

## NOTES ON THE COMPLETE ELLIPTIC INTEGRAL OF THE FIRST KIND

ZHEN-HANG YANG, WEI-MAO QIAN, WEN ZHANG AND YU-MING CHU

*Abstract.* In the article, we present several monotonicity properties and bounds for the complete elliptic integral of the first kind. As applications, we find sharp bounds for the arithmetic-geometric mean.

*Mathematics subject classification (2010):* 33E05, 26E60.

*Keywords and phrases:* Gaussian hypergeometric function, complete elliptic integral, arithmetic-geometric mean.

### REFERENCES

- [1] M. ABRAMOWITZ, I. A. STEGUN, *Handbook of Mathematical Functions with Formulas, Graphs and Mathematical Tables*, Dover, New York, 1965.
- [2] M. ADIL KHAN, S. BEGUM, Y. KHURSHID, Y.-M. CHU, *Ostrowski type inequalities involving conformable fractional integrals*, J. Inequal. Appl. **2018** (2018), Article 70, 14 pages.
- [3] M. ADIL KHAN, Y.-M. CHU, A. KASHURI, R. LIKO, G. ALI, *Conformable fractional integrals versions of Hermite-Hadamard inequalities and their generalizations*, J. Funct. Spaces **2018** (2018), Article ID 6928130, 9 pages.
- [4] M. ADIL KHAN, Y.-M. CHU, T. U. KHAN, J. KHAN, *Some new inequalities of Hermite-Hadamard type for  $s$ -convex functions with applications*, Open Math. **15**, 1 (2017), 1414–1430.
- [5] M. ADIL KHAN, M. HANIF, Z. A. KHAN, K. AHMAD, Y.-M. CHU, *Association of Jensen's inequality for  $s$ -convex function with Csiszár divergence*, J. Inequal. Appl. **2019**, (2019), Article 162, 14 pages.
- [6] M. ADIL KHAN, A. IQBAL, M. SULEMAN, Y.-M. CHU, *Hermite-Hadamard type inequalities for fractional integrals via Green's function*, J. Inequal. Appl. **2018**, (2018), Article 161, 15 pages.
- [7] M. ADIL KHAN, Y. KHURSHID, T.-S. DU, Y.-M. CHU, *Generalization of Hermite-Hadamard type inequalities via conformable fractional integrals*, J. Funct. Spaces **2018**, (2018), Article ID 5357463, 12 pages.
- [8] M. ADIL KHAN, S.-H. WU, H. ULLAH, Y.-M. CHU, *Discrete majorization type inequalities for convex functions on rectangles*, J. Inequal. Appl. **2019**, (2019), Article 16, 18 pages.
- [9] M. ADIL KHAN, S. ZAHEER ULLAN, Y.-M. CHU, *The concept of coordinate strongly convex functions and related inequalities*, Rev. R. Acad. Cienc. Exactas Fís. Nat. Ser. A Mat. RACSAM **113**, 3 (2019), 2235–2251.
- [10] H. ALZER, S.-L. QIU, *Monotonicity theorems and inequalities for the complete elliptic integrals*, J. Comput. Appl. Math. **172**, 2 (2004), 289–312.
- [11] G. D. ANDERSON, M. K. VAMANAMURTHY, M. VUORINEN, *Functional inequalities for hypergeometric functions and complete elliptic integrals*, SIAM J. Math. Anal. **23**, 2 (1992), 512–524.
- [12] G. D. ANDERSON, M. K. VAMANAMURTHY, M. VUORINEN, *Conformal Invariants, Inequalities, and Quasiconformal Maps*, John Wiley & Sons, New York, 1997.
- [13] Z.-W. CAI, J.-H. HUANG, L.-H. HUANG, *Generalized Lyapunov-Razumikhin method for retarded differential inclusions: applications to discontinuous neural networks*, Discrete Contin. Dyn. Syst. **22B**, 9 (2017), 3591–3614.
- [14] Z.-W. CAI, J.-H. HUANG, L.-H. HUANG, *Periodic orbit analysis for the delayed Filippov system*, Proc. Amer. Math. Soc. **146**, 11 (2018), 4667–4682.
- [15] B. C. CARLSON, J. L. GUSTAFSON, *Asymptotic expansion of the first elliptic integral*, SIAM J. Math. Anal. **16**, 5 (1985), 1072–1092.

- [16] Y.-M. CHU, M. ADIL KHAN, T. ALI, S. S. DRAGOMIR, *Inequalities for  $\alpha$ -fractional differentiable functions*, J. Inequal. Appl. **2017** (2017), Article 93, 12 pages.
- [17] Y.-M. CHU, Y.-F. QIU, M.-K. WANG, *Hölder mean inequalities for the complete elliptic integrals*, Integral Transforms Spec. Funct. **23**, 7 (2012), 521–527.
- [18] Y.-M. CHU, M.-K. WANG, *Optimal inequalities between harmonic, geometric, logarithmic, and arithmetic-geometric means*, J. Appl. Math. **2011** (2011), Article ID 618929, 9 pages.
- [19] Y.-M. CHU, M.-K. WANG, *Inequalities between arithmetic-geometric, Gini, and Toader means*, Abstr. Appl. Anal. **2012** (2012), Article ID 830585, 11 pages.
- [20] Y.-M. CHU, M.-K. WANG, *Optimal Lehmer mean bounds for the Toader mean*, Results Math. **61**, 3–4 (2012), 223–229.
- [21] Y.-M. CHU, M.-K. WANG, Y.-P. JIANG, S.-L. QIU, *Concavity of the complete elliptic integrals of the second kind with respect to Hölder means*, J. Math. Anal. Appl. **395**, 2 (2012), 637–642.
- [22] Y.-M. CHU, M.-K. WANG, Y.-F. QIU, *On Alzer and Qiu's conjecture for complete elliptic integral and inverse hyperbolic tangent function*, Abstr. Appl. Anal. **2011** (2011), Article ID 697547, 7 pages.
- [23] Y.-M. CHU, M.-K. WANG, S.-L. QIU, *Optimal combinations bounds of root-square and arithmetic means for Toader mean*, Proc. Indian Acad. Sci. Math. Sci. **122**, 1 (2012), 41–51.
- [24] Y.-M. CHU, M.-K. WANG, S.-L. QIU, Y.-P. JIANG, *Bounds for complete elliptic integrals of the second kind with applications*, Comput. Math. Appl. **63**, 7 (2012), 1177–1184.
- [25] Z.-F. DAI, X.-H. CHEN, F.-H. WEN, *A modified Perry's conjugate gradient method-based derivative-free method for solving large-scale nonlinear monotone equations*, Appl. Math. Comput. **270** (2015), 378–386.
- [26] L. DUAN, X.-W. FANG, C.-X. HUANG, *Global exponential convergence in a delayed almost periodic Nicholson's blowflies model with discontinuous harvesting*, Math. Methods Appl. Sci. **41**, 5 (2018), 1954–1965.
- [27] L. DUAN, C.-X. HUANG, *Existence and global attractivity of almost periodic solutions for a delayed differential neoclassical growth model*, Math. Methods Appl. Sci. **40**, 3 (2017), 814–822.
- [28] L. DUAN, L.-H. HUANG, Z.-Y GUO, X.-W. FANG, *Periodic attractor for reaction-diffusion high-order Hopfield neural networks with time-varying delays*, Comput. Math. Appl. **73**, 2 (2017), 233–245.
- [29] X.-P. FANG, Y.-J. DENG, J. LI, *Plasmon resonance and heat generation in nanostructures*, Math. Methods Appl. Sci. **38**, 18 (2015), 4663–4672.
- [30] K. GOU, B. SUN, *Numerical solution of the Goursat problem on a triangular domain with mixed boundary conditions*, Appl. Math. Comput. **217**, 21 (2011), 8765–8777.
- [31] X.-H. HE, W.-M. QIAN, H.-Z. XU, Y.-M. CHU, *Sharp power mean bounds for two Sándor-Yang means*, Rev. R. Acad. Cienc. Exactas Fís. Nat. Ser. A Mat. RACSAM **113**, 3 (2019), 2627–2638.
- [32] H.-J. HU, X.-F. ZOU, *Existence of an extinction wave in the Fisher equation with a shifting habitat*, Proc. Amer. Math. Soc. **145**, 11 (2017), 4763–4771.
- [33] C.-X. HUANG, J. GAO, P. WANG, *Attractor and boundedness of switched stochastic Cohen-Grossberg neural networks*, Discrete Dyn. Nat. Soc. **2016** (2016), Article ID 4958217, 19 pages.
- [34] C.-X. HUANG, S. GUO, L.-Z. LIU, *Boundedness on Morrey space for Toeplitz type operator associated to singular integral operator with variable Calderón-Zygmund kernel*, J. Math. Inequal. **8**, 3 (2014), 453–464.
- [35] T.-R. HUANG, B.-W. HAN, X.-Y. MA, Y.-M. CHU, *Optimal bounds for the generalized Euler-Mascheroni constant*, J. Inequal. Appl. **2018** (2018), Article 118, 9 pages.
- [36] C.-X. HUANG, L.-Z. LIU, *Boundedness of multilinear singular integral operator with a non-smooth kernel and mean oscillation*, Quaest. Math. **40**, 3 (2017), 295–312.
- [37] C.-X. HUANG, C.-L. PENG, X.-H. CHEN, F.-H. WEN, *Dynamics analysis of a class of delayed economic model*, Abstr. Appl. Anal. **2013** (2013), Article ID 962738, 12 pages.
- [38] C.-X. HUANG, Y.-C. QIAO, L.-H. HUANG, R. P. AGARWAL, *Dynamical behaviors of a food-chain model with stage structure and time delays*, Adv. Difference Equ. **2018** (2018), Article 186, 26 pages.
- [39] T.-R. HUANG, S.-Y. TAN, X.-Y. MA, Y.-M. CHU, *Monotonicity properties and bounds for the complete  $p$ -elliptic integrals*, J. Inequal. Appl. **2018** (2018), Article 239, 11 pages.
- [40] C.-X. HUANG, Z.-C. YANG, T.-S. YI, X.-F. ZOU, *On the basins of attraction for a class of delay differential equations with non-monotone bistable nonlinearities*, J. Differential Equations **256**, 7 (2014), 2101–2114.

- [41] C.-X. HUANG, H. ZHANG, L.-H. HUANG, *Almost periodicity analysis for a delayed Nicholson's blowflies model with nonlinear density-dependent mortality term*, Commun. Pure Appl. Anal. **18**, 6 (2019), 3337–3349.
- [42] C.-X. HUANG, H. ZHANG, J.-D. CAO, H.-J. HU, *Stability and Hopf bifurcation of a delayed prey-predator model with disease in the predator*, Internat. J. Bifur. Chaos Appl. Sci. Engrg. **29**, 7 (2019), Article ID 1950091, 23 pages.
- [43] Y.-J. JIANG, J.-T. MA, *Spectral collocation methods for Volterra-integro differential equations with noncompact kernels*, J. Comput. Appl. Math. **244** (2013), 115–124.
- [44] Y. KHURSHID, M. ADIL KHAN, Y.-M. CHU, *Conformable integral inequalities of the Hermite-Hadamard type in terms of GG- and GA-convexities*, J. Funct. Spaces **2019** (2019), Article ID 6926107, 8 pages.
- [45] Y. KHURSHID, M. ADIL KHAN, Y.-M. CHU, Z. A. KHAN, *Hermite-Hadamard-Fejér inequalities for conformable fractional integrals via preinvex functions*, J. Funct. Spaces **2019** (2019), Article ID 3146210, 9 pages.
- [46] R. KÜHNAU, *Eine Methode, die Positivität einer Funktion zu prüfen*, Z. Angew. Math. Mech. **74**, 2 (2012), 140–143.
- [47] J. LI, J.-Y. YING, D.-X. XIE, *On the analysis and application of an ion size-modified Poisson-Boltzmann equation*, Nonlinear Anal. Real World Appl. **47** (2019), 188–203.
- [48] Y.-C. LIU, J. WU, *Fixed point theorems in piecewise continuous function spaces and applications to some nonlinear problems*, Math. Methods Appl. Sci. **37**, 4 (2014), 508–517.
- [49] W.-M. QIAN, Y.-M. CHU, *Sharp bounds for a special quasi-arithmetic mean in terms of arithmetic and geometric means with two parameters*, J. Inequal. Appl. **2017** (2017), Article 274, 10 pages.
- [50] W.-M. QIAN, Z.-Y. HE, H.-W. ZHANG, Y.-M. CHU, *Sharp bounds for Neuman means in terms of two-parameter contraharmonic and arithmetic mean*, J. Inequal. Appl. **2019** (2019), Article 168, 13 pages.
- [51] W.-M. QIAN, H.-Z. XU, Y.-M. CHU, *Improvements of bounds for the Sándor-Yang means*, J. Inequal. Appl. **2019** (2019), Article 73, 8 pages.
- [52] W.-M. QIAN, X.-H. ZHANG, Y.-M. CHU, *Sharp bounds for the Toader-Qi mean in terms of harmonic and geometric means*, J. Math. Inequal. **11**, 1 (2017), 121–127.
- [53] S.-L. QIU, X.-Y. MA, Y.-M. CHU, *Sharp Landen transformation inequalities for hypergeometric functions, with applications*, J. Math. Anal. Appl. **474**, 2 (2019), 1306–1337.
- [54] S.-L. QIU, M. K. VAMANAMURTHY, M. VUORINEN, *Some inequalities for the growth of elliptic integrals*, SIAM J. Math. Anal. **29**, 5 (1998), 1224–1237.
- [55] Y.-Q. SONG, M. ADIL KHAN, S. ZAHEER ULLAH, Y.-M. CHU, *Integral inequalities involving strongly convex functions*, J. Funct. Spaces **2018** (2018), Article ID 6595921, 8 pages.
- [56] Y.-X. TAN, C.-X. HUANG, B. SUN, T. WANG, *Dynamics of a class of delayed reaction-diffusion systems with Neumann boundary condition*, J. Math. Anal. Appl. **458**, 2 (2018), 1115–1130.
- [57] Z.-L. TIAN, Y. LIU, Y. ZHANG, Z.-Y. LIU, M.-Y. TIAN, *The general inner-outer iteration method based on regular splittings for the PageRank problem*, Appl. Math. Comput. **356** (2019), 479–501.
- [58] W.-S. WANG, *On A-stable one-leg methods for solving nonlinear Volterra functional differential equations*, Appl. Math. Comput. **314**, (2017), 380–390.
- [59] M.-K. WANG, Y.-M. CHU, *Refinements of transformation inequalities for zero-balanced hypergeometric functions*, Acta Math. Sci. **37B**, 3 (2017), 607–622.
- [60] M.-K. WANG, Y.-M. CHU, *Landen inequalities for a class of hypergeometric functions with applications*, Math. Inequal. Appl. **21**, 2 (2018), 521–537.
- [61] M.-K. WANG, Y.-M. CHU, Y.-P. JIANG, *Ramanujan's cubic transformation inequalities for zero-balanced hypergeometric functions*, Rocky Mountain J. Math. **46**, 2 (2016), 679–691.
- [62] M.-K. WANG, Y.-M. CHU, S.-L. QIU, Y.-P. JIANG, *Convexity of the complete elliptic integrals of the first kind with respect to Hölder means*, J. Math. Anal. Appl. **388**, 2 (2012), 1141–1146.
- [63] M.-K. WANG, Y.-M. CHU, Y.-F. QIU, S.-L. QIU, *An optimal power mean inequality for the complete elliptic integrals*, Appl. Math. Lett. **24**, 6 (2012), 887–890.
- [64] M.-K. WANG, Y.-M. CHU, W. ZHANG, *Monotonicity and inequalities involving zero-balanced hypergeometric function*, Math. Inequal. Appl. **22**, 2 (2019), 601–617.
- [65] M.-K. WANG, Y.-M. CHU, W. ZHANG, *Precise estimates for the solution of Ramanujan's generalized modular equation*, Ramanujan J. **49**, 3 (2019), 653–668.

- [66] W.-S. WANG, Y.-Z. CHEN, H. FANG, *On the variable two-step IMEX BDF method for parabolic integro-differential equations with nonsmooth initial data arising in finance*, SIAM J. Numer. Anal. **57**, 3 (2019), 1289–1317.
- [67] J.-F. WANG, X.-Y. CHEN, L.-H. HUANG, *The number and stability of limit cycles for planar piecewise linear systems of node-saddle type*, J. Math. Anal. Appl. **469**, 1 (2018), 405–427.
- [68] J.-F. WANG, C.-X. HUANG, L.-H. HUANG, *Discontinuity-induced limit cycles in a general planar piecewise linear system of saddle-focus type*, Nonlinear Anal. Hybrid Syst. **33** (2019), 162–178.
- [69] M.-K. WANG, Y.-M. LI, Y.-M. CHU, *Inequalities and infinite product formula for Ramanujan generalized modular equation function*, Ramanujan J. **46**, 1 (2018), 189–200.
- [70] H. WANG, W.-M. QIAN, Y.-M. CHU, *Optimal bounds for Gaussian arithmetic-geometric mean with applications to complete elliptic integral*, J. Funct. Spaces **2016** (2016), Article ID 3698463, 6 pages.
- [71] J.-L. WANG, W.-M. QIAN, Z.-Y. HE, Y.-M. CHU, *On approximating the Toader mean by other bivariate means*, J. Funct. Spaces **2019** (2019), Article ID 6082413, 7 pages.
- [72] M.-K. WANG, S.-L. QIU, Y.-M. CHU, *Infinite series formula for Hübner upper bound function with applications to Hersch-Pfluger distortion function*, Math. Inequal. Appl. **21**, 3 (2018), 629–648.
- [73] G.-D. WANG, X.-H. ZHANG, Y.-M. CHU, *A power mean inequality involving the complete elliptic integrals*, Rocky Mountain J. Math. **44**, 5 (2014), 1661–1667.
- [74] M.-K. WANG, W. ZHANG, Y.-M. CHU, *Monotonicity, convexity and inequalities involving the generalized elliptic integrals*, Acta Math. Sci. **39B**, 5 (2019), 1440–1450.
- [75] S.-H. WU, Y.-M. CHU, *Schur  $m$ -power convexity of generalized geometric Bonferroni mean involving three parameters*, J. Inequal. Appl. **2019** (2019), Article 57, 11 pages.
- [76] J. WU, Y.-C. LIU, *Note for the tripled and quadruple fixed points of the mixed monotone mappings*, Bull. Korean Math. Soc. **50**, 3 (2013), 993–1005.
- [77] D.-X. XIE, J. LI, *A new analysis of electrostatic free energy minimization and Poisson-Boltzmann equation for protein in ionic solvent*, Nonlinear Anal. Real World Appl. **21** (2015), 185–196.
- [78] H.-Z. XU, Y.-M. CHU, W.-M. QIAN, *Sharp bounds for the Sándor-Yang means in terms of arithmetic and contra-harmonic means*, J. Inequal. Appl. **2018** (2018), Article 127, 13 pages.
- [79] ZH.-H. YANG, Y.-M. CHU, *A monotonicity property involving the generalized elliptic integral of the first kind*, Math. Inequal. Appl. **20**, 3 (2017), Article 127, 729–735.
- [80] ZH.-H. YANG, Y.-M. CHU, M.-K. WANG, *Monotonicity criterion for the quotient of power series with applications*, J. Math. Anal. Appl. **428**, 1 (2015), 587–604.
- [81] ZH.-H. YANG, Y.-M. CHU, W. ZHANG, *High accuracy asymptotic bounds for the complete elliptic integral of the second kind*, Appl. Math. Comput. **348** (2019), 552–564.
- [82] X.-S. YANG, C.-X. HUANG, Z.-C. YANG, *Stochastic synchronization of reaction-diffusion neural networks under general impulsive controller with mixed delays*, Abstr. Appl. Anal. **2012** (2012), Article ID 603535, 25 pages.
- [83] ZH.-H. YANG, W.-M. QIAN, Y.-M. CHU, *Monotonicity properties and bounds involving the complete elliptic integrals of the first kind*, Math. Inequal. Appl. **21**, 4 (2018), 1185–1199.
- [84] ZH.-H. YANG, W.-M. QIAN, Y.-M. CHU, W. ZHANG, *Monotonicity rule for the quotient of two functions and its application*, J. Inequal. Appl. **2017** (2017), Article 106, 13 pages.
- [85] ZH.-H. YANG, W.-M. QIAN, Y.-M. CHU, W. ZHANG, *On rational bounds for the gamma function*, J. Inequal. Appl. **2017** (2017), Article 210, 17 pages.
- [86] ZH.-H. YANG, W.-M. QIAN, Y.-M. CHU, W. ZHANG, *On approximating the error function*, Math. Inequal. Appl. **21**, 2 (2018), 469–479.
- [87] ZH.-H. YANG, W.-M. QIAN, Y.-M. CHU, W. ZHANG, *On approximating the arithmetic-geometric mean and complete elliptic integral of the first kind*, J. Math. Anal. Appl. **462**, 2 (2018), 1714–1726.
- [88] ZH.-H. YANG, Y.-Q. SONG, Y.-M. CHU, *Bounds for the arithmetic-geometric mean*, J. Inequal. Appl. **2014** (2014), Article 192, 13 pages.
- [89] ZH.-H. YANG, W. ZHANG, Y.-M. CHU, *Monotonicity of the incomplete gamma function with applications*, J. Inequal. Appl. **2016** (2016), Article 251, 10 pages.
- [90] ZH.-H. YANG, W. ZHANG, Y.-M. CHU, *Sharp Gautschi inequality for parameter  $0 < p < 1$  with applications*, Math. Inequal. Appl. **20**, 4 (2017), 1107–1120.
- [91] S. ZAHEER ULLAH, M. ADIL KHAN, Y.-M. CHU, *Majorization theorems for strongly convex functions*, J. Inequal. Appl. **2019** (2019), Article 58, 13 pages.

- [92] S. ZAHEER ULLAH, M. ADIL KHAN, Z. A. KHAN, Y.-M. CHU, *Integral majorization type inequalities for the functions in the sense of strong convexity*, J. Funct. Spaces **2019** (2019), Article ID 9487823, 11 pages.
- [93] T.-H. ZHAO, Y.-M. CHU, *A class of logarithmically completely monotonic functions associated with a gamma function*, J. Inequal. Appl. **2010** (2010), Article ID 392431, 11 pages.
- [94] T.-H. ZHAO, Y.-M. CHU, H. WANG, *Logarithmically complete monotonicity properties relating to the gamma function*, Abstr. Appl. Anal. **2011** (2011), Article ID 896483, 13 pages.
- [95] T.-H. ZHAO, M.-K. WANG, W. ZHANG, Y.-M. CHU, *Quadratic transformation inequalities for Gaussian hypergeometric function*, J. Inequal. Appl. **2018** (2018), Article 251, 15 pages.
- [96] T.-H. ZHAO, B.-C. ZHOU, M.-K. WANG, Y.-M. CHU, *On approximating the quasi-arithmetic mean*, J. Inequal. Appl. **2019** (2019), Article 42, 12 pages.
- [97] L. ZHANG, J.-L. LI, *A new globalization technique for nonlinear conjugate gradient methods for nonconvex minimization*, Appl. Math. Comput. **217**, 24 (2011), 10295–10304.
- [98] W.-J. ZHOU, F. WANG, *A PRP-based residual method for large-scale monotone nonlinear equations*, Appl. Math. Comput. **261** (2015), 1–7.
- [99] K.-X. ZHU, Y.-Q. XIE, F. ZHOU, *Pullback attractors for a damped semilinear wave equation with delays*, Acta Math. Sin. **34**, 7 (2018), 1131–1150.