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**PEAK INTERPOLATION SETS FOR SOME ALGEBRAS OF
ANALYTIC FUNCTIONS**

ALEXANDER MUNRO DAVIE AND BERNT KARSTEN OKSENDAL

PEAK INTERPOLATION SETS FOR SOME ALGEBRAS OF ANALYTIC FUNCTIONS

A. M. DAVIE AND B. K. ØKSENDAL

For certain algebras of analytic functions on holomorphically convex sets in C^n metric sufficient conditions are given for a set (not necessarily compact) to be an interpolation set. The results extend the Rudin-Carleson theorem for the disc algebra.

Let K be a compact subset of C^n which is holomorphically convex, i.e. K is the intersection of a decreasing sequence of pseudoconvex domains (see [4], Ch. 2). We denote by $H(K)$ the uniform closure on K of the algebra of all functions analytic in a neighborhood of K , and by $A(K)$ the algebra of all continuous functions on K analytic on K^0 (the interior of K). If E is any subset of the boundary ∂K of K then we denote by H_E^∞ the algebra of all bounded continuous functions on $K^0 \cup E$ which are analytic on K^0 . We show that if the boundary of K is well behaved at each point of E , and E satisfies a metric condition which says roughly that E has zero 2-dimensional measure in the directions of the complex tangent and zero one dimensional measure in the orthogonal direction, then E is a peak interpolation set (in an appropriate sense) for $H_{E \cup (\partial K \setminus E)}^\infty$. If E is compact then it is a peak interpolation set in the usual sense ([2], p. 59) for the uniform algebra $H(K)$. We show also that if E has zero one-dimensional measure then the conditions on ∂K can be relaxed.

We say that ∂K is strictly pseudoconvex in a neighborhood of a point $\zeta \in \partial K$ if there is an open neighborhood V of ζ such that $V \cap \partial K$ is a C^2 -submanifold of V and the Levi form is positive definite at ζ . Then we can find an open neighborhood V of ζ and a C^2 strictly plurisubharmonic function ρ in V such that $K \cap V = \{z \in V: \rho(z) \leq 0\}$ and $\text{grad } \rho \neq 0$ on $V \cap \partial K$. (See [3] Prop. IX. A4).

LEMMA 1. *Let K be a holomorphically convex compact set in C^n and let ζ be a point of ∂K in a neighborhood of which ∂K is strictly pseudoconvex. We can find positive numbers m_ζ and M_ζ and $G_\zeta \in H(K)$, such that*

- (a) $\text{Re } G_\zeta(z) \geq m_\zeta |\zeta - z|^2, z \in K$
- (b) $\text{Re } G_\zeta(z) \leq M_\zeta |\zeta - z|^2, z \in \partial K$
- (c) $\text{grad } (\text{Re } G_\zeta)(\zeta) = -\text{grad } \rho(\zeta)$.

Proof. Put

$$F(z) = \sum_{i=1}^n \frac{\partial \rho(\zeta)}{\partial \zeta_i} (z_i - \zeta_i) + \frac{1}{2} \sum_{i,j=1}^n \frac{\partial^2 \rho(\zeta)}{\partial \zeta_i \partial \zeta_j} (z_i - \zeta_i)(z_j - \zeta_j).$$

Then the Taylor expansion of ρ about ζ is

$$\rho(z) = 2 \operatorname{Re} F(z) + \sum_{i,j=1}^n \frac{\partial^2 \rho(\zeta)}{\partial \zeta_i \partial \zeta_j} (z_i - \zeta_i)(z_j - \zeta_j) + o(|z - \zeta|^2).$$

Since ρ is strictly plurisubharmonic at ζ it follows that, shrinking V if necessary, we can find $m > 0$ with $\operatorname{Re} F(z) \leq -m|\zeta - z|^2$ for $z \in K \cap V$. Since $\rho = 0$ on $\partial K \cap V$ we also deduce that for some constant M

$$\operatorname{Re} F(z) \geq -M|\zeta - z|^2; z \in \partial K \cap V.$$

Choose a pseudoconvex open neighborhood U of K so that $\operatorname{Re} F < 0$ on an open neighborhood W of $\partial V \cap U$ in U . Let $W_1 = W \cup (V \cap U)$ and $W_2 = W \cup (U \setminus \bar{V})$, so that $W_1 \cup W_2 = U$ and $W_1 \cap W_2 = W$. By solving a Cousin problem in U (see [4], Theorem 5.5.1) we can find analytic functions g_1 and g_2 on W_1 and W_2 respectively such that $g_2 - g_1 = F^{-2} \log F$ on W .

$$\text{Put } h(z) = \begin{cases} F(z) \exp(F(z)^2 g_1(z)), & z \in W_1 \\ \exp(F(z)^2 g_2(z)), & z \in W_2. \end{cases}$$

The definitions agree on W so h is an analytic function on U , $h(z) = 0$ only when $z = \zeta$, and in a neighborhood of ζ , $h(z) = F(z) + o(|z - \zeta|^3)$. Thus $\operatorname{Re} h \leq 0$ near ζ , so there exists $\varepsilon > 0$ such that if $z \in K$ and $|h(z) - \varepsilon| \leq \varepsilon$ then $z = \zeta$. Put

$$G(z) = -\frac{h(z)}{\varepsilon - h(z)}, z \in K.$$

Then $G \in \bar{H}(K)$, $\operatorname{Re} G(z) > 0$ for $z \in K \setminus \{\zeta\}$. Finally, near ζ , $\operatorname{Re} G(z) = -\varepsilon^{-1} \operatorname{Re} F(z) + \varepsilon^{-2} (\operatorname{Im} F)^2 + o(|z - \zeta|^3)$ from which it follows that $G_\zeta = 2\varepsilon G$ has the required properties.

If S is a real subspace of C^n and Y is any subset we denote by $d_S(Y)$ the diameter (in the Euclidean metric) of the (real) orthogonal projection of Y on S .

Let K be a compact holomorphically convex subset of C^n and suppose ∂K is strictly pseudoconvex in a neighborhood of a point $\zeta \in \partial D$. Then in a neighborhood of ζ we can write $\partial K = \{z: \rho(z) = 0\}$ where $\rho(z)$ is strictly plurisubharmonic in a neighborhood of ζ and $\operatorname{grad} \rho \neq 0$. The vector $i \operatorname{grad} \rho$ is orthogonal to $\operatorname{grad} \rho$ and so lies in the (real) tangent space to ∂K at ζ ; let $T(\zeta)$ be the orthogonal complement to $i \operatorname{grad} \rho$ in this space. Then $T(\zeta)$ is the unique complex subspace of the real tangent space with complex dimension $n - 1$. Let $L(\zeta)$ be the real

line spanned by the vector $i \operatorname{grad} \rho$.

If E is any subset of ∂K we denote by H_E^∞ the set of all bounded continuous functions on $K^0 \cup E$ which are analytic on K^0 . We define $A(K) = H_{\partial K}^\infty$.

THEOREM 1. *Let F be a subset of ∂K such that ∂K is strictly pseudoconvex in a neighborhood of F . Suppose that for every $\varepsilon > 0$ the set F can be covered by a sequence $\{V_i\}$ of open sets with diameter $< \varepsilon$ such that if $\zeta_i \in F \cap V_i$ for each i then $\sum_i d_{L(\zeta_i)}(V_i) < \varepsilon$ and $\sum_i \{d_{T(\zeta_i)}(V_i)\}^2 < \varepsilon$. Let V be a neighborhood of F , let $\eta > 0$, and let g be a bounded continuous function on F with $\|g\| \leq 1$.*

Then we can find $f \in H_{F \cup (K \setminus \bar{V})}^\infty$ with $f|_F = g$, $\|f\| \leq 1$, and $|f| < \eta$ on $K \setminus V$.

The proof will be split up into lemmas.

LEMMA 2. *Let F, V and η be as in the theorem. Then we can find $f \in H_{F \cup (K \setminus \bar{V})}^\infty$ with $f = 1$ on F , $\|f\| \leq 2$ and $|f| < \eta$ on $K \setminus V$.*

Proof. For each $\zeta \in F$ we choose $m_\zeta, M_\zeta > 0$, and a function $G_\zeta \in H(K)$ as in Lemma 1.

If W_ζ is a sufficiently small open neighborhood of ζ , then whenever $\zeta \in U \subseteq W_\zeta$ and $z \in U \cap \partial K$ we have

$$\begin{aligned} |G_\zeta(z)| &\leq \operatorname{Re} G_\zeta(z) + |\operatorname{Im} G_\zeta(z)| \\ &\leq A_\zeta |z - \zeta|^2 + |\langle \operatorname{grad} (\operatorname{Im} G_\zeta)(\zeta), z - \zeta \rangle| \\ &\leq 2A_\zeta (d_1^2 + d_2^2) + |\operatorname{grad} \rho(\zeta)| d_1 \\ &\leq B_\zeta (d_1 + d_2^2) \end{aligned}$$

where $d_1 = d_{L(\zeta)}(U)$, $d_2 = d_{T(\zeta)}(U)$, A_ζ, B_ζ do not depend on z , and \langle, \rangle denotes the real scalar product.

For each positive integer n let

$$F_n = \{\zeta \in F: B_\zeta < n, \Delta(\zeta, 1/n) \subseteq W_\zeta, m_\zeta d(\zeta, K \setminus V)^2 > 1/n, m_\zeta > 1/n\}.$$

Then $F = \bigcup_n F_n$. For each n we choose a sequence $\{V_i^{(n)}\}$ of open sets with diameter less than $1/n$ such that each point of F_n is contained in infinitely many $V_i^{(n)}$, and $\sum_i \{d_{L(\zeta_i^{(n)})}(V_i^{(n)}) + (d_{T(\zeta_i^{(n)})}(V_i^{(n)})\}^2 < \eta n^{-2} 2^{-n-2}$ for some choice of $\zeta_i^{(n)} \in V_i^{(n)} \cap F_n$. Renumber the collection of all $V_i^{(n)}$ as V_1, V_2, \dots . For each j choose n_j so that $V_j = V_i^{(n_j)}$ for some i , and let $\zeta_j = \zeta_i^{(n_j)}$. Let $G_j = G_{\zeta_j}$. Writing $c_j = d_{L(\zeta_j)}(V_j) + \{d_{T(\zeta_j)}(V_j)\}^2$ we define

$$B_r(z) = \prod_{j=1}^r \frac{G_j(z)}{2n_j c_j + G_j(z)}, \quad z \in K, \quad r = 1, 2, \dots$$

Then $B_r \in H(K)$ and $|B_r| \leq 1$ on K . We claim that $\{B_r\}$ converges pointwise on $F \cup (K \setminus \bar{F})$ to a limit B which is continuous on $F \cup (K \setminus \bar{F})$, analytic on K° , zero at each point of F , with $\|B\| \leq 1$ and $|1 - B| < \eta$ on $K \setminus V$.

If $z \in K \setminus V$ then $\operatorname{Re} G_j(z) \geq m_{\zeta_j} |z - \zeta_j|^2 > 1/n_j$, so

$$\begin{aligned} \sum_{j=1}^{\infty} \left| 1 - \frac{G_j(z)}{2n_j c_j + G_j(z)} \right| &= \sum_{j=1}^{\infty} \frac{2n_j c_j}{|2n_j c_j + G_j(z)|} \\ &\leq \sum_{j=1}^{\infty} 2n_j^2 c_j < \eta/2, \end{aligned}$$

which proves that $B_r(z)$ converges to a limit $B(z)$ with $|1 - B(z)| < \eta$. If $z \in K \setminus \bar{F}$ then

$$\sum_{j=j_0}^{\infty} \frac{2n_j c_j}{|2n_j c_j + G_j(z)|} \leq \sum_{j=j_0}^{\infty} \frac{2n_j^2 c_j}{|z - \zeta_j|^2} \leq d(z, F)^{-2} \sum_{j=j_0}^{\infty} 2n_j^2 c_j.$$

The series on the right converges, so B_r converges uniformly to a limit B on sets at positive distance from F , so B is continuous on $K \setminus \bar{F}$ and analytic on K° .

Finally let $z \in F$. Then $z \in V_j$ for infinitely many j . For each such j we have $V_j \subseteq W_{\zeta_j}$ and for all $w \in W_{\zeta_j}$,

$$\left| \frac{G_j(w)}{2n_j c_j + G_j(w)} \right| \leq \frac{n_j c_j}{2n_j c_j} = \frac{1}{2}.$$

It follows that $B_r(z) \rightarrow 0$ and $\lim |B_r|$ is continuous at z . Thus B has the asserted properties, and $f = 1 - B$ satisfies the requirements of the theorem.

LEMMA 3. *Let X be a compact subset of K , W a neighborhood of X , and h a continuous function on K with support in X such that $\|h\| \leq 1$. Let $\eta > 0$.*

Then there exists $f \in H_{F \cup (K \setminus \bar{F})}^\infty$ such that $|f - h| < \eta$ on F , $\|f\| \leq 3$, and $|f| < \eta$ on $K \setminus W$.

Proof. Choose $0 < \delta < d(X, K \setminus W)$ so small that $|h(x) - h(y)| < \eta/8$ whenever $x, y \in K$, $|x - y| < \delta$. We can easily find an integer $N > 0$, compact sets $X_1 \cdots X_r$ contained in X , and open sets $W_1 \cdots W_r$, with diameters $< \delta$, with $W_i \supseteq X_i$, $W_i \subseteq W$, such that

(a) if $x \in X$ and N_x is the number of integers i in $\{1, \dots, r\}$ for which $x \in X_i$, $|N_x - N| < \eta N/8$

(b) if $x \in C^n$ the number of integers i for which $x \in W_i \setminus X_i$ is less than ηN .

Let $F_i = F \cap X_i$. For $i = 1, 2 \cdots r$ we can find by Lemma 2 functions $f_i \in H_{F_i \cup (K \setminus \bar{F}_i)}^\infty$ with $f_i = 1$ on F_i , $\|f_i\| \leq 2$ and $|f_i| < \eta/3r$ on $K \setminus W_i$.

Choose $x_i \in X_i$ for each i and put $f(z) = 1/N \sum_{i=1}^r f_i(z)h(x_i)$, $z \in F \cup (K \setminus \bar{F})$. Clearly $f \in H_{F \cup (K \setminus \bar{F})}^\infty$ and $\|f\| \leq 3$ by (a). If $z \in K \setminus W$ then $|f_i(z)| < \eta/r$ for each i so $|f(z)| < \eta$.

Finally let $z \in F$. Then

$$\begin{aligned} f(z) &= \frac{1}{N} \left(\sum_{z \in X_i} + \sum_{z \in W_i \setminus X_i} + \sum_{z \notin W_i} \right) f_i(z)h(x_i) \\ &= f_1(z) + f_2(z) + f_3(z), \text{ say.} \end{aligned}$$

We have

$$\begin{aligned} |f_1(z) - h(z)| &\leq \left| \frac{1}{N} \sum_{z \in X_i} f_i(z)(h(z) - h(x_i)) \right| \\ &+ \left| 1 - \frac{N_z}{N} \right| < \frac{\eta N_z}{8N} + \left| 1 - \frac{N_z}{N} \right| < \eta/3, \end{aligned}$$

by (a), since $|z - x_i| < \delta$. Moreover, $|f_2(z)| < \sum_{i=1}^r \eta/3$, by (b) and $|f_3(z)| < \sum_{i=1}^r \eta/3r = \eta/3$, so that we have $|f(z) - h(z)| < \eta$ as required.

LEMMA 4. *With F as in the theorem, if W is any open neighborhood of F and h a bounded continuous function on W with $\|h\| \leq 1$, we can find $G \in H_{F \cup (K \setminus \bar{F})}^\infty$ with $|G - h| < \eta$ on F , $\|G\| \leq 7$, and $|G| < \eta$ outside W .*

Proof. Choose a sequence $\{W_n\}$ of relatively compact open subsets of W with $W = \bigcup_{n=1}^\infty W_n$, such that $\bar{W}_m \cap \bar{W}_n = \emptyset$ if $|m - n| > 1$. We can write $h = \sum_{n=1}^\infty h_n$ on W where $h_n \in C(K)$ has support in W_n and $\|h_n\| \leq 1$. By Lemma 3 for each n we can find $f_n \in H_{F \cup (K \setminus \bar{F})}^\infty$ with $|f_n - h_n| < 2^{-n}\eta$ on F , $|f_n| < 2^{-n}\eta$ on $K \setminus W$, and $\|f_n\| \leq 3$. Then $G = \sum_{n=1}^\infty f_n$ has the required properties.

Proof of Theorem 1. By Lemma 4 and using the fact that g can be approximated uniformly by functions continuous in a neighborhood of F , we can construct by induction on n a sequence $\{G_n\}_{n=0}^\infty$ in $H_{F \cup (K \setminus \bar{F})}^\infty$ such that, writing $f_n = G_0 + \dots + G_n$ we have:

$$(1) \quad |G_0 - g| < \lambda/7 \text{ on } F,$$

$$(1)_n \quad |G_n + f_{n-1} - (1 + \lambda + \dots + \lambda^n)g| < \frac{\lambda^{n+1}}{7}$$

on F , $n > 1$, where $\lambda = 9/10$

$$(2)_n \quad \|G_n\| \leq 7 \|f_{n-1} - (1 + \lambda + \dots + \lambda^n)g\|_F < 8\lambda^n$$

$$(3)_n \quad \|f_n\| \leq 1 + \lambda + \dots + 9\lambda^n.$$

(To get $(3)_n$ observe that by $(1)_{n-1}$ we have $|f_{n-1}| < 1 + \lambda + \dots + \lambda^{n-1} + \lambda^n/7$ on F , and hence on a neighborhood of F ; if we make $|G_n| < \lambda^{n-1}/10$ outside this neighborhood then $(3)_n$ follows from $(2)_n$ and $(3)_{n-1}$).

$$(4)_n \quad |G_n| < 2^{-n} \text{ on } K \setminus V.$$

Then $(2)_n$ shows that $f_n \rightarrow G$ say uniformly on K , so $G \in H_{F \cup (K \setminus \bar{F})}^\infty$; by $(1)_n$ $G = 10g$ on F and by $(3)_n$ $\|G\| \leq 10$. Finally by $(4)_n$ $|G| < \eta$ on $K \setminus V$. Then $f = (1/10)G$ is the required function.

REMARK. The metric condition on F in Theorem 1 is clearly satisfied if F has zero one-dimensional Hausdorff measure; however it is also satisfied by sets which are thicker in the direction of the complex tangent space, e.g. any smooth arc in ∂K whose tangent at each point lies in the complex tangent space.

If F is compact then of course it is a peak interpolation set, so Theorem 1 extends the Rudin-Carleson theorem. The extension to non-closed sets in the case of the disc has been obtained independently by Detraz [1], and subsequently generalized to other domains in the plane by A. Stray (private communication).

If we assume that F has zero one-dimensional Hausdorff measure then we can make do with a weaker pseudoconvexity hypothesis at the points of F . We say that ∂K is point pseudoconvex at ζ if there exists a neighborhood N of ζ and a real C^2 strictly plurisubharmonic function ρ in N such that $\rho(\zeta) = 0$ and $\rho(z) \leq 0$ in $N \cap K$.

THEOREM 2. *Let K be holomorphically convex, and let F be a subset of ∂K with zero one-dimensional Hausdorff outer measure such that ∂K is point pseudoconvex at each point of F . Let V be a neighborhood of F in K , let $\eta > 0$, and let g be a bounded continuous function on F with $\|g\| \leq 1$.*

Then we can find $f \in H_{F \cup (K \setminus \bar{F})}^\infty$ with $f|_F = g$, $\|f\| \leq 1$ and $|f| < \eta$ on $K \setminus V$.

Proof. We show that the conclusion of Lemma 2 holds; the rest of the proof is just as before. As in the proof of Lemma 2 for each $\zeta \in F$ we can find positive constants m_ζ and M_ζ , a neighborhood W_ζ of ζ , and $G_\zeta \in H(K)$ such that

- (a) $m_\zeta |\zeta - z|^2 \leq \operatorname{Re} G_\zeta(z)$, $z \in K$
- (b) $|G_\zeta(z)| \leq M_\zeta |\zeta - z|$, $z \in K$.

Then whenever $\zeta \in U \subset W_\zeta$ and $z \in U$ we have $|G_\zeta(z)| \leq M_\zeta \operatorname{diam}(U)$. We define F_n as before and cover F_n by balls $\Delta_i^{(n)}$ such that $\sum_i \operatorname{diam}(\Delta_i^{(n)}) < \varepsilon n^{-2} 2^{-n-2}$. The rest of the proof goes just as before, with c_j replaced by $\operatorname{diam}(\Delta_j)$.

COROLLARY. *Let F be a compact subset of ∂K with zero 1-dimensional Hausdorff measure and assume ∂K is point pseudoconvex at each point of F . Then F is a peak interpolation set for $A(K)$.*

Finally we remark that the functions obtained in Theorem 1 and 2 are actually pointwise limits on K^0 of bounded sequences in $H(K)$; this follows from the construction. If F is compact the peak-interpolating functions constructed are in $\bar{H}(K)$; in this case the proof simplifies somewhat since it is only necessary to take finite products in Lemma 2 and the theorem follows from Lemma 2 by general theorems on peak interpolation sets.

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Vol. 41, No. 1

November, 1972

Anatole Beck and Peter Warren, <i>Weak orthogonality</i>	1
Jonnie Bee Bednar and Howard E. Lacey, <i>Concerning Banach spaces whose duals are abstract L-spaces</i>	13
Louis Harvey Blake, <i>Canonical extensions of measures and the extension of regularity of conditional probabilities</i>	25
R. A. Brooks, <i>Conditional expectations associated with stochastic processes</i>	33
Theodore Allen Burton and Ronald Calvin Grimmer, <i>On the asymptotic behavior of solutions of $x'' + a(t)f(x) = e(t)$</i>	43
Stephen LaVern Campbell, <i>Operator-valued inner functions analytic on the closed disc</i>	57
Yuen-Kwok Chan, <i>A constructive study of measure theory</i>	63
Alexander Munro Davie and Bernt Karsten Oksendal, <i>Peak interpolation sets for some algebras of analytic functions</i>	81
H. P. Dikshit, <i>Absolute total-effective $(N, p_n)(c, 1)$ method</i>	89
Robert E. Edwards, Edwin Hewitt and Kenneth Allen Ross, <i>Lacunarity for compact groups. II</i>	99
James Daniel Halpern, <i>On a question of Tarski and a maximal theorem of Kurepa</i>	111
Gerald L. Itzkowitz, <i>A characterization of a class of uniform spaces that admit an invariant integral</i>	123
Mo Tak Kiang, <i>Semigroups with diminishing orbital diameters</i>	143
Glenn Richard Luecke, <i>A class of operators on Hilbert space</i>	153
R. James Milgram, <i>Group representations and the Adams spectral sequence</i>	157
G. S. Monk, <i>On the endomorphism ring of an abelian p-group, and of a large subgroup</i>	183
Yasutoshi Nomura, <i>Homology of a group extension</i>	195
R. Michael Range, <i>Approximation to bounded holomorphic functions on strictly pseudoconvex domains</i>	203
Norman R. Reilly, <i>Inverse semigroups of partial transformations and θ-classes</i>	215
Chris Rorres, <i>Strong concentration of the spectra of self-adjoint operators</i>	237
Saharon Shelah, <i>A combinatorial problem; stability and order for models and theories in infinitary languages</i>	247
George Gustave Weill, <i>Vector space decompositions and the abstract imitation problem</i>	263
Arthur Thomas White, <i>On the genus of the composition of two graphs</i>	275