3.1, we obtain Re \( (S Aw, x_0) = 0 \) for all \( w \in H \). Replacing \( w \) by \( iw \), we also obtain Im \( (S Aw, x_0) = 0 \), hence \( (S Aw, x_0) = 0 \). Thus, \( A^*Sx_0 = 0 \), which is equivalent to \( A^{n+1}x_0 = 0 \).

\[ \Box \]

Corollary 3.4. Assume the hypotheses of Theorem 3.1. Let \( \mathcal{M}_+(z_0) \) be a maximal \( S \)-positive subspace generated by vectors \( x \neq 0 \) such that \( z_0 = (S Ax, x) / (S x, x) \). Assume that \( \mathcal{M}_+(z_0) \) is \( S \)-regular. Then \( \mathcal{M}_+(z_0) \) is an \( A \)-reducing subspace, and

\[
(3.7) \quad z_0 \notin W^+_S(A|\mathcal{M}_+(z_0)^\perp).
\]

Proof. Except for (3.7), all parts of the corollary follow from Theorem 3.1. If (3.7) were not true, then \( z_0 \) would be an angle point of \( W^+_S(A|\mathcal{M}_+(z_0)^\perp) \) (because of Proposition 2.2(b)), and an application of Theorem 3.1 would produce a vector \( x_0 \in M_+(z_0)^\perp \) such that \( Ax_0 = z_0x_0 \) and \( (Sx_0,x_0) = 1 \). Then \( M := \mathcal{M}_+(z_0) + \text{Span}\{x_0\} \) would be an \( S \)-positive subspace generated by the vectors \( x \neq 0 \) such that \( (S Ax, x) / (S x, x) = z_0 \). But \( M \) is larger than \( \mathcal{M}_+(z_0) \), a contradiction with the maximality of \( \mathcal{M}_+(z_0) \).

\[ \Box \]

Note that in the finite-dimensional case every \( S \)-positive subspace is \( S \)-regular. This is generally false in infinite-dimensional Krein spaces.

4. Matrices having polygonal numerical range

We continue to assume in this section that \( S \) is nonsingular. In addition, it will be assumed in this section that \( H \) is finite dimensional.

We say that \( W^+_S(A) \) is \textit{polygonal} if \( W^+_S(A) \) is the intersection of a finite number of closed half-planes.

In the definite case \( (S \text{ positive definite, and we may assume } S = I \) without essential loss of generality), the answer is well known (see, for example, section 3.10 in [GL], or section 1.6 in [HJ]): \( W^+_S(A) \) is polygonal if and only if there is an \( A \)-reducing subspace \( \mathcal{M} \) such that \( A|\mathcal{M} \) is normal with eigenvalues at the vertices of \( W^+_S(A) \), and \( W^+_S(A|\mathcal{M}) \) is contained in \( W^+_S(A) \) but does not contain any vertices of \( W^+_S(A) \).

In the indefinite case the situation is more complicated because \( W^+_S(A) \) is often unbounded (see Theorem 2.3).

Consider first the case when \( W^+_S(A) \) has no angle points.

Theorem 4.1. Assume that \( W^+_S(A) \) is polygonal and has no angle points. Then only the following cases can occur:

(a) \( W^+_S(A) \) is a straight line. This happens if and only if \( A \) has the form \( A = \alpha I + \beta B \), where \( \alpha, \beta \in \mathbb{C} \), and \( B \) is \( S \)-self-adjoint such that \( SB \) is indefinite;
(b) $W^+_S(A)$ coincides with $C$;
(c) $W^+_S(A)$ is a closed half-plane.

Proof. Observe that under the hypotheses of the theorem the set $W^+_S(A)$ is unbounded. We show first of all that the case when $W^+_S(A)$ is the strip between two parallel lines is impossible. Assume the contrary. Using Proposition 2.2(a), we can assume without loss of generality that

$$W^+_S(A) = \{(x, y) \in \mathbb{R}^2 : -1 \leq x \leq 1\}.$$ 

By Proposition 2.1,

$$W^+_S(A) = K(G_1, G_2, S) \cap \{(x, y, 1) : x, y \in \mathbb{R}\},$$

where

$$K(G_1, G_2, S) = \{\langle u^* G_1 u, u^* G_2 u, u^* S u \rangle : u \in \mathbb{C}^n \},$$

and the Hermitian matrices $G_1, G_2$ are such that $SA = G_1 + iG_2$. Since $K(G_1, G_2, S)$ is a closed convex cone (see, e.g., [AT]), we must have that $K(G_1, G_2, S)$ coincides with the wedge $\{(x, y, z) \in \mathbb{R} : z \geq 0, |x| \leq z\}$. In particular, $S \geq 0$. But $S$ is invertible, so, in fact, $S$ is positive definite, a contradiction with $W^+_S(A)$ being an unbounded set.

Now clearly one of (a), (b), or (c) holds. It follows from [BL] that $W^+_S(A)$ is a straight line if and only if the condition indicated in (a) holds.

$$\square$$

Remark 4.2. Note that Theorem 4.1 actually holds for singular $S$ as well. One can use the same arguments in the first paragraph of our proof until we arrive at the conclusion that $S \geq 0$. At this point, if $S$ is singular, we can find a unitary matrix $U$ such that $U^* SU = S_1 \oplus 0$, where $S_1$ is positive definite. Then $U^* (G_1 + iG_2) U = (U^* S U) (U^* A U)$ is of the form $\begin{pmatrix} B_1 & 0 \\ 0 & 0 \end{pmatrix}$, where $B_1$ has the same size as $S_1$. By Theorem 2.3 in [LTU], if $B_2 \neq 0$ then $W^+_S(A) = C$; if $B_2 = 0$ then $W^+_S(A)$ is bounded. Both cases contradict the assumption that $W^+_S(A)$ is a strip between two parallel lines. One can then complete the proof as before.

Consider now the case when $W^+_S(A)$ has angle points.

Theorem 4.3. Let $z_1, \ldots, z_k$ be the angle points of $W^+_S(A)$. Then there exist mutually $S$-orthogonal $A$-reducing subspaces $\mathcal{M}_1, \ldots, \mathcal{M}_{k+1}$ with the following properties:

(i) $\mathcal{M}_1, \ldots, \mathcal{M}_k$ are $S$-positive;
(ii) $Ax = z_j x$ for every $x \in \mathcal{M}_j$ ($j = 1, \ldots, k$);
(iii) $z_1, \ldots, z_k$ do not belong to $W^+_S(A)$.

Proof. Let $\mathcal{M}_1$ be a maximal $S$-positive subspace generated by vectors $x \neq 0$ such that $z_1 = \frac{\langle SAx, x \rangle}{\langle Sx, x \rangle}$. By Theorem 3.1, $Ax = z_1 x$ for every $x \in \mathcal{M}_1$. By Corollary 3.4, $\mathcal{M}_1$ is $A$-reducing, and $z_1 \notin W^+_S(\mathbb{P}_1^{\perp} | \mathcal{M}_1^{\perp})$, where $\mathbb{P}_1$ is the orthogonal projection on $\mathcal{M}_1^{\perp}$. By Proposition 2.2(b),

$$W^+_S \mathbb{P}_1^{\perp} | \mathcal{M}_1^{\perp}) \subseteq W^+_S(A).$$

On the other hand, we claim that $z_2, \ldots, z_k$ are angle points of $W^+_S(\mathbb{P}_1^{\perp} | \mathcal{M}_1^{\perp})$. Indeed, in view of (4.1) we only have to prove that $z_2, \ldots, z_k \in W^+_S(\mathbb{P}_1^{\perp} | \mathcal{M}_1^{\perp})$. 

Consider $z_2$. By Proposition 2.4 we have (in view of $W_{(I-P_1)S(I-P_1)}(A|\mathcal{M}_1) = \{z_1\}$,\(^{(4.2)}\)

$$W_S^+(A) = \bigcup_{0 \leq \alpha < 1} \{\alpha z_1 + (1 - \alpha)W^+_{P_1SP_1}(A|\mathcal{M}_1^+)\} \cup \bigcup_{\alpha > 1} \{\alpha z_1 + (1 - \alpha)W^-_{P_1SP_1}(A|\mathcal{M}_1^+)\} \cup \{z_1\} + W^0_{P_1SP_1}(A|\mathcal{M}_1^+)\}.$$\(^{(4.3)}\)

According to (4.2), three cases (which are not mutually exclusive) can occur:

(3)

$$z_2 = \alpha z_1 + (1 - \alpha)u, \quad u \in W^+_{P_1SP_1}(A|\mathcal{M}_1^+), \quad 0 \leq \alpha < 1;$$

(4)

$$z_2 = \alpha z_1 + (1 - \alpha)v, \quad v \in W^-_{P_1SP_1}(A|\mathcal{M}_1^+), \quad \alpha > 1;$$

(5)

$$z_2 = z_1 + w, \quad w \in W^0_{P_1SP_1}(A|\mathcal{M}_1^+).$$

If (4.3) holds, then clearly $u = z_2$ and $\alpha = 0$ (otherwise $z_2$ would not be an angle point of $W_S^+(A)$). If (4.4) holds, then by (4.2) the whole ray $\{\alpha z_1 + (1 - \alpha)v : \alpha \geq 1\}$ belongs to $W_S^+(A)$, again a contradiction with $z_2$ being an angle point of $W_S^+(A)$. If (4.5) holds, then (since $W^0_{P_1SP_1}(A|\mathcal{M}_1^+)$ is a cone) in view of (4.2) the whole ray $\{z_1 + \alpha w : \alpha > 0\}$ belongs to $W_S^+(A)$, a contradiction again. It follows therefore that $z_2 \in W^+_{P_1SP_1}(A|\mathcal{M}_1^+)$, as claimed.

The proof of Theorem 4.3 is now easily completed using induction on $k$, and applying the induction hypothesis to $P_1SP_1$ in place of $S$ and to $A|\mathcal{M}_1^+$ in place of $A$. \(\square\)

In contrast with the classical numerical range result, one cannot claim in Theorem 4.3 that $W_S^+(A|\mathcal{M}_{k+1})$ is always contained in $W_S^+(A|\mathcal{M})$, where $\mathcal{M} = \mathcal{M}_1 + \cdots + \mathcal{M}_k$. Indeed, since $\mathcal{M}$ is $S$-positive, the numerical range $W_S^+(A|\mathcal{M})$ is bounded, while $W_S^+(A|\mathcal{M}_{k+1})$ need not be bounded. Using Theorem 2.3 it is easy to check that if $W_S^+(A)$ is bounded, then (under the hypotheses of Theorem 4.3) the containment $W_S^+(A|\mathcal{M}_{k+1}) \subseteq W_S^+(A|\mathcal{M})$ holds true.

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**REFERENCES**


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