

ON THE CONSTRUCTION OF HADAMARD MATRICES

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ABSTRACT. This paper constructs Hadamard matrices of order $4n$. Given the first 4 rows and columns of a Hadamard matrix of order $4n$, we study its $(n-1) \times (n-1)$ block matrix properties. Since the incidence matrices of symmetric 2-designs do not violate the obtained properties, we use them in the construction. We obtained the total number of Hadamard matrix construction structures by only using incidence matrices of symmetric 2-designs. Furthermore, at most 4 different incidence matrices with their corresponding complements can have a Hadamard matrix structure. Other than this number is not possible.

1. INTRODUCTION

A *Hadamard matrix* of order n is a square matrix H whose entries consist of 1's and -1 's satisfying

$$HH^T = nI$$

where H^T is the transpose of H and I is the identity matrix of order n . It is known that Hadamard matrices exist only when $n = 2$ or n is a multiple of 4. However, the converse still remains as a conjecture at present[11]. In particular, for $n \leq 28$, Hadamard matrices are completely classified and the complete listing of such matrices can be found in Sloane's homepage[14]. This paper aims to construct Hadamard matrices of order $4n$ by investigating Kimura's structure [9] for length 32. We determine the appropriate parameters of all the

Date: March 29, 2004.

†This work is (partially) supported by Kyushu University 21st Century COE Program, Development of Dynamic Mathematics with High Functionality, of the Ministry of Education, Culture, Sports, Science and Technology of Japan.

submatrices, having order $n - 1$, that will yield a Hadamard matrix of order $4n$. It is seen that the appropriate choice of incidence matrices of symmetric $2 - (n - 1, \frac{n}{2} - 1, \frac{n}{4} - 1)$ designs and their corresponding complements can be such submatrices. The obtained Hadamard matrices are generator matrices to self-orthogonal codes over $\text{GF}(2)$.

2. THE CONSTRUCTION

Let $n \equiv 0 \pmod{4}$. We construct a Hadamard matrix of order $4n$ from a given $2 - (n - 1, \frac{n}{2} - 1, \frac{n}{4} - 1)$ Hadamard design $\mathcal{D}$. We consider the following structure of a Hadamard matrix of order $4n$ and denote it by H_{4n} .

$$H_{4n} := \left[\begin{array}{c|c|c|c|c} \begin{array}{c} 1111 \\ 1100 \\ 1010 \\ 1001 \\ \hline 1111 \\ \vdots \\ 1111 \\ \hline 1100 \\ \vdots \\ 1100 \\ \hline 1010 \\ \vdots \\ 1010 \\ \hline 1001 \\ \vdots \\ 1001 \end{array} & \begin{array}{c} 1111111 \dots \\ 1111111 \dots \\ 1111111 \dots \\ 0000000 \dots \\ \hline A_1 \\ \hline B_1 \\ \hline C_1 \\ \hline D_1 \end{array} & \begin{array}{c} 1111111 \dots \\ 1111111 \dots \\ 0000000 \dots \\ 1111111 \dots \\ \hline A_2 \\ \hline B_2 \\ \hline C_2 \\ \hline D_2 \end{array} & \begin{array}{c} 1111111 \dots \\ 0000000 \dots \\ 1111111 \dots \\ 1111111 \dots \\ \hline A_3 \\ \hline B_3 \\ \hline C_3 \\ \hline D_3 \end{array} & \begin{array}{c} 1111111 \dots \\ 0000000 \dots \\ 0000000 \dots \\ 0000000 \dots \\ \hline A_4 \\ \hline B_4 \\ \hline C_4 \\ \hline D_4 \end{array} \end{array} \right] \quad (1)$$

3. PROPERTIES OF THE $(n - 1) \times (n - 1)$ BLOCK MATRICES

To construct matrix (1), we need to find the block matrices $A_1, A_2, A_3, A_4, B_1, B_2, B_3, B_4, C_1, C_2, C_3, C_4, D_1, D_2, D_3$ and D_4 . All of these are $(n - 1) \times (n - 1)$ matrices. We denote the *weight* (number of 1's entry) of a vector x as $wt(x)$ and the number of 1's intersection between any two row vectors x, y as $x * y$.

Lemma 3.1. *Row vectors of block matrices $A_1, A_2, A_3, A_4, B_1, B_2, C_1, C_3, D_2$ and D_3 are of weight $(\frac{n}{2} - 1)$. Also, row vectors of block matrices B_3, B_4, C_2, C_4, D_1 , and D_4 are of weight $\frac{n}{2}$.*

To construct matrix (1), we make use of the $(n-1) \times (n-1)$ incidence matrices of $\mathfrak{D}$ that is, block matrices $A_1, A_2, A_3, A_4, B_1, B_2, C_1, C_3, D_2$ and D_3 are incidence matrices of some $2 - (n-1, \frac{n}{2}-1, \frac{n}{4}-1)$ Hadamard designs and, block matrices B_3, B_4, C_2, C_4, D_1 , and D_4 are incidence matrices of some complements of the above designs. We can also consider incidence matrices from inequivalent $2 - (n-1, \frac{n}{2}-1, \frac{n}{4}-1)$ Hadamard designs. Let M be the $(4n-4) \times (4n-4)$ matrix obtained from deleting the first four rows and columns of matrix (1). Then

$$M := \left[\begin{array}{c|c|c|c} A_1 & A_2 & A_3 & A_4 \\ B_1 & B_2 & B_3 & B_4 \\ C_1 & C_2 & C_3 & C_4 \\ D_1 & D_2 & D_3 & D_4 \end{array} \right] \quad (2)$$

We define β_i ($i = 1, 2, 3, 4$) as follows:

$$\beta_1 = (A_1, A_2, A_3, A_4)$$

$$\beta_2 = (B_1, B_2, B_3, B_4)$$

$$\beta_3 = (C_1, C_2, C_3, C_4)$$

$$\beta_4 = (D_1, D_2, D_3, D_4)$$

Let S be the set of $(n-1) \times (n-1)$ incidence matrices of some $2 - (n-1, \frac{n}{2}-1, \frac{n}{4}-1)$ designs and M_i be an element of S . Denote M'_i as the incidence matrix of its corresponding complement and S' as the set of M'_i . We check some conditions of the block matrices in M to obtain different constructions of a Hadamard matrix using the given structure. Also, we determine the maximum number σ of distinct matrices from S which can altogether construct a Hadamard matrix. Observe that $\sigma \leq 16$ since matrix M has 16 block matrices.

Lemma 3.2. *Let $A, B \in S$. Then for any vectors $x_A \in A$ and $y_B \in B$,*

$$x_A * y_B = 0, 1, \dots \text{ or } \frac{n}{2} - 1.$$

Lemma 3.3. *Let $A, B \in S$ and $0 \leq k \leq \frac{n}{2} - 1$. Then for any vectors $x_A \in A$ and $y_B \in B$,*

$$x_A * y_B = (\frac{n}{2} - 1) - k \text{ if and only if } x_A * y_B = k.$$

Lemma 3.4. *Let $A, B \in S$ and $0 \leq k \leq \frac{n}{2} - 1$. Then for any vectors $x_A \in A$ and $y_B \in B$,*

$$x_{A'} * y_{B'} = k + 1 \text{ if and only if } x_A * y_B = k.$$

Let $A_1 = M_i$. Then we have the following possible values of β_1 :

- (i) If the A_i 's ($i = 1, 2, 3, 4$) are equal, then we have
 - 1. $\beta_1 = (M_i, M_i, M_i, M_i)$.
- (ii) If A_i ($i = 1, 2, 3, 4$) have two different values, then we have
 - 2. $\beta_1 = (M_i, M_i, M_j, M_j)$
 - 3. $\beta_1 = (M_i, M_j, M_j, M_i)$
 - 4. $\beta_1 = (M_i, M_j, M_i, M_j)$
 - 5. $\beta_1 = (M_i, M_i, M_i, M_j)$
 - 6. $\beta_1 = (M_i, M_i, M_j, M_i)$
 - 7. $\beta_1 = (M_i, M_j, M_i, M_i)$
 - 8. $\beta_1 = (M_i, M_j, M_j, M_j)$.
- (iii) If A_i ($i = 1, 2, 3, 4$) have three different values, then we have
 - 9. $\beta_1 = (M_i, M_j, M_k, M_i)$
 - 10. $\beta_1 = (M_i, M_j, M_k, M_k)$
 - 11. $\beta_1 = (M_i, M_j, M_k, M_j)$
 - 12. $\beta_1 = (M_i, M_i, M_j, M_k)$
 - 13. $\beta_1 = (M_i, M_j, M_j, M_k)$
 - 14. $\beta_1 = (M_i, M_j, M_i, M_k)$
- (iv) If A_i ($i = 1, 2, 3, 4$) have four different values, then we have
 - 15. $\beta_1 = (M_i, M_j, M_k, M_l)$

The following is an algorithm in constructing the possible structures of M which would generate a Hadamard matrix of order $4n$:

- (1) Consider the 15 possible values of β_1 above.
- (2) For each case, generate the possible values of β_2 . At this point, 15 sets of β_2 are generated.
- (3) For every pair of β_1 and β_2 , generate the possible values of β_3 .
- (4) For every triple of β_1 , β_2 and β_3 , generate the possible values of β_4 .

Theorem 3.5. *There are 149 possible structures of M which would generate a Hadamard matrix of order $4n$.*

In finding values of β_i ($i = 1, 2, 3, 4$), we use different variables and check all possibilities to find the maximum number of distinct block matrices which can altogether construct a Hadamard matrix of order $4n$. Hence we also have the following theorem:

Theorem 3.6. *The maximum number of distinct block matrices in matrix M which would construct a Hadamard matrix of order $4n$ is 4.*

4. THE HADAMARD MATRIX OF ORDER 32

We construct a Hadamard matrix of order 32 using the method in the previous section. $n = 32$ is the next length to be classified as $n \leq 28$ are completely classified. There are 26 matrices found in Seberry's homepage[15] and 6 matrices found in Sloane's page[14]. Araya, Harada and Kharaghani[1] also enumerated a number of them. It is known that there are at least 66,000 inequivalent Hadamard matrices of length 32[3].

The following are direct consequences of the results in the previous section:

- (1) Let x_1 be the first row vector and let x, y be any distinct row vectors other than x_1 . Then $x_1 * y = \frac{n}{2} = 16$ and $x * y = \frac{n}{4} = 8$ when $x \neq 1$.
- (2) Row vectors of block matrices $A_1, A_2, A_3, A_4, B_1, B_2, C_1, C_3, D_2$ and D_3 are of weight 3. Also, row vectors of block matrices B_3, B_4, C_2, C_4, D_1 , and D_4 are of weight 4.

We investigate other properties of the block matrices of a Hadamard matrix of order 32 by asking the question, "How many repetitions of row vectors are possible in constructing each block matrix?" The answer to this question gives the following result.

Proposition 4.1. *3 repetitions of a vector in a block matrix is not possible, for block matrices A_i, B_i, C_i and $D_i (i = 1, 2, 3, 4)$.*

Hence, we are left with two remaining possibilities i.e., either a row vector in a block matrix can be repeated twice or each row vector is distinct.

5. SOME EXAMPLES

We make use of the incidence matrices of the isomorphic $2 - (7, 3, 1)$ designs and their respective complements, the $2 - (7, 4, 2)$ designs. Note that these designs are unique and are self-dual[2]. There are 30 cosets of the $2 - (7, 3, 1)$ designs and there are $(7!)^2/168$ incidence matrices. We use MAGMA in computing some Hadamard matrix examples. The following are some construction examples.

Example 5.1.

$$\left[\begin{array}{c|c|c|c} M_i & M_i & M_i & M_i \\ M_i & M_i & M'_i & M'_i \\ M_i & M'_i & M_i & M'_i \\ M'_i & M_i & M_i & M'_i \end{array} \right]$$

If the construction used has one distinct block matrix, we obtain 1 inequivalent Hadamard matrix of order 32 with automorphism group order equal to 16515072.

Example 5.2.

$$\left[\begin{array}{c|c|c|c} M_i & M_i & M_i & M_i \\ M_j & M_j & M'_j & M'_j \\ M_i & M'_i & M_j & M'_j \\ M'_i & M_i & M_j & M'_j \end{array} \right]$$

If the construction used has two distinct block matrices, we can obtain at most $\frac{71^2}{168} \times \left(\frac{71^2}{168} - 1\right)$ Hadamard matrices of order 32. We have computed some Hadamard matrix examples from the above particular construction and obtained 11 different automorphism group orders namely: 256, 768, 1024, 2048, 3072, 24576, 384, 512, 4096, 6144 and 65536.

Example 5.3.

$$\left[\begin{array}{c|c|c|c} M_i & M_i & M_i & M_i \\ M_j & M_j & M'_j & M'_j \\ M_k & M'_k & M_j & M'_j \\ M'_k & M_k & M_j & M'_j \end{array} \right]$$

If the construction used has three distinct block matrices, we can obtain at most $\frac{71^2}{168} \times \left(\frac{71^2}{168} - 1\right) \times \left(\frac{71^2}{168} - 2\right)$ Hadamard matrices of order 32. We have computed some Hadamard matrix examples from the above particular construction and obtained 13 different automorphism group orders namely: 256, 768, 1024, 2048, 3072, 24576, 64, 128, 192, 384, 512, 1536 and 4096.

Example 5.4.

$$\left[\begin{array}{c|c|c|c} M_i & M_j & M_k & M_l \\ M_i & M_j & M'_k & M'_l \\ M_i & M'_j & M_k & M'_l \\ M'_i & M_j & M_k & M'_l \end{array} \right]$$

If the construction used has four distinct block matrices, we can obtain at most $\frac{7!^2}{168} \times \left(\frac{7!^2}{168} - 1\right) \times \left(\frac{7!^2}{168} - 2\right) \times \left(\frac{7!^2}{168} - 3\right)$ Hadamard matrix of order 32.

To classify the obtained Hadamard matrices of order 32, equivalence and automorphism group order must be considered. This can be done using MAGMA, too. Since computing requires a massive time, the total number of inequivalent Hadamard matrix of order 32 from the different obtained structures were not completely computed.

6. RANKS OF A HADAMARD MATRIX OF ORDER 32 OVER $GF(2)$ AND CODES

Let H_n be a generator matrix of a linear binary $[n, k]$ code. The codes obtained from H_n when $n \equiv 0 \pmod{8}$ is self-orthogonal and in particular, it yields self dual when $k = \frac{n}{2}$. The 2-rank of H_n is the dimension of the $[n, k]$ code over $GF(2)$, and is written as $rank_2(H_n)$. This section enumerates $rank_2(H_n)$ of examples 5.1, 5.2, 5.3 and 5.4. Ranks of H_n were also computed using MAGMA.

We denote a Hadamard matrix of order 32 as H_{32} . From [2], $6 \leq rank_2(H_{32}) \leq 16$. $Rank_2(H_{32})$ in example 5.1 is 7; in examples 5.2 and 5.3 are 8, 9, 10, 11, 12 and 13. $Rank_2(H_{32}) = 14, 15, 16$ are not obtained from the computed examples but the author is hopeful to find examples of such ranks from the 149 different constructions. If H_{32} exists with $rank_2(H_{32}) = 16$ from any of our constructions, then we can also classify the $[32, 16]$ type II self dual codes obtained from Hadamard matrices with Hall sets[8].

7. CONCLUSIONS AND RECOMMENDATIONS

In this paper, after checking the properties and conditions of the block matrices of matrix (1), we had come up with the following:

- Construction of Hadamard matrices of order $4n$ if $n \equiv 0 \pmod{4}$ and $2 - (n - 1, \frac{n}{2} - 1, \frac{n}{4} - 1)$ Hadamard designs exist.
- We were successful in enumerating all the possible constructions of a Hadamard matrix of order $4n$ using Kimura's structure, restricting the row vectors of each block matrix to be distinct and using the incidence matrices of a symmetric 2-design as block matrices of of such matrix.

For a Hadamard matrix of order 32 in particular, we also have come up with the following:

- a. Some examples with their automorphism group orders and $\text{Rank}_2(H_{32})$ were computed,
- b. 3 or more repetitions of a row vector in any of the 7×7 block matrices do not yield Hadamard matrix.
- c. The possibility of constructing a Hadamard matrix using block matrices with vector/s repeated twice has not been explored.

Thus we are left with the following questions:

- (1) Is there a possibility to construct a Hadamard matrix of order $4n$ using Kimura's structure if for any n , Hadamard $2 - (n - 1, \frac{n}{2} - 1, \frac{n}{4} - 1)$ design does not exist?
- (2) If for $n = 8$, 3 or more repetitions of a row vector in any of the 7×7 block matrices of H_{32} do not yield Hadamard matrix, what would be the case for $n > 8$?
- (3) Is there any relationship between the rank of a Hadamard matrix of order $4n$ ($n \geq 8$) and the constructions?
- (4) Which of the constructions could generate Hadamard matrix of order $4n$ of highest rank?
- (5) Let H_{4n} be a Hadamard matrix of order $4n$. Is $\text{rank}_2(H_{4n}) = \frac{n}{2}$ possible in these constructions? If so, then we can also classify some Type II self dual codes from H_{4n} .

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