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ON GENERATING RELATIONS ASSOCIATED WITH THE EXTENDED GAUSS AND CONFLUENT HYPERGEOMETRIC FUNCTIONS

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Abstract. In this research note, we establish a new class of generating relations associated with the extended Gauss and confluent hypergeometric functions using the concept of Hadamard product. Some deductions of our main results are also indicated.

1. Introduction and Preliminaries

The generating relations play a very important role in the study of the functions. In particular, in the field of special functions several important and useful properties have been investigated by making use of the generating relations (see, for example, [3,4,7,9,13] and [14]). Due to great importance of such type of relations, in this paper, we establish some new interesting generating relations of the extended Gauss and confluent hypergeometric functions using the Hadamard product of two functions.

The Hadamard product of two functions is defined as follows.

Let $f(z) = \sum_{n=0}^{+\infty} a_n z^n$ and $g(z) = \sum_{n=0}^{+\infty} b_n z^n$ be two power series whose radii of convergence are given by R_f and R_g, respectively. Then, the Hadamard product is defined by (see [16])

$$(f * g)(z) = \sum_{n=0}^{+\infty} a_n b_n z^n, \tag{1.1}$$

whose radius of convergence R satisfies $R_f R_g \leq R$.

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In recent years, numerous extensions of some well known special functions have been introduced and investigated by a number of authors (see, for example, [1, 2, 5–8, 10–13, 17, 18] and [19]). In particular, in 2014, Srivastava et al. [3] proposed a very interesting generalization of the Gauss hypergeometric function as follows:

(1.2)
$$F_p^{(\alpha,\beta,u,v)}(a,b;c;z) = \sum_{n=0}^{+\infty}(a)_n \frac{B_p^{(\alpha,\beta,u,v)}(b+n,c-b)\ z^n}{B(b,c-b)\ n!}$$
$$(\min\{\mathrm{Re}\,(\alpha),\mathrm{Re}\,(\beta),\mathrm{Re}\,(u),\mathrm{Re}\,(v)\}>0;\ \mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0;\ \mathrm{Re}\,(p)\geq 0;\ |z|<1),$$

where $B_p^{(\alpha,\beta,u,v)}$ is the extended beta function defined by

(1.3)
$$B_p^{(\alpha,\beta,u,v)}(x,y) = \int_0^1 t^{x-1}(1-t)^{y-1}\Phi\left(\alpha;\beta;-\frac{p}{t^u(1-t)^v}\right)dt$$
$$(\min\{\mathrm{Re}\,(x),\mathrm{Re}\,(y),\mathrm{Re}\,(\alpha),\mathrm{Re}\,(\beta)\}>0;\ \min\{\mathrm{Re}\,(u),\mathrm{Re}\,(v)\}>0;\ \mathrm{Re}\,(p)\geq 0).$$

With the help of (1.3), we can write the integral representation of (1.2) as follows:

$$F_p^{(\alpha,\beta,u,v)}(a,b;c;z) = \frac{\Gamma(c)}{\Gamma(b)\Gamma(c-b)}\int_0^1 t^{b-1}(1-t)^{c-b-1}(1-zt)^{-a} \times \Phi\left(\alpha;\beta;\frac{-p}{t^u(1-t)^v}\right)dt, \tag{1.4}$$

where $(\mathrm{Re}\,(p)\geq 0;\ |\arg(1-z)|<\pi;\ \mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0;\ \min\{\mathrm{Re}\,(u),\mathrm{Re}\,(v)\}>0)$.

Moreover, Khan et al. [12] proposed a new generalized form of the confluent hypergeometric function as follows:

$$\Phi_p^{(\alpha,\beta;u,v)}(b;c;z) = \sum_{n=0}^{+\infty}\frac{B_p^{(\alpha,\beta;u,v)}(b+n,c-b)}{B(b,c-b)}\cdot\frac{z^n}{n!}. \tag{1.5}$$

They also defined its integral representation as

(1.6)
$$\Phi_p^{(\alpha,\beta;u,v)}(b;c;z) = \frac{\Gamma(c)}{\Gamma(b)\Gamma(c-b)}\int_0^1 t^{b-1}(1-t)^{c-b-1}\exp(zt)\Phi\left(\alpha;\beta;\frac{-p}{t^u(1-t)^v}\right)dt$$
$$(\mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0;\ \mathrm{Re}\,(u)>0,\mathrm{Re}\,(v)>0;\ \mathrm{Re}\,(p)\geq 0).$$

The case $u=v$ in (1.4) and (1.6), respectively, yields the extended Gauss and confluent hypergeometric functions defined by Parmar [15], which further gives the known generalization of Gauss and confluent hypergeometric functions given by Özergin et al. [2] by taking $v=1$. Also, it is noticed that, if we set $\alpha=\beta$ and $u=v$ in (1.4) and (1.6), respectively, we get the extended Gauss and confluent hypergeometric functions defined by Lee et al. [1] and if we set $\alpha=\beta$ and $u=v=1$ in (1.4) and (1.6), respectively, then we get the extended Gauss and confluent hypergeometric functions defined by Chaudhry et al. [8]. Clearly, for $p=0$, (1.4) and (1.6) immediately reduces to the classical Gauss and confluent hypergeometric functions (see [4]).

Also, in 2014, Choi et al. [5] introduced the following extension of Gauss and confluent hypergeometric functions by introducing another parameter:

$$F_{p,q}(a,b;c;z)=\sum_{n=0}^{+\infty}(a)_n\frac{B_{p,q}(b+n;c-b)\ z^n}{B(b,c-b)\ n!} \tag{1.7}$$
$$(\mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0;\ \mathrm{Re}\,(p)\geq 0,\ \mathrm{Re}\,(q)\geq 0;\ |z|<1).$$

and

$$\Phi_{p,q}(b;c;z)=\sum_{n=0}^{+\infty}\frac{B_{p,q}(b+n;c-b)\ z^n}{B(b,c-b)\ n!} \tag{1.8}$$
$$(\mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0;\ \mathrm{Re}\,(p)\geq 0,\ \mathrm{Re}\,(q)\geq 0;\ |z|<1),$$

where

$$B_{p,q}(x,y)=\int_0^1 t^{x-1}(1-t)^{y-1}\exp\left(-\frac{p}{t}-\frac{q}{1-t}\right)dt \tag{1.9}$$
$$\mathrm{Re}\,(p),\mathrm{Re}\,(q),\mathrm{Re}\,(x),\mathrm{Re}\,(y)>0.$$

They also give their integral representation by

$$F_{p,q}(a,b;c;z)=\frac{1}{B(b,c-b)}\int_0^1 t^{b-1}(1-t)^{c-b-1}(1-zt)^{-a}\exp\left(-\frac{p}{t}-\frac{q}{1-t}\right)dt \tag{1.10}$$
$$(\mathrm{Re}\,(p)>\mathrm{Re}\,(q)>0;\ \mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0)$$

and

$$\Phi_{p,q}(b;c;z)=\frac{1}{B(b,c-b)}\int_0^1 t^{b-1}(1-t)^{c-b-1}\exp\left(zt-\frac{p}{t}-\frac{q}{1-t}\right)dt \tag{1.11}$$
$$(\mathrm{Re}\,(p)>\mathrm{Re}\,(q)>0;\ \mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0).$$

For $q=p$, (1.7) and (1.8) reduces to the known extension of Gauss and confluent hypergeometric functions defined by Chaudhary et al. [8], which again for $p=0$, yields the classical Gauss and confluent hypergeometric functions (see [4]).

2. Main Results

In this section, we derive a new class of generating relations of extended Gauss and confluent hypergeometric functions by using the Hadamard product of two functions.

Theorem 2.1. *For* $\min\{\mathrm{Re}\,(\alpha),\mathrm{Re}\,(\beta),\mathrm{Re}\,(u),\mathrm{Re}\,(v)\}>0;\ \mathrm{Re}\,(c)>\mathrm{Re}\,(b)>0$ *and* $\mathrm{Re}\,(p)\geq 0$*, the following result holds true:*

$$(1+t)^{-\lambda}F_p^{(\alpha,\beta,u,v)}\left(a,b;c;\frac{z}{1+t}\right) \tag{2.1}$$
$$=\sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r F_p^{(\alpha,\beta,u,v)}(a,b;c;z)*{}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z\in\mathbb{C},\lambda\in\mathbb{C}\backslash Z_0^-,\ |t|<1),$$

where ${}_2F_1(a,b;c;z)$ *represents the classical Gauss hypergeometric function* (*see* [4, p. 29, Eq. (4)]).

Proof. In order to derive (2.1), we denote the left-hand side of (2.1) by $f(s)$ and $(1+t)$ by s, then we get

$$f(s) = s^{-\lambda} F_p^{(\alpha,\beta,u,v)}\left(a,b;c;\frac{z}{s}\right). \tag{2.2}$$

On expanding $F_p^{(\alpha,\beta,u,v)}$ with the help of (1.2), we arrive at

$$f(s) = \sum_{n=0}^{+\infty} \frac{(a)_n\ B_p^{(\alpha,\beta,u,v)}(b+n,c-b)}{B(b,c-b)} s^{-\lambda-n}\frac{z^n}{n!}. \tag{2.3}$$

Now differentiating (2.3) r times with respect to s and after some simplification, we get

$$f^{(r)}(s) = (-1)^r\ s^{-\lambda-r}(\lambda)_r \sum_{n=0}^{+\infty} \frac{(a)_n\ B_p^{(\alpha,\beta,u,v)}(b+n,c-b)}{B(b,c-b)n!}\cdot\frac{(\lambda+r)_n(1)_n}{(\lambda)_n\ n!}\left(\frac{z}{s}\right)^n. \tag{2.4}$$

By applying (1.1) in (2.4), we have

$$f^{(r)}(s) = (-1)^r\ s^{-\lambda-r}(\lambda)_r\ F_p^{(\alpha,\beta,u,v)}\left(a,b;c;\frac{z}{s}\right) * {}_2F_1\left(\lambda+r,1;\lambda;\frac{z}{s}\right). \tag{2.5}$$

Now, on replacing s by $s+t$ in (2.2), and then expanding $f(s+t)$ by Taylor's series, we get

$$(s+t)^{-\lambda}\ F_p^{(\alpha,\beta,u,v)}\left(a,b;c;\frac{z}{s+t}\right) = \sum_{r=0}^{+\infty}\frac{t^r}{r!}\ f^{(r)}(s). \tag{2.6}$$

Using (2.5) in (2.6), we obtain

$$\begin{aligned}(s+t)^{-\lambda}F_p^{(\alpha,\beta,u,v)}\left(a,b;c;\frac{z}{s+t}\right) &= \sum_{r=0}^{+\infty}(-1)^r\ s^{-\lambda-r}(\lambda)_r \\ &\quad\times F_p^{(\alpha,\beta,u,v)}\left(a,b;c;\frac{z}{s}\right) * {}_2F_1\left(\lambda+r,1;\lambda;\frac{z}{s}\right)\frac{t^r}{r!}.\end{aligned} \tag{2.7}$$

Finally, on setting $s=1$ in (2.7), we get our claimed result (2.1). □

Theorem 2.2. *For* $\min\{\mathrm{Re}(\alpha),\mathrm{Re}(\beta),\mathrm{Re}(u),\mathrm{Re}(v)\}>0;\ \mathrm{Re}(c)>\mathrm{Re}(b)>0$ *and* $\mathrm{Re}(p)\geq 0$, *the following result holds true:*

(2.8)

$$(1+t)^{-\lambda}\Phi_p^{(\alpha,\beta,u,v)}\left(b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r\Phi_p^{(\alpha,\beta,u,v)}(b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$

$(z\in\mathbb{C}, \lambda\in\mathbb{C}\backslash Z_0^-,\ |t|<1)$.

Theorem 2.3. *For* $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$, $\mathrm{Re}\,(p) \geq 0$ *and* $\mathrm{Re}\,(q) \geq 0$*, the following result holds true:*

$$(1+t)^{-\lambda} F_{p,q}\left(a,b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r(\lambda)_r F_{p,q}(a,b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!} \tag{2.9}$$

$$(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t|<1).$$

Theorem 2.4. *For* $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$, $\mathrm{Re}\,(p) \geq 0$ *and* $\mathrm{Re}\,(q) \geq 0$*, the following result holds true:*

$$(1+t)^{-\lambda} \Phi_{p,q}\left(b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r(\lambda)_r \Phi_{p,q}(b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!} \tag{2.10}$$

$$(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t|<1).$$

Proof. The proofs of Theorem 2.2, Theorem 2.3 and Theorem 2.4 are similar to Theorem 2.1. □

3. Special Cases

Corollary 3.1. *For* $\min\{\mathrm{Re}\,(\alpha), \mathrm{Re}\,(\beta), \mathrm{Re}\,(v)\} > 0$, $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$\begin{aligned} &(1+t)^{-\lambda} F_p^{(\alpha,\beta,v)}\left(a,b;c;\frac{z}{1+t}\right) \\ &= \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r F_p^{(\alpha,\beta,v)}(a,b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!} \\ &(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t|<1), \end{aligned} \tag{3.1}$$

where $F_p^{(\alpha,\beta;v)}(\cdot)$ *is the extended Gauss hypergeometric function defined by Parmar* [15].

This corollary can be established with the help of (2.1) by putting $u = v$.

Corollary 3.2. *For* $\min\{\mathrm{Re}\,(\alpha), \mathrm{Re}\,(\beta)\} > 0$, $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$\begin{aligned} &(1+t)^{-\lambda} F_p^{(\alpha,\beta)}\left(a,b;c;\frac{z}{1+t}\right) \\ &= \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r F_p^{(\alpha,\beta)}(a,b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!} \\ &(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t|<1), \end{aligned} \tag{3.2}$$

where $F_p^{(\alpha,\beta)}(\cdot)$ *represents the extended Gauss hypergeometric function given by Özergin et al.* [2].

This corollary can be derived with the help of (2.1) by putting $u = v = 1$.

Corollary 3.3. *For* $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0,\ \mathrm{Re}\,(v) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$(3.3)\quad (1+t)^{-\lambda} F_p^v\left(a,b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r F_p^v(a,b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t| < 1),$$

where $F_p^v(\cdot)$ *denotes the extended Gauss hypergeometric function introduced by Lee et al.* [1].

The above corollary can be obtained with the help of (2.1) by setting $\alpha = \beta$ and $u = v$.

Corollary 3.4. *For* $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$(3.4)\quad (1+t)^{-\lambda} F_p\left(a,b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r F_p(a,b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z \in \mathbb{C}, \lambda \in \mathbb{C}\backslash Z_0^-,\ |t| < 1),$$

where $F_p(\cdot)$ *is the extended Gauss hypergeometric function defined by Chaudhry et al.* [8].

This corollary can be proved with the help of (2.1) by setting $\alpha = \beta$ and $u = v = 1$.

Corollary 3.5. *For* $\min\{\mathrm{Re}\,(\alpha), \mathrm{Re}\,(\beta), \mathrm{Re}\,(v)\} > 0;\ \mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

(3.5)
$$(1+t)^{-\lambda} \Phi_p^{(\alpha,\beta,v)}\left(b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{\infty}(-1)^r\ (\lambda)_r \Phi_p^{(\alpha,\beta,v)}(b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t| < 1),$$

where $\Phi_p^{(\alpha,\beta;v)}(\cdot)$ *is the extended confluent hypergeometric function defined by Parmar* [15].

This corollary can be established with the help of (2.8) by putting $u = v$.

Corollary 3.6. *For* $\min\{\mathrm{Re}\,(\alpha), \mathrm{Re}\,(\beta)\} > 0,\ \mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$(3.6)\quad (1+t)^{-\lambda} \Phi_p^{(\alpha,\beta)}\left(b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r \Phi_p^{(\alpha,\beta)}(b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z \in \mathbb{C},\ \lambda \in \mathbb{C}\backslash Z_0^-,\ |t| < 1),$$

where $\Phi_p^{(\alpha,\beta)}(\cdot)$ *represents the extended confluent hypergeometric function given by Özergin et al.* [2].

This corollary can be derived with the help of (2.8) by putting $u = v = 1$.

Corollary 3.7. *For* $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0,\ \mathrm{Re}\,(v) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$(3.7)\qquad (1+t)^{-\lambda}\Phi_p^v\left(b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r\Phi_p^v(b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z\in\mathbb{C},\ \lambda\in\mathbb{C}\backslash Z_0^-,\ |t|<1),$$

where $\Phi_p^v(\cdot)$ *denotes the extended confluent hypergeometric function introduced by Lee et al.* [1]*.*

This corollary can be established with the help of (2.8) by setting $\alpha = \beta$ and $u = v$.

Corollary 3.8. *For* $\mathrm{Re}\,(c) > \mathrm{Re}\,(b) > 0$ *and* $\mathrm{Re}\,(p) \geq 0$*, we have*

$$(3.8)\qquad (1+t)^{-\lambda}\Phi_p\left(b;c;\frac{z}{1+t}\right) = \sum_{r=0}^{+\infty}(-1)^r\ (\lambda)_r\Phi_p(b;c;z) * {}_2F_1(\lambda+r,1;\lambda;z)\frac{t^r}{r!}$$
$$(z\in\mathbb{C},\ \lambda\in\mathbb{C}\backslash Z_0^-,\ |t|<1),$$

where $\Phi_p(\cdot)$ *is the extended confluent hypergeometric function defined by Chaudhry et al.* [8]*.*

This corollary can be obtained with the help of (2.8) by setting $\alpha = \beta$ and $u = v = 1$.

Remark 3.1. If we set $q = p$ in (2.9) and (2.10), then we can easily get our known results given in (3.4) and (3.8), respectively.

Conclusion

In this paper, we have derived a set of generating relations associated with the extended Gauss and confluent hypergeometric functions, which are defined by some well known authors namely Srivastava et al. [3], Khan et al. [12] and Choi et al. [5]. Also, we have investigated the special cases of our main findings. Very recently, numerous authors have introduced and studied several extensions of Gauss and confluent hypergeometric functions (see, for example, [1,2] and [3]). Therefore, it is noticed that by using the method outlined in this paper we can establish some more interesting generating relations for the functions given in [1, 2] and [3]. Thus, the technique adopted in this article provides a very flexible and powerful tool of yielding the new results in the theory of special functions.

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