ON THE STRONG LAW OF LARGE NUMBERS

BY
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In the present note $f(x)$, $-\infty < x < \infty$, will denote a function satisfying the following conditions: (1) $f(x+1) = f(x)$, (2) $\int_0^1 f(x) = 0$, $\int_0^1 f(x)^2 = 1$. By $n_1 < n_2 < \cdots$ we shall denote an arbitrary sequence satisfying $n_{k+1}/n_k > c > 1$, and by $S_n(f)$ the nth partial sum of the Fourier series of $f(x)$.

In a recent paper Kac, Salem, and Zygmund[1] prove (among others) that if for some $\epsilon > 0$

$$\int_0^1 (f(x) - \phi_n(f))^2 = O\left(\frac{1}{(\log n)^\epsilon}\right), \tag{1}$$

then for almost all x

$$\lim_{N\to\infty} \frac{1}{N}\left(\sum_{k=1}^{N} f(n_k x)\right) = 0, \tag{2}$$

or roughly speaking the strong law of large numbers holds for $f(n_k x)$ (in fact the authors prove that $\sum f(n_k x)/k$ converges almost everywhere).

The question was raised whether (2) holds for any $f(x)$. This was known for the case $n_k = 2^k$[2]. In the present paper it is shown that this is not the case. In fact we prove the following theorem.

THEOREM 1. *There exists an $f(x)$ and a sequence n_k so that for almost all x*

$$\limsup_{N\to\infty} \frac{1}{N}\left(\sum_{k=1}^{N} f(n_k x)\right) = \infty. \tag{3}$$

Further we prove the following sharpening of the result of Kac-Salem-Zygmund:

THEOREM 2. *Assume that for some $\epsilon > 0$*

$$\int_0^1 (f(x) - \phi_n(f))^2 = O\left(\frac{1}{(\log\log n)^{2+\epsilon}}\right), \tag{4}$$

then (2) *holds.*

By a slight modification of the construction of the $f(x)$ of Theorem 1 it is easy to construct an $f(x)$ and a sequence n_k for which (3) holds and for which

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(1) Trans. Amer. Math. Soc. vol. 63 (1948) pp. 235–243.

(2) This result is due to Raikov. See F. Riesz, Comment. Math. Helv. vol. (17) (1944) p. 223.

$$(5)\qquad \int_0^1 (f(x) - \phi_n(f))^2 < \frac{1}{(\log\log\log n)^c}.$$

There is clearly a gap between (4) and (5). It seems probable that, in Theorem 2, (4) can be replaced by $1/(\log\log\log n)^\eta$, but much sharper methods would be needed than used here.

The following problem also seems of some interest: By an easy modification in the construction of the $f(x)$ of Theorem 1 we can show the existence of an $f(x)$ and a sequence n_k, so that for almost all x

$$(6)\qquad \limsup_{N\to\infty} \frac{1}{N(\log\log N)^{1/2-\epsilon}}\left(\sum_{k=1}^{N} f(n_k x)\right) = \infty.$$

On the other hand we can show that for almost all x

$$(7)\qquad \lim_{N\to\infty} \frac{1}{N(\log N)^{1/2+\epsilon}}\left(\sum_{k=1}^{N} f(n_k x)\right) = 0.$$

Again there is a gap between (6) and (7). (6) seems to give the right order of magnitude, but I can not prove this.

One final remark. The $f(x)$ of Theorem 1 is unbounded. The possibility that (2) holds for all bounded functions $f(x)$ remains open.

Proof of Theorem 1. Let u_k, v_k, and A_k tend to infinity sufficiently fast (their growth will be specified later). $r_m(x)$ denotes the mth Rademacher function[3]. Put

$$(8)\qquad f(x) = \sum_{k=1}^{\infty} \sum_{m=u_k+1}^{v_k} \frac{r_m(x)}{(A_k(v_k - u_k))^{1/2}}, \qquad \sum_{k=1}^{\infty} \frac{1}{A_k} = 1.$$

Clearly the series for $f(x)$ converges almost everywhere and $\int_0^1 f(x) = 0$, $\int_0^1 f(x)^2 = 1$. Now we define the n_k. Put $j_k = [e^{A_k^2}]$. Denote by $I_t^{(k)}$ the interval

$$((2t-1)v_k,\ (2t-1)v_k + l_t^{(k)}), \qquad t = 1, 2, \cdots, j_k,$$

where $l_t^{(k)} = 2l_{t-1}^{(k)}$ and $l_1^{(k)}$ is very large compared to v_{k-1}, A_{k-1}, $l_{j_{k-1}}^{(k-1)}$, and will be specified later. If we choose $v_k > l_{j_k}^{(k)}$ then the $I_t^{(k)}$ don't overlap. The n_k are the integers of the form 2^m where $m \subset I_t^{(k)}$, $k = 1, 2, \cdots;\ t = 1, 2, \cdots, j_k$.

Order the l's according to their size. Clearly each l is greater than the sum of all previous l's. Thus a simple argument shows that to prove (3) it will be sufficient to show that for every fixed c and almost all x

$$(9)\qquad \limsup \frac{1}{l_t^{(k)}}\left(\sum_{m\subset I_t^{(k)}} f(2^m x)\right) > c, \qquad k = 1, 2, \cdots;\ t = 1, 2, \cdots, j_k.$$

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(3) Instead of $r_m(x)$ I originally used $\cos 2^m x$. The advantage of using Rademacher functions was pointed out to me by Kac.

(Since if $m_{r+1}>2m_r$, and for every c lim sup $(1/(m_{r+1}-m_r))\sum_{m_r}^{m_{r+1}}a_u>c$, then lim sup $(1/u)\sum_{k=1}^{u}a_k=\infty$. Let now m_r be the sum of the r first l's, then clearly (3) is a consequence of (9).)

Hence it will suffice to show that for every ϵ and sufficiently large k the measure of the set in x satisfying at least one of the inequalities

$$\frac{1}{l_t^{(k)}}\left(\sum_{m\subset I_t^{(k)}} f(2^m x)\right) > c, \qquad t = 1, 2, \cdots, j_k, \tag{10}$$

is greater than $1-\epsilon$.

Put

$$f(x) = f_1(x) + f_2(x) + f_3(x)$$

where

$$f_1(x) = \sum_{s=1}^{k-1}\sum_{m=u_s+1}^{v_s}\frac{r_m(x)}{(A_s(v_s-u_s))^{1/2}}, \qquad f_2(x) = \sum_{m=u_k+1}^{v_k}\frac{r_m(x)}{(A_k(u_k-v_k))^{1/2}},$$

$$f_3(x) = \sum_{s>k}\sum_{m=u_s+1}^{v_s}\frac{r_m(x)}{(A_s(v_s-u_s))^{1/2}}.$$

A simple calculation shows that

$$\begin{aligned}\sum_{m\subset I_t^{(k)}} f_2(2^m x) &= \frac{l_t^{(k)}}{(A_k(v_k-u_k))^{1/2}}\sum r_m(x) + \sum\nolimits_1 + \sum\nolimits_2 \\ &= \sum + \sum\nolimits_1 + \sum\nolimits_2\end{aligned} \tag{11}$$

where m runs in the interval

$$(u_k + (2t-1)v_k + l_t^{(k)},\ 2tv_k)$$

and

$$\sum\nolimits_1 = \sum_{a=1}^{l_t^{(k)}}\frac{l_t^{(k)}-a}{(A_k(v_k-u_k))^{1/2}}r_{y-a}(x), \qquad y = u_k + (2t-1)v_k + l_t^{(k)},$$

$$\sum\nolimits_2 = \sum_{a=1}^{l_t^{(k)}}\frac{l_t^{(k)}-a}{(A_k(v_k-u_k))^{1/2}}r_{2tv_k+a}(x).$$

Now $\sum r_m(x)$ is the sum of

$$v_k - u_k - l_t^{(k)} > v_k/2$$

Rademacher functions (we choose $v_k>2(u_k+l_t^{(k)})$). It is well known([4]) that

([4]) See, for example, P. Erdős, Ann. of Math. vol. 43 (1942) p. 420, formula (0.7). Incidentally the formula in question should read $c_1(x^2/n)e^{-2x^2/n}<\Pr(A_n(x))<c_2(x^2/n)e^{-2x^2/n}$.

the measure of the set in x for which

$$\sum r_m(x) > 4c(A_k)^{1/2}(v_k)^{1/2}$$

is greater than

$$c_1 A_k e^{-32c^2 A_k} > e^{-A_k^2}$$

for sufficiently large A_k. Thus the measure of the set in x for which

$$\sum = \frac{l_t^{(k)}}{(A_k(v_k - u_k))^{1/2}} \sum r_m(x) > 4cl_t^{(k)} \tag{12}$$

is greater than $e^{-A_k^2}$. Clearly for all x

$$\left| \sum_1 + \sum_2 \right| < \frac{2(l_t^{(k)})^2}{(A_k(v_k - u_k))^{1/2}} < \frac{4(l_t^{(k)})^2}{(v_k)^{1/2}} < 1 \tag{13}$$

if we choose $v_k > 16(l_t^{(k)})^4$. Thus finally from (11), (12), and (13) the measure of the set in x for which

$$\sum_{m \subset I_t^{(k)}} f_2(2^m x) > 4cl_t^{(k)} - 1 > 3cl_t^{(k)} \tag{14}$$

is greater than $e^{-A_k^2}$.

If $v_k > 2l_t^{(k)}$ for all t, then the functions

$$\sum_{m \subset I_t^{(k)}} f_2(2^m x), \qquad t = 1, 2, \cdots j_k,$$

are independent (since the same $r_m(x)$ does not appear in two different sums). Thus the measure of the set in x for which one of the j_k inequalities

$$\sum_{m \subset I_t^{(k)}} f_2(2^m x) > 3cl_t^{(k)}, \qquad t = 1, 2, \cdots, j_k, \tag{15}$$

holds, is greater than

$$1 - (1 - 1/y)^z > 1 - \epsilon/2 \, (y = e^{A_k^2},\ z = e^{A_k^3}). \tag{16}$$

Further if $l_t^{(k)} > v_{k-1}$

$$\int_0^1 \Big(\sum_{m \subset I_t^{(k)}} f_1(2^m x) \Big)^2 < v_{k-1}^2 (l_t^{(k)} + v_{k-1}) < 2v_{k-1}^2 l_t^{(k)}$$

since only the r_m's with $m \leq l_t^{(k)} + v_{k-1}$ occur and the coefficients of all of them are not greater than v_{k-1}. Thus from Tchebychef's inequality we obtain that the measure of the set in x for which one of the j_k inequalities

$$\sum_{m \subset I_t^{(k)}} f_1(2^m x) > cl_t^{(k)}, \qquad t = 1, 2, \cdots, j_k, \tag{17}$$

holds is less than

$$\sum_{t=1}^{j_k} \frac{2v_{k-1}^2}{c^2 l_t^{(k)}} < \frac{4v_{k-1}^2}{c l_1^{(k)}} < \frac{\epsilon}{4}, \quad l_1^{(k)} > 16v_{k-1}^2/c\epsilon. \tag{18}$$

Finally we have by a simple computation

$$\int_0^1 \Big(\sum_{m \subset I_t^{(k)}} f_k(2^m x) \Big)^2 < 4(l_t^{(k)})^2 \sum_{r>k} \frac{1}{A_r} < 1$$

if $A_{k+1}, \cdots$ are sufficiently large. Thus the measure of the set in x for which one of the inequalities

$$\sum_{m \subset I_t^{(k)}} f_k(2^m x) > c l_t^{(k)}, \qquad t = 1, 2, \cdots, j_k, \tag{19}$$

holds is less than

$$\sum_{t=1}^{j_k} \frac{1}{(c l_t^{(k)})^2} < \frac{\epsilon}{4}. \tag{20}$$

Thus finally from (15), (16), (17), (18), (19), and (20) we obtain (10) and this completes the proof of Theorem 1.

Sketch of the Proof of Theorem 2. Put $j-i=r$, then $n_j/n_i > c^r$. Denote by $a_1, b_1, a_2, b_2, \cdots$ the Fourier coefficients of $f(x)$. By (4) we evidently have

$$\int_0^1 f(n_i x) f(n_j x) = \sum_{n_i u = n_j v} (a_u a_v + b_u b_v) \leq \Big(\sum_{k=1}^{\infty} a_k^2 \sum_{k > c^r} a_k^2 \Big)^{1/2} + \Big(\sum_{k=1}^{\infty} b_k^2 \sum_{k>c^r} b_k^2 \Big)^{1/2} < \frac{c_1}{(\log r)^{1+\epsilon/2}}.$$

Hence

$$\int_0^1 \Big(\sum_{s}^{s+N} f(n_k x) \Big)^2 = O\Big(\frac{N^2}{(\log N)^{1+\epsilon/2}} \Big),$$

or the measure of the set $M(s, N, A)$ in x for which

$$\Big| \sum_{s}^{s+N} f(n_k x) \Big| > A \cdot N$$

is less than

$$c/A^2(\log N)^{1+\epsilon/2}. \tag{21}$$

Consider the sets

$$\begin{aligned} &M(1, 2^n, \delta);\ M(2^n, 2^{n-1}, 2\delta/2^2);\\ &M(2^n, 2^{n-2}, 4\delta/3^2),\ M(2^n + 2^{n-1}, 2^{n-2}, 4\delta/3^2); \cdots. \end{aligned} \tag{22}$$

There are 2^{k-1} sets of order k, that is, sets of the form

(23) $$M(2^n + 2u2^{n-k}, 2^{n-k}, \delta 2^k/(k+1)^2), \ 0 \leqq u < 2^{k-1}.$$

From (21) it follows that the measure of any set of order k does not exceed

$$c(k+1)^4/\delta^2 2^{2k}(n-k)^{1+\epsilon/2}.$$

Thus the measure of all the sets in (23) is less than $c(k+1)^4/\delta^2 2^k(n-k)^{1+\epsilon/2}$, and the measure of all the sets M_n in (22) does not exceed

$$\sum_{k=0}^{n} \frac{c(k+1)^4}{\delta^2 2^k (n-k)^{1+\epsilon/2}} < \frac{c_1}{\delta^2 n^{1+\epsilon/2}}.$$

Thus

(24) $$\sum_{n=1}^{\infty} M_n < \infty.$$

But if x does not belong to any of the sets (22) we have by a simple argument for all $2^n \leqq m < 2^{n+1}$ (every m is the sum of powers of 2)

(25) $$\left| \sum_{k=1}^{m} f(n_k x) \right| < \delta 2^n + \frac{\delta 2^n}{2^2} + \frac{\delta 2^n}{3^2} + \cdots + \frac{\delta 2^n}{k^2} + \cdots < 2\delta 2^n \leqq 2\delta m.$$

(24) and (25) clearly prove theorem 2(5).

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(5) The method used here is due to Hobson-Plancherel-Rademacher-Menchof. (See, for example, Rademacher, Math. Ann. vol. 87 (1922) p. 117–121.)