A SET WITH NO RIESZ BASIS OF EXPONENTIALS

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Abstract. We show that there exists a bounded subset of $\mathbb{R}$ such that no system of exponentials can be a Riesz basis for the corresponding Hilbert space. An additional result gives a lower bound for the Riesz constant of any putative Riesz basis of the two dimensional disk.

1. Introduction

A system of vectors $\{u_\lambda\}$ in a separable Hilbert space $H$ is called a basis if every vector $f \in H$ can be represented by a series

$$f = \sum c_\lambda u_\lambda$$

and the representation is unique. The best kind of basis is the orthonormal basis. In this paper we are interested in questions revolving around the existence of bases when $u_\lambda$ are taken from a specific, pre-given set. More specifically, we are interested in the case that $H = L^2(S)$ for some $S \subset \mathbb{R}$ or $\mathbb{R}^d$, bounded and of positive measure, and the $u_\lambda$ are exponential functions. In this case it is not always possible to find an orthogonal basis: If $S$ is an interval then the classic Fourier system is an orthogonal basis. However, for the union of two intervals it is easy to see that in general, no exponential orthogonal basis exists, say for $[0, 2] \cup [3, 5]$. See [12] for a full treatment. So one needs some generalisation of orthogonal bases, which would possess many of their good properties, but would be more available for constructions.

Definition. The image of an orthonormal basis by a linear isomorphism of the space is called a Riesz basis. Equivalently, a system $\{u_\lambda\}$ is Riesz basis if:

(i) It is complete in $H$;

(ii) There is a constant $K$ such that for any (finite) sum $P = \sum c_l u_l$ the following condition holds:

$$\frac{1}{K} ||c||^2 \leq ||P||^2 \leq K ||c||^2,$$

where $||c||^2 = \sum |c_l|^2$.

Remark. One may ask: is any basis in $H$ a Riesz basis? Babenko [1] gave a counterexample. His example was a system of exponentials in a weighted $L^2$ space. Later, it turned out that the weights defined by Babenko are a specific case of the so-called Muckenhoupt weights [16] (we remark that the same condition was discovered independently and simultaneously by Krantsberg, see [10] or [17, pg. 73]).

Thus the question we are interested in is as follows. Given an $S \subset \mathbb{R}$, is there a $\Lambda \subset \mathbb{R}$ such that the system $E(\Lambda) := \{e^{2\pi i \lambda t} : \lambda \in \Lambda\}$ is a Riesz basis? It turns
out that it is neither easy to construct Riesz bases, nor to prove that none exist. For the construction problem, Seip [19] constructed Riesz bases of exponentials for unions of two intervals (and some cases of unions of larger numbers of intervals). Riesz bases for arbitrary finite unions of intervals were constructed in [9]. See [6, 11] for a construction of Riesz bases for multitiling sets, and [15] for exponentials with complex frequencies. See [4, 2, 14] for some recent work. Nevertheless, for many natural sets the question is still open, with famous examples being the ball and triangle in two dimensions.

In this paper we give an example of a set $S$ for which no Riesz basis of exponentials exists. The same technique allows us to show that, even if a Riesz basis of exponentials existed for a two-dimensional ball, its defining constant $K$ (the $K$ from (1)) cannot be too close to 1. In particular this reproduces Fuglede’s result that the ball has no orthogonal basis of exponentials [5], as that would correspond to $K = 1$. For a different generalisation of Fuglede’s result, see [8].

2. Preliminaries

Let us start by recalling the Paley-Wiener perturbation theorem.

**Theorem** (Paley and Wiener). Let $S \subset \mathbb{R}^d$ be a bounded set of positive measure, and let $\Lambda = \{\lambda_n\} \subset \mathbb{R}$ such that $E(\Lambda)$ is a Riesz basis for $L^2(S)$. Then there exists a constant $\mu = \mu(S, \Lambda)$ such that if a second sequence $\Gamma = \{\gamma_n\}$ satisfies $|\lambda_n - \gamma_n| < \mu$ for all $n$, then $E(\Gamma)$ is also a Riesz basis for $L^2(S)$.

See, e.g., [9, §2.3] for a proof in $d = 1$. The proof in higher dimensions is similar.

We say that a set $\Lambda \subset \mathbb{R}$ is uniformly discrete if there exists some $c > 0$ such that if $\lambda \neq \mu$ are both in $\Lambda$ then $|\lambda - \mu| > c$. It is easy to see that any Riesz basis of exponentials of $L^2(S)$ for some $S \subset \mathbb{R}^d$ is uniformly discrete. On the other hand, any set which is uniformly discrete satisfies the right inequality in (1), namely

$$\left\| \sum_{\lambda \in \Lambda} c_\lambda e(\lambda x) \right\|^2 \leq C \sum_{\lambda \in \Lambda} |c_\lambda|^2.$$

(This inequality is called Bessel’s inequality). See [18, Proposition 2.7] — the formulation here follows from the formulation in the book by a simple duality argument.

Throughout we use the usual notation $e(x) = e^{2\pi ix}$ and $E(\Lambda) = \{e(\lambda x) : \lambda \in \Lambda\}$. We use $c$ and $C$ for constants (usually depending on the Riesz basis involved), whose value may change from formula to formula and even inside the same formula. We use $c$ for constants which are ‘small enough’ and $C$ for constants which are ‘large enough’.

3. Proofs

We start with a result of the third named author which remained unpublished, but a version of it was included (with his permission) in the book of Heil [7, pg. 296] (see also [3] for a proof in the more general context of frames, or ‘overcomplete’ bases). We chose to present it here as it provides the simplest demonstration of the ‘translation’ technique which we apply throughout this note.

**Theorem 1.** Let $S \subset \mathbb{R}$ and let $w \in L^1(S)$ be a positive function. If $w$ is not bounded away from 0 or $\infty$, then there is no $\Lambda \subset \mathbb{R}$ such that $E(\Lambda)$ is a Riesz basis for the weighted space $L^2(S, w)$. 
The Riesz basis property tells us that the series converges in $w$ that
by the definition of $A$ by the definition of $A$.

On the other hand, for every $x \in A + t$ we have
$$f(x) = \sum_{\lambda \in \Lambda} c_\lambda e(\lambda x),$$

The Riesz basis property tells us that the series converges in $L^2$ and that
$$\sum |c_\lambda|^2 \leq K \|f\|^2_{L^2(S, w)} \leq K \varepsilon, \quad (2)$$

by the definition of $A$. Now perform a formal translation (by $-t$) of the series
$$\sum c_\lambda e(\lambda x),$$

namely, consider a new series with coefficients $d_\lambda := c_\lambda e(-\lambda t)$. Since
$$\sum |d_\lambda|^2 = \sum |c_\lambda|^2 < \infty,$$

the Riesz basis property gives that the series $\sum d_\lambda e(\lambda x)$ converges in $L^2(S, w)$ and the limit, $g$, satisfies
$$\|g\|^2_{L^2(S, w)} \leq K \sum_{\lambda \in \Lambda} |d_\lambda|^2 = K \sum_{\lambda \in \Lambda} |c_\lambda|^2 \leq K^2 \varepsilon. \quad (3)$$

On the other hand, for every $x \in A + t$ we have
$$g(x) = \sum_{\lambda \in \Lambda} d_\lambda e(\lambda x) = \sum_{\lambda \in \Lambda} c_\lambda e(\lambda (x - t)) = f(x - t) = \frac{1}{\sqrt{|A|}},$$

(it is perhaps easiest to consider the equalities as holding almost everywhere and the sums converging in measure — we use here that convergence in $L^2$ implies convergence in measure; and that if a sum converges both in $L^2$ and in measure then the two limits are almost everywhere equal). But this is a contradiction because then
$$\|g\|_{L^2(S, w)} \geq \int_{A + t} |g(x)|^2 w(x) \, dx \geq \int_{A + t} \frac{1}{|A|} c \, dx = c,$$

contradicting (3), since $\varepsilon$ was arbitrary.

The case that $w$ is not bounded away from $\infty$ is treated in a similar way. \qed

Next, we turn to the main result of this note.

**Theorem 2.** There exists a bounded set $S \subset \mathbb{R}$ for which no $\Lambda \subset \mathbb{R}$ may satisfy that $E(\Lambda)$ is a Riesz basis for $L^2(S)$

It might be interesting to remark already at this point that the set is an infinite collection of intervals with one accumulation point.

For the proof, we will use the following auxiliary claim.

**Claim.** Let $A \subset \mathbb{R}$ be a set of positive finite measure, and let $\{g_i\}_{i=1}^N \subset L^2(A)$. If for every $U \subset \{1, \ldots, N\}$ we have
$$\left| \sum_{i \in U} g_i(x) \right| \leq M \sqrt{|U|}, \quad \forall x \in A,$$

then there exists some $i_0$ such that
$$\int_A |g_{i_0}|^2 \leq \frac{6M^2 |A|}{\sqrt{N}}.$$
Proof. Assume that \( \int_A |g_i|^2 > \delta \) for some \( \delta \) and all \( i \). We get
\[
\sum_i \int_A |g_i(x)|^2 \, dx > \delta N.
\]
Hence there exists some \( x_0 \) such that
\[
\sum_i |g_i(x_0)|^2 > \delta N \frac{\delta^N}{|A|}.
\]
Condition (4) implies in particular that \( |g_i(x_0)| \leq M \) for all \( i \) and so
\[
\sum_i |g_i(x_0)| \geq \frac{\delta N}{3|A|M}. \tag{5}
\]
Let \( U_1, U_2, U_3 \) be defined by
\[
U_j = \left\{ i : \arg g_i(x_0) \in \left[ 2\pi j - \frac{1}{3}, 2\pi j \frac{1}{3} \right] \right\}.
\]
Hence for some \( j \),
\[
\sum_{i \in U_j} |g_i(x_0)| > \delta N \frac{\delta^N}{3|A|M}.
\]
Denote \( U := U_j \) for this \( j \) for short. If a collection of complex numbers \( c_i \) is in a sector of opening \( 120^\circ \) then \( \sum |c_i| \geq \frac{1}{2} \sum |c_i| \) and hence
\[
\left| \sum_{i \in U} g_i(x_0) \right| \geq \frac{\delta N}{6|A|M}.
\]
Since \( |U| \leq N \), combining this with (4) gives the required result.

We are now ready to prove Theorem 2.

Proof. We start with \( S_1 = [0, 1] \cup [2, 3] \). We then break the interval \([2, 3]\) into \( 4^2 + 1 \) intervals of equal length, and keep for each one only the left half (this is \( S_2 \)). We next take the last interval of \( S_2 \), break it into \( 4^2 + 1 \) intervals of equal length, and keep for each one only the left third. We continue this way and denote \( S = \bigcap S_i \).

Assume by contradiction that \( S \) has a Riesz basis \( E(\Lambda) \) of exponentials. By the Paley-Wiener theorem we may assume without loss of generality that \( \Lambda \subset \frac{1}{\ell} \mathbb{Z} \) for some integer \( \ell \geq 4 \). Let \( K \) be a Riesz constant for \( \Lambda \), i.e. every \( f \in L^2(S) \) can be expanded into a sum
\[
f(x) = \sum_{\lambda \in \Lambda} c_\lambda e(\lambda x)
\]
such that
\[
\frac{1}{K} \sum |c_\lambda|^2 \leq \int_S |f|^2 \leq K \sum |c_\lambda|^2.
\]
Assume for simplicity that \( K \geq \ell \).

Fix some \( n \). The construction of \( S \) implies that one may find \( 4^n \) intervals \( I_1, \ldots, I_{4^n} \) of equal length (call it \( \epsilon \)) and distance between them \( \epsilon(n - 1) \). For \( i = 1, \ldots, 4^n \) let
\[
f_i = \frac{1}{\sqrt{\epsilon}} \mathbb{1}_{I_i}
\]
so that \( \|f_i\|_{L^2(S)} = 1 \). Expand \( f_i(x) = \sum c_{\lambda,i} e(\lambda x) \). Since \( \Lambda \subset \frac{1}{\ell} \mathbb{Z} \), this sum converges in \( L^2[0, \ell] \) and the limit is an extension of \( f \) to the whole of \( L^2[0, \ell] \) (to
the whole of $\mathbb{R}$, if you prefer). Call these extensions $\tilde{f}_i$ and note that the Riesz basis property gives that $\sum |c_i|^2 \leq K$ and hence
\[ ||\tilde{f}_i||_{L^2([0,\ell])}^2 \leq \ell K \leq K^2. \]
A similar argument shows that for any coefficients $\beta_i$
\[ \left\| \sum_i \beta_i \tilde{f}_i \right\|^2_{L^2([0,\ell])} \leq K^2 \sum_i |\beta_i|^2. \tag{5} \]
Let us further define
\[ h = \frac{4}{\epsilon} 1_{[-\epsilon/8,\epsilon/8]} \]
so that $||h||_1 = 1$. Let $g_i = \tilde{f}_i * h$. By the Cauchy-Schwarz inequality, for every $U \subset \{1, \ldots, 4^n\}$ we have
\[ \left| \sum_{i \in U} g_i(x) \right| \leq \left\| \sum_{i \in U} \tilde{f}_i \right\|_{L^2([0,\ell])} \left\| h \right\|_2 \leq K \sqrt{|U|} \cdot \frac{2}{\sqrt{\epsilon}} \quad \forall x \in \mathbb{R}. \]
Hence the functions $g_i$ satisfy condition (4) with $M = 2K/\sqrt{\epsilon}$.

Further, enumerate all intervals comprising $S$ which have length strictly bigger than $\epsilon$ as $[a_1, b_1], \ldots, [a_e, b_e]$ where $\epsilon = \sum_{k<n} 4^k \leq 2 \cdot 4^{n-1}$. Let
\[ A := \bigcup_{i=1}^e [a_i - n\epsilon, a_i + \epsilon]. \]
($A$ is the set of left edges of these intervals). Then $|A| = e(n+1)\epsilon \leq 2(n+1)e4^{n-1}$. By the auxiliary claim (with $N = 4^n$ and $M$ as above) there exists an $i_0$ such that
\[ \int_A |g_{i_0}|^2 \leq \frac{6M^2|A|}{\sqrt{N}} \leq \frac{CK^2n}{4^{n-1}}. \]
With $i_0$ selected and this crucial property of $g_{i_0}$ proved, the theorem follows by examining a few translations of $g_{i_0}$.

To see this, expand $f_{i_0}$ using the Riesz basis property and denote the coefficients by $c_\lambda$ so that $f_{i_0}(x) = \sum c_\lambda e(\lambda x)$, and recall that we have extended $f_{i_0}$ so that a similar equality holds also for $f_{i_0}$ over all of $\mathbb{R}$. Hence
\[ g_{i_0}(x) = \sum_{\lambda \in \Lambda} c_\lambda \tilde{h}(\lambda) e(\lambda x). \]
So $g_{i_0}$ is supported spectrally on $A$ and therefore
\[ \sum_{\lambda \in \Lambda} |c_\lambda \tilde{h}(\lambda)|^2 \geq \frac{1}{K} \int_S |g_{i_0}|^2 \geq \frac{1}{2K}, \tag{6} \]
where the last inequality follows from the definition of $g_{i_0}$ as $\tilde{f}_{i_0} * h$ which allows to calculate $g_{i_0}$ in the middle half of the interval $I_{i_0}$. On the other hand, the Plancharell formula on $[0,\ell]$ and the Riesz property imply that
\[ \int_0^\ell |g_{i_0}|^2 = \ell \sum |c_\lambda|^2 |\tilde{h}(\lambda)|^2 \leq K \sum |c_\lambda|^2 \leq K^2 \int_S |f_{i_0}|^2 = K^2. \tag{7} \]
Consider the following $n - 1$ translations of $g_{i_0}$:
\[ G_k(x) = g_{i_0}(x - k\epsilon) = \sum_{\lambda \in \Lambda} c_\lambda \tilde{h}(\lambda) e(-\lambda k\epsilon) e(\lambda x). \]
Each $G_k$ is also supported spectrally on $\Lambda$ and hence
\[
\int_S |G_k|^2 \geq \frac{1}{K} \sum |c_{\lambda} \hat{h}(\lambda)|^2 \geq \frac{1}{2K^2}.
\]

Consider now an interval $J$ whose length is larger than $\epsilon$. Since $\tilde{f}_{i_0}$ is zero on $J$, we have that $g_{i_0}$ is zero except on the $\frac{1}{8\epsilon}$ edges of $J$. Hence $G_k|_J$, $k \geq 1$ is zero on most of the interval, except for its left end, where $G_k$ is a translation of $g_{i_0}$ on some part of $A$. Therefore
\[
\sum_{j:|J|>\epsilon} \int_J |G_k|^2 \leq \int_A |g_{i_0}|^2 \leq \frac{CK^2 n}{4^{4n-1}}.
\]

This means that, if $I$ is the union of all intervals of length $\epsilon$ or less (all the $I_i$ and then the shorter intervals) then
\[
\int_I |G_k|^2 \geq \frac{1}{2K^2} - \frac{CK^2 n}{4^{4n-1}}
\]
and since $G_k$ is a translation of $g_{i_0}$ we get
\[
\int_{I-\epsilon k} |g_{i_0}|^2 \geq \frac{1}{2K^2} - \frac{CK^2 n}{4^{4n-1}}.
\]
Since the sets $I-\epsilon k$ are disjoint, for $k = 1, \ldots, n-1$, we get
\[
K^2 \geq \int_0^\ell |g_{i_0}|^2 \geq (n-1) \left( \frac{1}{2K^2} - \frac{CK^2 n}{4^{4n-1}} \right).
\]
Since $n$ was arbitrary, we have reached a contradiction. \qed

Our last result is that, even if a Riesz basis of exponentials would exist for the disk, its constant cannot be too close to 1. The way we defined the Riesz constant in (1), though, makes it easy to compare to orthonormal bases only when $|S| = 1$ (otherwise even an orthogonal basis of exponentials would not be normalised and would not satisfy (1) with $K = 1$). For simplicity we let $D = \frac{1}{\sqrt{\pi}} \mathbb{D}$ i.e. a disk with area 1, and prove the result for it.

**Theorem 3.** Any Riesz basis of exponentials for $D$ must have $K \geq \sqrt{\frac{1+\sqrt{5}}{2}}$.

**Proof.** Assume by contradiction that $\Lambda \subset \mathbb{R}^2$ satisfies that $E(\Lambda)$ is a Riesz basis for $L^2(D)$, with the Riesz constant $K$ (the $K$ from (1)) satisfying $K < \sqrt{\frac{1+\sqrt{5}}{2}}$.

Fix $\epsilon > 0$ and examine the function
\[
f = \frac{1}{\sqrt{\pi \epsilon}} \mathbb{1}_{\epsilon \mathbb{D}}
\]
i.e. a normalised indicator of a disk of radius $\epsilon$ around 0. Use the Riesz basis property to write
\[
f(x) = \sum_{\lambda \in \Lambda} c_{\lambda} e(\langle \lambda, x \rangle)
\]
with the sum converging in $L^2(D)$. As before, we use this representation to extend $f$ to $[-2, 2]^2$, though there will be two differences from the previous theorem. First, it will be more convenient to not distinguish between $f$ and its extension, and call the extension $f$ as well. And second, rather than using Paley-Wiener, this time
we use the fact $E(\Lambda)$ is a Riesz basis in $L^2(D)$ to conclude that $\Lambda$ is uniformly separated and hence $E(\Lambda)$ satisfies Bessel’s inequality in $L^2([-2,2]^2)$, i.e
\[ \|f\|_{L^2([-2,2]^2)} \leq C \sum_{\lambda \in \Lambda} |c_\lambda|^2 \leq CK \|f\|_2^2 = CK. \] (8)

For a $\theta \in [0,2\pi]$ denote $t_\theta = (\sqrt{\pi} - \varepsilon)(\cos \theta, \sin \theta)$ and consider the translation of $f$ by $t_\theta$ i.e.
\[ g_\theta(x) := \sum_{\lambda \in \Lambda} c_\lambda e(\langle \lambda, x - t_\theta \rangle). \]

As before, we must have
\[ \|g_\theta\|_{L^2(D)}^2 \leq K \sum_{\lambda \in \Lambda} |c_\lambda|^2 = K \sum_{\lambda \in \Lambda} |c_\lambda|^2 \leq K^2. \]

However, $g_\theta(x) = \frac{1}{\sqrt{\pi}}$ for a disk of radius $\varepsilon$ contained in $D$. Hence
\[ \int_{D \setminus (D + t_\theta)} |g_\theta|^2 \leq K^2 - 1. \]

Translating back we get an estimate for (the extended) $f$ outside $D$, namely
\[ \int_{(D - t_\theta) \setminus D} |f|^2 \leq K^2 - 1. \] (9)

This is our upper bound for $f$.

To get a lower bound we again examine one $\theta$, and this time translate by $s_\theta = (\sqrt{\pi} + \varepsilon)(\cos \theta, \sin \theta)$. Denote the translated function by $h_\theta$, namely
\[ h_\theta(x) := \sum_{\lambda \in \Lambda} c_\lambda e(\langle \lambda, x - s_\theta \rangle) \]
and get
\[ \|h_\theta\|_{L^2(D)}^2 \geq \frac{1}{K} \sum_{\lambda \in \Lambda} |c_\lambda|^2 \geq \frac{1}{K^2}. \]

which we again map back to $f$ to get
\[ \int_{(D - s_\theta) \setminus (D - t_\theta)} |f|^2 \geq \frac{1}{K^2} \]
(note that we used in this last step that the little disk that allowed to subtract 1 when we did the corresponding calculations for $g$ is outside $D$ for $h$, so does not contribute to $\|h\|_{L^2(D)}$). With the lower bound (9) we get
\[ \int_{(D - s_\theta) \setminus (D - t_\theta)} |f|^2 \geq \frac{1}{K^2} - (K^2 - 1). \]

When $K < \sqrt{\frac{1+\sqrt{5}}{2}}$ we get that the right-hand side is at least some constant $c > 0$. Integrating over $\theta$ and using Fubini gives (omitting the details of the elementary geometry exercise involved)
\[ c \leq \int_0^{2\pi} \int_{(D - s_\theta) \setminus (D - t_\theta)} |f(x)|^2 \, dx \, d\theta \leq \int_{(2/\sqrt{\pi} + \varepsilon)D} C\sqrt{\varepsilon} |f(x)|^2 \, dx \]
Or, in other words,
\[ \int_{(2/\sqrt{\pi} + \varepsilon)D} |f(x)|^2 \geq \frac{C}{\sqrt{\varepsilon}} \]
contradicting (8) if $\varepsilon$ is taken to be sufficiently small.

\[\square\]

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