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Investigation of improved aerodynamic performance of isolated airfoils using CIRCLE method

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Abstract

The PresCrIbed suRface Curvature distribution bLade dEsign (CIRCLE) method, proposed by T Korakianitis, is a direct method for designing (or redesigning) high efficiency turbomachinery and fan blades, and isolated airfoils. It was initially introduced to improve the design of high efficiency turbomachinery blades. It is now extended for use with 2D and 3D turbomachinery blades and isolated airfoils. The connection of the profile's leading edge (LE) to the trailing edge (TE), on both sides, is defined using continuity in the surface curvature and its derivatives. Improvements to the aerodynamic performance of the Eppler airfoil are presented in this paper. Improved geometries with continuous curvature have been produced using the CIRCLE method. The performances of Eppler and the redesigned A5 and A6 have been studied using CFD analysis. They are analyzed considering low subsonic flow condition (Reynolds number~10^5). These are compared to a previous airfoil A4. The redesigned blades' LE proved favorable as they succeeded in removing pressure 'spikes' on the suction side. Comparative analysis with the original results showed significant aerodynamic improvements. Airfoils A4, A5 and A6 have comparatively thicker TE section compared to Eppler. Despite the changes made to the geometry and continuous curvature distribution in A4, A5 and A6 (from Eppler), there appear a separated region on the suction side at about 60% of the chord downstream from the LE. The new blades exhibit higher aerodynamic efficiencies, in terms of overall lift-to-drag ratio up to 40% than the original. The investigations are performed at on and off design conditions.

Keywords: aerodynamics; blade; CIRCLE method; design;

Nomenclature

$c_0, c_1\ldots$	thickness coefficients	Subscripts	
$C1, C2$..	Bezier control points	*in*	inlet station
$\mathbf{C}=1/r$	curvature defined with its radius	*o*	stagnation point
$k1, k2\ldots$	exponential thickness polynomials	*ot*	outlet station
M	Mach number	*p*	pressure side
o	throat circle	*p2*	pressure side TE circle to y1
p	pressure	*pm*	pressure side y1 to y2
P	points on airfoil	*pk*	pressure side y2 to y3
$C_{p/L/D}$	Co-efficient of pressure/lift/drag	*p1*	pressure side y3 to LE circle
		s	suction side
Greek		*s2*	suction side TE circle to y1

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α	flow angle	*sm*	suction side y1 to y2
β	blade surface angle	*sk*	suction side y2 to y3
λ	stagger angle	*s1*	suction side y3 to LE circle
[illegible]	angle of throat diameter		

1. Introduction

Gas turbines have been among the most efficient energy conversion devices developed so far. Wind and hydro turbines have also secured a good place in the category. With increasing advancements in fluid dynamics and thermodynamics, the overall performances of these devices have enhanced [1]. One of the major components in these devices is the blade or airfoil [1]. They are placed in the fluid flow either to work on, or to extract work out of the flow. The blades operate under complex harsh conditions [2]. Blade design process, therefore, has a significant influence on the performance of the whole machine [3]. In general, 3D blade geometry is obtained by arranging 2D geometries along the center of gravity considering the associated limitations [3]. And the relevant 2D profiles are defined by streamlined curvature calculations based on the flow angles from hub to tip at the leading edge (LE) and trailing edge (TE) [3]. In order to make the design process simpler 3D blade cascades are considered to be 2D geometries placed in stream-wise direction [3, 4].

Performance of the blade profiles is expressed by blade surface and cascade passage property (such as Mach number, pressure, velocity, etc.) distribution along the chord [5]. Numerous techniques have been applied in blade designing, such as, direct method, inverse and semi-inverse method, optimization methods and etc. [5]. The objective of any method is to define the best profile which exhibits good aerodynamic and heat transfer performance with adequate structural integrity. This means disturbances upstream and downstream the profile should be minimized while complying with the constraints within the design conditions. For 3D profile generation, compromises are made to allow location of cooling and hollow passages. This paper presents a blade design approach using direct method. The process is defined by analyzing the aerodynamic performance of a specified blade profile. On the other hand, a typical inverse blade design method is defined as a method in which the preferred blade performance is defined and the geometry satisfying this performance is calculated [4].

Numerous works [3,4,6,7] have shown that it is difficult to obtain a desirable aerodynamic blade profile using inverse method. The inverse method has difficulties in both the LE and TE due to zero velocity at the stagnation points [3,4]. Inverse method can be applicable for generating compressor blades with very thin TE, but not to define a blade with thicker TE. Any blade which is designed with zero thickness TE becomes difficult to manufacture [4].

The work presented here, depicts a way of designing blades using PresCrIbed suRface Curvature distribution bLade dEsign (CIRCLE) method. It defines both turbomachinery and isolated profiles with continuous surface curvature and slope of curvature from the LE to TE for the suction and pressure sides. It can be used to design and redesign (improve) blades with higher efficiencies than their contemporaries, and can also be coupled with genetic algorithm based optimization method. CIRCLE method has evolved from a 2D turbomachinery blade design method to a 3D turbomachinery and isolated profile design method. Past studies [4,5] showed its applications in gas turbine blade redesign. Here the method's robustness in redesigning isolated wind turbine airfoils is presented. Following the global growing concern to switch to renewable energy source for the longevity of world's natural resources and environmental sustainability, wind turbine is one of the best choices for power plants. Results of redesigned wind turbine isolated airfoil, using CIRCLE method, is presented and discussed with few examples of other turbomachinery blades.

2. Background theory

The CIRCLE method defines each side of a 2D shape in three parts: *y1* near the LE; *y2* in the middle part of the surface; and *y3* near the TE. The stream-wise surface and slope of the curvature distribution is manipulated to optimize the aerodynamic performance. 2D shapes are designed near the hub, mean and tip regions and then the 3D shape is designed by maintaining continuity in the 2D parameters from hub to tip. This method does not use the traditional maximum thickness and maximum camber principles. It is guided by the surface pressure and Mach number distribution with their relation to continuous surface curvature distribution, and the outcome is the blade profile. Theoretical and experimental evidences presented in [5] show curvature and slope of curvature affects aerodynamic performance of blade profiles. Continuous slope of curvature requires continuous third derivative of the splines used in the method. It is illustrated in the following two equations for curvature ***C*** and slope of curvature ***C'***, where *y=f(x)* as:

$$C = \frac{1}{r} = \frac{y''}{\left[1+y'^2\right]^{\frac{3}{2}}} \quad (1)$$

$$C' = \frac{dC}{dx} = \frac{y'''\left[1+y'^2\right]-3y'y''^2}{\left[1+y'^2\right]^{\frac{5}{2}}} \quad (2)$$

Figure 1 depicts CIRCLE method's background and its modification for generating compressor and isolated profiles. The LE and TE shapes are circular geometries defined by their corresponding radii, and inlet and outlet flow angles α_1 and α_2 (Fig 1). Blade pitch plays an important parameter in turbomachinery profile while it is not used in isolated airfoils. Turbomachinery blades are set at their stagger angle λ (Fig 1a-c) while it is set to zero for isolated profiles. Turbomachinery blades are defined on the suction by the distribution of the flow area and the minimum area along the passage (Fig 1). The throat circle *o* and its angle □ determine the suction side blade control point P_{sm} and the corresponding blade angle β_{sm}. The corresponding input values for the pressure side control point P_{pm} and blade angle β_{pm} are arbitrary values. The P_{sm} and β_{sm}, for isolated airfoils, are independent of the passage area. The LE and TE circles are very difficult to connect with the other blade segments, as the circles have continuous curvature and rest of the surface have locally varying curvature. The TE radius and the λ locate the TE circle. The two sides disengage from the TE circle at P_{s2} and P_{p2}. This is controlled by β_{s2} and β_{p2}.

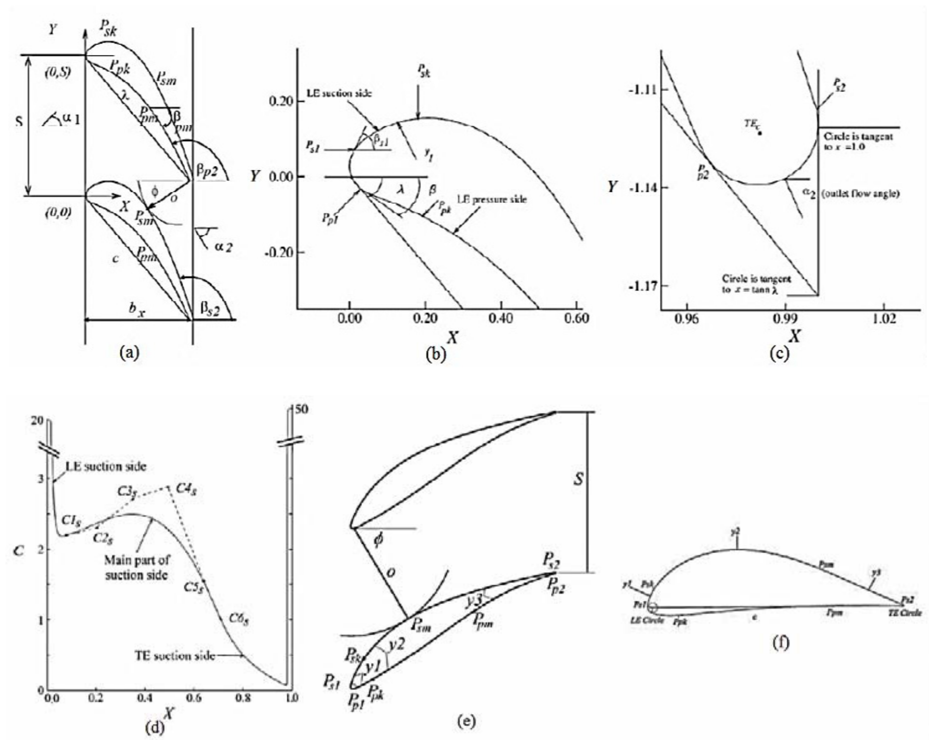

Fig. 1. CIRCLE method's blade geometry development process [3]

The TE segment *y3* from P_{s2} to P_{sm} is defined by an analytic polynomial *y=f(x)* of exponential form [5]:

$$y3 = f(x) = c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 k_1[x - x(P_{s2})] + c_5 k_2[x - x(P_{s2})] \quad (3)$$

where, k_1 and k_2 are exponential functions depending on P_{s2}. The six coefficients c_0 to c_5 are evaluated from the slope and other derivatives' continuity at P_{s2} and P_{sm}. The line segment *y2* between P_{sm} and P_{sk} is defined by mapping the curvature ***C*** vs *X* to the plane *Y* vs *X* using multiple point Bezier spline (e.g. Fig 1d). The curvature segment corresponding from P_{s2} to P_{sm} is evaluated from analytic polynomial *y1* using Eq. (3). It is plotted on the ***C*** vs. *X* plane, from the TE at X = 1.0 and to point $C6_s$ (Fig 1d). The slope of the curvature $C_s(x)$ at point $C6_s$ is computed from Eq. (3) and becomes an input to further calculations. Using central difference Eq. (1) is written for curvature at airfoil point *I* as a function of *(x,y)*. Then the Bezier spline is iteratively computed until the slope and the *y* coordinate at P_{sk}, and the shape of the curvature distribution matches reasonably. The LE circle similarly disengages at P_{s1} and P_{p1}, defined by β_{s1} and β_{p1}. Then a parabolic construction line *y* and a thickness distribution y_t are defined from the LE origin or circle center. They are defined to have continuous point and derivatives of the curvature at points P_{s1} and P_{sk}. For instance, construction line *y* may be defined as:

$$y = f(x) = Ax^2 + Bx + C \quad (4)$$

$$y_t = c_0 + c_1 x + c_2 x^2 + c_3 x^3 + c_4 k_{11}[x - x(P_{s1})] + c_5 k_{12}[x - x(P_{sk})] + c_6 k_{13}[x - x(P_{s1})] + c_7 k_{14}[x - x(P_{sk})] \quad (5)$$

where, k_{11}, k_{12}, k_{13} and k_{14} are exponential polynomials and are dependent on P_{s1} and P_{sk}. And similar to Eq. (3) the c_0 to c_7 are evaluated from the continuity in *y* and its derivatives at P_{s1} and P_{sk}. Thus the whole approach ensures that continuity of curvature and slope of curvature from the TE circle to the main part of the blade surface through the LE y_t and into the LE circle, for both surfaces of the blade. The control parameters C1, C2, C3 and C4 (Fig. 1) are specified smoothly to vary along the curvature's radius with the Bezier curves. Desired changes in 2D surface pressure or streamlines are compared with changes in 2D curvature distributions and the location of the 2D blade surfaces. After the first iteration (i.e. first geometric design and analysis) the user examines the resulting blade loading distributions, and decides where to alter local curvature and loading. After the second iteration the user gains an understanding of the magnitude of the required changes in curvature to cause the desired changes in Mach number or pressure distribution. The procedure is repeated until a desirable profile and aerodynamic performance are obtained.

3. 2D turbomachinery blade redesign

Performance of four redesigned cascades L25, L30, L35 and L40 was presented in [5]. For all cases, the cascades have been designed by changing the stagger angle while keeping the other variable constant. The computed results showed that increasing the λ, while keeping other parameters constant, results in thinner and more front loaded cascades. As λ increases, the *o* pushes both the blade surfaces farther down. This located the throat of the blade farther upstream on the suction side making the blade thinner. Consequently, this increased the curvature of the suction side and in turn increases the Mach number while loading the front accordingly [5]. It is predicted that there is one optimum λ for which the wake thickness is minimum.

The LE has significant effects on the aerodynamic performance of an airfoil. Defining airfoil's LE with any method is very difficult. The approach in CIRCLE method is discussed earlier. Hodson [8] detected spikes on the LE experimentally due to discontinuity in the curvature. They experimentally tested HD blade. The redesigned HD blade, in Fig. 2, shows that the leading edge seperation spikes have been removed. This improvement is depicted with CFD computations in Fig. 2. I1, I4 and I9 are the redesigned stages of the original HD blade. The modified blades are restricted to have the same LE circle diameter and chord length. Therefore they ended up being a bit thinner near the LE, due to the reduction in the wedge angle. The curvature distribution (Fig. 2b) shows smoother lines for the redesigned profile than the original HD profile, obtained from [9]. The Mach number plot shows successful removal of suction side discrepancies and pressure side diffusion in the

LE region of the redesigned profiles compared to the experimental results obtained from [9]. Experimental and computational results for Kiock blade show the existence of significant disorders on both surfaces [10]. Fig. 3a shows the surface curvature distribution of Kiock and S1, which is evident enough to show the improvements in the surface curvature discontinuity. Fig.3b indicates a variation in the thickness to compensate for a smooth continuous curvature around the profile. This resulted in the removal of small disturbances in the blade's Mach number distribution (Fig. 3c). This has resulted in smoother boundary layer displacement thickness and reduced the local entropy generation [3].

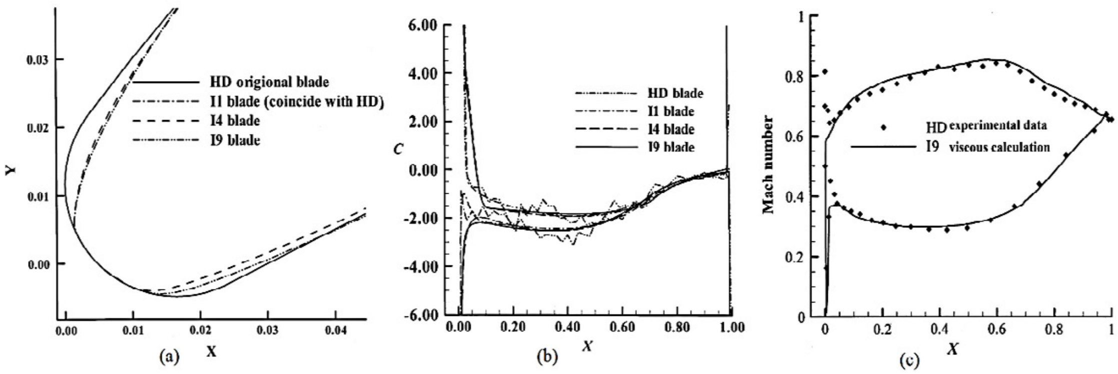

Fig. 2. Original and redesigned HD blade's (a) LE, (b) curvature distribution and (c) Mach number distribution [4]

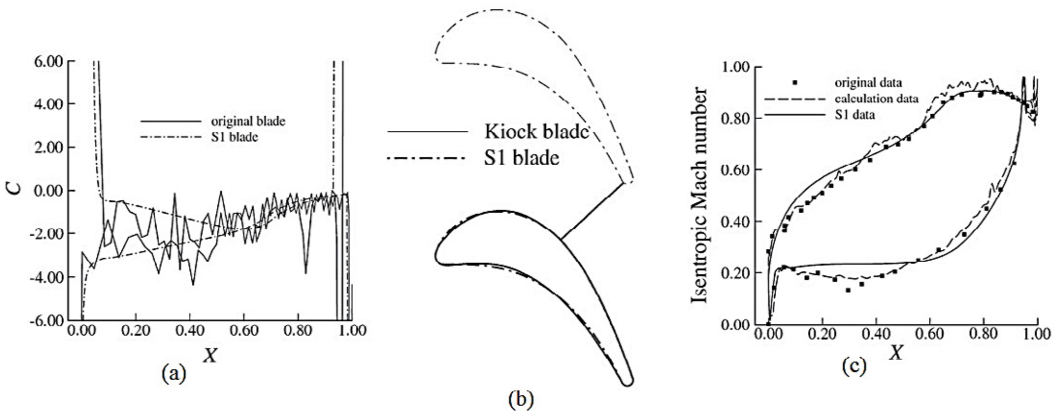

Fig. 3. Comparison of original Kiock blade with modified S1 blade (a) curvature distribution (b) geometry and (c) Mach number plot [3]

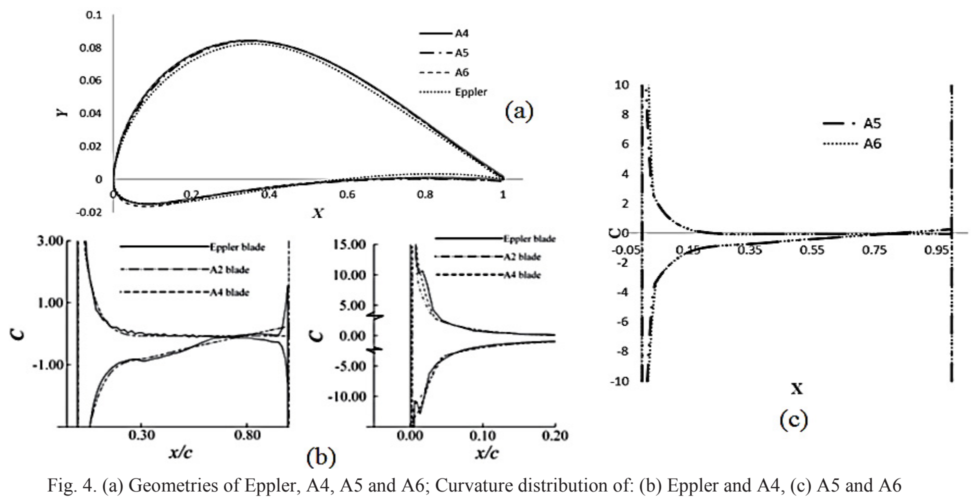

Fig. 4. (a) Geometries of Eppler, A4, A5 and A6; Curvature distribution of: (b) Eppler and A4, (c) A5 and A6

4. 2D isolated airfoil redesign

Isolated airfoils appear to be sparsely arranged, e.g. wind turbine airfoils, compared to clustered turbomachinery blades, i.e. turbine/compressor blades. Eppler 387 is a wind turbine airfoil candidate. From Fig. 4b, curvature discontinuity on its surface appears apparent. The CFD (depicted in Fig 4 and 5) and the experimental results [11] clearly show the LE disturbances on Eppler. Isolated airfoil appears to have 'curved-out' pressure side; therefore a slight modification in the CIRCLE method to define the pressure side has been used to redesign Eppler. Fig. 4a shows the geometries of Eppler with its stages of redesign: A4, A5 and A6. The redesigned blades appear thicker in the LE and TE regions. This removed the LE curvature disturbances that exist in Eppler. A4 shows better continuity in curvature compared to Eppler (Fig. 4b). A5 shows further improvement than A4 and A6 more than A5 (Fig. 4c and 5). The computations are based on typical wind turbine flow conditions [3], unlike high speed unsteady turbulent flow in turbomachinery. It was computed in a flow with Reynolds number 10^5; turbulence intensity 0.5% at various incidences, i.e. on and off design points. The C_p contours are plotted using CFD RANS model – Transition SST in ANSYS 13.0, with a 2D structured C grid, giving a $y^+<1.5$. Figs 5a, b and c refer to computational and experimental C_p of Eppler and the redesigned blades. Figs 5b and c show the removal of the Eppler's LE noise from all the redesigned blades at α=4□ (comparison to experimental data [11]) and α=8□ (design point), respectively. Despite smooth curvature there exist boundary layer separation bubbles at 65-70% of the chord on the suction-side at α=4□, and 45-60% of the chord on the suction-side at α=8□; but reattaches turbulent soon after. This is due to the aerodynamic behavior of flow at such low Reynolds number. The laminar boundary layer becomes too weak to remain attached at that Reynolds number for those incidences. Nevertheless, suitable active or passive flow control method can be used to investigate further and optimize the aerodynamics at those instances. The polars results for the airfoils, which are obtained using XFoil [12], (Fig 5h, i & j) show the incremental aerodynamic improvement among the stages of Eppler's redesign. They exhibit a trend where A6 has overall better C_L, C_D and C_L/C_D performances, with a slight deviation near α=7□ where A4 dominated till α=8□.

Percentage improvements in C_D, C_L and C_L/C_D calculated as, for C_D: $(\Delta C_D/C_{D\text{-Eppler}})$ x 100; for C_L: $(\Delta C_L/C_{L\text{-Eppler}})$ x 100; and for C_L/C_D: $(\Delta(C_L/C_D)/(C_L/C_D)_{Eppler})$ x 100 at design point. The following table depicts the implicit values from the polar calculations.

Table 1 Showing the polar results for C_D, C_L and C_L/C_D and their percentage improvements

Items	Eppler	A4	A5	A6
C_D	0.031494	0.025046	0.02373	0.023304
C_L	1.156052	1.196228	1.177495	1.196925
C_L/C_D	36.70733	47.76206	49.62153	51.36147
% improvements from Eppler in C_D	--	20.47451	24.65324	26.00452
% improvements from Eppler in C_L	--	3.475276	1.854847	3.635568
% improvements from Eppler in C_L/C_D	--	30.11587	35.18153	39.92156

5. Conclusion

The paper presents the effect of CIRCLE method on airfoil design and redesign. It successfully comprehended the improvement of the Eppler 387 isolated airfoil. The references to the turbomachinery blade redesign show its overall proficiency in this field. From the polar results, it is found comparing with Eppler, the drag reduced 20.5% in A4, 24.7% in A5 and 26% in A6 at design point, and the lift improved 3.5% in A4, 1.9% in A5 and 3.6% in A6. These indicate an overall C_L/C_D performance improvement of 30.1% in A4, 35.2% in A5 and 40% in A6. It is deemed necessary for a paradigm shift to sustainable energy systems to meet global energy demand and emission targets. And it can be concluded from here, CIRCLE method can contribute in to the solution to current global energy crisis and emission problems.

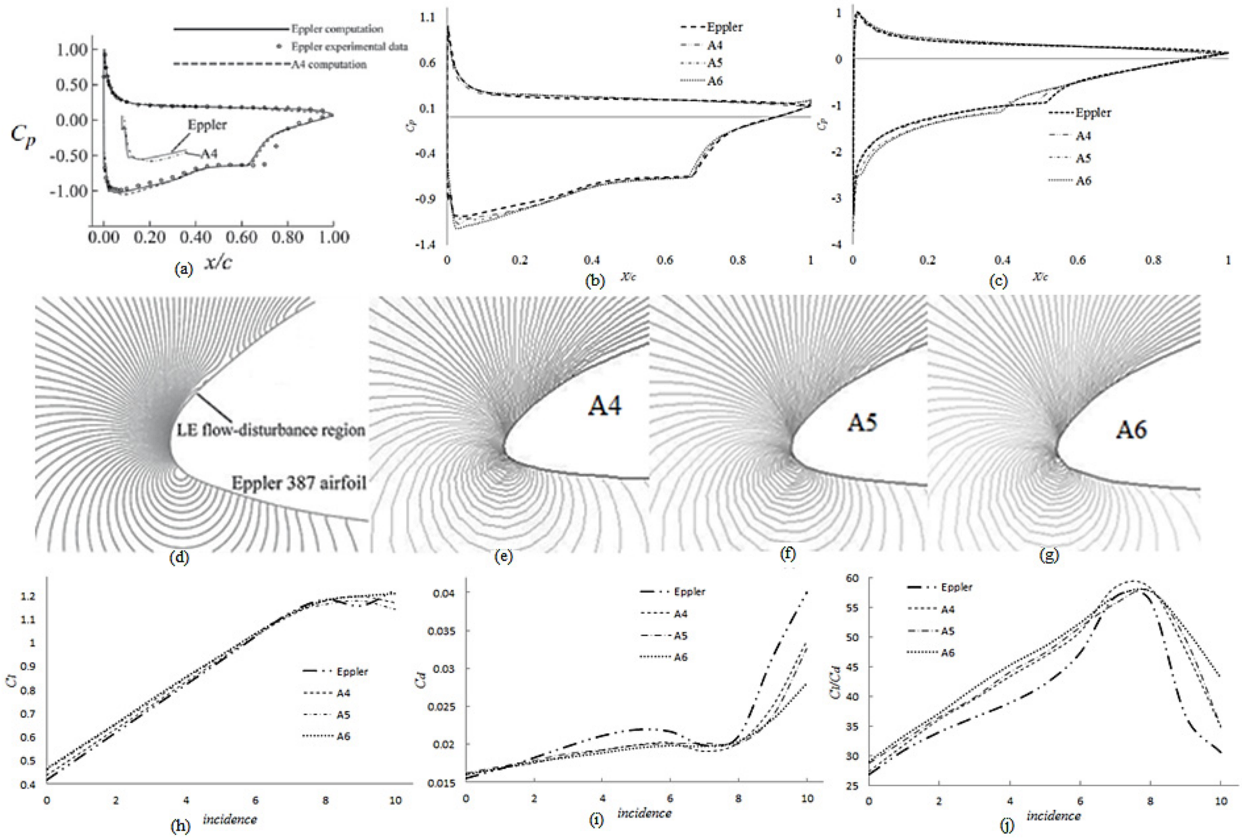

Fig. 5. Comparison of Eppler and the redesigned airfoils: (a) C_p distributions of Eppler computational with experimental and A4 computational results; C_p distributions of Eppler computational vs A4, A5 and A6 for: (b) $\alpha=4^\circ$, (c) $\alpha=8^\circ$ (design point); (d) LE C_p contour plot of Eppler; (e) LE C_p contour plot of A4; (f) LE C_p contour plot of A5; (g) LE C_p contour plot of A6; (h) C_L variation against α; (i) C_D variation against α; (j) C_L/C_D variation against α;

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