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On the inverse Laplace transform of special functions containing the Rodrigues type polynomial

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ABSTRACT. In the present paper, we obtain the inverse Laplace transform involving the product of a general class of polynomials $\prod_{j=1}^{r} S_{n_j}^{m_j}(x_j)$, the polynomial set $S_{\mu}^{\alpha,\beta,0}[x]$, and the H-function of several complex variables. On account of the most general character of the general class of polynomials, generalized polynomial set and the H-function of several complex variables involved herein, the inverse Laplace transform of the product of a large number of special functions involving one or more variables, occurring frequently in the problems of theoretical physics and engineering sciences can be obtained as particular cases of our main findings. For the sake of illustration, we obtain the inverse Laplace transform of product of two generalized Hermite polynomials given by Gould and Hopper [9], and the H-function of several complex variables. Our result provides a unification of the inverse Laplace transform pertaining to the product of polynomials and special functions earlier obtained by Soni and Singh [14,15], Gupta and Soni [10,11], Srivastava [2], and Rathie [13].

1. Introduction

The Laplace transform of the function $f(x)$ is defined in the following usual manner:

$$F(p) = L\{f(x), p\} = \int_0^\infty e^{-px} f(x)dx. \tag{1.1}$$

The function $f(x)$ is called the inverse Laplace transform of $F(p)$ and will be denoted by $L^{-1}\{F(p)\}$ in the paper.
The general class of polynomials introduced by Srivastava [5, p. 1, eq. (1)] is defined in the following manner:

$$S_n^m[x] = \sum_{K=0}^{[\frac{n}{m}]} \frac{(-n)_{mK}}{K!} A_{n,K} x^K, \quad n = 0, 1, 2, ..., \tag{1.2}$$

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where m is an arbitrary positive integer and the coefficients $A_{n,K}$ $(n, K \geqslant 0)$ are arbitrary constants, real or complex.
Also, $S_{\mu}^{\alpha,\beta,\tau}[x]$ occurring in the sequel denotes the generalized polynomial set introduced by Raizada [18], and is defined by the following Rodrigues type formula [18, p. 64, eq. (2.1.8)]:

(1.3)
$$S_{\mu}^{\alpha,\beta,\tau}[x;\xi,\zeta,q,A,B,m,k,l] = (Ax+B)^{-\alpha}(1-\tau x^{\xi})^{\frac{-\beta}{\tau}} T_{k,l}^{m+\mu}\Big[(Ax+B)^{\alpha+q\mu}(1-\tau x^{\xi})^{\frac{\beta}{\tau}+\zeta\mu}\Big],$$

where the differential operator $T_{k,l}$ being defined as

$$T_{k,l} = x^{l}\left(k + x\frac{d}{dx}\right). \tag{1.4}$$

The explicit form of this generalized polynomial set [18, p.71, eq.(2.3.4)] is given by

$$S_{\mu}^{\alpha,\beta,\tau}[x:\xi,\zeta,q,A,B,m,k,l] \tag{1.5}$$

$$= B^{q\mu}x^{l(m+\mu)}(1-\tau x^{\xi})^{\zeta\mu}l^{(m+\mu)}\sum_{v=0}^{m+\mu}\sum_{u=0}^{v}\sum_{j=0}^{m+\mu}\sum_{i=0}^{j}\frac{(-1)^{j}(-j)_{i}\alpha_{j}(-v)_{u}(-\alpha-q\mu)_{i}}{u!v!i!j!(1-\alpha-j)!}\left(\frac{-\beta}{\tau}-\zeta\mu\right)_{v}$$

$$.\left(\frac{i+k+\xi u}{l}\right)_{m+\mu}\left(\frac{-\tau x^{\xi}}{1-\tau x^{\xi}}\right)^{v}\left(\frac{Ax}{B}\right)^{i}.$$

Note that the polynomial set defined by (1.3) is very general in nature and it unifies and extends a number of classical polynomials introduced and studied by various research workers such as Chatterjea [17], Gould-Hopper [9], Krall and Frink [4], Singh and Srivastava [16] etc. Some of the special cases of (1.3) are given by Raizada in a tabular form [18, p. 65]. We shall require the following explicit form of (1.3) which will be obtained by taking $A = 1$, $B = 0$ and let $\tau \to 0$ in (1.3) and use the well known confluence principle

$$\begin{bmatrix} limit & = (b)_{n}(\frac{x}{b})^{n} = x^{n} \\ |b| \to \infty & \end{bmatrix} \tag{1.6}$$

there in, we arrive at the following polynomial set

$$S_{\mu}^{\alpha,\beta,0}[x] = S_{\mu}^{\alpha,\beta,0}[x:\xi,q,1,0,m,k,l] \tag{1.7}$$

$$= x^{q\mu+l(m+\mu)} l^{m+\mu} \sum_{v=0}^{m+\mu} \sum_{u=0}^{v} \frac{(-v)_u}{u!v!} \left(\frac{\alpha + q\mu + k + \xi u}{l} \right)_{m+\mu} (\beta x^{\xi})^v.$$

The H-function of several complex variables introduced by Srivastava and Panda [7, p. 265-274] is defined as

$$H\left[z_1, ..., z_r\right] \tag{1.8}$$

$$= H^{0,N:(M',N');...;(M^{(r)},N^{(r)})}_{P,Q:(P',Q');...;(P^{(r)},Q^{(r)})}$$

$$\begin{bmatrix} [(a^{'}) : \theta^{'}, ..., \theta^{(r)}] : [(b^{'}) : \phi^{'}], ..., [(b^{(r)}) : \phi^{(r)}]; & . \\ [(c^{'}) : \psi^{'}, ..., \psi^{(r)}] : [(d^{'}) : \delta^{'}], ..., [(d^{(r)}) : \delta^{(r)}]; & z_1, ..., z_r \end{bmatrix}$$

$$= \frac{1}{(2\pi\omega)^r} \int_{L_1} .... \int_{L_r} R_1(\xi_1)....R_r(\xi_r) N(\xi_1, ..., \xi_r) z_1^{(\xi_1)}....z_r^{(\xi_r)} d\xi_1...d\xi_r,$$

where

$$\omega = \sqrt{-1}.$$

The convergence conditions and other details of the above function are given by Srivastava, Gupta and Goyal [6, p. 251, eq. (c.1)].
For the sake of brevity

$$T_i = -\sum_{j=N+1}^{P} \theta_j^{(i)} - \sum_{j=1}^{Q} \psi_j^{(i)} + \sum_{j=1}^{N^{(i)}} \phi_j^{(i)} - \sum_{j=N^{(i)}+1}^{P^{(i)}} \phi_j^{(i)} + \sum_{j=1}^{M^{(i)}} \delta_j^{(i)} - \sum_{j=M^{(i)}+1}^{Q^{(i)}} \delta_j^{(i)} > 0 \tag{1.9}$$

$$i \in (1, 2, ..., r);$$

$$\Lambda_i = min \left\{ Re \left(\frac{d_j^{(i)}}{\delta_j^{(i)}} \right) \right\}, \qquad (j = 1, 2, ..., M^{(i)}). \tag{1.10}$$

We assume that the convergence and existence conditions of above function are satisfied by each of the various H-functions involved throughout the present work.
The following inverse Laplace transform which can be easily obtained after a little simplification with the help of a known formula [12, p. 122, eq. (2.2)] will be required later on

$$L^{-1} \left\{ S^{\sum_{i=1}^{\tau} (l_i a_i - \lambda)} \prod_{i=1}^{\tau} (S^{l_i} + \lambda_i)^{-a_i} \right\} \tag{1.11}$$

$$= \frac{t^{\lambda-1}}{\prod_{i=1}^{\tau} \Gamma(a_i)} . H^{0,0:(1,1);...;(1,1)}_{0,1:(1,1);...;(1,1)}$$

$$\left[\begin{matrix} ---:[(1-a_1):1],...,[(1-a_\tau):1] \\ [(1-\lambda):l_1,...,l_\tau]:[(0):1],...,[(0):1]: \quad \lambda_1 t^{l_1},...,\lambda_\tau t^{l_\tau}\end{matrix}\right],$$

where $Re(S)>0$, $Re(\lambda)>0$, $0<l_i<2$, $|arg\lambda_i|<(2-l_i)\frac{\pi}{2}$ or $l_i=2$ and $\lambda_i>0$ $(i=1,2,...,\tau)$.

2. Main Result

We shall establish the following result:

$$L^{-1}\left\{p^{-\eta}\prod_{i=1}^{\tau}(p^{l_i}+q_i)^{-\sigma_i}\prod_{i=1}^{\varsigma}S_{n_j}^{m_j}[x_j p^{-\lambda_j}\prod_{i=1}^{\tau}(p^{l_i}+q_i)^{-\rho_i^j}]S_\mu^{\alpha,\beta,0}[p^{-a}\prod_{i=1}^{\tau}(p^{l_i}+q_i)^{-b_i}]\right.$$

$$\left. .H[z_1 p^{-u_1}\prod_{i=1}^{\tau}(p^{l_i}+q_i)^{-v_i^1},...,z_r p^{-u_r}\prod_{i=1}^{\tau}(p^{l_i}+q_i)^{-v_i^r}]\right\}$$

$$=t^{\eta+aq\mu+a\lambda m+a\lambda\mu+av\xi+l_1\sigma_1+...+l_\tau\sigma_\tau+b_1\{q\mu+\lambda m+\lambda\mu+v\xi\}+...+b_\tau\{q\mu+\lambda m+\lambda\mu+v\xi\}-1}$$

$$.\sum_{K_1}^{[\frac{n_1}{m_1}]}...\sum_{K_\varsigma}^{[\frac{n_\varsigma}{m_\varsigma}]}\sum_{u=0}^{v}\sum_{v=0}^{m+\mu}\frac{(-n_1)_{m_1K_1}}{K_1!}...\frac{(-n_\varsigma)_{m_\varsigma K_\varsigma}}{K_\varsigma!}(A_1)_{n_1,K_1}...(A_\varsigma)_{n_\varsigma,K_\varsigma}(-v)_u$$

$$.\left(\frac{\alpha+q\mu+\xi u+k}{\lambda}\right)_{m+\mu}\frac{\beta^\nu}{u!v!}\lambda^{m+\mu}(x_1 t^{\lambda_1+\rho_1^{'}l_1+...+\rho_\tau^{'}l_\tau})^{k_1}...(x_\varsigma t^{\lambda_\varsigma+\rho_1^{\varsigma}l_1+...+\rho_\tau^{\varsigma}l_\tau})^{k_\varsigma}$$

$$.H^{0,N+\tau:(M',N');...;(M^{(r)},N^{(r)});1,0;...;1,0}_{P+\tau,Q+\tau+1:(P',Q');...;(P^{(r)},Q^{(r)});0,1;...;0,1}$$

(2.1)

$$\left[\begin{array}{cc}
[1-\sigma_1-b_1(q\mu+\lambda(m+\mu)+\nu\xi)-\rho_1^{'}K_1- & z_1t^{u_1+l_1v_1^{'}+...+l_\tau v_\tau^{'}} \\
...-\rho_1^{\varsigma}K_\varsigma; v_1^{'},...,v_1^{r},1,0,...,0],... & . \\
[1-\sigma_\tau-b_\tau(q\mu+\lambda(m+\mu)+\nu\xi)-\rho_\tau^{'}K_1- & \\
...-\rho_\tau^{\varsigma}K_\varsigma; v_\tau^{'},...,v_\tau^{r},0,0,...,1], & . \\
[1-\sigma_1-b_1(q\mu+\lambda(m+\mu)+\nu\xi)-\rho_1^{'}K_1- & \\
...-\rho_1^{\varsigma}K_\varsigma; v_1^{'},...,v_1^{r},0,0,...,0],... & . \\
[1-\sigma_\tau-b_\tau(q\mu+\lambda(m+\mu)+\nu\xi)-\rho_\tau^{'}K_1- & \\
...-\rho_\tau^{\varsigma}K_\varsigma; v_\tau^{'},...,v_\tau^{r},0,0,...,0], & . \\
[(a^{'}):\theta^{'},...\theta^{(r)},0,...,0]: & z_rt^{u_r+l_1v_1^{r}+...+l_\tau v_\tau^{r}} \\
[1-\eta-a(q\mu+\lambda(m+\mu)+\nu\xi)-l_1\sigma_1-...-l_\tau\sigma_\tau- & q_1t^{l_1} \\
b_1(q\mu+\lambda(m+\mu)+\nu\xi)-...-b_\tau(q\mu+\lambda(m+\mu)+\nu\xi)- & . \\
(\lambda_1+\rho_1^{'}l_1+...+\rho_\tau^{'}l_\tau)K_1-... & \\
-(\lambda_\varsigma+\rho_1^{\varsigma}l_1+...+\rho_\tau^{\varsigma}l_\tau)K_\varsigma; & . \\
u_1+v_1^{'}l_1+...+v_\tau^{'}l_\tau,...,u_r+v_1^{r}l_1+...+v_\tau^{r}l_\tau,l_1,...,l_\tau], & . \\
----:[(b^{'}):\phi^{'}],...,[(b^{(r)}):\phi^{(r)}];...;...;... & \\
[(c^{'}):\psi^{'},...,\psi^{(r)},0,...,0]:[(d^{'}):\delta^{'}], & \\
...,[(d^{(r)}):\delta^{(r)}];(0,1);...;(0,1) & q_\tau t^{l_\tau}
\end{array}\right],$$

provided that the quantities $\lambda_1,\rho_1^{'},...,\rho_\tau^{'},...,\lambda_\varsigma,\rho_1^{\varsigma},...,\rho_\tau^{\varsigma},u_1,v_1^{'},...,v_\tau^{'},...,u_r,v_1^{r},...,v_\tau^{r}$ are all positive, $Re(p)>0$ and

$$Re(\eta+l_1\sigma_1+...+l_\tau\sigma_\tau)+\min(1\leqslant j\leqslant M^{(i)})\left[Re(u_i+l_1v_1^{i}+...+l_\tau v_\tau^{i})\left(\frac{d_j^{i}}{\delta_j^{i}}\right)\right]>0,$$

$$\sum_{j=1}^{P}\alpha_j^{(i)}+\sum_{j=1}^{P^{(i)}}\gamma_j^{(i)}-\sum_{j=1}^{Q}\beta_j^{(i)}-\sum_{j=1}^{Q^{(i)}}\delta_j^{(i)}-(u_i+l_1v_1^{i}+...+l_\tau v_\tau^{i})<0,\quad(i=1,2,...,r)$$

$$\Omega_i=-\sum_{j=N+1}^{P}\alpha_j^{(i)}+\sum_{j=1}^{N^{(i)}}\gamma_j^{(i)}-\sum_{j=N^{(i)}+1}^{P^{(i)}}\gamma_j^{(i)}-\sum_{j=1}^{Q}\beta_j^{(i)}+\sum_{j=1}^{M^{(i)}}\delta_j^{(i)}-\sum_{j=M^{(i)}+1}^{Q^{(i)}}\delta_j^{(i)}-[u_i+(l_1+1)v_1^{i}+....+(l_\tau+1)v_\tau^{i}]>0,$$

$|argz_i|<\frac{1}{2}\Omega_i\pi$ or $\Omega_i=0$ and $z_i>0$ $(i=1,2,...,r)$,

$$0<l_i<1,\quad |arg\alpha_j|<\frac{\pi}{2}(1-l_j),\quad (j=1,2,...,\tau)\quad or\quad l_1=...=l_\tau=1,\quad \alpha_1>0,.....,\alpha_\tau>0.$$

It may be remarked here that some of the exponents

$$l_1,...,l_\tau,\lambda_1,\eta_1^{'},....,\eta_\tau^{'},...,\lambda_\varsigma,\eta_1^{\varsigma},....,\eta_\tau^{\varsigma},u_1,v_1^{'},...,v_\tau^{'},...,u_r,v_1^{r},...,v_\tau^{r},$$

in (2.1) can decrease to zero provided that both sides of the resulting equation has a meaning.

PROOF. In order to prove (2.1), first we express the general class of polynomials and the generalized polynomial set occurring on the left-hand side of (2.1) in the series form given by (1.2) and (1.7) respectively, replace the H-function of several complex variables occurring therein by its well known Mellin-Barnes contour integral with the help of (1.8). Now, on interchanging the orders of summations and integration, and taking the inverse Laplace transform by using the formula (1.11). Finally, interpreting the resulting Mellin-Barnes contour integral in the form of the H-function of $r+\tau$ variables which is permissible under the conditions stated with (2.1). □

3. Particular cases

(i) If we take $\tau = 2$, $\varsigma = 1$, $l_1 = q_1$, $l_2 = q_2$ in (2.1), and reducing the general class of polynomials in terms of Gould-Hopper polynomials [9, p. 58, eq. (6.2); see also 8, p. 161, eq. (1.15)]

$$g_{n_1}^{m_1}[x_1 p^{-\lambda_1}(p^{l_1}+l_1)^{\rho_1'}(p^{l_2}+l_2)^{\rho_2'}, h],$$

also the generalized polynomial set in terms of Gould-Hopper polynomial [9, p. 52; see also 12, p. 65]

$$H_\mu^{(\xi)}[p^{-a}(p^{l_1}+l_1)^{-b_1}(p^{l_2}+l_2)^{-b_2}, \alpha, \beta],$$

we arrive at the following interesting result

$$L^{-1}\left\{p^{-\eta}(p^{l_1}+l_1)^{-\sigma_1}(p^{l_2}+l_2)^{-\sigma_2}\right.$$

$$.g_{n_1}^{m_1}[x_1 p^{-\lambda_1}(p^{l_1}+l_1)^{\rho_1'}(p^{l_2}+l_2)^{\rho_2'}, h].H_\mu^{(\xi)}[p^{-a}(p^{l_1}+l_1)^{-b_1}(p^{l_2}+l_2)^{-b_2}, \alpha, \beta]$$
$$\left..H[z_1 p^{-u_1}(p^{l_1}+l_1)^{-v_1'}(p^{l_2}+l_2)^{-v_2'}, ..., z_r p^{-u_r}(p^{l_1}+l_1)^{-v_1^r}(p^{l_2}+l_2)^{-v_2^r}]\right\}$$

$$= t^{\eta+l_1\sigma_1+l_2\sigma_2-1}\sum_{K_1}^{[\frac{n_1}{m_1}]}\sum_{u=0}^{v}\sum_{v=0}^{\mu}\frac{n_1!}{K_1!(n_1-m_1K_1)}\frac{(-v)_u(-\alpha-\xi u)_\mu h^K}{u!v!}$$

$$.t^{(a+l_1b_1+l_2b_2)(v\xi-\mu)}(x_1 t^{\lambda_1+l_1\rho_1'+l_2\rho_2'})^{n_1-m_1K_1}$$

$$.H^{0,N+2:(M',N');...;(M^{(r)},N^{(r)});1,0;1,0}_{P+2,Q+3:(P',Q');...;(P^{(r)},Q^{(r)});0,1;0,1}$$

$$
(3.1)\qquad \left[\begin{array}{cc}
[1-\sigma_1-\rho_1^{'}(n_1-m_1K_1)- & z_1 t^{u_1+l_1v_1^{'}+l_2v_2^{'}} \\
b_1(\xi v-\mu); v_1^{'},...,v_1^{r},1,0] & \\
[1-\sigma_1-\rho_1^{'}(n_1-m_1K_1)- & . \\
b_1(\xi v-\mu); v_1^{'},...,v_1^{r},0,0] & \\
[1-\sigma_2-\rho_2^{'}(n_1-m_1K_1)- & . \\
b_2(\xi v-\mu); v_2^{'},...,v_2^{r},0,1] & \\
[1-\sigma_2-\rho_2^{'}(n_1-m_1K_1)- & . \\
b_2(\xi v-\mu); v_2^{'},...,v_2^{r},0,0] & \\
[(a^{'}):\theta^{1},...\theta^{r},0,...,0]: & z_r t^{u_r+l_1v_1^{r}+l_2v_2^{r}} \\
[1-(\eta+l_1\sigma_1+l_2\sigma_2)- & \\
(\lambda_1+\rho_1^{'}l_1+\rho_2^{'}l_2)(n_1-m_1K_1); & \\
u_1+v_1^{'}l_1+v_2^{'}l_2,...,u_r+v_1^{r}l_1+v_2^{r}l_2,l_1,l_2] & \\
----:[(b^{'}):\phi^{'}],...,[(b^{(r)}):\phi^{(r)}];-;- & \\
[(c^{'}):\psi^{'},...,\psi^{(r)},0,0]:[(d^{'}):\delta^{'}], & l_1t^{l_1} \\
...,[(d^{(r)}):\delta^{(r)}];(0,1),(0,1) & l_2t^{l_2}
\end{array}\right],
$$

The result in (3.1) is valid under the conditions surrounding (2.1).

(ii)

If the generalized polynomial set $S_{\mu}^{\alpha,\beta,0}$ in our main result (2.1) reduces to unity by some suitably specialization of the coefficients then we get a known result due to Soni and Singh [14, p. 51-52, eq. (2.1)].

(iii)

On taking $\tau = \varsigma = 2$ in (2.1), and $S_{\mu}^{\alpha,\beta,0}$ reduces to unity by some suitably specialization of the coefficients ,we get a known result due to Gupta and Soni [10, p. 21-22, eq. (2)].

(iv)

If in the main result (2.1), we reduce the H-function of several complex variables to the product of the Whittaker function and the Meijer's G-function and take the other factor/functions occurring therein to be unity,we arrive after a little simplification at a result which is in essence the formula obtained earlier by Srivastava [2, p. 827, eq. (2.4)].

(v)

If the Meijer's G-function reduces to Bessel function by suitably specialization of factors in case (iv), then we easily yield a result obtained by Rathie [13, p. 368, eq. (3.2)].

(vi)

Putting $\varsigma = 2$ in (2.1),the H-function of r-variables breaks up into the product of r Fox H-function [3] and reduce the generalized polynomial set into unity, then we arrive at a result obtained by Soni and Singh [15, p. 90, eq.(2.1)].

(vii)
Let $\tau = \varsigma = 2$, and $N = P = Q = 0$, $M^{(i)} = Q^{(i)} = 1$, $N^{(i)} = P^{(i)} = 0$, $d^{(i)} = 0, \delta^{(i)} = 1$, $u_i = 1, v_1^{(i)} = v_2^{(i)} = 0$, and z_i tends to zero (i=1,2,...,r),the H-function of r-variables reduces to Fox H-function [3] and the generalized polynomial set reduces into unity, then we arrive at another result obtained by Gupta and Soni [11, p. 2-3, eq. (2.1)].

The results presented in this paper would at once yield a very large number of results involving special functions in the problem of mathematical analysis, applied mathematics and mathematical physics.

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