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Remarks on a formula of Blagouchine

Marc-Antoine Coppo*

Université Côte d'Azur, CNRS, LJAD (UMR 7351), Nice, France

Abstract We provide a proof and give some applications of an amazing formula discovered by Blagouchine.

Keywords Complex integration, generalized Glaisher-Kinkelin constants, infinite series with zeta values.

1 Introduction

The purpose of this short note is twofold: first, we provide a complete proof of a complex valued integral formula recently discovered by Blagouchine [2, Theorem 2], and then we relate this integral to some important mathematical constants, namely the Euler-Mascheroni constant, the Cohen-Boyadzhiev constant, the generalized Glaisher-Kinkelin constants (also known as Bendersky's constants) which occur quite naturally in analysis and number theory [9, 10]. Let us note in passing that a special case of Blagouchine's formula has already been mentioned (without proof) on page 1836 of [7].

2 Blagouchine's integral

Proposition 1. For any integer $k \geq 0$, let μ_k be the infinite sum

$$\mu_k := \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\zeta(n+1)}{n+k}$$

and \mathcal{I}_k be the complex valued integral

$$\mathcal{I}_k := \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(2k+1+2ix) \cosh(\pi x)} dx.$$

Then we have the identity

$$\mu_k = \mathcal{I}_k. \tag{1}$$

*Corresponding author. *Email address:* coppo@unice.fr

Proof. For $k \geq 0$, let us consider the function

$$f_k(z) = \frac{\zeta\left(\frac{3}{2} + iz\right)}{\left(\frac{1}{2} + k + iz\right) \cosh(\pi z)}.$$

We have $\cosh(\pi z) = 0$ if and only if $z = i/2 + in$ with $n \in \mathbb{Z}$. For $n \geq 1$, the residue of f_k at $z = i/2 - in$ is

$$\frac{\zeta(1+n)}{(n+k)\pi \sinh(i\pi(\frac{1}{2}-n))} = \frac{\zeta(1+n)}{(n+k)i\pi \sin(\pi(\frac{1}{2}-n))} = \frac{(-1)^n \zeta(1+n)}{(n+k)i\pi}.$$

We integrate on a closed contour composed of the interval $D_R = [-R, R]$ and the lower semicircle C_R of radius R with center at 0. Using the Cauchy residue theorem, we can then write the following relation:

$$\frac{1}{2i\pi} \int_{C_R} f_k(z) dz + \frac{1}{2i\pi} \int_{D_R} f_k(z) dz = - \sum_{n=1}^{N_R} \text{Res}(f_k; \frac{i}{2} - in),$$

which, from the foregoing, translates into the identity

$$\int_{C_R} f_k(z) dz + \int_{D_R} f_k(z) dz = 2 \sum_{n=1}^{N_R} (-1)^{n+1} \frac{\zeta(1+n)}{(n+k)}. \quad (2)$$

For $z \in C_R$, the parameterization $iz = Re^{it}$ with $-\pi/2 < t < \pi/2$, enables us to write

$$\begin{aligned} \left| \int_{C_R} f_k(z) dz \right| &= \left| \int_{-\pi/2}^{+\pi/2} \frac{\zeta\left(\frac{3}{2} + Re^{it}\right)}{\left(\frac{1}{2} + k + Re^{it}\right) \cosh(i\pi Re^{it})} Re^{it} dt \right| \\ &\leq \int_{-\pi/2}^{+\pi/2} \left| \frac{\zeta\left(\frac{3}{2} + Re^{it}\right)}{\left(\frac{1}{2} + k + Re^{it}\right) \cosh(i\pi Re^{it})} \right| R dt. \end{aligned}$$

Since $\frac{3}{2} + Re^{it}$ is in the half-plane $\text{Re}(z) > 3/2$, its absolute value is bounded by $\zeta\left(\frac{3}{2}\right)$, i.e.

$$\left| \zeta\left(\frac{3}{2} + Re^{it}\right) \right| \leq \zeta\left(\frac{3}{2}\right).$$

Hence, when R increases towards infinity, we have the following limits:

$$\begin{aligned} \lim_{R \rightarrow \infty} \int_{C_R} f_k(z) dz &= 0, \\ \lim_{R \rightarrow \infty} \int_{D_R} f_k(z) dz &= \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{\left(\frac{1}{2} + k + ix\right) \cosh(\pi x)} dx = 2\mathcal{I}_k, \end{aligned}$$

and

$$\lim_{R \rightarrow \infty} \sum_{n=1}^{N_R} (-1)^{n+1} \frac{\zeta(1+n)}{(n+k)} = \sum_{n=1}^{\infty} (-1)^{n+1} \frac{\zeta(1+n)}{(n+k)} = \mu_k.$$

This allows us to deduce formula (1) by passing to the limit in (2). \square

Remark 1. The constant

$$\mu_0 = \sum_{n=1}^{\infty} (-1)^{n-1} \frac{\zeta(n+1)}{n} = \sum_{n=1}^{\infty} \frac{1}{n} \ln \left(1 + \frac{1}{n} \right) = 1.257746 \dots$$

has been thoroughly studied by Boyadzhiev [4] (see also [6, p. 142]). This constant is noted M in [4], K in [6], and it also appears as ν_{-1} in [7]. By a well-known series representation of Euler's constant γ , we also have

$$\mu_1 = \sum_{n=2}^{\infty} (-1)^n \frac{\zeta(n)}{n} = \sum_{n=1}^{\infty} \left(\frac{1}{n} - \ln \left(1 + \frac{1}{n} \right) \right) = \gamma = 0.577215 \dots$$

Example 1. For $k = 0$ and 1, formula (1) translates into

$$\mathcal{I}_0 = \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(1 + 2ix) \cosh(\pi x)} dx = \int_0^1 \frac{\psi(x+1) + \gamma}{x} dx, \quad (3)$$

where ψ is the digamma function, and

$$\mathcal{I}_1 = \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(3 + 2ix) \cosh(\pi x)} dx = \gamma = -\psi(1). \quad (4)$$

3 Link with the generalized Glaisher-Kinkelin constants

Definition 1 ([1, 9, 10]). For any integer $k \geq 0$, the constant A_k is defined by

$$\ln(A_k) = \lim_{N \rightarrow \infty} \left(\sum_{n=1}^N n^k \ln n - P_k(N) \right),$$

where $P_k(N)$ is given by $P_0(N) = \left(N + \frac{1}{2}\right) \ln N - N$, and

$$P_k(N) = \left(\frac{N^{k+1}}{k+1} + \frac{N^k}{2} + k! \sum_{j=1}^k \frac{N^{k-j} B_{j+1}}{(j+1)!(k-j)!} \right) \ln N - \frac{N^{k+1}}{(k+1)^2} + k! \sum_{j=1}^k \frac{N^{k-j} B_{j+1}}{(j+1)!(k-j)!} \left\{ (1 - \delta_{k,j}) \sum_{i=1}^j \frac{1}{k-i+1} \right\} \quad (k \geq 1),$$

where B_j is the j th Bernoulli number and $\delta_{k,j}$ the Kronecker symbol. The numbers A_k for $k \geq 0$ are the generalized Glaisher-Kinkelin constants (sometimes called the Bendersky-Adamchik constants). Adamchik [1, Proposition 4] has shown that

theses constants admit a nice expression in terms of the derivatives of the Riemann zeta function:

$$A_k = \exp \left\{ \frac{H_k B_{k+1}}{k+1} - \zeta'(-k) \right\} \quad (k \geq 0), \quad (5)$$

where H_k denotes the k th harmonic number

$$H_0 = 0, \quad H_k = \sum_{j=1}^k \frac{1}{j} \quad (k \geq 1).$$

Remark 2. Bendersky [3] introduced for the first time the sequence of numbers $L_k := \ln(A_k)$ without any consideration of their relation with the ζ -function. From the point of view of the summation of divergent series, the constants L_k should be interpreted as follows:

$$\ln(A_k) - \frac{H_k B_{k+1}}{k+1} - \frac{1}{(k+1)^2} = \int_0^1 \ln \Gamma_k(x+1) dx = \sum_{n \geq 1}^{\mathcal{R}} n^k \ln n \quad (k \geq 0),$$

where Γ_k is Bendersky's generalized gamma function [3], and $\sum_{n \geq 1}^{\mathcal{R}} n^k \ln n$ is the sum (in the sense of Ramanujan's summation method) of the divergent series $\sum_{n \geq 1} n^k \ln n$ [5]. Actually, Kurokawa and Ochoai [8, Theorem 2] have shown that

$$\Gamma_k(x) = \exp \{ \zeta'(-k, x) - \zeta'(-k) \} \quad \operatorname{Re}(x) > 0,$$

where $\zeta(s, x)$ is the Hurwitz zeta function. This expression is consistent with Adamchik's formula (5).

Remark 3. The following relations are easily deduced by differentiation of Riemann's functional equation for the zeta function: we have

$$\zeta'(-2k) = (-1)^k \frac{(2k)!}{2(2\pi)^{2k}} \zeta(2k+1) \quad (k \geq 1),$$

and

$$\zeta'(1-2k) = (-1)^{k+1} \frac{(2k)!}{k(2\pi)^{2k}} \zeta'(2k) + \frac{B_{2k}}{2k} (H_{2k-1} - \gamma - \ln 2\pi) \quad (k \geq 1).$$

Hence, it follows from Adamchik's formula (5) that

$$A_{2k-1} = \exp \left\{ (-1)^k \frac{(2k)!}{k(2\pi)^{2k}} \zeta'(2k) + \frac{B_{2k}}{2k} (\gamma + \ln 2\pi) \right\} \quad (k \geq 1) \quad (6)$$

and

$$A_{2k} = \exp \left\{ (-1)^{k+1} \frac{(2k)!}{2(2\pi)^{2k}} \zeta(2k+1) \right\} \quad (k \geq 1). \quad (7)$$

Example 2. The constant $A_0 = \exp(-\zeta'(0)) = \sqrt{2\pi}$ is the Stirling constant,

$$A_1 = \exp\left(\frac{1}{12} - \zeta'(-1)\right) = \exp\left(-\frac{\zeta'(2)}{2\pi^2} + \frac{\ln(2\pi) + \gamma}{12}\right)$$

is the Glaisher-Kinkelin constant, and

$$A_2 = \exp(-\zeta'(-2)) = \exp\left(\frac{\zeta(3)}{4\pi^2}\right).$$

Proposition 2. For any integer $k \geq 1$, we have the following identity:

$$\mathcal{I}_{k+1} = \frac{\gamma}{k+1} + \frac{1}{k} - \sum_{j=0}^{k-1} (-1)^j \binom{k}{j} \ln(A_j). \quad (8)$$

Proof. Setting $\nu_k = \mu_{k+1}$, we have shown [7, Proposition 1] that

$$\nu_k = \frac{\gamma}{k+1} + \sum_{j=0}^{k-1} (-1)^j \binom{k}{j} \zeta'(-j) + C_k$$

with

$$C_k = \frac{1}{k} + \sum_{j=1}^{k-1} \binom{k}{j} \frac{B_{j+1} H_j}{j+1}.$$

Thus, formula (8) is easily deduced from this relation by means of formula (5) and Proposition 1. \square

Example 3. For small values of k , formula (8) translates into the following identities:

$$\mathcal{I}_2 = \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(5 + 2ix) \cosh(\pi x)} dx = \frac{1}{2}\gamma + 1 - \frac{1}{2} \ln(2\pi) \quad (9)$$

$$\mathcal{I}_3 = \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(7 + 2ix) \cosh(\pi x)} dx = \frac{1}{2}\gamma + \frac{1}{2} - \frac{1}{3} \ln(2\pi) - \frac{\zeta'(2)}{\pi^2} \quad (10)$$

$$\mathcal{I}_4 = \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(9 + 2ix) \cosh(\pi x)} dx = \frac{1}{2}\gamma + \frac{1}{3} - \frac{1}{4} \ln(2\pi) - \frac{3\zeta'(2)}{2\pi^2} - \frac{3\zeta(3)}{4\pi^2} \quad (11)$$

In the general case, we obtain the following expression which, by means of formulas (6)–(7), is equivalent to (8):

Corollary 1. For any integer $k \geq 4$, we have

$$\begin{aligned} \mathcal{I}_k &= \int_{-\infty}^{+\infty} \frac{\zeta\left(\frac{3}{2} + ix\right)}{(2k+1 + 2ix) \cosh(\pi x)} dx = \frac{1}{2}\gamma + \frac{1}{k-1} - \frac{1}{k} \ln(2\pi) \\ &+ \sum_{j=1}^{\lfloor \frac{k-1}{2} \rfloor} (-1)^j \binom{k-1}{2j-1} \frac{(2j)!}{j(2\pi)^{2j}} \zeta'(2j) + \sum_{j=1}^{\lfloor \frac{k}{2} \rfloor - 1} (-1)^j \binom{k-1}{2j} \frac{(2j)!}{2(2\pi)^{2j}} \zeta(2j+1). \quad (12) \end{aligned}$$

Remark 4. Blagouchine [2] also established the relation

$$\mathcal{I}_{k+1} = \frac{\gamma}{k+1} - \frac{1}{(k+1)^2} - \int_{-\infty}^{+\infty} \frac{\zeta(\frac{1}{2} + ix)}{(2k+1 + 2ix) \cosh(\pi x)} dx \quad (k \geq 0).$$

This allows us to deduce from (8) the following identity:

$$\sum_{j=0}^{k-1} (-1)^j \binom{k}{j} \ln(A_j) = \frac{1}{k} + \frac{1}{(k+1)^2} + \int_{-\infty}^{+\infty} \frac{\zeta(\frac{1}{2} + ix)}{(2k+1 + 2ix) \cosh(\pi x)} dx \quad (k \geq 1). \quad (13)$$

In particular,

$$\ln(\sqrt{2\pi}) = \frac{5}{4} + \int_{-\infty}^{+\infty} \frac{\zeta(\frac{1}{2} + ix)}{(3 + 2ix) \cosh(\pi x)} dx.$$

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