

COMPLETE (p, q) -ELLIPTIC INTEGRALS WITH APPLICATION TO A FAMILY OF MEANS

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*Dedicated to Professor Tomomi Kojo
on the occasion of his retirement*

Abstract. The complete elliptic integrals are generalized by using the generalized trigonometric functions with two parameters. As an application of the integrals, an alternative proof of a result for a family of means by Bhatia and Li, which involves the logarithmic mean and the arithmetic-geometric mean, is given. Moreover, it is shown that a particular relation holds for the generalized integrals.

1. Introduction

In this paper, we deal with a *complete (p, q) -elliptic integral of the first kind*

$$\mathcal{K}_{p,q}(k) := \int_0^{\pi_{p,q}/2} \frac{d\theta}{(1 - k^q \sin_{p,q}^q \theta)^{1-1/p}} = \int_0^1 \frac{dt}{(1-t^q)^{1/p}(1-k^q t^q)^{1-1/p}},$$

where $\sin_{p,q} \theta$ is the generalized (p, q) -trigonometric function and $\pi_{p,q}$ denotes the half-period of $\sin_{p,q} \theta$. The function $\sin_{p,q} \theta$ and the number $\pi_{p,q}$ play important roles to express the solutions (λ, u) of inhomogeneous eigenvalue problem of p -Laplacian $-(|u'|^{p-2}u')' = \lambda|u|^{q-2}u$ with a boundary condition. See Section 2 for the definition of $\sin_{p,q} \theta$ and $\pi_{p,q}$; also [5, 6, 7, 9, 10] for details. For $p = q = 2$, it is easy to see that $\sin_{p,q} \theta$, $\pi_{p,q}$ and $\mathcal{K}_{p,q}(k)$ are identical to the classical $\sin \theta$, π and $\mathcal{K}(k)$, respectively, where $\mathcal{K}(k)$ is the complete elliptic integral of the first kind

$$\mathcal{K}(k) := \int_0^{\pi/2} \frac{d\theta}{\sqrt{1 - k^2 \sin^2 \theta}} = \int_0^1 \frac{dt}{\sqrt{(1-t^2)(1-k^2 t^2)}}.$$

Moreover, $\mathcal{K}_{p,q}(k)$ for $p = q$ has been already studied in [11].

In this paper we will apply the complete (p, q) -elliptic integral $\mathcal{K}_{p,q}(k)$ to study a family of means defined by Bhatia and Li [2] and to give an alternative proof of their theorem.

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For a while, we will describe a part of the study in [2]. Let a and b be positive numbers. The *logarithmic mean* $L(a, b)$ of a and b is defined by

$$L(a, b) := \begin{cases} \frac{a-b}{\log a - \log b} & (a \neq b), \\ a & (a = b). \end{cases}$$

The *arithmetic-geometric mean* $AG(a, b)$ of a and b is defined as follows: Let us consider the sequences $\{a_n\}$ and $\{b_n\}$ satisfying

$$a_{n+1} = \frac{a_n + b_n}{2}, \quad b_{n+1} = \sqrt{a_n b_n}, \quad n = 0, 1, 2, \dots$$

with $a_0 = a$ and $b_0 = b$. The sequences $\{a_n\}$ and $\{b_n\}$ converge to a common limit, and

$$AG(a, b) := \lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} b_n.$$

It is known that $L(a, b)$ and $AG(a, b)$ have integral expressions as

$$\begin{aligned} \frac{1}{L(a, b)} &= \int_0^\infty \frac{dt}{(t+a)(t+b)}, \\ \frac{1}{AG(a, b)} &= \frac{2}{\pi} \int_0^\infty \frac{dt}{\sqrt{(t^2+a^2)(t^2+b^2)}}. \end{aligned}$$

Indeed, the first one follows from direct calculation of the right-hand side and the second one is a celebrated result of Gauss (e.g., [1, Theorem 3.2.3] and [4, Theorem 1.1] with setting $b \tan \theta = t$).

Motivated by these expressions, Bhatia and Li introduced an interpolating family of means $M_p(a, b)$ by

$$\frac{1}{M_p(a, b)} := c_p \int_0^\infty \frac{dt}{((t^p + a^p)(t^p + b^p))^{1/p}}, \quad p \in (0, \infty),$$

where c_p is defined to satisfy $M_p(a, a) = a$, hence,

$$\frac{1}{c_p} := \int_0^\infty \frac{dt}{(1+t^p)^{2/p}}.$$

Moreover, M_0 is defined by taking limit:

$$M_0(a, b) = \lim_{p \rightarrow +0} M_p(a, b) = \sqrt{ab}.$$

Clearly, $M_1(a, b) = L(a, b)$ and $M_2(a, b) = AG(a, b)$, thus $M_p(a, b)$ is a generalization of $L(a, b)$ and $AG(a, b)$. It is easily seen that $M_p(a, b)$ is a *binary symmetric mean* of positive numbers a and b , that is

$$(i) \quad \min\{a, b\} \leq M_p(a, b) \leq \max\{a, b\}$$

- (ii) $M_p(a, b) = M_p(b, a)$
- (iii) $M_p(\alpha a, \alpha b) = \alpha M_p(a, b)$ for all $\alpha > 0$
- (iv) $M_p(a, b)$ is non-decreasing in a and b .

They studied relation between $M_p(a, b)$ and $K_p(a, b)$, the *power difference mean* of a and b . This is defined for any $p \in \mathbb{R}$ and $a, b > 0$ by

$$K_p(a, b) := \begin{cases} \frac{p-1}{p} \frac{a^p - b^p}{a^{p-1} - b^{p-1}} & (a \neq b), \\ a & (a = b), \end{cases}$$

where it is understood that

$$K_0(a, b) := \lim_{p \rightarrow 0} K_p(a, b) = \frac{ab}{L(a, b)},$$

$$K_1(a, b) := \lim_{p \rightarrow 1} K_p(a, b) = L(a, b).$$

For more details of $K_p(a, b)$, see [2, 8] and the references given there.

These two means are related in the following sense. It is easy to check that $1/M_p(a, b)$ can be written as $(t^p + a^p = a^p s^{-1})$

$$\frac{1}{M_p(a, b)} = \frac{\int_0^1 \frac{s^{1/p-1}(1-s)^{1/p-1}}{(a^p(1-s) + b^p s)^{1/p}} ds}{\int_0^1 s^{1/p-1}(1-s)^{1/p-1} ds}$$

and $1/K_p(a, b)$ also admits the following integral expression:

$$\frac{1}{K_p(a, b)} = \int_0^1 \frac{ds}{(a^p(1-s) + b^p s)^{1/p}}. \tag{1.1}$$

Thus $1/M_p(a, b)$ and $1/K_p(a, b)$ are the weighted means with the beta distribution and with the continuous uniform distribution, respectively, of the function $(a^p(1-s) + b^p s)^{-1/p}$.

Bhatia and Li concluded the following theorem with easy but technical calculation. But, it is hard to say that these calculations are natural.

Theorem 1.1. ([2]) *Given $a, b > 0$ and $a \neq b$, we have*

- (i) $M_p(a, b) > K_p(a, b)$ if $0 \leq p < 1$
- (ii) $M_1(a, b) = K_1(a, b)$
- (iii) $M_p(a, b) < K_p(a, b)$ if $p > 1$.

In this paper, we will give an alternative proof of Theorem 1.1. Using the complete (p, q) -elliptic integral, we can easily give a hypergeometric representation (1.2) in Theorem 1.2 below for $1/M_p(a, b)$. Applying a formula of hypergeometric function to (1.2) and (1.4), we have (1.3) and (1.5). We emphasize that Theorem 1.1 of Bhatia and Li follows immediately from Theorem 1.2 with comparing only the third parameters of (1.3) and (1.5).

Theorem 1.2. *Let $p \in \mathbb{P} := (0, 1) \cup (1, \infty)$ and $x \in (0, 1]$. Then*

$$\begin{aligned} \frac{1}{M_p(1, x)} &= \frac{2}{\pi_{p^*, p}} \mathcal{K}_{p^*, p}((1-x^p)^{1/p}) \\ &= F\left(\frac{1}{p}, \frac{1}{p}; \frac{2}{p}; 1-x^p\right), \end{aligned} \quad (1.2)$$

$$= \left(\frac{2}{1+x^p}\right)^{1/p} F\left(\frac{1}{2p}, \frac{1}{2p} + \frac{1}{2}; \frac{1}{p} + \frac{1}{2}; \left(\frac{1-x^p}{1+x^p}\right)^2\right), \quad (1.3)$$

$$\frac{1}{K_p(1, x)} = F\left(1, \frac{1}{p}; 2; 1-x^p\right), \quad (1.4)$$

$$= \left(\frac{2}{1+x^p}\right)^{1/p} F\left(\frac{1}{2p}, \frac{1}{2p} + \frac{1}{2}; \frac{3}{2}; \left(\frac{1-x^p}{1+x^p}\right)^2\right). \quad (1.5)$$

Therefore, Theorem 1.1 immediately follows.

Moreover, we define a complete (p, q) -elliptic integral of the second kind

$$\mathcal{E}_{p, q}(k) := \int_0^{\pi_{p, q}/2} (1 - k^q \sin_{p, q}^q \theta)^{1/p} d\theta = \int_0^1 \left(\frac{1 - k^q t^q}{1 - t^q}\right)^{1/p} dt.$$

It is clear that $\mathcal{E}_{2, 2}(k)$ is identical to the complete elliptic integral of the second kind

$$\mathcal{E}(k) = \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 \theta} d\theta = \int_0^1 \sqrt{\frac{1 - k^2 t^2}{1 - t^2}} dt.$$

Then, we can show the following relation for $p \neq q$.

Theorem 1.3. *Let $p, q \in (1, \infty)$ and $k \in [0, 1)$. Then*

$$p \mathcal{E}_{p, q}(k^{1/q}) \mathcal{K}_{q, p}(k^{1/p}) - q \mathcal{K}_{p, q}(k^{1/q}) \mathcal{E}_{q, p}(k^{1/p}) = \frac{(p-q)\pi_{p, q}\pi_{q, p}}{4}. \quad (1.6)$$

This paper is organized as follows. In Section 2 we prepare properties of the complete (p, q) -elliptic integrals and show Theorem 1.3. Section 3 is devoted to give a proof of Theorem 1.2 and an alternative proof of Theorem 1.1.

REMARK 1.4. $\mathcal{K}_{p, q}(k)$ and $\mathcal{E}_{p, q}(k)$ have been studied in [10] and in [3, 13], respectively. For the particular case $p = q$, we refer the reader to [11]. See also Remark 2.2 for other generalized complete elliptic integrals.

2. Complete (p, q) -elliptic integrals

Let p and q be real numbers satisfying $p^* := p/(p-1) > 0$ and $q > 0$ (note that p is allowed to be negative). The (p, q) -trigonometric function $\sin_{p,q} x$ is the inverse function of

$$\sin_{p,q}^{-1} x := \int_0^x \frac{dt}{(1-t^q)^{1/p}}, \quad x \in [0, 1].$$

Clearly, $\sin_{p,q} x$ is increasing function from $[0, \pi_{p,q}/2]$ onto $[0, 1]$, where

$$\pi_{p,q} := 2 \sin_{p,q}^{-1} 1 = 2 \int_0^1 \frac{dt}{(1-t^q)^{1/p}} = \frac{2}{q} B\left(\frac{1}{p^*}, \frac{1}{q}\right),$$

where B denotes the beta function.

For $x \in (0, \pi_{p,q}/2)$, we also define

$$\cos_{p,q} x := \frac{d}{dx}(\sin_{p,q} x),$$

These functions satisfy, for $x \in (0, \pi_{p,q}/2)$,

$$\begin{aligned} \cos_{p,q}^p x + \sin_{p,q}^q x &= 1, & \frac{d}{dx}(\sin_{p,q} x) &= \cos_{p,q} x, \\ \frac{d}{dx}(\cos_{p,q} x) &= -\frac{q}{p} \sin_{p,q}^{q-1} x \cos_{p,q}^{2-p} x, \\ \frac{d}{dx}(\cos_{p,q}^{p-1} x) &= -\frac{q}{p^*} \sin_{p,q}^{q-1} x. \end{aligned}$$

Now, for any $k \in [0, 1)$ we define the *complete (p, q) -elliptic integral of the first kind* and of the *second kind* as follows.

$$\begin{aligned} \mathcal{K}_{p,q}(k) &:= \int_0^{\pi_{p,q}/2} \frac{d\theta}{(1-k^q \sin_{p,q}^q \theta)^{1/p^*}} = \int_0^1 \frac{dt}{(1-t^q)^{1/p} (1-k^q t^q)^{1/p^*}}, \\ \mathcal{E}_{p,q}(k) &:= \int_0^{\pi_{p,q}/2} (1-k^q \sin_{p,q}^q \theta)^{1/p} d\theta = \int_0^1 \left(\frac{1-k^q t^q}{1-t^q}\right)^{1/p} dt. \end{aligned}$$

It is easy to see that $\mathcal{K}_{p,q}(k)$ is increasing on $[0, 1)$ and

$$\mathcal{K}_{p,q}(0) = \frac{\pi_{p,q}}{2}, \quad \lim_{k \rightarrow 1-0} \mathcal{K}_{p,q}(k) = \infty,$$

and $\mathcal{E}_{p,q}(k)$ is decreasing on $[0, 1)$ and

$$\mathcal{E}_{p,q}(0) = \frac{\pi_{p,q}}{2}, \quad \lim_{k \rightarrow 1-0} \mathcal{E}_{p,q}(k) = 1,$$

The functions $\mathcal{K}_{p,q}(k)$ and $\mathcal{E}_{p,q}(k)$ satisfy a system of differential equations.

Proposition 2.1.

$$\frac{d\mathcal{E}_{p,q}}{dk} = \frac{q(\mathcal{E}_{p,q} - \mathcal{K}_{p,q})}{pk}, \quad \frac{d\mathcal{K}_{p,q}}{dk} = \frac{\mathcal{E}_{p,q} - (1-k^q)\mathcal{K}_{p,q}}{k(1-k^q)}.$$

Proof. Differentiating $\mathcal{E}_{p,q}(k)$ we have

$$\begin{aligned} \frac{d\mathcal{E}_{p,q}}{dk} &= \int_0^{\pi_{p,q}/2} \frac{d}{dk} (1 - k^q \sin_{p,q}^q \theta)^{1/p} d\theta \\ &= \frac{q}{p} \int_0^{\pi_{p,q}/2} \frac{-k^{q-1} \sin_{p,q}^q \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} d\theta \\ &= \frac{q}{pk} \left(\int_0^{\pi_{p,q}/2} \frac{1 - k^q \sin_{p,q}^q \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} d\theta - \int_0^{\pi_{p,q}/2} \frac{d\theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} \right) \\ &= \frac{q}{pk} (\mathcal{E}_{p,q} - \mathcal{K}_{p,q}). \end{aligned}$$

Next, for $\mathcal{K}_{p,q}(k)$

$$\frac{d\mathcal{K}_{p,q}}{dk} = \frac{q}{p^*} \int_0^{\pi_{p,q}/2} \frac{k^{q-1} \sin_{p,q}^q \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1+1/p^*}} d\theta. \quad (2.1)$$

Here we see that

$$\begin{aligned} \frac{d}{d\theta} \left(\frac{-\cos_{p,q}^{p-1} \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} \right) &= \frac{q(1-k^q) \sin_{p,q}^{q-1} \theta}{p^* (1 - k^q \sin_{p,q}^q \theta)^{1+1/p^*}}, \\ \lim_{\theta \rightarrow \pi_{p,q}/2} \cos_{p,q}^{p-1} \theta &= \lim_{\theta \rightarrow \pi_{p,q}/2} (1 - \sin_{p,q}^q \theta)^{1/p^*} = 0; \end{aligned}$$

so that we use integration by parts as

$$\begin{aligned} \frac{d\mathcal{K}_{p,q}}{dk} &= \int_0^{\pi_{p,q}/2} \frac{k^{q-1}}{1-k^q} \frac{d}{d\theta} \left(\frac{-\cos_{p,q}^{p-1} \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} \right) \sin_{p,q} \theta d\theta \\ &= \frac{k^{q-1}}{1-k^q} \left[\frac{-\cos_{p,q}^{p-1} \theta \sin_{p,q} \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} \right]_0^{\pi_{p,q}/2} + \frac{k^{q-1}}{1-k^q} \int_0^{\pi_{p,q}/2} \frac{\cos_{p,q}^p \theta}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} d\theta \\ &= \frac{k^{q-1}}{1-k^q} \int_0^{\pi_{p,q}/2} \frac{1}{k^q} \cdot \frac{1 - k^q \sin_{p,q}^q \theta - (1 - k^q)}{(1 - k^q \sin_{p,q}^q \theta)^{1/p^*}} d\theta \\ &= \frac{1}{k(1-k^q)} (\mathcal{E}_{p,q} - (1-k^q)\mathcal{K}_{p,q}). \end{aligned}$$

This completes the proof. \square

Proposition 2.1 now yields Theorem 1.3.

Proof of Theorem 1.3. We will differentiate the left-hand side of (1.6) and apply Proposition 2.1. A direct computation shows that

$$\begin{aligned}
& \frac{d}{dk} (p\mathcal{E}_{p,q}(k^{1/q})\mathcal{K}_{q,p}(k^{1/p}) - q\mathcal{K}_{p,q}(k^{1/q})\mathcal{E}_{q,p}(k^{1/p})) \\
&= p \cdot \frac{1}{pk} (\mathcal{E}_{p,q}(k^{1/q}) - \mathcal{K}_{p,q}(k^{1/q})) \cdot \mathcal{K}_{q,p}(k^{1/p}) \\
&\quad + p\mathcal{E}_{p,q}(k^{1/q}) \cdot \frac{1}{pk(1-k)} (\mathcal{E}_{q,p}(k^{1/p}) - (1-k)\mathcal{K}_{q,p}(k^{1/p})) \\
&\quad - q \cdot \frac{1}{qk(1-k)} (\mathcal{E}_{p,q}(k^{1/q}) - (1-k)\mathcal{K}_{p,q}(k^{1/q})) \cdot \mathcal{E}_{q,p}(k^{1/p}) \\
&\quad - q\mathcal{K}_{p,q}(k^{1/q}) \cdot \frac{1}{qk} (\mathcal{E}_{q,p}(k^{1/p}) - \mathcal{K}_{q,p}(k^{1/p})) \\
&= 0.
\end{aligned}$$

Therefore the left-hand side of (1.6) is a constant C . Letting $k = 0$, we obtain

$$C = p \frac{\pi_{p,q}}{2} \frac{\pi_{q,p}}{2} - q \frac{\pi_{p,q}}{2} \frac{\pi_{q,p}}{2} = \frac{(p-q)\pi_{p,q}\pi_{q,p}}{4},$$

and the proof is complete. \square

REMARK 2.2. For the other type of generalized complete elliptic integrals

$$\begin{aligned}
K_{p,q}(k) &:= \int_0^{\pi_{p,q}/2} \frac{d\theta}{(1-k^q \sin_{p,q}^q \theta)^{1/q^*}} = \int_0^1 \frac{dt}{(1-t^q)^{1/p} (1-k^q t^q)^{1/q^*}}, \\
E_{p,q}(k) &:= \int_0^{\pi_{p,q}/2} (1-k^q \sin_{p,q}^q \theta)^{1/q} d\theta = \int_0^1 \frac{(1-k^q t^q)^{1/q}}{(1-t^q)^{1/p}} dt,
\end{aligned}$$

it is possible to show

$$E_{p,q}(k)K_{p,q}(k') + K_{p,q}(k)E_{p,q}(k') - K_{p,q}(k)K_{p,q}(k') = \frac{\pi_{p,q}\pi_{s,q}}{4}, \quad (2.2)$$

where $k' := (1-k^q)^{1/q}$ and $1/s = 1/p - 1/q$ ($\pi_{s,q} := 2$ if $p = q$). In case $p = q = 2$, this is reduced to Legendre's relation (cf. [1, Theorem 3.2.7] and [4, Theorem 1.6])

$$\mathcal{E}(k)\mathcal{K}(k') + \mathcal{K}(k)\mathcal{E}(k') - \mathcal{K}(k)\mathcal{K}(k') = \frac{\pi}{2}.$$

For generalization of Legendre's relation including (2.2), see [12] and the references given there.

For a real number a and a natural number n , we define

$$(a)_n := \frac{\Gamma(a+n)}{\Gamma(a)} = a(a+1)\cdots(a+n-2)(a+n-1),$$

where Γ denotes the gamma function. We adopt the convention that $(a)_0 := 1$. For $|x| < 1$ the series

$$F(a, b; c; x) := \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n} \frac{x^n}{n!}$$

is called a *Gaussian hypergeometric series*. See [1] for more details.

Lemma 2.3. For $n = 0, 1, 2, \dots$

$$\int_0^{\pi_{p,q}/2} \sin_{p,q}^{qn} \theta d\theta = \frac{\pi_{p,q}}{2} \frac{(1/q)_n}{(1/p^* + 1/q)_n}.$$

Proof. Letting $\sin_{p,q}^q \theta = t$, we have

$$\int_0^{\pi_{p,q}/2} \sin_{p,q}^{qn} \theta d\theta = \frac{1}{q} \int_0^1 t^{n+1/q-1} (1-t)^{-1/p} dt = \frac{1}{q} B\left(n + \frac{1}{q}, \frac{1}{p^*}\right).$$

Moreover,

$$\begin{aligned} \frac{1}{q} B\left(n + \frac{1}{q}, \frac{1}{p^*}\right) &= \frac{1}{q} B\left(\frac{1}{q}, \frac{1}{p^*}\right) \frac{B(n+1/q, 1/p^*)}{B(1/q, 1/p^*)} \\ &= \frac{\pi_{p,q}}{2} \frac{\Gamma(n+1/q)\Gamma(1/q+1/p^*)}{\Gamma(1/q)\Gamma(n+1/q+1/p^*)} \\ &= \frac{\pi_{p,q}}{2} \frac{(1/q)_n}{(1/p^* + 1/q)_n}, \end{aligned}$$

and the lemma follows. \square

Proposition 2.4.

$$\begin{aligned} \mathcal{K}_{p,q}(k) &= \frac{\pi_{p,q}}{2} F\left(\frac{1}{p^*}, \frac{1}{q}; \frac{1}{p^*} + \frac{1}{q}; k^q\right), \\ \mathcal{E}_{p,q}(k) &= \frac{\pi_{p,q}}{2} F\left(-\frac{1}{p^*}, \frac{1}{q}; \frac{1}{p^*} + \frac{1}{q}; k^q\right). \end{aligned}$$

Proof. Binomial series expansion gives

$$\begin{aligned} \mathcal{K}_{p,q}(k) &= \int_0^{\pi_{p,q}/2} (1 - k^q \sin_{p,q}^q \theta)^{-1/p^*} d\theta \\ &= \sum_{n=0}^{\infty} (-1)^n \binom{-1/p^*}{n} k^{qn} \int_0^{\pi_{p,q}/2} \sin_{p,q}^{qn} \theta d\theta. \end{aligned}$$

Here, using Lemma 2.3 and the fact

$$(-1)^n \binom{-1/p^*}{n} = \frac{(1/p^*)_n}{n!},$$

we see that

$$\mathcal{K}_{p,q}(k) = \frac{\pi_{p,q}}{2} \sum_{n=0}^{\infty} \frac{(1/p^*)_n (1/q)_n}{(1/p^* + 1/q)_n} \frac{k^{qn}}{n!} = \frac{\pi_{p,q}}{2} F\left(\frac{1}{p^*}, \frac{1}{q}; \frac{1}{p^*} + \frac{1}{q}; k^q\right).$$

The proof of $\mathcal{E}_{p,q}(k)$ is similar, so that we omit it. \square

3. Proof of Theorem 1.2

By properties (ii) and (iii) of binary symmetric mean in the introduction, we may assume that $a \geq b > 0$ and it is enough to consider $M_p(1, x)$ for any $x \in (0, 1]$ instead of $M_p(a, b)$.

The following is a fundamental quadratic transformation of hypergeometric functions. For the proof, see for instance [1, Theorem 3.1.3].

Lemma 3.1. *For all x where the series converge*

$$F(a, b; 2a; x) = \left(1 - \frac{x}{2}\right)^{-b} F\left(\frac{b}{2}, \frac{b+1}{2}; a + \frac{1}{2}; \left(\frac{x}{2-x}\right)^2\right).$$

Now we are in a position to prove Theorem 1.2. Let $p \in \mathbb{P}$. Then, $(p^*)^* = p > 0$ and $\sin_{p^*, p} \theta$ is defined. Setting

$$t = x \frac{\sin_{p^*, p} \theta}{\cos_{p^*, p}^{p^*-1} \theta}$$

in the right-hand side of

$$\frac{1}{M_p(1, x)} = c_p \int_0^\infty \frac{dt}{((t^p + 1)(t^p + x^p))^{1/p}},$$

we have (note that $\cos_{p^*, p}^{p^*-1} \theta = (1 - \sin_{p^*, p}^p \theta)^{1/p} \rightarrow 0$ as $\theta \rightarrow \pi_{p^*, p}/2$ even if $p^* < 1$)

$$\begin{aligned} \frac{1}{M_p(1, x)} &= c_p \int_0^{\pi_{p^*, p}/2} \frac{x \cos_{p^*, p}^{2(1-p^*)} \theta d\theta}{\left(x^p \frac{\sin_{p^*, p}^p \theta}{\cos_{p^*, p}^{p^*} \theta} + 1\right)^{1/p} \left(x^p \frac{\sin_{p^*, p}^p \theta}{\cos_{p^*, p}^{p^*} \theta} + x^p\right)^{1/p}} \\ &= c_p \int_0^{\pi_{p^*, p}/2} \frac{d\theta}{(x^p \sin_{p^*, p}^p \theta + \cos_{p^*, p}^{p^*} \theta)^{1/p}} \\ &= c_p \int_0^{\pi_{p^*, p}/2} \frac{d\theta}{(1 - (1 - x^p) \sin_{p^*, p}^p \theta)^{1/p}} \\ &= c_p \mathcal{K}_{p^*, p}((1 - x^p)^{1/p}), \end{aligned}$$

where

$$\frac{1}{c_p} = \int_0^\infty \frac{dt}{(1 + t^p)^{2/p}} = \mathcal{K}_{p^*, p}(0) = \frac{\pi_{p^*, p}}{2}.$$

Thus, Proposition 2.4 yields (1.2), i.e.,

$$\frac{1}{M_p(1, x)} = F\left(\frac{1}{p}, \frac{1}{p}; \frac{2}{p}; 1 - x^p\right).$$

Applying Lemma 3.1 with $a = b = 1/p$ and x replaced by $1 - x^p$ to (1.2), we have (1.3), i.e.,

$$\frac{1}{M_p(1, x)} = \left(\frac{2}{1+x^p} \right)^{1/p} F \left(\frac{1}{2p}, \frac{1}{2p} + \frac{1}{2}; \frac{1}{p} + \frac{1}{2}; \left(\frac{1-x^p}{1+x^p} \right)^2 \right).$$

Next, recall that $1/K_p(1, x)$ can be written as (1.1). As in the proof of Proposition 2.4, we obtain

$$\begin{aligned} \frac{1}{K_p(1, x)} &= \int_0^1 (1 - (1 - x^p)s)^{-1/p} ds \\ &= \sum_{n=0}^{\infty} (-1)^n \binom{-1/p}{n} (1 - x^p)^n \int_0^1 s^n ds \\ &= \sum_{n=0}^{\infty} \frac{(1/p)_n}{(n+1)!} (1 - x^p)^n \\ &= F \left(1, \frac{1}{p}; 2; 1 - x^p \right), \end{aligned}$$

which implies (1.4). Applying Lemma 3.1 with $a = 1$, $b = 1/p$ and x replaced by $1 - x^p$ to the last series, we have (1.5), i.e.,

$$\frac{1}{K_p(1, x)} = \left(\frac{2}{1+x^p} \right)^{1/p} F \left(\frac{1}{2p}, \frac{1}{2p} + \frac{1}{2}; \frac{3}{2}; \left(\frac{1-x^p}{1+x^p} \right)^2 \right).$$

Therefore, we accomplished the proof of Theorem 1.2.

Theorem 1.1 immediately follows from Theorem 1.2. Indeed, we assume $p \in \mathbb{P}$. Comparing the third parameters of (1.3) and (1.5), we can see that

$$\frac{1}{M_p(1, x)} \geq \frac{1}{K_p(1, x)} \quad \Leftrightarrow \quad \frac{1}{p} + \frac{1}{2} \leq \frac{3}{2},$$

hence

$$M_p(1, x) \geq K_p(1, x) \quad \Leftrightarrow \quad p \leq 1.$$

We leave it to the reader to verify that $M_1(1, x) = K_1(1, x)$ and $M_0(1, x) > K_0(1, x)$.

REMARK 3.2. Motivated by the expression in [2]:

$$\frac{1}{M_p(a, b)} = \frac{1}{\max\{a, b\}} \sum_{k=0}^{\infty} \prod_{i=0}^{k-1} \frac{(1/p+i)^2}{2/p+i} \frac{1}{k!} \left[1 - \left(\frac{\min\{a, b\}}{\max\{a, b\}} \right)^p \right]^k, \quad (3.1)$$

Nakamura [8, Remark 3.9] also indicates that $1/M_p(1, x)$ is nothing but (1.2). On the other hand, our proof gives (1.2) without deducing (3.1).

REMARK 3.3. Each mean of $L(a, b)$, $AG(a, b)$ and $K_p(a, b)$ has the other characterization than the integral expression. It is of interest to characterize Bhatia-Li's mean $M_p(a, b)$ with no use of integral, but we have not been able to do this.

REFERENCES

- [1] G. ANDREWS, R. ASKEY AND R. ROY, *Special functions*, Encyclopedia of Mathematics and its Applications, 71. Cambridge University Press, Cambridge, 1999.
- [2] R. BHATIA AND R.-C. LI, *An interpolating family of means*, Commun. Stoch. Anal. **6** (2012), no. 1, 15–31.
- [3] B. A. BHAYO AND L. YIN, *On generalized (p, q) -elliptic integrals*, preprint, arXiv:1507.00031.
- [4] J. M. BORWEIN AND P. B. BORWEIN, *Pi and the AGM*, A study in analytic number theory and computational complexity. Reprint of the 1987 original. Canadian Mathematical Society Series of Monographs and Advanced Texts, 4. A Wiley-Interscience Publication. John Wiley & Sons, Inc., New York, 1998
- [5] P. DRÁBEK AND R. MANÁSEVICH, *On the closed solution to some nonhomogeneous eigenvalue problems with p -Laplacian*, Differential Integral Equations **12** (1999), 773–788.
- [6] J. LANG AND D. E. EDMUNDS, *Eigenvalues, embeddings and generalised trigonometric functions*, Lecture Notes in Mathematics, 2016. Springer, Heidelberg, 2011.
- [7] P. LINDQVIST, *Some remarkable sine and cosine functions*, Ricerche Mat. **44** (1995), no. 2, 269–290.
- [8] N. NAKAMURA, *Order relations among some interpolating families of means*, Toyama Math. J. **35** (2012), 35–48.
- [9] S. TAKEUCHI, *Generalized Jacobian elliptic functions and their application to bifurcation problems associated with p -Laplacian*, J. Math. Anal. Appl. **385** (2012), no. 1, 24–35.
- [10] S. TAKEUCHI, *The basis property of generalized Jacobian elliptic functions*, Commun. Pure Appl. Anal. **13** (2014), no. 6, 2675–2692.
- [11] S. TAKEUCHI, *A new form of the generalized complete elliptic integrals*, Kodai Math. J. **39**, no. 1 (2016), 202–226.
- [12] S. TAKEUCHI, *Legendre-type relations for generalized complete elliptic integrals*, J. Class. Anal. **9**, no. 1 (2016), 35–42.
- [13] L. YIN AND L.-G. HUANG, *Inequalities for the generalized trigonometric and hyperbolic functions with two parameters*, J. Nonlinear Sci. Appl. **8** (2015), no. 4, 315–323.

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