Geometric Modeling and Numerical Simulation of Airfoil Shapes Using Integrated MATLAB®and COMSOL Multiphysics®

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Abstract: This paper proposes a framework for an efficient integration betweengeometric modeling program and analysistoolfor a comingautomated aerodynamic design optimization mission.The mathematical modeling of a turbomachinery airfoil shape using NURBS curve is carried outwithin MATLAB, and then is automatically taken to COMSOL Multiphysics for two-dimensional numerical simulation of the flow around the airfoil. To establish an integratedprocess in analysis software, use of LiveLink™ for MATLAB, which is an important option of COMSOL Multiphysics, has been used. The results demonstrate the high ability of COMSOL to be a really helpful analysis tool in an automated design optimization loop.

Keywords: Turbomachinery airfoil shapes, Geometry modeling, Flow analysis, MATLAB and COMSOL integration.

1. Introduction

Over the past two decades, many researches in turbomachinery performance enhancement have been performed with emphasis on compressor/turbine upgrades through optimization of blades' profile shape. Because of themultidisciplinary nature of turbomachines' aerodynamic behavior, however, the designer has to investigate the performance from several different physics point of view involving fluid flow analysis, structural examination, and sometimes fluid-structure interaction considerations. In other words, computer-based simulation of turbomachinery blades -like most other types of engineering analyses- characteristically require multi-physics approach to precisely predict what happens in the real world in compressors/turbines.

On the other hand, in terms of the ability to use the blading process in real applications, a well-organized integration amongairfoil/blade geometrical parameters, fluid/structural analysis results, field experimental data, and optimization program will be a must and can be sorted as one of the most important bottlenecks specifically for industrial applications where computer-aided design (CAD) modeling systems should be integrated with other downstream computer-based processes such as finite element analysis (FEA). This demand can be addressed by using both in-house codes and commercial software such as iSight or modeFRONTIER [1-3].

Among the available alternatives to integrate design and product development processes down to analysis and optimization, COMSOL Multiphysics is mentioned as a strong and reliable tool. This is because of its unparalleled ability to include all relevant physical effects as well as its interface products including CAD import module, LiveLink™ for SolidWorks® and LiveLink™ for MATLAB®[4]. Using this tool, turbomachinery designers/analysts can implement their own integrated blading design/optimization and use the developed geometriesin industrialprocedure in a single environment with several interfaced products.

A well-organized automated integration between geometric modeling program and analysis tool to efficiently model and to precisely analyze a typical complex shape has been developedand reported in this paper. As the case study, the profileparameterizationof the hub section of the first stage rotor blade for an existing heavy-duty gas turbine (GT) compressor is firstly considered by using Non-Uniform Rational B-Splines (NURBS) curve fitting tool. This part is completed using MATLAB R2010b scripts, thanks to its functionality property.Then, a 2D numerical simulation of the flow around the created airfoil shapeis carried out by COMSOL Multiphysics 4.2. Then integration between the geometry and flow analyzer is accomplished using LiveLink™ for MATLAB.

Following this introduction, the problem is clearly stated in Part 2. This section defines our approachto the geometry modeling, and also a brief background on mathematics of NURBS curve fitting tool. In Part 3, we clarify what has been done to integrate COMSOL and MATLAB in our specific problem. Finally, the numerical simulation results have been discussed in the last part of the paper in Section 4.

2. Geometry Modeling in MATLAB

This section focuses on the modeling part of the research work. First, an overview of NURBS curve fitting tool from mathematical point of view is discussed. Then, the strategy used for airfoil geometry modeling by means of the measured point cloud of existing blades and MATLAB programing is presented.

2.1 Background of NURBS curves

In the early 1970s, Cox [5] and de Boor [6] suggested new blending functions $N_{i,k}(u)$ expressed in Equation (1):

$$N_{i,k}(u) = \frac{(u-t_i)N_{i,k-1}(u)}{t_{i+k-1}-t_i} + \frac{(t_{i+k}-u)N_{i+1,k-1}(u)}{t_{i+k}-t_{i+1}} \quad (1)$$

where $N_{i,1}(u) = \begin{cases} 1 & for \;\; t_i \le u \le t_{i+1} \;\; and \\ 0 & otherwise \end{cases}$

Based on this equation, we get the B-Spline curve defined by Equation (2) as follows:

$$P(u) = \sum_{i=0}^{n} N_{i,k}(u)P_i \quad (2)$$

In these equations,*n* is the number of control points used to construct the B-spline, *k* is the order of the curve, *n+k+1* is the number of knot values, and 0/0 is assumed to be equal to zero. This equation gives equally spaced knot vectors in the parameter space and thusthe extracted curve is called a uniform B-Spline curve. Some knot values, however, may be added/deleted so that there will be non-uniform gaps between the knots. These new generated non-periodic/non-uniform curves are also properly matched with CAD systems. In the end, a NURBS curve, which is similar to a non-uniform B-Spline curve, is defined by the following equation:

$$P(u) = \frac{\sum_{i=0}^{n} w_i N_{i,k}(u)P_i}{\sum_{i=0}^{n} w_i N_{i,k}(u)} \quad (3)$$

where *n, k* and *k+n* are as defined above, p_i are control points, and w_i are the corresponding weights of control points. Further details of these curves are available elsewhere [7].

NURBS geometry contains rational functions that enable the extension of surface descriptions in CAD models to a volume parameterization. NURBS curves have some really useful properties involving numerical stability, local shape control or local modification property, coincidence of endpoints with first/last control points, convex hull property and more versatile modification of the created curve.

2.2 Airfoil geometry representation

The point cloudsforseveral sections of an existing GT compressor blade is first measured using a touch trigger probe in a precision measuring instruments laboratory. The geometry modeling based on the collected point clouds and the curve fitting optimization procedure has been coded using MATLAB script and this has been reported in a previous publication [8] by the authors. Then, the blade is dividedinto five sections from the hub to the tip.However, only the first section, i.e. the blade hub sectionhas been modeled, analyzedand reported in this paper.

After indicating the coordinate points of the airfoil profile and selectingNURBS curve fitting as our tool for airfoil shape modeling in this study, based on its merits mentioned in Section 2.1, four curves are separately fitted to the airfoil shape. The method of direct handling of an airfoil shape has been implemented. It means that distinct parameterized curvesare considered to fit the four blade section: the suction surface, pressure surface, leading edge, and trailing edge.

Theinitially defined control points to create a NURBS fitted curve to the airfoil point cloud are not necessarily expected to be the coordinates of an optimal curve fitting. Thus, a genetic algorithm (GA)based optimizationhas been used to locate the optimal position of the control points for a set of open NURBS curves based ona Least Squares Method as an objective function.

It isworthy to mention that this parameterization process will be an important step for both reverse engineering and profile optimization missions. Nevertheless, these goals are not within the scope of the present work.

3. COMSOL and MATLAB integration

To enhance complicated engineering tasks such as modeling and simulation that are beyond the capability of standalone software packages, several integration attempts are reported in diverse fields [9]. Since many of these tools are developed to handle a specific task, the need for smooth and seamless flow of engineering data is sought. For instance, the CAD files generated by designers must be translated into suitable formats for other computer-aided tasks such as analysis, manufacturing, optimization and simulation. In a numerical simulation driven design and product development process, integrating these tasks based on the initial CAD model data is crucial.

In an optimization task, for example, using unguided search and optimization techniques that operate in iterative loops with poor communication with the geometry modeling andthe analysis partis almost unfeasible and computationally expensive. To cope with this problem, an automated integration of geometry and analysis using a COMSOL Multiphysics interface product named LiveLinkTM for MATLAB is proposed. This automated loop is illustrated in Figure 1. The approach involves geometry modeling and optimization in MATLAB and geometry analysis in COMSOL. The interface is realized using COMSOL Multiphysics within the MATLAB scripting environment.

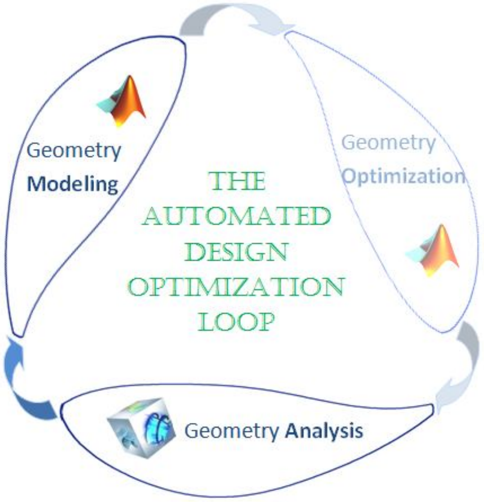


Figure1.The proposed automated loop for aerodynamic design optimization

In other words, the model object is numerically solved at the MATLAB prompt that is in turn implemented in MATLAB m-files. After that, the analysis results are imported at the MATLAB prompt for post-processed data outputs and plots. Moreover, defining model properties such as boundary conditions or material definitions was performed within m-function.

4. Numerical Results

To limit the scope and pages of the paper, we eliminate to describe the CFD governing equations as well as to define common initial and boundary conditions and some other information related to such flow analysis. Everybody can find such information in many literatures and studies on airfoils flow analysis and computational fluid dynamic.

COMSOL Multiphysics version 4.2 and the Heat Transfer Module are used in these simulations. The κ-ε turbulence model is applied as the mathematical tool for the CFD simulations.

The simulations were carried out for three angles of attacks (α); -15, 0 and 15 degrees. The aim is to figure out different pressure and velocity profiles around the airfoil for these angles.

The mesh consists of about 8818 elements for normal mesh size, 3626 elements for coarse mesh size, and 13904 elements for fine mesh size. Figures 2, 3 and 4 (b) show an example of these different mesh sizes applied here. A finer mesh size was carried out without significant impact on the results.

4.1 Zero degree angle of attack

Simulation results with zero degrees angle of attack is outlined in Figure 2. Figure 2(c) shows the surface and contour velocity magnitude, and Figure 2(d) the corresponding pressure. Figures 2(e) and 2(f) depict the corresponding line graphs for velocity and pressure respectively at the airfoil surface.

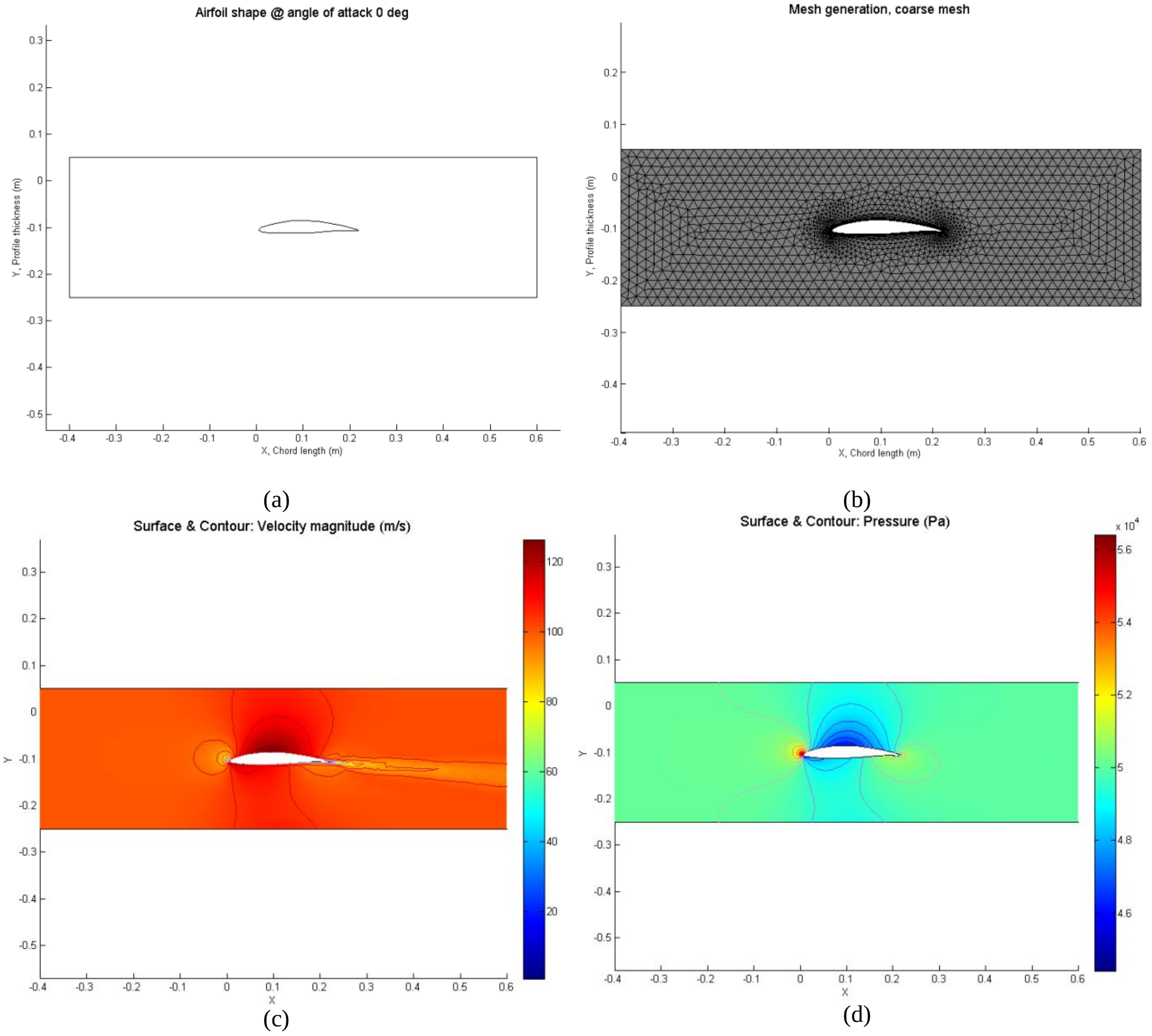
Zero degrees angle of attack gives a maximum increase in velocity at the suction side of about 5 %, and decreases of about 30% at the pressure side (bottom), see Figures 2(c) and 2(e). At the suction side this maximum value takes place about 9 cm from the leading edge. At pressure side, the reduction in velocity shows a relatively flat pattern 5 to 11 cm from the leading edge, from where it falls significantly and achieving a minimum value about 4 cm from the trailing edge. At the trailing edge the velocities are equal and about 50% of initial value. The corresponding pressure is 46 kPa at the suction side. The maximum pressure achieved at the pressure side is 51 kPa. More details are in Figure 2.

4.2 +15 degree angle of attack

According to Figure 3, with +15 degrees angle of attack the profiles change dramatically. At the pressure side the velocity is decreased with 75 – 90 %, highest at the beginning of the first half length of the profile. This gives relative high pressure at the near the leading edge; up to 57.5 kPa. Then the pressure falls considerable over the half profile length, down to below 46 kPa. In average the pressure at the suction side is 46 kPa and at pressure side about 50 kPa.

4.3 -15 degree angle of attack

With -15^o angle of attack the air velocity at the airfoil surface is reduced at both pressure and suction side (Figure 4). At pressure side it's reduced with 40 %, and at suction side 30%. At pressure side the pressure is relative homogenous, varying between 52 and 57 kPa. At suction side the pressure increasing more or less linearly from 42.5 kPa at the leading edge to 50 kPa at the trailing edge, with 46 kPa in average, as shown in Figure 4.

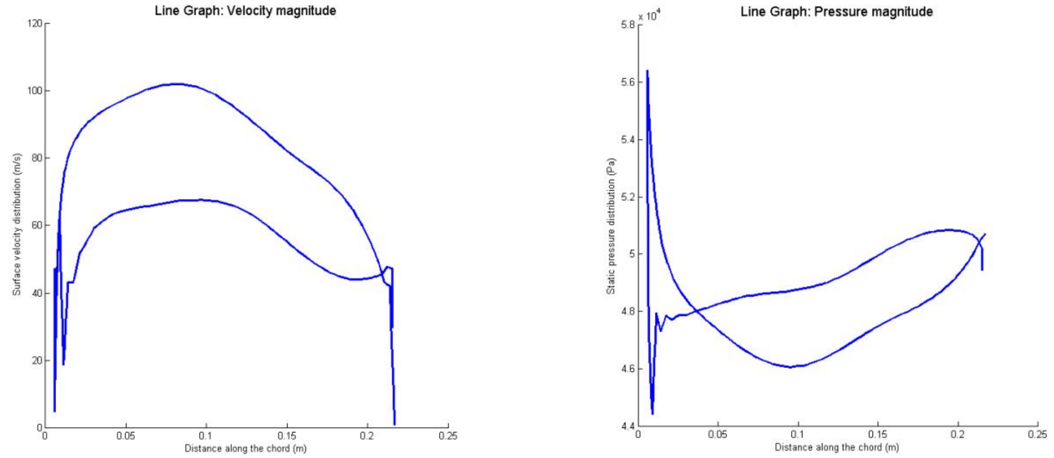


(a)

(b)

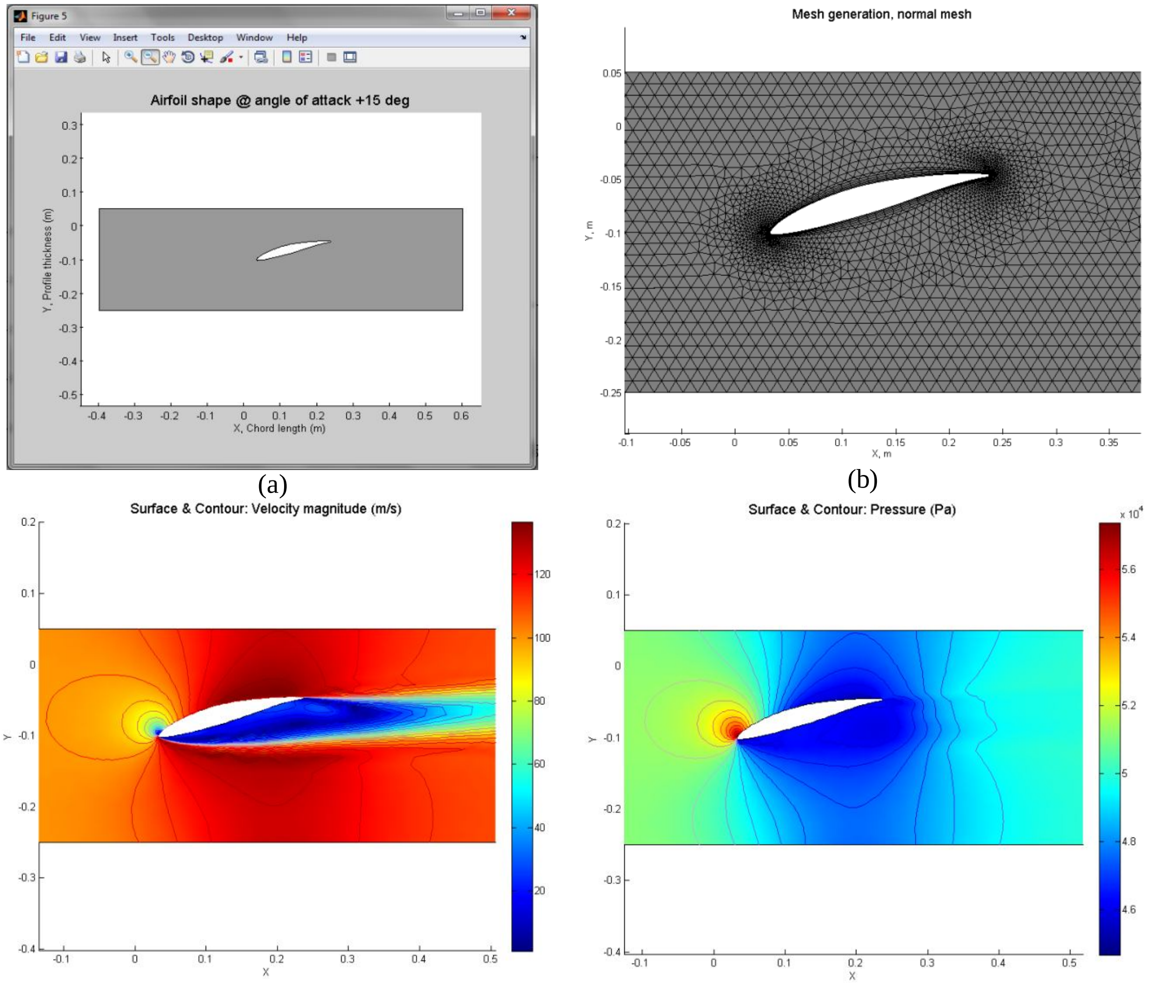
(c)

(d)



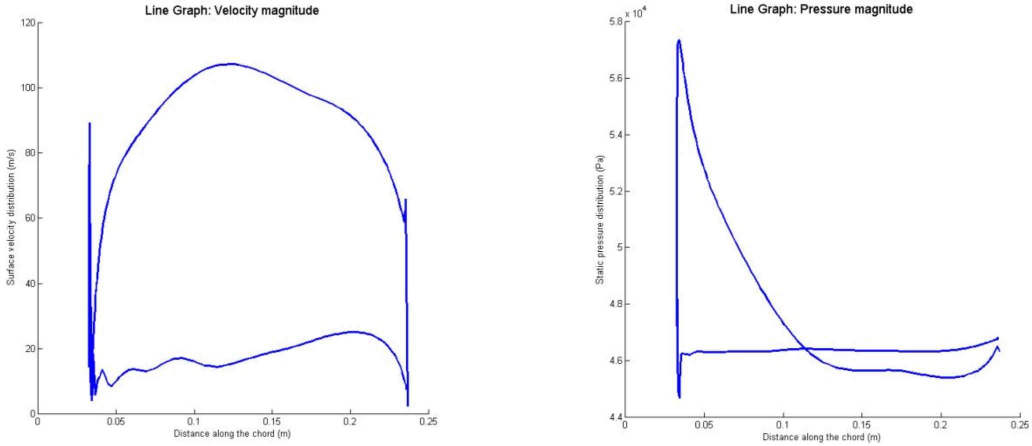
(e) (f)

Figure 2. Hubsection of GT compressor first stage rotor blade at zero angle of attack; (a) airfoil geometry definition, (b) mesh generation, (c) velocity distribution, (d) pressure distribution, (e) velocity graph, and (f) pressure graph. (all figures in MATLAB)



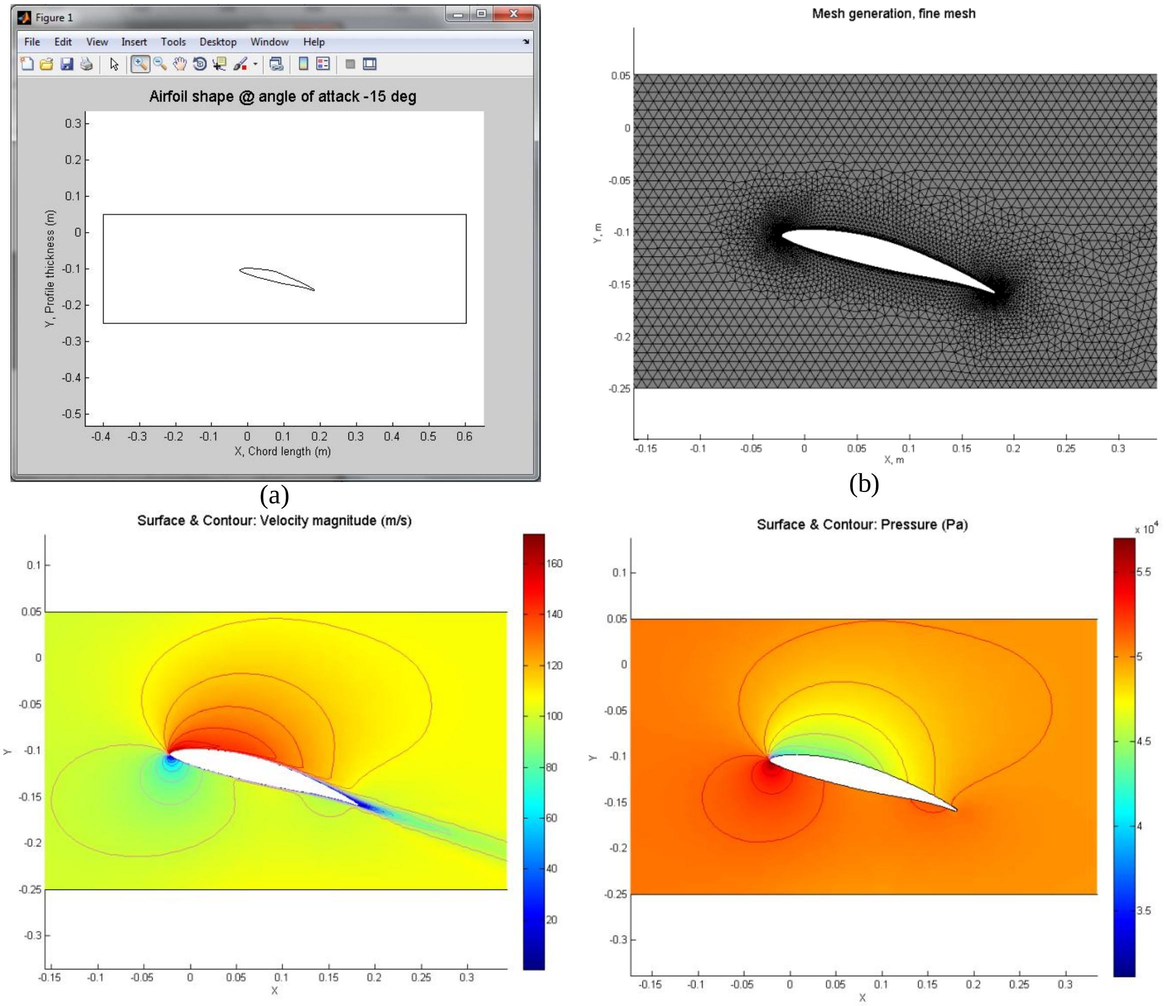
(a) (b)

(c) (d)



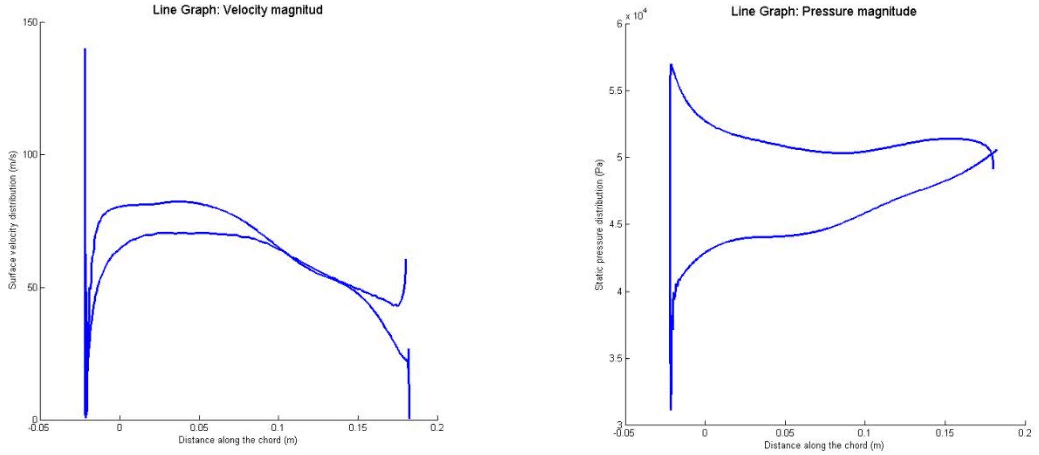
(e) (f)

Figure 3. Hubsection of GT compressor first stage rotor blade at +15 angle of attack; (a) airfoil geometry definition, (b) mesh generation, (c) velocity distribution, (d) pressure distribution, (e) velocity graph, and (f) pressure graph. (all figures in MATLAB)



(a) (b)

(c) (d)



(e) (f)

Figure 4. Hubsection of GT compressor first stage rotor blade at -15 angle of attack; (a) airfoil geometry definition, (b) mesh generation, (c) velocity distribution, (d) pressure distribution, (e) velocity graph, and (f) pressure graph. (all figures in MATLAB)

5. Conclusions

The results demonstrate the high ability of COMSOL to be a really helpful analysis tool in an automated design optimization loop, including geometric models, fluid/structural analysis results, field experimental data and an optimization program. This study, however, included only the geometry modeling and flow analysis parts so that is certainly enough to prove the possibility of using this framework for the ongoing research project in blading optimization.

6. References

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