Identities related to the Stirling numbers and modified Apostol-type numbers on Umbral Calculus

Takao Komatsu and Yilmaz Simsek

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Abstract By using umbral calculus and umbral algebra methods, we derive several interesting identities and relations related to the modified and unification of the Bernoulli, Euler and Genocchi polynomials and numbers and the generalized (β -) Stirling numbers of the second kind. Finally, we give some applications and remarks related to these numbers and polynomials.

Introduction, definitions and preliminaries

Throughout this paper, we use the following standard notations: Let $\mathbb{N}, \mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{R}^+$ and \mathbb{C} denote the sets of positive integers, integers, rational numbers, real numbers, positive real numbers and complex numbers, respectively, and $\mathbb{N}_0 := \mathbb{N} \cup \{0\}$. We also assume that $\log z$ denotes the principal branch of the multi-valued function $\log z$ with the imaginary part $\Im(\log z)$ constrained by $-\pi < \Im(\log z) < \pi$. For all $0 \le k \le n$, let $(n)_k = k! \binom{n}{k}$ (cf. [17]).

The unification of the Bernoulli, Euler and Genocchi polynomials is defined by Ozden [6]:

$$g_{\beta}(x,t;k,a,l) := \frac{2^{1-k}t^{k}e^{tx}}{\beta^{l}e^{t} - a^{l}} = \sum_{n=0}^{\infty} \mathcal{Y}_{n,\beta}(x;k,a,l) \frac{t^{n}}{n!},$$
(0.1)

where if $\beta = a$, then $|t| < 2\pi$ and if $\beta \neq a, k \in \mathbb{N}_0, a, l \in \mathbb{C} \setminus \{0\}$, then $|t| < l \log \left(\frac{\beta}{a}\right)$.

Remark 0.1. Note that Equation (0.1) with x = 1 reduces to the generating functions for the unification of the Bernoulli, Euler and Genocchi numbers.

Remark 0.2. Using the special values of a, l, k and β in (0.1), the polynomials $\mathcal{Y}_{n,\beta}(x; k, a, l)$ provide us with a generalization and unification of the Apostol-Bernoulli polynomials, Apostol-Euler polynomials and Apostol-Genocchi polynomials, respectively:

$$\mathcal{B}_n(x,\beta) = \mathcal{Y}_{n,\beta}(x;1,1,1),$$

$$\mathcal{E}_n(x,\beta) = \mathcal{Y}_{n,\beta}(x;0,-1,1)$$

and

$$\mathcal{G}_n(x,\beta) = 2\mathcal{Y}_{n,\beta}(x;1,-1,1)$$

(cf. [1]-[19] and the references cited in each of these earlier works). Moreover, for the classical Bernoulli polynomials $B_n(x)$, the classical Euler polynomials $E_n(x)$ and the classical Genocchi polynomials $G_n(x)$, one easily has

$$B_n(x) = \mathcal{B}_n(x, 1),$$
$$E_n(x) = \mathcal{E}_n(x, 1)$$

and

Substituting

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l Euler numbers

and

$$G_n = G_n(0)$$

 $E_n = 2^n E_n(\frac{1}{2}),$

(cf. [1]-[19] and the references cited in each of these earlier works).

In [9], Ozden and Simsek modified the polynomials $\mathcal{Y}_{n,\beta}(x; k, a, l)$ as follows:

$$f(t;k,a,b,\beta) = \left(\frac{t^k 2^{1-k}}{\beta b^t - a^t}\right)^v b^{xt} = \sum_{n=0}^{\infty} Y_{n,\beta}^{(v)}(x,k,a,b) \frac{t^n}{n!},$$
(0.2)

where the polynomials $Y_{n,\beta}^{(v)}(x,k,a,b)$ are called *modification and unification of the Apostol-type* polynomials of order v. One easily sees that

$$Y_{n,\beta}^{(v)}(0,k,a,b) = Y_{n,\beta}^{(v)}(k,a,b),$$

which denotes modification and unification of the Apostol-type numbers of order v, and

$$\mathcal{Y}_{n,\beta}^{(v)}(x;k,1,1) = Y_{n,\beta}^{(v)}(x,k,1,e)$$

which denotes Apostol-type polynomials (cf. [6], [8]).

Ozden and Simsek [9] gave an explicit formula for the polynomials $Y_{n,\beta}^{(v)}(x,k,a,b)$ as follows:

$$Y_{n,\beta}^{(v)}(x,k,a,b) = \sum_{j=0}^{n} \binom{n}{j} x^{n-j} \left(x \ln b\right)^{n-j} Y_{j,\beta}^{(v)}(k,a,b).$$

Ozden and Simsek [9] also gave the following recurrence relation for the numbers $Y_{\beta}(k, a, b)$ as follows:

$$\beta \left(Y_{\beta}(k,a,b) + \ln b \right)^{n} - \left(Y_{\beta}(k,a,b) + \ln a \right)^{n} = \begin{cases} 2^{1-k}k! & n=k \\ 0 & n \neq k \end{cases}$$

where $(Y_{\beta}(k, a, b))^m$ is replaced by $Y_{m,\beta}(k, a, b)$.

Remark 0.3. If we substitute $k = a = \beta = v = 1$ and b = e into (0.2), we have

$$Y_{n,1}^{(1)}(1,1,e) = B_n$$

where B_n denotes the classical Bernoulli numbers. If we substitute $k = 0, a = v = 1, \beta = -1$ and b = e into (0.2), we have

$$Y_{n,-1}^{(1)}(0,1,e) = -E_n,$$

where E_n denotes the classical Euler numbers. If we substitute k = a = v = 1, $\beta = -1$ and b = e into (0.2), we have

$$Y_{n,-1}^{(1)}(1,1,e) = -\frac{1}{2}G_n$$

where G_n denotes the classical Genocchi numbers.

The generalized β -Stirling type numbers of the second kind are given by the following definition:

74

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generalized λ -Stirling following generating

(0.3)

Substituting a = 1 and b = e into (0.3), we have the β -Stirling numbers of the second kind

$$\mathcal{S}(n,v;1,e;\beta) = S(n,v;\beta)$$

(cf. [5], [16], [17]). If $\beta = 1$, then we get the classical Stirling numbers of the second kind as follows:

$$S(n,v;1) = S(n,v)$$

(cf. [1]-[19]).

Proof of the following theorem was given by Simsek [15].

Theorem 0.5. We have

$$S(n,v;a,b;\beta) = \frac{1}{v!} \sum_{j=0}^{v} (-1)^{j} {\binom{v}{j}} \beta^{v-j} \left(j \ln a + (v-j) \ln b\right)^{n}$$
(0.4)

and

$$S(n,v;a,b;\beta) = \frac{1}{v!} \sum_{j=0}^{v} (-1)^{v-j} {\binom{v}{j}} \beta^{j} \left(j \ln b + (v-j) \ln a\right)^{n}.$$
(0.5)

Remark 0.6. Note that by setting a = 1 and b = e in the assertions (0.4) of Theorem 0.5, we have the following result:

$$S(n,v;\beta) = \frac{1}{v!} \sum_{j=0}^{v} \begin{pmatrix} v \\ j \end{pmatrix} \beta^{v-j} (-1)^j (v-j)^n$$

The above relation has been studied by Srivastava [16] and Luo [5]. For $\beta = 1$, we have

$$S(n,v) = \frac{1}{v!} \sum_{j=0}^{v} \begin{pmatrix} v \\ j \end{pmatrix} (-1)^{j} (v-j)^{n}$$

(cf. [1]-[19]).

Definition 0.7. ([15]) Let $a, b \in \mathbb{R}^+$ $(a \neq b), x \in \mathbb{R}, \beta \in \mathbb{C}$ and $v \in \mathbb{N}_0$. The generalized array type polynomials $S_v^n(x; a, b; \beta)$ are defined by means of the following generating function:

$$g_v(x,t;a,b;\beta) = \frac{1}{v!} \left(\beta b^t - a^t\right)^v b^{xt} = \sum_{n=0}^{\infty} \mathcal{S}_v^n(x;a,b;\beta) \frac{t^n}{n!}.$$
 (0.6)

By using (0.6), we have

$$S_{v}^{n}(x;a,b;\beta) = \frac{1}{v!} \sum_{j=0}^{v} (-1)^{v-j} \begin{pmatrix} v \\ j \end{pmatrix} \beta^{j} \left(\ln \left(a^{v-j} b^{x+j} \right) \right)^{n}$$
(0.7)

(*cf.* [15]).

We here note that the polynomials $S_v^n(x; a, b; \beta)$ are called the generalized λ -array type polynomials.

Substituting x = 0 into (0.7), we arrive at (0.5):

$$\mathcal{S}_v^n(0; a, b; \beta) = \mathcal{S}(n, v; a, b; \beta).$$



In this paper, by using umbral calculus and umbral algebra methods, we derive many interesting identities and relations related to the modified and unification of the Bernoulli, Euler and Genocchi polynomials and numbers and the generalized (β -) Stirling numbers of the second kind. We also give some applications and remarks related to these numbers and polynomials.

1 Identities on Umbral Calculus and Umbral Algebra

In this section, we give relation between the modification and unification of the Apostol-type polynomials of order v and the Stirling numbers of the second kind on the umbral calculus and umbral algebra.

We need some identities of the umbral algebra and calculus. Here we note that the following formulas and notations are given in work of Roman [11]:

Let P be the algebra of polynomials in the single variable x over the complex number field. Let P^* be the vector space of all linear functionals on P. Let $\langle L | p(x) \rangle$ be the action of a linear functional L on a polynomial p(x). Let F denote the algebra of formal power series

$$f(t) = \sum_{k=0}^{\infty} \frac{a_k}{k!} t^k.$$
 (1.1)

Let $f \in F$ define a linear functional on P and for all $k \in \mathbb{N}_0$,

$$a_{k} = \left\langle f\left(t\right) \mid x^{k}\right\rangle. \tag{1.2}$$

The order o(f(t)) of a power series f(t) is the smallest integer k for which the coefficient of t^k does not vanish. A series f(t) for which o(f(t)) = 1 is called a delta series. And a series f(t) for which o(f(t)) = 0 is called a invertible series.

Let f(t), g(t) be in F. Then we have

$$\langle f(t)g(t) \mid p(x) \rangle = \langle f(t) \mid g(t)p(x) \rangle.$$
(1.3)

For all p(x) in P, we have

$$\left\langle e^{yt} \mid p\left(x\right) \right\rangle = p\left(y\right) \tag{1.4}$$

and

$$e^{yt}p(x) = p(x+y).$$
 (1.5)

The Appell polynomials are defined by means of the following generating function

$$\sum_{k=0}^{\infty} \frac{s_k(x)}{k!} t^k = \frac{1}{g(t)} e^{xt}.$$
(1.6)

(*cf.* [11]).

Theorem 1.1. ([11, p. 20, Theorem 2.3.6]) Let f(t) be a delta series and let g(t) be an invertible series. Then there exist a unique sequence $s_n(x)$ of polynomials satisfying the orthogonality conditions

$$\left\langle g(t)f(t)^{k} \mid s_{n}(x) \right\rangle = n! \delta_{n,k} \tag{1.7}$$

for all $n, k \in \mathbb{N}_0$.

Let Retracted because of unfortunate communications between the first author and the guest editors. The paper was submitted by the first author for presentation only during the conference, but not for publication in the special issue of Palestine Journal of Mathematics. (1.9)

Lemma 1.3. Let $n \in \mathbb{N}_0$. The following relationship holds true:

$$\left\langle (\beta b^t - a^t)^j \mid Y_{n,\beta}(x;k,a,b) \right\rangle = \sum_{m=0}^j \binom{j}{m} (-1)^{(j-m)} \beta^m Y_{n,\beta}(m\ln b + (j-m)\ln a,k,a,b).$$

Proof.

$$\left\langle (\beta b^t - a^t)^j \mid Y_{n,\beta}(x;k,a,b) \right\rangle$$

$$= \left\langle \sum_{m=0}^j (-1)^{j-m} {j \choose m} \beta^m e^{t(m\ln b + (j-m)\ln a)} \mid Y_{n,\beta}(x;k,a,b) \right\rangle$$

$$= \sum_{m=0}^j (-1)^{j-m} {j \choose m} \beta^m \left\langle e^{t(m\ln b + (j-m)\ln a)} \mid Y_{n,\beta}(x;k,a,b) \right\rangle$$

Substituting Equation (1.4) into the above equation, we arrive at the desired result. **Remark 1.4.**

$$\left\langle (\beta b^t - 1)^j \mid Y_{n,\beta}(x;k,1,e) \right\rangle = \left\langle (\beta e^t - 1)^j \mid \mathcal{Y}_{n,\beta}(x,k,1,1) \right\rangle$$

(cf. [4, Lemm 2. Eq- (3.1)]).

Lemma 1.5. Then the following identity holds:

$$v^{n}S(n,l) = \frac{1}{l!} \left\langle \left(e^{vt} - 1\right)^{l} \mid x^{n} \right\rangle$$

where S(n, l) is the Stirling numbers of the second kind. Proof. We set

$$\frac{1}{l!} \left(e^{vt} - 1 \right)^l = \sum_{j=0}^{\infty} v^n S\left(n, l\right) \frac{t^n}{n!}$$

By using (1.1) and (1.2), we get the desired result.

Remark 1.6. Substituting v = 1 into Lemma 1.5, we have

$$S(n,l) = \frac{1}{l!} \left\langle \left(e^t - 1 \right)^l \mid x^n \right\rangle$$

(*cf.* [11]).

Theorem 1.7. The following identity holds true:

$$\sum_{m=0}^{j} {j \choose m} (-1)^{(j-m)} \beta^{m} Y_{n,\beta}(m \ln b + (j-m) \ln a, k, a, b)$$

= $2^{1-k} (\ln b)^{n} \beta^{j-1} k! {n \choose k} \sum_{l=0}^{j-1} l! {j-1 \choose l} \left(1 - \frac{1}{\beta}\right)^{j-l-1}$
 $\times \sum_{v=0}^{n-k} {n-k \choose v} ((j-1) \ln a)^{n-k-v} \left(\ln \frac{b}{a}\right)^{v} S(v, l).$

where S(u, v) denote the Stirling numbers of the second kind.

Proof Using Lemma 1.2 we get

11000

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After some elementary calculations in the above equation, we obtain

$$\begin{split} &\left\langle (\beta b^t - a^t)^j \mid Y_{n,\beta}(x;k,a,b) \right\rangle \\ = & 2^{1-k} (\ln b)^n k! \binom{n}{k} \beta^{j-1} \sum_{l=0}^{j-1} \binom{j-1}{l} \left(1 - \frac{1}{\beta}\right)^{j-l-1} e^{t((j-1)\ln a)} \\ & \times \left\langle \left(e^{t\left(\ln \frac{b}{a}\right)} - 1\right)^l \mid x^{n-k} \right\rangle. \end{split}$$

By applying Lemma 1.5 with (1.3) in the above equation, after some calculation, we obtain the desired result.

Remark 1.8. Substituting a = 1 and b = e into Theorem 1.7, we arrive at the work of Dere et al. [4, Thorem 3, p. 3253 and Corollary 2, p. 3254]

$$\sum_{m=0}^{j} {j \choose m} (-1)^{(j-m)} \beta^{m} \mathcal{Y}_{n,\beta}(m;k,1,1)$$

= $\frac{\beta^{j-1}}{2^{k-1}} k! {n \choose k} \sum_{l=0}^{j-1} \frac{(j-1)!}{(j-l-1)!} \left(1 - \frac{1}{\beta}\right)^{j-l-1} S(n-k,l).$

Remark 1.9. By setting $\beta = k = a = 1$ and b = e in Theorem 1.7, we arrive at the following well-known results which was proved by Roman [11, P. 94]:

$$\langle (e^t - 1)^j | B_n(x) \rangle = n (j - 1)! S (n - 1, j - 1)$$

or

$$\sum_{m=0}^{j} {j \choose m} (-1)^{j-m} B_n(m) = n (j-1)! S (n-1, j-1).$$

Substituting a = 1, k = 0, $\beta = -1$ and b = e into Theorem 1.7, we arrive at the following corollary:

Corollary 1.10.

$$\sum_{m=0}^{j} {j \choose m} E_n(m) = \sum_{l=0}^{j-1} {j-l \choose l} 2^{j-l} l! S(n,l) \,.$$

Substituting $a = 1, k = 1, \beta = -1$ and b = e into Theorem 1.7, we arrive at the following corollary:

Corollary 1.11.

$$\sum_{m=0}^{j} {j \choose m} G_n(m) = n \sum_{l=0}^{j-1} {j-l \choose l} 2^{j-l-2} l! S(n-1,l).$$

Corollary 1.12.

$$\langle (e^t+1)^j \mid G_n(x) \rangle = \sum_{m=0}^j {j \choose m} G_n(m).$$

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$$\begin{split} \beta Y_{n,\beta}^{(v)}(x+\ln b;k,a,b) &= Y_{n,\beta}^{(v)}(x+\ln a;k,a,b) \\ &+ 2^{1-k}(n)_k (\ln b)^k Y_{n-k,\beta}^{(v-1)}(x;k,a,b). \end{split}$$

Proof. By using Lemma 1.2, we get

$$(\beta b^t - a^t) Y_{n,\beta}^{(v)}(x;k,a,b) = 2^{1-k} (n)_k (\ln b)^k Y_{n-k,\beta}^{(v-1)}(x;k,a,b).$$
(1.10)

We also use (1.5), we obtain

$$(\beta b^{t} - a^{t})Y_{n,\beta}^{(v)}(x;k,a,b) = \beta Y_{n,\beta}^{(v)}(x + \ln b;k,a,b) - Y_{n,\beta}^{(v)}(x + \ln a;k,a,b).$$
(1.11)

By combining (1.10) and (1.11), we get the desired result.

Remark 1.14. If we set a = 1 and b = e in Theorem 1.13, we obtain [4, p. 3256, Theorem 6]

$$\beta \mathcal{Y}_{n,\beta}^{(v)}(x+1;k,1,1) = \mathcal{Y}_{n,\beta}^{(v)}(x;k,1,1) + 2^{1-k}(n)_k \mathcal{Y}_{n-k,\beta}^{(v-1)}(x;k,1,1)$$

Remark 1.15. By substituting a = 1, k = 0, b = e and $\beta = -1$ into Theorem 1.13, we arrive at the recurrence relations for the Euler polynomials of higher-order as follows: let $v \ge 2$ and $n \in \mathbb{N}$. Then we have

$$E_n^{(v)}(x+1) = -E_n^{(v)}(x) + 2E_n^{(v-1)}(x)$$

(*cf.* [4], [11, p.103]).

Remark 1.16. By substituting a = k = 1, b = e and $\beta = -1$ into Theorem 1.13, we have recurrence relations for the Genocchi polynomials of higher-order as follows: let $v \ge 2$ and $n \in \mathbb{N}$.

$$(e^{t} + 1)G_{n}^{(v)}(x) = 2nG_{n-1}^{(v-1)}(x)$$

(cf. [3, p. 760, Theorem7]).

Remark 1.17. By substituting a = k = 1, b = e and $\beta = 1$ into Theorem 1.13, Dere et al [4] and Roman [11, p. 95, Eq. (4.2.6)] gave recurrence relations for the Bernoulli polynomials of higher-order as follows: Let $v \ge 2$ and $n \in \mathbb{N}$. Then we have

$$B_n^{(v)}(x+1) = B_n^{(v)}(x) + nB_{n-1}^{(v-1)}(x).$$

By using Lemma 1.2 with (1.10), for v = 1, we get the following theorem, which is very useful in the theory of the Diophantine equation:

Theorem 1.18. Let $n, k \in \mathbb{N}_0$ with $n \ge k$. Then we have

$$\left(\beta b^t - a^t\right) Y_{n,\beta}(x;k,a,b) = 2^{1-k} (n)_k (\ln b)^n x^{n-k}.$$
(1.12)

Remark 1.19. Substituting a = 1 and b = e into (1.12), we have

$$\beta \mathcal{Y}_{n,\beta}(x+1;k,1,1) - \mathcal{Y}_{n,\beta}(x;k,1,1) = 2^{1-k}(n)_k x^{n-k}$$

(cf. [10]). By substituting a = k = 1, b = e and $\beta = 1$ into (1.12), we have

$$B_n(x+1) - B_n(x) = nx^{n-1}$$

(cf. [10], [11, p. 95], [17]). By substituting a = 1, k = 0, b = e and $\beta = -1$ into (1.12), we have $E_n(x+1) + E_n(x) = 2x^n$

(cf. [10], [11, p. 95], [17]). By substituting a = k = 1, b = e and $\beta = -1$ into (1.12), we have $G_n(x+1) + G_n(x) = 2nx^{n-1}$

(*cf.* [3, p. 760, Corollary 1], [10]).

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Author information

Takao Komatsu and Yilmaz Simsek, School of Mathematics and Statistics, Wuhan University, Wuhan, 430072, CHINA. Department of Mathematics, Faculty of Science, University of Akdeniz, 07058 Antalya, Turkey, TURKEY. E-mail: komatsu@whu.edu.cn, ysimsek@akdeniz.edu.tr

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