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ERGODIC BANACH PROBLEM, FLAT POLYNOMIALS AND MAHLER'S MEASURES WITH COMBINATORICS

EL HOUCEIN EL ABDALAOUI^b

ABSTRACT. Using the combinatorial Singer's construction, we exhibit a sequence of flat polynomials with coefficients $0, 1$. We thus get that there exist a sequences of Newman polynomials that are L^α -flat, $0 \leq \alpha < 2$. This settles an old question of Littlewood. In the opposite direction, we prove that the Newman polynomials are not L^α -flat, for $\alpha \geq 4$. We further establish that there is a conservative, ergodic, σ -finite measure preserving transformation with simple Lebesgue spectrum. This answer affirmatively a long-standing problem of Banach from the Scottish book. Consequently, we obtain a positive answer to Mahler's problem in the class of Newman polynomials, and this allows us also to answer a question raised by Bourgain on the supremum of the L^1 -norm of L^2 normalized idempotent polynomials.



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1. INTRODUCTION

The main purpose of this paper is to produce a sequence of flat polynomials with coefficients $0, 1$. This answer an old question of Littlewood on finding a sequence of analytic trigonometric polynomials with coefficients $0, 1$ that are L^1 -flat. As a consequence, We obtain that there exist a conservative, ergodic, σ -finite measure preserving transformation on a Lebesgue space with simple Lebesgue spectrum. This gives an affirmative answer to a long-standing spectral problem of Banach from the Scottish book. It turns out that our approach allows us to obtain also an affirmative answers to the problem of Mahler (whether there exists a sequence of analytic trigonometric polynomials with integer coefficients for which the Mahler measure of the L^2 -normalized sequence converges to 1). We further get that the supremum of the L^1 -norm of the L^2 -normalized analytic trigonometric polynomials with coefficients $0, 1$ is 1. This answer a question raised by J. Bourgain [18].

A key point in our proof is the construction of a sequence of analytic trigonometric polynomials with coefficients $0, 1$ that are L^α -flat, $0 < \alpha < 2$. This is done by appealing to the combinatorial Singer's construction combined with Marcinkiewicz-Zygmund interpolation inequalities [99, p.28, chp. X] and its refinements. Form this, we obtain that there exist a sequence of analytic trigonometric polynomials with coefficients $0, 1$ that are flat in the almost everywhere sense.

Marcinkiewicz-Zygmund interpolation inequalities and its extensions lies in the heart of the interpolation theory. It follows that the Hardy spaces and the Carleson interpolation theory play an important role in our proofs. For a nice account on the interpolation theory and the H^p theory, we refer the reader to [38, p.147, Chap. 9] and [47, p.275, Chap. 7], [55, p.194], [88, p.328].

Our construction benefited also from the ideas of Ben Green and Gowers related to the flatness problem in connection with Singer and Sidon sets [35], [50]. We also take advantage from the recent investigations on the Marcinkiewicz-Zygmund inequalities and its refinements

[31], [29], [70].

We stress that this paper is deeply indebted to the investigation started in [2], [3] and [4]. So, it may be seen as a companion to those papers.

The flatness problem was initiated by Erdős [41] and Littlewood [68], and it has a long history. In the beginning, Erdős and Newman [40] asked if there is a positive absolute constant C such that

$$\max_{|z|=1} \left| \sum_{j=0}^n a_j z^j \right| \geq (1 + C)\sqrt{n}, \quad (EN)$$

where $|a_j| = 1$.

Subsequently, Littlewood asked on the existence of the sequence of the polynomials on the circle $P_n(z) = \sum_{j=0}^{n-1} \epsilon_j z^{n_j}$ with $\epsilon_j = \pm 1$ such that

$$(1.1) \quad A_1\sqrt{n} \leq |P_n(z)| \leq A_2\sqrt{n},$$

where A_1, A_2 are positive absolute constants and uniformly on z of modulus 1. Nowadays the analytic polynomials on the circle with ± 1 coefficients are called Littlewood polynomials.

Later, Beller and Newman produced a sequence of polynomials P with degree n and coefficients bounded by 1 satisfying $\min_{|z|=1} |P| \geq C\sqrt{n}$ [15]. In the opposite, J-P. Kahane disproved the conjecture (EN) [56].

Besides, T. Körner [64] obtained a positive answer to the Littlewood question (1.1) in the class of polynomials with coefficients of modulus one by appealing to the Byrnes's construction [23]. But, it turns out that the main ingredient form [23] used by Körner is not valid [84]. However, Kahane's proof does not use this flawed argument.

Later, J. Beck proves that one can obtain a positive answer to Littlewood question (1.1) by producing a sequence of polynomials from the class of polynomials of degree n whose coefficients are 400th roots

of unity [13]. J. Beck's construction is essentially based on the random construction of Kahane.

Since then, it was a long standing problem to obtain effective construction of ultraflat polynomials until solved very recently by Bombieri and Bourgain [17]. For a deeper treatment on the Kahane ultraflat polynomials, we refer the reader to [84].

The third extremal problem in the class of analytic trigonometric polynomials concern L^1 -flatness problem. This problem seems to be mentioned first in [77]. Therein, Newman mentioned the following conjecture:

Conjecture (Newman [77]). For any Littlewood polynomial P of degree n , $\|P(z)\|_1 < c\sqrt{n+1}$, where $c < 1$.

Newman in his 1965's paper [78] solved the problem of L^1 -flatness in the class of analytic trigonometric polynomials with coefficients of modulus 1. He proved that the Gauss-Fresnel polynomials are L^1 -flat. We refer to [4] for a simple proof. This result has been strengthened by Beller [14], and Beller & Newman in [16] by proving that the sequence of the Mahler measure of the L^2 normalized Gauss-Fresnel polynomials converge to one.

For the polynomials with random coefficients $a_k \in \{+1, -1\}$, Salem and Zygmund [92] proved that for all but $o(2^n)$ choices of $a_k = \pm 1$,

$$c_1\sqrt{n \ln(n)} < \left\| \sum_{k=0}^n a_k z^k \right\|_{\infty} < c_2\sqrt{n \ln(n)},$$

for some absolute constant $c_1, c_2 > 0$. Halàz [52] strengthened this result by proving

$$\left\| \sum_{k=0}^n a_k z^k \right\|_{\infty} = (1 + o(1))C\sqrt{n \ln(n)},$$

For some absolute constant $C > 0$. Byrnes and Newman computed L^4 -norm of those polynomials [24]. Later, Browein & Lokhart [22], and Choi & Erdélyi [33] used the central limit theorem to compute

the limit of the L^p -norm and the Mahler measure of the polynomials with random coefficients ± 1 . Their results can be linked to the recent results of Peligrad & Wu [81], Barrera & Peligrad, Cohen & Conze [30] and Thouvenot & Weiss [97]. Therein, the authors investigated a dynamical approach with dynamical coefficients, that is, $a_k = f(T^k x)$, where T is a measure-preserving transformation on some probability space and f is a square-integrable function.

The polynomials with coefficients $a_k \in \{0, 1\}$ and the constant term equal to 1 are nowadays called Newman polynomials. We further notice those polynomials are also known as idempotent polynomials, and since we are concern with L^1 -flatness, we may assume that the constant term is 1.

The connection between the Banach problem in ergodic theory and the L^1 -flatness problem in the class of Littlewood polynomials or Newman polynomials was established by Bourgain [18], Guenais [48], and Downarowicz & Lacroix [37]. M. Guenais proved that the Littlewood problem and the Banach problem are equivalent in some class of dynamical system [48]. She further constructed a generalized Fekete polynomials on some torsion groups, and proved that those polynomials are L^1 -flat. As a consequence, M. Guenais obtained that there exist a group action with simple Lebesgue component. A straightforward application of Gauss formula yields that the generalized Fekete polynomials constructed by Guenais are ultraflat. Very recently, el Abdalaoui and Nadkarni strengthened Guenais's result [4] by proving that there exist an ergodic non-singular dynamical system with simple Lebesgue component.

Here, we exhibit a class of L^α -flat Newman polynomials with $\alpha \in]0, 2[$. This allow us to produce a conservative, ergodic, σ -finite measure preserving transformation with simple Lebesgue spectrum. We thus get an affirmative answer to the Banach problem from the Scottish book.

Moreover, combining our result with that of [2], we provide a positive answer to the Mahler's problem in the class of Newman polynomials

[19, p.6], [20],[71].

Our methods breaks down for the polynomials with coefficients ± 1 . Thus, we are not able to answer the weaker form of Littlewood question on the existence of L^1 -flat polynomials with coefficients ± 1 .

We notice that the flatness problem is connected to the number theory and to some practical issues arising in the design of a mobile cellular wireless OFDM system [86]. Consequently, it is related to some engineering issues [37], [20], [21].

For the convenience of the reader, we repeat the relevant material from [2],[4] and [99], without proofs, thus making our exposition self-contained.

The paper is organized as follows. In section 2, we state our main results. In section 3, we remind the notion of generalized Riesz products and its connection to ergodic theory. In section 4, we present several definitions of flatness in the class of analytic trigonometric polynomials and the fundamental characterization of L^1 -flatness. In section 5, we remind the notion of Singer and Sidon sets in the number theory, and we establish that the L^2 -normalized Newman polynomials are not L^α -flat, for $\alpha \geq 4$. Finally, we prove our main results in section 6.

2. MAIN RESULTS

Consider the torus $\mathbb{T} = \{z \in \mathbb{C} : |z| = 1\}$ equipped with the normalized Lebesgue measure dz . Let $n_0 < n_1 < n_2 < \dots$ be a positive sequence of integers and put

$$P_n(z) = \sum_{j=0}^{n-1} \epsilon_j \sqrt{p_j} z^{n_j},$$

with $|\epsilon_j| = 1$ and (p_0, \dots, p_{n-1}) is a probability vector. Such polynomials are raised in the study of the spectral type of some class of dynamical systems in ergodic theory. For more details we refer to [3].

Here, we restrict ourself to the case $\epsilon_i = 1$ and $p_i = \frac{1}{n}$. We thus concentrated our investigations on the flatness problem in the class of polynomials of the form

$$P_n(z) = \frac{1}{\sqrt{n}} \sum_{j=0}^{n-1} z^{n_j}.$$

Following [2], this class is called class B.

We state our main results as follows.

Theorem 2.1. *There exist a sequence of analytic trigonometric polynomials $(P_n)_{n \in \mathbb{N}}$ with coefficients 0 and 1 such that the polynomials $\frac{P_n(z)}{\|P_n\|_2}$ are flat in almost everywhere sense, that is,*

$$\frac{P_n(z)}{\|P_n\|_2} \xrightarrow{n \rightarrow +\infty} 1,$$

for almost all z with respect to the Lebesgue measure dz .

As a consequence, we obtain the following theorem.

Theorem 2.2. *There exist a conservative ergodic measure preserving transformation on σ -finite space (X, \mathcal{A}, μ) with simple Lebesgue spectrum.*

We further establish the following:

Theorem 2.3. *Any sequence of analytic trigonometric polynomials $(P_n)_{n \in \mathbb{N}}$ with coefficients 0 and 1 is not L^α -flat, for any $\alpha \geq 4$.*

We recall that T is a measure preserving transformation on σ -finite space if (X, \mathcal{A}, μ) is a Lebesgue space with μ is σ -finite measure and nonatomic, and for any Borel set A , we have $\mu(T^{-1}A) = \mu(A)$. T is ergodic if every invariant Borel set A under T (i.e. $\mu(T^{-1}A \Delta A) = 0$), we have $\mu(A) = 0$ or $\mu(A^c) = 0$, where A^c is the complement of A .

The key point in the proof of Theorem 2.2 is the construction of a rank-one infinite measure preserving transformation with desired properties. This done by applying the cutting and staking method. We will assume that the reader is familiar with this method and we refer to

[45] for a nice account.

Theorem 2.2 answer affirmatively the long-standing problem attributed to Banach on the existence of dynamical system which simple Lebesgue spectrum and with no-atomic measure. We remind that Ulam in his book [98, p.76] stated the Banach problem as follows.

Questions (Banach Problem). Does there exist a square integrable function $f(x)$ and a measure preserving transformation $T(x)$, $-\infty < x < \infty$, such that the sequence of functions $\{f(T^n(x)); n = 1, 2, 3, \dots\}$ forms a complete orthogonal set in Hilbert space?

The most famous Banach problem in ergodic theory asks if there is a measure preserving transformation on a probability space which has simple Lebesgue spectrum. A similar problem is mentioned by Rokhlin in [87]. Precisely, Rokhlin asked on the existence of an ergodic measure preserving transformation on a finite measure space whose spectrum is Lebesgue type with finite multiplicity. Later, Kirillov in his 1966's paper [59] wrote "there are grounds for thinking that such examples do not exist". However he has described a measure preserving action (due to M. Novodvorskii) of the group $(\bigoplus_{j=1}^{\infty} \mathbb{Z}) \times \{-1, 1\}$ on the compact dual of discrete rationals whose unitary group has Haar spectrum of multiplicity 2. Similar group actions with higher finite even multiplicities are also given.

Subsequently, finite measure preserving transformation having Lebesgue component of finite even multiplicity have been constructed by J. Mathew and M. G. Nadkarni [75], Kamae [57], M. Queffelec [85], and O. Ageev [8]. Fifteen years later, M. Guenais produce a torsion group action with Lebesgue component of multiplicity one [48]. However, despite all these efforts, it is seems that the question of Rokhlin still open since the maps constructed does not have a *pure Lebesgue spectrum*.

Our methods is far from making any contribution to this problem. At know, it is seems that this problem is a "dark continent" for the ergodic theory.

Nevertheless, our results allows us to answer a question raised by Bourgain on the supremum of the L^1 -norm over all polynomials from class B [18]. Indeed, Theorem 2.1 gives the following

Corollary 2.4. $\beta = \sup_{n>1} \sup_{k_1 < k_2 < k_3 < \dots < k_n} \left\| \frac{1}{\sqrt{n}} \sum_{j=1}^n z^{k_j} \right\|_1 = 1.$

In [2], [9] and [32], the authors established already that $\beta \geq \frac{\sqrt{\pi}}{2}$, and, it easy to see that the simple case $n = 2, k_1 = 0, k_2 = 1$, gives $\beta \geq \frac{2\sqrt{2}}{\pi}$. We further have.

Corollary 2.5. There exist a sequence of analytic trigonometric polynomials $(P_k)_{k \in \mathbb{N}}$ with coefficients 0 and 1 such the Mahler measure of the polynomials $\frac{P_k}{\|P_k\|_2}$ converge to 1.

The Mahler measure of analytic trigonometric polynomials P_k is given by

$$M(P_k) = \exp \left(\int_{\mathbb{T}} \log (|P_k(z)|) dz \right).$$

Using Jensen's formula [88], it can be shown that

$$M(P_k) = \frac{1}{\sqrt{m_k}} \prod_{|\alpha|>1} |\alpha|,$$

where, α denoted the zero of the polynomial $\sqrt{m_k}P_k$. In this definition, an empty product is assumed to be 1 so the Mahler measure of the non-zero constant polynomial $P(x) = a$ is $|a|$. A nice account on the subject may be founded in [44, pp.2-11], [19].

The next proposition list some elementary properties of the Mahler measure. For the reader's convenience, we provide its proof.

Proposition 2.6. Let (X, \mathcal{B}, ρ) be a probability space. Then, for any two positive functions $f, g \in L^1(X, \rho)$, we have

- (i) $M_\rho(f) \stackrel{\text{def}}{=} \exp \left(\rho(\log(f)) \right)$ is a limit of the norms $\|f\|_\delta$ as δ goes to 0, that is,

$$\|f\|_\delta \stackrel{\text{def}}{=} \left(\int f^\delta d\rho \right)^{\frac{1}{\delta}} \xrightarrow{\delta \rightarrow 0} M_\rho(f),$$

provided that $\log(f)$ is integrable.

- (ii) If $\rho\{f > 0\} < 1$ then $M_\rho(f) = 0$.
- (iii) If $0 < p < q < 1$, then $\|f\|_p \leq \|f\|_q$.
- (iv) If $0 < p < 1$, then $M_\rho(f) \leq \|f\|_p$.
- (v) $\lim_{\delta \rightarrow 0} \int f^\delta d\rho = \rho\{f > 0\}$.
- (vi) $M_\rho(f) \leq \|f\|_1$.
- (vii) $M_\rho(fg) = M_\rho(f)M_\rho(g)$.

Proof. We start by proving (ii). Without loss of generality, assume that $f \geq 0$ and put

$$B = \{f > 0\}.$$

Let $\delta = 1/k$ be in $]0, 1[$, $k \in \mathbb{N}^*$. Then $1/(1/\delta) + 1/(1 - \delta) = 1/k + (k - 1)/k = 1$. Hence, by Hölder inequality, we have

$$\begin{aligned} \int f^\delta d\rho &= \int f^{1/k} \cdot 1_B d\rho \\ &\leq \left(\int (f^{1/k})^k dz \right)^{1/k} \left(\int 1_B^{k/k-1} dz \right)^{k-1/k} \\ &\leq \left(\int f d\rho \right)^{1/k} \left(\int 1_B dz \right)^{k-1/k} \\ &\leq \left(\int f d\rho \right)^{1/k} (\rho(B))^{(k-1)/k}. \end{aligned}$$

Thus we have proved

$$\begin{aligned} \|f\|_\delta &\leq \left(\int f d\rho \right) (\rho(B))^{(1-\delta)/\delta} \\ &\leq \left(\int f d\rho \right) (\rho(B))^{k-1} \xrightarrow[k \rightarrow +\infty]{} 0. \end{aligned}$$

To prove (i), apply the mean value theorem to the following functions

$$\begin{cases} \delta \mapsto x^\delta, & \text{if } x \in]0, 1[; \\ t \mapsto t^\delta, & \text{if } x > 1, \end{cases}$$

Hence, for any $\delta \in]0, 1[$ and for any $x > 0$, we have

$$\left| \frac{x^\delta - 1}{\delta} \right| \leq x + |\log(x)|.$$

Furthermore, it is easy to see that

$$\frac{f^\delta - 1}{\delta} = \frac{e^{\delta \log(f)} - 1}{\delta} \xrightarrow{\delta \rightarrow 0} \log(f),$$

and, by Lebesgue dominated convergence theorem, we get that

$$\int \frac{f^\delta - 1}{\delta} d\rho \xrightarrow{\delta \rightarrow 0} \int \log(f) d\rho.$$

On the other hand, for any $\delta \in]0, 1[$, we have

$$\|f\|_\delta = \exp\left(\frac{1}{\delta} \log\left(\int f^\delta d\rho\right)\right),$$

and for a sufficiently small δ , we can write

$$\frac{1}{\delta} \log\left(\int f^\delta d\rho\right) \sim \int \frac{f^\delta - 1}{\delta} d\rho$$

since $\log(x) \sim x - 1$ as $x \rightarrow 1$. Summarizing we have proved

$$\lim_{\delta \rightarrow 0} \|f\|_\delta = \exp\left(\int \log(f) d\rho\right) = M_\rho(f).$$

For the proof of (iii) and (iv), notice that the function $x \mapsto x^{\frac{q}{p}}$ is a convex function and $x \mapsto \log(x)$ is a concave function. Applying Jensen's inequality to $\int |f|^p d\rho$ we get

$$\|f\|_p \leq \|f\|_q, \quad \int \log(|f|) d\rho \leq \log\left(\|f\|_p\right),$$

and this finishes the proof, the rest of the proof is left to the reader. \square

Using the classical Beurling's outer and inner decomposition, el Abdalaoui and Nadkarni in [2] computed the Mahler measure of P_k . They further apply the H^p theory to establish a formula for the Mahler measure of the generalized Riesz product. We recall a part of this in the next section.

3. GENERALIZED RIESZ PRODUCTS AND CONNECTION TO ERGODIC THEORY

The classical notion of Riesz products is based on the notion of dissociation, which can be defined as follows.

Consider the polynomial $P(z) = 1 + z$. Then, we have

$$P(z)^2 = 1 + z + z + z^2.$$

For any integer $N \geq 2$, we can write

$$P(z)P(z^N) = 1 + z + z^N + z^{N+1}.$$

In the first case we group terms with the same power of z , while in the second case all the powers of z in the formal expansion are distinct. In the second case we say that the polynomials $P(z)$ and $P(z^N)$ are dissociated. More generally, we have

Lemma 3.1 ([4]). *If $P(z) = \sum_{j=-m}^m a_j z^j, Q(z) = \sum_{j=-n}^n b_j z^j, m \leq n$, are two trigonometric polynomials then for some $N, P(z)$ and $Q(z^N)$ are dissociated.*

It is well know that if the sequence of polynomials $(|P_j|^2)$ is dissociated (each finite product has dissociation property) with constant term equal to 1. Then, the sequence of probability measures $\left(\prod_{j=1}^N |P_j|^2 dz\right)$ converge to some probability measure called a Riesz product and denoted by $\prod_{j=1}^{+\infty} |P_j|^2$.

More generally, we have the following definition:

Definition 3.2. Let P_1, P_2, \dots , be a sequence of trigonometric polynomials such that

- (i) for any finite sequence $i_1 < i_2 < \dots < i_k$ of natural numbers

$$\int_{S^1} |(P_{i_1} P_{i_2} \dots P_{i_k})(z)|^2 dz = 1,$$

where S^1 denotes the circle group and dz the normalized Lebesgue measure on S^1 ,

- (ii) for any infinite sequence $i_1 < i_2 < \dots$ of natural numbers the weak limit of the measures $| (P_{i_1} P_{i_2} \dots P_{i_k})(z) |^2 dz, k = 1, 2, \dots$ as $k \rightarrow \infty$ exists.

Then the measure μ given by the weak limit of $| (P_1 P_2 \dots P_k)(z) |^2 dz$ as $k \rightarrow \infty$ is called generalized Riesz product of the polynomials $| P_1 |^2, | P_2 |^2, \dots$ and denoted by

$$\mu = \prod_{j=1}^{\infty} |P_j|^2. \quad (1.1)$$

Connection to ergodic theory and rank one transformations.

Using the cut and stack procedure described in [45], [46], one can construct inductively a family of measure-preserving transformations, called rank one transformations or rank one maps, as follows.

Let B_0 be the unit interval equipped with Lebesgue measure. At stage one we divide B_0 into m_0 equal parts, add spacers and form a stack of height h_1 in the usual fashion. At the k^{th} stage we divide the stack obtained at the $(k-1)^{th}$ stage into m_{k-1} equal columns, add spacers and obtain a new stack of height h_k . If during the k^{th} stage of our construction the number of spacers put above the j^{th} column of the $(k-1)^{th}$ stack is $a_j^{(k-1)}$, $0 \leq a_j^{(k-1)} < \infty$, $1 \leq j \leq m_k$, then we have

$$h_k = m_{k-1} h_{k-1} + \sum_{j=1}^{m_{k-1}} a_j^{(k-1)}.$$

Proceeding in this way, we get a rank one map T on a certain measure space $(X, \mathcal{B}, | \cdot |)$ which may be finite or σ -finite depending on the number of spacers added.

The construction of a rank one map thus needs two parameters, $(m_k)_{k=0}^{\infty}$ (cutting parameter), and $((a_j^{(k)})_{j=1}^{m_k})_{k=0}^{\infty}$ (spacers parameter). Put

$$T \stackrel{def}{=} T_{(m_k, (a_j^{(k)})_{j=1}^{m_k})_{k=0}^{\infty}}$$

In [34] and [61] it is proved that the spectral type of this map is given (up to possibly some discrete measure) by

$$(3.1) \quad d\mu = W^* \lim \prod_{k=1}^n |P_k|^2 dz,$$

where

$$P_k(z) = \frac{1}{\sqrt{m_k}} \left(1 + \sum_{j=1}^{m_k-1} z^{-(jh_k + \sum_{i=1}^j a_i^{(k)})} \right),$$

W^* lim denotes weak star limit in the space of bounded Borel measures on \mathbb{T} .

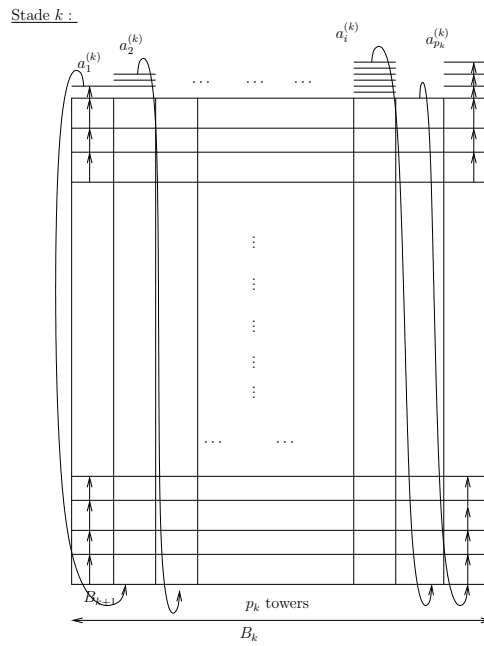


Fig. $(k + 1)$ th tower.

As mentioned by Nadkarni in [76], the infinite product

$$\prod_{l=1}^{+\infty} |P_{j_l}(z)|^2$$

taken over a subsequence $j_1 < j_2 < j_3 < \dots$, also represents the maximal spectral type (up to discrete measure) of some rank one maps. In case $j_l \neq l$ for infinitely many l , the maps acts on an infinite measure space.

The spectrum of any rank one map is simple and using a random procedure, D. S. Ornstein produced a family of mixing rank one maps [80]. It follows that Ornstein's class of maps may possibly contain a candidate for Banach's problem. Unfortunately, in 1993, J. Bourgain proved that almost surely Ornstein's maps have singular spectrum [18]. Subsequently, using the same methods, I. Klemes [60] showed that the subclass of staircase maps has singular maximal spectral type. In particular, this subclass contains the mixing staircase maps of Adams-Smorodinsky [6]. Using a refinement of Peyrière criterion [83], I. Klemes & K. Reinhold proved that the rank one maps have a singular spectrum if the inverse of the cutting parameter is not in ℓ^2 (that is, $\sum_{k=1}^{+\infty} \frac{1}{m_k^2} = +\infty$, where $(m_k) \subset \{2, 3, 4, \dots\}$ is the cutting parameter) [61]. This class contains the mixing staircase maps of Adams &

Friedman [7]. In 1996, H. Dooley and S. Eigen adapted the Brown-Moran methods [49, pp.203-209] and proved that the spectrum of a subclass of Ornstein maps is almost surely singular [36].

Later, el Abdalaoui-Parreau and Prikhod'ko extended Bourgain theorem [18] by proving that for any family of probability measures in Ornstein type constructions, the corresponding maps have almost surely a singular spectrum [5]. They obtained the same result for Rudolph's construction [89]. In 2007, el Abdalaoui showed that the spectrum of the rank one map is singular provided that the spacers $(a_j)_{j=1}^{m_k} \subset \mathbb{N}$, are lacunary for all k [1]. The author used the Salem-Zygmund central limit theorem methods. As a consequence, the author presented a

simple proof of Bourgain's theorem [18].

Recently, by appealing to a martingale approximation technique, C. Aistleitner and M. Hofer [10] proved a counterpart of the result of [1]. Precisely, they proved that the spectrum of the rank one maps is singular provided that the cutting parameter $(m_k) \in \mathbb{N}^*$ and the spacers $(a_j)_{j=1}^{m_k} \subset \mathbb{N}$ satisfy

- (i) $\frac{\log(m_{k_n})}{h_{k_n}}$ converge to 0;
- (ii) the proportion of equal terms in the spacers is at least $c.m_{k_n}$ for some fixed constant c and some subsequence (k_n) .

We further recall that I. Klemes & K. Reinhold in [61] conjectured that all rank one maps have singular spectrum, and in the same spirit, C. Aistleitner and M. Hofer wrote in the end of their paper "several authors believe that all rank one transformations could have singular maximal spectral type." It seems that this conjecture was formulated since Baxter result [12], [96]. We remind that the cutting and stacking rank one construction may goes back to Ornstein's paper in 1960 [79]. Indeed, therein, Ornstein constructed a non-singular map for which there is non σ -finite measure equivalent to Lebesgue measure. Of course, this example is connected to the example of non-singular map with simple Lebesgue component obtain by el Abdalaoui and Nadkarni [3]. Notice that in [80], the rank one maps are called transformations of class one.

It follows from Bourgain's observation ((eq 2.15)[18]) that if the spectral type of any rank one map acting on infinite measure is singular then the spectral type of any rank one is singular. Unfortunately, by our main result, this strategy fails. Therefore, the new approaches are needed to tackle this conjecture.

We remind that in [2], it is proved that if $\mu = \prod_{n=1}^{+\infty} |P_n|^2$, then the absolutely continuous part $\frac{d\mu}{dz}$ verify

$$\left\| \prod_{n=1}^N |P_n| - \sqrt{\frac{d\mu}{dz}} \right\|_1 \xrightarrow{N \rightarrow +\infty} 0.$$

Furthermore, the Mahler measure of μ ¹ satisfy

$$(3.2) \quad M\left(\frac{d\mu}{dz}\right) = \prod_{n=0}^{+\infty} M(P_n^2).$$

We further remind from [2] the following notion of generalized Riesz products from dynamical origin.

Definition 3.3. A generalized Riesz product $\mu = \prod_{j=1}^{\infty} |Q_j(z)|^2$, where $Q_j(z) = \sum_{i=0}^{n_j} b_{i,j} z^{r_{i,j}}$, $b_{i,j} \neq 0$, $\sum_{i=0}^{n_j} |b_{i,j}|^2 = 1$, $\prod_{j=1}^{\infty} |b_{n_j,j}| = 0$, is said to be of dynamical origin if with

$$h_0 = 1, h_1 = r_{n_1,1} + h_0, \dots, h_j = r_{n_j,j} + h_{j-1}, j \geq 2$$

it is true that for $j = 1, 2, \dots$,

$$r_{1,j} \geq h_{j-1}, r_{i+1,j} - r_{i,j} \geq h_{j-1}.$$

If, in addition, the coefficients $b_{i,j}$ are all positive, then we say that μ is of purely dynamical origin.

The following is proved in [2].

Lemma 3.4. Given a sequence $P_n = \sum_{j=0}^{m_n} a_{j,n} z^j$, $n = 1, 2, \dots$ of analytic trigonometric polynomials in $L^2(S^1, dz)$ with non-zero constant

¹The Mahler measure of the finite measure μ on the circle is given by

$$M\left(\frac{d\mu}{dz}\right) = \inf_P \|P - 1\|_{L^2(\mu)},$$

where P ranges over all analytic trigonometric polynomials with zero constant term.

terms and $L^2(S^1, dz)$ norm 1, $\prod_{n=1}^{\infty} |a_{m_n, n}| = 0$. Then there exist a sequence of positive integers N_1, N_2, \dots such that

$$\prod_{j=1}^{\infty} |P_j(z^{N_j})|^2$$

is a generalized Riesz product of dynamical origin.

Applying carefully the previous lemma, the following theorem is proved in [2].

Theorem 3.5. *Let $P_j, j = 1, 2, \dots$ be a sequence of non-constant polynomials of $L^2(S^1, dz)$ norm 1 such that $\lim_{j \rightarrow \infty} |P_j(z)| = 1$ a.e. (dz) then there exists a subsequence $P_{j_k}, k = 1, 2, \dots$ and natural numbers $l_1 < l_2 < \dots$ such that the polynomials $P_{j_k}(z^{l_k}), k = 1, 2, \dots$ are dissociated and the infinite product $\prod_{k=1}^{\infty} |P_{j_k}(z^{l_k})|^2$ has finite nonzero value a.e (dz) .*

4. FLATS POLYNOMIALS

A sequence $P_j, j = 1, 2, \dots$ of trigonometric polynomials is said to be L^p -flat if the sequence $\frac{|P_j|}{\|P_j\|_2}, j = 1, 2, \dots$ converge to the constant function 1 in the L^p -norm, $p \in [1, +\infty], p \neq 2$. If $p = +\infty$ the sequence P_j is said to be ultraflat.

The flatness issue can be considered for three class of analytic trigonometric polynomials. The polynomials with non-negative coefficients, the Littlewood polynomials which correspond to the polynomials with coefficients ± 1 , and the Newman polynomials which correspond to the polynomials with coefficients 0 or 1 and the constant term 1. For all those polynomials, it seems that the existence of L^p -flat polynomials is unknown.

The following notion of almost everywhere flatness is introduced in [2].

Definition 4.1. A sequence $P_j, j = 1, 2, \dots$ of trigonometric polynomials with L^2 -norm one is said to be flat almost everywhere, if $P_j(z)$ converge almost everywhere to 1 with respect to dz .

Applying Vitali convergence theorem [88] one can see that if P_j is almost everywhere flat then P_j is L^1 -flat. In the opposite direction, if P_j is L^1 -flat then one can drop a subsequence over which P_j is almost everywhere flat.

We further have the following.

Proposition 4.2. Let $(P_n)_{n \in \mathbb{N}}$ be a sequence of analytic trigonometric polynomials with L^2 -norm one. Then, the following are equivalent

- (1) (P_n) is L^1 -flat,
- (2) $(\|P_n\|_1)$ converge to 1.

Moreover, if (P_n) is almost everywhere flat then

$$\| |P_n|^2 - 1 \|_1 \xrightarrow{n \rightarrow +\infty} 0.$$

Proof. (1) implies (2) is straightforward. For (2) implies (1), notice that

$$(4.1) \quad \| |P_n| - 1 \|_2^2 = 1 = 2(1 - \|P_n\|_1).$$

For the last fact, by Cauchy-Schwarz inequality, we have

$$\| |P_n|^2 - 1 \|_1 \leq \| |P_n| - 1 \|_2 \| |P_n| + 1 \|_2 \leq 2 \| |P_n| - 1 \|_2.$$

The last inequality is due to $\|P_n\|_2 = 1$ combined with the triangle inequality. Thus, it is suffice to see that

$$\| |P_n| - 1 \|_2 \xrightarrow{n \rightarrow +\infty} 0.$$

But, by (4.1), this equivalent to $(\|P_n\|_1)_{n \in \mathbb{N}}$ converge to 1 which follows from the Vitali convergence theorem. \square

We remind that the classical strategy introduced by Newman and Beller to produce the L^1 -flat polynomials is based on the reduction of the problem of L^1 -flatness to L^4 -flatness problem. For the polynomials form class B this strategy fails. This is proved in [2]. In the next section we will prove much more by giving the proof of Theorem 2.3.

5. SIDON SETS, SINGER SETS AND FLATNESS

Let R be a positive integer and let $S = \{s_1 < s_2 < s_3 < \cdots < s_R\}$ be a subset of $[0, R)$. Put

$$[S - S]^+ = \left\{ s_j - s_i, i < j \right\} = \left\{ r_1, r_2, \cdots, r_{N(n)} \right\}.$$

Evidently, $[S - S]^+$ is a subset of $[0, R)$ since

$$0 \leq s_j - s_i \leq s_j < s_R < R.$$

It can be useful to see $[S - S]^+$ as a upper part of the following matrix

$$\mathcal{M}_S = \begin{pmatrix} 0 & s_2 - s_1 & s_3 - s_1 & \cdots & s_{R-1} - s_1 & s_R - s_1 \\ \cdot & 0 & s_3 - s_2 & \cdots & s_{R-1} - s_2 & s_R - s_2 \\ \cdot & \cdot & 0 & s_4 - s_3 & \cdots & s_R - s_3 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \cdot & \cdot & \cdot & \cdots & 0 & s_R - s_{R-1} \\ \cdot & \cdot & \cdot & \cdot & \cdot & 0 \end{pmatrix}$$

We will denote by $m(l)$ the multiplicity of r_l which correspond to the number of the pair (s_i, s_j) such that $s_j - s_i = r_l$, and we set

$$M(R) = \sup \left\{ m(l), l = 1, \cdots, N(R) \right\}.$$

Following Chidambaraswamy and Kurtz-Shah [27], [65], the sequence $\{s_1 < s_2 < s_3 < \cdots < s_R\}$ is δ -admissible if $M(R) = \delta$, $\delta \geq 1$. If $\delta = 1$, then S is called Sidon set. We remind that the classical definition of Sidon sets goes back to Sidon how introduce the notion in 1932 or 1933 according to Erdős [40]. This definition can be stated as follows.

Definition 5.1. A set S is called a Sidon set if all the sums $s + t$, $s \leq t \in S$, are distinct.

More generally, one can defined $B_h[g]$ sets, where h and g are a positive integers. A subset A of $[1, N]$ is said to be $B_h[g]$ set if the linear equation $n = \sum_{i=1}^h a_i$, has at most g solutions up to permutations. $B_2[1]$ correspond to the Sidon sets. It is easy to see that a subset is Sidon set if and only if all the difference are distinct. This last property is not shared with the $B_h[g]$ sets, $h \geq 3$ [62].

Sidon asked on the maximal size of the Sidon set subset of $\{1, \dots, H\}$. Erdős and Turán [40] proved that if $T \subset [0, H]$ is a Sidon set then

$$|T| < \sqrt{H} + 10\sqrt[4]{H} + 1.$$

Lindström strengthened this result and proved [67]

$$|T| < \sqrt{H} + \sqrt[4]{H} + 1.$$

In the other direction it has been shown by Chowla [28] and Erdős using a theorem of Singer [94] that

$$|T| \geq \sqrt{H} - o(\sqrt{H}).$$

Nowadays, it is customary to use algorithmically a Singer's theorem to produce a Sidon subset of the given set $\{1, \dots, N\}$. Furthermore, the construction can be used to produce a Sidon subset with some desired proprieties of its sumsets [51, p.83], [90]. We notice that Singer established his theorem in the finite projective geometry setting. In the number theoretic setting, the theorem can be stated as follows.

Theorem 5.2 (Singer [94]). *Let p be a prime and let $q = p^2 + p + 1$. Then, there exist $A \subset \mathbb{Z}/q\mathbb{Z}$ with $|A| = p + 1$ such that for all $x \in \mathbb{Z}/q\mathbb{Z} \setminus \{0\}$, there exist a_1, a_2 such that $x = a_1 - a_2$.*

Such set, in which every non-zero difference mod q arises exactly one is called a perfect difference set or Singer set. For the construction of Singer set, we refer the reader to [94]. Using the Singer sets, Erdős-Sárközy-Sós [42], [43] and Rusza [90], [91] constructed a Sidon set S subset of $\{1, \dots, N\}$ such that

$$|S| \geq \sqrt{N} - o(\sqrt{N}) \tag{ER},$$

With some desired properties.

We notice that Singer's construction is based on the nice properties of finite fields [94].

Let us further mention that the lower bound and the upper bound of the quantities $M(R)$ and $N(R)$ can be obtained by considering the following toy examples.

For the first example we take $s_i = i$. This gives

$$P_S(z) = \frac{1}{\sqrt{R}} \sum_{i=1}^R z^i,$$

and

$$\left| P_S(z) \right|^2 = 1 + \frac{1}{R} \sum_{l=1}^R (R-l)z^l + \frac{1}{R} \sum_{l=1}^R (R+l)z^{-l}.$$

Therefore $M(R) = R - 1$ and $N(R) = R$. We thus have $M(R)$ is maximal and $N(R)$ is minimal. Indeed, For any $n \in \mathbb{N}^*$, the number of solution of the equation $n = s_j - s_i$ is less than $R - n$ since any solution (s_j, s_i) , when it exists, satisfy $n \leq s_j \leq R$.

The second example correspond to the case for which the support of the Fourier transform is a Sidon subset S of $[1, R]$. In this case $M(R) = 1$ and $N(R) = \frac{|S|(|S|-1)}{2}$. Indeed, by definition of the Sidon set all $(s_j - s_i)$ are distinct. Hence, the first row of the matrix \mathcal{M}_S contain $R - 1$ elements, the second row $R - 2$, and the last row one element. By adding, we get

$$(R - 1) + (R - 2) + \cdots + 1 = \frac{R(R - 1)}{2}.$$

Whence $M(R)$ is minimal and $N(R)$ is maximal. It is seems that the quantity $M(R)N(R)$ is balanced.

It is hidden in the proof given by Chidambaraswamy [27] that the L^2 -norm of the polynomials $(|P_n(z)|^2 - 1)$ does not converge to 0. Indeed, write

$$\left| P_n(z) \right|^2 - 1 = \frac{1}{n} \sum_{l=1}^{N(n)} m(l)z^{r_l} + \frac{1}{n} \sum_{l=1}^{N(n)} m(l)z^{-r_l},$$

where $m(l)$ is the multiplicity of r_l given by

$$m(l) = \left| \left\{ (i, j) : s_j - s_i = r_l \right\} \right|,$$

and r_l is defined by

$$\left\{ s_j - s_i, j < i \right\} = \left\{ r_1, r_2, \cdots, r_{N(n)} \right\}.$$

Whence

$$\begin{aligned} \left\| |P_n(z)|^2 - 1 \right\|_2^2 &= \frac{2}{n^2} \sum_{j=1}^{N(n)} m(j)^2 \\ &\geq \frac{2}{n^2} \sum_{j=1}^{N(n)} m(j) \\ &\geq \frac{2}{n^2} \frac{n(n-1)}{2}, \end{aligned}$$

since

$$\sum_{j=1}^{N(n)} m(j) = \frac{n(n-1)}{2}.$$

Therefore

$$\left\| |P_n(z)|^2 - 1 \right\|_2^2 \geq 1 + \frac{1}{n},$$

which complete the proof of the claim. From this it easy to see that $\|P_n\|_4 \geq 2$, for any n . Hence, $\|P_n\|_4$ never converge to 1. We thus get that for any $\alpha \geq 4$, (P_n) are not L^α -flat, since if not then $\|P_n\|_\alpha$ will converge to 1 which is impossible. This achieve the proof of Theorem 2.3.

6. PROOFS OF THE MAIN RESULTS

Let us first outline the main ideas of our strategy. The proof is divided into two part. In the first part, we construct a sequence of analytic polynomials (P_q) , $q = p^2 + p + 1$ and p prime with coefficients given by the indicator function of Singer sets, and we proved that the sequences $|P(z_{q,j})|$ where $z_{q,j}$ are not trivial q -root of unity, converge to 1. We proceed next to establish that the sequence of analytic polynomials (P_q) is L^α -flat, $\alpha \in (0, 2)$. For that we need to estimate the L^α -norms of the sequence of trigonometric polynomials $(|P_q|^2 - 1)$. For that, we use Marcinkiewicz-Zygmund inequalities with the nodal points $\left\{ z_{q,j,\delta} \right\}_{j=0, \dots, 2q-1}$ given by the q -root of unity and its δ -perturbation. This sequence of the nodal points has the property that each element is invariant under the map $j \mapsto j + q$. Therefore, by taking into account the nice properties of Singer sets, we conclude that the sequence

$\left(\left\| |P_q|^2 - 1 \right\|_\alpha\right)$, $\alpha \in (0, 2)$ converge to zero.

In the second part, we use the material from [2],[3] and [4] to conclude that there exist a conservative map on σ -finite measure space with simple Lebesgue spectrum. This answer affirmatively Banach question from the Scottish book. As a consequence, we obtain an answer to Bourgain's question and Mahler's question.

Let us now proceed to the proof.

We start by putting, for any finite subset of integer A ,

$$P_A(z) = \frac{1}{\sqrt{|A|}} \sum_{a \in A} z^a, \quad z \in \mathbb{T},$$

Where $|A|$ is the number of elements in A . The L^2 -norm of P_A is one since

$$(6.1) \quad |P_A(z)|^2 = 1 + \frac{1}{|A|} \sum_{\substack{a, b \in A-A \\ a \neq b}} z^{b-a},$$

where $A - A$ is the set of difference of A .

If $|A - A| = |A|^2$ then A is a Sidon set. The nice properties of Singer's set allows us to prove the following.

Lemma 6.1. *Let p be a prime number and S a Singer set of $\mathbb{Z}/q\mathbb{Z}$ with $q = p^2 + p + 1$. Then for any $r \in \mathbb{Z}/q\mathbb{Z} \setminus \{0\}$, we have*

$$\left| P_S(e^{2\pi i \frac{r}{q}}) \right| = \sqrt{\frac{p}{p+1}}.$$

Proof. Applying (6.1) we get

$$\begin{aligned} \left| P_S(e^{2\pi i \frac{r}{q}}) \right|^2 &= 1 + \frac{1}{|S|} \sum_{t=1}^{q-1} e^{2\pi i \frac{t.r}{q}} \\ &= 1 - \frac{1}{|S|}, \end{aligned}$$

since

$$\sum_{t=0}^{q-1} e^{2\pi i \frac{t.r}{q}} = 1 + \sum_{t=1}^{q-1} e^{2\pi i \frac{t.r}{q}} = 0.$$

Therefore, we can write

$$\left| P_S(e^{2\pi i \frac{r}{q}}) \right|^2 = \frac{|S| - 1}{|S|} = \frac{p}{p+1},$$

and the proof of the lemma is complete. \square

The second main ingredient of our proof is based on the classical Marcinkiewicz-Zygmund inequalities (see [99, Theorem 7.5, Chapter X, p.28]) and some ideas linked to its recent refinement obtained by Chui-Shen-Zhong [31] and many others authors. Therefore, by appealing to some classical results from the H^p theory and interpolation theory of Carleson, we will give an alternative proof to the proof given in [?].

D_n is the Dirichlet kernel, K_n is the Fejér kernel and V_n is the de la Vallé-Poussin kernel. We remind that

$$D_n(x) = \sum_{j=-n}^n e^{2\pi i j x} = \frac{\sin(\pi(2n+1)x)}{\sin(\pi x)},$$

$$K_n(x) = \sum_{j=-n}^n \left(1 - \frac{|j|}{n+1} e^{2\pi i j x}\right) = \frac{1}{n+1} \left\{ \frac{\sin(\pi(n+1)x)}{\sin(\pi x)} \right\}^2,$$

and

$$V_n(x) = 2K_{2n+1}(x) - K_n(x).$$

We also put

$$D_n^*(e^{2\pi i x}) = \sum_{j=0}^{n-1} e^{2\pi i j x}.$$

We recall that the Poisson kernel P_r , $0 < r < 1$, is given by

$$\begin{aligned}
 P_r(\theta) &= \sum_{-\infty}^{+\infty} r^{|n|} e^{in\theta} \\
 (6.2) \qquad &= \frac{1 - r^2}{|1 - re^{i\theta}|^2} \\
 &= \frac{1 - r^2}{1 - 2r \cos(\theta) + r^2}.
 \end{aligned}$$

This kernel is related to the Cauchy kernel $C_r(\theta) \stackrel{\text{def}}{=} \frac{1}{1 - re^{i\theta}}$ by the following relation

$$P_r = \text{Re}(H_r), \text{ where } H_r = 2C_r - 1.$$

The imaginary part of H_r is called the conjugate Poisson kernel and denoted by

$$Q_r(\theta) = \frac{2r \sin(\theta)}{1 - 2r \cos(\theta) + r^2}.$$

Let us also remind that if $f = u + i\tilde{u}$ is analytic in the closed disc with $f(0)$ is real then

$$f(re^{i\theta}) = u * H_r(\theta),$$

and

$$\tilde{u}(\theta) = u * Q_r(\theta).$$

We notice that \tilde{u} is the harmonic conjugate to u , which vanishes at the origin, and of course, Q_r is the the harmonic conjugate to P_r . For $f \in L^1(\mathbb{T})$, the harmonic conjugate of f is given by

$$\tilde{f}(re^{i\theta}) = Q_r * f(\theta) = -i \sum_{\substack{n=-\infty \\ n \neq 0}}^{+\infty} \frac{n}{|n|} r^{|n|} \hat{f}(n) e^{int}.$$

It is well known that the radial limit of $\tilde{f}(re^{i\theta})$ exist almost everywhere, and this radial limit denoted by \tilde{f} is the conjugate function of f .

We will use often the following classical property: If $F = \exp(H)$, where H is an analytic function. Then

$$|F| = \exp(\text{Re}(H)).$$

Given a continuous function f on the torus \mathbb{T} and a triangular family of equidistant points $z_{n,j} \in \mathbb{T}, j = 0, \dots, 2n, n \in \mathbb{N}^*$, that is,

$$z_{n,j} = z_{n,0} + \frac{j}{2n+1}, j = 0, \dots, 2n.$$

We define the Lagrange polynomial interpolation of f at $\{z_{n,j}\}$ by

$$L_n(f, \{z_{n,j}\})(e^{2\pi i x}) = \frac{1}{2\pi} \int_0^{2\pi} f(t) D_n(x - z_{n,j}) d\omega_{2n+1}(t),$$

where ω_{2n+1} is a function defined by

$$\omega_{2n+1}(t) = \frac{2\pi j}{2n+1} \text{ for } \frac{2\pi j}{2n+1} \leq t < \frac{2\pi(j+1)}{2n+1}, j = 0, \pm 1, \pm 2, \dots.$$

ω_{2n+1} is a step function with jump $\frac{2\pi}{2n+1}$ at the points $\frac{2\pi j}{2n+1}$ and $d\omega_{2n+1}$ its Riemann-Stieltjes integral. In the same manner, we define the step function ω_m , for any $m \in \mathbb{N}^*$ and we denote its Riemann-Stieltjes integral by $d\omega_m$.

We will need the following classical inequality due to S. Bernstein and A. Zygmund. For its proof, we refer to [99, Theorem 3.13, Chapter X, p. 11].

Theorem 6.2. *[Bernstein-Zygmund inequality]. For any $p \geq 1$, for any polynomial P of degree n , we have*

$$\|P'\|_p \leq n \|P\|_p,$$

where P' is the derivative of P . The equality holds if and only if $P(e^{ix}) = M \cos(nx + \xi)$.

Máté, Nevai and Arestov extended Bernstein-Zygmund inequality by proving that it is valid for $p \geq 0$. [19, p.142]. For $p = 0$, the result is due to Mahler, a simple proof can be found in [44]. Although we will not need this result in such generality.

The Marcinkiewicz-Zygmund interpolation inequalities assert that for $\alpha > 1, n \geq 1$, and a polynomial P of degree $\leq n - 1$,

$$(6.3) \frac{A_\alpha}{n} \sum_{j=0}^{n-1} |P(e^{2\pi i \frac{j}{q}})|^\alpha \leq \int_{\mathbb{T}} |P(z)|^\alpha dz \leq \frac{B_\alpha}{n} \sum_{j=0}^{n-1} |P(e^{2\pi i \frac{j}{q}})|^\alpha,$$

where A_α and B_α are independent of n and P .

The left hand inequality in (6.3) is valid for any non-negative non-decreasing convex function and in the more general form [99, Remark, Chapter X, p. 30].

The next lemma is crucial for the proof of our main result.

Lemma 6.3. *Let p be a prime number and S a Singer set of $\mathbb{Z}/q\mathbb{Z}$ with $q = p^2 + p + 1$. Then, for any $\alpha > 1$, we have*

$$\frac{1}{q} \sum_{r=0}^{q-1} \left| P_S(e^{2\pi i \frac{r}{q}}) \right|^\alpha = \frac{1}{q} \left((p+1)^{\frac{\alpha}{2}} + (q-1) \left(\frac{p}{p+1} \right)^{\frac{\alpha}{2}} \right).$$

Proof. It is straightforward from Lemma 6.1. \square

Lemma 6.3 yields for any $0 < \alpha < 4$,

$$(6.4) \quad \lim_{q \rightarrow +\infty} \frac{1}{q} \sum_{r=0}^{q-1} \left| P_S(e^{2\pi i \frac{r}{q}}) \right|^\alpha = 1.$$

Now, following the strategy in [31], we perturb the root of unity as follows. Put

$$\begin{aligned} t_{q,r} &= \frac{r}{q}, \text{ and} \\ t_{q,r}^* &= \frac{r}{q} \pm \frac{\delta}{q \cdot p^{1/2+\epsilon}}, \quad \delta > 0, \epsilon > 0. \end{aligned}$$

We thus have

Lemma 6.4. *For any $0 < \alpha < 4$,*

$$\lim_{q \rightarrow +\infty} \frac{1}{q} \sum_{r=0}^{q-1} \left| P_S(e^{2\pi i t_{q,r}^*}) \right|^\alpha = 1.$$

Proof. Applying Bernstein theorem (Theorem 6.2), we get

$$\begin{aligned} |P(e^{2\pi i t_{r,q}}) - P(e^{2\pi i t_{q,r,\delta}^*})| &\leq q \|P_S\|_\infty \left| e^{2\pi i t_{r,q}} - e^{2\pi i t_{q,r,\delta}^*} \right| \\ &\leq \frac{\sqrt{p+1}}{2\pi} \frac{\delta}{p^{1/2+\epsilon}} \xrightarrow{q \rightarrow \infty} 0. \end{aligned}$$

This combined with the standard triangle inequalities gives

$$\begin{aligned} & \left| \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| P_S(e^{2\pi i t_{q,r}}) \right|^\alpha \right)^{\frac{1}{\alpha}} - \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| P_S(e^{2\pi i t_{q,r,\delta}^*}) \right|^\alpha \right)^{\frac{1}{\alpha}} \right| \\ & \leq \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| P_S(e^{2\pi i t_{q,r}}) - P_S(e^{2\pi i t_{q,r,\delta}^*}) \right|^\alpha \right)^{\frac{1}{\alpha}} \\ & \leq \frac{\sqrt{p+1}}{2\pi} \frac{\delta}{p^{1/2+\epsilon}} \xrightarrow{q \rightarrow \infty} 0, \end{aligned}$$

and the proof of the lemma is complete. \square

Lemma 6.4 allow us to construct a new families of nodal points for which (6.4) holds.

Now, we will follows the spirit of this strategy to prove our main results.

6.1. Proof of Theorems 2.1, 2.2. Following the spirit of the Kadets 1/4 theorem for polynomials due to Marzo-Seip [74], and the very recent refinement of the Marcinkiewicz-Zygmund inequalities, we start by establishing a necessary and sufficient conditions for a sequence of the analytic trigonometric polynomials to be L^α -flat, $\alpha > 0$.

Let S be a fixed Singer set in $\mathbb{Z}/q\mathbb{Z}$ with $q = p^2 + p + 1$, p prime number and put

$$P_q(z) = P_S(z).$$

Define

$$z_{j,q} = e^{2\pi i \frac{j}{q}},$$

and for a given $\delta_{q,j} > 0$, $j = 0, \dots, q-1$, we put

$$z_{r,q,(\delta_{q,j})}^* = e^{2\pi i \left(\frac{j}{q} + \frac{\delta_{q,j}}{q} \right)}.$$

Let $\delta > 0$. We define

$$z_{r,2q,\delta} = \begin{cases} z_{\frac{r}{2},q}, & \text{if } r \text{ is even;} \\ z_{\frac{r-1}{2},q,\delta}^*, & \text{if } r \text{ is odd,} \end{cases}$$

with $\delta_{q,j} = \delta, j = 0, \dots, q-1$, and $\rho_q = 1 - \frac{1}{2q}$. We thus have

$$\{z_{r,2q,\delta}\} = \{z_{r,q}\}_{r=0}^{q-1} \cup \{z_{r,q,\delta}^*\}_{r=0}^{q-1},$$

and we set

$$F_{2q-1}(z) = \prod_{r=0}^{2q-1} \left(1 - \rho_q \overline{z_{r,2q,\delta}} z\right), \text{ where } \rho_q = \frac{2q-1}{2q}.$$

We remind that the family of nodal points $\mathcal{Z} = \left\{ \{z_{j,n}\}_{j=0}^n \right\}_{n \geq 0}$ is said to be an L^α Marcinkiewicz-Zygmund family if the L^α Marcinkiewicz-Zygmund inequalities holds for the nodal points $\{z_{j,n}\}_{j=0}^n$, for every $n \geq 0$.

We associate to any family of nodal points $\mathcal{Z} = \left\{ \{z_{j,n}\}_{j=0}^n \right\}_{n \geq 0}$ the function F_n defined by

$$F_n(z) = \prod_{r=0}^n \left(1 - \rho_n \overline{z_{r,n}} z\right), \text{ where } \rho_n = 1 - \frac{1}{n+1}.$$

The family \mathcal{Z} is said to be uniformly separated if there is a positive number c such that

$$\inf_{j \neq k} |z_{n,j} - z_{n,k}| \geq \frac{c}{n+1}, \quad \forall n \geq 0.$$

This notion is related to the notion of Carleson measures and following [93] the sequence $\mathcal{X} = \{\xi_n\}$ of points in the open unit disk \mathbb{D} is said to satisfy Carleson's condition if,

$$(6.5) \quad \gamma = \inf_k \prod_{\substack{j=1 \\ j \neq k}}^{\infty} \left| \frac{\xi_j - \xi_k}{1 - \overline{\xi_k} \xi_j} \right| > 0.$$

Of course this condition is connected to the well-known Carleson's interpolation theorem [26]. For the proof of Carleson's interpolation theorem, we refer the reader to [38, p.157], [63, p.1], [47, p.274].

We remind that a finite measure μ is a Carleson measure if the injection mapping from H^α , $\alpha > 0$ to the space $L^\alpha(\mathbb{D}, \mu)$ is bounded. These measures were described geometrically in Carleson's theorem

[25], [38, p.156], which assert that the finite measure μ is a Carleson measure if and only if there exist a constant $C_\alpha > 0$ such that

$$\int_{\mathbb{D}} |f(z)|^\alpha d\mu \leq C_\alpha \|f\|_{H^\alpha}^\alpha \quad f \in H^\alpha,$$

for any $\alpha > 0$. Furthermore, by Carleson's interpolation theorem, we have that the discrete measure μ given by

$$\mu = \sum_{n=1}^{+\infty} (1 - |z_k|^2) \delta_{z_k},$$

where δ_w is the Dirac measure on w , is a Carleson measure if the family $\{z_k\}$ is uniformly separated. This result was strengthened in [15] by McDonald and Sundberg [72], who proved that the sequence $\{z_k\}$ of points in \mathbb{D} generates a discrete Carleson measure μ if and only if $\{z_k\}$ is a finite union of uniformly separated sequences. For a simple proof, we refer to [39]. We notice that if the sequence is uniformly separated then the constant C_α depend uniquely on γ . In this setting, we have the following lemma

Lemma 6.5. *The sequences $\mathcal{Z} = \left\{ \{\rho_q z_{r,q}\} \right\}_{q \geq 0}$ and $\mathcal{Z}^* = \left\{ \{\rho_q z_{r,q,\delta}^*\} \right\}_{q \geq 0}$ are uniformly separated sequences.*

Proof. Put

$$\xi_r^* = \rho_q z_{r,q,\delta}^* = \rho_q e^{it_{r,q}},$$

where $t_{r,q} = 2\pi\left(\frac{r}{q} + \frac{\delta}{q}\right)$, $r = 0, \dots, q-1$. Then

$$\begin{aligned} (6.6) \quad \left| \frac{\xi_r^* - \xi_s^*}{1 - \overline{\xi_s^*} \xi_r^*} \right|^2 &= \frac{2\rho_q^2 \left(1 - \cos(t_{r,q} - t_{s,q})\right)}{1 - 2\rho_q^2 \cos(t_{r,q} - t_{s,q}) + \rho_q^4} \\ &= \frac{4\rho_q^2 \left(\sin\left(\frac{t_{r,q} - t_{s,q}}{2}\right)\right)^2}{(1 - \rho_q^2)^2 + 4\rho_q^2 \left(\sin\left(\frac{t_{r,q} - t_{s,q}}{2}\right)\right)^2} \\ &= \frac{4\rho_q^2 \left(\sin\left(\pi \frac{r-s}{q}\right)\right)^2}{(1 - \rho_q^2)^2 + 4\rho_q^2 \left(\sin\left(\pi \frac{r-s}{q}\right)\right)^2} \end{aligned}$$

Notice that $\pi \cdot \frac{r-s}{q} \in]-\pi, \pi[$, and the function $x \mapsto \sin^2(x)$ is an even function. We further have, for any $x \in \mathbb{R}$,

$$\sin^2(x - \pi) = \sin^2(x).$$

Therefore, we can reduce our study to the case of $\pi \cdot \frac{r-s}{q} \in]0, \pi/2]$, and if $\pi \cdot \frac{r-s}{q} \in [\pi/2, \pi[$ we substitute $\pi \cdot \frac{r-s}{q}$ by $\pi \cdot \frac{r-s}{q} - \pi \in [-\pi/2, 0[$. Now, assuming $\pi \cdot \frac{r-s}{q} \in]0, \pi/2]$, it follows that

$$\sin^2\left(\pi \cdot \frac{r-s}{q}\right) \geq 4 \frac{(r-s)^2}{q^2},$$

since, for any $x \in]0, \pi/2]$, we have $\sin(x) \geq \frac{2}{\pi}x$. Whence

$$(6.7) \quad \frac{4\rho_q^2 \left(\sin\left(\pi \frac{r-s}{q}\right)\right)^2}{(1 - \rho_q^2)^2 + 4\rho_q^2 \left(\sin\left(\pi \frac{r-s}{q}\right)\right)^2} \geq \frac{4\rho_q^2 \left(4 \frac{(r-s)^2}{q^2}\right)}{(1 - \rho_q^2)^2 + 4\rho_q^2 \left(4 \frac{(r-s)^2}{q^2}\right)},$$

by the monotonicity of the function $\phi(x) = \frac{4\rho_q^2 x}{(1 - \rho_q^2)^2 + 4\rho_q^2 x}$.

We further have

$$(1 - \rho_q^2)^2 \leq \frac{8\rho_q^2}{q^2} \leq \frac{16\rho_q^2}{q^2},$$

since, for any $n \geq 1$, $(n-1) \leq 2\sqrt{2}(n-1)$. This combined with (6.6) and (6.7) gives

$$(6.8) \quad \left| \frac{\xi_r^* - \xi_s^*}{1 - \overline{\xi_s^*} \xi_r^*} \right|^2 \geq \frac{(r-s)^2}{1 + (r-s)^2}.$$

We thus get

$$\inf_s \prod_{\substack{r=0 \\ r \neq s}}^{q-1} \left| \frac{\xi_r^* - \xi_s^*}{1 - \overline{\xi_s^*} \xi_r^*} \right|^2 \geq \prod_{t=1}^{+\infty} \left(1 - \frac{1}{1+t^2}\right) \stackrel{\text{def}}{=} \gamma^2 > 0,$$

by the convergence of $\sum_{t=1}^{+\infty} \frac{1}{1+t^2}$. □

It follows from Lemma 6.5 that the union of the families \mathcal{Z} and \mathcal{Z}^* generates a Carleson measure since the sum of two Carleson measures is a Carleson measure. We further deduce the following

Lemma 6.6. *The sequence $\mathcal{Z} = \left\{ \left\{ \rho_q z_{r,q} \right\}_{q \geq 0} \cup \left\{ \left\{ \rho_q z_{r,q,\delta}^* \right\}_{q \geq 0} \right\}$ is uniformly separated, and we have*

$$\inf_{\substack{\xi \in \mathcal{Z} \\ \chi \in \mathcal{Z} \\ \chi \neq \xi}} \prod \left| \frac{\chi - \xi}{1 - \bar{\xi}\chi} \right| \geq \gamma^2 \cdot \frac{\delta}{\sqrt{1 + \delta^2}},$$

where

$$\gamma^2 = \prod_{t=1}^{+\infty} \left(1 - \frac{1}{1 + t^2} \right).$$

Proof. Put

$$\xi_r = \rho_q z_{r,q}, \text{ and } \xi_r^* = \rho_q z_{r,q,\delta}^*,$$

and let $\xi_s \in \mathcal{Z}$, $s = 0, \dots, q-1$. Then, either $\xi_s \in \left\{ \rho_q z_{r,q} \right\}$ or $\xi_s \in \left\{ \rho_q z_{r,q,\delta}^* \right\}$. Assuming that $\xi_s \in \left\{ \rho_q z_{r,q} \right\}$, it follows that

$$\begin{aligned} \prod_{\substack{\chi \in \mathcal{Z} \\ \chi \neq \xi}} \left| \frac{\chi - \xi}{1 - \bar{\xi}\chi} \right| &= \prod_{r \neq s} \left| \frac{\xi_r - \xi_s}{1 - \bar{\xi}_s \xi_r} \right| \prod_{r=0}^{q-1} \left| \frac{\xi_r^* - \xi_s}{1 - \bar{\xi}_s \xi_r^*} \right| \\ &= \prod_{r \neq s} \left| \frac{\xi_r - \xi_s}{1 - \bar{\xi}_s \xi_r} \right| \prod_{r \neq s} \left| \frac{\xi_r^* - \xi_s}{1 - \bar{\xi}_s \xi_r^*} \right| \left| \frac{\xi_s^* - \xi_s}{1 - \bar{\xi}_s \xi_s^*} \right| \\ &\geq \gamma^2 \frac{\delta}{\sqrt{1 + \delta^2}}, \end{aligned}$$

by the same arguments as in Lemma 6.5 (see also [29]) combined with (6.8). The same conclusion can be drawn for the case $\xi_s \in \left\{ \rho_q z_{r,q,\delta}^* \right\}$ since the two sets plays symmetric roles. The proof of the lemma is complete. \square

According to Chui-Zhong's theorem [29] the family $\mathcal{X} = \left\{ \left\{ \xi_{n,j} \right\}_{j=0}^n \right\}_{n \geq 0}$ of the points on the unit circle is an L^α Marcinkiewicz-Zygmund family if and only if it is uniformly separated and there exist

a constant K_α such that

$$(6.9) \quad \left(\frac{1}{|I|} \int_I |F_n(e^{i\theta})|^\alpha d\theta \right)^{\frac{1}{\alpha}} \left(\frac{1}{|I|} \int_I |F_n(e^{i\theta})|^{-\frac{\alpha}{\alpha-1}} d\theta \right)^{\frac{1}{\alpha}} \leq K_\alpha$$

For every subarc I of the unit circle and every $n \geq 0$.

We notice that the fact that the family is uniformly separated insure that this family generates a Carleson measure, and it is turn out that the second condition (6.9) is well-known as A_α condition in the setting of the BMO spaces (Bounded Mean Oscillation) [47, p.215]. We remind that locally integrable positive function w satisfy A_α condition if

$$(6.10) \quad \sup_I \left(\frac{1}{|I|} \int_I w(x) dx \right) \left(\frac{1}{|I|} \int_I w(x)^{-\frac{1}{\alpha-1}} dx \right)^{\alpha-1} < \infty.$$

It turn out that in the case $p = 2$ the condition (6.10) is equivalent to the following Helson-Szegö condition:

Helson-Szegö condition. There are real-valued function $u, v \in L^\infty(\mathbb{T})$ such that

$$\|v\|_\infty < \frac{\pi}{2} \text{ and } w = e^{u+\tilde{v}}, \text{ (HS)}$$

where \tilde{v} is the conjugate function of v .

For the proof of the equivalence of (6.10) when $p = 2$ and (HS), we refer to [47, p.246-259]. Therein, the reader can found also the proof of the prediction Helson-Szegö's theorem related to (HS) [54].

Now, according to the equivalence of (6.10) when $p = 2$ and (HS), Marzo and Seip [74] observe that in order to prove that the condition (6.9) holds it suffices to establish that the following uniform Helson-Szegö condition holds:

Uniform Helson-Szegö condition. There exist sequence u_n and v_n of real-valued function in $L^\infty(\mathbb{T})$ such that

$$\sup_n \|v_n\|_\infty < \frac{\pi}{2}, \quad \sup_n \|u_n\|_\infty < +\infty \text{ and } |F_n|^2 = e^{u_n+\tilde{v}_n},$$

where \tilde{v}_n is the conjugate function of v_n .

We are going to prove that the uniform Helson-Szegö condition holds. Let $\kappa > 0$ and $n = 2q - 1$. We claim first that we have

$$|F_n(e^{i\theta})|^2 = e^{u_{n,\kappa}(\theta)} |F_{n,\kappa}(e^{i\theta})|^2,$$

where

$$F_{n,\kappa}(z) = \prod_{r=0}^n \left(1 - \rho_{n,\kappa} \overline{z_{r,n+1,\delta}} z\right) \text{ and } \rho_{n,\kappa} = \max \left\{ \frac{1}{2}, 1 - \frac{\kappa}{n+1} \right\}.$$

Indeed, the Mahler measure of the function $\phi_{n,\kappa}(\theta) \stackrel{\text{def}}{=} \frac{F_n(e^{i\theta})^2}{F_{n,\kappa}(e^{i\theta})^2}$ verify

$$M(|\phi_{n,\kappa}|) = \prod_{r=0}^n \left(\frac{M(1 - \rho_n \overline{z_{r,n+1,\delta}} e^{i\theta})}{M(1 - \rho_{n,\kappa} \overline{z_{r,n+1,\delta}} e^{i\theta})} \right) = 1,$$

by Proposition 2.6 combined with the well-know Jensen formula. We further have

$$\begin{aligned} \frac{1 - \rho_n \overline{z_{r,n+1,\delta}} e^{i\theta}}{1 - \rho_{n,\kappa} \overline{z_{r,n+1,\delta}} e^{i\theta}} &= (1 - \rho_n \overline{z_{r,n+1,\delta}} e^{i\theta}) \left(\sum_{l=0}^{+\infty} \rho_{n,\kappa}^l \overline{z_{r,n+1,\delta}}^l e^{il\theta} \right) \\ &= 1 + \sum_{l=0}^{+\infty} \rho_{n,\kappa}^{l-1} \overline{z_{r,n+1,\delta}}^l (\rho_{n,\kappa} - \rho_n) e^{il\theta}. \end{aligned}$$

Therefore $\phi_{n,\kappa}$ is in H^1 and $\log |\phi_{n,\kappa}|$ is integrable. Put

$$G(z) = \exp \left(\frac{1}{2\pi} \int_0^{2\pi} \frac{e^{i\theta} + z}{e^{i\theta} - z} \log |\phi_{n,\kappa}(\theta)| d\theta \right).$$

Then G is an analytic function in the unit disc \mathbb{D} and $|G| = e^{u_{n,\kappa}}$, where $u_{n,\kappa}$ is the Poisson integral of $\log(|\phi_{n,\kappa}|)$, that is, $u_{n,\kappa}(re^{i\theta}) = P_r * \log(|\phi_{n,\kappa}|)$ where P_r is the Poisson kernel and $*$ is the convolution operator. By Fatou theorem [55, p.34], $|G| = e^{u_{n,\kappa}} = |\phi_{n,\kappa}|$ almost everywhere on the unit circle \mathbb{T} . We further have

$$\begin{aligned} u_{n,\kappa}(\theta) &= 2\text{Re} \left(\text{Log}(F_n(\theta)) - \text{Log}(F_{n,\kappa}(\theta)) \right) \\ &= 2\text{Re} \left(\sum_{r=0}^n \left(\text{Log} \left(1 - \rho_n \overline{z_{r,n+1,\delta}} e^{i\theta} \right) - \text{Log} \left(1 - \rho_{n,\kappa} \overline{z_{r,n+1,\delta}} e^{i\theta} \right) \right) \right) \\ &= 2\text{Re} \left(\sum_{r=0}^n \left(\sum_{l=1}^{+\infty} \frac{\rho_{n,\kappa}^l - \rho_n^l}{l} \overline{z_{r,n+1,\delta}}^l e^{il\theta} \right) \right), \end{aligned}$$

where Log is the principal value of the logarithm. Writing

$$u_{n,\kappa}(\theta) = 2\text{Re}(I + II),$$

where

$$I = \sum_{r=0}^{q-1} \sum_{l=1}^{+\infty} \frac{\rho_{n,\kappa}^l - \rho_n^l}{l} \bar{z}_{r,q}^{-l} e^{il\theta}, \text{ and } II = \sum_{r=0}^{q-1} \sum_{l=1}^{+\infty} \frac{\rho_{n,\kappa}^l - \rho_n^l}{l} \bar{z}_{r,q}^{-l} e^{-2i\pi \frac{l\delta}{2q}} e^{il\theta}.$$

It follows that

$$I = \sum_{l=1}^{+\infty} \frac{\rho_{n,\kappa}^{lq} - \rho_n^{lq}}{l} e^{ilq\theta}, \text{ and } II = \sum_{l=1}^{+\infty} \frac{\rho_{n,\kappa}^{lq} - \rho_n^{lq}}{l} e^{-2il\pi \frac{\delta}{2}} e^{ilq\theta},$$

since

$$\sum_{r=0}^{q-1} \bar{z}_{r,q}^{-l} = \begin{cases} q, & \text{if } l \in q\mathbb{Z}; \\ 0, & \text{if not.} \end{cases}$$

We can thus write

$$\begin{aligned} |u_{n,\kappa}| &\leq |I| + |II| \\ &\leq 2 \left(\sum_{l=1}^{+\infty} \frac{\rho_{n,\kappa}^{lq}}{l} + \sum_{l=1}^{+\infty} \frac{\rho_n^{lq}}{l} \right) \\ &\leq 2 \left(\log \left(\frac{1}{1 - \rho_{n,\kappa}^q} \right) + \log \left(\frac{1}{1 - \rho_n^q} \right) \right), \\ &\leq \frac{2}{1 - e^{-\frac{\kappa}{2}}} + \frac{2}{1 - e^{-\frac{1}{2}}} \end{aligned}$$

since $\log(x) \leq x$ for any $x > 0$, and $\log(1 - x) \leq -x$ for $0 \leq x < 1$. We thus conclude that

$$\sup_n \|u_{n,\kappa}\|_\infty < +\infty,$$

and the proof of the claim is complete.

We move now to construct the functions v_n . For that, we start by proving the following lemma

Lemma 6.7. *Let $F(z) = (1 - rz_0z)$, with $0 < r < 1$ and $z_0 = e^{i\theta_0}$. Then $|F|^2(e^{i\theta}) = e^{\tilde{v}}$, where \tilde{v} is the conjugate function of the function v given by*

$$(6.11) \quad v(\theta) = P_r * \mathbb{1}_{[0,\theta]}(\theta_0) - \theta - c,$$

and c is any suitable constant.

Proof. Obviously F^2 is an outer function since the zeros of F^2 are out of the disc \mathbb{D} . We further have $F^2(0) = 1$. Whence $|F|^2 = e^{\tilde{v}}$, where \tilde{v} is the conjugate function of the function v given by (6.11). Indeed, for any θ , we have

$$\begin{aligned}
 \text{Log}(F(e^{i\theta})) &= -\sum_{n=1}^{+\infty} \frac{r^n}{n} e^{in(\theta-\theta_0)} \\
 (6.12) \quad &= -\sum_{n=1}^{+\infty} \frac{r^n}{n} \cos(n(\theta-\theta_0)) + i \sum_{n=1}^{+\infty} \frac{r^n}{n} \sin(n(\theta-\theta_0)),
 \end{aligned}$$

where Log is *the principal value of the logarithm*. We further have

$$\begin{aligned}
 v(\theta) &= P_r * \mathbb{1}_{[0,\theta]}(\theta_0) - \theta - c = \int_0^\theta P_r(\theta_0 - t) dt - \theta - c \\
 &= \int_0^\theta P_r(t - \theta_0) dt - \theta - c,
 \end{aligned}$$

Since P_r is an even function. But

$$\begin{aligned}
 \int_0^\theta P_r(t - \theta_0) dt &= \int_0^\theta \sum_{n=-\infty}^{+\infty} r^{|n|} e^{in(t-\theta_0)} dt \\
 (6.13) \quad &= \sum_{n \neq 0} \frac{r^{|n|}}{in} e^{in(\theta-\theta_0)} - \sum_{n \neq 0} \frac{r^{|n|}}{in} e^{-in\theta_0} + \theta,
 \end{aligned}$$

by (6.2). Consequently

$$v(\theta) = \sum_{n \neq 0} \frac{r^{|n|}}{in} e^{in(\theta-\theta_0)} - \sum_{n \neq 0} \frac{r^{|n|}}{in} e^{-in\theta_0} - c,$$

and

$$\begin{aligned}
 \tilde{v}(\theta) &= -i \sum_{n \neq 0} \frac{n}{|n|} \frac{r^{|n|}}{in} e^{in(\theta-\theta_0)}, \\
 (6.14) \quad &= -2 \sum_{n=1}^{+\infty} \frac{r^n}{n} \cos(n(\theta-\theta_0))
 \end{aligned}$$

Combining (6.12) with (6.14), we obtain

$$\text{Re}\left(\text{Log}(F^2(e^{i\theta}))\right) = \tilde{v}(\theta),$$

which gives

$$|F^2| = e^{\tilde{v}},$$

since for any analytic function g , we have

$$|e^g| = e^{\operatorname{Re}(g)},$$

and the proof of the lemma is complete. \square

We now apply Lemma 6.11 to write

$$|F_{n,\kappa}(e^{i\theta})|^2 = e^{\widetilde{v_{n,\kappa}}(\theta)},$$

where

$$(6.15) \quad v_{n,\kappa}(\theta) = \sum_{j=0}^n \int_0^\theta P_{\rho_{n,\kappa}}(\theta_{n,j} - t) dt - (n+1)\theta - c,$$

$$\theta_{n,j} = \begin{cases} 2\pi \frac{j}{2q}, & \text{if } j \text{ is even;} \\ 2\pi \left(\frac{j-1}{2q} + \frac{\delta}{q} \right), & \text{if } j \text{ is odd,} \end{cases}$$

and c is any suitable constant. Taking

$$c = \sum_{j=0}^n \int_{-2\pi\gamma_{n,j}}^0 P_{\rho_{n,\kappa}} \left(\left(2\pi \frac{j-1}{2q} \right) - t \right) dt,$$

with

$$\gamma_{n,j} = \begin{cases} 0, & \text{if } j \text{ is even;} \\ 2\pi \frac{\delta}{q}, & \text{if } j \text{ is odd.} \end{cases}$$

We can rewrite (6.15) as

$$(6.16) \quad v_{n,\kappa}(\theta) = \sum_{j=0}^n \int_0^{\theta - 2\pi\gamma_{n,j}} P_{\rho_{n,\kappa}}(\theta_{n,j} - t) dt - (n+1)\theta,$$

since, for any odd j , we have

$$\begin{aligned} \int_0^\theta P_{\rho_{n,\kappa}}(\theta_{n,j} - t) dt &= \int_0^\theta P_{\rho_{n,\kappa}} \left(\left(2\pi \left(\frac{j-1}{2q} \right) + \gamma_{n,j} \right) - t \right) dt, \\ &= \int_{-2\pi\gamma_{n,j}}^{\theta - 2\pi\gamma_{n,j}} P_{\rho_{n,\kappa}} \left(\left(2\pi \left(\frac{j-1}{2q} \right) \right) - t \right) dt \end{aligned}$$

Again writing

$$v_{n,\kappa}(\theta) = I + II,$$

where

$$I = \sum_{r=0}^{q-1} \int_0^\theta P_{\rho_{n,\kappa}}\left(\frac{2\pi j}{q}-t\right) dt - q\theta \quad \text{and} \quad II = \sum_{r=0}^{q-1} \int_0^{\theta - \frac{2\pi\delta}{q}} P_{\rho_{n,\kappa}}\left(\frac{2\pi j}{q}-t\right) dt - q\theta.$$

We thus need to estimate $|I|$ and $|II|$. But, by the same reasoning as above, it is easy to check that

$$I = \sum_{l \neq 0} \rho_{n,\kappa}^{lq} \frac{1 - e^{-ilq\theta}}{il} \quad \text{and} \quad II = \sum_{l \neq 0} \rho_{n,\kappa}^{lq} \frac{1 - e^{-ilq(\theta - \frac{2\pi\delta}{q})}}{il} - 2\pi\delta.$$

Consequently, we get

$$|I| \leq 4 \sum_{l \geq 1} \frac{\rho_{n,\kappa}^{lq}}{l} = -4 \log(1 - \rho_{n,\kappa}^q).$$

Whence

$$|I| \lesssim -4 \log(1 - e^{-\frac{\kappa}{2}}).$$

It is still to estimate $|II|$. In the same manner, it can be seen that

$$|II| \lesssim 2\pi\delta + 4 \sum_{l \geq 1} \frac{\rho_{n,\kappa}^{lq}}{l} \leq 2\pi\delta - 4 \log(1 - e^{-\frac{\kappa}{2}}),$$

and by choosing κ sufficiently large and $\delta < \frac{1}{8}$, we obtain

$$\sup_n \|v_{n,\kappa}(\theta)\|_\infty < \frac{\pi}{2}.$$

From this we conclude that the uniform Helson-Szegö condition holds for $\alpha = 2$.

For the case $1 < \alpha \neq 2$. Assuming $\delta < \frac{1}{8\beta}$ where $\beta = \max\{\alpha, \frac{\alpha}{\alpha-1}\}$, one may apply the standard argument from the H^p theory combined with the Hölder inequality and Lemma 2 from [74] to conclude that the uniform Helson-Szegö condition holds.

Now, let $1 < \alpha < 2$ and $0 < \delta < \frac{1}{4\beta}$, with $\beta = \frac{\alpha}{\alpha-1}$. By Lemma 6.6 the family $\mathcal{Z} = \left\{ \left\{ \rho_q z_{r,q} \right\}_{q \geq 0} \right\} \cup \left\{ \left\{ \rho_q z_{r,q,\delta}^* \right\}_{q \geq 0} \right\}$ is uniformly separated.

We can thus write

$$(6.17) \leq C_{\alpha,\delta} \left(\frac{1}{2q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q})|^2 - 1 \right|^\alpha + \frac{1}{2q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q,\delta}^*)|^2 - 1 \right|^\alpha \right),$$

where

$$C_{\alpha,\delta} = \frac{2C_\gamma}{\gamma^2 \cdot \frac{\delta}{\sqrt{1+\delta^2}}} = \frac{2C_\gamma \sqrt{1+\delta^2}}{\gamma^2 \cdot \delta}.$$

The computation of constant $C_{\alpha,\delta}$ can be found in [38, p.153]. Therein, by appealing to the duality argument, it is shown that for any $w = (w_j) \in \ell^\alpha$, there exist $g \in H^\alpha$ such that for some $f \in H^\beta$, with $\|f\|_\beta = 1$, and β is the conjugate of α , one can assert

$$\|g\|_\alpha \leq \frac{\sqrt{1+\delta^2}}{\gamma^2 \cdot \delta} \|w\|_\alpha \left(\int_{\mathbb{D}} |f(z)|^\beta d\mu_{\mathcal{Z}} + \int_{\mathbb{D}} |f(z)|^\beta d\mu_{\mathcal{Z}^*} \right),$$

where

$$\mu_{\mathcal{Z}} = \sum_{q=3}^{+\infty} \left(\sum_{r=0}^{q-1} (1 - |\rho_q z_{r,q}|) \right) \delta_{z_{r,q}}, \quad \text{and} \quad \mu_{\mathcal{Z}^*} = \sum_{q=3}^{+\infty} \left(\sum_{r=0}^{q-1} (1 - |\rho_q z_{r,q,\delta}^*|) \right) \delta_{z_{r,q}}.$$

But the measures $\mu_{\mathcal{Z}}$ and $\mu_{\mathcal{Z}^*}$ are a Carleson measures. Therefore,

$$\int_{\mathbb{D}} |f(z)|^\beta d\mu_{\mathcal{Z}} + \int_{\mathbb{D}} |f(z)|^\beta d\mu_{\mathcal{Z}^*} \leq 2C_\gamma \|f\|_\beta = 2C_\gamma,$$

where

$$C_\gamma = \frac{2}{\gamma^4} (1 - 2 \log(\gamma)).$$

An alternative proof can be found in [55, p.195-202]. The reader may notice that the proof of Theorem F in [31] can be drawn from the above proof.

Let us stress at this point that we have proved that for any $\alpha > 0$, the sequence of polynomials $(P_q(z))$ is L^α -flat if and only if

$$\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q})|^2 - 1 \right|^\alpha \xrightarrow{q \rightarrow +\infty} 0,$$

and

$$\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q,\delta}^*)|^2 - 1 \right|^\alpha \xrightarrow{q \rightarrow +\infty} 0.$$

Now, we are going to prove that (P_q) is L^α -flat, $1 < \alpha < 2$. We start by writing

$$\begin{aligned} & \left| \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q})|^2 - 1 \right|^\alpha \right)^{\frac{1}{\alpha}} - \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q,\delta}^*)|^2 - 1 \right|^\alpha \right)^{\frac{1}{\alpha}} \right| \\ (6.18) \quad & \leq \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q})|^2 - |P_q(z_{r,q,\delta}^*)|^2 \right|^\alpha \right)^{\frac{1}{\alpha}} \end{aligned}$$

Moreover, by the nice properties of Singer sets, we have

$$\begin{aligned} \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q})|^2 - |P_q(z_{r,q,\delta}^*)|^2 \right|^\alpha \right)^{\frac{1}{\alpha}} &= \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| D_q^*(z_{r,q}) - D_q^*(z_{r,q,\delta}^*) \right|^\alpha \right)^{\frac{1}{\alpha}} \\ &= \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| \frac{1}{|S|} \sum_{\ell=0}^{q-1} z_{r,q}^\ell (1 - e^{2\pi i \frac{\ell \delta}{q}}) \right|^\alpha \right)^{\frac{1}{\alpha}} \\ &\leq \left(\frac{1}{q} \sum_{r=0}^{q-1} \left| \frac{1}{|S|} \sum_{\ell=0}^{q-1} z_{r,q}^\ell (1 - e^{2\pi i \frac{\ell \delta}{q}}) \right|^2 \right)^{\frac{1}{2}} \end{aligned}$$

We further have

$$\begin{aligned} \frac{1}{q} \sum_{r=0}^{q-1} \left| \frac{1}{|S|} \sum_{\ell=0}^{q-1} z_{r,q}^\ell (1 - e^{2\pi i \frac{\ell \delta}{q}}) \right|^2 &= \int \left| \frac{1}{|S|} \sum_{\ell=0}^{q-1} z^\ell (1 - e^{2\pi i \frac{\ell \delta}{q}}) \right|^2 dz \\ &= \frac{1}{|S|^2} \sum_{\ell=0}^{q-1} |1 - e^{2\pi i \frac{\ell \delta}{q}}|^2 \\ &\leq 2\pi \frac{q}{|S|^2} \cdot \delta^2 \\ &\leq 2\pi \delta^2. \end{aligned}$$

Whence

$$\begin{aligned} & \frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q,\delta}^*)|^2 - 1 \right|^\alpha \\ & \leq \left(\left(\frac{1}{q} \sum_{r=0}^{q-1} \left| |P_q(z_{r,q})|^2 - 1 \right|^\alpha \right)^{\frac{1}{\alpha}} + \sqrt{2\pi\delta} \right)^\alpha. \end{aligned}$$

Combined these inequalities with Lemma 6.3, we can rewrite (6.17) as

$$\int \left| |P_q|^2 - 1 \right|^\alpha d\theta \leq C_{\alpha,\delta} \left(\frac{1}{2} I_{\alpha,p} + \frac{1}{2} \left(I_{\alpha,p}^{\frac{1}{\alpha}} + \sqrt{2\pi\delta} \right)^\alpha \right),$$

where

$$I_{\alpha,p} = \frac{p^\alpha}{q} + \left(\frac{q-1}{q} \right) \left(\frac{p}{p+1} - 1 \right),$$

Letting $q \rightarrow +\infty$, we obtain

$$\lim_{q \rightarrow +\infty} \int \left| |P_q|^2 - 1 \right|^\alpha d\theta \leq C_{\alpha,\delta} (2\pi)^{\frac{\alpha}{2}} \delta^\alpha = \frac{2C_\gamma}{\gamma^2} \sqrt{1+\delta^2} (2\pi)^{\frac{\alpha}{2}} \delta^{\alpha-1},$$

and by letting $\delta \rightarrow 0$, we conclude that

$$\lim_{q \rightarrow +\infty} \int \left| |P_q|^2 - 1 \right|^\alpha d\theta = 0,$$

Hence the sequence of polynomials $(P_q)_{q \in \mathbb{N}}$ is L^α -flat, for $0 < \alpha < 2$.

Therefore, by appealing to Proposition 4.2, we deduce that the sequence of polynomials $(P_q(z))$ is almost everywhere flat over some subsequence, and the proof of Theorem 2.1 is complete.

Theorem 2.2 follows from Theorem 2.1 combined with Proposition 4.2. Finally, by (3.2), we deduce that the spectral type σ of the rank one map constructed in Theorem 2.2 verify

$$M\left(\frac{d\sigma}{dz}\right) = \prod_{j=0}^{+\infty} M(P_j^2) > 0.$$

Whence

$$M(P_j) \xrightarrow{j \rightarrow +\infty} 1.$$

This finishes the proof. For more details on the construction of rank one map in Theorem 2.2, we refer the reader to [2] and [3].

Remarks. Obviously, as in the proof given by Zygmund in [99, p.29, Chap X], we take advantage of the following classical identity [99, p.35, Chap II]

$$\frac{1}{d} \sum_{j=0}^{d-1} e^{\frac{2\pi i j k}{d}} = \begin{cases} 0 & \text{if } d \nmid k \\ 1 & \text{if } d \mid k, \end{cases}$$

for any $d, k \geq 1$.

The reader may notice that there is some analogies between our proof and the Fast Fourier Transform algorithm (FFT). We refer the reader to [95] for more details on the FFT.

Applying Carleson interpolation theory, one can prove that for any $p > 0$, there is a constant $C_p > 0$ such that, for any polynomial P of degree less than n ,

$$\frac{C_p^{-1}}{4n} \sum_{j=0}^{4n-1} |P(e^{2\pi i \frac{j}{2n}})|^p \leq \|P\|_p^p.$$

An alternative proof can be found in [82]. Besides this, Marcinkiewicz and Zygmund proved [73] that for any $p \geq 1$ and for any polynomial P of degree less or equal than n , we have

$$\left(\frac{1}{2n} \sum_{j=0}^{2n-1} |P(e^{2\pi i \frac{j}{2n}})|^p \right)^{\frac{1}{p}} \leq (p\pi + 1)^{\frac{1}{p}} \|P\|_p.$$

To the best of this author's knowledge, the explicit constant for the case $p = 0$ seems not to be known. Nevertheless, in the case of the classical Riesz product, if we consider the polynomial

$$P(\theta) = 1 + \alpha \cos(n\theta),$$

where α is non-negative number less than 1. Then

$$\begin{aligned} (6.19) \quad M_{d\omega_{4n+1}}(P) &= \exp \left(\frac{1}{4n} \sum_{j=0}^{4n-1} \log \left(|P(e^{2\pi i \frac{j}{2n}})| \right) \right) \\ &\leq M_{dz}(P). \end{aligned}$$

This can be proved as follows.

Following [58], we put

$$P(\theta) = |Q(e^{i\theta})|^2,$$

where

$$Q(z) = \frac{1 + az^n}{1 + a^2}, \text{ with } a = \frac{\alpha}{1 + \sqrt{1 - \alpha^2}}.$$

It is easily seen that $Q(z)$ does not vanish on the disc $D \stackrel{\text{def}}{=} \{|z| \leq 1\}$. We thus get that the function $\log(|Q(e^{i\theta})|^2)$ is harmonic. Applying the mean property, we obtain

$$(6.20) \quad \log(|Q(0)|^2) = \frac{1}{2\pi} \int_0^{2\pi} \log(|Q(e^{i\theta})|^2) d\theta.$$

Rewriting (6.20), we see that

$$M(P) = \frac{1}{1 + a^2}.$$

Now, any easy computation shows that

$$P(e^{2\pi i \frac{j}{2n}}) = 1 + \alpha(-1)^j,$$

for $j = 0, \dots, 2n - 1$.

Whence

$$M_{d\omega_{4n+1}}(P) = \sqrt{1 - \alpha^2}.$$

Obviously

$$\sqrt{1 - \alpha^2} \leq \frac{1}{1 + a^2}.$$

We conclude that (6.19) holds.

This leads us to ask.

Questions.

- (1) Can one prove or disapprove that $C_p^{\frac{1}{p}}$ converge to 1 as $p \rightarrow 0$.

- (2) Let S_p be a family of Singer sets, p is a prime number and consider the sequence of polynomials

$$P_q(z) = \frac{1}{\sqrt{|S_p|}} \sum_{s \in S_q} z^s, \quad |z| = 1.$$

Can one prove or disapprove that the sequence of the Mahler measure of P_q converge to 1.

- (3) Let (X, \mathcal{B}, μ, T) be an ergodic dynamical system where μ is a finite measure. Can one prove or disapprove that there exist a Borel set A with $\mu(A) > 0$ such that for μ -almost all $x \in X$,

$$\int \left| \frac{1}{\sqrt{N\mu(A)}} \sum_{j=0}^{N-1} \mathbb{1}_A(T^j x) z^j \right| dz \xrightarrow{N \rightarrow +\infty} 1.$$

- (4) In the same setting as in the previous question, can one prove or disapprove that for any measurable f with values ± 1 , for μ -almost all $x \in X$, we have

$$\limsup_{N \rightarrow +\infty} \int \left| \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} f(T^j x) z^j \right| dz < 1.$$

As mentioned in introduction, this problem can be linked to the annealed and quenched business.

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