SOME RECURRENCE FORMULAE FOR G-FUNCTION OF TWO VARIABLES—II

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The object of this paper is to establish more recurrence relations for G-function of two variables. Certain known results for Meijer's G-function have been shown as particular cases.

Some identities and recurrence relations were recently given by the author as particular cases of finite series[1] by using the derivatives of G-function of two variables[2,3]. The symbol (k, δ) represents the set of parameters $k/\delta, (k+1)/\delta, \ldots, (k+\delta-1)/\delta$, where δ is a positive integer and (a_p) stands for $a_1, a_2, \ldots, a_p$ throughout this paper.

The G-function of two variables defined by Agarwal[4] and Sharma[5] has been denoted by Bajpai[6] as

$$G^{(m_1, m_2); (n_1, n_2), n_3}_{(p_1, p_2), p_3; (q_1, q_2), q_3}\left[\begin{matrix} x \\ \\ y \\ \end{matrix}\;\middle|\;\begin{matrix} (a_{p_1}); (c_{p_2}) \\ (e_{p_3}) \\ (b_{q_1}); (d_{q_2}) \\ (f_{q_3}) \end{matrix}\right] =$$

$$= \frac{1}{(2\pi i)^2} \int_{L_1}\int_{L_2} \frac{\prod_{j=1}^{m_1}\Gamma(b_j-s)\prod_{j=1}^{n_1}\Gamma(1-a_j+s)\prod_{j=1}^{m_2}\Gamma(d_j-t)\prod_{j=1}^{n_2}\Gamma(1-c_j+t)\prod_{j=1}^{n_3}\Gamma(1-e_j+s+t)}{\prod_{j=m_1+1}^{q_1}\Gamma(1-b_j+s)\prod_{j=n_1+1}^{p_1}\Gamma(a_j-s)\prod_{j=m_2+1}^{q_2}\Gamma(1-d_j+t)\prod_{j=n_2+1}^{p_2}\Gamma(c_j-t)}.$$

$$\cdot \frac{x^s\, y^t}{\prod_{j=n_3+1}^{p_3}\Gamma(e_j-s-t)\prod_{j=1}^{q_3}\Gamma(1-f_j+s+t)}\, ds\, dt. \tag{1}$$

The contour L_1 is in the s-plane and runs from $-i\infty$ to $+i\infty$ with loops if necessary, to ensure that the poles of $\Gamma(b_j-s), j = 1, 2, \ldots, m_1$ lie on the right and the poles of $\Gamma(1-a_j+s)$, $j = 1, 2, \ldots, n_1$ and $\Gamma(1-e_j+s+t), j=1, 2, \ldots, n_3$ to the left of the contour. Similarly the contour L_2 is in the t-plane and runs from $-i\infty$ to $+i\infty$ with loops if necessary, to ensure that the poles of $\Gamma(d_j-t), j=1, 2, \ldots, m_2$ lie on the right and the poles of $\Gamma(1-c_j+t), j=1, 2, \ldots, n_2$ and $\Gamma(1-e_j+s+t), j=1,2, \ldots, n_3$ on the left of the contour.

Provided that

$$0 \leqslant m_1 \leqslant q_1,\; 0 \leqslant m_2 \leqslant q_2,\; 0 \leqslant n_1 \leqslant p_1,\; 0 \leqslant n_2 \leqslant p_2,\; 0 \leqslant n_3 \leqslant p_3;$$

the integral converges if

$$(p_3+q_3+p_1+q_1) < 2\,(m_1+n_1+n_3);\ (p_3+q_3+p_2+q_2) < 2\,(m_2+n_2+n_3)$$
$$|\arg x| < [m_1+n_1+n_3-\tfrac{1}{2}(p_3+q_3+p_1+q_1)]\,\pi,$$
$$|\arg y| < [m_2+n_2+n_3-\tfrac{1}{2}(p_3+q_3+p_2+q_2)]\,\pi.$$

The right hand side of (1) shall henceforth be denoted by $G\begin{bmatrix} x \\ y \end{bmatrix}$, whenever there is no chance of misunderstanding, and is the required G-function of two variables.

We establish the following identities :

If one value of a_h, $h=1, 2, \ldots, n_1$ is equal to one value of b_j, $j=m_1+1, \ldots, q_1$; one value of c_h, $h=1, 2, \ldots, n_2$ is equal to one value of d_j, $j=m_2+1, \ldots, q_2$ and one value of e_h, $h=1, 2, \ldots, n_3$ is equal to one value of f_j, $j=1, 2, \ldots, q_3$, the G-function of two variables reduces to one of lower order. For example

$$G\left[\begin{array}{c|l} x & (a_{p_1});\ (c_{p_2}) \\ & (e_{p_3}) \\ y & b_1, b_2, \ldots, b_{q_1-1}, a_1;\ (d_{q_2}) \\ & (f_{q_3}) \end{array}\right] =$$

$$= G^{(m_1, m_2);\ (n_1-1,\ n_2),\ n_3}_{(p_1-1,\ p_2),\ p_3\ ;\ (q_1-1,\ q_2)\ q_3}\left[\begin{array}{c|l} x & a_2, \ldots, a_{p_1};\ (c_{p_2}) \\ & (e_{p_3}) \\ y & b_1, \ldots, b_{q_1-1}\ (d_{q_2}) \\ & (f_{q_3}) \end{array}\right] \tag{2}$$

$$G\left[\begin{array}{c|l} x & (a_{p_1});\ (c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1});\ d_1, \ldots, d_{q_2-1}, c_1 \\ & (f_{q_3}) \end{array}\right] = G^{(m_1, m_2)\ ;\ (n_1,\ n_2-1),\ n_3}_{(p_1, p_2-1),\ p_3;(q_1,\ q_2-1),\ q_3}\left[\begin{array}{c|l} x & (a_{p_1});\ c_2, \ldots, c_{p_2} \\ & (e_{p_3}) \\ y & (b_{q_1});\ d_1, \ldots, d_{q_2}-1 \\ & (f_{q_3}) \end{array}\right] \tag{3}$$

$$G\left[\begin{array}{c|l} x & (a_{p_1});\ (c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1});\ (d_{q_2}) \\ & e_1, f_2, f_3, \ldots, f_{q_3} \end{array}\right] = G^{(m_1, m_2);\ (n_1,\ n_2),\ n_3-1}_{(p_1, p_2),\ p_3-1;\ (q_1,\ q_2),\ q_3-1}\left[\begin{array}{c|l} x & (a_{p_2});\ (c_{p_2}) \\ & e_2, \ldots, e_{p_3} \\ y & (b_{q_1});\ (d_{q_2}) \\ & f_2, \ldots, f_{q_3} \end{array}\right] \tag{4}$$

$$G\left[\begin{array}{c|l} x & (a_{p_1});\ (c_{p_2}) \\ & (e_{p_3}) \\ y & b_1, \ldots, b_{q_1-1}, a_1;\ d_1, \ldots, d_{q_2-1},\ c_1 \\ & e_1, f_2, f_3, \ldots, f_{q_3} \end{array}\right] =$$

$$= G^{(m_1, m_2);\ (n_1-1,\ n_2-1),\ n_3-1}_{(p_1-1, p_2-1),\ p_3-1;\ (q_1-1,\ q_2-1),\ q_3-1}\left[\begin{array}{c|l} x & a_2, \ldots, a_{p_1};\ c_2, \ldots, c_{p_2} \\ & e_2, \ldots, e_{p_3} \\ y & b_1, \ldots, b_{q_1-1};\ d_1, \ldots, d_{q_2-1} \\ & f_2, \ldots, f_{q_3} \end{array}\right] \tag{5}$$

Also, if one value of a_h, $h=n_1+1, \ldots, p_1$ is equal to one value of b_j, $j=1, 2, \ldots, m_1$; one value of c_h, $h=n_2+1, \ldots, p_2$ is equal to one value of $d_j, j=1, 2, \ldots, m_2$, then the G-function of two variables reduces to one of a lower order. For example

$$G\begin{bmatrix} x & a_1,\ldots,a_{p_1-1}, b_1; (c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1}); (d_{q_2}) \\ & (f_{q_3}) \end{bmatrix} = G^{(m_1-1, m_2); (n_1, n_2), n_3}_{(p_1-1, p_2), p_3; (q_1-1, q_2), q_3}\begin{bmatrix} x & a_1,\ldots,a_{p_1-1}; (c_{p_2}) \\ & (e_{p_3}) \\ y & b_2,\ldots,b_{q_1}; (d_{q_2}) \\ & (f_{q_3}) \end{bmatrix} \quad (6)$$

$$G\begin{bmatrix} x & (a_{p_1}); c_1,\ldots,c_{p_2-1}, d_1 \\ & (e_{p_3}) \\ y & (b_{q_1}); (d_{q_2}) \\ & (f_{q_3}) \end{bmatrix} = G^{(m_1, m_2-1); (n_1, n_2), n_3}_{(p_1, p_2-1), p_3; (q_1, q_2-1), q_3}\begin{bmatrix} x & (a_{p_1}); c_1,\ldots,c_{p_2-1} \\ & (e_{p_3}) \\ y & (b_{q_1}); d_2,\ldots,d_{q_2} \\ & (f_{q_3}) \end{bmatrix} \quad (7)$$

$$G\begin{bmatrix} x & a_1,\ldots a_{p_1-1}, b_1; c_1,\ldots, c_{p_2-1}, d_1 \\ & (e_{p_3}) \\ y & (b_{q_1}); (d_{q_2}) \\ & (f_{q_3}) \end{bmatrix} =$$

$$= G^{(m_1-1, m_2-1); (n_1, n_2), n_3}_{(p_1-1, p_2-1), p_3; (q_1-1, q_2-1), q_3}\begin{bmatrix} x & a_1,\ldots, a_{p_1}-1; c_1,\ldots, c_{p_2-1} \\ & (e_{p_3}) \\ y & b_2,\ldots, b_{q_1}; d_2,\ldots, d_{q_2} \\ & (f_{q_3}) \end{bmatrix} \quad (8)$$

The proofs of the above-mentioned identities are very simple and are therefore omitted.

$$G\begin{bmatrix} x \\ \\ y \end{bmatrix} = (2\pi)^u k^v G^{(m_1 k, m_2 k); (n_1 k, n_2 k), n_3 k}_{(kp_1, kp_2), kp_3; (kq_1, kq_2), kq_3}\left[\begin{matrix} \dfrac{x^k}{(k)^{k(q_1+q_3-p_1-p_3)}} \\ \dfrac{y^k}{(k)^{k(q_2+q_3-p_2-p_3)}} \end{matrix}\right| \begin{matrix} \triangle(k, a_1),\ldots,\triangle(k, a_{p_1}); \triangle(k, c_1),\ldots,\triangle(k, c_{p_2}) \\ \triangle(k, e_1),\ldots,\triangle(k, e_{p_3}) \\ \triangle(k, b_1),\ldots,\triangle(k, b_{q_1}); \triangle(k, d_1),\ldots,\triangle(k, d_{q_2}) \\ \triangle(k, f_1),\ldots,\triangle(k, f_{q_3}) \end{matrix}\Bigg] \quad (9)$$

where

$$u = (k-1)\left[\tfrac{1}{2}(p_1 + q_1 + p_2 + q_2 + p_3 + q_3) - (m_1 + n_1 + m_2 + n_2 + n_3)\right]$$

$$v = \sum_{j=1}^{q_1} b_j - \sum_{j=1}^{p_1} a_j + \sum_{j=1}^{q_2} d_j - \sum_{j=1}^{p_2} c_j + \sum_{j=1}^{q_3} f_j - \sum_{j=1}^{p_3} e_j + \tfrac{1}{2}(p_1 + p_2 + p_3 - q_1 - q_2 - q_3) + 2$$

Proof

To prove (9), expressing G-function on the left hand side as (1) and replacing s by ks and t by kt, we get

$$k^2 \frac{1}{(2\pi i)^2} \int_{L_1}\int_{L_2} \frac{\prod_{=1}^{m_1} \Gamma(b_j - ks) \prod_{j=1}^{n_1} \Gamma(1-a_j+ks) \prod_{j=1}^{m_2} \Gamma(d_j - kt) \prod_{j=1}^{n_2} \Gamma(1-c_j+kt)}{\prod_{j=m_1+1}^{q_1} \Gamma(1-b_j+ks) \prod_{j=n_1+1}^{p_1} \Gamma(a_j - ks) \prod_{j=m_2+1}^{q_2} \Gamma(1-d_j+kt) \prod_{j=n_2+1}^{p_2} \Gamma(c_j - kt)} \cdot$$

$$\cdot \frac{\prod_{j=1}^{n} \Gamma(1-e_j+ks+kt)\; x^{ks}\; y^{kt}}{\prod_{j=n_3+1}^{p_3} \Gamma(e_j - ks - kt) \prod_{j=1}^{q_3} \Gamma(1-f_j+ks+kt)} ds\, dt.$$

Now using multiplication formula for Gamma function [7, p. 11, (1)] and (1), the formula (9) is established.

$$G\left[\begin{matrix} x \\ \\ y \end{matrix}\right] = \frac{1}{2\pi i}\Bigg\{ (e)^{i\pi b_{m_1+1}} G^{(m_1+1, m_2);\,(n_1, n_2),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} xe^{-i\pi} & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right] -$$

$$- (e)^{-i\pi b_{m_1+1}} G^{(m_1+1, m_2);\,(n_1, n_2),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} xe^{i\pi} & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right]\Bigg\} \quad (10)$$

$$G\left[\begin{matrix} x \\ \\ y \end{matrix}\right] = \frac{1}{2\pi i}\Bigg\{ (e)^{i\pi d_{m_2+1}} G^{(m_1, m_2+1);\,(n_1, n_2),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} x & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ ye^{-i\pi} & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right] -$$

$$- (e)^{-i\pi d_{m_2+1}} G^{(m_1, m_2+1);\,(n_1, n_2),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} x & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ ye^{i\pi} & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right]\Bigg\} \quad (11)$$

$$G\left[\begin{matrix} x \\ \\ y \end{matrix}\right] = \frac{1}{2\pi i}\Bigg\{ (e)^{i\pi a_{n_1+1}} G^{(m_1, m_2);\,(n_1+1, n_2),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} xe^{-i\pi} & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right] -$$

$$- (e)^{-i\pi a_{n_1+1}} G^{(m_1, m_2);\,(n_1+1, n_2),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} xe^{i\pi} & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right]\Bigg\} \quad (12)$$

$$G\left[\begin{matrix} x \\ \\ y \end{matrix}\right] = \frac{1}{2\pi i}\Bigg\{ (e)^{i\pi c_{n_2+1}} G^{(m_1, m_2);\,(n_1, n_2+1),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} x & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ ye^{-i\pi} & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right] -$$

$$- (e)^{-i\pi c_{n_2+1}} G^{(m_1, m_2);\,(n_1, n_2+1),\, n_3}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} x & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ ye^{i\pi} & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right]\Bigg\} \quad (13)$$

$$G\left[\begin{matrix} x \\ \\ y \end{matrix}\right] = \frac{1}{2\pi i}\Bigg\{ (e)^{i\pi e_{n_3+1}} G^{(m_1, m_2);\,(n_1, n_2),\, n_3+1}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} xe^{-i\pi} & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ ye^{-i\pi} & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right] -$$

$$- (e)^{-i\pi e_{n_3+1}} G^{(m_1, m_2);\,(n_1, n_2),\, n_3+1}_{(p_1, p_2),\, p_3;\,(q_1, q_2),\, q_3}\left[\begin{array}{c|l} xe^{i\pi} & (a_{p_1});(c_{p_2}) \\ & (e_{p_3}) \\ ye^{i\pi} & (b_{q_1});(d_{q_2}) \\ & (f_{q_3}) \end{array}\right]\Bigg\} \quad (14)$$

Proof

To prove (10), expressing the G-function on the left hand side as (1) and multiplying the numerator and denominator by $\Gamma(b_{m_1+1}-s)$, we get,

$$\frac{1}{(2\pi i)^2}\int_{L_1}\int_{L_2}\frac{\prod_{j=1}^{m_1+1}\Gamma(b_j-s)\prod_{j=1}^{n_1}\Gamma(1-a_j+s)\prod_{j=1}^{m_2}\Gamma(d_j-t)\prod_{j=1}^{n_2}\Gamma(1-c_j+t)\prod_{j=1}^{n_3}\Gamma(1-e_j+s+t)}{\prod_{j=m_1+2}^{q_1}\Gamma(1-b_j+s)\prod_{j=n_1+1}^{p_1}\Gamma(a_j-s)\prod_{j=m_2+1}^{q_2}\Gamma(1-d_j+t)\prod_{j=n_2+1}^{p_2}\Gamma(c_j-t)}\cdot$$

$$\cdot\frac{x^s\, y^t}{\prod_{j=n_3+1}^{p_3}\Gamma(e_j-s-t)\prod_{j=1}^{q_3}\Gamma(1-f_j+s+t)\;\Gamma(b_{m_1+1}-s)\;\Gamma(1-b_{m_1+1}+s)}\,ds\,dt. \quad (15)$$

Now by virtue of the relation

$$\Gamma_z\;\Gamma(1-z)=\frac{\pi}{\sin\pi z}=\frac{2\pi i}{e^{i\pi z}-e^{-i\pi z}}$$

we see that

$$\Gamma(b_{m_1+1}-s)\;\;\Gamma(1-b_{m_1+1}+s)=\frac{2\pi i}{(e)^{i\pi}(b_{m_1+1}-s)-(e)^{-i\pi}(b_{m_1+1}-s)} \quad (16)$$

The relation (10) is proved by using (15), (16) and (1).

By adopting the same procedure as for (10), the formulae (11)–(14) are proved.

$$G^{(m_1+1,\,m_2+1);\,(n_1,\,n_2),\,n_3}_{(p_1+1,\,p_2+1),\,p_3;\,(q_1+1,\,q_2+1),\,q_3}\left[\begin{array}{c|l} x & a,(a_{p_1});\,c,(c_{p_2}) \\ & (e_{p_3}) \\ y & a,(b_{q_1});\,c,(d_{q_2}) \\ & (f_{q_3})\end{array}\right]=(-1)^r(-1)^k G\left[\begin{array}{c} x \\ y\end{array}\right] \quad (17)$$

where $a_{n_1}=a+r$, $c_{n_2}=c+k$, r and k are integers.

$$G^{(m_1,\,m_2);\,(n_1+1,\,n_2+1),\,n_3}_{(p_1+1,\,p_2+1),\,p_3;\,(q_1+1,\,q_2+1),\,q_3}\left[\begin{array}{c|l} x & a,(a_{p_1});\,c,(c_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1}),b;\,(d_{q_2}),d \\ & (f_{q_3})\end{array}\right]=$$

$$=(-1)^r(-1)^k\,G^{(m_1+1,\,m_2+1);\,(n_1,\,n_2),\,n_3}_{(p_1+1,\,p_2+1),\,p_3;\,(q_1+1,\,q_2+1),\,q_3}\left[\begin{array}{c|l} x & (a_{p_1}),a;\,(c_{p_2})\,c \\ & (e_{p_3}) \\ y & b,(b_{q_1});\,d,(d_{q_2}) \\ & (f_{q_3})\end{array}\right] \quad (18)$$

where $a-b=r$, $c-d=k$, r and k are integers or zero.

(17) and (18) are proved by using (1) and Rainville[8]

$$x^n\frac{\partial^n}{\partial x^n}G\left[\begin{array}{c} x \\ y\end{array}\right]=G^{(m_1,\,m_2);\,(n_1+1,\,n_2),\,n_3}_{(p_1+1,\,p_2),\,p_3;\,(q_1+1,\,q_2),\,q_3}\left[\begin{array}{c|l} x & 0,(a_{p_1});\,(a_{p_2}) \\ & (e_{p_3}) \\ y & (b_{q_1}),n;\,(d_{q_2}) \\ & (f_{q_3})\end{array}\right] \quad (19)$$

A similar result is true for

$$y^n \frac{\partial^n}{\partial y^n} G\left[\begin{matrix} x \\ y \end{matrix}\right]$$

$$x^n \frac{\partial^n}{\partial x^n} G\left[\begin{matrix} x^{-1} \\ \\ y \end{matrix}\right] = (-)^n G^{(m_1, m_2);\,(n_1+1, n_2),\, n_3}_{(p_1+1, p_2),\, p_3;\,(q_1+1, q_2),\, q_3}\left[\begin{matrix} x^{-1} \\ \\ y \end{matrix}\left|\begin{matrix} 1-n, (a_{p_1}); (c_{p_2}) \\ (e_{p_3}) \\ (b_{q_1}), 1; (d_{q_2}) \\ (f_{q_3}) \end{matrix}\right.\right] \qquad (20)$$

A similar result holds for

$$y^n \frac{\partial^n}{\partial y^n} G\left[\begin{matrix} x \\ y^{-1} \end{matrix}\right]$$

The proofs for (19) and (20) are very simple and follow by expressing the G-function on the left hand side as in (1), changing the order of integration and differentiation and again using (1).

Particular cases:—Putting $m_2 = q_2 = 1$, $n_2 = n_3 = p_2 = p_3 = q_3 = 0$ and making use of the formula given by Bajpai[6] viz.

$$G^{(m, 1);\,(n, 0),\, 0}_{(p, 0),\, 0;\,(q, 1),\, 0}\left[\begin{matrix} x \\ \\ y \end{matrix}\left|\begin{matrix} (a_p); —— \\ —— \\ (b_q); 0 \\ —— \end{matrix}\right.\right] = e^{-y} G^{m,\, n}_{p,\, q}\left(x \left|\begin{matrix} (a_p) \\ (b_q) \end{matrix}\right.\right)$$

we get the known results[6] from (2), (6), (10), (12), (19) and (20).

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