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# Airfoil Blender for Blade Optimizations

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**Abstract.** An airfoil database was developed in the present work. The database includes a multivariate, unstructured grid, Radial Basis Function (RBF), optimization-compatible interpolator for airfoil aerodynamic coefficients. The database was designed to aid complex blade design optimizations carried out in a novel optimization framework, HAWTOpt2, being currently developed at DTU Wind Energy. In the database, the lift, drag and moment coefficients are stored as functions of airfoil family, thickness, Reynolds number and angle of attack. Aerodynamic add-ons and airfoil modifications are included in the database as separate airfoil families. Additionally, the database includes two different 3D correction methods and two different 360 degree extrapolation methods. Further, the database stores airfoil coordinates as functions of airfoil family and thickness. Those coordinates may also be interpolated using the RBF method. Present work included a demonstration of the coefficient interpolator in an optimization aimed at indicating the optimal layout of Vortex Generators on eroded blades of the DTU 10MW Reference Wind Turbine in order to maximize the Annual Energy Production.

## 1. Introduction

More and more complex and sophisticated design tools are necessary to fulfil the demand for larger, more effective and competitive wind turbines. One of those tools is the novel optimization framework, HAWTOpt2 [1], being developed at DTU Wind Energy. One of the components of this framework will be, introduced in the present work, airfoil database, being an extension of AirfoilPrep.py by Ning [2]. The database is intended to store aerodynamic coefficients and shape coordinates of various airfoils, including those modified and with aerodynamic add-ons. The essential feature of the database is the optimizer-friendly, multivariate, unstructured grid, Radial Basis Function (RBF) interpolator for both airfoil aerodynamic coefficients and shape coordinates, i.e. *Airfoil Blender*. Its use in a simple optimization involving layout of Vortex Generators on a DTU 10 MW Reference Wind Turbine [3] blade with eroded surface is demonstrated in the present work. The aforementioned interpolator was based on the SciPy's interpolate.Rbf [4] class and designed to aid complex blade design optimizations carried out in HAWTOpt2 where the choice of airfoil and/or aerodynamic add-ons at a specific blade section would become another optimization variable. In the database, aerodynamic coefficients are stored as functions of airfoil family, thickness, Reynolds number and angle of attack. The coordinates are stored as functions of airfoil family and thickness. The optimizer may request lift, drag and moment coefficients for a specific blend of airfoil families, thickness, Reynolds number and angle of attack regime. It may also request airfoil coordinates for a specific blend of airfoil families and thickness. The requested values are then interpolated in all relevant variables simultaneously. SciPy's Radial Basis Function ensures continuous interpolation, making the routine optimizer-friendly. The user needs to ensure sufficient amount and density of input data in all the variables in order to be able

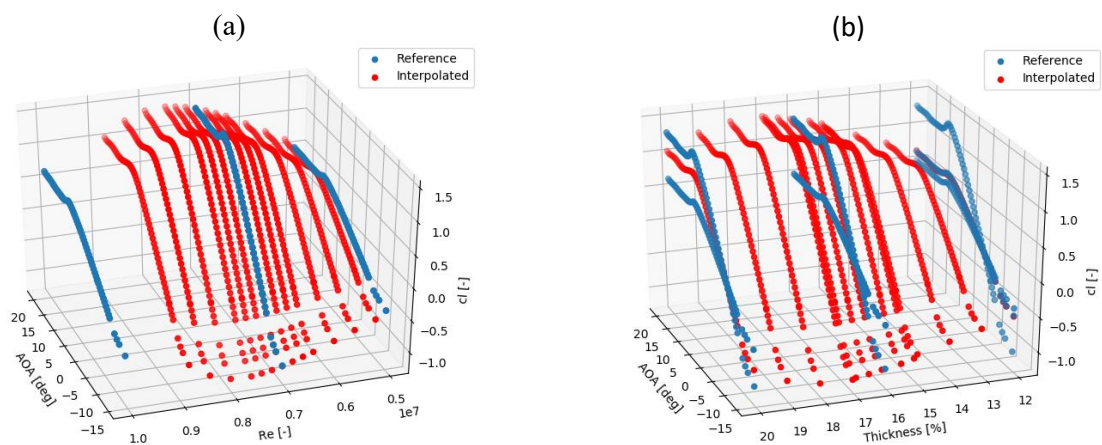


to rely on the interpolated values. However, the Radial Basis Function method is also known for delivering sensible results where reference data is relatively scarce although it is the safest to remain skeptical about such results. Aerodynamic add-ons and airfoil modifications may be introduced as separate airfoil families. Additionally, the airfoil database includes AirfoilPrep.py's 3D correction by Selig [5] and the 3D correction by Bak [6] as well as AirfoilPrep.py's 360 degree extrapolation by Viterna [7] and the one from DTU's Power Pack [8].

## 2. Demonstration of Airfoil Blender

### 2.1 Aerodynamic coefficients

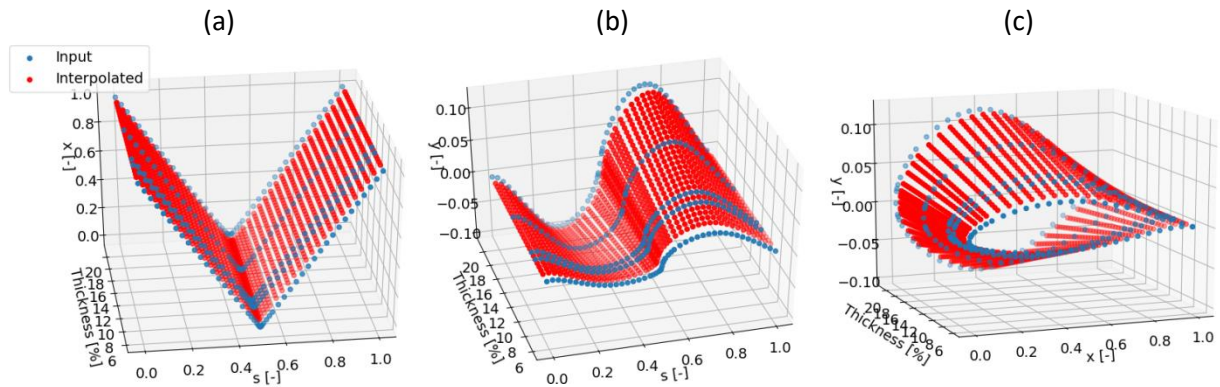
A feature of Airfoil Blender that sets it apart from similar codes interpolating linearly between requested airfoils is that the continuous interpolation across the whole variable space makes the code more effective in optimizations than those providing linear interpolations and hence producing discontinuities that may mislead optimizers. Continuous interpolation of exemplary lift coefficient curves is presented in Figure 1, both as the function of  $Re$  and AOA as well as the function of airfoil thickness and AOA. The reason for multiple lift coefficient curves plotted for the same thickness values in Figure 1(b) is that those curves correspond to different  $Re$ .



**Figure 1:** Visualization of the continuous interpolation of exemplary lift coefficient curves, as the function of: (a) Reynolds number and Angle of Attack (b) thickness and Angle of Attack

### 2.2 Shape coordinates

Figure 2 presents visualization of the continuous interpolation of NACA 65-2XX airfoils between 6% and 21% thickness. Dimensionless  $x$  and  $y$  coordinates were independently interpolated as functions of the dimensionless surface coordinate,  $s$ , which assumes zero value at the trailing edge and follows the airfoil surface along pressure and suction sides until assuming the value of one back at the trailing edge. This method provides better results than sole interpolation of  $y$  coordinates, especially for relatively thin airfoils. In optimizations, coordinate interpolation allows for the use of a structural solver and hence for taking structural aspects of airfoils into consideration in blade design optimizations.

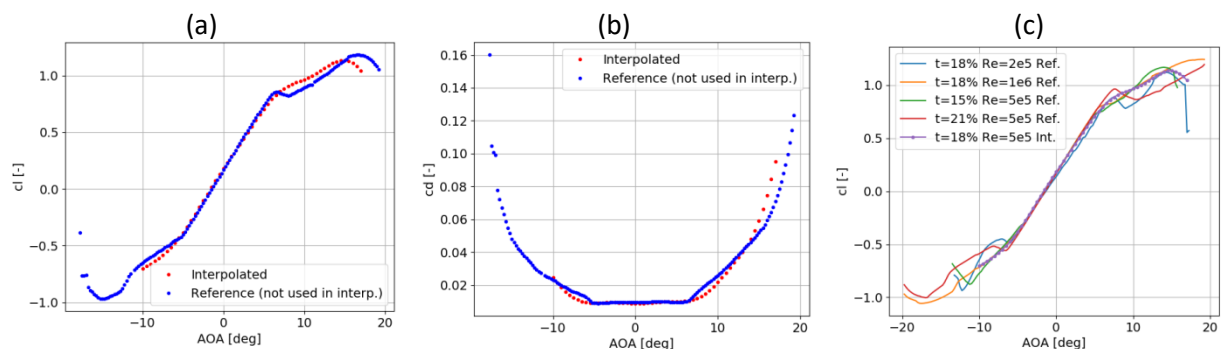


**Figure 2:** Visualization of the continuous interpolation of NACA 65-2XX airfoils between 6% and 21% thickness; all coordinates dimensionless; (a) x coordinates as a function of the  $s$  (surface) coordinates; (b) y coordinates as a function of the  $s$  coordinates; (c) y coordinates as functions of the  $x$  coordinates

### 3. Validation of the interpolation

#### 3.1 Aerodynamic coefficients

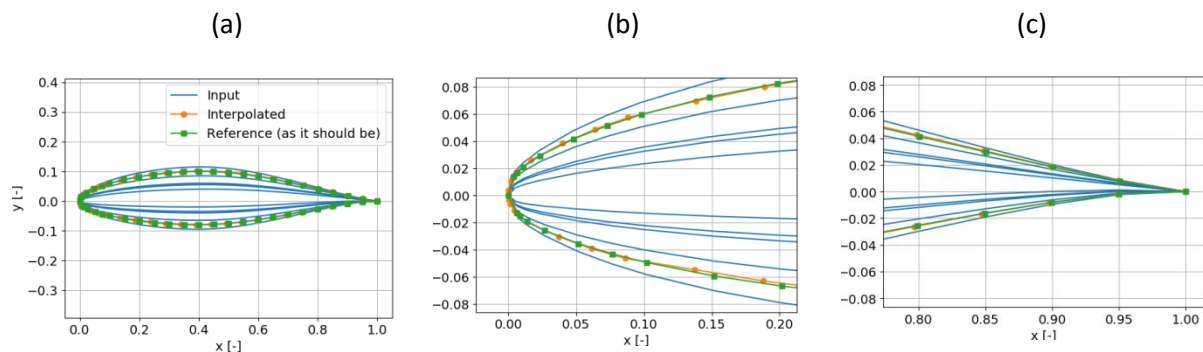
Airfoil Blender was initially validated by interpolating  $cl$   $cd$  curves in the single NACA 65-2XX airfoil family in the  $2e5$ - $1e6$   $Re$  and 6%-21% airfoil thickness ranges. Figure 2 presents results of the interpolation of the 18% airfoil at  $5e5$   $Re$ . Figure 2(a) presents the interpolated  $cl$  curve plotted together with the reference (as the interpolated curve should look ideally). Figure 2(b) presents the interpolated  $cd$  curve plotted together with the reference whereas Figure 2(c) presents the interpolated  $cl$  curve plotted together with the neighbouring curves in terms of thickness and  $Re$ . Figure 2(c) is presented because the plotted curves, being the closest to the interpolated in terms of interpolation variables, have the highest influence on the interpolated shape. Hence, Figure 3(c) serves as a sanity check. There, visible discrepancies exist between the input curves, especially in the stall regime, hence making the interpolation difficult. Larger amount of data in the database, ideally both in terms of  $Re$  and thickness, would increase the accuracy of the interpolation both in terms of  $cl$  in the stall regime as well as in terms of  $cd$ . Further validation of the method including the effect of discrepancies on the results of BEM computations is intended for future work.



**Figure 3:**(a) Interpolated lift coefficient vs. the reference curve; (b) Interpolated drag coefficient vs. the reference curve; (c) Interpolated lift coefficients vs the neighboring input curves in terms of airfoil thickness and  $Re$ .

### 3.2 Shape coordinates

Figure 4 presents visual validation of the coordinate interpolation. Plotted in orange are the interpolated NACA 65(3)-218 airfoil coordinates, together with the reference (green) as well as the input NACA 65-2XX airfoil coordinates of thickness between 6% and 21%. The interpolated airfoil appears satisfactorily close to the reference. However, future work includes detailed validation of the interpolation by comparing the results obtained with the interpolated and reference airfoils in a structural solver as well as a panel code and/or CFD solver. The present results will also be compared with result of other available interpolation methods.



**Figure 4:** (a) Interpolated NACA 65(3)-218 airfoil coordinates plotted against the reference as well as input NACA 65-2XX airfoils of thickness between 6% and 21%; (b) Leading Edge region; (c) Trailing Edge region

### 4. Demonstration of the use of interpolation in an optimization

The use of Airfoil Blender in an optimization was demonstrated on the blade of the DTU 10 MW RWT [3]. Here, the blade model comprised three airfoils, i.e. 24.1% thick at 71%-100% span, 30.1% thick at 41% span, 36.0% thick at 32% span. However, Airfoil Blender was used to interpolate nine airfoils ranging between 25.6% and 91.4% rotor radius. That corresponds to a thickness range of 43.6% to 24.1%.

The present study refers to a study by Skrzypiński et al. [9] where the layout of Vortex Generators (VG's) to maximize the Annual Energy Production (AEP) of the DTU 10MW Reference Wind Turbine with eroded blades was found. In [9], the level of erosion (also termed Leading Edge Roughness, i.e. LER) corresponded to a 3.5% loss in the AEP whereas the resulting layout of 1% VG's, mounted approximately between 17% and 34% rotor radius, corresponded to a 1.5% regain in the AEP.

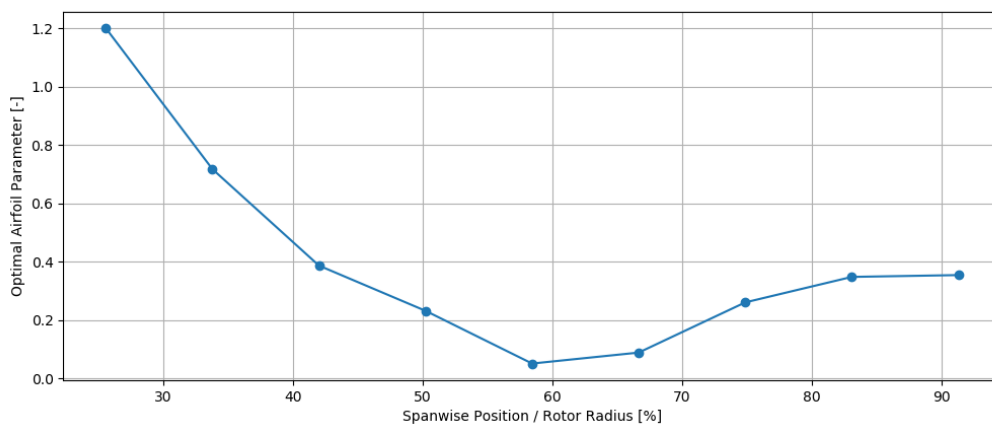
In the present work the LER and VG's are introduced as two separate airfoil families. The first, having assigned a family parameter of zero, corresponds to eroded airfoils without VG's where the level of erosion corresponds to a 3.7% loss in the AEP. The other family, having assigned a family parameter of one, corresponds to the same level of erosion yet with installed 1% VG's at 20%-25% chord length on the suction side. The same chordwise position of VG's is considered in [9].

In the present numerical design optimization, Scipy's Sequential Least Squares Programming minimizer [10] (SLSQP) was used in order to solve the following problem. The optimizer was requested to maximize the AEP of the turbine with the aforementioned level of LER. Each of the nine sections had assigned an independent optimization variable being a scalar blend between the set with LER and no VG's (value of zero) and the set with LER and 1% VG's (value of one). For each optimization step and each section, Airfoil Blender was fed the requested blend and returned corresponding aerodynamic coefficients. Then, HAWC Stab 2's steady BEM model by Hansen [11] was run in order to compute the corresponding power curve. Finally, at each step, assuming the statistical Weibull wind speed distribution of parameters 9.59 and 2.00, the AEP was calculated. Uniform wind speed and no additional constraints were used.

If, for a given section, the optimal blending factor was found to be one, that would mean that the highest energy production was obtained with the aforementioned 1% VGs. If the optimal blend factor was found a value in-between zero and one, it would mean that neither of the input polars but their blend gave the highest energy production. In practical terms that could correspond to a less aggressive VG layout at that section, i.e. VG's being smaller and/or installed closer to the Trailing Edge. In principle, it should be possible to map different VG configurations on the values of the optimal blending factor found for each section. That would result in a generic VG design tool. Alternatively, different VG layouts could be introduced in the database as separate airfoil families and utilized in the optimization as such. Such a tool could also be used for other aerodynamic add-ons, airfoil modifications or simply different airfoil families.

If the optimal blend factor was found to be close to zero, it would indicate that the corresponding Angles of Attack are low enough for the section to operate in the attached-flow regime despite the erosion (note that erosion always accelerates stall). In such a case, delay of stall due to VG's will not improve aerodynamic performance whereas the drag of the VGs themselves added in the attached-flow regime will decrease the performance.

The present work also comprised the engineering models for the LER and VG's presented in [9] and the 3D correction by Bak [6]. The optimization result is presented in **Figure 5**.



**Figure 5:** Optimal blend factors resulting from the optimization plotted as a function of the DTU 10MW RWT radial position; at any radial position: values close to one indicate that optimal are 1% high Vortex Generators (VG's) mounted at 20%-25% chordwise position at the suction side, values close to zero indicate that no VG's should be mounted, values inbetween indicate that optimal would be less aggressive VG layouts, i.e. preferably smaller VG's mounted either at the same location or further away from the Leading Edge

The present result agrees with [9] where 1% VG's are shown to increase the AEP if installed approximately up to 34% rotor radius. In the present result, the highest values of the optimal blending factor are present in the same region whereas smaller values present further out on the blade may advocate for less aggressive VG layouts. Note that the upper boundary of the optimization was set to 1.2 instead of 1.0 and 1.2 was obtained at the first section. This indicates that close to the root even a more aggressive VG layout than the aforementioned could be beneficial. Compared to the case with erosion and no VG's, the optimized layout presented in **Figure 5** increased the AEP by 1.0%.

## 5. Conclusions

An airfoil database was developed in the present work. The database includes a multivariate, unstructured grid, Radial Basis Function (RBF), optimization-compatible interpolator for airfoil aerodynamic coefficients. The database was designed to aid complex blade design optimizations carried out in a novel optimization framework, HAWTOpt2 [1], being currently developed at DTU Wind Energy. In the database, the lift, drag and moment coefficients are stored as functions of airfoil

family, thickness, Reynolds number and angle of attack. Aerodynamic add-ons and airfoil modifications are included in the database as separate airfoil families. Additionally, the database includes two different 3D correction methods and two different 360 degree extrapolation methods. Further, the database stores airfoil coordinates as functions of airfoil family and thickness. Those coordinates may also be interpolated using the RBF method. Present work included a demonstration of the coefficient interpolator in an optimization aimed at indicating the optimal layout of Vortex Generators on eroded blades of the DTU 10MW Reference Wind Turbine in order to maximize the Annual Energy Production. The optimizer managed to increase the modelled AEP by 1.0% relative to the case with eroded blades and no VG's. Note that in order to utilize the optimization result in real life, specific VG layouts need to be mapped on the values of the resulting parameter. Alternatively, different VG layouts could be introduced in the database as separate airfoil families and utilized in the optimization as such.

## 6. Future work

Based on the conclusions drawn from the present work and the literature study, the following tasks were assigned to future work:

1. Further validation of the coefficient interpolator by using interpolated lift and drag coefficients in BEM computations and comparing the results with those obtained with reference coefficients.
2. Further validation of the coordinate blender by using interpolated coordinates in a structural solver as well as a panel code or CFD solver and comparing the results with those obtained with reference coordinates.
3. Multi-objective design optimization study – carried out in HAWT Opt2 with Airfoil Blender – of the trade-offs between the use of aerodynamically superior airfoils (larger camber, larger L/D) vs those structurally superior and thicker.
4. Integral blade design – for practical reasons airfoils closest to those resulting from optimizations would be used rather than new airfoils being developed

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