Paper-258-20

18th International Conference on Renewable Energies and Power Quality (ICREPQ'20)
Granada (Spain), 1st to 2nd April 2020
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.18, June 2020

UNIVERSIDAD DE ANTIOQUIA
Facultad de Ingeniería

GEA
Grupo Energía Alternativa

Tecnológico de Antioquia Institución Universitaria

Surrogate modelling for high-lift multi-element hydrofoil shape optimization of a hydrokinetic turbine blade

Rubio-Clemente A.[1], Aguilar J.[2], Chica E.[2]

[1]Facultad de Ingeniería, Tecnológico de Antioquia–Institución Universitaria TdeA, Calle 78b, No. 72A-220, Medellín (Colombia)
Phone/Fax number: +0057 2198553, e-mail: ainhoarubioclem@gmail.com
[2]Departamento de Ingeniería Mecánica, Facultad de Ingeniería, Universidad de Antioquia UdeA, Calle 70, No. 52-21, Medellín, Colombia.

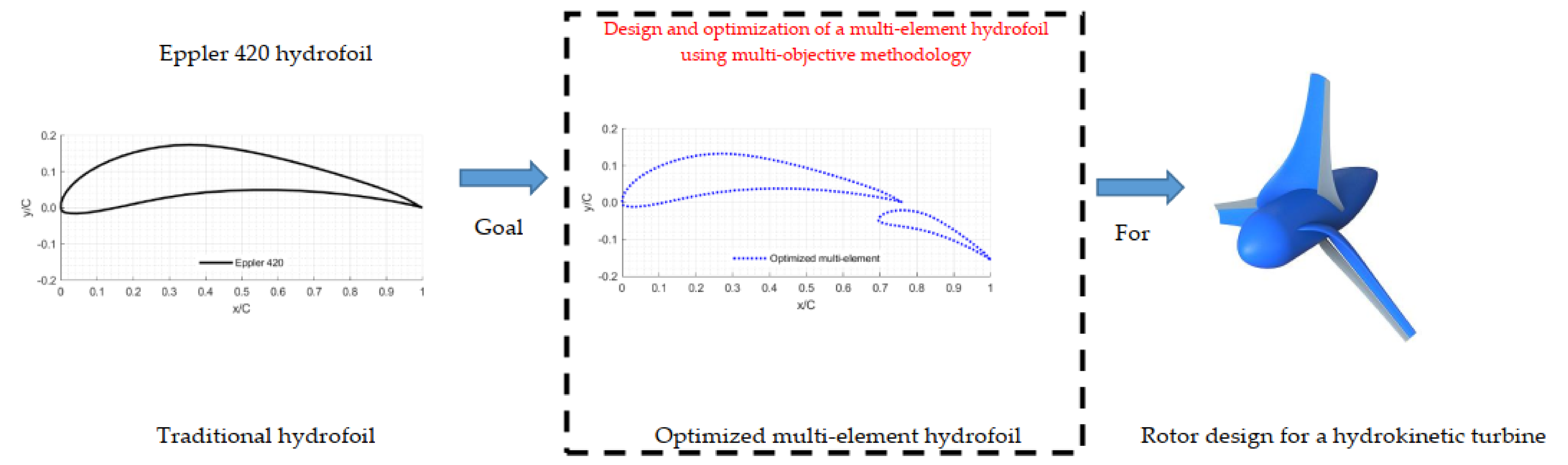
Introduction

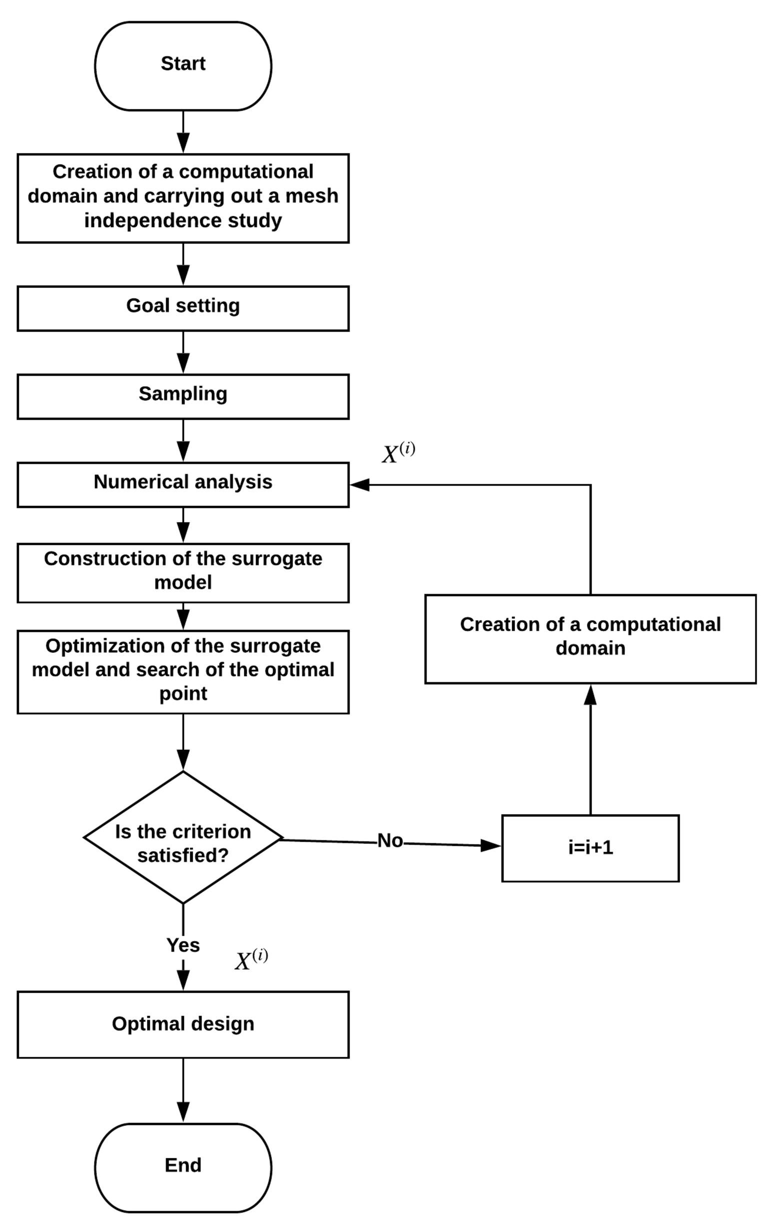
The hydrodynamic shape of a blade is one of the most important factors in the design process of a horizontal-axis hydrokinetic turbine influencing its performance. The present work is focused on the design and the hydrodynamic analysis of a high-lift system using the optimization method of surrogate models and computational fluid dynamics (CFD).

The parameters affecting the amount of the lift and the drag force that a hydrofoil can generate are the gap, the overlap, the flap deflection angle (δ), the flap chord length (C_2) and the angle of attack (α) of the hydrofoil. These factors were varied to examine the turbine performance in terms of the ratio between the lift (C_L) and the drag coefficient (C_D), and the minimum negative pressure coefficient (min C_{pre}) in order to avoid the cavitation inception. For this purpose, surrogate models were implemented to analyse the CFD results and find the optimal combination of the design parameters involved in the high-lift hydrofoil. The traditional Eppler 420 hydrofoil was utilized for the design of the multi-element profile, which was composed of a main element and a flap. The multi-element design selected as optimal had a gap of 2.825 %C_1, an overlap of 8.52 %C_1, a δ of 19.765˚, a C_2 of 42.471 %C_1 and a α of -4˚, where C_1 refers to the chord length of the main element. In comparison with the traditional Eppler 420 hydrofoil, C_L/C_D ratio increases from 39.050 to 42.517.

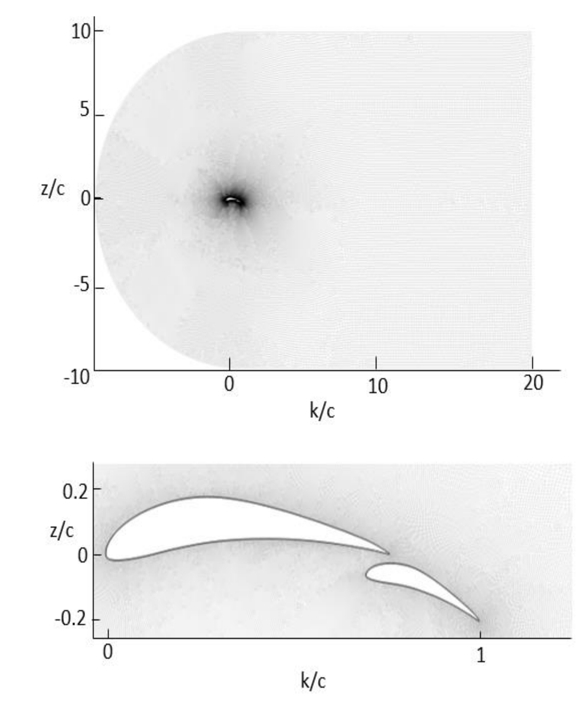
Research problem: Optimization of a two-dimensional multi-element hydrofoil shape for small horizontal-axis hydrokinetic turbines

Material and methods



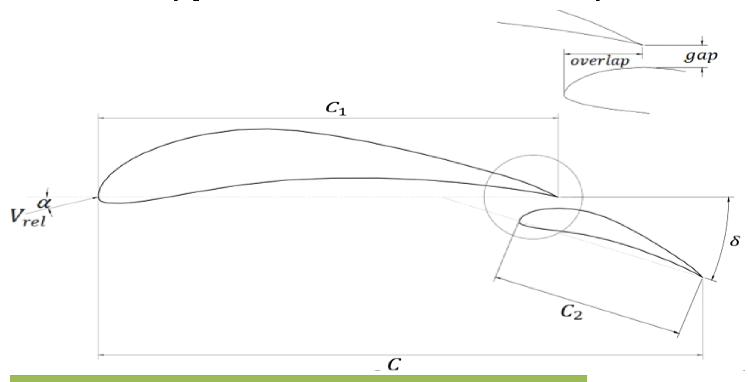


Optimization procedure



A computational grid with a C-topology for a Eppler 420 multi-element hydrofoil. b) A view of the computational grid close to the Eppler 420 multi-element hydrofoil.

Geometry parametrization of the multi-element hydrofoil.



Parameter (units)	Values
C (m)	0.1773
$V_{rel} = U_\infty$ (m/s)	5.517
α (°)	$-10° \leq \alpha \leq 10°$
δ (°)	$10° \leq \delta \leq 30$
gap (°)	$1\%C_1 \leq gap \leq 5\%C_1$
ovl (m)	$-5\%C_1 \leq ovl \leq 20\%C_1$
C_2 (m)	$30\%C_1 \leq C_2 \leq 75\%C_1$

Objective

In this study, the objective functions were related to the maximization of the C_L and the minimization of C_D of the multi-element hydrofoil

$$max\ C_L \text{ or } -min\ C_L$$

$$min\ C_D$$

$$|min\ C_{pre}| \leq 4$$

where $min\ C_{pre}$ refers to the minimum negative pressure coefficient to avoid the cavitation inception.

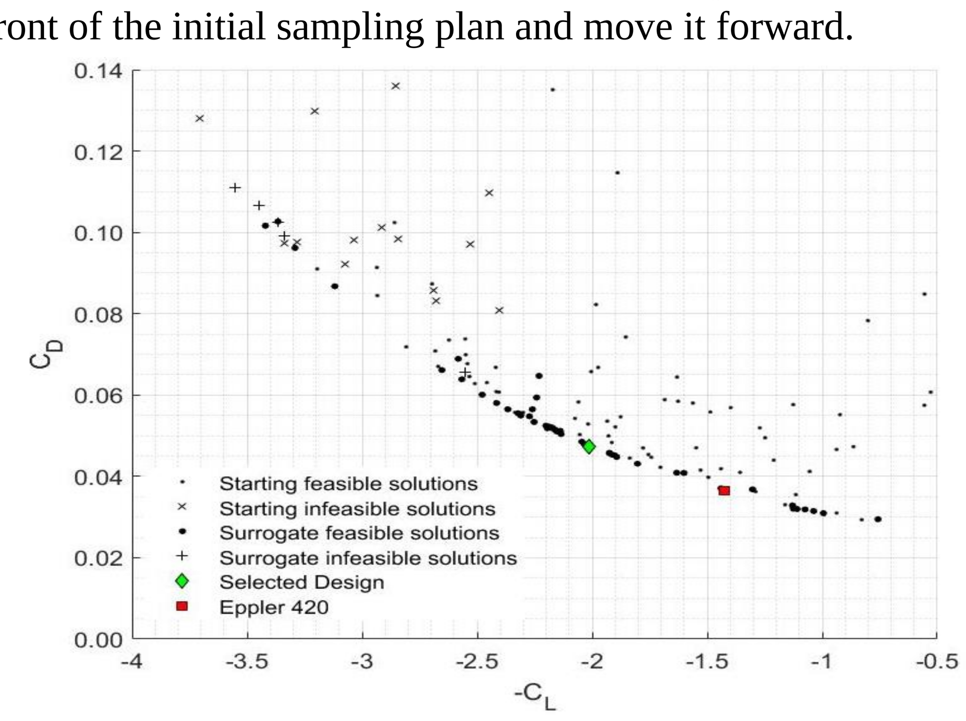
Geometric hydrofoil and boundary condition specifications

Parameter (units)	Description
Blade profile	Eppler 420
Blade chord length (C)	0.177 m
Fluid	Water at 25 °C
Turbulence model	$k-\omega$ SST
Inlet	Velocity inlet
Outlet	Pressure outlet
Upper boundaries (top edge)	Symmetric boundary
Lower boundaries (bottom edge)	Symmetric boundary
Hydrofoil	No-slip wall

Results and discussion

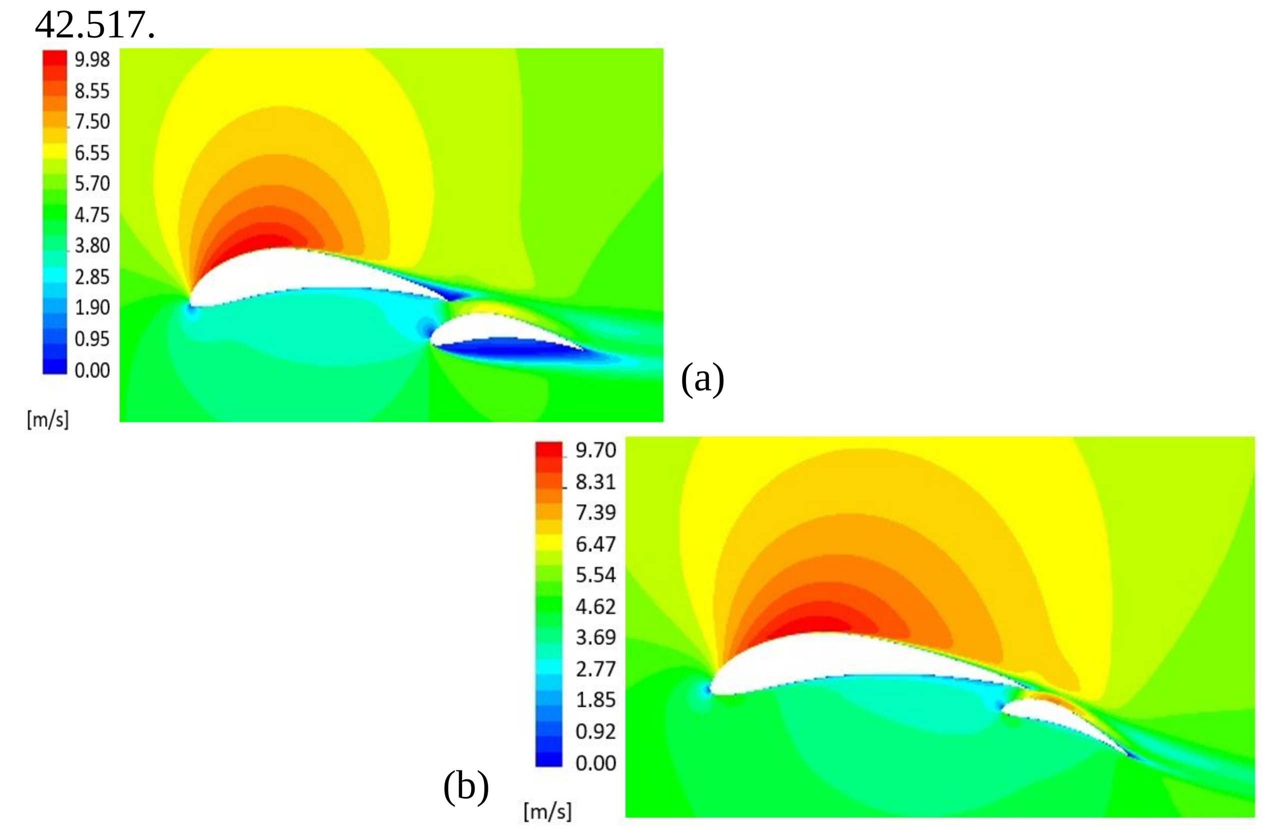
Through the established Surrogate Model (SM), a Pareto front was constructed, as shown in the figure below. In the figure, the results concerning the initial sampling, the design suggested by the SM, the starting design (Eppler 420 hydrofoil) and the selected multi-element design based on the C_L/C_D ratio are illustrated.

It is shown that few of the initial designs contributed to the Pareto front and some of them granted a better C_L/C_D ratio than that corresponding to the starting Eppler 420 hydrofoil. Additionally, the designs supplied by the SM contributed to the Pareto front with new designs that fill the gaps in the Pareto front of the initial sampling plan and move it forward.



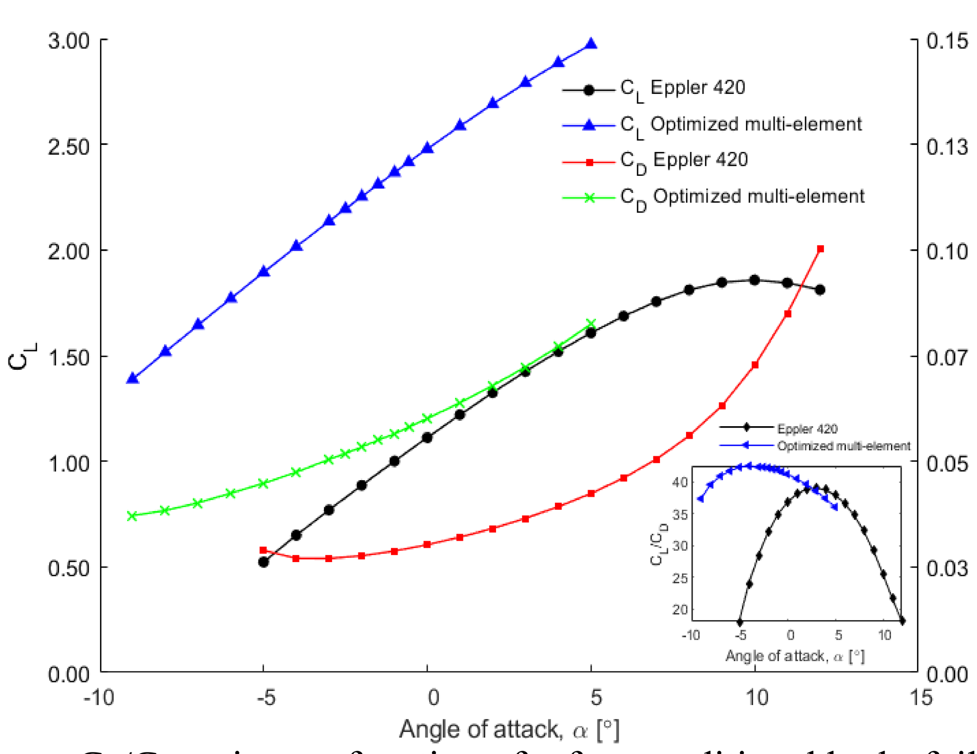
Pareto front.

The initial and optimized multi-element hydrofoil shapes are represented in the figure below. It can be observed that the resulting flow was more aligned with the flap compared to the traditional hydrofoil. The multi-element design selected as the optimal one had a gap of 2.825 %C_1, an overlap of 8.52 %C_1, a δ of 19.765˚, a C_2 of 42.471 %C_1 and a α of -4˚. C_L and C_D were equal to 2.016 and 0.047, respectively, providing a C_L/C_D of 42.517.



Contours of velocity of the flow around the initial (a) and optimized (b) multi-element hydrofoil.

The variation of C_L, C_D and C_L/C_D with α are shown in the figure below. It can be clearly found that there was a large performance improvement of the optimized shape in comparison with the initial one (i.e., C_L/C_D increased from 39.050 to 42.517).



C_L/C_D ratio as a function of α for a traditional hydrofoil and for an optimized multi-element hydrofoil using the Eppler 420 profile.

Conclusion

The design of a multi-element hydrofoil based on SM was presented in this study. The use of SM refers to an approach that can be employed for the design of hydrokinetic turbines, allowing the correction of a multi-element hydrofoil shape, aiming at preventing cavitation. In this study, the objective was to maximize C_L and minimize C_D subjected to C_{pre} < 4 constraint. The results showed that the improvement of C_L/C_D was significant compared to the conventional hydrofoil. The multi-element hydrofoil had a C_L/C_D of 8.87% larger than that of the traditional hydrofoil.

The design of the optimal hydrofoil for hydrokinetic appliances always requires an amount of time experiments and computational analysis in order to achieve the planned goals. In this work, the SM allowed reducing the time of multi-element hydrofoil design process involved in the blade manufacture of a horizontal-axis hydrokinetic turbine due to the reduction of the iterations number and the CFD analysis within the optimization procedure.

References

[1] D. Kumar and S. Sarkar, "A review on the technology, performance, design optimization, reliability, techno-economics and environmental impacts of hydrokinetic energy conversion systems", Renewable and Sustainable Energy Reviews, (2016). Vol. 58, pp. 796-813.
[2] E. Chica and A. Rubio-Clemente, "Design of Zero Head Turbines for Power Generation", Renewable Hydropower Technologies Basel I. Ismail, IntechOpen, DOI: 10.5772/66907. Available from: https://www.intechopen.com/books/renewable-hydropower-technologies/design-of-zero-head-turbines-for-power-generation July 26th 2017.
[3] E. Chica, J. Aguilar and A. Rubio-Clemente, "Analysis of a lift augmented hydrofoil for hydrokinetic turbines", Renewable Energy and Power Quality Journal, (2019). Vol. 17, pp. 49-55
[4] J. Aguilar, A. Rubio-Clemente, L. Velàsquez and E. Chica. "Design and optimization of a multi-element hydrofoil for a horizontal-axis hydrokinetic turbine", Energies, (2019), Vol. 12 (4679), pp. 1-18.
[5] E. Chica, J. Aguilar and A. Rubio-Clemente, "Investigación numérica sobre el uso de álabes multi-elemento en turbina hidrocinética de eje horizontal", Revista UIS Ingenierías, (2019). Vol. 10 (3), pp. 117-128.
[6] E. Benini, R. Ponza and A. Massaro, "High-lift multi-element airfoil shape and setting optimization using multi-objective evolutionary algorithms", Journal of Aircraft, (2011). Vol. 48(2), pp. 683-696.
[7] P.M. Kumar, J. Seo, W. Seok, S.H. Rhee and A. Samad, "Multi-fidelity optimization of blade thickness parameters for a horizontal axis tidal stream turbine", Renewable energy, (2019). Vol. 135, pp. 277-287.
[8] A.I. Forrester, N.W. Bressloff and A.J. Keane, "Optimization using surrogate models and partially converged computational fluid dynamics simulations", Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, (2006). Vol 462(2071), pp. 2177-2204.
[9] R. Yondo, E. Andres and E. Valero, "A review on design of experiments and surrogate models in aircraft real-time and many-query aerodynamic analyses", Progress in Aerospace Sciences, (2018). Vol. 96, pp. 23-61.
[10] S. Jeong, M. Murayama and K. Yamamoto, "Efficient optimization design method using kriging model", Journal of aircraft, (2005). Vol. 42(2), pp. 413-420.
[11] J.D. Feldhacker, B.A. Jones, A. Doostan and J. Hampton, "Reduced cost mission design using surrogate models", Advances in Space Research, (2016). Vol. 57(2), pp. 588-603.
[12] V. Díaz-Casás, J.A Becerra, F. Lopez-Peña and R.J. Duro, "Wind turbine design through evolutionary algorithms based on surrogate CFD methods", Optimization and engineering, (2013). Vol. 14(2), pp. 305-329.
[13] A.D.V. Carrasco, D.J. Valles-Rosales, L.C. Mendez and M.I. Rodriguez, "A site-specific design of a fixed-pitch fixed-speed wind turbine blade for energy optimization using surrogate models", Renewable energy, (2016). Vol. 88, pp. 112-119.
[14] A.F. Molland, A.S Bahaj, J.R. Chaplin and W.M.J. Batten, "Measurements and predictions of forces, pressures and cavitation on 2-D sections suitable for marine current turbines", Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, (2004). Vol. 218(2), pp. 127-138.
[15] P.A.S.F da Silva, L.D. Shinomiya, T.F. de Oliveira, J.R.P. Vaz, A.L.A. Mesquita and A.C.P.B. Junior, "Design of hydrokinetic turbine blades considering cavitation", Energy Procedia, (2015). Vol. 75, pp. 277-282.
[16] N.V. Qoeipo, R.T. Haftka, W. Shyy, T. Goel, R. Vaidyanathan, and P.K. Tucker, "Surrogate-based analysis and optimization", Progress in Aerospace Sci-ences, (2005). Vol. 41 (1), pp. 1–28.
[17] A. Bhosekar and M. Ierapetritou, "Advances in surrogate based modeling, feasibility analysis, and optimization: A review", Computers & Chemical Engineering, (2018). Vol. 108, pp. 250-267.
[18] L. Leifsson, E. Hermannsson and S. Koziel, "Optimal shape design of multi-element trawl-doors using local surrogate models", Journal of Computational Science, (2015). Vol. 10, pp. 55-62.
[19] Y. Jin, "A comprehensive survey of fitness approximation in evolutionary computation", Soft computing, (2005). Vol. 9(1), pp. 3-12.
[20] A.F.P. Ribeiro, A.M. Awruch and H.M. Gomes, "An airfoil optimization technique for wind turbines", Applied Mathematical Modelling, (2012). Vol. 36(10), pp. 4898-4907.