An Iterative Method for Estimating Airfoil Deformation due to Solid Particle Erosion

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Abstract: *Helicopter blades are currently constructed with composite materials enveloping honeycomb cores with only the leading and trailing edges made of metal alloys. In some cases, the erosive wear of the bound between the composite skin and metallic leading edge leads to full blade failure. It is therefore the goal of this paper to provide a method for simulating the way an airfoil is deformed through the erosion process. The method involves computational fluid dynamics simulations, scripts for automatic meshing and spreadsheet calculators for estimating the erosion and, ultimately, the airfoil deformation. Further work could include more complex meshing scripts allowing the use of similar methods for turbo-machineries.*

Key Words: *ICEM-CFD, scripting, erosion, k-omega SST, Wallace erosion model.*

1. INTRODUCTION

The erosion in the case of aerospace components is an important factor in the life cycle of any machine, particularly that of turbo machines. An example of helicopter blades failure due to erosion is presented in [1] while other references [2-5] study the deterioration of several types of turbine engine components due to the solid particle ingested.

This paper proposes a semi-automatic method that combines advanced CFD methods with advanced erosion models.

Our objectives are listed below, along with some explanations regarding the thought process and methods used:

1. Standardization and facilitation of the meshing process.
2. Implementation of various erosion models, independent of the CFD solver
3. Determination of the eroded airfoil geometry

- Because the meshing process is lengthy and generally the same steps.
- Fluent permits the selection of a certain basic class of erosion models. This means that more complex erosion models must make use of user defined functions which requires programming skills. Even with UDFs, the mathematical modeling of erosion is limited to a specific shape of equation Ref [6].

By outsourcing the erosion calculator, any type of mathematical erosion model can be used directly in its original form (without transformation).

This permits the use of empirical or semi-empirical erosion models like the ones used for composite materials.

Because the mesh must envelope the existing airfoil surface, it is difficult to simulate real-time erosion processes in steady solvers.

On the other hand, unsteady simulations with adapting grids and deformable meshes consume more computational time and are difficult to implement.

This problem is solved by the deformation by erosion calculator which uses a local offset function with a set magnitude (imposed at 0.01% of the chord) and the relative erosion rate calculated at the step before.

The eroded airfoil is then passed to the automatic pre-processors and the entire process is repeated.

This insures that, throughout the computation, the mesh has the same parameters, limiting errors caused by the user's negligence.

It must be said that the mesh generator only generates, links and attributes the geometry and blocking structure while meshing only the boundary layer.

The user must decide whether the blocking remains the same or if adjustments are required. The meshing scripts are, therefore, just automated assistants and do not restrict the user's freedom.

The block splitting method also insures the connectivity of the blocking structure and, subsequently, the continuity of the final mesh.

Below, the flowchart of the entire process is presented.

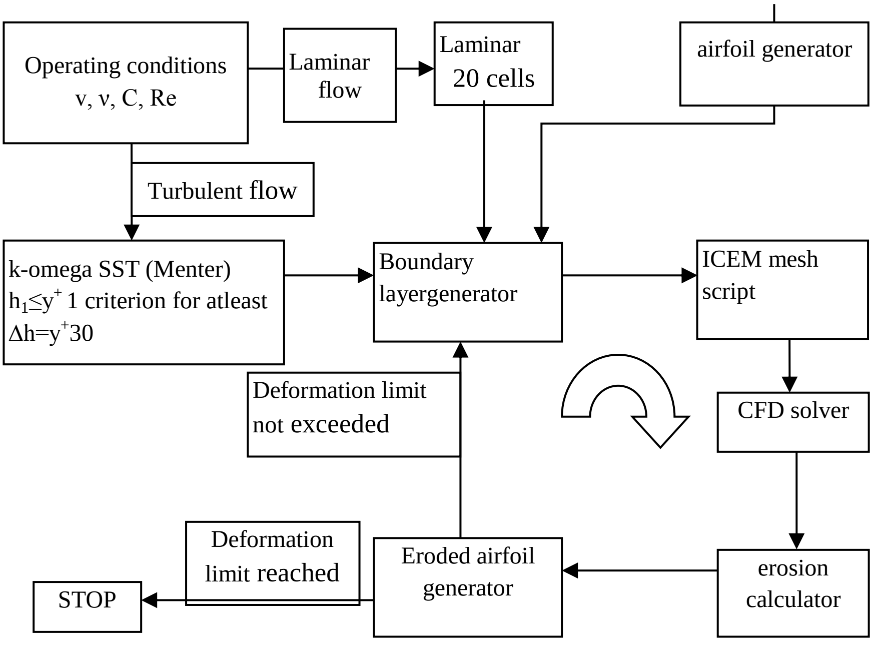


Fig. 1 – Flowchart of the computation for the aerosol erosion of airfoils

2. THE METHODS USED

In order to apply meshing scripts, it is useful to establish a standardized data input which will be independent of the particular geometry of the airfoil. ICEM-CFD permits the import of formatted point data Ref [7] and the automatic reconstruction of spline curves, such as the ones describing the boundaries of the computational domain. Since the scripts will repeat the same operations for every case, the geometry must always be described in the same way.

This was achieved by developing a spreadsheet domain geometry generator which can work with any airfoil generator, such as DesignFoil Ref [8] or X-Foil Ref [9]. In addition to the airfoil geometry, the geometry generator requires the following parameters to be inputted by the used:

-upstream boundary distance (ideally 10 x aerodynamic chord) Ref [10]
-downstream boundary distance (ideally15 x aerodynamic chord) Ref [10]
-flow velocity
-fluid dynamic viscosity
-desired turbulence model (used to calculate the optimal y^+ value)

Figure 2 presents the two types of blocking structures generated by the two dedicated scripts. The preferable structure is the one of a sharp trailing edge because it simplifies the mesh and leads to less user input for the same mesh quality.

On the other hand, a script was conceived for blunt trailing edge airfoils which are closer to the real geometry.

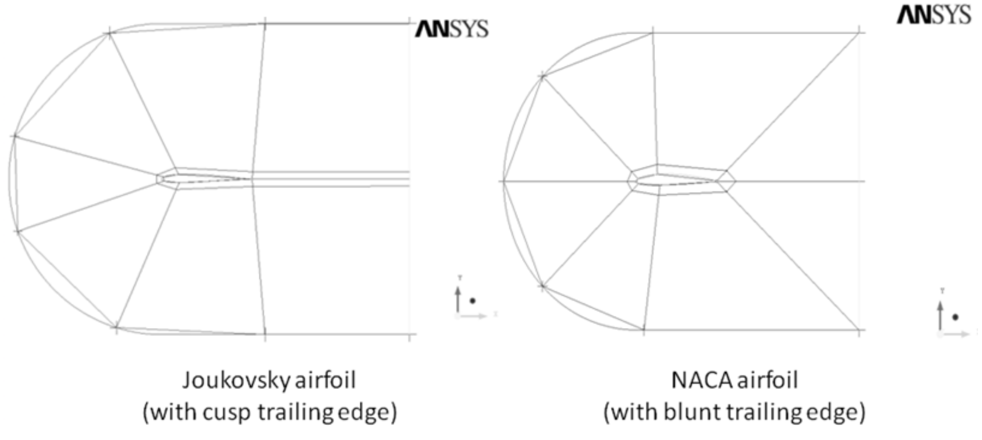


Fig. 2 – The two types of blocking structure permitted by the meshing scripts

The two cases presented in Fig. 2 have an exaggerated boundary layer thickness as well as a very small computational domain in order to illustrate the blocking structure. In a real case, the topology of the blocking structure will be maintained while the geometry will be adequate to the flow conditions.

3. THE EROSION CALCULATION

Since the boundary layer was introduced, we assume that the velocity of the fluid at the wall surface is zero (for the cases of non-slip walls). Therefore it is impossible to determine the velocity magnitude.

However, we can calculate it by assuming that the total pressure is known, subtracting the static pressure at the airfoil surface and extracting the velocity magnitude from the dynamic pressure equation.

Another way to do that is to use the pressure coefficients to determine the relative velocity outside the boundary layer.

However, or the erosion calculation, we need to also know the direction of the entrained particles. This requires a different approach. Since Fluent allows us to plot velocity on a sketch contour, we can use the offset curve (defining the y^+=10 contour) for plotting the velocity components on Oy and Ox.

The flow angle is then corroborated with the airfoil discretized angle in order to calculate the impact angle of the aerosol particle.

The process begins with the initial airfoil. Based on it, the solid geometry is generated. After inputting the boundary conditions we determine the scale of the boundary layer. Because the meshing will, largely, be automated, the offset will be at $y^+=10$ with 10 equally spaced cells meshing it in order to obtain y+=1 at the airfoil wall boundaries. The spreadsheet finally arranges the geometry into a formatted point data for ICEM-CFD input. In order to determine the offset distance, the spreadsheet uses the following mathematical model for y+ estimation.

First, the spreadsheet determines if the flow is turbulent or laminar. For turbulent flow, the y+ criterion is applied.

$$\textit{if}$$

$$\mathrm{Re} < 100000$$

$$\textit{then}$$

$$\delta = 10 \cdot \delta_{lam} = 10 \cdot \frac{4.91 \cdot s}{\sqrt{\mathrm{Re}}} \tag{1}$$

$$\textit{else}$$

$$\delta = 10 \cdot \delta_{turb} = 10 \cdot \frac{0.382 \cdot s}{\mathrm{Re}^{1/5}} \tag{2}$$

$$\textit{endif}$$

Because the values of the thicknesses are expressed relative to the aerodynamic chord, the scaling factor *s* (in this case *s* = 1) is introduced. The scaling factor converts the chord from the non-dimensional unit to the real size in meters.

As a convention, the y value for the offset is imposed to *y* = 10, outside the viscous sub-layer, in order to capture the flow angle close to the airfoil Ref [11].

$$y = \frac{y^+ \cdot \mu}{\rho \cdot u_*} \tag{3}$$

$$u_* = \sqrt{\tau_w / \rho} \tag{4}$$

$$\tau_w = C_f \cdot \rho \cdot \frac{u^2}{2} \tag{5}$$

$$C_f = \frac{0.455}{(\log_{10} \mathrm{Re})^{2.58}} \tag{6}$$

$$\mathrm{Re} = \frac{\rho \cdot u \cdot s}{\mu} \tag{7}$$

$$s = scaling\_factor$$

4. CASE STUDY

An airfoil was chosen in order to demonstrate the procedure. The airfoil is a NACA 3411, similar in shape with a Robinson R22 helicopter blade airfoil.

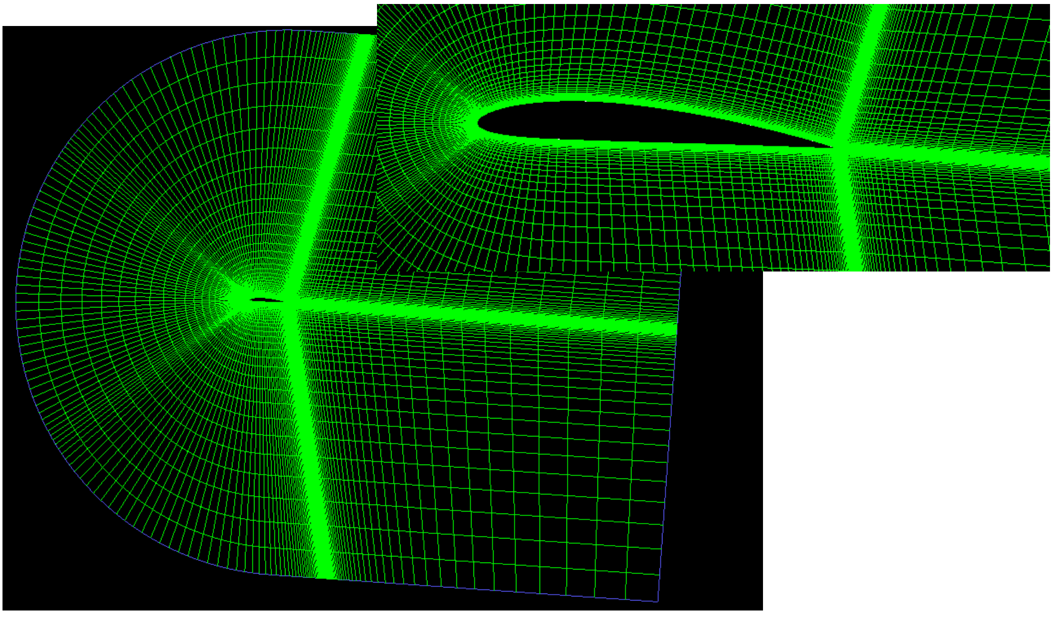


Fig. 3 – The mesh of the computational domain, 4° angle of attack

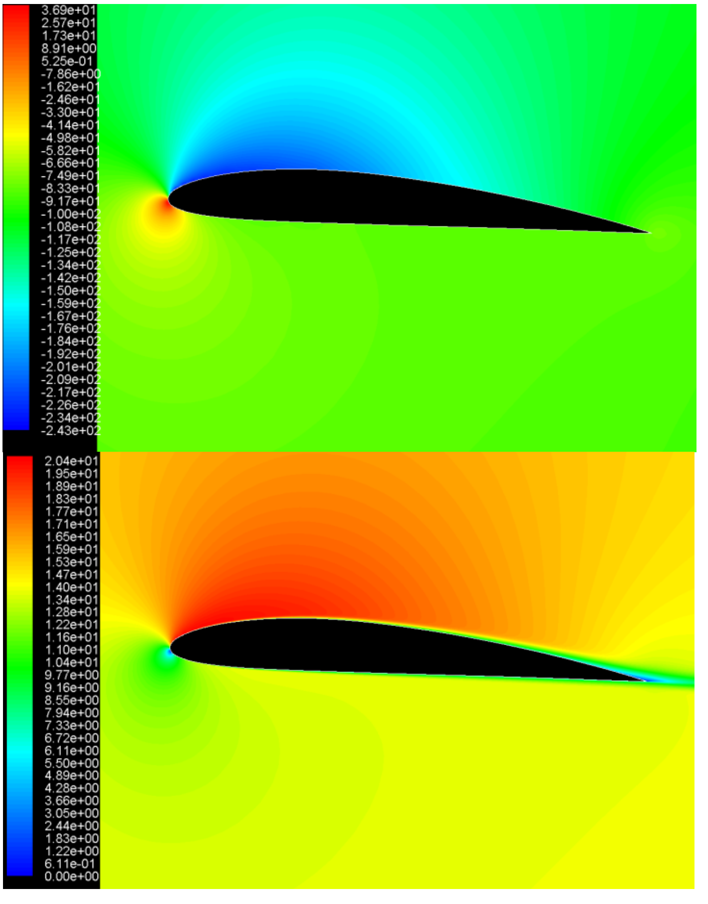


Fig. 4 – Pressure and velocity contours for a case of the 1 [m] NACA 3411 at 4º AoA case

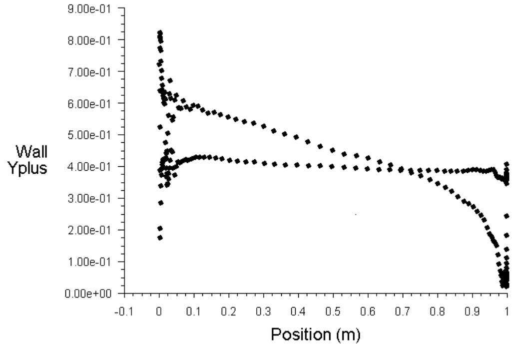


Fig. 5 – The y+ distribution along the chord line of the airfoil

The erosion rate calculation uses Wallace's model Ref [12, 13], described by the equations below:

$$E = \left\{ \frac{\frac{1}{2} u_p^2 \cos^2 \alpha_{impact} \sin 2\alpha_{impact}}{\Upsilon} + \frac{\frac{1}{2} u_p^2 \sin^2 \alpha_{impact}}{\sigma} \right\} \quad for\ \alpha_{impact} \leq \ 45° \tag{8}$$

$$E = \left\{ \frac{\frac{1}{2} u_p^2 \cos^2 \alpha_{impact}}{\Upsilon} + \frac{\frac{1}{2} u_p^2 \sin^2 \alpha_{impact}}{\sigma} \right\} \quad for\ \alpha_{impact} > \ 45° \tag{9}$$

E= the erosion rate in mg/g

The cutting coefficient $\Upsilon = 33316.9$

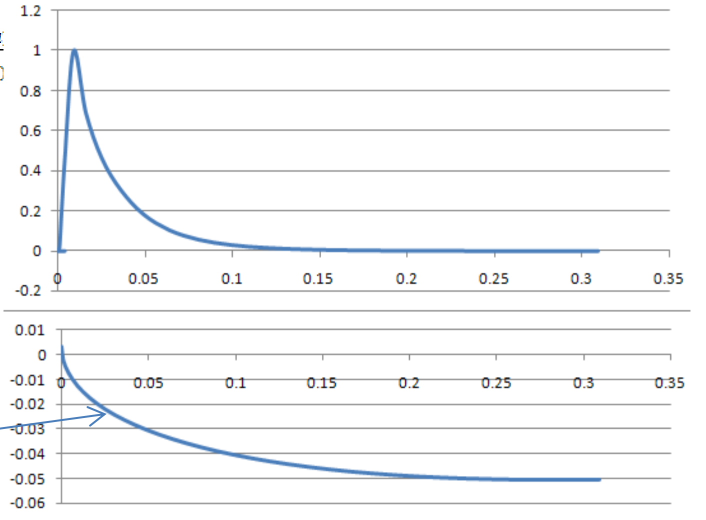
And the wear deformation coefficient $\sigma = 77419.7$

$\alpha_{impact} = the\ impact\ angle$

$u_p = the\ particle\ velocity$

Following the calculation for the erosion rate in each individual point, the erosion rate relative to the maximum was plotted against the airfoil geometry. Figure 6 shows the relative erosion rate distribution near the leading edge of the airfoil.

$$E_{r(local\%)} = 100 \frac{E_{r(local}}{E_{r(max)}}$$



Leading edge
underside

The Relative Erosion Rate near the underside of the leading edge

Fig. 6 – The relative erosion rate distribution near the leading edge of the NACA 3411 airfoil

Next, the erosion rate is used to calculate the new geometric airfoil. This is achieved by locally offsetting the current airfoil geometry proportionately to the relative erosion rate. By convention, the magnitude of the maximal offset (corresponding to the highest erosion rate) is set by the user to 0.01% of the chord. The process is then repeated until the cumulated offset reaches the required imposed value.

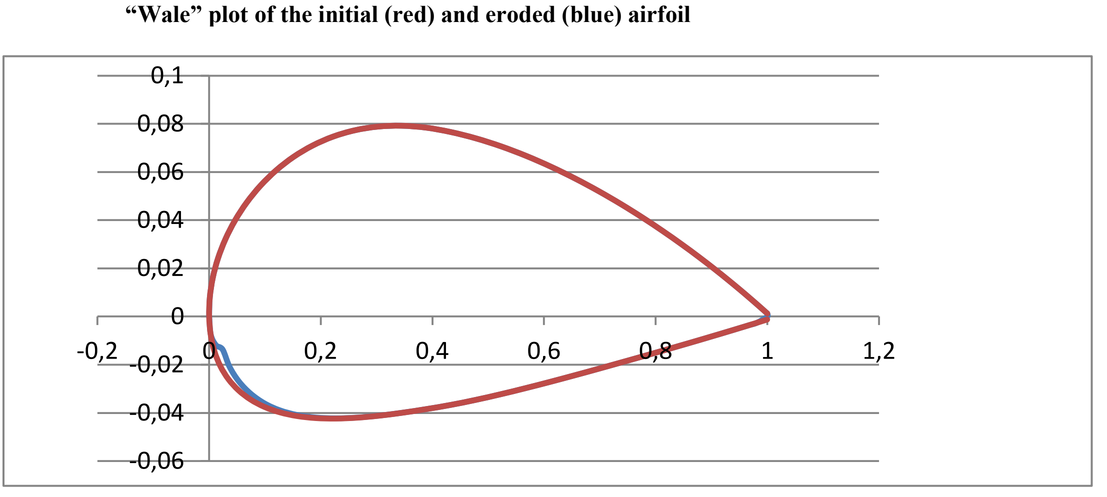


Fig. 7 – The Wale-plot of the eroded airfoil superimposed on the original geometry

5. CONCLUSIONS

The paper deals with the aerosol erosion of helicopter blades, in particular to solid particle micro-impacts. A methodology that combines state of the art fluid dynamics RANS models as well as state of the art erosion models is proposed for estimating helicopter airfoil deformation.

The procedure contains a number of automatic processing leading to lower meshing time requirements and insuring the constant quality of the computational mesh (with implications on the CFD case).

Our contributions may be summed up as follows:

- A semi-automated CFD simulation procedure was developed for solid particle erosion
- An erosion and geometric deformation calculator was developed
- A geometric domain generator for use in ICEM-CFD input which includes
  - Reference geometry for boundaries
  - Airfoil geometry
  - Boundary layer estimation and generation
  - Structured meshing scripts were developed for singular airfoils (with sharp or blunt trailing edges)

Further work may include development of geometry generators for blade arrays (such as fans, compressors and turbines) as well as meshing scripts with improved blocking structures for the above mentioned geometries.

Other erosion models may also be implemented in the erosion calculator, allowing for erosion rates estimations of composite materials Ref [14, 15].

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