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GAUTAMI BHOWMIK

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DIVISOR FUNCTIONS OF INTEGER MATRICES: EVALUATIONS, AVERAGE ORDERS AND APPLICATIONS

Gautami BHOWMIK*

Divisor functions have been extensively studied in classical number theory. We examine the corresponding functions for matrices over the ring of integers. These functions not only are a natural generalisation of historically important concepts, but their study also yields applications and some new interpretations.

We deal only with $r \times r$ nonsingular matrices with entries from the ring of integers. Since there are an infinite number of unimodular matrices, it is necessary to identify *canonical factorisations* of matrices. In his study of arithmetic of matrices, Nanda [8] defines them as follows:

DEFINITION 1. The decomposition of the matrix A as

$$A = A_1 A_2 \dots A_k, \quad (1)$$

where A_k, A_{k-1}, \dots, A_2 are matrices in nonsingular Hermite Normal Form (HNF), is said to be a k -order (canonical) factorisation of A .

Since an HNF matrix uniquely represents a class under one-sided equivalence, two factorisations defined as in (1) are *inequivalent*.

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DEFINITION 2. The function $\tau_k^{(r)}$ counts the number of k -order factorisations of an $r \times r$ matrix A , i.e.,

$$\tau_k^{(r)}(A) = \sum_{A=A_1 A_2 \dots A_k} 1. \quad (2)$$

When we restrict ourselves to the case $k = 2$, A_2 above is called a *divisor* of A . As in classical theory, we define the functions $\sigma_a^{(r)}$.

DEFINITION 3. For a non-negative integer a , let $\sigma_a^{(r)}(A)$ be the sum of the a^{th} powers of the determinants of divisors of a matrix A , i.e.,

$$\sigma_a^{(r)}(A) = \sum_{A=A_1 A_2} (\det A_2)^a. \quad (3)$$

We notice that $\tau_2^{(r)} = \sigma_0^{(r)}$.

Evaluations

For evaluating divisor functions, it is enough to consider A to be in non-singular Smith Normal Form (SNF) with prime-power determinant. We use the notation F_r for the matrix

$$(\text{diag } [p^{f_1}, p^{f_1+f_2}, \dots, p^{f_1+f_2+\dots+f_r}])$$

and may also denote it by $\langle f_1, f_2, \dots, f_r \rangle$, where $f_1 \geq 1$, $f_i \geq 0$ for $i > 1$, and p is a prime number. We write G_r for the matrix $\langle f_1, f_2, \dots, f_{r-1}, f_r - 1 \rangle$.

It is clear that the evaluation of $\sigma_a^{(r)}$ involves the solving of a system of diophantine equations with rather stringent side conditions and is therefore not easy.

In [4] we proved the result :

$$\tau_2(F_r) - \tau_2(G_r) = \sigma_1(F_{r-1}), \quad (4)$$

which helped us evaluate $\tau_2^{(2)}$ and $\tau_2^{(3)}$. Here we generalise (4) and prove a recurrence between $\sigma_a^{(r)}$ and $\sigma_{a+1}^{(r-1)}$. Thus it becomes possible to reduce the problem to evaluations on F_1 or on *prime matrices* $P_r = \langle 1, 0, \dots, 0 \rangle$. We prove:

THEOREM 1. $\sigma_a(F_r) - p^a \sigma_a(G_r) = \sigma_{a+1}(F_{r-1})$.

Proof. Let $\nu = f_1 + f_2 + \dots + f_r$. Now

$$F_r = \begin{pmatrix} A_{r-1} & 0 \\ Y & p^t \end{pmatrix} \begin{pmatrix} B_{r-1} & 0 \\ X & p^{\nu-t} \end{pmatrix}, \quad 0 \leq t \leq \nu \quad (5)$$

$$G_r = \begin{pmatrix} A_{r-1} & 0 \\ Y & p^t \end{pmatrix} \begin{pmatrix} B_{r-1} & 0 \\ X & p^{\nu-t-1} \end{pmatrix}, \quad 0 \leq t < \nu \quad (6)$$

are factorisations of F_r and G_r whenever B_{r-1} is a divisor of F_{r-1} and $YB_{r-1} + Xp^t = 0$. Then

$$\sigma_a(F_r) = \sum_{\substack{YB_{r-1} + Xp^t = 0 \\ 0 \leq t < \nu}} (\det B_{r-1})^a p^{(\nu-t)a} + \sum_{YB_{r-1} + Xp^\nu = 0} (\det B_{r-1})^a \quad (7)$$

and

$$\sigma_a(G_r) = \sum_{\substack{YB_{r-1} + Xp^t = 0 \\ 0 \leq t < \nu}} (\det B_{r-1})^a p^{(\nu-t-1)a} \quad (8)$$

Thus

$$\sigma_a(F_r) = p^a \sigma_a(G_r) + \sum_{YB_{r-1} + Xp^\nu = 0} (\det B_{r-1})^a. \quad (9)$$

But, as in the proof of (4), we can show that the equation $YB_{r-1} + Xp^\nu = 0$ has solutions for all possible choices of X by considering the cases where the matrix

$$\begin{pmatrix} B_{r-1}^{-1} F_{r-1} & 0 \\ -p^\nu X B_{r-1}^{-1} & p^\nu \end{pmatrix}$$

is integral. Since X can be chosen in $\det(B_{r-1})$ ways, we have:

$$\sigma_a(F_r) = p^a \sigma_a(G_r) + \sum_{B_{r-1} | F_{r-1}} (\det B_{r-1})^{a+1}.$$

□

It is easy to evaluate $\sigma_a(P_r)$ by generalising Nanda's result [7] for $a = 0$:

THEOREM 2. $\sigma_a(P_r) = \sum_{j=0}^r p^{aj} \begin{bmatrix} r \\ j \end{bmatrix}$, where $\begin{bmatrix} r \\ j \end{bmatrix}$ are the Gaussian polynomials in p .

Proof. Nanda [7] gives a combinatorial argument to show that the number of divisors of P_r with p occurring exactly j times on the diagonal is given by $\begin{bmatrix} r \\ j \end{bmatrix}$. The factor p^{aj} is obviously the a^{th} power of the determinant of the divisor. \square

The above theorems give us a method for evaluation, but the calculations involved are cumbersome, as the following example shows.

EXAMPLE.

$$\begin{aligned} \sigma_1(F_3) &= (p^{f_3} + p^{f_3-1} + \dots + 1)\sigma_2(F_2) \\ &+ p^{f_3+1}(p+1)(\sigma_2\langle f_1, f_2-1 \rangle + p^2\sigma_2\langle f_1, f_2-2 \rangle + \dots + p^{2f_2-2}\sigma_2\langle f_1, 0 \rangle) \\ &+ p^{f_3+2f_2+1}\sigma_2\langle f_1-1, 1 \rangle + p^{f_3+2f_2+2}(p+1)\sigma_2\langle f_1-1, 0 \rangle \\ &+ p^{f_3+2f_2+4}\sigma_2\langle f_1-2, 1 \rangle + p^{f_3+2f_2+5}(p+1)\sigma_2\langle f_1-2, 0 \rangle + \dots \\ &+ p^{f_3+2f_2+3f_1+2}(p+1)\sigma_2\langle 1, 0 \rangle + p^{f_3+2f_2+3f_1+4}\sigma_1\langle 1, 0 \rangle, \end{aligned}$$

where

$$\begin{aligned} \sigma_2(F_2) &= (p^{2f_2} + p^{2f_2-2} + \dots + 1)\sigma_3\langle f_1 \rangle + p^{2f_2+2}(p^2+1)\sigma_3\langle f_1-1 \rangle \\ &+ p^{2f_2+6}(p^2+1)\sigma_3\langle f_1-2 \rangle + \dots + p^{2f_2+4f_1-6}(p^2+1)\sigma_3\langle 1 \rangle \\ &+ p^{2f_2+4f_1-2}\sigma_2\langle 1 \rangle. \end{aligned}$$

Average orders

In [3] we evaluated $T(x) = \sum_{\det A \leq x} \tau_2^{(2)}(A)$, where A is in SNF. The absence of a zeta function does not allow satisfactory extension of this result.

Here we instead allow A to be in HNF and consider the following zeta function [5]:

$$Z_r(s) = \sum_{A \text{ in HNF, } r \times r} (\det A)^{-s} = \sum \alpha_r(n) n^{-s}, \quad s = \sigma + it, \quad \sigma > 1, \tag{10}$$

where $\alpha_r(n)$ is the HNF class-number, i.e., the number of $r \times r$ HNF matrices with determinant n .

Thus

$$Z_r(s) = \zeta(s)\zeta(s-1)\dots\zeta(s-r+1), \tag{11}$$

where $\zeta(s)$ is the Riemann zeta-function. $Z_r(s)$ is a holomorphic function with simple poles at $s = r, r-1, r-2$. It is, in fact, a special case of the Koecher zeta-function [10].

Authors (e.g. [9]) have evaluated $\alpha_r(n)$, and in [3] we obtained an average order for $\alpha_r(n)$ by using elementary methods.

Here we give a few asymptotic results for divisor functions obtained by using $Z_r(s)$ for

$$A_r(x) = \sum_{n \leq x} \alpha_r(n), \quad T_k(x) = \sum_{A \text{ in HNF, } \det A \leq x} \tau_k(A)$$

and $S_a^{(r)}(x) = \sum_{A \text{ in HNF, } \det A \leq x} \sigma_a^{(r)}(A)$. These are only first results. We should be able to prove sharper results in [5].

THEOREM 3.

$$A_r(x) = \frac{1}{r} L_r x^r - \frac{1}{2(r-1)} L_{r-1} x^{r-1} + o(x^{r-1}),$$

where $L_k = \prod_{j=2}^k \zeta(j)$.

Proof. From Perron's formula we have:

$$A_r(x) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \frac{Z_r(s) x^s}{s} ds.$$

The main terms can be obtained as residues at $s = r, r-1$. □

THEOREM 4. $T_k(x) \sim P_r(x)$,

where $P_r(x)$ is a polynomial in x of degree r .

Proof. Obvious. □

THEOREM 5.

$$S_a^{(r)}(x) = \frac{1}{a+r} L_r M_{a,0} x^{a+r} - \frac{1}{2(a+r-1)} L_{r-1} M_{a,1} x^{a+r-1} + o(x^{a+r-1}),$$

where

$$M_{b,t} = \prod_{j=1}^r \zeta(b+j-t).$$

Proof. Similar to that of Theorem 3. □

Restricted divisor functions

Here we consider factorisations on the subsets

(a) \mathcal{S}_r , of all $r \times r$ matrices in SNF, and

(b) \mathcal{D}_r of all $r \times r$ diagonal matrices,

and show their connection with average orders of functions of integers.

DEFINITION 4. The decompositions

$$\begin{aligned} S &= S_1 S_2 \dots S_k, & S, S_i &\in \mathcal{S}_r \\ \text{and } D &= D_1 D_2 \dots D_k, & D, D_i &\in \mathcal{D}_r \end{aligned}$$

are said to be k -order SNF (resp., *diagonal*) factorisations of S (resp., D).

In [3] we have defined the SNF zeta function

$$\widehat{Z}_r(s) = \sum \beta_r(n)/n^s = \zeta(s)\zeta(2s) \dots \zeta(rs) \tag{12}$$

and proved :

THEOREM 6.

$$\begin{aligned} \sum_{\substack{S \in \mathcal{S}_r \\ \det S \leq x}} \widehat{\sigma}_a(r)(S) &= \frac{1}{a+1} L_r^{(1)} K_1 x^{a+1} + \frac{1}{a+\frac{1}{2}} L_r^{(1/2)} K_2 x^{a+\frac{1}{2}} \\ &+ \frac{1}{a+\frac{1}{3}} L_r^{(1/3)} K_3 x^{a+\frac{1}{3}} + O(x^{a+\varepsilon}). \end{aligned}$$

where ε is the best known exponent in the error of the three-dimensional divisor problem, and the constants are defined as

$$L_r^{(i)} = \prod_{\substack{j=1 \\ j \neq i}}^r \zeta(ji), \quad K_i = \prod_{j=1}^r \zeta(j(a+i)).$$

We can similarly define the *diagonal zeta function* as

$$Z_{\mathcal{D}}(s) = \sum_{D \in \mathcal{D}_r} (\det D)^{-s} = \zeta^r(s) \tag{13}$$

and obtain the average order $B_a^{(r)}(x)$ for diagonal divisor functions. For example, when $a = r = 2$, we get

THEOREM 7.

$$B_2^{(2)} = \frac{1}{6}x \log^3 x + (2\gamma - \frac{1}{2})x \log^2 x + (6\gamma^2 - 4\gamma + 4\gamma_1 + 1)x \log x \\ + (-1 + 4(\gamma - \gamma_1 + \gamma_2) - 6\gamma^2 + 4\gamma^3 + 12\gamma\gamma_1)x + O(x^{1/2})$$

where the γ 's are constants.

Proof. We use the classical estimate for $\zeta^4(s)$. □

Applications

We can interpret some of the above results in different contexts. We give a few illustrations:

a) We consider the set $\Gamma = \text{GL}(r, \mathbb{Z})$ of all $r \times r$ integer unimodular matrices as the unimodular group of degree r over the ring of integers [6]. The divisor functions of matrices then appear in the formal power series over the *Hecke algebra*, which is a polynomial ring over \mathbb{Z} in infinitely many independent indeterminates. Thus, formally,

$$\sum \Gamma A \Gamma (\det A)^{-s} \sum \Gamma A \Gamma (\det A)^{a-s} = \sum \Gamma A \Gamma \sigma_a(A) (\det A)^{-s}, \tag{14}$$

where $A \in \mathcal{S}_r$.

b) We consider Ramanujan's classical formula

$$\frac{\zeta(s)\zeta(s-a)\zeta(s-b)\zeta(s-a-b)}{(2s-a-b)} = \sum_{n=1}^{\infty} \frac{\sigma_a(n)\sigma_b(n)}{n^s}$$

for the case $a = 1, b = 2$, to get

$$Z_4(s) = \zeta(2s - 3) \sum_{n=1}^{\infty} \sigma_1(n)\sigma_2(n)/n^s. \tag{15}$$

c) We can evaluate $\sigma_a(P_r)$ in terms of two different *partition functions*. We can show that to get the number of divisors of P_r , we may look at the number of $\underline{0}$'s to the right of each $\underline{1}$ in every string of length r with entries from $\{0, 1\}$. This can be expressed in terms of the function $\hat{q}(n, k, r)$, which counts the number of partitions of n into at most k parts (not necessarily distinct) each at most r , i.e.,

$$\sigma_a(P_r) = \sum \sum q(n - ka, k, r - k)p^n. \tag{16}$$

This, we note, agrees with Theorem 2 via Sylvester's generating function for $\hat{\sigma}$ (see, e.g. Andrews [1]). We can also evaluate $\sigma_a(P_r)$ using the function $q(n, k, r)$ which counts the number of partitions of n into exactly k distinct parts. In [2] we have shown that the number of divisors of P_r that are equivalent to P_k , $k \leq r$, is given by

$$\pi_{k,r} = \sum_{n=\frac{k(k+1)}{2}}^{kr - \frac{k(k-1)}{2}} q(n, k, r) p^{kr - \frac{k(k-1)}{2} - n}. \tag{17}$$

Thus we get

$$\sigma_a(P_r) = \sum \sum q(kr - \frac{k(k-1)}{2} - n - ak, k, r) p^n. \tag{18}$$

We see that there is no contradiction between these two results, for we can independently show that

$$\hat{q}(n, k, r - k) = q(kr - \frac{k(k-1)}{2} - n, k, r) \tag{19}$$

by writing n as a sum of parts n_1, n_2, \dots, n_k ; $r - k \geq n_i \geq n_{i+j} \geq 0$ and replacing n_i by $m_i = r - n_i - i + 1$.

As in [2], it is possible to obtain *polynomial* and *partition identities* from these results.

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Gautami Bhowmik
Jesus & Mary College
New Delhi – 110 021
India