On the Jackson-Type Inequality for the Best $S^p$-Approximations of Functions by Trigonometric Polynomials

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Abstract. We find the sharp constant in the Jackson-type inequality between the value of the best approximation of functions by trigonometric polynomials and moduli of continuity of $m$-th order in the spaces $S^p$, $1 \leq p < \infty$. In the particular case we obtain one result which in a certain sense generalizes the result obtained by L.V. Taykov for $m = 1$ in the space $L_2$ for the arbitrary moduli of continuity of $m$-th order ($m \in \mathbb{N}$).

Introduction

Trigonometric polynomials are the object of the study for a long time. The significant results in the approximation theory were obtained by Jackson. He proved that for an arbitrary $2\pi$-periodic continuous function the following inequality holds

$$E_{n-1}(f)_C \leq K \omega(f; \frac{1}{n}),$$

where

$$E_{n-1}(f)_C = \inf \{ \| f - T_{n-1} \|_C : T_{n-1} \in T_{n-1} \}$$

is the value of the best approximation of function $f$ by the subspace $T_{n-1}$ of trigonometric polynomials of degree $n - 1$ in the continuous metric;

$$\omega(f; t) = \sup \{ \| f(\cdot + h) - f(\cdot) \|_C : |h| \leq t \}$$

is the modulus of continuity of function $f$, and $K$ is a constant which doesn’t depend on $n$ and $f$. This inequality and analogous relations are known in the approximation theory as the Jackson-type inequalities. In approximation theory it is of importance to find the smallest constant from all possible ones in the Jackson-type inequalities. Such constants are called the sharp constants.

The questions of the obtaining the Jackson-type inequalities in case of approximation by trigonometric polynomials in the uniform and integral metrics were studied by many mathematicians, see for example the articles [1]-[25].

A.I. Stepanets in [26] introduced the normed spaces $S^p$ ($1 \leq p < \infty$) of the integrable functions $f(x)$ having the period $2\pi$ for which

$$\| f \|_{S^p} \overset{df}{=} \left\{ \sum_{k \in \mathbb{Z}} |\hat{f}(k)|^p \right\}^{1/p} < \infty,$$

where

$$\hat{f}(k) = (2\pi)^{-1/2} \int_{-\pi}^{\pi} f(x)e^{-ikx}dx$$ (1)

are the Fourier coefficients of the function $f(x)$ on the trigonometric system $(2\pi)^{-1/2}e^{ikx}$, $k \in \mathbb{Z}$. It was proved that the spaces $S^p$ ($1 \leq p < \infty$) have the substantial properties of the Hilbert spaces, i.e. the minimal property of the partial Fourier sums. If

$$E_{n-1}(f)_{S^p} \overset{df}{=} \inf \{ \| f - T_{n-1} \|_{S^p} : T_{n-1} \in T_{n-1} \}$$
is the value of the best approximation of function $f(x) \in S^p$ by the subspace $T_{n-1}$ of trigonometric polynomials of degree $n-1$ in the metric of the space $S^p$ then

$$E_{n-1}(f)_{S^p} = \|f - s_{n-1}(f)\|_{S^p} = \left\{ \sum_{|k| \geq n} |\hat{f}(k)|^p \right\}^{1/p}, \quad (2)$$

where

$$s_{n-1}(f, x) = (2\pi)^{-1/2} \sum_{|k| \leq n-1} \hat{f}(k)e^{ikx}$$

is the partial sum of the Fourier series

$$s(f, x) = (2\pi)^{-1/2} \sum_{k \in \mathbb{Z}} \hat{f}(k)e^{ikx}$$

of function $f(x) \in S^p$.

A.I. Stepanets stated in [26] that for $p = 2$ it is hold the equality

$$\|f\|_{L^2} = \|f\|_{S^2}.$$

Let

$$\omega_m(f, t)_X = \sup \left\{ \|\Delta_h^m f(\cdot)\|_X : 0 < h \leq t \right\}, \quad (3)$$

is a modulus of continuity of order $m$ of the function $f(x) \in X$, where

$$\Delta_h^m f(x) = \sum_{j=0}^{m} (-1)^{m-j}\binom{m}{j} f(x + jh)$$

is a finite difference of order $m$ of the function $f(x)$ at the point $x$ with the step $h$. If $X = L_p$ ($1 \leq p < \infty$) then the value $\omega_m(f, t)_{L_p}$ is the known integral modulus of continuity [27]. In case of $X = S^p$ the modulus of continuity $\omega_m(f, t)_{S^p}$ was introduced in the article [28].

Let $\Psi(k)$ and $\beta(k) \equiv \beta_k$ ($k \in \mathbb{N}$) are the constrictions on $\mathbb{N}$ of the arbitrary functions $\Psi(x)$ and $\beta(x)$ defined on the half-segment $[1, \infty)$. Let’s suppose that the series

$$\sum_{k=1}^{\infty} \frac{1}{\Psi(k)} \left( a_k(f) \cos (kx + \frac{\beta_k \pi}{2}) + b_k(f) \sin (kx + \frac{\beta_k \pi}{2}) \right)$$

is the Fourier series of some summable function which we denote by $f^{\Psi}_{\beta}(x)$ according to [29]. The function $f^{\Psi}_{\beta}(x)$ is called $(\Psi, \beta)$-derivative of the function $f(x)$. The concept of the $(\Psi, \beta)$-derivative is the generalization of the definition of the $r$-th derivative of function. When $\Psi(k) = k^{-r}$ ($0 < r < \infty$) and $\beta(k) = r$ then the $r$-th derivative of the function $f(x)$ differs from the $(k^{-r}, r)$-derivative only on the constant value.

Let $L^p_{\Psi}(S^p)$ is the set of integrable functions $f(x)$ having the period $2\pi$ which have the $(\Psi, \beta)$-derivatives. Also let $L^p_{\Psi}(S^p)$ is the set of the functions $f(x) \in L^p_{\Psi}$ such that their $(\Psi, \beta)$-derivatives belong to the space $S^p$. If $\Psi(k) = k^{-r}$ ($0 < r < \infty$) and $\beta(k) = r$ then we use notation $L^r(S^p); L^\infty \equiv L^r(S^2)$.

A lot of articles are devoted to solving problems of approximation theory in the spaces $S^p$ ($1 \leq p < \infty$). For example, in the articles [30]-[36] were studied the approximation properties of trigonometric system and were solved several problems on obtaining the Jackson-type inequalities

$$E_{n-1}(f)_{S^p} \leq \chi(t) \cdot n^{-r} \omega_m(f^{(r)}, \frac{t}{n})_{S^p} \quad (t > 0)$$

and finding the sharp constants for the fixed values of $m, n, t$ and $p$, that is the values
\[ \chi_{n,m}(t)_{S^p} = \sup \left\{ \frac{E_{n-1}(f)_{S^p}}{\omega_m(f; \frac{x}{n})_{S^p}} : f \in L^r(S^p), f \neq \text{const} \right\} \quad (t > 0). \]

We assume that the ratio \(0/0\) is equal to zero.

Let’s define the following notation
\[
\chi_{n,(\Psi, \beta), m,p,t}(F, t; S^p) \overset{df}{=} \sup_{f(x) \in L^2_\beta(S^p), f(x) \neq \text{const}} \frac{n^{-\frac{1}{p}}E_{n-1}(f)_{S^p}}{\Psi(n)} \left( \int_0^t \omega_m(f^{(\Psi, \beta)}; x)_{S^p} F(x) dx \right)^{1/p}. \quad (4)
\]

In the spaces \(S^p\) the values of the type (4) were studied by A.I. Stepanets, A.S. Serduk [28] \(\chi_{n,(1,0), m,p,1/p}(F, \frac{x}{n})_{S^p}, F(x) = \sin(nx)\), A.S. Serduk [31] \(\chi_{n,(\Psi, r), m,p,1/p}(F, \frac{x}{n})_{S^p}, F(x) = \sin(nx)\); \(\chi_{n,(\Psi, r), m,p,1}(F, t; S^p), F(x) \equiv 1, 0 < t \leq \frac{3\pi}{4}\). S.B. Vakarchuk [33] \(\chi_{n,(\Psi, 0), m,p,0}(F, t; S^p), F(x) \equiv 1, 0 < t \leq \frac{\pi}{n}\). The analogous to (4) values were considered by B.P. Voycheyhivskiy [34], S.B. Vakarchuk and A.N. Shchitov [35].

In the article [36] were obtained the exact values of extremal characteristics of a special form between the values of best polynomial approximations of functions \(E_{n-1}(f)_{S^p}\) and moduli of continuity of \(m\)-th order \(\omega_m(f^{(\Psi, \beta)}; t)_{S^p}\). The asymptotically sharp inequalities of Jackson type between the values \(E_{n-1}(f)_{S^p}\) and moduli of continuity of functions \(f(x) \in S^p\) were found in the article [36].

The aim of the current study is the obtaining of the sharp constant in the Jackson-type inequality between the value of the best approximation of functions from the class \(L^2_\beta(S^p)\) by trigonometric polynomials \(E_{n-1}(f)_{S^p}\) and moduli of continuity of \(m\)-th order \(\omega_m(f^{(\Psi, \beta)}; t)_{S^p}\) in the spaces \(S^p, 1 \leq p < \infty\).

**Sharp constant in the Jackson-type inequality for the best approximation of functions \(f(x) \in S^p\)**

Further we suppose that the function \(\Psi(x) (1 \leq x < \infty)\) is the positive function which monotonically decreases to zero with increasing of \(x\).

Sharp constant in the Jackson-type inequality for the best \(S^p\)-approximation of functions by trigonometric polynomials is found in the next theorem.

**Theorem 1.** For the arbitrary numbers \(n, m \in \mathbb{N}, 0 < \tau \leq \frac{3\pi}{4n}\) and \(1 \leq p < \infty\) the following equality holds
\[
\sup_{f(x) \in L^2_\beta(S^p), f(x) \neq \text{const}} \frac{E_{n-1}(f)_{S^p}}{\int_0^\pi \omega_m^{2/m}(f^{(\Psi, \beta)}; h)_{S^p} dh} \geq \Psi(n) \left\{ \frac{n}{2(n\tau - \sin n\tau)} \right\}^{m/2}. \quad (5)
\]

**Proof.** Using following
\[
a_k(f) = \frac{1}{\pi} \int_{-\pi}^\pi f(x) \cos kxdx;
\]
\[
b_k(f) = \frac{1}{\pi} \int_{-\pi}^\pi f(x) \sin kxdx \quad (k \in \mathbb{Z}_+),
\]
we can write the Fourier coefficients (1) in the form
\[
\hat{f}(k) = \left( \frac{\pi}{2} \right)^{1/2} (a_k(f) - ib_k(f) \text{sgn} k) \quad (k \in \mathbb{Z}). \quad (6)
\]
Then the relation (2) can be written in the next form

\[ E_{n-1}(f)_{S^p} = \left( \frac{\pi}{2} \right)^{1/2} \left\{ 2 \sum_{k=n}^{\infty} \rho_k^p(f) \right\}^{1/p}, \quad (7) \]

where

\[ \rho_k(f) \overset{df}{=} \sqrt{a_k^2(f) + b_k^2(f)}. \]

It is known [29] that Fourier coefficients of the functions \( f(x) \) and \( f_{\Psi}^\psi(x) \) are connected by the formula

\[
\begin{align*}
    a_k(f) &= \Psi(k) \left( a_k(f_{\Psi}^\psi) \cos \frac{\beta_k \pi}{2} - b_k(f_{\Psi}^\psi) \sin \frac{\beta_k \pi}{2} \right), \\
    b_k(f) &= \Psi(k) \left( a_k(f_{\Psi}^\psi) \sin \frac{\beta_k \pi}{2} + b_k(f_{\Psi}^\psi) \cos \frac{\beta_k \pi}{2} \right).
\end{align*}
\]

(8)

From (6) and (8) we have

\[ \hat{\rho}(k) = e^{-i \beta_k \pi \text{sgn}(k)/2} \Psi(|k|) \hat{f}_{\Psi}^\psi(k) \quad (k \in \mathbb{Z}\setminus\{0\}). \]

(9)

In the article [28] it was shown that for an arbitrary function \( f(x) \in S^p \) (1 \( \leq p < \infty \))

\[ \| \Delta_h^m f(\cdot) \|_{S^p}^p = 2^{mp/2} \sum_{k \in \mathbb{Z}} |\hat{\rho}(k)|^p (1 - \cos kh)^{mp/2}. \]

(10)

Using (6) and (10) we write

\[ \left\| \Delta_h^m f_{\Psi}^\psi(\cdot) \right\|_{S^p}^p = \pi^{p/2} 2^{1+(m-1)p/2} \sum_{k=1}^{\infty} \rho_k^p(f_{\Psi}^\psi)(1 - \cos kh)^{mp/2}. \]

(11)

From the (9) it immediately follows the equation

\[ \rho_k(f) = \Psi(k) \rho_k(f_{\Psi}^\psi). \]

Then using the last equation from the (11) we have

\[ \left\| \Delta_h^m f_{\Psi}^\psi(\cdot) \right\|_{S^p}^p = \pi^{p/2} 2^{1+(m-1)p/2} \sum_{k=1}^{\infty} \frac{1}{\Psi(k)} \rho_k^p(f_{\Psi}^\psi)(1 - \cos kh)^{mp/2}. \]

(12)

Using (7) we can write

\[ E_{n-1}(f)_{S^p} - \left( \frac{\pi}{2} \right)^{p/2} 2 \sum_{k=n}^{\infty} \rho_k^p(f) \cos kh = \]

\[ = \left( \frac{\pi}{2} \right)^{p/2} 2 \sum_{k=n}^{\infty} \rho_k^{p-2/m}(f) \rho_k^{2/m}(f)(1 - \cos kh). \]

(13)

Applying the Holder’s inequality to the right part of the (13), using (2), (12), definition of the modulus of continuity of the \( m \)-th order and the decreasing character of the function \( \Psi(x) \), from the (13) we get
\[ E_{n-1}^p(f)_{S^p} - \left( \frac{\pi}{2} \right)^{p/2} 2 \sum_{k=n}^{\infty} \rho_k^p(f) \cos kh \]
\[ \leq \left( \frac{\pi}{2} \right)^{p/2} 2 \left\{ \sum_{k=n}^{\infty} \rho_k^p(f) \right\}^{1-2/mp} \left\{ \sum_{k=n}^{\infty} \rho_k^p(f)(1 - \cos kh)^{mp/2} \right\}^{2/(mp)} \]
\[ \leq \left( \frac{\pi}{2} \right)^{1/m} \Psi^{2/m}(n) E_{n-1}^{p-2/m}(f)_{S^p} \left\{ 2 \sum_{k=n}^{\infty} \frac{1}{\Psi^p(k)} \rho_k^p(f)(1 - \cos kh)^{mp/2} \right\}^{1/2/mp} \]
\[ \leq \frac{1}{2} \Psi^{2/m}(n) E_{n-1}^{p-2/m}(f)_{S^p} \omega_m^{2/m}(f_{\Psi}, h)_{S^p} . \] (14)

Integrating the relation (14) by the variable \( h \) over the limits from 0 to \( \tau \) we have
\[ \tau E_{n-1}^p(f)_{S^p} \leq \left( \frac{\pi}{2} \right)^{p/2} 2 \sum_{k=n}^{\infty} \rho_k^p(f) \frac{\sin k\tau}{k} \]
\[ + \frac{\Psi^{2/m}(n)}{2} E_{n-1}^{p-2/m}(f)_{S^p} \int_0^\tau \omega_m^{2/m}(f_{\Psi}, h)_{S^p} \, dh . \] (15)

In the [3] it was obtained the relation
\[ \max_{n\tau \leq u} \left| \frac{\sin u}{u} \right| = \frac{\sin n\tau}{n\tau} \quad (0 < n\tau \leq \frac{3\pi}{4}) . \] (16)

Dividing the inequality (15) by \( \tau \) and taking into account (7) and (16) we have
\[ E_{n-1}^p(f)_{S^p} \leq \frac{\sin n\tau}{n\tau} E_{n-1}^p(f)_{S^p} \]
\[ + \frac{\Psi^{2/m}(n)}{2\tau} E_{n-1}^{p-2/m}(f)_{S^p} \int_0^\tau \omega_m^{2/m}(f_{\Psi}, h)_{S^p} \, dh . \] (17)

Therefore from (17) we get
\[ E_{n-1}(f)_{S^p} \leq \Psi(n) \left\{ \frac{n}{2(n\tau - \sin n\tau)} \right\}^{m/2} \left\{ \int_0^\tau \omega_m^{2/m}(f_{\Psi}, h)_{S^p} \, dh \right\}^{m/2} . \] (18)

From (18) for an arbitrary \( 0 < \tau \leq \frac{3\pi}{4n} \) we have the upper bound
\[ \sup_{f(\cdot) \in L_p^p(S^p)} \frac{E_{n-1}(f)_{S^p}}{\int_0^\tau \omega_m^{2/m}(f_{\Psi}, h)_{S^p} \, dh} \leq \Psi(n) \left\{ \frac{n}{2(n\tau - \sin n\tau)} \right\}^{m/2} . \] (19)

To obtain the lower bound we consider the function
\[ \tilde{f}(x) = \sqrt{2/\pi} \cos(nx) , \]
which belongs to the class \( L_{\Psi}^p(S^p) \).

Based on the (7) we have
\[ E_{n-1}(\tilde{f})_{S^p} = 2^{1/p} . \] (20)
For \((\Psi, \beta)\)-derivative of the function \(\tilde{f}\)

\[
\tilde{f}_\beta^\Psi(x) = \sqrt{2/\pi} \Psi^{-1}(n) \cos(nx + \beta_n \pi/2)
\]
due to (11) and definition of the modulus of continuity of order \(m\) for \(0 < t \leq \frac{\pi}{n}\) we can write

\[
\omega_m(\tilde{f}_\beta^\Psi, t)_{S^p} = 2^{1/p+m/2} \frac{1}{\Psi(n)} (1 - \cos nt)^{m/2}.
\]  \(21\)

From the (21) for \(0 < t \leq \frac{\pi}{n}\) we obtain

\[
\left\{ \int_0^t \omega_m^2(\tilde{f}_\beta^\Psi, h)_{S^p} dh \right\}^{m/2} = \frac{1}{\Psi(n)} 2^{1/p+m/2} \{t - \frac{1}{n} \sin nt\}^{m/2}.
\]  \(22\)

Then taking into account (20) and (22) we get

\[
\sup_{f(x) \in L_2^p(S^p)} \frac{E_{n-1}(f)_{S^p}}{E_{n-1}(\tilde{f})_{S^p}} \geq \sup_{f(x) \in L_2^p(S^p)} \frac{n^{-r} E_{n-1}(f)_{L^2}}{E_{n-1}(\tilde{f})_{L^2}} \geq \left\{ \int_0^t \omega_m^2(f, h)_{L^2} dh \right\}^{m/2} = \Psi(n) \left\{ \frac{n}{2(n\tau - \sin n\tau)} \right\}^{m/2}.
\]  \(23\)

From the upper bound (19) and lower bound (23) it follows the equality (5). Theorem 1 is proved.

If \(\Psi(n) = n^{-r}, r \in \mathbb{Z}_+\), then from the theorem 1 it follows the next result.

**Theorem 2.** Let \(r \in \mathbb{Z}_+\) and \(n, m \in \mathbb{N}\). Then for an arbitrary \(0 < \tau \leq \frac{3\pi}{4n}\) the following equality holds

\[
\sup_{f(x) \in L_2^p(S^p)} \frac{n^{-r} E_{n-1}(f)_{L^2}}{E_{n-1}(f)_{S^p}} \geq \left\{ \int_0^t \omega_m^2(f, h)_{L^2} dh \right\}^{m/2} = \left\{ \frac{n}{2(n\tau - \sin n\tau)} \right\}^{m/2}.
\]

The result of the theorem 2 in a certain sense generalizes for the arbitrary modulus of continuity of \(m\)-th order \((m \in \mathbb{N})\) one result obtained by L.V. Taykov for the case \(m = 1\) in the article [3].

**Conclusions**

For the functions from the class \(L_2^p(S^p) (1 < p < \infty)\) the sharp constant in the Jackson-type inequality between the value of the best approximation \(E_{n-1}(f)_{S^p}\) of functions by trigonometric polynomials and moduli of continuity of \(m\)-th order \(\omega_m(f^\psi, t)_{S^p}\) in the spaces \(S^p\) has been found.

From the obtained result it follows the statement which in a certain sense generalizes for the arbitrary modulus of continuity of \(m\)-th order \(\omega_m(f^\psi, t)_{L^2} (m \in \mathbb{N})\) the result obtained by L.V. Taykov for \(m = 1\) in the space \(L_2\).
References


