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New Unified Integral Formula Involving the Function and General Multivariable Polynomials

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Abstract: ***The primary objective of this research paper is to evaluate and analyses a new class of integrals involving the $\bar{H}$-function in conjunction with Srivastava's polynomial. The study seeks to derive explicit integral representations by employing standard integrals from the well-established table of Mellin transforms. Through this investigation, we aim to establish novel identities and functional relationships that emerge from the interplay between the $\bar{H}$-function and Srivastava's polynomial, thereby contributing to the broader theory of special functions. The outcomes of this research are expected to generalize and unify various known results, while also offering new mathematical tools for application in fields such as mathematical physics, engineering, and computational analysis.***

Keywords: $\bar{H}$-function, General polynomial, Meijer G-function, hypergeometric function.

MSC: 33C45, 33C60.

1. Introduction

The generalized fox H-function known as $\bar{H}$-function introduced by Inayat Hussain (1987) [1, 2] represent as

$$\bar{H}_{p,q}^{m,n}\left[z\left|\begin{matrix}(a_i,\alpha_i,A_i)_{1,n};(a_i,\alpha_i)_{n+1,p}\\(b_i,\beta_i,)_{1,m};(b_i,\beta_i,B_i)_{m+1,q}\end{matrix}\right.\right]=\frac{1}{2\pi\omega}\int_{-\omega\infty}^{\omega\infty}\bar{\phi}(s)z^s ds$$

for $z \neq 0$ (1)

Where $i=\sqrt{-1}$ and

$$\bar{\phi}(s)=\frac{\prod_{k=1}^{m}\Gamma(b_k-\beta_k s)\prod_{k=1}^{n}\Gamma(1-a_k+\alpha_k s)^{A_k}}{\prod_{k=m+1}^{q}\Gamma(1-b_k+\beta_k s)^{B_k}\prod_{k=n+1}^{p}\Gamma(a_k-\alpha_k s)} \quad (2)$$

In which some of the gamma function hold fractional power. The parameters $a_k\ (k=1,2,...,p)$ and $b_k\ (k=1,2,..,q)$ are complex numbers, $(\alpha_k)_{1,p}>0$ and $(\beta_k)_{1,q}>0$ are real positive numbers, powers $(A_k)_{1,n}$ and $(B_k)_{m+1,q}$ can take fractional values. m,n,p,q are integers value such that $1\le m\le q;1\le n\le p$ which we assume to be positive for standardization purpose.

Just like in the usual definition of the H-function, the contour is assumed to be along the imaginary axis, but it is slightly bent to avoid the points where the gamma functions become undefined, and to make sure those points stay on the appropriate sides.

The other necessary conditions on the parameters are the same as those given by Srivastava and others (1982) [5, 6].

We also recall from Erdelyi and others (1953) [3] the conditions needed for the convergence of the integral (1) that defines the H-function.

$$|\Gamma(x+iy)| \sim \sqrt{2\pi}\,|y|^{x-\frac{1}{2}}\,e^{\frac{-\pi|y|}{2}} \qquad (|y|\to\infty) \quad (3)$$

Following the same method and using equation (3), we can easily find the asymptotic form of the function. So, we just need to make a small change in the condition that ensures the contour integral (1) converges absolutely, as explained below.

$$\Lambda \equiv \sum_{k=1}^{m}|\beta_k|+\sum_{k=1}^{n}|\alpha_k A_k|-\sum_{k=m+1}^{q}|\beta_k B_k|-\sum_{k=n+1}^{p}|\alpha_k|>0 \quad (4)$$

This condition clearly causes the integrand in equation (1) to decrease rapidly, and the region where the integral in (1) converges is given by

$$|\arg(z)|<\frac{1}{2}\pi\Lambda \quad (5)$$

The general class of polynomials will be defined and represented as follows

$$S_{n_1,n_2,...,n_r}^{m_1,m_2,...,m_r}[t_1,t_2,...,t_r]=\sum_{\delta_1=0}^{\frac{n_1}{m_1}}...\sum_{\delta_r=0}^{\frac{n_r}{m_r}}\frac{(-n_1)_{m_1\delta_1}}{\delta_1!}...\frac{(-n_r)_{m_r\delta_r}}{\delta_r!}A[n_1,\delta_1;...;n_r,\delta_r]t_1^{\delta_1}...t_r^{\delta_r} \quad (6)$$

where, $m_1,...,m_r;n_1,..,n_r$ are any positive integers, and the coefficients $A[n_1,\delta_1;...;n_r,\delta_r]$ can be any constants, whether real or complex. This general form includes many well-known polynomials as special cases, such as the Jacobi polynomials, Bessel polynomials, Laguerre polynomials, and several others.

By the definition of Millen's Transform, from the table of Millen's Transform [4] (eq. 2.47 pg. 22).

$$M[\phi(x),z]=\int_0^\infty x^{z-1}\phi(x)dx$$

$$M\left[\left\{x+a+\sqrt{x^2+2ax}\right\}^{-\lambda};z\right]=\frac{\lambda}{2^{z-1}a^{\lambda-z}}\frac{\Gamma(2z)\Gamma(\lambda-z)}{\Gamma(1+\lambda+z)} \qquad 0<\mathrm{Re}(z)<\lambda \tag{7}$$

We shall require the following formula for the evaluation of our main integrals

$$\int_0^\infty x^{\rho-1}\left\{x+a+\sqrt{x^2+2ax}\right\}^{-\lambda}dx=\frac{\lambda}{2^{\rho-1}a^{\lambda-\rho}}\frac{\Gamma(2\rho)\Gamma(\lambda-\rho)}{\Gamma(1+\lambda+\rho)} \qquad 0<\mathrm{Re}(\rho)<\lambda \tag{8}$$

2. Main Result

In this section, we have derived the following result

$$\int_0^\infty \frac{x^{\rho-1}}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\lambda}}\bar{H}^{m,n}_{p,q}\left[\frac{z}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\eta}}\left|\begin{matrix}(a_k,\alpha_k,A_k)_{1,n};(a_k,\alpha_k)_{n+1,p}\\(b_k,\beta_k,)_{1,m};(b_k,\beta_k,B_k)_{m+1,q}\end{matrix}\right.\right]\times$$

$$S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_1}},\frac{t_2}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_2}},\ldots,\frac{t_r}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_r}}\right]dx=\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}}\times$$

$$\bar{H}^{m,n+2}_{p+2,q+2}\left[\frac{z}{a^\eta}\left|\begin{matrix}(a_k,\alpha_k,A_k)_{1,n};\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right);\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r+\rho;\eta;1\right)(a_k,\alpha_k)_{n,p+2}\\\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right);\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r-\rho;\eta;1\right);(b_k,\beta_k,)_{1,m};(b_k,\beta_k,B_k)_{m+1,q}\end{matrix}\right.\right]S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{a^{\mu_1}},\ldots,\frac{t_r}{a^{\mu_r}}\right] \tag{9}$$

Proof:

$$\int_0^\infty \frac{x^{\rho-1}}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\lambda}}\bar{H}^{m,n}_{p,q}\left[\frac{z}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\eta}}\left|\begin{matrix}(a_k,\alpha_k,A_k)_{1,n};(a_k,\alpha_k)_{n+1,p}\\(b_k,\beta_k,)_{1,m};(b_k,\beta_k,B_k)_{m+1,q}\end{matrix}\right.\right]\times$$

$$S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_1}},\frac{t_2}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_2}},\ldots,\frac{t_r}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_r}}\right]dx$$

$$=\int_0^\infty \frac{x^{\rho-1}}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\lambda}}\frac{1}{2\pi i}\int_{-i\infty}^{i\infty}\bar{\phi}(s)\left[\frac{z}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\eta}}\right]^s\sum_{\delta_1=0}^{\frac{n_1}{m_1}}\ldots\sum_{\delta_r=0}^{\frac{n_r}{m_r}}\frac{(-n_1)_{m_1\delta_1}}{\delta_1!}\ldots\frac{(-n_r)_{m_r\delta_r}}{\delta_r!}\times$$

$$A[n_1,\delta_1;\ldots;n_r,\delta_r]\left\{t_1\left\{x+a+\sqrt{x^2+2ax}\right\}^{-\mu_1}\right\}^{\delta_1}\ldots\left\{t_r\left\{x+a+\sqrt{x^2+2ax}\right\}^{-\mu_r}\right\}^{\delta_r}dsdx$$

$$=\frac{1}{2\pi i}\int_{-i\infty}^{i\infty}\bar{\phi}(s)z^s\int_0^\infty x^{\rho-1}\left\{x+a+\sqrt{x^2+2ax}\right\}^{-\lambda-\eta s-\sum_{j=1}^{r}\mu_r\delta_r}dx\sum_{\delta_1=0}^{\frac{n_1}{m_1}}\ldots\sum_{\delta_r=0}^{\frac{n_r}{m_r}}\frac{(-n_1)_{m_1\delta_1}}{\delta_1!}\ldots\frac{(-n_r)_{m_r\delta_r}}{\delta_r!}A[n_1,\delta_1;\ldots;n_r,\delta_r]t_1^{\delta_1}\ldots t_r^{\delta_r}ds$$

$$=\frac{1}{2\pi i}\int_{-i\infty}^{i\infty}\bar{\phi}(s)z^s\frac{\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r\right)}{2^{\rho-1}a^{\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r\right)-\rho}}\frac{\Gamma(2\rho)\Gamma\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r-\rho\right)}{\Gamma\left(1+\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r+\rho\right)}\sum_{\delta_1=0}^{\frac{n_1}{m_1}}\ldots\sum_{\delta_r=0}^{\frac{n_r}{m_r}}\frac{(-n_1)_{m_1\delta_1}}{\delta_1!}\ldots\frac{(-n_r)_{m_r\delta_r}}{\delta_r!}A[n_1,\delta_1;\ldots;n_r,\delta_r]t_1^{\delta_1}\ldots t_r^{\delta_r}ds$$

$$=\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}2\pi i}\int_{-i\infty}^{i\infty}\bar{\phi}(s)\frac{\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r\right)\Gamma\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r-\rho\right)}{\Gamma\left(1+\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r+\rho\right)}\left(\frac{z}{a^\eta}\right)^s$$

$$\sum_{\delta_1=0}^{\frac{n_1}{m_1}}\ldots\sum_{\delta_r=0}^{\frac{n_r}{m_r}}\frac{(-n_1)_{m_1\delta_1}}{\delta_1!}\ldots\frac{(-n_r)_{m_r\delta_r}}{\delta_r!}A[n_1,\delta_1;\ldots;n_r,\delta_r]\left(\frac{t_1}{a^{\mu_1}}\right)^{\delta_1}\ldots\left(\frac{t_r}{a^{\mu_r}}\right)^{\delta_r}ds$$

$$=\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}2\pi i}\int_{-i\infty}^{i\infty}\frac{\prod_{k=1}^{m}\Gamma(b_k-\beta_k s)\prod_{k=1}^{n}\Gamma(1-a_k+\alpha_k s)^{A_k}\,\Gamma\left(1+\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r\right)}{\prod_{k=m+1}^{q}\Gamma(1-b_k+\beta_k s)^{B_k}\prod_{k=n+1}^{p}\Gamma(a_k-\alpha_k s)\Gamma\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r\right)}\frac{\Gamma\left(\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r-\rho\right)}{\Gamma\left(1+\lambda+\eta s+\sum_{j=1}^{r}\mu_r\delta_r+\rho\right)}\left(\frac{z}{a^{\eta}}\right)^{s}ds\times$$

$$\sum_{\delta_1=0}^{\frac{n_1}{m_1}}\cdots\sum_{\delta_r=0}^{\frac{n_r}{m_r}}\frac{(-n_1)_{m_1\delta_1}}{\delta_1!}\cdots\frac{(-n_r)_{m_r\delta_r}}{\delta_r!}A[n_1,\delta_1;\ldots;n_r,\delta_r]\left(\frac{t_1}{a^{\mu_1}}\right)^{\delta_1}\cdots\left(\frac{t_r}{a^{\mu_r}}\right)^{\delta_r}$$

$$\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}}\overline{H}^{m,n+2}_{p+2,q+2}\left[\frac{z}{a^{\eta}}\left|\begin{matrix}(a_k,\alpha_k,A_k)_{1,n};\left(-\lambda-\sum_{j=1}^{r}\mu_j\delta_j;\eta;1\right);\left(1-\lambda-\sum_{j=1}^{r}\mu_j\delta_j+\rho;\eta;1\right);(a_k,\alpha_k)_{n,p+2}\\\left(1-\lambda-\sum_{j=1}^{r}\mu_j\delta_j;\eta;1\right)\left(-\lambda-\sum_{j=1}^{r}\mu_j\delta_j-\rho;\eta;1\right);(b_k,\beta_k)_{1,m};(b_k,\beta_k,B_k)_{m+1,q}\end{matrix}\right.\right]S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{a^{\mu_1}},\ldots,\frac{t_r}{a^{\mu_r}}\right]$$

3. Special Cases

(i) If we put $A_k=1,(\forall k=1,2,\ldots n)$; and $B_k=1$, then $\overline{H}$-function reduce to Fox's H-function and equation (9) reduces to

$$\int_0^{\infty}\frac{x^{\rho-1}}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\lambda}}H^{m,n}_{p,q}\left[\frac{z}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\eta}}\left|\begin{matrix}(a_k,\alpha_k)_{1,p}\\(b_k,\beta_k)_{1,q}\end{matrix}\right.\right]S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_1}},\ldots,\frac{t_r}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_r}}\right]dx$$

$$=\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}}H^{m,n+2}_{p+2,q+2}\left[\frac{z}{a^{\eta}}\left|\begin{matrix}\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right)\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r+\rho;\eta;1\right)(a_k,\alpha_k)_{1,p}\\\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right)\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r-\rho;\eta;1\right)(b_k,\beta_k)_{1,q}\end{matrix}\right.\right]\times S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{a^{\mu_1}},\ldots,\frac{t_r}{a^{\mu_r}}\right]\quad(10)$$

(ii) Put $\alpha_k=1,(\forall k=1,2,..p)$; $\beta_k=1,(\forall k=1,2,..q)$; $A_k=1,(\forall k=1,2,\ldots n)$; and $B_k=1,(\forall k=m+1,m+2,\ldots,q)$ then $\overline{H}$-function reduce to Meijer's G-function then the main result (9) reduces to new result is

$$\int_0^{\infty}\frac{x^{\rho-1}}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\lambda}}G^{m,n}_{p,q}\left[\frac{z}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\eta}}\left|\begin{matrix}(a_k,1)_{1,p}\\(b_k,1)_{1,q}\end{matrix}\right.\right]S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_1}},\ldots,\frac{t_r}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_r}}\right]dx$$

$$=\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}}G^{m,n+2}_{p+2,q+2}\left[\frac{z}{a^{\eta}}\left|\begin{matrix}(a_k,1)_{1,p};\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right)\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r+\rho;\eta;1\right)\\\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right)\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r-\rho;\eta;1\right)(b_k,1)_{1,q}\end{matrix}\right.\right]S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{a^{\mu_1}},\ldots,\frac{t_r}{a^{\mu_r}}\right]\quad(11)$$

(iii) If we put $n=p$, $m=1$, $q=q+1$, $b_1=1$, $\beta_1=1$, $a_k=1-a_k$, $b_k=1-b_k$ in equation (1) then the $\overline{H}$-function reduces to generalized Wright hypergeometric function

$$\overline{H}^{1,p}_{p,q+1}\left[z\left|\begin{matrix}(1-a_k,\alpha_k;A_k)_{1,p}\\(0,1)(1-b_k,\beta_k;B_k)_{1,q}\end{matrix}\right.\right]={}_p\psi_q\left[\begin{matrix}(a_k,\alpha_k;A_k)_{1,p}\\(b_k,\beta_k;B_k)_{1,q}\end{matrix};(-z)\right]\quad(12)$$

Using the same assumptions in the main result in equation (9) then they takes the following form

$$\int_0^{\infty}\frac{x^{\rho-1}}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\lambda}}\,{}_p\psi_q\left[\begin{matrix}(1-a_k,\alpha_k,A_k)_{1,p}\\(0,1);(1-b_k,\beta_k,B_k)_{1,q}\end{matrix};\frac{-z}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\eta}}\right]\times$$

$$S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_1}},\frac{t_2}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_2}},\ldots,\frac{t_r}{\left\{x+a+\sqrt{x^2+2ax}\right\}^{\mu_r}}\right]dx=\frac{\Gamma(2\rho)}{2^{\rho-1}a^{\lambda-\rho}}\times$$

$${}_{p+2}\psi_{q+2}\left[\begin{matrix}(a_k,\alpha_k,A_k)_{1,p};\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right);\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r+\rho;\eta;1\right)(a_k,\alpha_k)_{n,p+2}\\\left(1-\lambda-\sum_{j=1}^{r}\mu_r\delta_r;\eta;1\right)\left(-\lambda-\sum_{j=1}^{r}\mu_r\delta_r-\rho;\eta;1\right);(b_k,\beta_k,B_k)_{1,q}\end{matrix};\frac{-z}{a^{\eta}}\right]S^{m_1,m_2,\ldots,m_r}_{n_1,n_2,\ldots,n_r}\left[\frac{t_1}{a^{\mu_1}},\ldots,\frac{t_r}{a^{\mu_r}}\right]\quad(13)$$

4. Conclusion

In this paper, we have successfully derived a set of generalized integrals involving the $\bar{H}$-function and Srivastava's polynomials using known results from the table of Mellin transforms. The resulting expressions not only encompass a variety of special cases available in the existing literature but also provide a more unified framework for evaluating complex integrals involving special functions. These findings enrich the theory of integral transforms and special functions, and open up new avenues for further research in analytical and applied mathematics. Potential applications of these integrals can be explored in mathematical modeling, quantum mechanics, and signal processing, where such advanced functions frequently arise.

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