AN INEQUALITY FOR MINKOWSKI MATRICES

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Introduction. The class of Minkowski matrices consists of square matrices of the form $\delta - a$, where $\delta$ is the identity matrix and $a$, with real or complex elements, satisfies the condition (1). The inequality is given in the lemma, which improves the author's previous result [3, p. 239] by removing two restrictions. Refinements of the inequality are given in §3.

G. B. Price [2] and A. M. Ostrowski [1] give bounds for determinants with dominant principal diagonal. It loses no generality to consider the square matrices with units on the principal diagonal. Thus our results may be applied to the determinants studied by Price and Ostrowski. We apply the inequality of our lemma to obtain bounds for the determinant of $\delta - a$. Our results in (9) and (15) are better estimates than those of Price and Ostrowski. The main idea of our method centers on (13) and (14). The concept of quasi-inverse, which was used in [3], is no longer needed.

We use the notation $a(i, j)$ instead of $a_{ij}$.

1. An inequality for Minkowski matrices. We assume that

$$s^{(n)}(j) = \sum_{i=1}^{n} | a(i, j) | \leq 1, \quad | a(j, j) | < 1 \quad (j = 1, \ldots, n).$$

The notation $s^{(k)}(j), \ j = 1, \ldots, k,$ has similar meaning.

In the sequel, we let $\delta - a_k$ be the principal minor, which consists of the first $k$ rows and columns of $\delta - a$. $\delta$ will always be the identity matrix of the same order as $a_k$. Let $M_k$ and $D_k$ be the adjoint and determinant of $\delta - a_k$ respectively. For simplicity, we let all the summations extend from 1 to $n-1$, unless otherwise specified.

Lemma. If (1) is satisfied for $j = 1, \ldots, n-1$, then

$$\sum_{j} | a(n, i) | \cdot | M_{n-1}(i, k) | \leq s^{(n)}(k) | D_{n-1}|, \quad k = 1, \ldots, n-1.$$

Proof. From (1), we have

Received by the editors April 28, 1952.

1 The paper was prepared under the Navy contract N6onr-27009.

2 In [3], the author considered only matrices with non-negative elements, and assumed the nonsingularity for the principal minor of $\delta - a$ with the $n$th row and column omitted.
Multiplying both sides by $|M_{n-1}(j, k)|$ and summing for $j = 1, \ldots, n - 1$, we get

\[
\sum_j |a(n, j)| \cdot |M_{n-1}(j, k)| = \sum_j s^{(n)}(j) |M_{n-1}(j, k)| - \sum_j \sum_i |a_{n-1}(i, j)| \cdot |M_{n-1}(j, k)|.
\]

By putting

\[
|M_{n-1}(j, k)| = |D_{n-1}| \delta(j, k) + |M_{n-1}(j, k)| - |D_{n-1}| \delta(j, k),
\]

the first summation on the right side of (3) becomes

\[
|D_{n-1}| s^{(n)}(k) + \sum_j s^{(n)}(j) \left[ |M_{n-1}(j, k)| - |D_{n-1}| \delta(j, k) \right] \leq |D_{n-1}| s^{(n)}(k) + \sum_j s^{(n)}(j) |M_{n-1}(j, k) - D_{n-1} \delta(j, k)|.
\]

The double summation on the right-hand side of (3) is

\[
\sum_j \sum_i |a_{n-1}(i, j)M_{n-1}(j, k)| \geq \sum_i \sum_j |a_{n-1}(i, j)M_{n-1}(j, k)| = \sum_i |M_{n-1}(i, k) - D_{n-1} \delta(i, k)|,
\]

since $(\delta - a_{n-1})M_{n-1} = D_{n-1} \delta$. Combining (3), (4), and (5), we have

\[
\sum_j |a(n, j)| \cdot |M_{n-1}(j, k)| \leq |D_{n-1}| s^{(n)}(k) - \sum_j (1 - s^{(n)}(j)) |M_{n-1}(j, k) - D_{n-1} \delta(j, k)| \leq |D_{n-1}| s^{(n)}(k),
\]

which proves our lemma.

Let $\delta - a_{n-1}$ be nonsingular and $R_{n-1}$ be its inverse. Then, with assumption (1),

\[
\sum_j |a(n, j)R_{n-1}(j, k)| \leq s^{(n)}(k), \quad k = 1, \ldots, n - 1.
\]

2. An application. By Cauchy’s expansion,

\[
D_n = [1 - a(n, n)]D_{n-1} - \sum_{j, k} a(n, j)M_{n-1}(j, k)a(k, n),
\]

where $M_{n-1}$ is the adjoint of $\delta - a_{n-1}$. With assumption (1), it follows from (2) and (8) that
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\[ |1 - a(n, n)| - N^{(n)}|D_{n-1}| \leq |D_n| \leq \left| |1 - a(n, n)| + N^{(n)}|D_{n-1}|, \right.

where

\[ N^{(n)} = \sum_{j=1}^{n-1} s^{(n)}(j) |a(j, n)|. \]

It requires to show that \( |1 - a(n, n)| - N^{(n)} \) is non-negative, for otherwise the lower bound would not be effective. By (10) and (1),

\[ N^{(n)} = \sum_{j} s^{(n)}(j) |a(j, n)| \]

\[ \leq \sum_{j} |a(j, n)| \leq 1 - |a(n, n)| \leq |1 - a(n, n)|. \]

This completes the proof of (9).

**Corollary 1.** If condition (1) holds, and for \( k = 2, \cdots, n, \)

\[ \sum_{j=1}^{k-1} s^{(k)}(j) |a(j, k)| < |1 - a(k, k)|, \text{ then } D_n \neq 0. \]

**Corollary 2.** If condition (1) holds, then

\[ \sum_{i,j} |a(n, i)M_{n-1}(i, j)|a(j, n)| \leq |1 - |a(n, n)|| |D_{n-1}|. \]

Inequality (12) follows from (11), (2), and (8).

A better approximation for \( D_n \) may be obtained as follows: Let \( k = 2, \cdots, n, \) and \( M_k \) be the adjoint of \( \delta - a_k. \) Then

\[ M_k - D_k \delta = a_k M_k = M_k a_k. \]

Repeated applications of (13) give

\[ M_k = (\delta + a_k + \cdots + a_k^m)D_k + M_k a_k^{m+1}, \quad a_k = (a_k^m), \quad m \geq 0. \]

**Our assumption is given by (1).** Substituting (14) with \( k = n - 1 \) into (8) and making use of (2), we have

\[ (|S_m^{(n)}| - P_m^{(n)})|D_{n-1}| \leq |D_n| \leq (|S_m^{(n)}| + P_m^{(n)})|D_{n-1}|, \]

\[ m \geq 0, \]

where

\[ S_m^{(n)} = 1 - a(n, n) - \sum_{i,j<n} a(n, i) \sum_{h=0}^{m} a_{m-1}(i, j)a(j, n), \quad m \geq 0, \]
We may replace $P_m^{(n)}$ by
\begin{equation}
P_m^{(n)} = c^{(n)} \sum_i s^{(n-1)}(i) \left| \sum_j a_{n-1}^{m+1}(i, j)a(j, n) \right|, \quad m \geq 0.
\end{equation}

where
\begin{equation}
c^{(n)} = \max \{ s^{(n)}(j) \text{ for } j = 1, 2, \ldots, n - 1 \}.
\end{equation}

Obviously,
\begin{equation}
c^{(n)} \leq 1, \quad P_m^{(n)} \leq Q_m^{(n)}, \quad m \geq 0.
\end{equation}

To show that $|S_m^{(n)}| - Q_m^{(n)}$ is non-negative, observe that
\begin{align}
|S_0^{(n)}| - Q_0^{(n)} & \geq 1 - a(n, n) - N^{(n)} \geq 0, \\
|S_{r+1}^{(n)}| - Q_{r+1}^{(n)} & \geq |S_r^{(n)}| - P_r^{(n)} \geq |S_r^{(n)}| - Q_r^{(n)}.
\end{align}

The proof may, thus, be completed by induction. One can easily furnish the detail by using the triangle property of the complex numbers.

3. Refinements of inequality (2). Condition (1) is assumed for $j=1, \ldots, n-1$. The interesting part is that we may use inequality (2) to obtain some refinement. The first method has its underlying idea given in (13) and (14). By (3.5),
\begin{align}
\sum |a(n, j)| & (|D_{n-1}| \delta(j, k) + |M_{n-1}(j, k)| - |D_{n-1}| \delta(j, k)) \\
& \leq |a(n, k)| \cdot |D_{n-1}| \\
& + \sum |a(n, j)| \cdot |M_{n-1}(j, k)| - |D_{n-1}| \delta(j, k)| \\
& \leq |a(n, k)| \cdot |D_{n-1}| \\
& + \sum |a(n, j)| \cdot |\sum M_{n-1}(j, h)a_{n-1}(h, k)| \\
& \leq |a(n, k)| \cdot |D_{n-1}| \\
& + \sum(\sum |a(n, j)|M_{n-1}(j, h)|a_{n-1}(h, k)| \\
& \leq (|a(n, k)| + \sum s^{(n)}(h)|a_{n-1}(h, k)|) |D_{n-1}|.
\end{align}

The quantity within the parentheses is less than $s^{(n)}(k)$ if $s^{(n)}(j) < 1$ for some $j=1, \ldots, n-1$. If we use (23) in (8), the resulting inequalities are better than (9), but not as good as (15) for $m=0$.

The second method is as follows: Let $d$ be a diagonal matrix with
1/(1 - a(k, k)) on the kth row and column. Then \((\delta - a)d = \delta - a^0\), where \(a^0(i, i) = 0\) and \(a^0(i, k) = a(i, k)/(1 - a(k, k))\) for \(i \neq k\). Applying (2) to \(\delta - a^0\), we obtain, after simplification,

\[
(24) \quad \sum |a(n, i)| \cdot |M_{n-1}(i, k)| \leq |D_{n-1}| \frac{s^{(n)}(k) - |a(k, k)|}{1 - a(k, k)},
\]

which is strictly less than \(s^{(n)}(k)|D_{n-1}|\) if \(a(k, k) \neq 0\) and \(s^{(n)}(k) < 1\) (and in that case the inequality (24) is also strictly \(<\). The preceding inequality is sharper than the result of Ostrowski.

**References**


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*See [1, inequality (13)]. Ostrowski actually proved that \(|M(n, k)/D_n| \leq |D_{n-1}/D_n| \sigma_b (M = \text{adj}(\delta - a), D_{n-1} = M(n, n))\) where \(\sigma_b\) is the fractional expression on the right side of (24), under the assumption that all \(\sigma_b < 1\) to assure the nonvanishing of \(D_n\). Note that \(\pm M(n, k) = \sum a(n, i)M_{n-1}(i, k)\).*