

INEQUALITIES FOR GENERALIZED TRIGONOMETRIC AND HYPERBOLIC FUNCTIONS WITH ONE PARAMETER

MIAO-KUN WANG, MIAO-YING HONG, YANG-FAN XU, ZHONG-HUA SHEN AND
YU-MING CHU

Abstract. In the article, we establish several new inequalities for the generalized trigonometric and hyperbolic functions with one parameter, generalize the well known Mitrinović-Adamović, Lazarević, Huygens-type, Wilker-type and Cusa-Huygens-type inequalities to the cases of the generalized trigonometric and hyperbolic functions with one parameter.

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REFERENCES

- [1] M. ADIL KHAN, Y.-M. CHU, A. KASHURI, R. LIKO AND G. ALI, *Conformable fractional integrals versions of Hermite-Hadamard inequalities and their generalizations*, J. Funct. Spaces, **2018** (2018), Article ID 6928130, 9 pages.
- [2] M. ADIL KHAN, Y.-M. CHU, T. U. KHAN AND J. KHAN, *Some new inequalities of Hermite-Hadamard type for s -convex functions with applications*, Open Math., **15**, 1 (2017), 1414–1430.
- [3] M. ADIL KHAN, M. HANIF, Z. A. KHAN, K. AHMAD AND Y.-M. CHU, *Association of Jensen's inequality for s -convex function with Csiszár divergence*, J. Inequal. Appl., **2019** (2019), Article 162, 14 pages.
- [4] M. ADIL KHAN, A. IQBAL, M. SULEMAN AND Y.-M. CHU, *Hermite-Hadamard type inequalities for fractional integrals via Green's function*, J. Inequal. Appl., **2018** (2018), Article 161, 15 pages.
- [5] M. ADIL KHAN, Y. KHURSHID, T.-S. DU AND Y.-M. CHU, *Generalization of Hermite-Hadamard type inequalities via conformable fractional integrals*, J. Funct. Spaces, **2018** (2018), Article ID 5357463, 12 pages.
- [6] M. ADIL KHAN, S.-H. WU, H. ULLAH AND Y.-M. CHU, *Discrete majorization type inequalities for convex functions on rectangles*, J. Inequal. Appl., **2019** (2019), Article 16, 18 pages.
- [7] M. ADIL KHAN, S. ZAHEER ULLAH AND 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.
- [8] G. D. ANDERSON, M. K. VAMANAMURTHY AND M. VUORINEN, *Conformal Invariants, Inequalities, and Quasiconformal Maps*, John Wiley & Sons, New York, 1997.
- [9] Ö. BAKŞI, P. GURKA, J. LANG AND O. MÉNDEZ, *Basis properties of Lindqvist-Peetre functions on $L^r(0,1)^n$* , Rev. Mat. Complut., **30**, 1 (2017), 1–12.
- [10] Á. BARICZ, B. A. BHAYO AND M. VUORINEN, *Turán inequalities for generalized inverse trigonometric functions*, Filomat, **29**, 2 (2015), 303–313.
- [11] B. A. BHAYO AND M. VUORINEN, *On generalized trigonometric functions with two parameters*, J. Approx. Theory, **164**, 10 (2012), 1415–1426.
- [12] Z.-W. CAI, J.-H. HUANG AND 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.

- [13] Z.-W. CAI, J.-H. HUANG AND L.-H. HUANG, *Periodic orbit analysis for the delayed Filippov system*, Proc. Amer. Math. Soc., **146**, 11 (2018), 4667–4682.
- [14] Y.-M. CHU, M. ADIL KHAN, T. ALI AND S. S. DRAGOMIR, *Inequalities for α -fractional differentiable functions*, J. Inequal. Appl., **2017** (2017), Article 93, 12 pages.
- [15] Y.-M. CHU, M.-K. WANG AND 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.
- [16] Z.-F. DAI, *Comments on a new class of nonlinear conjugate gradient coefficients with global convergence properties*, Appl. Math. Comput., **276** (2016), 297–300.
- [17] Z.-F. DAI, X.-H. CHEN AND 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.
- [18] Z.-F. DAI, D.-H. LI AND F.-H. WEN, *Worse-case conditional value-at-risk for asymmetrically distributed asset scenarios returns*, J. Comput. Anal. Appl., **20**, 2 (2016), 237–251.
- [19] Z.-F. DAI AND F.-H. WEN, *Another improved Wei-Yao-Liu nonlinear conjugate gradient method with sufficient descent property*, Appl. Math. Comput., **218**, 14 (2012), 7421–7430.
- [20] Z.-F. DAI AND F.-H. WEN, *Robust CVaR-based portfolio optimization under a genal affine data perturbation uncertainty set*, J. Comput. Anal. Appl., **16**, 1 (2014), 93–103.
- [21] L. DUAN, X.-W. FANG AND 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.
- [22] L. DUAN AND 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.
- [23] L. DUAN, L.-H. HUANG, Z.-Y. GUO AND 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.
- [24] D. E. EDMUNDSON, P. GURKA AND J. LANG, *Properties of generalized trigonometric functions*, J. Approx. Theory, **164**, 1 (2012), 47–56.
- [25] X.-P. FANG, Y.-J. DENG AND J. LI, *Plasmon resonance and heat generation in nanostructures*, Math. Methods Appl. Sci., **38**, 18 (2015), 4663–4672.
- [26] X.-H. HE, W.-M. QIAN, H.-Z. XU AND 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.
- [27] H.-J. HU AND L.-Z. LIU, *Weighted inequalities for a general commutator associated to a singular integral operator satisfying a variant of Hörmander’s condition*, Math. Notes, **101**, 5-6 (2017), 830–840.
- [28] H.-J. HU AND 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.
- [29] C.-X. HUANG AND J.-D. CAO, *Stochastic dynamics of nonautonomous Cohen-Grossberg neural networks*, Abstr. Appl. Anal., **2011** (2011), Article ID 297147, 17 pages.
- [30] C.-X. HUANG, S. GUO AND 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.
- [31] T.-R. HUANG, B.-W. HAN, X.-Y. MA AND Y.-M. CHU, *Optimal bounds for the generalized Euler-Mascheroni constant*, J. Inequal. Appl., **2018** (2018), Article 118, 9 pages.
- [32] C.-X. HUANG, H.-F. KUANG, X.-H., CHEN AND F.-H. WEN, *An LMI approach for dynamics of switched cellular neural networks with mixed delays*, Abstr. Appl. Anal., **2013** (2013), Article ID 870486, 8 pages.
- [33] C.-X. HUANG AND B.-W. LIU, *New studies on dynamic analysis of inertial neural networks involving non-reduced order method*, Neurocomputing, **325**, 24 (2019), 283–287.
- [34] C.-X. HUANG, B.-W. LIU, X.-M. TIAN, L.-S. YANG AND X.-X. ZHANG, *Global convergence on asymptotically almost periodic SICNNs with nonlinear decay functions*, Neural Process. Lett., **49**, 2 (2019), 625–641.
- [35] C.-X. HUANG, C.-L. PENG, X.-H. CHEN AND F.-H. WEN, *Dynamics analysis of a class of delayed economic model*, Abstr. Appl. Anal., **2013** (2013), Article ID 962738, 12 pages.
- [36] C.-X. HUANG, Y.-C. QIAN, L.-H. HUANG AND 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.

- [37] T.-R. HUANG, S.-Y. TAN, X.-Y. MA AND Y.-M. CHU, *Monotonicity properties and bounds for the complete p -elliptic integrals*, J. Inequal. Appl., **2018** (2018), Article 239, 11 pages.
- [38] C.-X. HUANG, Z.-C. YANG, T.-S. YI AND X.-F. ZHOU, *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.
- [39] C.-X. HUANG AND H. ZHANG, *On Periodicity of non-autonomous inertial neural networks involving proportional delays and non-reduced order method*, Int. J. Biomath., **12**, 2 (2019), Article ID 1950016, 13 pages.
- [40] C.-X. HUANG, H. ZHANG AND L.-H. HUANG, *Almost periodicity analysis for a delayed Nicholson's blowflies model with nonlinear density-dependent mortality term*, Commun. Pure Appl. Anal., **18** (2019), 3337–3349.
- [41] Y.-J. JIANG AND J.-T. MA, *Spectral collocation methods for Volterra-integro differential equations with noncompact kernels*, J. Comput. Appl. Math., **244** (2013), 115–124.
- [42] Y.-J. JIANG AND X.-J. XU, *A monotone finite volume method for time fractional Fokker-Planck equations*, Sci. China Math., **62**, 4 (2019), 783–794.
- [43] Y. KHURSHID, M. ADIL KHAN, Y.-M. CHU AND Z. A. KHAN, *Hermite-Hadamard-Fejér inequalities for conformable fractional integrals via preinvex functions*, J. Funct. Spaces, **2019** (2019), Article ID 3146210, 9 pages.
- [44] R. KLÉN, M. VUORUNEN AND X.-H. ZHANG, *Inequalities for the generalized trigonometric and hyperbolic functions*, J. Math. Anal. Appl., **409**, 1 (2014), 521–529.
- [45] J.-L. LI, G.-Y. SUN AND R.-M. ZHANG, *The numerical solution of scattering by infinite rough interfaces based on the integral equation method*, Comput. Math. Appl., **71**, 7 (2016), 1491–1502.
- [46] X.-F. LI, G.-J. TANG AND B.-Q. TANG, *Stress field around a strike-slip fault in orthotropic elastic layers via a hypersingular integral equation*, Comput. Math. Appl., **66**, 11 (2013), 2317–2326.
- [47] J. LI, Y.-Y. YANG AND 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] P. LINDQVIST, *Some remarkable sine and cosine functions*, Ricerche Mat., **44**, 2 (1995), 269–290.
- [49] P. LINDQVIST AND J. PEETRE, *p -arc length of the q -circle*, Math. Student, **72**, 1-4 (2003), 139–145.
- [50] Y.-C. LIU AND 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.
- [51] Z.-Y. LIU, N.-C. WU, X.-R. QIN AND Y.-L. ZHANG, *Trigonometric transform splitting methods for real symmetric Toeplitz systems*, Comput. Math. Appl., **75**, 8 (2018), 2782–2794.
- [52] Z.-Y. LIU, Y.-L. ZHANG, J. SANTOS AND R. RALHA, *On computing complex square roots of real matrices*, Appl. Math. Lett., **25**, 10 (2012), 1565–1568.
- [53] J.-Y. PENG AND Y. ZHANG, *Heron triangles with figurate number sides*, Acta Math. Hungar., **157**, 2 (2019), 478–488.
- [54] W.-M. QIAN, Z.-Y. HE, H.-W. ZHANG AND 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.
- [55] W.-M. QIAN, H.-Z. XU AND Y.-M. CHU, *Improvements of bounds for the Sándor-Yang means*, J. Inequal. Appl., **2019** (2019), Article 73, 8 pages.
- [56] W.-M. QIAN, Y.-Y. YANG, H.-W. ZHANG AND Y.-M. CHU, *Optimal two-parameter geometric and arithmetic mean bounds for the Sándor-Yang mean*, J. Inequal. Appl., **2019** (2019), Article 287, 12 pages.
- [57] S. RASHID, M. A. NOOR, K. I. NOOR, F. SAFDAR AND Y.-M. CHU, *Hermite-Hadamard type inequalities for the class of convex functions on time scale*, Math., **2009**, 7 (2019), Article 956, 20 pages, DOI:10.3390/math7100956.
- [58] Y.-Q. SONG, M. ADIL KHAN, S. ZAHEER ULLAH AND Y.-M. CHU, *Integral inequalities involving strongly convex functions*, J. Funct. Spaces, **2018** (2018), Article ID 6595921, 8 pages.
- [59] Y.-X. TAN, C.-X. HUANG, B.-SUN AND T. WANG, *Dynamics of a class of delayed reaction-diffusion systems with Neumann boundary condition*, J. Math. Anal. Appl., **458**, 2 (2018), 1115–1130.
- [60] Y.-X. TAN, K. JIANG, *Existence and global exponential stability of almost periodic solution for delayed competitive neural networks with discontinuous activations*, Math. Methods Appl. Sci., **39**, 11 (2016), 2821–2839.
- [61] W.-S. TANG AND Y.-J. SUN, *Construction of Runge-Kutta type methods for solving ordinary differential equations*, Appl. Math. Comput., **234** (2014), 179–191.

- [62] W.-S. TANG AND J.-J. ZHANG, *Symplecticity-preserving continuous-stage Runge-Kutta-Nyström methods*, Appl. Math. Comput., **323** (2018), 204–219.
- [63] Z.-L. TIAN, Y. LIU, Y. ZHANG, Z.-Y. LIU AND M.-Y. TIAN, *The general inner-outer iteration method based on regular splittings for the PageRank problem*, Appl. Math. Comput., **356** (2019), 479–501.
- [64] W.-S. WANG, *On A-stable one-leg methods for solving nonlinear Volterra functional differential equations*, Appl. Math. Comput., **314** (2017), 380–390.
- [65] W.-S. WANG AND Y.-Z. CHEN, *Fast numerical valuation of options with jump under Merton's model*, J. Comput. Appl. Math., **318** (2017), 79–92.
- [66] W.-S. WANG, Y.-Z. CHEN AND H. FENG, *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.-H. CHEN AND 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 (2019), 405–427.
- [68] M.-K. WANG, H.-H. CHU AND Y.-M. CHU, *Precise bounds for the weighted Hölder mean of the complete p -elliptic integrals*, J. Math. Anal. Appl., **480**, 2 (2019), Article ID 123388, 9 pages, DOI: 10.1016/j.jmaa.2019.123388.
- [69] M.-K. WANG, Y.-M. CHU AND W. ZHANG, *Monotonicity and inequalities involving zero-balanced hypergeometric function*, Math. Inequal. Appl., **22**, 2 (2019), 601–617.
- [70] M.-K. WANG, Y.-M. CHU AND W. ZHANG, *Precise estimates for the solution of Ramanujan's generalized modular equation*, Ramanujan J., **49**, 3 (2019), 653–668.
- [71] T. WANG AND H. GUO, *Existence and nonexistence of nodal solutions for Choquard type equations with perturbation*, J. Math. Anal. Appl., **480**, 2 (2019), Article ID 123438, 20 pages, DOI: 10.1016/j.jmaa.2019.123438.
- [72] J.-F. WANG, C.-X. HUANG AND 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.
- [73] J.-L. WANG, W.-M. QIAN, Z.-Y. HE AND Y.-M. CHU, *On approximating the Toader mean by other bivariate means*, J. Funct. Spaces, **2019** (2019), Article ID 6082413, 7 pages.
- [74] M.-K. WANG, W. ZHANG AND Y.-M. CHU, *Monotonicity, convexity and inequalities involving the generalized elliptic integrals*, Acta Math. Sci., **39B**, 5 (2019), 1440–1450.
- [75] S.-H. WU AND 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] C.-E. XIAO, J.-B. LIU AND Y.-L. LIU, *An inverse pollution problem in porous media*, Appl. Math. Comput., **218**, 7 (2011), 3649–3653.
- [77] D.-X. XIE AND 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 AND 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] Z.-H. YANG, W.-M. QIAN, Y.-M. CHU AND W. ZHANG, *On rational bounds for the gamma function*, J. Inequal. Appl., **2017** (2017), Article 210, 17 pages.
- [80] S. ZAHEER ULLAH, M. ADIL KHAN AND Y.-M. CHU, *Majorization theorems for strongly convex functions*, J. Inequal. Appl., **2019** (2019), Article 58, 13 pages.
- [81] S. ZAHEER ULLAH, M. ADIL KHAN AND Y.-M. CHU, *A note on generalized convex functions*, J. Inequal. Appl., **2019** (2019), Article 291, 10 pages.
- [82] S. ZAHEER ULLAH, M. ADIL KHAN, Z. A. KHAN AND 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.
- [83] L. ZHANG AND S.-Y. JIAN, *Further studies on the Wei-Yao-Liu nonlinear conjugate gradient method*, Appl. Math. Comput., **219**, 14 (2013), 7616–7621.
- [84] T.-H. ZHAO, Y.-M. CHU AND H. WANG, *Logarithmically complete monotonicity properties relating to the gamma function*, Abstr. Appl. Anal., **2011** (2011), Article ID 896483, 13 pages.
- [85] W.-J. ZHOU, *On the convergence of the modified Levenberg-Marquardt method with a nonmonotone second order Armijo type line search*, J. Comput. Appl. Math., **239** (2013), 152–161.

- [86] X.-S. ZHOU, *Weighted sharp function estimate and boundedness for commutator associated with singular integral operator satisfying a variant of Hörmander's condition*, J. Math. Inequal., **9**, 2 (2015), 587–596.
- [87] W.-J. ZHOU, AND X.-L. CHEN, *On the convergence of a modified regularized Newton method for convex optimization with singular solutions*, J. Comput. Appl. Math., **239** (2013), 179–188.
- [88] W.-J. ZHOU AND F. WANG, *A PRP-based residual method for large-scale monotone nonlinear equations*, Appl. Math. Comput., **261** (2015), 1–7.
- [89] Q.-X. ZHU, C.-X. HUANG AND X.-S. YANG, *Exponential stability for stochastic jumping BAM neural networks with time-varying and distributed delays*, Nonlinear Anal. Hybrid Syst., **5**, 1 (2011), 52–77.