RANKED SOLUTIONS OF THE MATRICE EQUATION $A_1X_1 = A_2X_2$

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ABSTRACT. Let $GF(p^z)$ denote the finite field of $p^z$ elements. Let $A_1$ be $s \times m$ of rank $r_1$ and $A_2$ be $s \times n$ of rank $r_2$ with elements from $GF(p^z)$. In this paper, formulas are given for finding the number of $X_1, X_2$ over $GF(p^z)$ which satisfy the matric equation $A_1X_1 = A_2X_2$, where $X_1$ is $m \times t$ of rank $k_1$, and $X_2$ is $n \times t$ of rank $k_2$. These results are then used to find the number of solutions $X_1, \ldots, X_n, Y_1, \ldots, Y_m, n > 1$, of the matric equation $A_1X_1 \ldots X_n = A_2Y_1 \ldots Y_m$.

KEY WORDS AND PHRASES. Finite Field, Matrice equation, Ranked Solutions.

1. **Introduction.** Let $GF(q)$ denote the finite field with $q = p^r$ elements, $p$ odd. Matrices with elements from $GF(q)$ will be denoted by Roman capitals $A$, $B$, ... $A(n,s)$ will denote a matrix of $n$ rows and $s$ columns, and $A(n,s;r)$ will denote a matrix of the same dimensions with rank $r$. $I_r$ denotes the identity matrix of order $r$, and $I(n,s;r)$ denotes a matrix of $n$ rows and $s$ columns having $I_r$ in its upper left hand corner and zeros elsewhere.

In this paper we find the number of solutions $X_1(m,t;k_1), X_2(n,t;k_2)$ to the matrix equation

$$A_1 X_1 = A_2 X_2, \quad (1.1)$$

where $A_1 = A_1(s,m;r_1)$ and $A_2 = A_2(s,n;r_2)$. Since the ranks of $X_1, X_2$ are specified, we call this the ranked case. If the ranks were not specified, we would call it the unranked case. In section 4 we apply this result to find the number of solutions $X_1, \ldots, X_n, Y_1, \ldots, Y_m$, $m, n \geq 1$, to the matrix equation

$$A_1 X_1 \ldots X_n = A_2 Y_1 \ldots Y_m, \quad (1.2)$$

both in the unranked and ranked cases.

Equation (1.1) is a special case of the matrix equation

$$A_1 X_1 + \ldots + A_n X_n = B, \quad (1.3)$$

and equation (1.2) is a special case of the more general equation

$$A_1 X_{11} \ldots X_{1m(1)} + \ldots + A_n X_{n1} \ldots X_{nm(n)} = B. \quad (1.4)$$

Porter [6] found the number of solutions $X_1, \ldots, X_n$ to (1.3) in the unranked case. We could find the number of solutions to (1.3) in the ranked case if we could find the number of ranked solutions to $A_1 X_1 + A_2 X_2 = B$. The number of ranked solutions to $A_1 X_1 + A_2 X_2 = B$ together with the formulae for the number of solutions to $X_1 \ldots X_n = B$ would give the number of solutions to (1.4). The number of unranked solutions to $X_1 \ldots X_n = B$ is given by Porter in [5]. The
number of ranked solutions to \(X_1 \ldots X_n = B\) appears in [9], by the authors.

Presently the authors know of no published results, unranked or ranked, giving the number of solutions to (1.4) except when (1.4) reduces to (1.3). There are partial results in the unranked case to the analogous problem

\[ U_a \ldots U_1 A + BV_1 \ldots V_b = C. \]

Hodges [1] found the number of unranked solutions with \(a = b = 1\). Hodges [2] and Porter [7] found partial results in the unranked case when \(a, b\) are arbitrary and Hodges [3] discussed ranked solutions when \(a = b = 1\).

2. NOTATION AND PRELIMINARIES. A well known formula due to Landsberg [4] gives the number \(g(m,t;s)\) of \(m \times t\) matrices of rank \(s\) over \(\text{GF}(q)\).

\[
g(m,t;s) = q^{s(s-1)/2} \prod_{i=1}^{s} (q^{m-i+1} - 1)(q^{t-i+1} - 1)/(q^i - 1),
\]  

(2.1)

for \(1 \leq s \leq \min(m,t)\), \(g(m,t;0) = 1\), and \(g(m,t;s) = 0\) for \(\min(m,t) < s\) or \(s < 0\).

If \(X = X(e,t)\) and \(X = \text{col}[U,Y]\), where \(U\) is fixed, \(U = U(m,t;s)\) and \(Y = Y(e-m,t)\), then the number of ways that \(Y\) can be chosen such that \(X\) has rank \(k\) is given by Porter and Riveland [11] to be

\[
G(e,t,m;k,s) = q^{s(e-m)} g(e-m,t-s;k-s).
\]  

(2.2)

In [9, Theorem 3] the authors found the number of solutions \(X(m,f;k)\) to the matric equation \(AX = B\), where \(A = A(s,m;\rho)\) and \(B = B(s,f;\beta)\). This number is given by

\[
N(A,B,k) = h(B_o) q^{(m-\rho)\beta} g(m-\rho,f-\beta;k-\beta) = h(B_o) L(m,f;\rho,\beta,k),
\]  

(2.3)

where \(h(B_o)\) is defined as follows. If \(P, Q\) are nonsingular matrices such that \(PAQ = I(s,m;\rho)\), then \(B_o = PB = (\beta_{ij})\) and \(h(B_o) = 1\) if \(\beta_{ij} = 0\) for \(i > \rho\), \(h(B_o) = 0\) otherwise. The number of solutions, when there are any, is denoted by \(L(m,f;\rho,\beta,k)\).

Let \(A = A(n,s;r)\) and \(B = B(n,t;u)\). Then Porter [5] showed that the number
of solution \( X_1(s_1, s_1), X_i(s_{i-1}, s_i) \) for \( 1 < i < a \), \( X_a(s_{a-1}, t) \) to the matrix equation \( AX_1 \ldots X_a = B \). When there are solutions, this number can be represented by

\[
M_a(s_1, \ldots, s_{a-1}, t, u) = \begin{cases} 
N(a, s, t, s_1, s, u) & \text{for } a \geq 2, \\
1 & \text{for } a = 1.
\end{cases}
\] (2.5)

The number of matrices \( D = D(a, b; c) \) such that \( D \) contains \( D_1(d, b) \) and \( D_2(a - d, b; c - d) \), \( d \leq \min(a, c) \) is given in [10] to be

\[
K(a, b, c, d) = q^{(c-d)d} g(d, b + d - c; d) g(a - d, b; c - d).
\]

The number \( T_n(d_0, \ldots, d_n; k_1, \ldots, k_n, \beta) \) of solutions \( X_1(d_0, d_1; k_1), \ldots, X_n(d_{n-1}, d_n; k_n) \) to the matrix equation \( X_1 \ldots X_n = B \), where \( B = B(d_0, d_n; \beta) \), is given in [9] by the
following three formulae:

\[ T_1(d_0, d_1; k_1, \beta) = \begin{cases} 
0 & \text{if } k_1 \neq \beta, \\
1 & \text{if } k_1 = \beta,
\end{cases} \]

\[ T_2(d_0, d_1, d_2; k_1, k_2, \beta) = K(d_0, d_1, k_1, \beta)L(d_1, d_2; k_1, \beta, k_2), \quad (2.6) \]

\[ T_n(d_0, \ldots, d_n; k_1, \ldots, k_n, \beta) = \sum_{i_1=\beta}^{r_1} \sum_{i_2=\beta}^{r_2} \cdots \sum_{i_n=\beta}^{r_n} T_2(d_0, d_1, k_1, \beta, k_2) \times \]

\[ \times \prod_{m=3}^{n} K(d_0, d_{m-1}, i_m, i_{m+1})L(d_{m-1}, d_m, i_m, i_{m+1}, k_m), \]

where \( n \geq 3, r_j = \min(k_1, \ldots, k_{j-1}) \) for \( j = 3, \ldots, n \) and \( i_n+1 = \beta \).

3. THE MAIN RESULT.

THEOREM 1. If \( A = A(s, m; \rho) \), then the number of solutions \( X_1(m, t; k_1) \), \( X_2(s, t; k_2) \), for \( \rho, k_1 \geq k_2 \), to the matric equation

\[ AX_1 = X_2, \quad (3.1) \]

is given by \( N(m, t; \rho, k_1, k_2) = g(\rho, t; k_2)L(m, t; \rho, k_2, k_1) \), where \( g(\rho, t; k_2) \) is evaluated using (2.1) and \( L(m, t; \rho, k_2, k_1) \) is evaluated using (2.3).

PROOF: Let \( P, Q \) be nonsingular matrices such that \( PAQ = I(s, m; \rho) \). Then (3.1) can be rewritten as

\[ I(s, m; \rho)Q^{-1}X_1 = PX_2. \quad (3.2) \]
The left hand side of (3.2) is of the form \( \text{col}[Y,0] \) where \( Y = Y(\rho,t) \). For a particular \( X_2(s,t;k_2) \), there will be matrices \( X_1(m,t;k_1) \) which satisfy (3.2), and therefore (3.1), provided \( X_2 \) is the product of \( P^{-1} \) and a matrix of the form \( \text{col}[Y,0] \) where \( Y = Y(\rho,t;k_2) \). Since \( P^{-1} \) is nonsingular there are the same number of matrices \( X_2 \) with this property as there are \( \rho \times t \) matrices of rank \( k_2 \). The number of \( \rho \times t \) matrices of rank \( k_2 \) is given by Landsberg's formula (2.1) and denoted by \( g(\rho,t;k_2) \). For each such \( X_2 \) the number of \( X_1 \) such that \( X_1, X_2 \) satisfy (3.1) can be represented by \( L(m,t;\rho,k_2,k_1) \) as given by (2.3). Therefore the number of solutions \( X_1, X_2 \) to (3.1) is given by \( g(\rho,t;k_2)L(m,t;\rho,k_2,k_1) \), and the theorem is proved.

It should be noted that Theorem 1 is a special case of a theorem of Hodges [3]. However, our proof, and so the form of the resulting formula, is quite different since Hodges uses exponential sums in his proof and we do not. Our proof of Theorem 1 is consistent with the methods of proof used in the rest of this paper.

**Theorem 2.** Let \( A = A(s,m;\rho) = \text{col}[A_1,A_2] \) where \( A_1 = A_1(n,m;\alpha_1) \) and \( A_2 = A_2(s-n,m;\alpha_2) \) with \( n \leq s \). Let \( P,Q \) be nonsingular matrices such that \( PA_2Q = I(s-n,m;\alpha_2) \) and \( A_1Q = [B_1,B_2] \) where \( B_2 = B_2(n,m-\alpha_2;\beta) \). Then the number of solutions \( X_1(m,t;k_1), X_2(n,t;k_2) \) to the matrix equation
for $a_1 > k_2$ is given by
\[ N(m - a_2, t; \beta, k_1, k_2) = g(\beta, t; k_2) L(m - a_2, t; \beta, k_2, k_1), \]
where $g(\beta, t; k_2)$ is given by (2.1) and $L(m - a_2, t; \beta, k_2, k_1)$ is given by (2.3).

PROOF: For $A_1, A_2$ defined as above we can write (3.3) as the system of equations
\[ A_1 X_1 = X_2, \quad (3.4) \]
\[ A_2 X_1 = 0. \quad (3.5) \]
Substituting $A_2 = P^{-1}(s - n, m; a_2)Q^{-1}$ into (3.5) and multiplying on the left by $P$ we obtain
\[ I(s - n, m; a_2)Q^{-1}X_1 = 0. \quad (3.6) \]
Let $Q^{-1}X_1 = \text{col}[Y_1, Y_2]$, where $Y_1 = Y_1(\alpha, t)$ and $Y_2 = Y_2(m - \alpha, t)$. Replacing $Q^{-1}X_1$ in (3.6) by $\text{col}[Y_1, Y_2]$, we have that necessary and sufficient conditions for $X_1$ to be a solution of (3.6) are that $Y_1 = 0$, rank $Y_2 = k_1$ and $X_1 = Q\text{col}[0, Y_2]$. Using this formulation for $X_1$ in (3.4) gives
\[ A_1 Q \begin{bmatrix} 0 \\ Y_2 \end{bmatrix} = X_2. \quad (3.7) \]
Let $A_1 Q = [B_1, B_2]$, where $B_1(n, \alpha)$ and $B_2(n, m - \alpha, \beta)$ in (3.7) we then obtain
By Theorem 1 there are \( N(m - \alpha_2, t; \beta, k_1, k_2) \) pairs \( Y_2, X_2 \) which satisfy (3.8). Since \( Q \) is nonsingular there are the same number of pairs \( X_1, X_2 \) which satisfy (3.3).

Equations (3.4) and (3.5) represent a special system of two simultaneous equations in the two matrices \( X_1, X_2 \). Very few results seem to exist for such systems. The authors are unable to find the number of solutions to the general system of two simultaneous equations in \( X_1, X_2 \). Such information would allow us to enumerate the ranked solutions to \( A_1 X_1 + A_2 X_2 = B \).

**THEOREM 3.** Let \( A_1 = A_1(s, m; r_1) \) and \( A_2 = A_2(s, n; r_2) \). Let \( P_1, Q_1 \) be nonsingular matrices such that \( P_1 A_1 Q_1 \) \( l(s, m; r_1) \). Define \( P_1 \) \( A_2 = \text{col} [A_{21}, A_{22}], \) where \( A_{21} = A_{21}(r, n; a_1) \) and \( A_{22} = A_{22}(s - r_1, n; a_2) \). Let \( P_2, Q_2 \) be nonsingular matrices such that \( P_2 A_2 Q_2 \) \( l(s - r_1, n; a_2) \). Define \( A_{21} Q_2 = [B_1, B_2] \), where \( B_2 = B_2(r_1, n - \alpha_2; \beta) \). Then the number of solutions \( X_1(m, t; k_1), X_2(n, t; k_2) \) to the matrix equation

\[
A_1 X_1 = A_2 X_2 ,
\]

is given by

\[
N(m, n, t; r_1, r_2, k_1, k_2, \alpha_1, \alpha_2, \beta) \min(\alpha_1, k_1)
= \sum_{k_{11}=0}^\infty G(m, t, r_1; k_1, k_{11}) g(\beta, t; k_{11}) L(n - \alpha_2, t; \beta, k_{11}, k_2),
\]

where \( G(m, t, r_1; k_1, k_{11}) \) can be evaluated using (2.2), \( g(\beta, t; k_{11}) \) is given by (2.1), and \( L(n - \alpha_2, t; \beta, k_{11}, k_2) \) is given by (2.3).

**PROOF:** The number of solutions to (3.9) is the same as the number of solutions to

\[
I(s, m; r_1) X_1 = P_1 A_2 X_2 .
\]

(3.10)
Letting $X_1 = \text{col}[X_{11}, X_{12}]$, $X_{11} = X_{11}(r_1, t; k_{11})$, $X_{12} = X_{12}(m - r_1, t; k_{12})$ and $A = P_1A_2$, (3.10) becomes

$$AX_2 = \begin{bmatrix} X_{11} \\ 0 \end{bmatrix}.$$  \hfill (3.11)

Theorem 2 gives the number of pairs $X_{11}, X_2$ that satisfy (3.11). For each $X_{11}(r_1, t; k_{11})$ the number of $X_{12}(m - r_1, t; k_{12})$ such that $X_i(m, t; k_1) = \text{col}[X_{11}, X_{12}]$ is given by (2.2), denoted by $G(m, t, r_1, k_1, k_{11})$. Therefore the number of solutions $X_1, X_2$ to (3.9) is given by the product $G(m, t, r_1, k_1, k_{11})G(s, t, k_{11})L(n - a_2, t; \beta, k_{11}, k_2)$ summed over the possible values of $k_{11}$ where $k_{11} \leq a_1$ by the hypothesis of Theorem 2.

4. SOME APPLICATIONS.

We can now use Theorem 3 together with some other known results to find the number of solutions $X_1, \ldots, X_n, Y_1, \ldots, Y_m$ to (1.2) in both the unranked and unranked cases.

THEOREM 4. Let $A_1 = A_1(m, s_0; r_1)$ and $A_2 = A_2(m, t; r_2)$. Let $P_1Q_1$ be non-singular matrices such that $P_1A_1Q_1 = I(m, s_0; r_1)$. Define $P_1A_2 = \text{col}[A_{21}, A_{22}]$, where $A_{21} = A_{21}(r_1, t_0; a_1)$ and $A_{22} = A_{22}(m - r_1, t_0; a_2)$. Let $P_2Q_2$ be non-singular matrices such that $P_2A_{22}Q_2 = I(m - r_1, t_0; a_2)$. Define $A_{21}Q_2 = [B_1, B_2]$, where $B_2 = B_2(r_1, t_0 - a_2; \beta)$. Then the number of solutions $X_1(s_0, s_1), \ldots, X_n(s_{n-1}, s_n), Y_1(t_0, t_1), \ldots, Y_m(t_{m-1}, t_m), m, n \geq 1, s_n = t_m$ to (1.2) is given by

$$\min(s_0, \ldots, s_n) \min(t_0, \ldots, t_m) \prod_{i_1=0}^{\min(s_0, \ldots, s_n)} \prod_{i_2=0}^{\min(t_0, \ldots, t_m)} N(s_0, t_0, s_n, r_1, r_2, i_1, i_2, a_1, a_2, \beta).$$
where \( N(s_0, t_o, s_n, r_1, r_2, i_1, i_2, \alpha_1, \alpha_2, \beta) \) can be evaluated using (3.9),

\[ M_n(s_0, \ldots, s_n, i_1) \quad \text{and} \quad M_m(t_o, \ldots, t_m, i_2) \]

can be evaluated using (2.5).

**PROOF:** Consider the equations

\[ A_1 U = A_2 V, \quad (4.1) \]
\[ U = X_1 \cdots X_n, \quad (4.2) \]
\[ V = Y_1 \cdots Y_m, \quad (4.3) \]

where \( U = U(s_o, s_n; i_1), \quad V = V(t_o, t_m; i_2), \quad 0 \leq i_1 \leq \min(s_o, \ldots, s_n) \) and

\[ 0 \leq i_2 \leq \min(t_o, \ldots, t_m). \]

The number of solutions \( U, V \) to (4.1) is given by (3.9) and is represented by \( N(s_o, t_o, s_n, r_1, r_2, i_1, i_2, \alpha_1, \alpha_2, \beta) \). The numbers \( M_n(s_0, \ldots, s_n, i_1) \) and \( M_m(t_o, \ldots, t_m, i_2) \) represent the number of solutions to (4.2) and (4.3), respectively, for a fixed \( U \) or \( V \). \( M_n \) and \( M_m \) can be evaluated using (2.5).

The product \( N \prod M_n \) summed over the possible ranks of \( U \) and \( V \) gives the number of solutions to (1.2) in the unranked case.

The next theorem is proved in the same way that Theorem 4 is proved except that we use (2.6) to obtain the number of ranked solutions \( X_1, \ldots, X_n, Y_1, \ldots, Y_m \) to the matrix equations (4.2) and (4.3).

**THEOREM 5.** Let \( A_1, A_2, P_1, P_2, Q_1, Q_2, A_{21}, A_{22}, B_1, B_2, B_{11}, B_{12}, \alpha_1, \alpha_2, \beta \) be as in Theorem 4. Then the number of solutions

\[ X_1(s_o, s_1; i_1), \ldots, X_n(s_n, s_{n-1}; i_n), Y_1(t_o, t_1; i_1), \ldots, Y_m(t_{m-1}, t_m; i_m), m, n \geq 1, \]
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\[ s_n = t_m \] to (1.2) is given by

\[
\sum_{i_1=0}^{\min(j_1, \ldots, j_n)} \sum_{i_2=0}^{\min(k_1, \ldots, k_m)} N(s_o, t_o, s_n; r_1, r_2, i_1, i_2, a_1, a_2, \beta) \cdot T_n(s_o, \ldots, s_n; j_1, \ldots, j_n, i_1) T_m(t_o, \ldots, t_m; k_1, \ldots, k_m, i_2),
\]

where \( N(s_o, t_o, s_n; r_1, r_2, i_1, i_2, a_1, a_2, \beta) \) is evaluated using (3.9) and

\( T_n(s_o, \ldots, s_n; j_1, \ldots, j_n, i_1) \) and \( T_m(t_o, \ldots, t_m; k_1, \ldots, k_m, i_2) \) are evaluated using (2.6).

NOTE: This paper was written while the second named author was on leave at the University of Wyoming.

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