ON THE INTEGRAL MODULI OF CONTINUITY IN
L_{p} (1 < p < \infty) OF FOURIER SERIES WITH
MONOTONE COEFFICIENTS

S. ALJANČIĆ

1. Introduction and results. Let \( f(x) \) be of period \( 2\pi \) and integrable \( L_{p} (1 < p < \infty) \). The integral moduli of continuity of first and second order of \( f \) in \( L_{p} \) are defined by

\[
\omega_{p}(h; f) = \sup_{|t| \leq h} \|f(x + t) - f(x)\|_{p}
\]

and

\[
\omega_{p}^{*}(h; f) = \sup_{0 < t \leq h} \|f(x + t) + f(x - t) - 2f(x)\|_{p}
\]

respectively, where \( \| \cdot \|_{p} \) denotes the norm in \( L_{p} \). The Lipschitz and Zygmund classes \( \Lambda_{p} \) and \( \Lambda_{p}^{*} \) are then defined by \( \omega_{p}(h; f) = O(h) \) and \( \omega_{p}^{*}(h; f) = O(h) \) respectively.

The problem of what can be said about the integral modulus of continuity (of first order) of the functions of the class \( \Lambda_{p}^{*} \) \( (1 < p < \infty) \) was solved by A. Timan and M. Timan \[6\] for \( p = 2 \) and in the general case by Zygmund \[7\] in the following way:

\[
\begin{align*}
&f \in \Lambda_{p}^{*} \implies \omega_{p}(h; f) \lesssim A_{p}h \log h \lesssim 1 & \text{for } 1 < p \leq 2, \\
&f \in \Lambda_{p}^{*} \implies \omega_{p}^{*}(h; f) \lesssim A_{p}h \log h \lesssim 1/2 & \text{for } 2 \leq p < \infty.
\end{align*}
\]

Both estimates are best possible in general. Here we shall show that the second estimate can be improved for a special class of functions.

**Theorem 1.** If \( f \in L_{p} \ (1 < p < \infty) \) has a cosine or sine Fourier series with monotone coefficients, then

\[
f \in \Lambda_{p}^{*} \implies \omega_{p}(h; f) \lesssim A_{p}h \log h \lesssim 1/p.
\]

The example of the function \( f(x) = \sum_{n=1}^{\infty} n^{1/p - 2} \cos nx \ (1 < p < \infty) \), which belongs to \( \Lambda_{p}^{*} \) and whose integral modulus \( \omega_{p}(h; f) \) is \( > C_{p}h \log h \lesssim 1/p \). Zygmund \[7\] shows that the estimate of Theorem 1 is the best possible.

Recently Aljančić and Tomić \[1\] proved that if the sequence \( \{\mu_{n}\} \) satisfies \( \mu_{n} \geq \mu_{n+1} \to 0 \) and for a fixed \( \tilde{p} \ (1 < \tilde{p} < \infty) \)

\footnote{\( A_{p}, B_{p}, \ldots \) denote constants which depend at most on \( p \), but not necessarily always the same.}
(1) \( \sum_{r=1}^{n-1} r^{1-1/p} \mu_r = O(n^{2-1/p} \mu_n) \) and \( \left\{ \sum_{r=n}^{\infty} r^{p-2/p} \mu_r \right\}^{1/p} = O(n^{1-1/p} \mu_n) \),

then

(2) \( \omega_p(n^{-1}; f) \leq A_p n^{1-1/p} \mu_n \),

where \( f \) is the sum of either of the series

(3) \( \sum_{n=1}^{\infty} \mu_n \cos nx \) or \( \sum_{n=1}^{\infty} \mu_n \sin nx \).

We shall prove here a more complete result:

**Theorem 2.** Let \( \{\mu_n\} \) be a sequence which is monotonically decreasing to zero and such that for a fixed \( p \) (1 < \( p < \infty \))

(4) \( \sum_{n=1}^{\infty} n^{p-2/p} \mu_n < \infty \).

If \( f \) is the sum of either of the series (3), then

(5) \( \omega_p(n^{-1}; f) \leq A_p n^{-1} \left\{ \sum_{r=1}^{n-1} r^{2p-2/p} \mu_r \right\}^{1/p} + B_p \left\{ \sum_{r=n}^{\infty} r^{p-2/p} \mu_r \right\}^{1/p} \).

On account of A. Timan [5, p. 339]

\[ \left\{ \sum_{r=1}^{n-1} r^{2p-2/p} \mu_r \right\}^{1/p} \leq A_p \sum_{r=1}^{n-1} r^{-1/p} \mu_r, \]

the estimate (2) is included in that of (5). On the other hand, if \( \mu_n = n^{-\alpha} \) with \( \alpha > 1 - 1/p \), both (2) and (5) give the same estimate

\[ \omega_p(n^{-1}; f) = O(n^{1-1/p-\alpha}) = O(n^{1-1/p} \mu_n) \] when \( \alpha < 2 - 1/p \),

but, for \( \alpha = 2 - 1/p \), (2) cannot be applied because of (1), whereas (5) gives

\[ \omega_p(n^{-1}; f) = O(n^{-1} \log^{1/p} n) = O(n^{1-1/p} \mu_n \log^{1/p} n). \]

As well as Theorem 1, the following theorem is partly based on a special case of Theorem 2.

**Theorem 3.** If \( \mu_n \geq \mu_{n+1} \to 0 \), then

(6) \( \sum_{n=1}^{\infty} n^{2p-2/p} \mu_n < \infty \) for a fixed \( p \) (1 < \( p < \infty \)).
is a necessary and sufficient condition that the sum \( f \) of either of the series (3)
(i) belongs to \( \Lambda_p \), or
(ii) is equivalent to an absolutely continuous function whose derivative belongs to \( L_p \).

We remark that the results of Theorems 1–3 can be extended in an obvious manner to higher moduli and derivatives respectively. For example, for the modulus of order \( k \), only the first term on the right side in (5) is to be replaced by

\[
A_{p,k}=\left\{ \sum_{m=1}^{n-1} (n+1-p)^{-p} m \right\}^{1/p}.
\]

2. *Proof of Theorem 2.* We note first that condition (4) is both necessary and sufficient that \( f \in L_p \) [8, Chapter XII, Lemma 6.6]. We shall prove the theorem for the cosine series, the proof for the sine series being analogous.

On account of the symmetry of \( f(x) \)

\[
\sup_{0<|t|\leq h} \left\{ \int_{-\pi}^{\pi} |f(x+t)-f(x)|^p \, dx \right\}^{1/p}
= \sup_{0<|t|\leq h} \left\{ \int_{-\pi}^{\pi} |f(x-t)-f(x)|^p \, dx + \int_{0}^{\pi} |f(x+t)-f(x)|^p \, dx \right\}^{1/p},
\]

the function of \( t \) in the braces on the right side being pair. Hence, it suffices to evaluate

\[
I = \left\{ \int_{0}^{\pi} |f(x\pm t)-f(x)|^p \, dx \right\}^{1/p} \quad \text{for } 0 < t \leq h.
\]

Let \( h=\pi/2n \). Owing to \( (a+b)^{1/p} \leq a^{1/p} + b^{1/p} \quad (p>1) \), we have

\[
I \leq \left\{ \int_{0}^{\pi/n} |f(x\pm t)-f(x)|^p \, dx \right\}^{1/p} + \left\{ \int_{\pi/n}^{\pi} |f(x\pm t)-f(x)|^p \, dx \right\}^{1/p} = I_1 + I_2.
\]

By Minkowski's inequality

\[
I_1 \leq 2 \left\{ \int_{0}^{\pi/n} \left| \sum_{m=1}^{n-1} \mu_{x} \sin \frac{1}{2} \nu t \sin \nu(x\pm \frac{1}{2}t) \right|^p \, dx \right\}^{1/p}
+ \left\{ \int_{0}^{\pi/n} \left| \sum_{m=1}^{\infty} \mu_{x} [\cos \nu(x\pm t) - \cos \nu x] \right|^p \, dx \right\}^{1/p} = I_{11} + I_{12}.
\]
As, by Hölder’s inequality,

\[ \sum_{\nu=1}^{n-1} \nu \mu_{\nu} \leq A_p n^{1/p} \left\{ \sum_{\nu=1}^{n-1} \nu^{2p-2} \mu_{\nu} \right\}^{1/p}, \]

we get

\[ I_{11} \leq t \left\{ \int_0^{\pi/n} \left( \sum_{\nu=1}^{n-1} \nu \mu_{\nu} \right)^p dx \right\}^{1/p} \leq A_p n^{-1} \left\{ \sum_{\nu=1}^{n-1} \nu^{2p-2} \mu_{\nu} \right\}^{1/p}. \]

For the latter of the integrals in (8) we find in virtue of \( t \leq \pi/2n \)

\[ I_{12} \leq \left\{ \int_{\pm t}^{\pi/n} \left| \sum_{\nu=1}^{\infty} \nu \mu_{\nu} \cos \nu x \right|^p dx \right\}^{1/p} + \left\{ \int_0^{\pi/n} \left| \sum_{\nu=1}^{\infty} \nu \mu_{\nu} \cos \nu x \right|^p dx \right\}^{1/p} \]

\[ \leq \left( 2^{1/p} + 1 \right) \left\{ \int_0^{3\pi/2n} \left| \sum_{\nu=1}^{\infty} \nu \mu_{\nu} \cos \nu x \right|^p dx \right\}^{1/p} \]

\[ \leq 3 \left\{ \sum_{m=1}^{\infty} \int_{3\pi/2m}^{3\pi/(m+1)} \left| \sum_{\nu=1}^{\infty} \nu \mu_{\nu} \cos \nu x \right|^p dx \right\}^{1/p}. \]

As, for \( 3\pi/2(m+1) \leq x \leq 3\pi/2m \) \( (m=n, n+1, \ldots) \),

\[ \left| \sum_{\nu=1}^{\infty} \nu \mu_{\nu} \cos \nu x \right| \leq \sum_{\nu=1}^{m} \mu_{\nu} + \pi x^{-1} \mu_{m+1} \leq \sum_{\nu=1}^{m} \mu_{\nu} + \frac{3}{4}(m + 1) \mu_{m+1}, \]

we see that

\[ I_{12}^p \leq A_p \sum_{m=1}^{\infty} m^{p-2} \left( \sum_{\nu=1}^{m} \mu_{\nu} \right)^p + B_p \sum_{m=1}^{\infty} m^{p-2} \mu_{m}. \]

Hardy’s inequality [3, Chapter IX, Miscellaneous theorems and examples 346]

\[ \sum_{m=1}^{\infty} m^{p-2} \left( \sum_{\nu=1}^{m} C_{\nu} \right)^p \leq K_p \sum_{m=1}^{\infty} m^{p-2} C_m^p \quad (C_m \geq 0, p > 1), \]

with \( C_m = 0 \) for \( m < n \) and \( C_m = \mu_m \) for \( m \geq n \), shows that the first of these sums is majorized by the latter. Hence,

\[ I_{12} \leq B_p \left\{ \sum_{\nu=1}^{\infty} \nu^{p-2} \mu_{\nu} \right\}^{1/p}. \]

If \( D_r(x) \) denotes the Dirichlet kernel, an Abel transformation
combined with Minkowski's inequality gives

$$I_2 \leq \left\{ \int_{\pi/n}^\pi \left| \sum_{r=1}^n \Delta\mu_r [D_r(x \pm t) - D_r(x)] \right|^p \, dx \right\}^{1/p}$$

$$+ \left\{ \int_{\pi/n}^\pi \left| \sum_{r=n+1}^\infty \Delta\mu_r [D_r(x \pm t) - D_r(x)] \right|^p \, dx \right\}^{1/p} = I_{21} + I_{22}. \quad (12)$$

By dividing the interval \((\pi/n, \pi)\) in subintervals \((\pi/(m+1), \pi/m)\) \((m=1, \ldots, n-1)\) and applying \(D'_r(x) = O(\nu^2)\) for \(0 \leq x \leq \pi\) and \(D'_r(x) = O(x^{-2}) + O(\nu x^{-1}) = O(\nu x^{-1})\) for \(\pi/\nu \leq x \leq \pi\), one obtains in such a subinterval

$$\left| \sum_{r=1}^n \Delta\mu_r [D_r(x \pm t) - D_r(x)] \right|$$

$$\leq t \left( \sum_{r=1}^m + \sum_{r=m+1}^n \right) \Delta\mu_r \left| D_r'(x + \theta_t) \right|$$

$$= O(t) \sum_{r=1}^m \nu^2 \Delta\mu_r + O(t) (x - t)^{-1} \sum_{r=m+1}^n \nu \Delta\mu_r, \quad (-1 < \theta_t < 1)$$

because, on account of \(x \geq \pi/(m+1)\), the second estimate for \(D'_r(x)\) is applicable to every member in the latter sum. If we remember that by Abel transformation

$$\sum_{r=1}^m \nu^2 \Delta\mu_r \leq 2 \sum_{r=1}^m \nu \mu_r, \quad \sum_{r=m+1}^n \nu \Delta\mu_r \leq \sum_{r=m+1}^n \mu_r + m \mu_{m+1},$$

and observe that, owing to \(t \leq \pi/2n\), the inequality \((x - t)^{-1} \leq 2x^{-1} (x \geq 2t)\) may be applied in any of the mentioned subintervals, we get at last the following estimate:

$$\left| \sum_{r=1}^n \Delta\mu_r [D_r(x \pm t) - D_r(x)] \right|$$

$$= O(t) \sum_{r=1}^m \nu \mu_r + O(t m) \sum_{r=m+1}^n \mu_r + O(t m^2 \mu_m).$$

Thus,

$$I_{21}^p = \sum_{m=1}^{n-1} \int_{\pi/(m+1)}^{\pi/m} \left| \sum_{r=1}^n \Delta\mu_r [D_r(x \pm t) - D_r(x)] \right|^p \, dx$$

$$= O(p^p) \left\{ \sum_{m=1}^{n-1} m^{-2} \left( \sum_{r=1}^m \nu \mu_r \right)^p + \sum_{m=1}^{n-1} m^{p-2} \left( \sum_{r=m+1}^n \mu_r \right)^p + \sum_{m=1}^{n-1} m^{2p-2} \mu_m \right\}. \quad (13)$$
By Hardy’s inequality (10) with $C_m = m\mu_m$ for $m < n$ and $C_m = 0$ for $m \geq n$, the first of these sums is essentially majorized by the third. The same holds for the second sum according to another inequality of Hardy [3, ibid.]:

$$\sum_{m=1}^{\infty} m^{-c} \left( \sum_{\nu=m}^{\infty} C_\nu \right)^p \leq K_p \sum_{m=1}^{\infty} m^{p-c} C_m^p$$

($c < 1, C_m \geq 0, p > 1$),

if we choose $c = 2 - p$ and $C_m = \mu_{m+1}$ for $m < n$ and $C_m = 0$ for $m \geq n$. Hence,

$$(13) \quad I_{21} \leq A_p n^{-1} \left\{ \sum_{\nu=1}^{n-1} \nu^{2p-2} \frac{\mu_\nu}{\mu_\nu} \right\}^{1/p}.$$ 

Lastly,

$$I_{22} \leq 2 \left\{ \int_{\pi/2n}^{\pi+\pi/2n} \left| \sum_{\nu=n+1}^{\infty} \Delta_\nu D_\nu(x) \right|^p dx \right\}^{1/p}$$

$$= O(\mu_n) \left\{ \int_{\pi/2n}^{\infty} x^{-p} dx \right\}^{1/p} = O(n^{1-1/p}\mu_n).$$

As

$$\left\{ \sum_{\nu=1}^{n-1} \nu^{2p-2} \frac{\mu_\nu}{\mu_\nu} \right\}^{1/p} \geq \mu_{n-1} \left\{ \sum_{\nu=1}^{n-1} \nu^{2p-2} \right\}^{1/p} \geq C_p n^{2-1/p}\mu_n,$$

one finds

$$(14) \quad I_{22} \leq A_p n^{-1} \left\{ \sum_{\nu=1}^{n-1} \nu^{2p-2} \frac{\mu_\nu}{\mu_\nu} \right\}^{1/p}.$$ 

Collecting in (8) and (12) the estimates (9), (11), (13) and (14), from (7) follows Theorem 2.

3. Proof of Theorem 1. Recently, Konjuškov [4] called attention to the fact that if $f \in L_p$ ($1 < p < \infty$) has a cosine or sine series with monotone coefficients, then

$$\omega_p^*(n^{-1}; f) \geq C_p n^{1-1/p}\mu_n \quad (C_p > 0).$$

Konjuškov deduced (15) from his results about the relationship between the best trigonometric approximation of $f$ in $L_p$ and the Fourier coefficients of $f$. As (15), together with a special case of Theorem 2, is essentially in the proof of Theorem 1, we give here a direct
proof of (15). It is based on the following identity, easily verified:

\[
(16) \quad \frac{1}{4\pi} \int_{-\pi}^{\pi} \left[ 2f(x) - f(x + \pi/n) - f(x - \pi/n) \right] T_m,n(x) \, dx = \sum_{r=m}^{n} \mu_r \sin^2 \frac{r\pi}{n},
\]

where \( T_m,n(x) = \sum_{r=-m}^{n} \cos rx \) and \( f \) is a cosine series. If we set \( t = \pi/n \) in (16) and choose \( m = \lfloor n/2 \rfloor \), then

\[
\sum_{r=m}^{n} \mu_r \sin^2 \frac{\nu \pi}{2n} \geq \frac{1}{n^2} \sum_{r=m}^{n} \nu^2 \mu_r \geq \frac{m^2}{n^2} \mu_n (n - m + 1) \geq C n \mu_n.
\]

On the other hand, in virtue of Hölder's inequality,

\[
\frac{1}{4\pi} \int_{-\pi}^{\pi} \left[ 2f(x) - f(x + \pi/n) - f(x - \pi/n) \right] T_m,n(x) \, dx \leq A_p n^{1/p} \left\{ \int_{-\pi}^{\pi} \left| f(x + \pi/n) + f(x - \pi/n) - 2f(x) \right|^p \, dx \right\}^{1/p}
\]

\[
\leq A_p n^{1/p} \omega^*_p (\pi/n; f),
\]

because \((1/q = 1 - 1/p)\)

\[
\int_{-\pi}^{\pi} T_{m,n}(x) \, dx = 2 \left\{ \int_{0}^{\pi/n} O(n^q) \, dx + \int_{\pi/n}^{\pi} O(x^{-q}) \, dx \right\} = O(n^{q-1}).
\]

Hence, (15) follows.

The proof of Theorem 1 is now immediate. If \( \mu_n \) are the coefficients of \( f \) and \( \omega^*_p (n^{-1}; f) \leq A_p n^{-1} \), then, according to (15), \( \mu_n \leq B_p n^{-2+1/p} \) and one has only to apply Theorem 2 in this special case.

4. Proof of Theorem 3. On account of the well-known theorem of Hardy and Littlewood [2], which asserts the equivalence of (i) and (ii) in the general case, we have only to prove that (6) \( \Rightarrow \) (i) and that (ii) \( \Rightarrow \) (6).

(6) \( \Rightarrow \) (i). Because of \( s_n = \sum_{r=1}^{n} \mu_r^{p-2} \mu_r^p < \infty \), an Abel transformation gives

\[
\sum_{r=1}^{\infty} \mu_r^{p-2} \mu_r^p = \sum_{r=1}^{\infty} \mu_r^{p} (s_r - s_{r-1}) = O(n^{1-p}).
\]

Hence, the second term in (5) is also of order \( O(n^{-1}) \), i.e. \( f \in A_p \).

(ii) \( \Rightarrow \) (6). The proof proceeds, with necessary changes, along the same lines as the necessity part in the proof of Lemma 6.6 in [8, Chapter XII], and is adapted for the sine series.

Let
Then, even simpler than in the proof of the cited lemma, \( F(\pi/n) \leq C\mu_n \).

If we set

\[
G(x) = \int_0^x dt \int_0^t |f'(u)| \, du.
\]

then \( F(x) \leq G(x) \). Hence, applying twice Hardy's inequality [8, Chapter I, p. 20], we get

\[
\sum_{n=2}^{\infty} n^{2p-2} \mu_n \leq A_p \sum_{n=2}^{\infty} n^{2p-2} G^p(\pi/n) \leq A_p \sum_{n=2}^{\infty} \int_{\pi/n}^{\pi/(n-1)} \left( \frac{G(x)}{x} \right)^p x^{-p} \, dx
\]

\[
= A_p \int_0^\pi \left( \frac{G(x)}{x} \right)^p x^{-p} \, dx \leq A_p \int_0^\pi \left( \int_0^x |f'(t)| \, dt \right)^p x^{-p} \, dx
\]

\[
\leq A_p \int_0^\pi |f'(x)|^p \, dx < \infty,
\]

which completes the proof of Theorem 3.

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PROLETERSKIH BRIGADA 62
Belgrad, Yugoslavia