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## SOME NEW INEQUALITIES FOR TRIGONOMETRIC POLYNOMIALS WITH SPECIAL COEFFICIENTS

ŽIVORAD TOMOVSKI

Faculty of Mathematics and Natural Sciences  
Department of Mathematics  
Skopje 1000 MACEDONIA.

*EMail:* [tomovski@iunona.pmf.ukim.edu.mk](mailto:tomovski@iunona.pmf.ukim.edu.mk)

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## Abstract

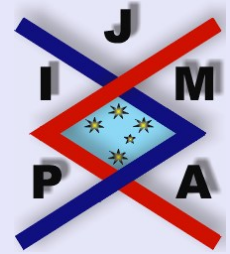
Some new inequalities for certain trigonometric polynomials with complex semi-convex and complex convex coefficients are given.

*2000 Mathematics Subject Classification:* 26D05, 42A05

*Key words:* Petrović inequality, Complex trigonometric polynomial, Complex semi-convex coefficients, Complex convex coefficients.

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# 1. Introduction and Preliminaries

Petrović [4] proved the following complementary triangle inequality for sequences of complex numbers  $\{z_1, z_2, \dots, z_n\}$ .

**Theorem A.** *Let  $\alpha$  be a real number and  $0 < \theta < \frac{\pi}{2}$ . If  $\{z_1, z_2, \dots, z_n\}$  are complex numbers such that  $\alpha - \theta \leq \arg z_\nu \leq \alpha + \theta$ ,  $\nu = 1, 2, \dots, n$ , then*

$$\left| \sum_{\nu=1}^n z_\nu \right| \geq (\cos \theta) \sum_{\nu=1}^n |z_\nu|.$$

For  $0 < \theta < \frac{\pi}{2}$  denote by  $K(\theta)$  the cone  $K(\theta) = \{z : |\arg z| \leq \theta\}$ .

Let  $\Delta\lambda_n = \lambda_n - \lambda_{n+1}$ , for  $n = 1, 2, 3, \dots$ , where  $\{\lambda_n\}$  is a sequence of complex numbers. Then,

$$\Delta^2\lambda_n = \Delta(\Delta\lambda_n) = \Delta\lambda_n - \Delta\lambda_{n+1} = \lambda_n - 2\lambda_{n+1} + \lambda_{n+2}, \quad n = 1, 2, 3, \dots$$

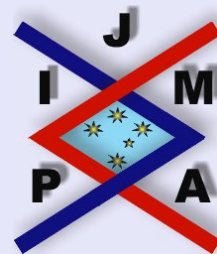
The author Tomovski (see [5]) proved the following inequality for cosine and sine polynomials with complex-valued coefficients.

**Theorem B.** *Let  $x \neq 2k\pi$  for  $k = 0, \pm 1, \pm 2, \dots$*

1. *Let  $\{b_k\}$  be a positive nondecreasing sequence and  $\{u_k\}$  a sequence of complex numbers such that  $\Delta\left(\frac{u_k}{b_k}\right) \in K(\theta)$ . Then*

$$\left| \sum_{k=n}^m u_k f(kx) \right| \leq \frac{1}{|\sin \frac{x}{2}|} \left[ \left(1 + \frac{1}{\cos \theta}\right) |u_m| + \frac{1}{\cos \theta} \frac{b_m}{b_n} |u_n| \right],$$

$$(\forall n, m \in \mathbb{N}, m > n).$$



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2. Let  $\{b_k\}$  be a positive nondecreasing sequence and  $\{u_k\}$  a sequence of complex numbers such that  $\Delta(u_k b_k) \in K(\theta)$ . Then

$$\left| \sum_{k=n}^m u_k f(kx) \right| \leq \frac{1}{|\sin \frac{x}{2}|} \left[ \left( 1 + \frac{1}{\cos \theta} \right) |u_n| + \frac{1}{\cos \theta} \frac{b_m}{b_n} |u_m| \right],$$

$$(\forall n, m \in \mathbb{N}, m > n).$$

Here  $f(x) = \sin x$  or  $f(x) = \cos x$ .

Similarly, the results of Theorem B were given by the author in [5] for sums of type  $\sum_{k=n}^m (-1)^k u_k f(kx)$ , where again  $f(x) = \sin x$  or  $f(x) = \cos x$ .

Mitrinović and Pečarić (see [2, 3]) proved the following inequalities for cosine and sine polynomials with nonnegative coefficients.

**Theorem C.** Let  $x \neq 2k\pi$  for  $k = 0, \pm 1, \pm 2, \dots$

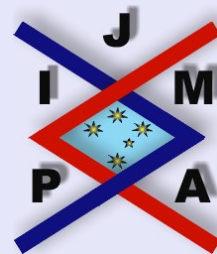
1. Let  $\{b_k\}$  be a positive nondecreasing sequence and  $\{a_k\}$  a nonnegative sequence such that  $\{a_k b_k^{-1}\}$  is a decreasing sequence. Then

$$\left| \sum_{k=n}^m a_k f(kx) \right| \leq \frac{a_n}{|\sin \frac{x}{2}|} \left( \frac{b_m}{b_n} \right), \quad (\forall n, m \in \mathbb{N}, m > n).$$

2. Let  $\{b_k\}$  be a positive nondecreasing sequence and  $\{a_k\}$  a nonnegative sequence such that  $\{a_k b_k\}$  is an increasing sequence. Then

$$\left| \sum_{k=n}^m a_k f(kx) \right| \leq \frac{a_m}{|\sin \frac{x}{2}|} \left( \frac{b_m}{b_n} \right), \quad (\forall n, m \in \mathbb{N}, m > n).$$

Here  $f(x) = \sin x$  or  $f(x) = \cos x$ .



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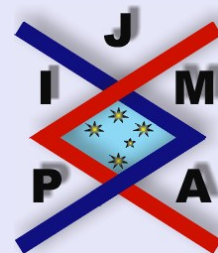
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The special cases of these inequalities were proved by G.K. Lebed for  $b_k = k^s$ ,  $s \geq 0$  (see [1]). Similarly, the results of Theorem C, were given by Mitri-nović and Pečarić in [2, 3] for sums of type  $\sum_{k=n}^m (-1)^k a_k f(kx)$ , where again  $f(x) = \sin x$  or  $f(x) = \cos x$ .

The sequence  $\{u_k\}$  is said to be **complex semiconvex** if there exists a cone  $K(\theta)$ , such that  $\Delta^2\left(\frac{u_k}{b_k}\right) \in K(\theta)$  or  $\Delta^2(u_k b_k) \in K(\theta)$ , where  $\{b_k\}$  is a positive nondecreasing sequence. For  $b_k = 1$ , the sequence  $\{u_k\}$  shall be called a **complex convex sequence**.

In this paper we shall give some estimates for cosine and sine polynomials with complex semi-convex and complex convex coefficients.




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## 2. Main Results

**Theorem 2.1.** Let  $\{z_k\}$  be a sequence of complex numbers such that  $A = \max_{n \leq p \leq q \leq m} \left| \sum_{j=p}^q \sum_{k=i}^j z_k \right|$ . Further, let  $\{b_k\}$  be a positive nondecreasing sequence. If  $\{u_k\}$  is a sequence of complex numbers such that  $\Delta^2 \left( \frac{u_k}{b_k} \right) \in K(\theta)$ , then

$$\left| \sum_{k=n}^m u_k z_k \right| \leq A \left[ |u_m| + b_m \left( 1 + \frac{1}{\cos \theta} \right) \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{b_m}{\cos \theta} \left| \Delta \left( \frac{u_n}{b_n} \right) \right| \right],$$

$$(\forall n, m \in \mathbb{N}, m > n).$$

*Proof.* Let us estimate the sum  $\sum_{k=n}^m b_k z_k$ .

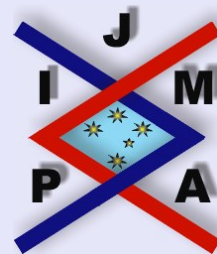
Since

$$\left| \sum_{k=n}^m z_k \right| \leq \sum_{j=n+1}^m \left| \sum_{k=n}^j z_k \right| \leq A,$$

we obtain

$$\begin{aligned} \left| \sum_{k=n}^m b_k z_k \right| &= \left| b_n \sum_{k=n}^m z_k + \sum_{j=n+1}^m \left( \sum_{k=j}^m z_k \right) (b_j - b_{j-1}) \right| \\ &\leq b_n \left| \sum_{k=n}^m z_k \right| + \sum_{j=n+1}^m \left| \sum_{k=j}^m z_k \right| (b_j - b_{j-1}) \end{aligned}$$

$$(*) \leq A (b_n + b_m - b_n) = Ab_m.$$



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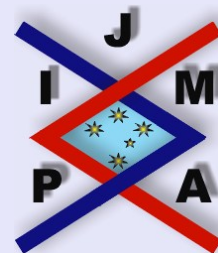
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Then,

$$\begin{aligned}
 \left| \sum_{k=n}^m u_k z_k \right| &= \left| \sum_{k=n}^m \frac{u_k}{b_k} (b_k z_k) \right| \\
 &= \left| \frac{u_m}{b_m} \sum_{k=n}^m b_k z_k + \sum_{j=n}^{m-1} \left( \sum_{k=n}^j b_k z_k \right) \Delta \left( \frac{u_j}{b_j} \right) \right| \\
 &= \left| \frac{u_m}{b_m} \sum_{k=n}^m b_k z_k + \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \sum_{j=n}^{m-1} \sum_{k=n}^j b_k z_k \right. \\
 &\quad \left. + \sum_{r=n}^{m-2} \Delta^2 \left( \frac{u_r}{b_r} \right) \sum_{j=n}^r \sum_{k=n}^j b_k z_k \right| \\
 &\leq \frac{|u_m|}{b_m} \left| \sum_{k=n}^m b_k z_k \right| + \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| \left| \sum_{j=n}^{m-1} \sum_{k=n}^j b_k z_k \right| \\
 &\quad + \sum_{r=n}^{m-2} \left| \Delta^2 \left( \frac{u_r}{b_r} \right) \right| \left| \sum_{j=n}^r \sum_{k=n}^j b_k z_k \right| \\
 &\leq A b_m \frac{|u_m|}{b_m} + A b_m \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{A b_m}{\cos \theta} \left| \sum_{r=n}^{m-2} \Delta^2 \left( \frac{u_r}{b_r} \right) \right| \\
 &= A \left[ |u_m| + b_m \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{b_m}{\cos \theta} \left| \Delta \left( \frac{u_n}{b_n} \right) - \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| \right]
 \end{aligned}$$



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$$\leq A \left[ |u_m| + b_m \left( 1 + \frac{1}{\cos \theta} \right) \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{b_m}{\cos \theta} \left| \Delta \left( \frac{u_n}{b_n} \right) \right| \right].$$

□

**Theorem 2.2.** Let  $\{z_k\}$  and  $\{b_k\}$  be defined as in Theorem 2.1. If  $\{u_k\}$  is a sequence of complex numbers such that  $\Delta^2(u_k b_k) \in K(\theta)$ , then

$$\left| \sum_{k=n}^m u_k z_k \right| \leq A \left[ |u_n| + b_n^{-1} \left( 1 + \frac{1}{\cos \theta} \right) (|\Delta(u_n b_n)| + |\Delta(u_{m-1} b_{m-1})|) \right],$$

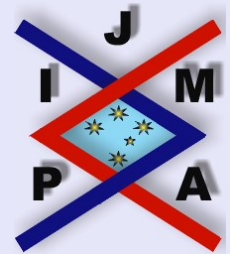
$$(\forall n, m \in \mathbb{N}, m > n).$$

*Proof.* The sequence  $\{b_k^{-1}\}_{k=n}^m$  is nonincreasing, so from (\*) we get

$$\left| \sum_{k=n}^m b_k^{-1} z_k \right| \leq A b_n^{-1}.$$

Now, we have:

$$\begin{aligned} \left| \sum_{k=n}^m u_k z_k \right| &= \left| \sum_{k=n}^m (u_k b_k) b_k^{-1} z_k \right| \\ &= \left| u_n b_n \sum_{k=n}^m b_k^{-1} z_k + \sum_{j=n+1}^m \left( \sum_{k=j}^m b_k^{-1} z_k \right) (u_j b_j - u_{j-1} b_{j-1}) \right| \\ &= \left| u_n b_n \sum_{k=n}^m b_k^{-1} z_k - \sum_{j=n+1}^{m-1} \Delta^2(u_{j-1} b_{j-1}) \sum_{r=n}^j \sum_{k=r}^m b_k^{-1} z_k \right| \end{aligned}$$



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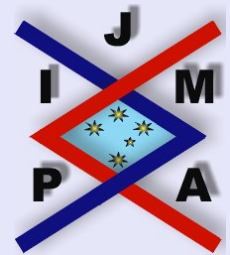
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$$\begin{aligned}
& + \Delta(u_n b_n) \left| \sum_{k=n}^m b_k^{-1} z_k - \Delta(u_{m-1} b_{m-1}) \sum_{r=n}^m \sum_{k=r}^m b_k^{-1} z_k \right| \\
\leq & |u_n| b_n \left| \sum_{k=n}^m b_k^{-1} z_k \right| + \sum_{j=n+1}^{m-1} |\Delta^2(u_{j-1} b_{j-1})| \left| \sum_{r=n}^j \sum_{k=r}^m b_k^{-1} z_k \right| \\
& + |\Delta(u_n b_n)| \left| \sum_{k=n}^m b_k^{-1} z_k \right| + |\Delta(u_{m-1} b_{m-1})| \left| \sum_{r=n}^m \sum_{k=r}^m b_k^{-1} z_k \right| \\
\leq & |u_n| b_n A b_n^{-1} + A b_n^{-1} \sum_{j=n+1}^{m-1} |\Delta^2(u_{j-1} b_{j-1})| + A b_n^{-1} |\Delta(u_n b_n)| \\
& + A b_n^{-1} |\Delta(u_{m-1} b_{m-1})| \\
\leq & A \left[ |u_n| + \frac{b_n^{-1}}{\cos \theta} \left| \sum_{j=n+1}^{m-1} \Delta^2(u_{j-1} b_{j-1}) \right| \right. \\
& \left. + b_n^{-1} |\Delta(u_n b_n)| + b_n^{-1} |\Delta(u_{m-1} b_{m-1})| \right] \\
= & A \left[ |u_n| + \frac{b_n^{-1}}{\cos \theta} |\Delta(u_n b_n) - \Delta(u_{m-1} b_{m-1})| \right. \\
& \left. + b_n^{-1} |\Delta(u_n b_n)| + b_n^{-1} |\Delta(u_{m-1} b_{m-1})| \right] \\
\leq & A \left[ |u_n| + b_n^{-1} \left( 1 + \frac{1}{\cos \theta} \right) (|\Delta(u_n b_n)| + |\Delta(u_{m-1} b_{m-1})|) \right].
\end{aligned}$$

□



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**Lemma 2.3.** For all  $p, q \in \mathbb{N}$ ,  $p < q$ , the following inequalities hold

$$(2.1) \quad \left| \sum_{j=p}^q \sum_{k=l}^j e^{ikx} \right| \leq \frac{q-p+2}{2 \sin^2 \frac{x}{2}}, \quad x \neq 2k\pi, \quad k = 0, \pm 1, \pm 2, \dots,$$

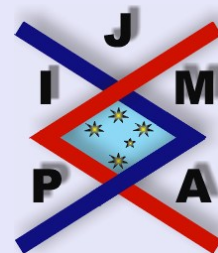
$$(2.2) \quad \left| \sum_{j=p}^q \sum_{k=l}^j (-1)^k e^{ikx} \right| \leq \frac{q-p+2}{2 \cos^2 \frac{x}{2}}, \quad x \neq (2k+1)\pi,$$

$$k = 0, \pm 1, \pm 2, \dots$$

*Proof.* It is sufficient to prove the first inequality, since the second inequality can be proved analogously.

$$\begin{aligned} \left| \sum_{j=p}^q \sum_{k=l}^j e^{ikx} \right| &= \left| \sum_{j=p}^q e^{ilx} \frac{e^{i(j-l+1)x} - 1}{e^{ix} - 1} \right| \\ &= \frac{1}{|e^{ix} - 1|} \left| \frac{1}{e^{i(l-1)x}} \sum_{j=p}^q e^{ijx} - (q-p+1) \right| \\ &\leq \frac{1}{|2 \sin \frac{x}{2}|} \frac{|e^{i(q-p+1)x} - 1|}{|e^{ix} - 1|} + \frac{q-p+1}{|2 \sin \frac{x}{2}|} \\ &\leq \frac{2}{4 \sin^2 \frac{x}{2}} + \frac{q-p+1}{2 \sin^2 \frac{x}{2}} = \frac{q-p+2}{2 \sin^2 \frac{x}{2}}. \end{aligned}$$

□



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By putting  $z_k = \exp(ikx)$  in Theorem 2.1 and Theorem 2.2 and using the inequality (2.1) of the above lemma, we have:

**Theorem 2.4.** (i) Let  $\{b_k\}$  and  $\{u_k\}$  be defined as in Theorem 2.1. Then

$$\left| \sum_{k=n}^m u_k \exp(ikx) \right| \leq \frac{m-n+2}{2 \sin^2 \frac{x}{2}} \left[ |u_m| + b_m \left( 1 + \frac{1}{\cos \theta} \right) \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{b_m}{\cos \theta} \left| \Delta \left( \frac{u_n}{b_n} \right) \right| \right],$$

$(\forall n, m \in \mathbb{N}, m > n).$

(ii) Let  $\{b_k\}$  and  $\{u_k\}$  be defined as in Theorem 2.2. Then

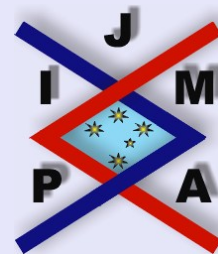
$$\left| \sum_{k=n}^m u_k \exp(ikx) \right| \leq \frac{m-n+2}{2 \sin^2 \frac{x}{2}} \left[ |u_n| + b_n^{-1} \left( 1 + \frac{1}{\cos \theta} \right) (|\Delta(u_n b_n)| + |\Delta(u_{m-1} b_{m-1})|) \right],$$

$(\forall n, m \in \mathbb{N}, m > n).$

In both cases  $x \neq 2k\pi$ ,  $k = 0, \pm 1, \pm 2, \dots$

Applying the known inequalities  $\operatorname{Re} z \leq |z|$  and  $\operatorname{Im} z \leq |z|$  for  $z \in \mathbb{C}$ , we obtain the following result:

**Theorem 2.5.** Let  $x \neq 2k\pi$  for  $k = 0, \pm 1, \pm 2, \dots$



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(i) Let  $\{b_k\}$  and  $\{u_k\}$  be defined as in Theorem 2.1. Then

$$\left| \sum_{k=n}^m u_k f(kx) \right| \leq \frac{m-n+2}{2 \sin^2 \frac{x}{2}} \left[ |u_m| + b_m \left( 1 + \frac{1}{\cos \theta} \right) \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{b_m}{\cos \theta} \left| \Delta \left( \frac{u_n}{b_n} \right) \right| \right],$$

( $\forall n, m \in \mathbb{N}, m > n$ ).

(ii) Let  $\{b_k\}$  and  $\{u_k\}$  be defined as in Theorem 2.2. Then

$$\left| \sum_{k=n}^m u_k f(kx) \right| \leq \frac{m-n+2}{2 \sin^2 \frac{x}{2}} \left[ |u_n| + b_n^{-1} \left( 1 + \frac{1}{\cos \theta} \right) (|\Delta(u_n b_n)| + |\Delta(u_{m-1} b_{m-1})|) \right],$$

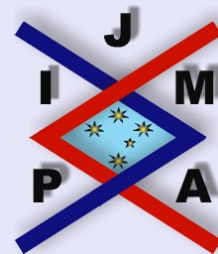
( $\forall n, m \in \mathbb{N}, m > n$ ).

Applying inequality (2.2) of Lemma 2.3, we obtain the following results:

**Theorem 2.6.** Let  $x \neq (2k+1)\pi$  for  $k = 0, \pm 1, \pm 2, \dots$  and let  $x \mapsto f(x)$  be defined as in Theorem 2.5.

(i) If  $\{b_k\}$  and  $\{u_k\}$  are defined as in Theorem 2.1, then

$$\left| \sum_{k=n}^m (-1)^k u_k f(kx) \right|$$



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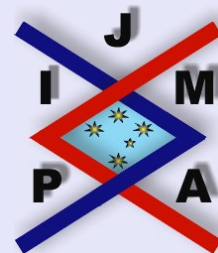


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$$\leq \frac{m-n+2}{2 \cos^2 \frac{x}{2}} \left[ |u_m| + b_m \left( 1 + \frac{1}{\cos \theta} \right) \left| \Delta \left( \frac{u_{m-1}}{b_{m-1}} \right) \right| + \frac{b_m}{\cos \theta} \left| \Delta \left( \frac{u_n}{b_n} \right) \right| \right],$$

( $\forall n, m \in \mathbb{N}, m > n$ ).

(ii) If  $\{b_k\}$  and  $\{u_k\}$  are defined as in Theorem 2.2, then

$$\left| \sum_{k=n}^m (-1)^k u_k f(kx) \right|$$

$$\leq \frac{m-n+2}{2 \cos^2 \frac{x}{2}} \left[ |u_n| + b_n^{-1} \left( 1 + \frac{1}{\cos \theta} \right) (|\Delta(u_n b_n)| + |\Delta(u_{m-1} b_{m-1})|) \right],$$

( $\forall n, m \in \mathbb{N}, m > n$ ).

For  $b_k = 1$ , we obtain the following theorem.

**Theorem 2.7.** Let  $\{u_k\}$  be a complex convex sequence.

(i) If  $x \neq 2k\pi$  for  $k = 0, \pm 1, \pm 2, \dots$ , then we have:

$$\left| \sum_{k=n}^m u_k f(kx) \right|$$

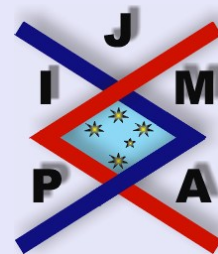
$$\leq \frac{m-n+2}{2 \sin^2 \frac{x}{2}} \left[ |u_m| + \left( 1 + \frac{1}{\cos \theta} \right) |\Delta u_{m-1}| + \frac{1}{\cos \theta} |\Delta u_n| \right],$$

( $\forall n, m \in \mathbb{N}, m > n$ ).

(ii) If  $x \neq (2k + 1) \pi$  for  $k = 0, \pm 1, \pm 2, \dots$ , then we have:

$$\left| \sum_{k=n}^m (-1)^k u_k f(kx) \right| \leq \frac{m-n+2}{2 \cos^2 \frac{x}{2}} \left[ |u_n| + \left( 1 + \frac{1}{\cos \theta} \right) (|\Delta u_n| + |\Delta u_{m-1}|) \right],$$

$(\forall n, m \in \mathbb{N}, m > n).$




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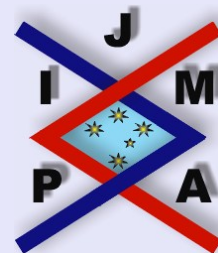
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