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THE NA-DEL AIRFOIL MODIFICATIONS FOR GENERAL AVIATION AND UAV APPLICATIONS

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Abstract: *This paper presents the NA-DEL geometric method for modifications of the so-called Dolphin family airfoils. Based on the original mathematical concept for Dolphin airfoils by Iosif Taposu, a new modification method was developed by the authors of this paper to achieve better aerodynamic efficiency than the original Dolphin airfoils and also their NACA geometrical counterparts. Bionic airfoils represent cutting-edge aerodynamic research. After the creation and integration of the natural optimization method - the semi-elliptical method, a new concept was introduced. The concept proposed that changing the shape of the leading edge of the original Dolphin airfoils could produce favorable outcomes in terms of aerodynamic efficiency. This method involves merging the two corresponding NACA and Dolphin airfoils to create a new hybrid airfoil in the leading edge zone. The NA-DEL method was tested both numerically and experimentally, and it showed noticeable improvements by modifying the airfoils of the 2410, 2412, and 2415 series. By numerical analyses, the NA-DEL 2410, 12, and 15 hybrid airfoils have been found to increase lift and lift-to-drag ratio, while also reducing drag in cases of standard roughness and MRe=6.0, which corresponds to the general aviation category. Through wind tunnel tests performed at the Belgrade University – Faculty of Mechanical Engineering, it has been discovered that the hybrid NA-DEL 2415 is also aerodynamically more effective than NACA and original Dolphin counterparts at a Reynolds number of 400.000. Results for this Reynolds number indicate that the NA-DEL airfoils are a suitable choice for fixed-wing UAVs and in that sense have potential military applications as well.*

Keywords: *NA-DEL, geometrical modification, Dolphin airfoils, CFD, wind tunnel tests, general aviation, UAV.*

1. INTRODUCTION

The study of airfoils remains a fascinating area in aviation. Despite extensive research and analysis of different geometric shapes in aerodynamics, as well as established practices of airfoil modification, special individuals push the boundaries and redefine our understanding of this scientific field. Bionic research in aerodynamics has made a significant breakthrough in the development of technologies inspired by biological systems. Animals, such as birds and aquatic mammals, have inspired scientists to discover new aerodynamic shapes.

In a recent study in [1], researchers introduced a new bionic airfoil inspired by the sturgeon. It has superior aerodynamic characteristics compared to the symmetric NACA 0015 airfoil, particularly in terms of the lift coefficient. The study involved the development of three bionic airfoils, followed by a Large Eddy Simulation (LES) to evaluate their performance. The results indicated a significant improvement in aerodynamic efficiency for the bionic airfoils showcasing their potential for enhancing the performance of various applications.

Researchers in [2] traced the wing geometry, angle of

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attack (AoA), camber, and other bionic and flight parameters of a three-dimensional flapping wing of a barn owl. They studied the kinematics of a single flight, providing valuable insight into the bionic mechanisms and paving the way for future bionic design. In a study conducted by scientists in [3], the leading edge of a long-eared owl's wing served as the basis for the design of a bionic airfoil. This innovative airfoil was developed using reverse engineering techniques. The research findings indicated that the bionic airfoil contributed significantly to aerodynamic enhancements, particularly in deep stall conditions.

In a study in [4], researchers drew inspiration from a seagull's wing to design a bionic airfoil resembling the classical NACA 4412 airfoil. The bionic airfoil showed improved aerodynamic performance at low Reynolds numbers compared to the NACA 4412. The authors suggested its suitability for use in UAVs. In a similar study in [5], the NACA 4412 airfoil was compared to an airfoil designed to mimic the shape of a swallow's wing. After conducting numerical calculations and experimentation in a wind tunnel, the results showed that the bionic airfoil outperformed the NACA 4412 in terms of lift coefficient, lift-to-drag ratio, and stall angle.

The study of aquatic mammals, such as humpback whales, porpoises, and dolphins, which fall under the classification of Cetacea, has become a focal point in the field of aerodynamics. The shape of the dolphin has fascinated many aerodynamicists, although this topic is not yet fully explored. In [6], a bionic airfoil was examined. This airfoil was inspired by the shape of a porpoise *Phocoenoides dalli,* which is a mammal from the same family as the dolphin. Based on the streamlined profile of the Phocoenoides dalli's head, the airfoil was modified into a new design with a leading edge similar to the streamlined profile of the porpoise's head. Minor adjustments were made to this new airfoil, resulting in three bionic dolphin airfoils: the Original Dolphin Airfoil, the Smooth Transition Dolphin Airfoil, and the Deflected Dolphin Airfoil.

Romanian scientist Taposu [7] developed a mathematical model to create an airfoil with a shape inspired by a dolphin. While this airfoil is not a replica of a dolphin's body in biological terms, the mathematical model offers the advantage of generating a variety of airfoils, allowing for the creation of entire families of airfoils. The authors of this paper have made several modifications to various specific Dolphin airfoils constructed using this mathematical model in [8, 9, 10, 11]. In the following sections of this paper, the NA-DEL geometrical modification of Taposu's Dolphin airfoils (referred to as "the original Dolphin airfoils" in the rest of the paper) will be explained, which is the main focus of this study.

2. DOLPHIN AIRFOILS

2.1. The original Dolphin airfoil

The original Dolphin airfoil in Figure 1. [7] is defined by piecewise mathematical functions that encompass four primary functions: the semi-thickness distribution function, the skeleton line function, the suction and pressure surface functions.

The designer specifies the constructive parameters governing the position of maximum thickness and maximum camber to facilitate the generation of a specific airfoil from the broad spectrum of airfoils that can be derived using this mathematical model.

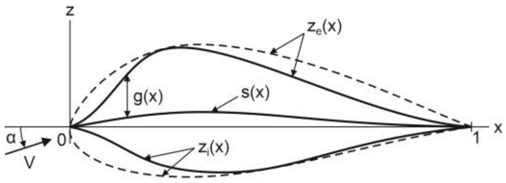

Figure 1. The original Dolphin airfoil geometry [7]

The functions of the semi-thickness distribution *g(x)* and skeleton line *s(x)* are given in Equations (1) and (2):

$$g(x)=\varepsilon\begin{cases}F_1(x), & 0\le x\le x_1\\ F_2(x), & x_1<x\le x_\varepsilon\\ F_3(x), & x_\varepsilon<x\le x_2\\ F_4(x), & x_2<x\le 1\end{cases} \quad (1)$$

$$s(x)=\begin{cases}\Phi_1(x), & 0\le x\le \xi_1\\ \Phi_2(x), & \xi_1<x\le x_\zeta\\ \Phi_3(x), & x_\zeta<x\le \xi_2\\ \Phi_4(x), & \xi_2<x\le 1\end{cases} \quad (2)$$

For an airfoil to be classified as a Dolphin-type, it must satisfy the condition given in Equation (3):

$$g'(0)=g'(1)=0 \quad (3)$$

along the unit chord on the x - axis for the interval $x \in [0, 1]$. In other words, the airfoil must have zero thickness at the leading and trailing edge, i.e. without any radius. Parameters in Equations (1) and (2) represent: ε – half-thickness, ζ - camber, ζ_1 - local camber at position x_1 (along the x-chord), ζ_2 - local camber at position x_2, x_ζ – position of the maximum camber, x_ε – position of the maximum thickness, x_1 and x_2 positions of the local half - thicknesses ε_1 and ε_2. The functions of the suction surface $z_e(x)$ and pressure surface $z_i(x)$ are given in Equations (4) and (5):

$$z_e=s(x)+g(x) \quad (4)$$

$$z_i=s(x)-g(x) \quad (5)$$

2.2. The NA-DEL airfoil modification method

The NA-DEL modification in [10] was developed to potentially enhance the hybrid Dolphin airfoils obtained through the semi-elliptical method using a geometric approach instead [10, 11]. While the semi-elliptical method can be described as a form of "natural modification" inspired by the contours of the velocity field at specific angles of attack and the flow field, leading to the creation of a new airfoil shape, the NA-DEL method differs as it is entirely based on geometric principles. The term NA-DEL was derived from the combination of NACA - NA and Delfin – DEL (Serbian for "Dolphin"). Upon careful consideration, it was determined that the NACA geometric counterparts would be connected tangentially to the original Dolphin airfoils in the leading edge zone. Specifically, the suction surface of the NACA geometric counterpart would be added up to the maximum thickness on the suction surface of the original Dolphin airfoil. Similarly, the pressure surface of the NACA geometric counterpart would be added up to the maximum thickness on the bottom, i.e. pressure surface of the original Dolphin airfoil. Subsequently, from those points to the trailing edge, the original Dolphin airfoil would be maintained. A geometrical counterpart in this sense is an airfoil that has the same relative maximum thickness in the same position on the unit chord, and the same maximum relative camber and position. This means that an airfoil like the NACA 2410 has its geometrical counterpart in the original Dolphin airfoil family with the Dolphin 2410. These airfoils have parameters according to the four-digit NACA series airfoil convention [12].

3. NA-DEL AIRFOILS

In this particular section, the NA-DEL Dolphin airfoils will be presented. Significant advancements have been made in modifying the NA-DEL 2410, 2412, and 2415 airfoils. Furthermore, experimental testing of the NA-DEL 2415 was conducted within the wind tunnel facilities at the University of Belgrade - Faculty of Mechanical Engineering [10]. The NA-DEL 2410, 2412, and 2415 were obtained through modifications of the following geometrical counterparts respectively: the NACA 2410 - and Dolphin 2410, the NACA 2412 - and Dolphin 2412, and the NACA 2415 - and Dolphin 2415 airfoils. All the aforementioned airfoils underwent numerical analyses in ANSYS FLUENT. The RANS equations with SST k-ω turbulent model were used for all calculations at Reynolds number of 6×10^6 (or MRe = 6; corresponds to the general aviation category), assuming standard roughness cases. A structured C-mesh was generated with a 2D control volume of 25 x 25*m*. All analyzed airfoils had a unit chord of 1*m* in length. The Sutherland viscosity equation was used with a density-based model for subsonic flow. A standard roughness case involves an early forced boundary layer transition. The temperature was set to T=288.15 K=const, and an operating pressure p=101325 Pa. The study employed the Full Multi-Grid method for initialization, as well as solution steering to optimize the Courant number. The mesh consists of 115600 elements. The number of iterations was set to 1000. The convergence criteria were set to absolute, with residuals set to a value of 1e-07. Convergence conditions were set to "All conditions met," and second-order discretization was used [8, 9, 10, 11].

3.1. The NA-DEL 2410 airfoil

The NA-DEL 2410 airfoil is a hybrid Dolphin airfoil obtained, as previously mentioned, by merging the two corresponding geometric counterparts, the NACA 2410 and the original Dolphin 2410 airfoils. These airfoils have a maximum camber of 2% positioned at 40% of the unit chord, and a relative maximum thickness of 10% positioned at 30% of the unit chord. The NA-DEL 2410 airfoil is presented in Figure 2, along with the original Dolphin 2410. The airfoil was obtained by merging the NACA and original Dolphin at coordinates for the upper surface: at x=0.35, z=0.069200655, and lower surface at x=0.29, z=0.031850023, assuming unit chord length. The results obtained by CFD calculations are given in Table 1.

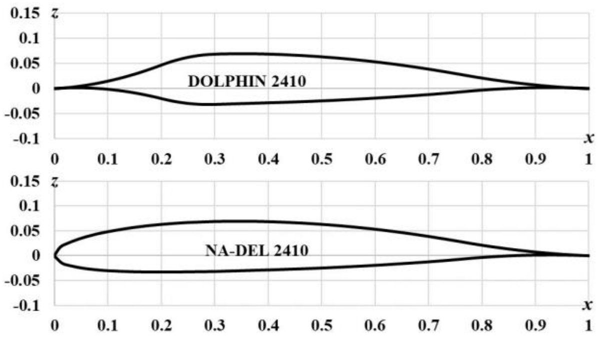

Figure 2. The original Dolphin airfoil geometry and hybrid NA-DEL 2410 counterpart

Table 1. The AoA, lift and drag coefficients, and the lift/drag ratio for the 2410 series

NACA 2410				DOLPHIN 2410				NA-DEL 2410			
α [º]	CL	CD	CL/CD	α [º]	CL	CD	CL/CD	α [º]	CL	CD	CL/CD
-6	-0.42	0.01132	-37.10	-6	-0.44	0.04950	-8.89	-6	-0.49	0.01150	-42.61
-4	-0.22	0.00943	-23.33	-4	-0.25	0.02625	-9.52	-4	-0.27	0.00919	-29.38
-2	-0.01	0.00863	-1.16	-2	-0.02	0.01285	-1.56	-2	-0.03	**0.00821**	-3.65
0	0.19	**0.00861**	22.07	0	0.20	**0.00778**	25.71	0	0.20	0.00824	24.27
2	0.40	0.00922	43.38	2	0.42	0.01144	**36.71**	2	0.43	0.00906	47.46
4	0.61	0.01059	57.60	4	0.63	0.02257	27.91	4	0.67	0.01080	62.04
6	0.81	0.01280	**63.28**	6	0.79	0.03858	20.48	6	0.89	0.01360	**65.44**
8	1.01	0.01636	61.74	**8**	**0.86**	0.06356	13.53	8	1.11	0.01810	61.33
10	1.18	0.02149	54.91	10	0.75	0.11994	6.25	10	1.30	0.02500	52.00
12	1.31	0.02929	44.73	/	/	/	/	**12**	**1.42**	0.03640	39.01
14	**1.39**	0.04654	29.87	/	/	/	/	14	1.40	0.06000	23.33
16	1.32	0.18530	7.12	/	/	/	/	16	/	/	/

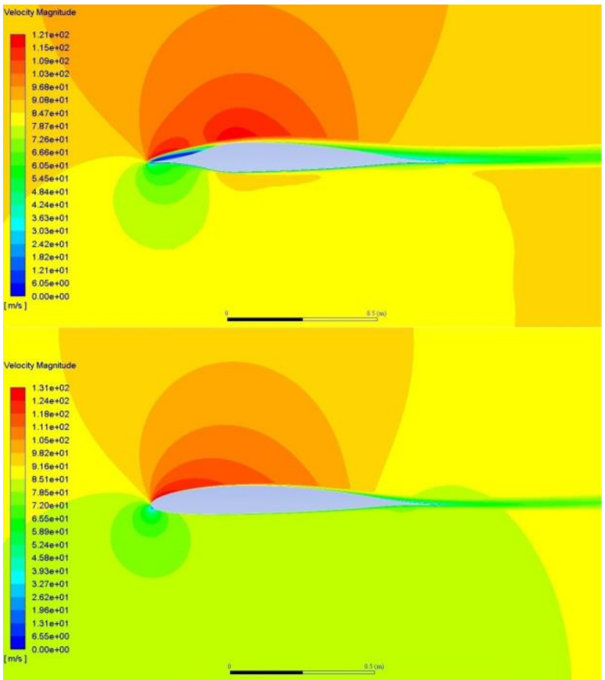

Figure 3. The velocity contours of the original Dolphin 2410 and hybrid NA-DEL 2410 airfoils at α=4°

The velocity contours indicate that, in the case of the original Dolphins, as well as the 2410 airfoil, separation occurs at the leading edge (blue bubble in Figure 3). This occurs even at low AoA, resulting in a significant loss of aerodynamic efficiency. Conversely, the smooth flow patterns over the NA-DEL 2410, without leading edge separation, indicate favorable aerodynamic characteristics of the airfoil design, Figure 3. The NA-DEL 2412 and 2415 exhibited similar behavior compared to their original Dolphin counterparts.

3.2. The NA-DEL 2412 airfoil

The NA-DEL 2412 airfoil is a hybrid Dolphin airfoil obtained by merging the NACA 2412 and the original Dolphin 2412 airfoils. The airfoil was obtained by merging the two airfoils at coordinates for the upper surface at x=0.35, z=0.0791241, and the lower surface at x=0.29, z=-0.0418166 unit chord. The flow patterns, i.e. velocity contours, show the same tendencies as in Figure 3 for the NA-DEL 2410. The original Dolphin 2412 airfoil exhibits a strong separation bubble on the leading edge at AoAs lower than 4 degrees. In contrast, the hybrid NA-DEL 2412 airfoil displays a smooth pattern, which is expected for airfoils at such AoAs. In Table 2, the numerical results of the CFD analysis are provided. Maximum values for each column are highlighted in bold. The values indicate that the Dolphin 2412 stalls at an AoA of 8 degrees, whereas the NACA 2412 and the NA-DEL 2412 at an AoA of 14 degrees. The NA-DEL 2412 lift, polar curves, and lift/drag ratios are given in Figures 4 and 5.

Table 2. The AoA, lift and drag coefficients, and the lift/drag ratio for the 2412 series

NACA 2412				DOLPHIN 2412				NA-DEL 2412			
α [°]	CL	CD	CL/CD	α [°]	CL	CD	Cl/CD	α [°]	CL	CD	CL/CD
-6	-0.41	0.01128	-36.35	-6	-0.44	0.06460	-6.81	-6	-0.50	0.01098	-45.54
-4	-0.21	0.00978	-21.47	-4	-0.26	0.03674	-7.08	-4	-0.27	0.00926	-29.16
-2	-0.01	**0.00910**	-1.10	-2	-0.04	0.01692	-2.36	-2	-0.02	**0.00853**	-2.34
0	0.18	0.00911	19.76	0	0.18	**0.00931**	19.33	0	0.21	0.00865	24.28
2	0.38	0.00970	39.18	2	0.40	0.01225	**32.65**	2	0.44	0.00948	46.41
4	0.59	0.01097	53.78	4	0.61	0.02455	24.85	4	0.67	0.01118	59.93
6	0.79	0.01300	60.77	6	0.78	0.04155	18.77	6	0.90	0.01375	**65.45**
8	0.98	0.01607	**60.98**	**8**	**0.86**	0.06807	12.63	8	1.12	0.01759	63.67
10	1.15	0.02055	55.96	10	0.84	0.10528	7.98	10	1.32	0.02312	57.09
12	1.29	0.02706	47.67	/	/	/	/	12	1.47	0.03176	46.28
14	**1.37**	0.03875	35.35	/	/	/	/	**14**	**1.54**	0.04576	33.65
16	1.28	0.06767	18.92	/	/	/	/	16	1.48	0.07227	20.48

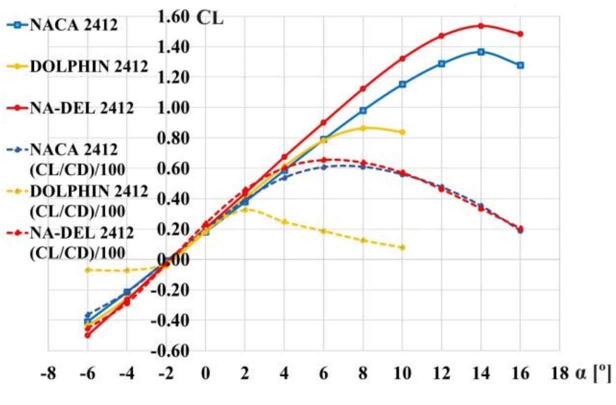

Figure 4. The lift and lift/drag curves for the 2412 airfoils

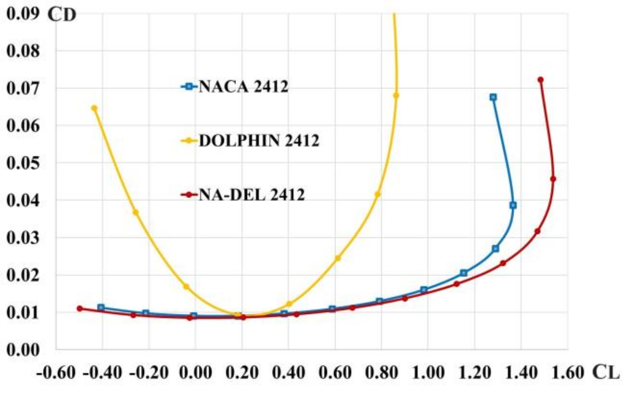

Figure 5. The polar curves for the 2412 airfoils

3.3. The NA-DEL 2415 airfoil

The NA-DEL 2415 airfoil is a hybrid Dolphin airfoil obtained by merging the NACA 2415 and the original Dolphin 2415 airfoils. The airfoil were merged at *x*=0.34, *z*=0.09403 coordinates for the upper surface, and at *x*=0.29, *z*=-0.05677 for the lower surface. The results obtained by CFD calculations are given in Table 3.

Table 3. The AoA, lift and drag coefficients, and the lift/drag ratio for the 2415 series

NACA 2415				DOLPHIN 2415				NA-DEL 2415			
α [º]	C_L	C_D	C_L/C_D	α [º]	C_L	C_D	C_L/C_D	α [º]	C_L	C_D	C_L/C_D
-6	-0.41	0.01135	-36.12	-6	-0.38	0.04045	-9.39	-6	-0.51	0.01144	-44.58
-4	-0.21	0.01008	-20.83	-4	-0.24	0.02409	-9.96	-4	-0.27	0.00978	-27.61
-2	-0.02	**0.00953**	-2.10	-2	-0.02	0.01384	-1.45	-2	-0.03	**0.00909**	-3.30
0	0.18	0.00962	18.71	0	0.21	**0.00936**	22.44	0	0.21	0.00925	22.70
2	0.38	0.01038	36.61	2	0.44	0.01253	**35.12**	2	0.45	0.01020	44.12
4	0.59	0.01183	49.87	4	0.64	0.02118	30.22	4	0.69	0.01199	57.55
6	0.79	0.01408	56.11	6	0.76	0.03520	21.59	6	0.92	0.01477	**62.29**
8	0.98	0.01727	**56.75**	**8**	**0.81**	0.05452	14.86	8	1.14	0.01895	60.16
10	1.14	0.02176	52.39	10	0.80	0.08298	9.64	10	1.32	0.02566	51.44
12	1.28	0.02838	45.10	12	/	/	/	12	1.43	0.03599	39.73
14	**1.36**	0.03965	34.30	14	/	/	/	**14**	**1.46**	0.05194	28.11
16	1.32	0.06288	20.99	16	/	/	/	16	1.41	0.07802	18.07

The velocity contours show flow patterns as similar to those shown in Figure 3. In Table 4 a comparison of the experimental results was presented to validate the general trends of the previously obtained numerical findings. The experiments (Figure 6) were conducted at a relatively low average Reynolds number of MRe≈ 0.4 (corresponding to the UAV category) due to power plant limitations [10]. The NA-DEL 2415 showed noticeably better aerodynamic characteristics, compared to its counterpart airfoils NACA 2415 and Dolphin 2415 at this Reynolds number, as well.

Figure 6. The NA-DEL 2415 airfoil in the wind tunnel test section (left and center) at Belgrade University - Faculty of Mechanical Engineering, Aerospace Department; airfoil models used in these experiments (right).

Table 4. Relative differences in experimentally obtained maximum lift and minimum drag coefficients, and lift/drag ratios of the original Dolphin and NA-DEL 215, compared to the NACA 2415 airfoil, used as reference.

Airfoil	C_{Lmax}	Relative change [%]	C_{Dmin}	Relative change [%]	$(C_L/C_D)_{max}$	Relative change [%]
NACA 2415	1.22	/	0.00540	/	58.21	/
DOLPHIN 2415	0.993	-18.60%	0.00418	-22.60%	54.73	-5.97%
NA-DEL 2415	**1.28**	**+4.91%**	**0.00362**	**-32.96%**	**73.13**	**+25.63%**

4. DISCUSSION

The new hybrid NA-DEL 2410 showed an increase in the maximum lift coefficient by 2.16% and a decrease in the minimum drag coefficient by 4.65%, according to Table 1., in comparison to the NACA 2410. It also exhibited an increase in the maximum lift-to-drag ratio by 3.41%. The velocity field contours in Figure 3 displayed the expected appearance, with separation near the trailing edge at the critical AoA. On average, the NA-DEL 2410 is 3.41% more efficient than its NACA 2410 counterpart. When comparing a newly designed hybrid airfoil to a benchmark NACA airfoil, the maximum lift, minimum drag, and maximum lift-to-drag coefficients are considered. To obtain an average value for comparison, these three values are added together and divided by three. If the result is greater than 100%, the hybrid airfoil is considered more aerodynamically efficient than the NACA counterpart. It is important to note the sign for the minimum drag coefficient, where a value less than 100% indicates an aerodynamic improvement.

The results for the hybrid NA-DEL 2412 in Table 2, in comparison to the NACA 2412 airfoil, show an increase in the maximum lift coefficient by 12.4% and a decrease in the minimum drag coefficient by 6.27%. Figures 4 and 5 illustrate that the NA-DEL 2412 polar curve is below the Dolphin 2412 and NACA 2412 airfoil polars (which is also a tendency observed in the NA-DEL 2410 and NA-DEL 2415 analyses). The maximum lift/drag ratio has increased by 7.33%. On the average, the NA-DEL 2412 is 8.67% more efficient than its NACA 2412 counterpart.

The results from Table 3 for the NA-DEL 2415 airfoil, in comparison to the NACA 2415 airfoil, show an increase in the maximum lift coefficient by 7.35%, a decrease in the minimum drag coefficient by 4.62%, and an increase in the maximum lift/drag ratio by 9.76%. The NA-DEL 2415 is on average more aerodynamically efficient than the NACA 2415 by 7.21%. Experimental results in Table 4 indicate that the NA-DEL 2415 has an increase in maximum lift coefficient by 4.91%, minimum drag coefficient decrease by 32.96%, and maximum lift-to-drag increase by 25.63% in comparison to the NACA 2415 airfoil.

5. CONCLUSION

The results outlined in this paper demonstrate obvious improvements in the aerodynamic performance of the new, and here presented airfoils NA-DEL 2410, 12, and 15 compared to the NACA counterparts, and significant improvements compared to the original Dolphin airfoils. The numerical calculations performed at MRe = 6 and standard roughness case revealed a noticeable increase in maximum lift coefficients, lift-to-drag ratios, and minimum drag coefficient reductions, along with enhancements in lift curve slopes, stall delay, and the creation of smooth flow patterns around the leading edge, which was not the case with the original Dolphins. Experiments performed at MRe = 0.4 and with natural boundary layer transition have confirmed all general improvement trends of NA-DEL airfoils. Consequently, the hybrid NA-DEL airfoils might be equally suitable both in general aviation designs (MRe = 6), and for fixed-wing UAV applications (MRe = 0.4), as suggested by the experimental results. Numerical results for the MRe=0.4 confirming experimental findings in this paper will be provided in future studies.

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