

## An Identity of Jack Polynomials

José A. Díaz-García<sup>1</sup>, Ramón Gutiérrez-Jáimez<sup>2</sup>

<sup>1</sup> Department of Statistics and Computation, Universidad Autónoma Agraria Antonio Narro, Mexico.

<sup>2</sup> Department of Statistics and O.R., University of Granada, Spain.

**Abstract.** In this work we give an alternative proof of one of basic properties of zonal polynomials and generalised it for Jack polynomials.

**Keywords.** Generalised hypergeometric functions; Jack polynomials; real, complex, quaternion and octonion random matrices.

**MSC:** Primary 43A90, 33C20; Secondary 15A52

### 1 Introduction

Many results in multivariate distribution theory have been proved using zonal and invariant polynomials. Moreover, these results, in their final version, have been derived in a very compact form, using hypergeometric functions with one or two matrix arguments. We refer the reader to Constantine (1963), James (1964), Davis (1979), Davis (1980) and Muirhead (1982), among many others.

Many such results obtained for the real line have also been studied in the complex, quaternion and octonion spaces (James (1964), Li and Xue (2009) and Forrester (2009)). However, although several properties of real and complex zonal polynomials have been extended to the quaternion and octonion spaces, many still remain to be studied.

In this paper, we are interested in the basic property of real zonal polynomials, examined in James (1961b, Theorem 5, eq. (27)) (see also

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José A. Díaz-García (✉) (jadiaz@uaaaan.mx),  
Ramón Gutiérrez-Jáimez (rgjaimez@ugr.es)

Received: December 7, 2011; Accepted: January 9, 2012

James (1964, eq. (22))), and proved by James (1961b), in terms of group representation theory. This property plays a fundamental role in the study of matrix multivariate elliptical distributions and, in particular, noncentral matrix multivariate distributions, such as the generalised noncentral Wishart and beta distributions, as well as generalised shape theory, (see Díaz-García and González-Farías (2005), Díaz-García and Gutiérrez-Jáimez (2006) and Caro-Lopera *et al.* (2009)).

In Section 2 of this paper, we give an alternative proof of one of the basic properties of zonal polynomials established by James (1961b, Theorem 5, eq. (27)) (see also James (1964, eq. (22))). This proof is given in terms of the results in Herz (1955) and Constantine (1963), and this property is generalised to real normed division algebras.

## 2 Main result

A detailed discussion of real normed division algebras may be found in Baez (2002) and Gross and Richards (1987), and that of Jack polynomials and hypergeometric functions, in Sawyer (1997), Gross and Richards (1987) and Koev and Edelman (2006). We shall introduce some new notation for convenience, although in general we adhere to the standard notation.

There are exactly four real finite-dimensional normed division algebras: the real numbers, the complex numbers, quaternions and octonions, generically denoted by  $\mathfrak{F}$ , see Baez (2002). All division algebras have a real dimension (denoted by  $\beta$ ) of 1, 2, 4 or 8, respectively, (see Baez (2002, Theorems 1, 2 and 3)).

$\mathcal{L}_{m,n}^\beta$  shall denote the linear space of all  $n \times m$  matrices of rank  $m \leq n$  over  $\mathfrak{F}$  with  $m$  distinct positive singular values, where  $\mathfrak{F}$  is a *real finite-dimensional normed division algebra*. If  $\mathbf{A} \in \mathfrak{F}^{n \times m}$  where  $\mathfrak{F}^{n \times m}$  be the set of all  $n \times m$  matrices over  $\mathfrak{F}$ , then  $\mathbf{A}^* = \overline{\mathbf{A}}^T$  shall denote the usual conjugate transpose.

The set of matrices  $\mathbf{H}_1 \in \mathfrak{F}^{n \times m}$  such that  $\mathbf{H}_1^* \mathbf{H}_1 = \mathbf{I}_m$ , is a manifold denoted by  $\mathcal{V}_{m,n}^\beta$  and termed the *Stiefel manifold*. In particular,  $\mathcal{V}_{m,m}^\beta$ , is the maximal compact subgroup  $\mathfrak{U}^\beta(m)$  of  $\mathcal{L}_{m,m}^\beta$  and consists of all matrices  $\mathbf{H} \in \mathfrak{F}^{m \times m}$  such that  $\mathbf{H}^* \mathbf{H} = \mathbf{I}_m$ . If  $\mathbf{H}_1 \in \mathcal{V}_{m,n}^\beta$  then

$$(\mathbf{H}_1^* d\mathbf{H}_1) = \bigwedge_{i=1}^m \bigwedge_{j=i+1}^n \mathbf{h}_j^* d\mathbf{h}_i.$$

where  $\mathbf{H} = (\mathbf{H}_1|\mathbf{H}_2) = (\mathbf{h}_1, \dots, \mathbf{h}_m|\mathbf{h}_{m+1}, \dots, \mathbf{h}_n) \in \mathcal{U}^\beta(m)$ . The surface area or volume of the Stiefel manifold  $\mathcal{V}_{m,n}^\beta$  is given by

$$\text{Vol}(\mathcal{V}_{m,n}^\beta) = \int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^\beta} (\mathbf{H}_1^* d\mathbf{H}_1) = \frac{2^m \pi^{mn\beta/2}}{\Gamma_m^\beta[n\beta/2]}, \tag{1}$$

where  $\Gamma_m^\beta[a]$  denotes the multivariate gamma function for the space of Hermitian matrices (see Gross and Richards (1987)).

Let  $C_\kappa^\beta(\mathbf{B})$  be the Jack polynomials of  $\mathbf{B} = \mathbf{B}^*$ , corresponding to the partition  $\kappa = (k_1, \dots, k_m)$  of  $k$ ,  $k_1 \geq \dots \geq k_m \geq 0$  with  $\sum_{i=1}^m k_i = k$ , see Sawyer (1997) and Koev and Edelman (2006). Moreover,

$${}_pF_q^\beta(a_1, \dots, a_p; b_1, \dots, b_q; \mathbf{B}) = \sum_{k=0}^\infty \sum_{\kappa} \frac{[a_1]_\kappa^\beta, \dots, [a_p]_\kappa^\beta}{[b_1]_\kappa^\beta, \dots, [b_p]_\kappa^\beta} \frac{C_\kappa^\beta(\mathbf{B})}{k!},$$

defines the hypergeometric function with one matrix argument on the space of Hermitian matrices, where  $[a]_\kappa^\beta$  denotes the generalised Pochhammer symbol of weight  $\kappa$ , defined as

$$[a]_\kappa^\beta = \prod_{i=1}^m (a - (i-1)\beta/2)_{k_i}$$

where  $\Re(a) > (m-1)\beta/2 - k_m$  and  $(a)_i = a(a+1)\dots(a+i-1)$  (see Gross and Richards (1987), Koev and Edelman (2006) and Díaz-García (2009)).

We first clarify an apparent discrepancy between the results obtained by the different approaches. From Muirhead (1982, Lemma 9.5.3, p. 397), it is easy to see that equality (3.5'), proved by Herz (1955, p. 494) using Laplace transform, and equality (27) in James (1964), proved using group representation theory (James (1961b, Theorem 5)), coincide. We have the following lemma (James (1961b, eq. (27)), James (1964, eq. (22))).

**Lemma 2.1.** *If  $\mathbf{X} \in \mathcal{L}_{n,m}^1$ , then*

$$\int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^1} (\text{tr}(\mathbf{X}\mathbf{H}_1))^{2k} (d\mathbf{H}_1) = \sum_{\kappa} \frac{(\frac{1}{2})_k}{[n/2]_\kappa^1} C_\kappa^1(\mathbf{X}\mathbf{X}^*). \tag{2}$$

*Proof.* From Herz (1955, eq. (3.5')), p. 494), expanding in a series of powers

$$\begin{aligned} {}_0F_1^1(n/2, \mathbf{X}\mathbf{X}^*/4) &= \int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^1} \text{etr}\{\mathbf{X}\mathbf{H}_1\} (d\mathbf{H}_1) \\ &= \sum_{k=0}^\infty \frac{1}{k!} \int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^1} (\text{tr}(\mathbf{X}\mathbf{H}_1))^k (d\mathbf{H}_1), \end{aligned}$$

where  $\text{etr}(\cdot) \equiv \exp(\text{tr}(\cdot))$ .

We recall that if one or more parts  $k_1, \dots, k_m$  of partition  $k$  is odd, then

$$\int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^1} (\text{tr}(\mathbf{X}\mathbf{H}_1))^k (d\mathbf{H}_1) = 0,$$

(James (1961a) and James (1964)). Therefore

$${}_0F_1^1(n/2, \mathbf{X}\mathbf{X}^*/4) = \sum_{k=0}^{\infty} \frac{1}{(2k)!} \int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^1} (\text{tr}(\mathbf{X}\mathbf{H}_1))^{2k} (d\mathbf{H}_1). \quad (3)$$

Now, by the definition of hypergeometric functions with one matrix argument in terms of zonal polynomials, we have (see Constantine (1963)),

$${}_0F_1^1(n/2, \mathbf{X}\mathbf{X}^*/4) = \sum_{k=0}^{\infty} \sum_{\kappa} \frac{1}{[n/2]_{\kappa}^1} \frac{C_{\kappa}^1(\mathbf{X}\mathbf{X}^*/4)}{k!}. \quad (4)$$

Hence comparing the two series on the right term-by-term, we obtain

$$\sum_{\kappa} \frac{1}{[n/2]_{\kappa}^1} \frac{C_{\kappa}^1(\mathbf{X}\mathbf{X}^*/4)}{k!} = \frac{1}{(2k)!} \int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^1} (\text{tr}(\mathbf{X}\mathbf{H}_1))^{2k} (d\mathbf{H}_1).$$

Finally, we note that  $4^k(1/2)_k/(2k)! = 1/k!$  and  $C_{\kappa}^1(a\mathbf{B}) = a^k C_{\kappa}^1(\mathbf{B})$  thus proving the lemma.  $\square$

Takemura (1984, Lemma 1, p. 40) gave a different proof of Property (2) for real case. With our approach, this property is easily extended to Jack polynomials in real normed division algebras.

**Theorem 2.1.** *Let  $\mathbf{X} \in \mathcal{L}_{n,m}^{\beta}$ , then*

$$\int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^{\beta}} (\text{tr}(\mathbf{X}\mathbf{H}_1))^{2k} (d\mathbf{H}_1) = \sum_{\kappa} \frac{(\frac{1}{2})_k}{[\beta n/2]_{\kappa}^{\beta}} C_{\kappa}^{\beta}(\mathbf{X}\mathbf{X}^*). \quad (5)$$

*Proof.* Observe that by Gross and Richards (1987) and Koev and Edelman (2006),

$${}_0F_1^{\beta}(\beta n/2, \mathbf{X}\mathbf{X}^*/4) = \sum_{k=0}^{\infty} \sum_{\kappa} \frac{1}{[\beta n/2]_{\kappa}^{\beta}} \frac{C_{\kappa}^{\beta}(\mathbf{X}\mathbf{X}^*/4)}{k!},$$

and by Díaz-García (2009),

$${}_0F_1^{\beta}(\beta n/2, \mathbf{X}\mathbf{X}^*/4) = \int_{\mathbf{H}_1 \in \mathcal{V}_{m,n}^{\beta}} \text{etr}\{\mathbf{X}\mathbf{H}_1\} (d\mathbf{H}_1).$$

This equality was found by James (1964), for the complex case, and by Li and Xue (2009), for the quaternion. The rest of the proof is similar to that of Lemma 2.1.  $\square$

## Acknowledgements

The authors wish to thank the Associate Editor and the anonymous reviewers for their constructive comments on the preliminary version of this paper. This work was partially supported by IDI-Spain, Grants No. FQM2006-2271 and MTM2008-05785. This paper was written during J. A. Díaz-García's stay as a visiting professor at the Department of Statistics and O. R. of the University of Granada, Spain.

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