On Designs of Maximal (+1, −1)-Matrices of Order $n \equiv 2 \pmod 4$

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When $n \equiv 2 \pmod 4$, it is known that the absolute value α_n of the determinant of nth order (+1, −1)-matrices satisfies the following inequalities:

$$\alpha_n^2 \leqq 4(n-1)^2(n-2)^{n-2} = \mu_n \qquad \text{(see [1])}$$

and

$$\alpha_n = \mu_n^{1/2}, \quad \text{for} \quad n \leqq 54, \quad \text{except} \quad n = 22, 34 \qquad \text{(see [1], [2] and [3])}.$$

Let M_n be a maximal (+1, −1)-matrix of order $n \equiv 2 \pmod 4$. Then such a maximal matrix M_n can be constructed by the following standard form:

$$M_n = \begin{pmatrix} A & B \\ -B^T & A^T \end{pmatrix},$$

where A, B are circulant matrices of order $n/2$. T indicates the transposed matrix. In this case, the gramian matrix $G(M_n)$ of M_n has the following form:

$$G(M_n) = M_n M_n^T = \begin{pmatrix} P & 0 \\ 0 & P \end{pmatrix},$$

where

$$P = AA^T + BB^T = \begin{pmatrix} n \cdot & \cdot & 2 \\ 2 & \cdot & \cdot n \end{pmatrix}.$$

More precisely, we have

$$G(A) = AA^T = (a_{ij}), \quad G(B) = BB^T = (b_{ij}),$$

$1 \leqq i, \ j \leqq n/2$; where $a_{ij} = b_{ij} = n/2$, for $1 \leqq i \leqq n/2$, and $a_{ij} + b_{ij} = 2$ for $i \neq j$. Since A, B are circulant (+1, −1)-matrices, it can be shown easily that $G(A)$, $G(B)$ are not only circulant but also symmetric, namely, $a_{ij} = a_{|i-j|}$ and $b_{ij} = b_{|i-j|}$. It follows that construction of M_n is reduced to finding two finite sequences $\{a_k\}$ and $\{b_k\}$, $1 \leqq k \leqq (n-2)/4$, such that $a_k + b_k = 2$.

Let $C = (c_{ij})$ be an mth order circulant (+1, −1)-matrix, then $G(C) = G(C^T) = G(C_{pq})$, where $C_{pq} = (c_{kl})$, $k \equiv p + i$, $l \equiv q + j \pmod m$ for fixed integers p and q. Consequently, the finite sequences of C, C^T and C_{pq} are identical; therefore, matrices C, C^T and C_{pq} are regarded as of the same type.

In the following table, all M_n, constructible by all distinct types of A and B with the restriction that $N(A) \leqq N(B) < n/4$, where $N(C)$ means the number of −1's in each row of C, are listed for $n \leqq 38$.

The following methods and theorems are helpful for constructions of M_n.

Let $S = (s_{ij})$ be the mth order circulant matrix such that

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$$s_{ij} = 1, \text{ if } j - i \equiv 1 \pmod m,$$
$$= 0, \text{ otherwise}.$$

Then the mth order circulant matrices C, D whose first row vectors are respectively $U = (u_1, \cdots, u_m)$, $V = (v_1, \cdots, v_m)$ can be represented as

$$C = \sum_{k=1}^{m} u_k S^{k-1} \quad \text{and} \quad D = \sum_{k=1}^{m} v_k S^{k-1}$$

where $S^0 = I =$ the mth order identity matrix.

THEOREM 1. *Let*

$$M = \begin{pmatrix} C & D \\ -D^T & C^T \end{pmatrix},$$

then the gramian matrix $G(M)$ becomes

$$G(M) = MM^T = \begin{pmatrix} G & 0 \\ 0 & G \end{pmatrix}, \tag{1}$$

where $G = (g_{ij}) = CC^T + DD^T$. And

$$g_{ij} = c_{ij} + d_{ij} = c_k + d_k = g_k = g_{m-k}, \tag{2}$$

if $k = |i - j|$, where $(c_{ij}) = CC^T$, $(d_{ij}) = DD^T$; $c_{ij} = c_k = c_{m-k}$ and $d_{ij} = d_k = d_{m-k}$, if $k = |i - j|$.

THEOREM 2. *Let p and q be respectively the number of 1's in the first row vectors U, V of C and D when u_k, v_k are 0 or 1. Then*

$$\sum_{k=1}^{m-1} c_k = p(p-1) \quad \text{and} \quad \sum_{k=1}^{m-1} d_k = q(q-1). \tag{3}$$

And

$$c_k + d_k = r, \quad \text{for } 1 \leqq k \leqq m-1, \tag{4}$$

implies

$$r(m-1) = p(p-1) + q(q-1). \tag{5}$$

THEOREM 3. *Let A and B be the matrices obtained by substituting -1's for 1's and 1's for 0's in C and D respectively. Then the elements g_k of G become*

$$\begin{aligned} g_k &= 2m, \quad \text{if } k = 0, \\ &= 2m - 4(p + q - c_k - d_k), \quad \text{otherwise}. \end{aligned} \tag{6}$$

And

$$g_k = 2, \quad \text{for } 1 \leqq k \leqq \tfrac{1}{2}(m-1), \tag{7}$$

if and only if

$$p + q - r = \tfrac{1}{2}(m-1). \tag{8}$$

Sketch of the proofs for Theorems 1, 2, *and* 3. Since the ith row vector and jth column vector of C can be expressed as US^{i-1} and $(US^{j-1})^T$, respectively, we have

n	$\{a_k\}$ or $\{b_k\}$	The first row of A or B
6	3 −1	+++ −++
10	1, 1 1, 1	−++++ −++++
14	3, 3, 3 −1, −1, −1	−++++ ++ −−+−+ ++
18	5, 1, 1, 1 −3, 1, 1, 1	−−+++ ++++ −+−++ −+++
	1, 5, 1, 1 1, −3, 1, 1	−+−++ ++++ −−++− ++++
	1, 1, 1, 5 1, 1, 1, −3	−+++− ++++ −−+−+ ++++
26	1, 1, 1, 1, 1, 1,	−−+−+ ++++− +++
	1, 1, 1, 1, 1, 1,	−−++− +−+++ +++
	5, 1, 5, 5, 1, 1, −3, 1, −3, −3, 1, 1,	−−++− +++++ +++ −−−+− ++−+− +++ −−+−+ −+−−+ +++
	1, 5, 1, 1, 5, 5 1, −3, 1, 1, −3, −3	−+−++ ++−++ +++ −−−−+ +−+++ −++ −−−+− −++−+ +++
30	3, 3, 3, 3, 3, 3, −1 −1, −1, −1, −1, −1, −1, 3	−−++− +−+++ +++++ −−+−− +++−+ −++++ −−+−+ −++−− +++++
	3, 3, 3, −1, 3, 3, 3, −1, −1, −1, 3, −1, −1, −1	−−+−+ +++++ −++++ −−−+− ++−++ +−+++ −−+−+ −++++ +−−++

	3, −1, 3, 3, 3, 3, 3 −1, 3, −1, −1, −1, −1, −1	−−++− −−−+− −−−+−	++++− +−++− +++++	+++++ +++++ −+−++	
	−1, 3, 3, 3, 3, 3, 3 3, −1, −1, −1, −1, −1, −1	−+−++ −−−−+ −−−++	−+++− +−+++ −−+−+	+++++ −++++ +++++	
	3, −1, 3, 3, 3, 7, −1 −1, 3, −1, −1, −1, −5, 3	−−++− −−+−+	+++++ −+−−+	−++++ +++++	
	−1, 3, 7, −1, 3, 3, 3, 3, −1, −5, 3, −1, −1, −1	−+−++ −−−−+	−++−+ ++−++	+++++ +−+++	
38	3, 3, 3, 3, 3, −1, −1, 3, −1 −1, −1, −1, −1, −1, 3, 3, −1, 3	−−+−+ −−+−+	−++−− ++−+−	+++++ −+++−	++++ ++++
	3, 3, 3, −1, 3, −1, 3, −1, 3 −1, −1, −1, 3, −1, 3, −1, 3, −1	−−+−+ −−+−+	++−−+ ++++−	+++++ +−+++	++−+ −−++
	3, 3, 3, −1, 3, −1, 3, 3, −1 −1, −1, −1, 3, −1, 3, −1, −1, 3	−−−+− −−+−+ −−+−− −−+−+	++−++ +++++ +++−+ −+++−	++−++ ++−+− −+++− −++++	++++ −+++ ++++ +−++
	3, 3, −1, 3, 3, 3, −1, −1, 3 −1, −1, 3, −1, −1, −1, 3, 3, −1	−−−++ −−+−−	−+−++ ++−++	+−+++ ++−+−	++++ ++++
	3, 3, −1, 3, −1, −1, 3, 3, 3 −1, −1, 3, −1, 3, 3, −1, −1, −1	−−−+− −−+−−	++++− ++−+−	+++−+ ++++−	++++ ++++
	3, −1, 3, 3, −1, 3, 3, 3, −1 −1, 3, −1, −1, 3, −1, −1, −1, 3	−−+−+ −−−+−	++−−+ +−+++	+++++ +−++−	+−++ ++++
	3, −1, −1, 3, −1, 3, 3, 3, 3, −1, 3, 3, −1, 3, −1, −1, −1, −1	−−−++ −−++− −−−+− −−+−+	+−+++ −++++ ++−++ −++++	−++−+ +−+−+ ++−++ +++−−	++++ ++++ ++−+ ++−+

n	$\{a_k\}$ or $\{b_k\}$	*The first row of A or B*
	3, −1, −1, −1, 3, 3, 3, 3, 3 −1, 3, 3, 3, −1, −1, −1, −1, −1	−−+−+ +++−− +++−+ ++++ −−+−+ −++++ +++−+ −−++
	−1, 3, 3, 3, 3, 3, −1, −1, 3 3, −1, −1, −1, −1, −1, 3, 3, −1	−−+−+ −++++ −++++ +−++ −−++− +−+++ ++++− +−++ −−−−+ ++−++ +−++− ++++ −−−++ −++++ ++−−+ −+++
	−1, 3, 3, 3, −1, 3, −1, 3, 3, 3, −1, −1, −1, 3, −1, 3, −1, −1	−−+−+ ++−++ +−+++ ++−+ −−−−+ ++−++ −++++ −+++
	−1, 3, 3, −1, 3, 3, 3, 3, −1 3, −1, −1, 3, −1, −1, −1, −1, 3	−−+−+ +−+−+ ++−++ ++++ −−−+− +++++ +−++− −+++
	−1, −1, 3, 3, 3, 3, 3, −1, 3 3, 3, −1, −1, −1, −1, −1, 3, −1	−−++− +−++− +++−+ ++++ −−−+− +++++ ++−+− −+++
	7, 3, 3, −1, −1, 3, −1, −1, 3 −5, −1, −1, 3, 3, −1, 3, 3, −1	−−−−+ +−+++ ++−++ ++++ −−+++ −+−+− ++−++ −+++
	7, 3, −1, −1, 3, −1, 3, −1, 3 −5, −1, 3, 3, −1, 3, −1, 3, −1	−−−−+ ++−++ ++−++ ++++ −−+−+ +−+−+ ++−++ +−++ −−+−+ ++−++ +−++− +−++
	3, 7, −1, 3, 3, −1, −1, −1, 3 −1, −5, 3, −1, −1, 3, 3, 3, −1	−−−+− +−+++ +−+++ ++++ −−+−+ +++−− +++−+ +−++ −−++− +−++− ++−−+ ++++
	3, 7, −1, 3, −1, 3, 3, −1, −1 −1, −5, 3, −1, 3, −1, −1, 3, 3	−−−+− +−+++ +++−+ ++++ −−+−+ +−+++ +−−++ −+++
	3, 3, 3, 3, −1, −1, −1, 7, −1 −1, −1, −1, −1, 3, 3, 3, −5, 3	−−−+− +++++ ++−++ −+++ −−−++ −+−++ +−++− ++++ −−+−+ ++−++ ++−−+ ++−+
	3, 3, 3, −1, −1, 7, 3, −1, −1 −1, −1, −1, 3, 3, −5, −1, 3, 3	−−−+− ++−++ +++−+ ++++ −−−++ −+++− +−+++ +−++

3, 3, −1, 7, −1, −1, −1, 3, 3 −1, −1, 3, −5, 3, 3, 3, −1, −1	− − − + − − − + − + − − + − +	+ + + + + + − + + + + − + − −	+ − + + + + + − − + + + + − +	− + + + + + − + + + + +
3, −1, 7, −1, −1, 3, −1, 3, 3 −1, 3, −5, 3, 3, −1, 3, −1, −1	− − − + + − − + − +	− + + − + − + − + +	+ − + + + + + + + −	+ + + + − + + +
3, −1, 3, −1, 3, −1, −1, 3, 7 −1, 3, −1, 3, −1, 3, 3, −1, −5	− − + − + − − − + −	+ − + + + + + + − +	− − + + + + + + + −	+ + + + + − + +
3, −1, −1, −1, 3, 3, 3, −1, 7 −1, 3, 3, 3, −1, −1, −1, 3, −5	− − + − + − − + − − − − + − +	+ + + + − + − + − + − + − − +	− + + + + + + − + + + − + + +	− + + + + + + + + + + +
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−1, 3, −1, 7, 3, −1, 3, 3, −1 3, −1, 3, −5, −1, 3, −1, −1, 3	− − + + − − − + − −	+ − + − + + − + + +	+ + + + + + + + − −	− + + + + + + +
−1, 3, −1, 3, 3, 3, 7, −1, −1, 3, −1, 3, −1, −1, −1, −5, 3, 3	− − + + − − − − + −	+ − + − + − + + + +	+ + + − + − + + − +	+ + + + + + + +
−1, −1, 3, 3, 3, −1, −1, 7, 3 3, 3, −1, −1, −1, 3, 3, −5, −1	− − + + − − − − − +	+ + + + + + − + + +	− + − + + + + + − +	− + + + − + + +
−1, −1, 3, 3, −1, 7, 3, 3, −1 3, 3, −1, −1, 3, −5, −1, −1, 3	− − + + − − − − − + − − − + +	+ + − + + − + + + + − + − + −	+ + + − + − + + + − − + + + +	− + + + + + + + + + + +
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−1, −1, 3, −1, 3, 3, 7, 3, −1 3, 3, −1, 3, −1, −1, −5, −1, 3	− − + + − − − − − + − − − + −	+ + − + + − + + + + + − + + −	+ + − + − + − + + + − + + + +	+ + + + − + + + + + + +
−1, −1, −1, 3, 7, −1, 3, 3, 3 3, 3, 3, −1, −5, 3, −1, −1, −1	− − + + + − − − + −	− + + + − + + − − +	+ + − + − − + + + +	+ + + + + + + +

$$\begin{aligned} c_{ij} &= (US^{i-1})(US^{j-1})^T = (US^{i-1})(S^{j-1})^T U^T \\ &= US^{i-1}S^{m-j+1}U^T \qquad [\cdots (S^k)^T = S^{m-k}] \\ &= (US^{m+i-j})U^T = c_{(m+i-j+1)1}, \qquad \text{if } j > i, \\ &= (US^{i-j})U^T = c_{(i-j+1)1}, \qquad \text{if } i \geqq j \qquad [\cdots S^m = I] \\ &= U(US^{j-1})^T = c_{1(j-i+1)}, \qquad \text{if } j \geqq i. \end{aligned}$$

Since the gramian matrix is symmetric, i.e., $c_{ij} = c_{ji}$, by defining $c_k \equiv c_{1(k+1)} = c_{(k+1)1}$, we have

$$\begin{aligned} c_k &= c_{|i-j|} = c_{1(j-i+1)} = c_{ij} \\ &= c_{(m+i-j+1)1} = c_{|m-(j-i)|} = c_{m-k}, \qquad \text{if } k = |i-j|. \end{aligned}$$

Similarly we have $d_k = d_{|i-j|} = d_{ij} = d_{m-k}$ if $k = |i - j|$.

The equalities (3) can be proved by mathematical induction. When $p = 1$, obviously they are true. Assuming that they are true for $p = N < m$, we have $\sum_{k=1}^{m-1} c_k = N(N-1)$ and N 1's in U. Without loss of generality, let us assume $u_j = 0$. Then by replacing $u_j = 0$ by $u_j = 1$ in U, which corresponds to $p = N + 1$, we observe that $2(m-1)$ terms $u_j u_k$, $u_k u_j$ $(k \neq j,\ 1 \leqq k \leqq m)$, in $\sum_{k=1}^{m-1} c_k = \sum_{k=1}^{m-1} U(US^k)^T = \sum_{k=1}^{m-1} \sum_{i=1}^{m} u_i u_l$ $[l \equiv i - k \pmod m]$, may be affected by this change. Among these $2(m-1)$ terms, exactly $2N$ terms change the value from 0 to 1, for there are N 1's among u_k $(k \neq j,\ 1 \leqq k \leqq m)$. Therefore, $\sum_{k=1}^{m-1} c_k = N(N-1) + 2N = (N+1)N$, thus they are also true for $p = N + 1$.

For proof of Theorem 3, let $AA^T = (a_{ij})$ and $a_k = a_{|i-j|} = a_{ij}$, if $k = |i - j|$. Since $a_k = U(US^k)^T = \sum_{i=1}^{m} u_i u_l$ $[l \equiv i - k \pmod m]$, by observing that there are c_k, $2(p - c_k)$, and $m - c_k - 2(p - c_k)$ terms of $u_i u_l$ respectively with $u_i = u_l = -1$, $u_i = -u_l = 1$ (or -1), and $u_i = u_l = 1$, we have $a_k = m - 4(p - c_k)$, for $1 \leqq k \leqq m - 1$. Similarly, $b_k = m - 4(q - d_k)$, where $b_k = b_{|i-j|} = b_{ij}$, if $k = |i - j|$ and $(b_{ij}) = BB^T$. Consequently, we have

$$g_k = a_k + b_k = 2m - 4(p + q - c_k - d_k), \qquad \text{for } 1 \leqq k \leqq m - 1.$$

The equality (8) can be derived easily from (3), (5), (6), and (7).

From (5) and (8), and for a given m and preassigned r, solutions for p and q can be obtained. When $m = 11, 17, \cdots$, there is no solution for p and q. (See [1] and the table of [2].) For constructions of M_n, it is noticed that finding two sequences $\{c_k\}$ and $\{d_k\}$ satisfying (4) is usually easier than finding two sequences $\{a_k\}$ and $\{b_k\}$ satisfying (7).

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